ROADMAPPING RESEARCH ON WARMING MARS: THE ULTIMATE IN-SITU RESOURCE UTILIZATION CHALLENGE.

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Introduction: We provide updates on research and pathfinder-mission concept designs for habitats and biospheres that can support large numbers of people on Mars [1-2]. Three complementary approaches appear promising: solid-state greenhouse (SSG) membranes offer local warming [3], aiding H_2O/food/O_2 supply near settlements. Orbiting reflectors can warm key sites [4]. Engineered aerosols offer regional/global warming [5-6].

Local warming: SSG materials can warm soil (e.g., aerogel: 3 cm of aerogel gives >60 K warming [3]), melting ice and creating habitats. A near-term application is sublimating ice to give abundant vapor that can be captured/condensed (a Rodwell alternative). *On-Earth testing (Years 0–5):* (a) Assess feasibility of on-Mars aerogel production. (b) Earth-based optical/thermal characterization of candidate bio-polyesters. (c) Seek lighter-than-aerogel SSG materials. (d) Tests of 3D-printer-assisted self-replication of bioplastic habitats [7-8]. (e) Develop pathfinder mission concept. (Even if on-Mars SSG production proves infeasible, SSGs could still support initial bases.)

In-space testing (Years 5–10): Flight-demonstrate (a) SSG materials for warming soil, for example at the Moon. (b) `Moisture farming'. (c) Biomaterial greenhouse. CLPS experiments cost \$4-\$50 mn, so costs of O(\$$10^7$-$10^8$) per Commercial Mars Payload Services experiment are reasonable. As the Mars-warming research community broadens (for more information, see marsterraforming.org), better precursor mission ideas may emerge.

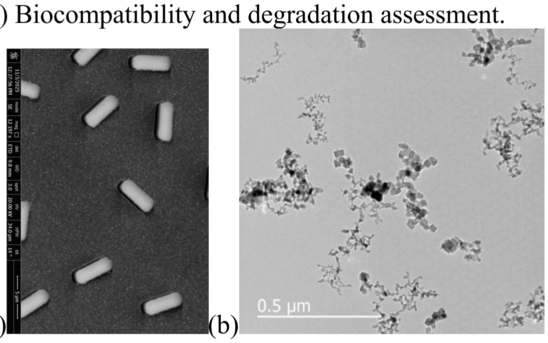
<u>*If research succeeds, potential milestones include:*</u> *Years 10+:* (1) Harvest enough liquid water on Mars to fuel a human-capable lander. (2) Test 3D-printer-assisted self-replication of bioplastic habitats [7-8]. (3) A warming blanket atop a debris-covered glacier drives sublimation and melting; confined by soil ridges, meltwater accumulates as an ice-covered lake sustained by continued melt [9]. The lake can support life.

Orbiting reflectors: Enough CO_2 ice is buried in the S Polar cap to 2× atmospheric pressure [10]. Orbiting reflectors can warm the poles. Reflectors could fly themselves from Earth orbit to Mars [4]. Cost-effectiveness depends on reflector mass, lifetime, and manufacturing assumptions that remain untested. We assume a sun-synchronous 700 km altitude polar orbit at Mars. A 1 km^2 sail [11] reflects light to the pole during ~20% of its orbit, yielding a time-averaged power of ≈75 MW (assuming sufficient attitude control to point precisely and station-keep). To double atmospheric pressure in 35 years, ≈575,000 such sails are needed. To keep costs below \$10bn/year over 35 years, assuming \$100/kg for launch to Low Earth Orbit, 35 year spacecraft lifetime, and \$100/kg sailcraft procurement costs, sailcraft areal density must be ≤4 g/m^2. Beyond doubling atmospheric pressure, reflectors can also supply light, heat, and meltwater to settlements: 1000 sails are needed to 2× time-averaged sunlight over a 20 km^2 area.

<u>*What research is needed to make it practical:*</u> Sailcraft should achieve areal densities lower than current state-of-the-art, requiring extensive in-space testing. As-built sail membranes mass <4 g/m^2. However, a sailcraft that serves as a reflector must also communicate with Earth, direct light efficiently to the targeted region, and control orientation. The trade-off among sailcraft number, size, complexity, and cost has not been studied. *On-Earth research (Years 0–3):* (1) Analyze climate feedbacks of polar warming. (2) Co-design an orbit and sailcraft that allows a stable, useful orbit around Mars with slew control sufficient to warm the S Pole. (3) Pathfinder-mission design: (3a) Design of demo reflectivity-control-device-based attitude control at relevant angular momentum scales. (3b) Alternatively: demo larger sail with (e.g.) reaction wheels, (3c) trajectory design, (3d) design of demo precise & accurate targeting of reflected beam, (3e) deployment design. Design could leverage existing interplanetary solar sail designs [12]. *In-space research:* (1) Flight test in cislunar space of pathfinder spacecraft. Success criterion: controlled flight with 1 km/sec of total photon-induced delta-V. (2) Launch of Earth-to-Mars solar sail flight.

Warming Mars with engineered aerosols: A few million tons of atmospheric aerosol can change a world's climate [6]. However, particles must have an effective lifetime long enough to have the desired climate effect, and degrade harmlessly. Preliminary cost estimates for Mars are on the order of \$0.5–1.0 bn/°C/yr: however, many assumptions underpin cost estimates. <u>*Using Mars' air as feedstock.*</u> Graphene disks and ribbons can resonate strongly with Mars infrared radiation [13]; models predict powerful greenhouse warming. MOXIE proved in-situ CO_2 electrolysis to CO and O_2. Endothermic disproportionation ($CO + CO \rightarrow CO_2 + C$) yields graphene [14]. Assuming N-doping to +0.6 eV [13] and 1-year particle lifetime, the power need to make enough particles to warm Mars globally by 35 K is ~5 GW. <u>*Using Mars soil and rocks to get metals to use as feedstock.*</u> Conductive particles can resonate with Mars IR. 60 mg/m^2 warms Mars by 35 K [6]. Test batches were fabricated in 2025 (Fig. 1a), and FTIR spectra validated simulations. Conductive particles could be made from Mars material. For example, Mars has abundant $MgSO_4$ salts [15]. Highly soluble, they can be leach-separated, for Mg production by carbothermal reduction. This is based on simulations suggesting that the amount of metal needed to warm Mars by >35 K is 60 L/s (for Al; simulations and/or experiments indicate similar volume fluxes for Fe and Mg) (e.g., [6]). Leaching requires H_2O, which could be recycled.

<u>What research is needed to make it practical.</u> *Show that effective particle lifetime can reach ⅓ years.* Particle lifetime against agglomeration depends on particle number concentration and charge state. Clumping might be mitigated by reducing particle number, engineering for radiatively advantageous clumping, design for ease of re-lofting, or anti-stick coatings. *On-Earth research (Year 0 to Year 3):* (1) Dispersal demonstrations. Gating criterion: >80% of particles get >1 km from release site as monomers. (2) Climate feedback analysis including dust cycle. (3) End-to-end analysis of the effect of clumping. (4) Biocompatibility and degradation assessment.



(a) (b)

Fig. 1. Test batches of small particles intended to demonstrate Mars-warming properties. a. Mg nanoribbons on negative-lift-off pillars. FTIR spectra (not shown) confirm Mars-warming radiative properties. (H. Mohseni/A. Bamba/S. Ansari, Northwestern University) b. Mg-aggregates made by aerosol-phase production (A. Boies/C. Jourdain, Stanford University).

If the <u>air-feedstock pathway is chosen:</u> ① Lab demonstrate that carbon-based particles can warm Mars. ② Kg/yr-scale batch production. If the <u>pathway using soil and rocks as feedstock</u> is chosen: ① Verify degradability. ② Pilot factory on Earth; test in dirty vacuum chamber. <u>Get data for microphysical parameters.</u> (1)(a) Measurements of dry deposition rate on Mars-analog sites. (b) Mars-pressure wind-tunnel tests, to assess re-lofting. (c) Clumping measurements. (d) Lab contact angle tests for H_2O ice. (e) Degradability and biocompatibility testing. <u>ISRU factory design maturation.</u> (1) Benchtop in-situ resource extraction experiments. (2) Technoeconomic analysis. *On-Mars research stage (Year 4+) and gating criteria:* (1) Aerosol release process experiment. Success criterion: Release and track >100 g of particles to >100 m altitude, with <50% of particles lost to clumping.

<u>What success could enable.</u> On-Earth ISRU testing should demonstrate a prototype pathway reducing consumables to <20% of initially deployed factory mass over 30 years. Next, a pilot factory on Mars (likely post-human-landing) would prove in-situ particle production. Later, a 2-5 K global warming experiment (doubling Mars' natural greenhouse effect) would create no habitable environments, but test climate feedback models, and modestly moderate temperatures at habitats.

Synergies with human needs on Mars include: (1) *Solid-state greenhouse material for warming ice to enable 'moisture farming' solves a near-term ISRU need.* (2) *A scaled-up MOXIE's waste stream generates feedstock for warming particles.* CO waste stream from CO_2 electrolysis can yield C by exothermic CO disproportionation. Reduced carbon can be used for graphene, bioplastics, or in fertilizer. *Local microbial habitats can make O_2 and biomass supporting settlement.* For biologically produced surface-warming membranes, production would take several years to initiate exponential growth [8].

Risks: 1. Would warming actually allow microbial life? Mars soil is harsh: salty, perchlorate-laden, high UV fluxes, etc. [16]. Membranes can shield life from most stressors. But synthetic biology advances are needed for life under open sky [17]. 2. Waste stream management. Mars-warming particles should break down into biocompatible, climate-neutral materials. 3. Scale-up bottlenecks. E.g., none of the particles in [6] are currently mass-produced, and scaling from lab to full production typically takes >10 yr on Earth.

Conclusion: Relatively modest research investments would keep open the option of extending life beyond Earth as Mars' scientific exploration continues, and inform future policy decisions about Mars.

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