Towards a Martian Terraforming Roadmap. A. J. Berliner[1], A. P. Arkin[1], C. P. McKay[2], [1]Department of Bioengineering, University of California Berkeley, Berkeley, CA 94704, <aaron.berliner@berkeley.edu>. [2]Space Sciences Division, NASA Ames Research Center, Mountain View, CA 94075.

Introduction: In the next 20-40 years we are planning on landing a small party of intrepid astronauts on our Mars. More than than just a demonstration of technological mastery and beyond the value of the scientific knowledge to be gained, the prospect of opening an entire planet for expansion of the human race and its works is both aspirational and inspiration if wrought through with ethical, social and technological challenges. Development of a detailed technological and ultimately economic and social plan seems a necessary step for understanding all these complexities of large scale colonization. One of the most extreme of the efforts involves the terraforming of an entire planet to make it fit for human existence and the supporting ecosystems we require[1,2]. Here we propose creating a techno-economically detailed roadmap for the possible terraforming of Mars.

There are two critical phases for Terraforming that involve distinct challenges and involve different time scales: (1) a warming phase (~100 years) and (2) an oxygenation phase (~100,000 years).

Pre-Terraforming: But before any terraforming begins, we propose: (1) that a serious planning effort be undertaken to determine the approaches, costs and risks to terraforming based on both accurate quantification of relevant resources, such as water, carbon dioxide, nitrate and other resources and whether there remains existent or extant life on the planet that such actions would disrupt their habitation or our ability to study them. And (2) to launch a serious planning effort for terraforming first entailing the justification of the need for Mars colonization and the scale of such an effort and of course, addressing the ethical concerns of planetary transformation.

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 seeded. While multiple methods for controlled warming have been proposed, a comparitve model of their costs and requirements is needed[3,4,5,6].

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, and 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%. On Earth, the photosynthetic efficiency 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[6].

Planning: 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 (and not in order of priority): (1) adaptation of current and future robotic Martian missions for measuring specific elemental and mineral samples such that a geo-located 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 initiative 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; (7) advances in photosynthetic efficiency engineering; and (8) 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 communities within space sciences, astrobiology, geosciences, and biological sciences. Thus, we argue that, in light of the lengthy terraforming timeline outlined above and that making a quantitative and computable roadmap as a tool for mission planning and science/tech investment will require almost as long to produce, that, in the words and spirit of the fictional Sax Russell, we "might as well start now." [7].

References: **[1]** A. A. Menezes et al. (2015) *J. R. Soc. Interface*, vol. 12, no. 113, 2015. **[2]** C. P. McKay. (2011) *Engineering Earth: The Impacts of Megaengineering Projects*, 2227–2232. **[3]** C. P. McKay et al. (1991) *Nature*, vol. 352. 489–496. **[4]** M. J. Fogg (1992) *Br. Interplanet. Soc*. 45, 315–329. **[5]** J. M. Graham. (2004) *Astrobiology*, vol. 4, no. 2, 168–195. **[6]** C. P. McKay. (2009) *Explor. Orig*. 1–15. **[7]** K.S. Robinson. (1993) "Red Mars".