The Terraforming Timeline. A. J. Berliner[1] and C. P. McKay[2], [1]University of California Berkeley, Berkeley, CA 94704, aaron.berliner@berkeley.edu, [2]Space Sciences Division, NASA Ames Research Center, Mountain View, CA 94075.

Introduction: Terraforming, the transformation of a planet so as to resemble the earth so that it can support widespread life, has been described as a grand challenge of both space sciences and synthetic biology [1,2]. We propose the following abstract on a Martian Terraforming timeline as a guide to shaping planetary science research over the coming century.

Terraforming Mars can be divided into two phases. The first phase is warming the planet from the present average surface temperature of -60ºC to a value close to Earth's average temperature to +15ºC, and re-creating a thick CO_2 atmosphere [3,4,5,6] This warming phase is relatively easy and quick, and could take ~100 years. The second phase is producing levels of O_2 in the atmosphere that would allow humans and other large mammals to breath normally. This oxygenation phase is relatively difficult and would take 100,000 years or more, unless one postulates a technological breakthrough [6].

Pre-Terraforming: Before any terraforming begins, some basic questions must be addressed by robotic and human missions to Mars. These are: (1) The amount of H_2O present on Mars? (2) The amount of CO_2 present on Mars as gas, as ice, or absorbed on soil? (3) The amount of nitrate in the soil on Mars? (4) And, finally, the presence of life, alive or revivable, and the relationship of that life to Earth life. The answers will be crucial to planning any terraforming effort. However, there is also a fundamental question about terraforming itself that we must answered on Earth before terraforming can begin: . (5) What is the purpose and ethical approach for making Mars habitable? It may be impossible to arrive at a unanimous and definitive answer for this, but at the least we need an operational consensus.

Adequate inventories of water, carbon dioxide, and nitrogen (nitrate) present on Mars are key to the practicality of making a biosphere on that planet. We know that Mars has enough H_2O to supply clouds in the sky, rain, rivers and lakes. Presently, this H_2O is mostly in the form of ice in the polar regions and polar caps, but once Mars is warmed this will melt. Carbon dioxide is needed to provide a thick atmosphere to contribute to the warming and which will constitute the thick atmosphere at the end of the warming phase. While CO_2 may be present on Mars in vast quantities tied up in carbonate minerals, this form is not easily released as gas in the warming phase. Only the CO_2 that is easily released as gas as the temperature increases will contribute to the atmosphere during the warming phase. This includes the small amount of CO_2 in the present atmosphere, the CO_2 that is contained in the polar caps, particularly the winter South Polar Cap, and any CO_2 that is absorbed into the cold ground in the polar regions. Once the warming starts all this releasable CO_2 will go into the atmosphere. Thus, it is important to know the total before warming starts. Current estimates of the releasable CO_2 on Mars today range from a little more than the present thin atmosphere to values sufficient to create a pressure on Mars equal to the sea level pressure on Earth. Nitrogen is a fundamental requirement for life and necessary constituent of a breathable atmosphere. The recent discovery by the Curiosity Rover of nitrate in the soil on Mars (~0.03% by mass) is therefore encouraging for terraforming [7]. The current measurements only pertain to surface samples at the Curiosity site but include windblown sand and ancient sedimentary mudstones. For terraforming we need to know the total amount on the planet and given the high solubility of nitrate it may well be concentrated in specific locations.

The presence and nature of life on Mars will definitely affect plans for terraforming. If there is no life on Mars, then the situation is relatively straightforward. However, even after extensive exploration it may be hard to conclude that life is completely absent on Mars rather than simply not present at the specific locations investigated. If life is discovered, then the nature and relationship between the Martian life and Earth life must be determined. If Martian life is related to Earth life – possibly due to meteorite exchange --- then the situation is familiar and issues of what other types of Earth like to introduce and when must be addressed. However, if Martian life in unrelated to Earth life and clearly represents a second genesis of life then significant technical and ethical issues are raised.

The question of possible Martian life leads to the fifth question that must be addressed before terraforming begins. But the overarching question is why, and for who whom, are we altering Mars? If we are determined to make Mars like the present Earth – as implied in the word "terraforming" – then this requires certain levels of O_2 and places upper limits on toxic gases such as CO_2. Alternatively, if we are interested in making Mars a planet rich in life, but not necessarily a world in which humans can move about unprotected, then the presence of a thick CO_2 may be an adequate goal.

Warming Phase (~100 years): The primary challenge to making Mars a world suitable for life is warming that planet and creating a thick atmosphere. A thick warm atmosphere would allow liquid water to be present and life could begin. Warming an entire plant may seem like a concept from the pages of science fiction but in fact we are demonstrating this capability on Earth now. By increasing the CO_2 content of the Earth's atmosphere and the addition of super greenhouse gases we are causing a warming on Earth that is of order a many degrees centigrade per century. Precisely these same effects could be used to warm Mars. Warming the Earth was not the intended purpose of either the CO_2 release or the use of super greenhouse gases by humans and indeed we are now seeking to limit both effects. On Mars we could purposefully produce super greenhouse gases and rely on CO_2 released from the polar caps and absorbed in the ground. The result would be a thick warm atmosphere on Mars. The timescale for warming Mars after a focused effort of super greenhouse gas production is short, only 100 years or so. Effectively, greenhouse gases warm Mars by trapping solar energy. If all the solar incident on Mars were to be captured with 100% efficiency, then Mars would warm to Earth-like temperatures in about 10 years. However, the efficiency of the greenhouse effect is plausibly about 10%, thus the time it would take to warm Mars would be ~100 years. This assumes, of course, adequate production of super greenhouse gases over that entire time. The super greenhouse gases desired for use on Mars would be per fluorinated compounds (PFCs) as these are not toxic, do not destroy ozone, will resist dedgradation by ultraviolet life, and are composed of elements (C, S, and F) that are present on Mars [8]. Fluorine has been detected on Mars by Curiosity [9]. The Warming Phase on Mars results in a planet with a thick CO_2 atmosphere. The thickness is determined by the total releasable CO_2 present on Mars. The temperatures are well above freezing and liquid water is common. An Earth-like hydrological cycle is maintained. Photosynthetic organisms can be introduced as conditions warm and organic biomass is thus produced. A rich flora and fauna are present. A natural result of this is the biological consumption of the nitrate and perchlorate in the Martian soil producing N_2 and O_2 gas. While the pressure is high enough that humans do not need a space suit, they need a gas mask to provide O_2 and prevent high levels of CO_2 in the lungs.

Oxygenation Phase (~100,000 years): To alter the thick CO_2 atmosphere of Mars produced in the Warming Phase to allow for humans to breathe naturally requires that the O_2 levels be above 13% and the CO_2 levels be below 1% of sea level pressure. The high O_2 and low CO_2 levels on Earth are due to photosynthesis which uses light to power the following transformation [$H_2O + CO_2 = CH_2O + O_2$] Where CH_2O is a chemical representation of biomass. If all the sunlight incident on Mars was harnessed with 100% efficiency to perform this chemical transformation it would take only 17 years to produce high levels of O_2.

However, the likely efficiency of any process that can transform H_2O and CO_2 into biomass and O_2 is much less than 100%. The only example we have of a process that can globally alter the CO_2 and O_2 of an entire plant is global biology. On Earth the efficiency of the global biosphere in using sunlight to produced biomass and O_2 is 0.01%. Thus the timescale for producing an O_2 rich atmosphere on Mars is 10,000 x 17 years, or ~ 170,000 years. In the future, synthetic biology and other biotechnologies may be able improve on this efficiency, reducing this to about 100,000 years. The 0.01% efficiency of the biosphere represents an ecological constraint, averaging over oceans, deserts and forests. The intrinsic efficiency of photosynthesis in terms of a unit leaf is much higher, about 5%. If this could be utilized over the entire area of Mars (an unlikely possibility) then the timescale for O_2 production becomes a few hundred years [6].

Next Steps: Given the long-term timeline of a possible terraforming endeavor, we propose the development of a roadmap that outlines the technological processes and advancements required including: (1) adaptation of current and future robotic Martian missions for measuring specific elemental and mineral samples such that a geolocated Martian resource database can be constructed; (2) mathematical modeling of Martian terraforming such that both Martian and Terran resource costs can be calculated for a specific set of terraform-related reactions; (3) development of computational models for biological metabolism under specific conditions in line with the Mathematical terraforming conditions; (4) a focused synthetic biology initative for engineering organisms for Martian in-situ resource utilization; (5) Earth-based experimental systems for emulating Martian conditions for local testing of biological and chemical processes; (6) development of localized para-terraforming systems for evaluating processes in a controlled area on Martian surface and subsurface via probes; and (7) a planetary protection agreement describing restrictions of terraforming processes such that Mars can be maintained for future studies and terraforming can be explored beyond experimental and computational means. We realize that such a roadmap will require the input from many communitites within space scienes, astrobiology, geosciences, and biological sciences. Thus, we argue that, in light of the lengthy timeline outlined above, that we "might as well start now"[10].

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