Terraforming Mars with Self-Replicating Robots and Oxygen

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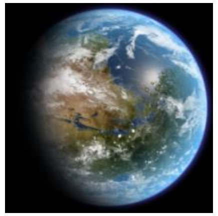
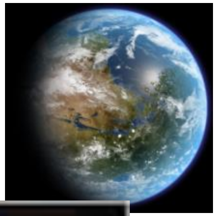
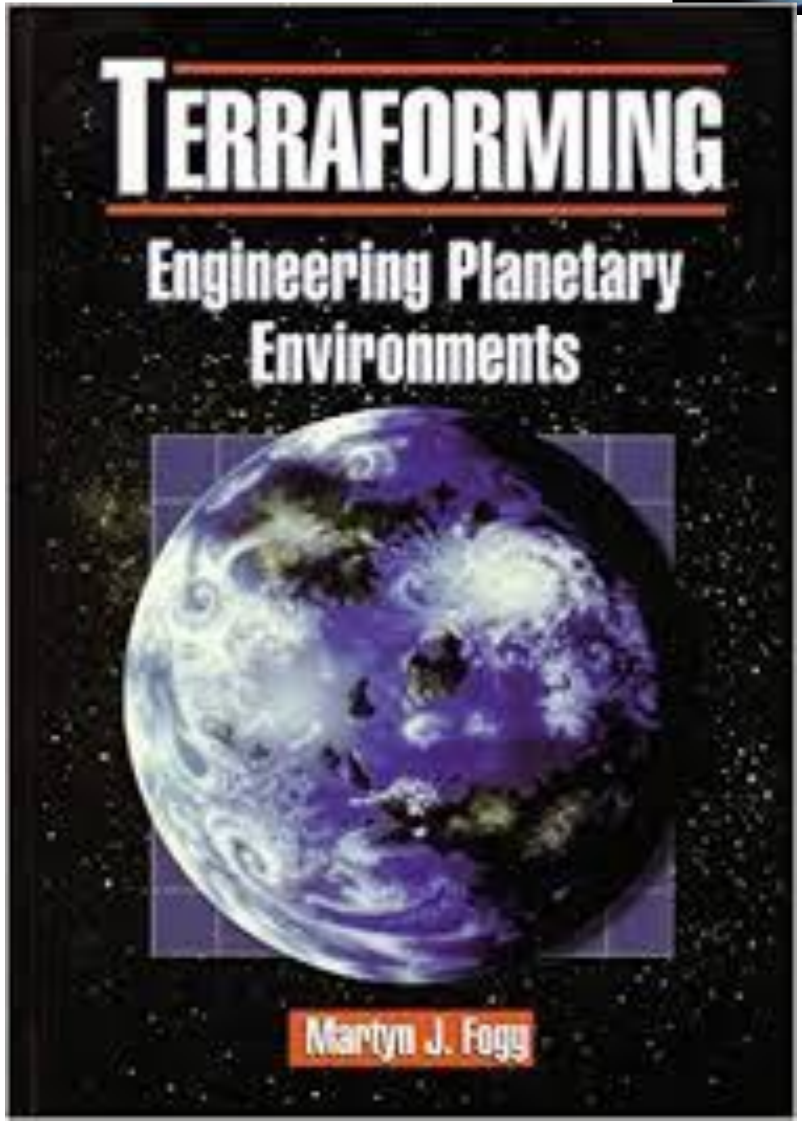
Outline



- Background
- A Very Recent Development in Terraforming
- Review of Previous Mars Terraforming Concepts and Issues
- Similar Prior Concepts
- Basics of Self-Replicating Robots
- Oxygen Production Technologies
- Mars Resources and Processes Needed for Robot Production
- Terraforming Approach
- Summary and Recommendations

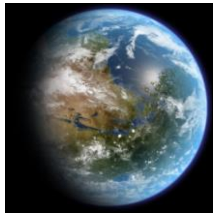
Terraforming: Engineering Planetary Environments





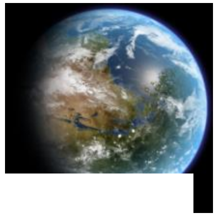
- Martin Fogg, 1995
- Only textbook in the field
- Highly recommended to those interested
- Out of print, but available on Amazon from $256 used
- (https://www.amazon.com/Terraforming-Engineering-Environments-Martyn-Fogg/dp/1560916095)

Very Recent Development – Not Enough CO_2 on Mars

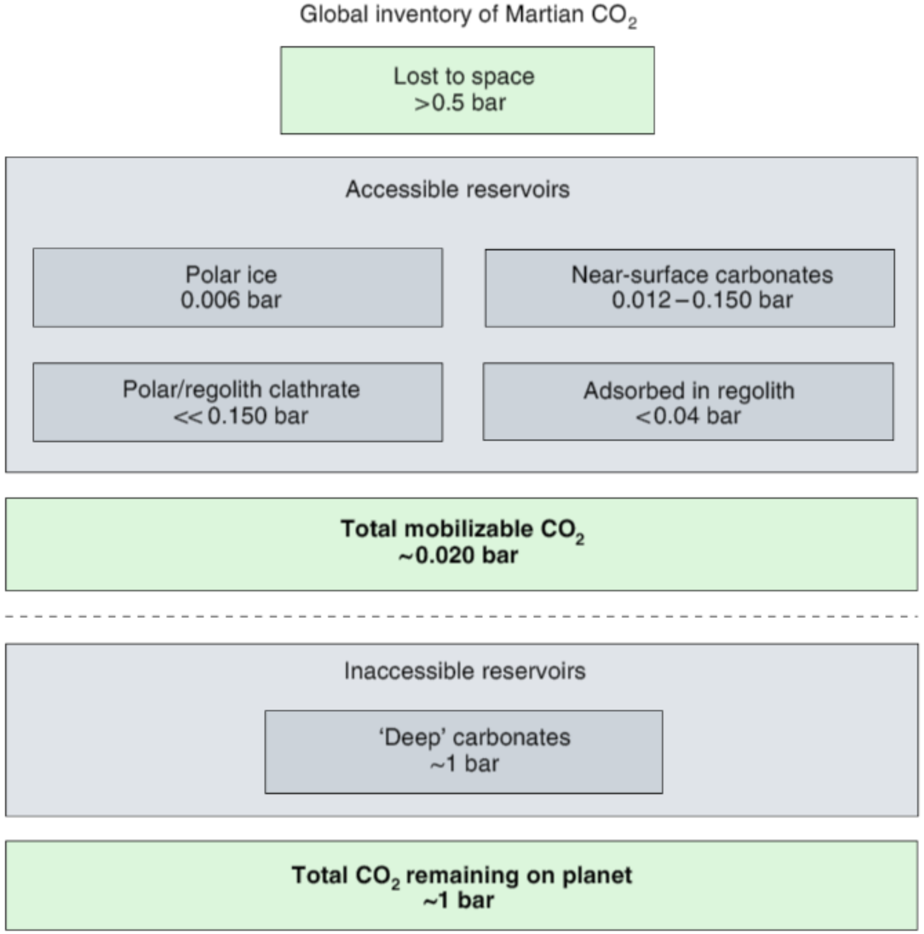


- Jakosky, B. M., & Edwards, C. S. (2018). Inventory of CO_2 available for terraforming Mars. *Nature Astronomy*, *2*(8), 634. (July, 30, 2018)
- Only CO_2 and H_2O are likely to be present in sufficient quantities
- Rejected chlorofluorocarbons
  - "short-lived and without a feasible source using current technologies"
- H_2O alone would freeze out w/o warming by CO_2
- Potential sources of CO_2: polar CO_2 ice and water-ice clathrate, CO_2 adsorbed on regolith, and carbonate rocks
- Current atmosphere = 6 mbar CO_2 = 15 g CO_2/cm^2

Very Recent Development – Not Enough CO_2 on Mars – CO_2 Sources



- Polar CO_2 ice and clathrate: 6 mbar dry ice, 0-150 mb from clathrate
  - Clathrate is unlikely
- Adsorbed CO_2: ~40 mbar (100 g CO_2/cm^2 of 100 m average depth)
  - Takes 10,000 y to reach thermal equilibrium w/warmer surface
- Carbon-bearing minerals: max ~50 mbar – requires ~300°C to release
  - Estimate 12 mbar as max plausible amount to be released
- CO_2 lost to space: currently 1.5 kg O/sec lost, higher early on, & up to 90% loss of original ~1 bar of CO_2 inferred from $^{13}C/^{12}C$ ratio
- Estimate 20 mbar CO_2 total possible → <10 K warming
  - Need ~60 K to have liquid water
  - Need 1 bar CO_2 to warm enough to melt water ice



Global inventory of Martian CO_2

Lost to space
>0.5 bar

Accessible reservoirs

Polar ice
0.006 bar

Near-surface carbonates
0.012–0.150 bar

Polar/regolith clathrate
<<0.150 bar

Adsorbed in regolith
<0.04 bar

Total mobilizable CO_2
~0.020 bar

Inaccessible reservoirs

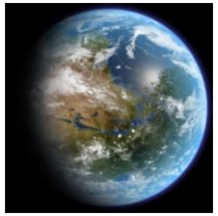
'Deep' carbonates
~1 bar

Total CO_2 remaining on planet
~1 bar

Fig. 3 | Summary of the remaining non-atmospheric reservoirs of CO_2 on Mars, including both those that can be readily mobilized and those that cannot be emplaced back into the atmosphere.

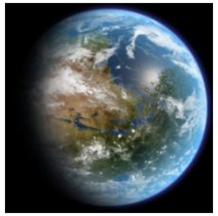
[Jakosky, B. M., & Edwards, C. S. (2018). Inventory of CO_2 available for terraforming Mars. *Nature Astronomy*, *2*(8), 634. (July, 30, 2018)]

Robert Zubrin’s Rebuttal to Jakosky & Edwards



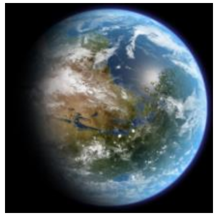
- https://t.co/vAzJmlDQId (Facebook): Refers to Zubrin, R., & McKay, C. (1993, June). Technological requirements for terraforming Mars. In *29th Joint Propulsion Conference and Exhibit* (p. 2005).
- Jakosky ignores making CF_4 (resistant to UV and does not destroy ozone) on Mars
  - Raises T by 10 K, liberates CO_2 from icecap and soil
  - Results in runaway greenhouse effect
  - Can also make methane and ammonia, strong greenhouse gases
- Adsorbed CO_2: if 1% CO_2 in soil → 300 mbar CO_2 in top 100 m, not ~40 mbar
  - Terrestrial minerals can adsorb 10% CO_2 by wt.
  - Takes only 500 y, not 10,000 y to reach thermal equilibrium w/warmer surface based on dry terrestrial soil
- No dependence on carbon-bearing minerals stated by Zubrin
- Zubrin does not address CO_2 lost to space, implying it’s not a factor
- Jakosky estimates 20 mbar CO_2 total possible though listing a total of 400 mb from various sources; “That makes no sense.”
- “the Jakosky paper is systematically pessimistic and without foundation.”

So, Is There Enough CO_2 on Mars?



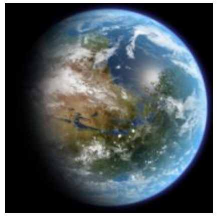
- Very difficult to say whether there is or is not right now
- Various terraforming concepts depend on a substantial inventory of CO_2 on Mars
- Relying on a large inventory is a high risk due to uncertainty
- Alternative methods can rely on more certain volatiles or ways to produce them

Prior Terraforming Concepts – Nuclear Explosives



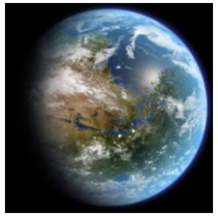
- Mole, R. A. (1995). Terraforming Mars with four war-surplus bombs. *Journal of the British Interplanetary Society*, *48*(7), 321. (http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.663.7945&rep=rep1&type=pdf)
- Depends on using nuclear weapons to spread dark dust on the south polar ice cap to sublimate it
  - Explode one every spring, four times
- Also depends on CO_2-rich Mars surface
- Lots of uncertainties: sinking of dust into ice (more frequent replenishment), wind direction, efficiency of lofting dust, fallout contamination, political issues with use of nuclear weapons

Prior Terraforming Concepts – Asteroid Impactors to Deliver Volatiles and Energy



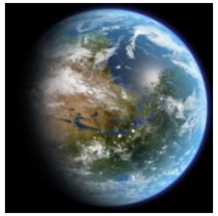
- For example: Zubrin, R., & McKay, C. (1993, June). Technological requirements for terraforming Mars. In *29th Joint Propulsion Conference and Exhibit* (p. 2005). (http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.24.8928&rep=rep1&type=pdf)
- Move outer solar system asteroids rich in ammonia and methane to Mars, if they exist
- Easier to move them than main belt by using gravity assist
- This is very expensive ($ billions) and time consuming, given that it takes many years to get to and from the outer solar system (>28 y transfer time) and prospecting for such asteroids will require an enormous exploration effort
- Each impact is equivalent to 70,000 1-megaton hydrogen bombs!
- Similar issues with other asteroid/cometary impact concepts

Similar Prior Terraforming Concepts – Self-Replicating Robots



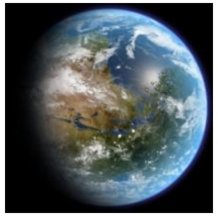
- Mole, R. A. (2003). Terraforming mars with (largely) self reproducing robots. *The Mars Society*. (http://www.marspapers.org/paper/Mole_2002.pdf)
- 100 kg, human-sized robots w/computer chips from Earth (0.5 g @)
- Human base established first with nuclear power
- Robots mine regolith and produce aluminum for major components
- Focuses on converting already-established thick CO_2 atmosphere into O_2 and carbon (which needs to be stored)
- Therefore, rather different from our concept

Similar Prior Terraforming Concepts – Self-Replicating Robots (Cont.)



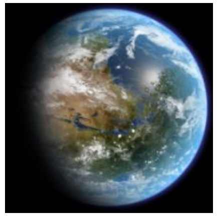
- Zubrin, R. (1995). The economic viability of Mars colonization. *Journal of the British Interplanetary Society*, *48*(10), 407-414. (http://pioneerastro.com/Team/RZubrin/The_Economic_Viability_of_Mars_Colonization.pdf)
- Mentions "self reproducing machines" as a possible method to generate 120 mb of oxygen atmosphere after warming Mars to earthlike temperatures, but no details given
- However, "Since such systems are well outside current engineering knowledge it is difficult to provide any useful estimate of how quickly they could complete the terraforming job."
- Notes self-replicating machines would be solar powered, so the upper bound of system performance is about 30 y if solar efficiency is 30% for entire planet covered with machines converting metal oxides to oxygen

Similar Prior Terraforming Concepts – Self-Replicating Robots (Cont.)



- Freitas, R. A. (1983). Terraforming Mars and Venus using machine self-replicating systems (SRS). *Journal of the British Interplanetary Society*, *36*, 139-142. (http://www.rfreitas.com/Astro/TerraformSRS1983.htm)
- Goal: "a minimum breathable (150 mbar) oxygen atmosphere planetwide, requiring the release of 6 x 10^{17} kg of oxygen into the existing 6 mbar predominantly CO_2 atmosphere" from silicates and oxides
- Average 10^7 J/kg to release O_2 from silicates and oxides on Mars
- Therefore, 6 x 10^{24} joules is needed to generate the O_2
- 24 y to cover Mars w/SRS units (100 tons @), then reconfigure to produce O_2
- 100 tons O_2/replica → 330 y to reach 150 mbar, <100 y if 4.4 tons O_2/y/replica
- Surface of Mars is excavated to 4 m depth, allowing surface to be prepared to create "artificial seas, lakes, canals, roadways, and subterranean agricultural greenhouses or cities"

Similar Prior Terraforming Concepts – Self-Replicating Robots (Freitas, Cont.)



- “The ultimate benefit of SRS terraforming on Mars is a fully industrialised planet, complete with a 10^{12}-ton/year reprogrammable general product factory manufacturing capability, 10^{18} kg of refined byproduct metals (Al, Fe, Ti) or enriched metal ores, and a 10^{10} megawatt self-repairing distributed solar power source for industrial use, or for further terraforming. Alternative terraforming methods provide no comparable benefits.”
- This approach is very similar to ours (but less detailed); we conceived our approach for terraforming Mars w/o knowledge of this work by Freitas, though his other work was (see below)
- [Lesson-Learned: do your background research earlier!]
- Derived from a 350 page report done for NASA: “Advanced Automation for Space Missions” (1982). (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19830007077.pdf)
- Includes “NONTERRESTRIAL UTILIZATION OF MATERIALS: AUTOMATED SPACE MANUFACTURING FACTORY AND DEMONSTRATION”
  - Solves many issues on how to deploy the system on the Moon; applicable to Mars
  - Also at http://www.rfreitas.com/Astro/GrowingLunarFactory1981.htm
- All Freitas’ concepts are general and based on traditional machining and manufacturing, not additive manufacturing (AM), which will greatly simplify the process

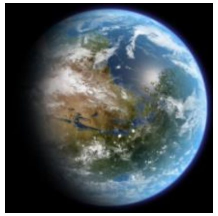
So what do we do?

- Appears to be room for a modified approach based on oxygen production using self-replicating robots
- Can be started robotically before people land on Mars
- While difficult, has the advantage of using a known Mars resource – regolith and well-known chemistry
- Self-replicating robot technology is in its infancy, but advancing
  - Additive manufacturing and 3D printing make it feasible, however
  - RepRap 3D printer makes the plastic parts for a new printer

(https://reprap.org/wiki/RepRap)

(https://en.wikipedia.org/wiki/RepRap_project)

Alex Ellery: Space Applications of Self-Replicating Robots - Examples



- Ellery, A. A. (2015). Are self-replicating machines feasible?. In *AIAA SPACE 2015 Conference and Exposition* (p. 4653).
- Ellery, A. (2015, August). Notes on extraterrestrial applications of 3D-printing with regard to self-replicating machines. In *Automation Science and Engineering (CASE), 2015 IEEE International Conference on* (pp. 930-935). IEEE.
- Ellery, A. (2018, March). The machine to end all machines—Towards self-replicating machines on the moon. In *2018 IEEE Aerospace Conference*. IEEE.
- Ellery, A. A. (2017). Space Exploration Through Self-Replication Technology Compensates for Discounting in Net Present Value Cost-Benefit Analysis: A Business Case?. *New Space*, *5*(3), 141-154.
- Ellery, A. A. and A. Muscatello, (2017). Provisioning the naked astronaut with bounty on Mars using robotic self-replicators, *International Astronautics Federation, 68th International Astronautical Congress, Space Life Sciences Symposium* (also submitted to *Journal of Spacecraft and Rockets*, 2018)

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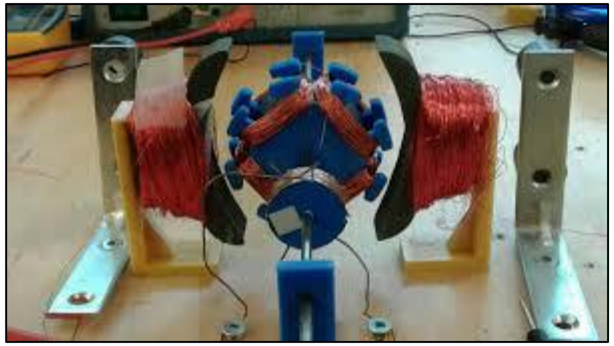


3D Electric Motor Printed with Parts Made with Materials Available on the Moon

Potential for Self-Replicating Robots on the Moon

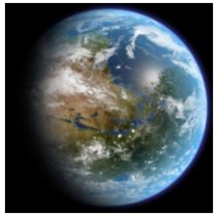
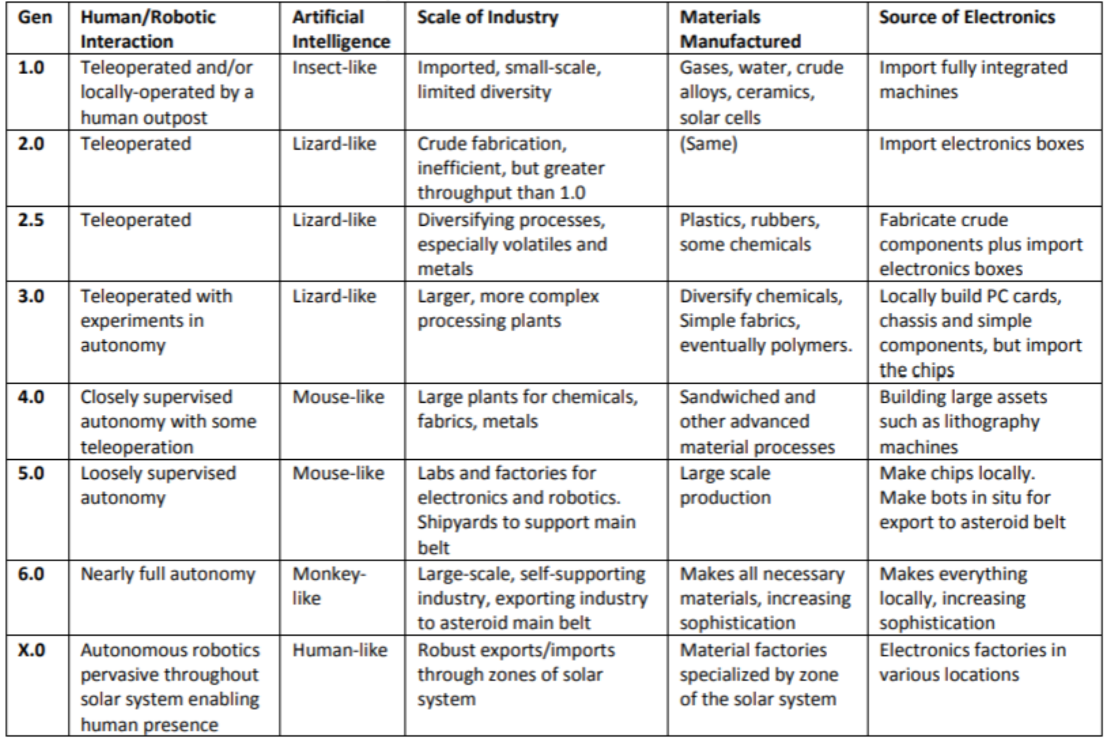
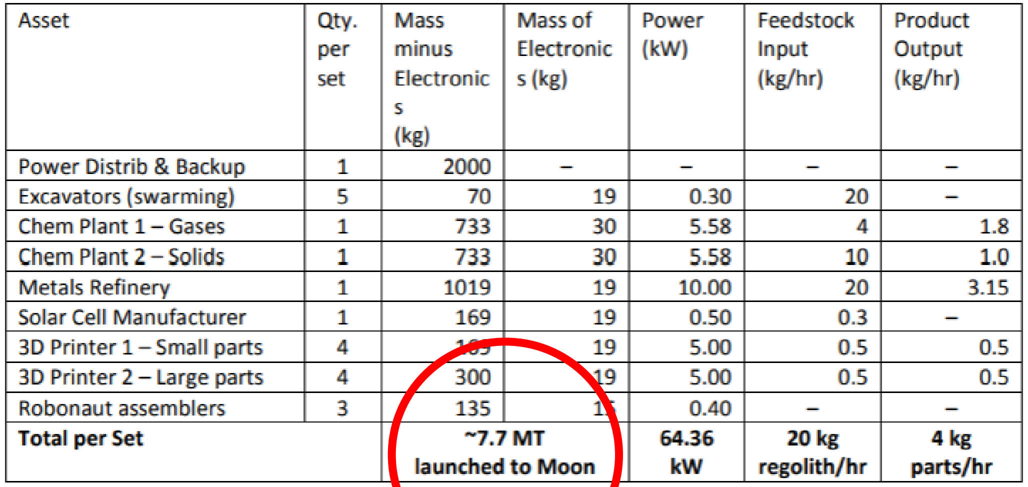


Table 1. Generations of lunar industry.

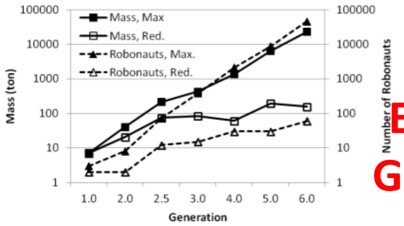


Gen	Human/Robotic Interaction	Artificial Intelligence	Scale of Industry	Materials Manufactured	Source of Electronics
1.0	Teleoperated and/or locally-operated by a human outpost	Insect-like	Imported, small-scale, limited diversity	Gases, water, crude alloys, ceramics, solar cells	Import fully integrated machines
2.0	Teleoperated	Lizard-like	Crude fabrication, inefficient, but greater throughput than 1.0	(Same)	Import electronics boxes
2.5	Teleoperated	Lizard-like	Diversifying processes, especially volatiles and metals	Plastics, rubbers, some chemicals	Fabricate crude components plus import electronics boxes
3.0	Teleoperated with experiments in autonomy	Lizard-like	Larger, more complex processing plants	Diversify chemicals, Simple fabrics, eventually polymers.	Locally build PC cards, chassis and simple components, but import the chips
4.0	Closely supervised autonomy with some teleoperation	Mouse-like	Large plants for chemicals, fabrics, metals	Sandwiched and other advanced material processes	Building large assets such as lithography machines
5.0	Loosely supervised autonomy	Mouse-like	Labs and factories for electronics and robotics. Shipyards to support main belt	Large scale production	Make chips locally. Make bots in situ for export to asteroid belt
6.0	Nearly full autonomy	Monkey-like	Large-scale, self-supporting industry, exporting industry to asteroid main belt	Makes all necessary materials, increasing sophistication	Makes everything locally, increasing sophistication
X.0	Autonomous robotics pervasive throughout solar system enabling human presence	Human-like	Robust exports/imports through zones of solar system	Material factories specialized by zone of the solar system	Electronics factories in various locations

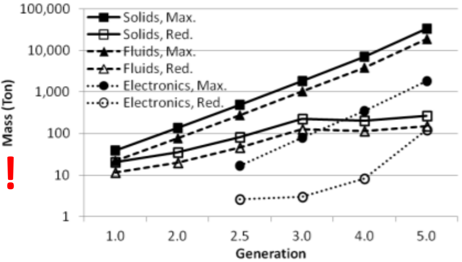
Table 2. Baseline values for Generation 1.0 in Bootstrapping Model.



Asset	Qty. per set	Mass minus Electronics (kg)	Mass of Electronics (kg)	Power (kW)	Feedstock Input (kg/hr)	Product Output (kg/hr)
Power Distrib & Backup	1	2000	–	–	–	–
Excavators (swarming)	5	70	19	0.30	20	–
Chem Plant 1 – Gases	1	733	30	5.58	4	1.8
Chem Plant 2 – Solids	1	733	30	5.58	10	1.0
Metals Refinery	1	1019	19	10.00	20	3.15
Solar Cell Manufacturer	1	169	19	0.50	0.3	–
3D Printer 1 – Small parts	4	169	19	5.00	0.5	0.5
3D Printer 2 – Large parts	4	300	19	5.00	0.5	0.5
Robonaut assemblers	3	135	15	0.40	–	–
Total per Set		**~7.7 MT launched to Moon**		**64.36 kW**	**20 kg regolith/hr**	**4 kg parts/hr**



Exponential Growth Rate!



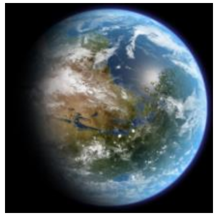
- Metzger, P. T., Muscatello, A., Mueller, R. P., & Mantovani, J. (2012). Affordable, rapid bootstrapping of the space industry and solar system civilization. *Journal of Aerospace Engineering*, *26*(1), 18-29.

Figure 2. Growth of lunar industry by generations in 2-year intervals. Connecting lines are a guide to the eye. Solid markers – Case with maximum manufacturing rate, demonstrating exponential growth. Open markers – case with manufacturing rate reduced by half. Solid lines – mass of assets, including both hardware brought from Earth and hardware built on the Moon. Dashed lines – number of robonauts.

Figure 3. Production of materials and parts by each generation in 2-year intervals. "Max" and "Red." refer to maximum and reduced manufacturing rates. Solids includes both plastics/rubbers and metals, but not electronics.

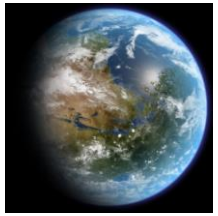
"Bootstrapping space industry can be achieved in a very short time, for relatively little cost, beginning immediately."

Similar Model Needed for Terraforming Mars



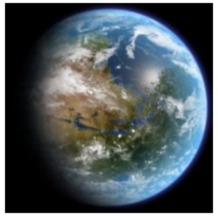
- Not yet available
- But will give similar <u>exponential growth in the number and mass of robots and rate of oxygen production</u>
- Minimal initial mass needed to be landed on Mars
- Minimal supply of electronics w/minimal mass needed early on during the process
- <u>Conclusion</u>: self-replicating robots are feasible for Mars as well
- Some risks with needing more autonomy earlier than the Moon due to light speed time delay and data transfer rates
  - Add crewed teleoperation from Deimos?
    - Delays start till human missions so not as desirable
  - Artificial Intelligence (AI) at a high level would be a better solution
    - “If we can have self-driving cars on Earth, we can have self-directing machinery on Mars”

How Much Oxygen Is Needed?



- Current Mars atmosphere: 7 mbar, 95.97% CO_2, 1.93% Ar, 1.89% N_2, 0.146% O_2, and 0.0557% CO (Curiosity data; Mahaffy, 2013)
- Goal: 300 mb O_2, 0.020 mbar CO_2 (Jakosky estimate for CO_2 availability), traces of Ar and N_2 - ~4.4 psi O_2 vs. 3.1 psi O_2 on Earth (Apollo spacecraft used 5 psi pure O_2, https://history.nasa.gov/SP-350/ch-4-4.html)
  - 300 mb recommended by McKay, Toon, and Kasting (1991)
  - Nothing flammable on Mars right now anyway ☺
- Surface area of Mars is 144,798,500 km^2 or 1.45×10^{14} m^2
- 4.4 psi on Mars requires 4.4/0.376 = 11.7 Earth psi or 8,227 kg/m^2 to adjust for lower Mars gravity
- Total O_2 = 1.2×10^{15} metric tons of O_2 = 1.2 quadrillion tons of oxygen
- Average rate = 120 trillion tons/y (10 y), 12 trillion tons/y (100 y)!

How Much Oxygen Is Needed (Cont.)?



- However, McKay, Toon, and Kasting (1991) modeled an Earthlike atmosphere on Mars:
  - 200 mb O_2, 790 mbar N_2, 10 mb CO_2 (breathable upper limit = 25 x current Earth CO_2 conc.) w/water vapor
  - Initial temperature set at 15^{o}C
- Their Figure 1 (at right) show the system is not stable, with the surface being too warm by ~70 C to be in equilibrium
- Though the 300 mb O_2, 0.020 mbar CO_2 atmosphere has twice as much CO_2, it still probably will not result in mild temperatures on Mars
- <u>Therefore, fluorocarbons need to be added to enhance the greenhouse effect</u>
  - Figure B.1 shows their IR absorption bands-<u>C_3F_8 is best</u>
  - (Martin. Beech. (2016). *Terraforming: the creating of habitable worlds*. Springer.)

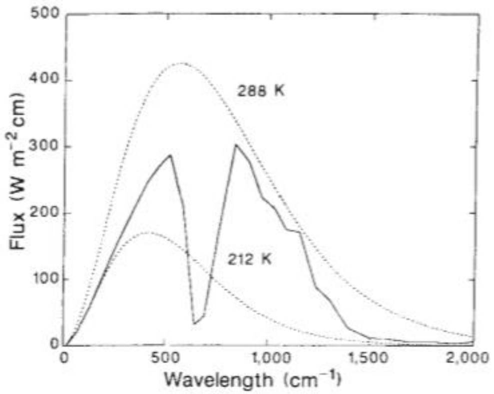


FIG. 1 Thermal balance of a 1-bar nitrogen–oxygen atmosphere on Mars with 10 mbar of CO_2 in equilibrium with water, and a surface temperature set to 15 °C. Shown as the solid line is the thermal infrared radiation emitted from the top of the atmosphere for $T_s = 288$ K. Also shown are the black-body curves at 15 °C and −60 °C (dotted lines). To be in equilibrium, the area under the curve of outgoing infrared flux must equal the area under the curve for the −60 °C black body. The surface is too warm (by ~70 °C) to be in equilibrium.

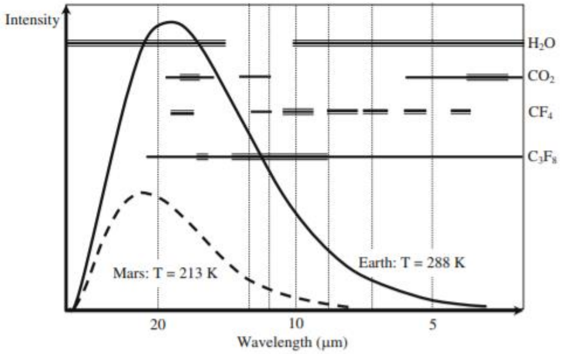


FIGURE B.1. Wavelength absorption bands corresponding to various greenhouse gases. Thick lines represent strong absorption bands, whereas thin lines represent weak absorption regions. The height of the absorption bands in the diagram is schematic and not intended to indicate relative absorption strengths. The wavelength axis is plotted on a logarithmic scale. Diagram based upon data published by Marinova et al. *Journal of Geophysical Research*, **110**, E03002 (2005).

How Do We Make the Oxygen?

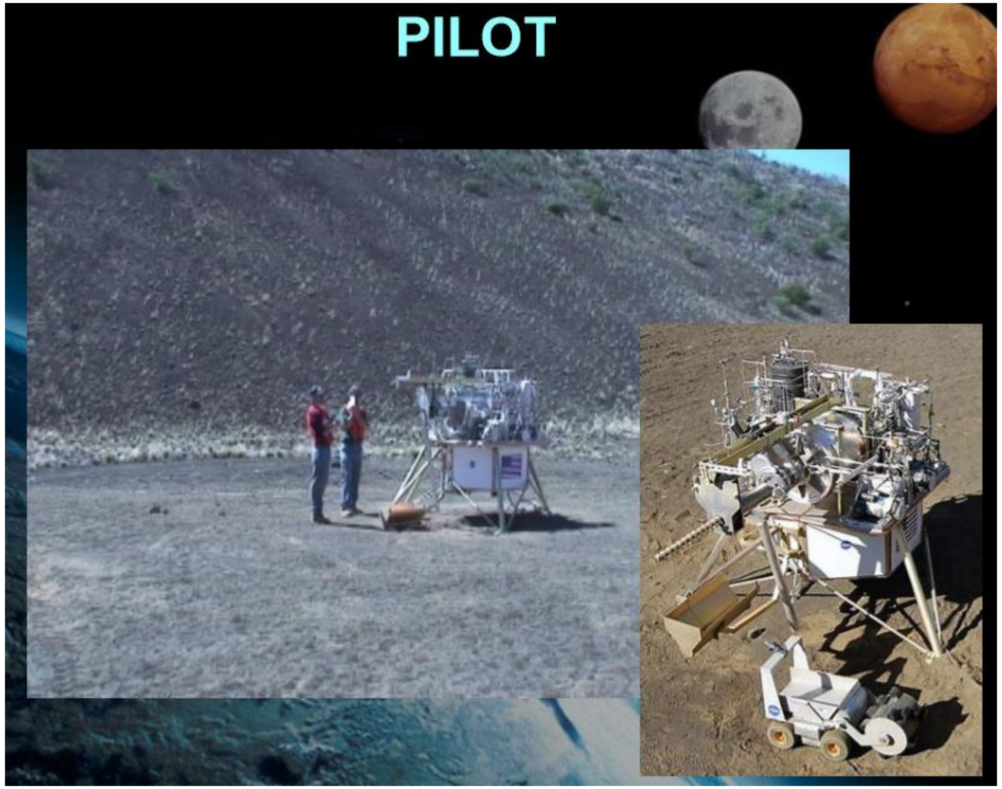
- Three main possibilities:

1. Hydrogen or Carbon Monoxide Reduction of Iron Oxides
    - $H_2 + FeTiO_3 \rightarrow H_2O + Fe^0 + TiO_2$ (T = 900ºC)
    - $H_2O + 2\,e^- \rightarrow H_2 + \frac{1}{2}\,O_2$ (O_2 Yield = ~1-2 wt%)

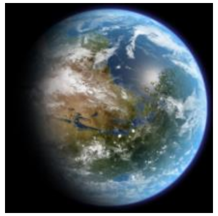
    or

    - $CO + FeTiO_3 \rightarrow CO_2 + Fe^0 + TiO_2$ (T = 900ºC)
    - $CO_2 + H_2 \rightarrow H_2O + CO$ (RWGS Reaction)
    - $H_2O + 2\,e^- \rightarrow H_2 + \frac{1}{2}\,O_2$ (O_2 Yield = ~1-2 wt%)

2008 PILOT (Lockheed Martin) Field Test
1000 kg O_2/y scale



How Do We Make the Oxygen (Cont.)?

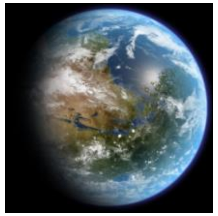


2. Carbothermal Reduction of Metal Oxides and Silicates w/Methane

- Methane Decomposition and Carbon Deposition:
  - $CH_4 \rightarrow C_{(s)} + 2\ H_2$ (T = >1600°C)
- Carbothermal Reduction:
  - $C_{(s)} + (Fe, Ti, Si)O_x \rightarrow x\ CO + Fe^0 + Ti^0 + Si^0$
- Methane Regeneration (Sabatier Reaction):
  - $CO + 3\ H_2 \rightarrow CH_4 + H_2O$ (T = ~400°C) •
- Water Electrolysis:
  - $H_2O + 2\ e^- \rightarrow H_2 + ½\ O_2$
  - O_2 Yield = <15 wt% with acceptable carbon losses
  - <u>10% observed yield during 2010 Field Test of Solar Carbothermal Reduction</u>
- Metals: Fe, Ti (if present), Si (Ferrosilicon alloy)

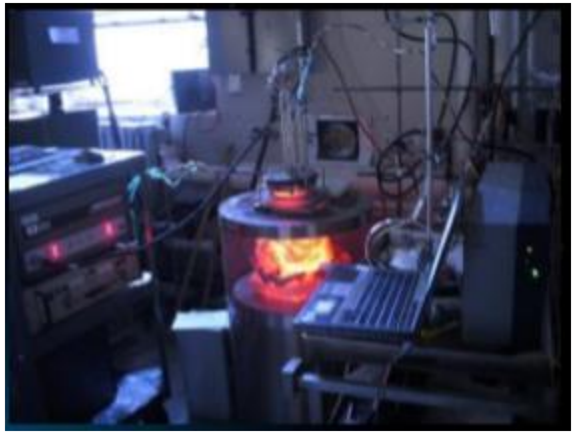
2010 (ORBITEC/PSI)
Field Test
1000 kg O2/y scale

How Do We Make the Oxygen (Cont.)?



3. Molten Regolith Electrolysis (MRE)

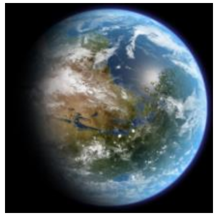
- $O^{-2} \rightarrow 2\ e^{-}$ (cathode) + ½ O_2 (gas) (T = >1600°C)
- Fe^{2+}(electrolyte) + 2 e^{-} (cathode) → Fe^{0} (liquid)
- Si^{4+} (electrolyte) + 4 e^{-} (cathode) → Si^{0} (liquid)
- O_2 Yield = 15-37 wt% depending on scale of operation and feed (lunar mare vs. lunar highlands)
- Metals: Fe, Si (Ferrosilicon alloy)



Furnace containing the cell in operation at 1600°C (MIT)

Small casting of molten ferrosilicon (lower layer) and molten oxide of lunar composition (top layer) withdrawn by counter-gravity suction at 1600°C from reactor furnace (Image credit: Ohio State U./KSC)

How Do We Make the Oxygen (Cont.)?



4. Combined CO/Carbothermal Reduction of Metal Oxides and Silicates and (Pioneer Astronautics, Mark Berggren, 2005, 2018)

- Carbon Monoxide Silicate Reduction System (COSRS)/Extraterrestrial Metals Processing (EMP):
- Iron oxide reduction (T = 800-850°C):
  - $FeO + CO \rightarrow Fe + CO_2$ $\Delta H = -15.7$ kJ
- Carbon deposition (carbon monoxide disproportionation) (T = 600°C):
  - $2\ CO \rightarrow C + CO_2$ $\Delta H = -18.7$ kJ
- Carbothermal reduction (T = up to 1600°C):
  - $FeO + C \rightarrow Fe + CO$ $\Delta H = 156.7$ kJ
  - $SiO_2 + 2\ C \rightarrow Si + 2\ CO$ $\Delta H = 689.8$ k

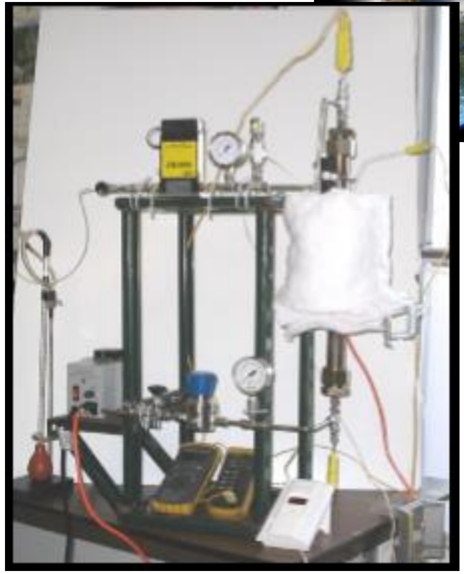
2018 - Extraterrestrial Metals Processing (EMP) system Pioneer Astronautics


Metallic iron from Mars-1 simulant Fe2O3 concentrate

How Do We Make the Oxygen (Cont.)?

4. Combined CO/Carbothermal Reduction of Metal Oxides and Silicates (COSRS) (Cont.)

- Reverse water gas shift (RWGS) reaction (T = 400°C):
  - $CO_2 + H_2 = CO + H_2O_{(l)}$ ΔH = -2.9 kJ
- Electrolysis:
  - $H_2O_{(l)} = H_2 + ½\ O_2$ ΔH = 571.7 kJ
- O_2 Yield = ~15-20 wt%
- Byproducts:
  - SiO (up to 5 wt%) can be reduced to nearly pure Si metal
  - Ferrosilicon alloy, up to 25 wt%



Iron Oxide Reduction - Carbon Deposition Reactor (81 g JSC-1)

Carbothermal Reduction Furnace

Solid Products

Comparison of Oxygen Production Technologies

- Solar Carbothermal Reduction has the highest demonstrated production rate with a reasonable O_2 yield
- <u>All technologies will release water and bound CO_2 during the regolith heating cycle</u>

Initial #1 Choice

Performance Parameters	H_2 Reduction	Solar Carbothermal Reduction	Molten Regolith Electrolysis	Combined CO/Carbothermal Reduction of Metal Oxides and Silicates
Oxygen Yield	1 wt%	10 wt%	15-37 wt%	15-20 wt%
Other Products and Yield (Not 100% Sure About %s)	2.3 wt% Fe	FeSi alloy (up to 25 wt%), ~60 wt% glass	FeSi alloy (up to 25 wt%), ~60 wt% glass	FeSi alloy (up to 25 wt%), Mg (? wt%) ~60 wt% glass SiO, up to 5 wt%
Demonstrated Scale	1000 kg/y	1000/6 kg/y	<100 kg/y	<100 kg/y
Number of Major Steps	2	4	1	4
Special Materials Required	Pt electrodes for water electrolysis	Pt electrodes for water electrolysis, Ru or Ni Sabatier catalyst on silica	Iridium electrodes for regolith	Pt electrodes for water electrolysis
Other Issues	Need to crush glass to get Fe Regenerable water purification	Need to crush glass to get FeSi alloy Regenerable water purification	(Vacuum extraction can collect molten metals separately)	Need to crush glass to get FeSi alloy Regenerable water purification

How Do We Make the Super Greenhouse Gases (SGGs)?

1. The reaction of cobalt difluoride with fluorine gas at 350^{o}C:

   $2 CoF_2 + F_2 \rightarrow 2 CoF_3$ (ΔH = -53 kcal/mol)

2. The organic substrate is passed over a bed of the cobaltic trifluoride and is fluorinated, such as propane:

   $CH_3CH_2CH_3 + 8 CoF_3 \rightarrow CF_3CF_2CF_3 + 8 HF + 8 CoF_2$

3. Any unreacted propane and partially fluorinated products are separated from the octafluoropropane and recycled through the CoF_3 bed after it is regenerated by fluorine
4. Marinova and McKay (2005) determined that octafluoropropane is the most effective SGG, but propane is difficult to produce

<u>Marinova and McKay (2005)</u>

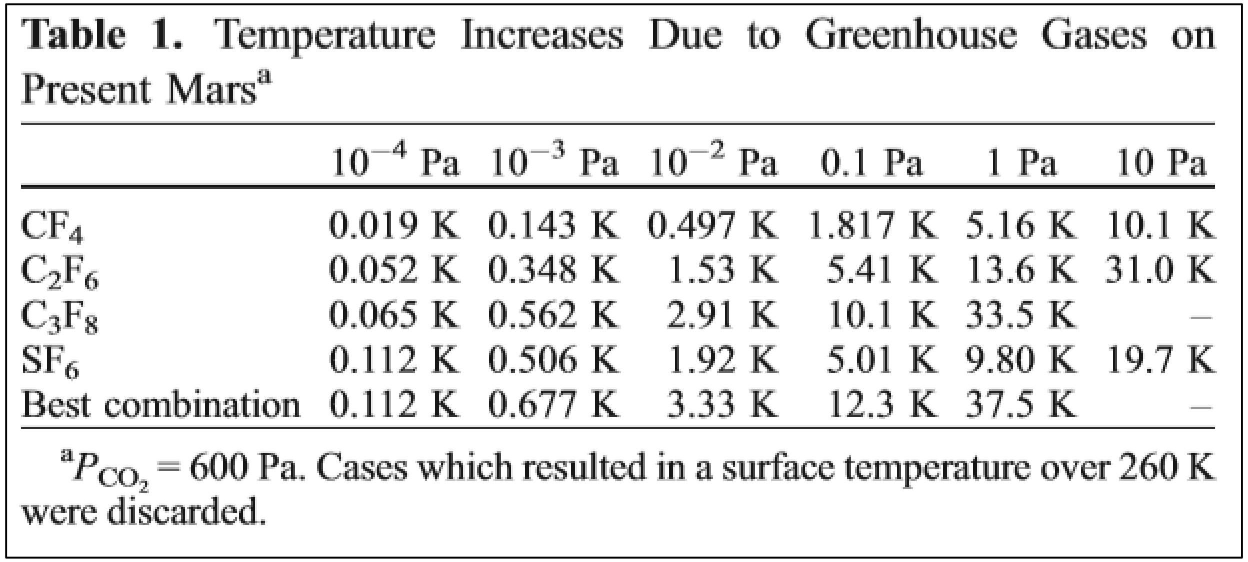


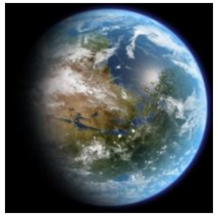
Table 1. Temperature Increases Due to Greenhouse Gases on Present Mars^a

	10^{-4} Pa	10^{-3} Pa	10^{-2} Pa	0.1 Pa	1 Pa	10 Pa
CF_4	0.019 K	0.143 K	0.497 K	1.817 K	5.16 K	10.1 K
C_2F_6	0.052 K	0.348 K	1.53 K	5.41 K	13.6 K	31.0 K
C_3F_8	0.065 K	0.562 K	2.91 K	10.1 K	33.5 K	–
SF_6	0.112 K	0.506 K	1.92 K	5.01 K	9.80 K	19.7 K
Best combination	0.112 K	0.677 K	3.33 K	12.3 K	37.5 K	–

$^a P_{CO_2}$ = 600 Pa. Cases which resulted in a surface temperature over 260 K were discarded.

5. Tetrafluoromethane (CF_4) from methane (CH_4) would be easier, but CF_4 is much less effective than C_3F_8 (5.2 K vs. 33.5 K for 1 Pa each, 10 Pa of CF_4 yields 31 K of temperature increase)
6. So produce 10 Pa of CF_4 or more as needed to achieve the right final temperature
7. C_2F_6, made from ethylene (also needed to make plastic) is better candidate (13.6 K for 1 Pa)
8. **<u>This topic needs more research!</u>**

How Much Super Greenhouse Gases Do We Need?



Marinova and McKay (2005)

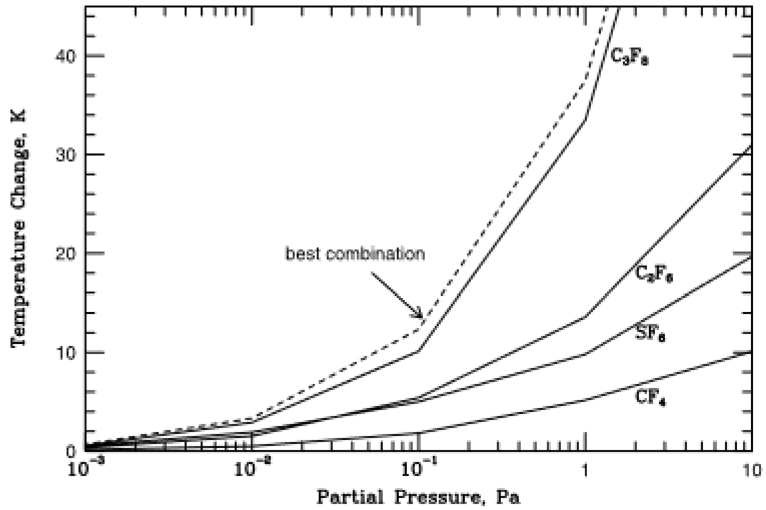
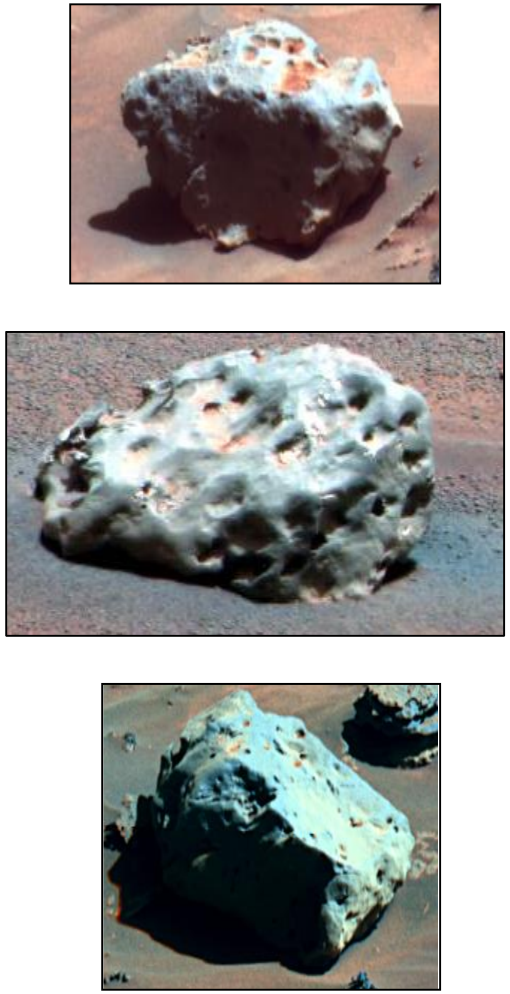


Figure 6. Comparing the warming caused by each fluorine-based gas independently and the best gases combination (dashed line) for the given total greenhouse gas amounts (P_{CO_2} = 600 Pa).

- We have not determined the temperature increase needed to sustain average temperatures over 0^{o}C to have liquid water w/300 mb (30,000 Pa) O_2 + 20 mbar (2000 Pa) CO_2
- **This topic also needs more research!**

Where Do We Get Fluorine, Cobalt and Nickel?

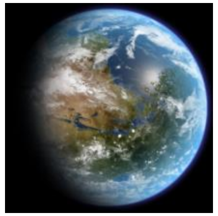
- In 2015, Forni et al. (Forni, O., Gaft, M., Toplis, M. J., Clegg, S. M., Maurice, S., Wiens, R. C., ... & Meslin, P. Y. (2015). First detection of fluorine on Mars: Implications for Gale Crater's geochemistry. *Geophysical Research Letters*, *42*(4), 1020-1028.) reported measurements of fluorine in conglomerates and fluoroapatites and/or fluorites using the ChemCam
    - **Fluorine ranges from 0.6 wt% to 5.5 wt% in various targets**
- Landis (Landis, G. A. (2009). Meteoritic steel as a construction resource on Mars. *Acta Astronautica*, *64*(2-3), 183-187.) notes that **metallic meteorites found on Mars** are a good source for metallic iron, **nickel**, **cobalt** and trace platinum group metals
    - Heat Shield Rock is 93% Fe, 7% Ni, w/trace Ge (~300 ppm) and Ga (<100 ppm)
    - Residue from Fe and Ni extraction by CO is primarily cobalt plus Pt-group metals
    - **>100 kg metallic meteorites are apparently common on the surface of Mars**
    - Yen et al. (Yen, A. S., Mittlefehldt, D. W., McLennan, S. M., Gellert, R., Bell, J. F., McSween, H. Y., ... & Economou, T. (2006). Nickel on Mars: Constraints on meteoritic material at the surface. *Journal of Geophysical Research: Planets*, *111*(E12).) state that “analyzed soils samples and certain sedimentary rocks contain an average of 1% to 3% contamination from meteoritic debris”



Metallic Meteorites on Mars

How Much Regolith Needs to Be Mined?

(A Lot!) – Surface Area of Mars = 1.45 x 10^8 km^2
(Mars Regolith Averages ~100 m Depth)



Process	**Hydrogen Reduction (1% O_2)**	**Solar Carbothermal Reduction (10% O_2)**	**Molten Regolith Electrolysis (20% O_2)**	**Combined CO/Carbothermal Reduction (15% O_2)**
Mass of Regolith to Make 1.2 x 10^{15} metric tons of O_2	1.2 x 10^{17} metric tons	1.2 x 10^{16} metric tons	5.9 x 10^{15} metric tons	7.9 x 10^{15} metric tons
Fraction of the Surface Area of Mars Required (@1.52 g/cm^3 Regolith Density)				
1 Meter Depth	53527%	5353%	2676%	3568%
10 Meters Depth	5353%	535%	268%	357%
50 Meters Depth	1071%	107%	54%	71%
100 Meters Depth	535%	54%	27%	36%

Production Equipment Mass and Power

- No detailed study yet for this application
- Model for Molten Regolith Electrolysis of lunar regolith prepared by Schreiner et al., 2016
- Using predictions at right, e.g. an MRE system with a 4000 kg/y output would mass 600 kg and take 20 kWe @1950 K, w/o power generation, replicators, mining equipment, etc.
- More study is needed to estimate the other items, but a 6.7:1 mass productivity is encouraging for the O_2 generation system

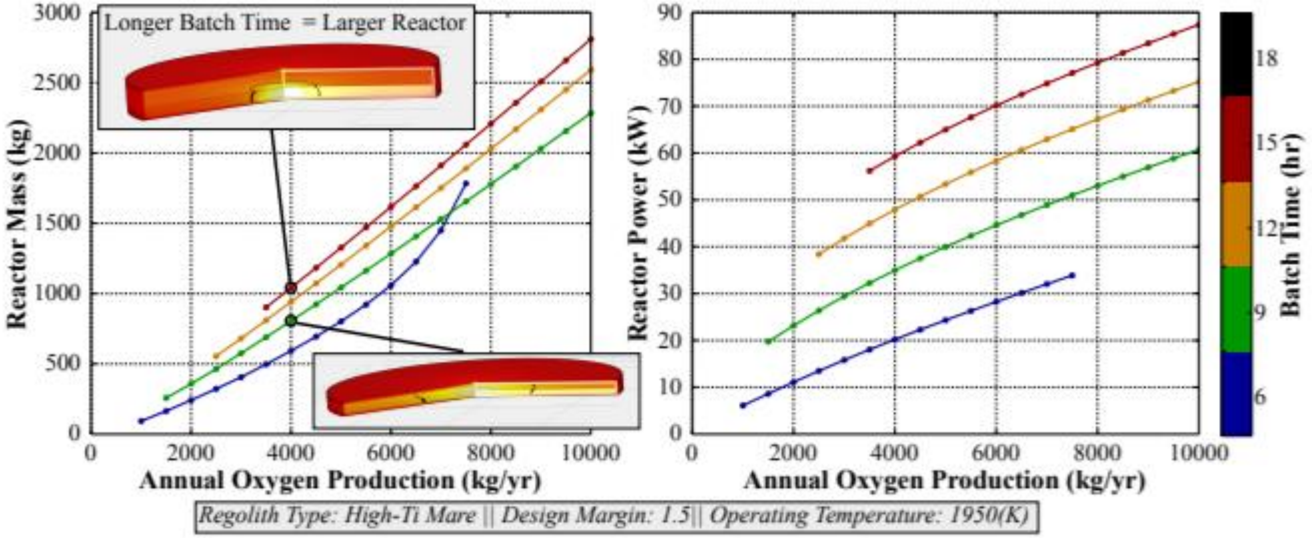
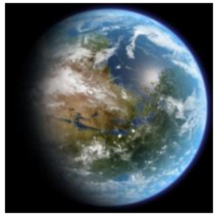


Figure 14: The mass and power of an MRE reactor as a function of oxygen production and batch time. Longer batch times increase reactor mass and power.

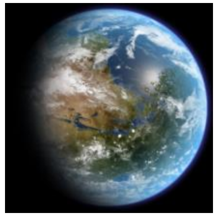
[Schreiner, S. S., Sibille, L., Dominguez, J. A., & Hoffman, J. A. (2016). A parametric sizing model for Molten Regolith Electrolysis reactors to produce oxygen on the Moon. *Advances in Space Research*, *57*(7), 1585-1603. (https://www.sciencedirect.com/science/article/pii/S0273117716000296)]

Use the Last Generation of Robots to Build Settlements



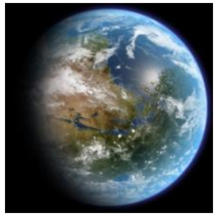
- Once the 300 mb O_2 atmosphere is in place, use the robots to build settlements for people
- Most of the robots can be reconfigured to make many settlements that will have an enormous industrial capacity
- <u>You don’t get just a close to breathable atmosphere (CO_2 removal will be required), you get enough infrastructure for a whole new civilization with room for millions of people!</u>

Other Observations and Conclusions



- A 300 mb O_2 atmosphere will give several very favorable conditions:
- Breathable (w/CO_2 removal to <6 mb)
- No pressure suit required
- Aircraft can fly through it w/o oxidizer on board, allowing aviation on Mars
- Ozone layer will form, shielding the surface from UV radiation and enhancing the greenhouse effect
- Oxygen is a mild greenhouse gas as well (Höpfner, M., Milz, M., Buehler, S., Orphal, J., & Stiller, G. (2012). The natural greenhouse effect of atmospheric oxygen (O2) and nitrogen (N2). *Geophysical Research Letters*, *39*(10).)
- 300 mb requires 8,136 kg O_2/m^2, 80% of Earth's 10,200 kg/m^2, giving 80% of Earth's shielding from Galactic Cosmic Radiation and Solar Flares
  - Equivalent to living in Denver, Colorado
- Water generated during mining can be stockpiled for release when its warm enough

Significant Issues

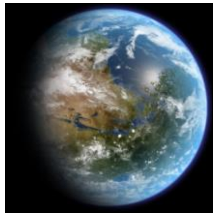


- Platinum on Nafion electrodes for water electrolysis
  - Possibly import from the asteroid belt
  - Possible limited source in metallic meteorites on Mars
  - 2-step thermal splitting of water with iron oxides (Charvin, 2007)
- Iridium electrodes for Molten Regolith Electrolysis
  - Possibly import from the asteroid belt
  - Replace with iron-chromium alloy (needs work)
- Ruthenium on alumina Sabatier catalyst
  - Nickel [from meteorites] works almost as well, if done properly (Lunde, 1974)
- Is there enough power?
  - Solar cells can be made from regolith
  - Direct solar thermal energy w/simple reflectors may be more efficient (can be used to generate electricity as well w/steam)
- Are there enough metals, etc. to make the robots?
  - Needs more work on recoverable amounts

How to Make Gas & Steam Powered mini Electric Generator

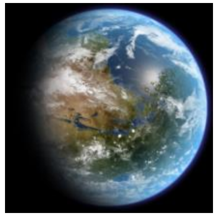
Easy HomeMade Projects
YouTube - Jan 4, 2017

Significant Issues (Cont.)



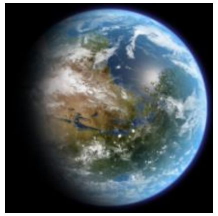
- Dust
  - Needs mitigation, but feasible
- Long-duration dust storms
  - Solution: generate and store methane to burn w/O_2 during storms and possibly to run 24/7 to avoid startup/shutdown cycles
- Solar Flares
  - Need to include some method of shielding the robots
- Will the metals left in the slag reoxidize and soak up the atmosphere?
  - Don’t think so – probably will be very slow with small surface area of melts
- Will plants grow in the processed regolith?
    - Unknown, perchlorates will be destroyed, though

Summary and Recommendations



- Appears to be a feasible concept, though very challenging
- Can be accomplished by mining ~50% or less of the surface of Mars
- Focus on between 45° north and south of the equator to have daily solar power and warmer temperatures
- Need much more detailed design to determine mass, power, and volume of hardware and robots to make O_2, metals, solar power sources (both thermal and electric), ceramics, plastics, wires, electronics, computers, cameras, etc.
- Optimal unit size of mining/production robots needs determination
- **An excellent opportunity for undergrads, graduate students, etc.!**

Questions?



- Mine is: <u>Who knew terraforming a planet would be so complicated?</u>