CHALLENGES OF UTILIZING MARS' RESOURCES TO WARM MARS. E. S. Kite[1,2], A. Kling[1], M. I. Richardson[3], S. Ansari[4], R. Ramirez[5], H. Mohseni[4], M.A. Mischna[6], M.H. Hecht[7], L.J. Steele[2,8]. [1]Astera Institute (edwin.kite@astera.org). [2]U. Chicago. [3]Aeolis Research. [4]Northwestern. [5]UCF. [6]JPL, Caltech. [7]MIT Haystack Observatory. [8]ECMWF.

Introduction: Warming Mars could be a step toward making it suitable for life, but would represent a major challenge for planetary science and engineering. Recent work suggests physically feasible methods [1,2], including engineered-aerosol warming [3]. However, before we can assess whether warming Mars is worthwhile, relative to the alternative of leaving Mars as a pristine wilderness, we must confront the practical requirements, cost, and possible risks [4]. In order for engineered aerosol global warming of Mars to start to melt the ice, basic challenges include that particles must be made on (or transported to) Mars, they must:- be released without clumping together, disperse globally, increase the warm-season average temperature of parts of Mars with shallow ground ice by >35 K, persist in the atmosphere for years, and degrade gracefully (without posing a hazard to human health). Moreover, making Mars' surface suitable for life would involve many additional steps beyond initial warming, for example, soil chemistry and suitability for biology [4].

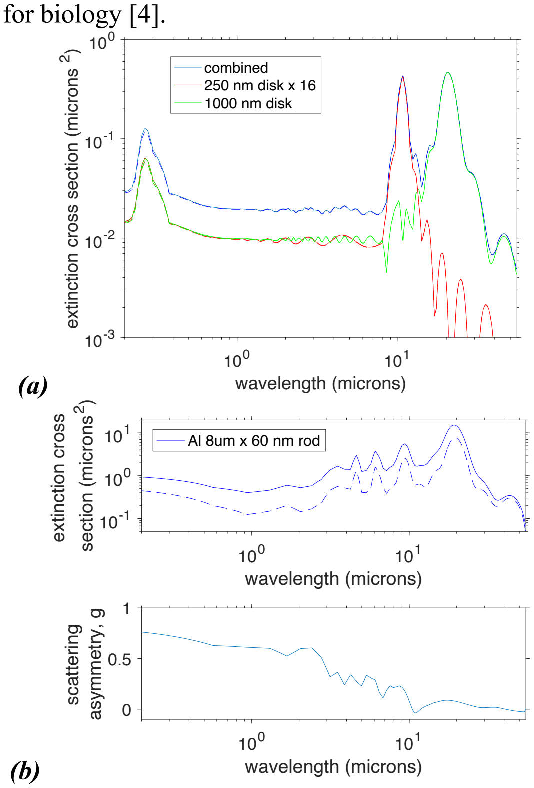

Fig. 1. Spectra for engineered aerosol. *(from 0.3-55 μm)* ***(a)*** *Graphene disk extinction spectrum. Sizes are disk diameters. Dashed lines show absorption contribution (close to 100%). Scattering asymmetry ≈ 0.* ***(b)*** *Al rod (8 μm, 60 nm wide) extinction spectrum. Dashed lines show the absorption contribution. Lower panel: scattering asymmetry.*

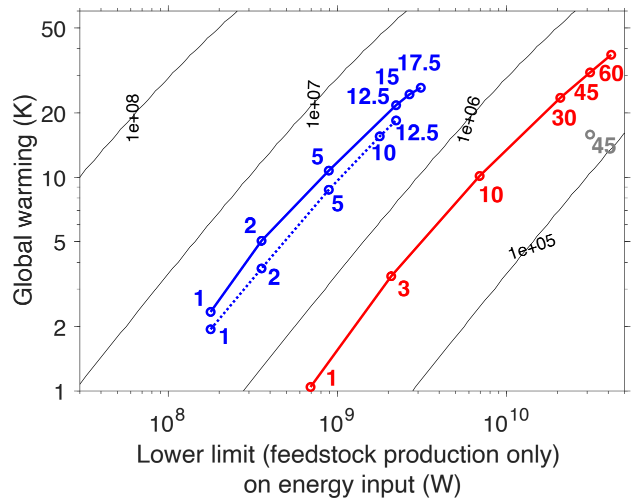

Fig. 2. *Steady-state temperature response as a function of steady-state energy input for graphene disk mix (blue) and thin Al rods (red). Colored numbers: loading rates in L/s. Labels on the thin black contours correspond to the approximate energy gain factor using this method, approximating the power emitted by the surface as σT_{av}^4. Results are from a plume-tracking GCM (MarsWRF, [13,14]). Solid lines: Release at Elysium (0°N, 135°E). Dashed line: Release at Arcadia (39.8°N, 157.9°W). Gray symbol shows the Al particle design emphasized in [3]; the graphene particles are ~20× more energy-effective.*

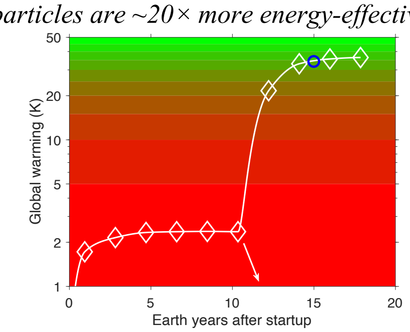

Fig. 3. Time evolution of surface temperature, assuming a 3 L/s global warming test for the first 10 Earth years, followed by a choice to increase to 60 L/s. *After 15 Earth-yr (blue circle), the average warm-season temperature at 47.5°S exceeds 280 K. Al particles assumed. If a choice is made to cease warming then the planet rapidly cools to the no-warming state (arrow).*

Methods: Warming Mars involves closing Mars' thermal infrared "windows" at ~10μm and ~20μm. In this abstract we emphasize graphene disks [7] (mix of 250nm and 1000nm diameters in 16:1 number ratio). (We also modeled Al nanorods: 60nm-width, 8μm long, one-eighth the mass of the particles in [3]). We calculate optical properties using FDTD electromagnetic simulation (Fig. 1) and estimate production requirements using a plume-tracking MarsWRF Global Climate Model (GCM) including radiative-dynamical feedbacks (Fig. 2). Graphene disks offer both advantages and disadvantages relative to Al rods. Energy efficiency is significantly improved, as graphite feedstock production via CO_2-electrolysis (demonstrated by the Mars OXygen In-situ resource utilization Experiment (MOXIE) on Perseverance [5]) requires less power than Al production. Graphene's UV absorption spectrum fortuitously matches that of ozone (Fig. 1), potentially ameliorating Mars' UV-B challenge to surface life without requiring oxygen production. On the other hand, peak extinction efficiency is lower for graphene disks, and the particle number density is higher, so preventing agglomeration is a bigger problem. Other options worth investigating include nanoribbons, other C nanomaterials, or Mg, and orbital deployment.

Production challenges for two-fold increase in Mars' greenhouse effect: As a point of comparison, we estimate requirements to double the strength of Mars' greenhouse effect and warm Mars globally by ~5 K (three times more than human-induced global warming of Earth). This is far below the warming needed to start to melt the ice. For this scenario, we assess mass flux requirements of 2 L/s (Fig. 2) and power requirements for producing graphene of approximately 360 MW (analysis uses [6-8] as a starting point).

Co-production of graphene and O_2 theoretically has the potential to require less overall energy than producing O_2 alone. Since a large mass of O_2 is needed for propellant for launches from Mars (e.g. 1,200 tonnes for a Starship launch), and humans need ~0.6 tonnes/(Mars year)/person of O_2 to breathe, it is of interest to quantify the synergy by coupling graphene and O_2 production. Subsequent steps in particle production (size sorting, etc) may be significant in terms of energy. In particular, the graphene disks' optical properties (wavelength of the peak of resonance, the width of the peak, etc.) change with the size of the disk [7]. Hence, the graphene disk size needs to be quite precisely controlled and the disks need to be uniform in size (the disks we have simulated are also very small which can make size control and uniformity more challenging). The methods that can produce high-quality uniform graphene are usually limited in throughput. One might try to generate randomly shaped flakes of graphene and only sort the ones that satisfy the size criteria. However, yield may be low leading to a need for recycling (or more energy). Building up such a system would require many Starship-class landings each opportunity [9] sustained for over a decade.

Power might be supplied by compact high-output power sources or by solar panels made in-situ (e.g., Blue Alchemist); in the latter case, the main ingredients for warming Mars might be Mars' air and sunlight. Graphene might be produced via CO disproportionation (Boudouard reactor), liquid-phase shear exfoliation [10] or flash Joule heating [11]. This simplified workflow omits many practical challenges. Near-release clumping must be prevented. Precipitation in the warmed climate might remove particles. Non-stick coatings might solve both issues but complicate production. Functionalization (irradiation, doping) and liquid adjuvants may also be required. This could further increase the required number of landings.

Discussion: Many additional challenges remain outstanding and require further research. These include preventing agglomeration during dispersal, functionalization for optimal performance, and anti-stick coating development. Production would involve scaling graphene production beyond current capabilities. Deployment issues include optimizing release timing and location. For full deployment scenarios targeting >30 K warming, additional uncertainties involve climate feedbacks. These include changes in dust storm frequency and water cycle feedbacks [12]. Full warming would harness around 10^{16} W of sunlight energy. Particles must be engineered to break down in the natural environment. Methods include (for rods) adding spacers, designing for water solubility, further thinning for oxidation frangibility, and functionalization. Graphene particles might offer additional benefits if doped with soil nutrients.

Next steps: Although much more modeling and laboratory work is needed, ultimately small-scale and reversible experiments would be needed to validate models. Initial spacecraft experiments might validate the self-lofting behavior seen in our simulations. If successful, global warming might proceed cautiously and reversibly. Fig. 3 demonstrates this approach using subscale infrastructure to achieve modest global warming, with many options for climate evaluation and optional offramps before reaching the 273K-season-at-50°S threshold. This work used the MarsWRF GCM [13,14]. See our LPSC 2025 abstracts for more details.

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References: [1] Wordsworth R. et al. (2019) *Nat. Astron.*, 3. [2] Handmer C. (2024) *10th Mars*, #3025. [3] Ansari S. et al. (2024) *Sci. Adv.,* 10. [4] DeBenedictis E. et al. (2025) *Nat. Astron.* in press. [5] Hoffman J. A. et al. (2022) *Sci. Adv.*, 8. [6] Rapp D. & Hinterman E. (2023) *Space: Sci. & Tech.*, 3. [7] Fang, Z., et al. 2013. *ACS Nano*, 7. [8] Hinterman, E., PhD thesis, MIT, 2022. [9] Heldmann J. L. et al. (2022) *New Space*, 10. [10] Paton, K., et al., *Nature Materials*, 13. [11] Luong, D., et al., 2020. *Nature*, 577. [12] Madeleine, J., et al. (2014) *GRL*, 41. [13] Richardson M. I. et al. (2007) *JGR-Planets*, 112. [14] Toigo A. et al. (2012) *Icarus*, 221.