

In-situ Resource Utilization for Mars Terraforming Nano Particle Material.

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Introduction: Mars terraforming has been considered for over 50 years [1], attracting interest from both scientists and engineers. Most proposed schemes begin by raising the planet's surface temperature to enable water ice to melt [2]. Among various approaches, aerosol-based heating offers a promising first step: dispersing particles into the atmosphere that trap outgoing infrared radiation while transmitting incoming solar radiation. Mars' winds disperse solid aerosol (mineral dust) to heights > 30 km [3]. Models indicate that global mean temperatures could rise by 30 K, provided that million-ton scale quantities of aerosol are deployed [4] [5].

Transporting such vast quantities of aerosol from Earth is impractical, which motivates in-situ production on Mars. Ansari et al. examine elongated conductive nanoparticles, specifically Al [4]. The article also mentioned the potential for using Fe. Their model indicates Al nanorod column density of 160 mg/m^2 yields surface temperatures and pressures permitting extensive summertime liquid water in locations with shallow ground ice, which is a necessary first step toward terraforming. The lifetime of nanoparticles in Martian atmosphere is still not determined but unlikely to be > 1 Earth year [5].

The overall CONOPS of the engineered-aerosol warming method is shown in Figure 1. This study evaluates ISRU architectures for producing Mars warming aerosol materials, comparing power and mass trade-offs across candidate approaches, with findings intended to inform technology development for the initial phase of Martian atmospheric engineering. Nanoparticle fabrication and dispersion are beyond the scope of this work.

Target Material: The material for the Mars warming nanoparticle must:

- 1) Be extractable in abundance from the resources on Mars.
- 2) Be convertible to engineered aerosols that trap outgoing infrared radiation, and transmit incoming solar radiation, while remaining in the atmosphere for as long as possible.

Criteria 1) can be evaluated using Mars mission data. Three primary sources of material are available: the soil, the atmosphere, and localized mineral deposits. Mars' atmosphere is 95% carbon dioxide. [7]: a potential source of carbon. Mars is more geologically diverse than the Moon, with local mineral deposits including Mg sulfate-rich formations [8] [9], in Gale, Meridiani & Valles Marineris.

Assessing criteria (2) requires optical constants and numerical calculations, which so far have been carried out for only selected particle sizes, shapes and compositions[4][5]. Combining the criteria, we prioritize Al, Fe, Mg, Mg sulfate, and carbon as potential material.

Proposed Architecture:

Molten Regolith Electrolysis (MRE) Architecture. This architecture uses Molten Regolith Electrolysis to extract metallic elements directly from Mars regolith. The primary target materials are Al, Mg, and Fe. Two operational scenarios are considered: one in which all extracted metals (Mg, Al, Fe) are utilized, and another in which only a single target metal is used [10].

Salty Rock Water Leach Architecture. This architecture targets salty rock deposits to extract either Mg or MgSO_4 . The rock is first crushed, then leached with water at 20°C to dissolve the MgSO_4 from the matrix. Two products are possible: drying the resulting brine yields MgSO_4 directly; obtaining metallic Mg requires additional steps in which SO_3 is evaporated from the salt, leaving MgO , which is then reduced via carbothermal reduction [9].

MOXIE-Based Carbon Architecture. Carbon nanoparticles can be produced as a byproduct of atmospheric processing. A scaled-up MOXIE system extracts oxygen from the Martian CO_2 atmosphere; rather than collecting the oxygen, the CO byproduct is redirected to a Boudouard reactor where elevated temperature drives carbon deposition and collection. Because the Boudouard reaction is exothermic and the MOXIE exhaust stream is already heated, no additional external power is required for the carbon deposition step [6].

Acid Leach Architecture. This architecture uses sulfuric acid to leach metal oxides from the soil. Sulfuric acid is formed from water and MgSO_4 recovered from salty rock. pH gradients then separate the dissolved metals by element. The extracted metal oxides are subsequently reduced to pure metals via carbothermal reduction, which also generates CO that can be recycled through the Boudouard reaction to regenerate solid carbon. This architecture is capable of producing Al, Mg, and Fe [11, 12].

Result: Overall system, and power system and total mass is shown in Table 1. Power system mass was calculated using the Mars nuclear power value of 54 kg/kW [13].

The MRE method is the most energy-intensive ap-

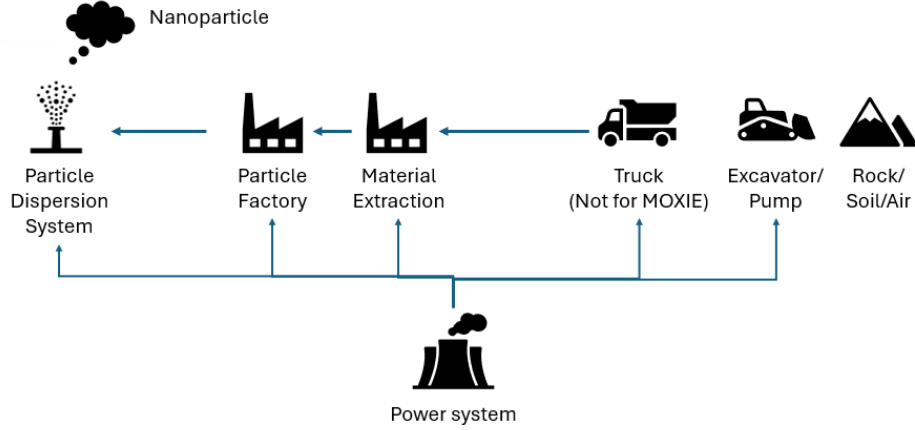


Figure 1: Overall CONOPS for Mars Warming Nanoparticle Production

Architecture	Source	Material	Power (kg)	Hardware (kg)*	Total (kg)
MRE	Soil	Al	1.2E+10	3.6E+09	1.6E+10
MRE	Soil	Mg	1.9E+10	5.8E+09	2.5E+10
MRE	Soil	Fe	1.1E+10	4.7E+09	1.6E+10
MRE	Soil	Mix	4.1E+09	1.2E+09	5.3E+09
Water Leach	Salty Rock	MgSO ₄	5.9E+07	3.6E+09	3.7E+09
Water Leach	Salty Rock	Mg	5.9E+08	1.8E+09	2.4E+09
MOXIE	Air	C	1.5E+08	3.2E+08	4.7E+08
Acid Leach	Soil	Al	4.5E+08	2.3E+09	2.7E+09
Acid Leach	Soil	Mg	2.2E+08	2.1E+09	2.3E+09
Acid Leach	Soil	Fe	3.1E+08	2.1E+09	2.4E+09
Acid Leach	Soil	Mix	2.7E+08	7.1E+08	9.8E+08

Table 1: System mass breakdown by architecture and material. *Excluding power system mass.

proach, with the power mass constituting the majority of the total system mass. The energy requirement per unit particle mass for MRE can be reduced by using all metals, which decreases the demand by more than half.

By contrast, using Mg-rich salty rock is more energy efficient than MRE, particularly when water recycling is employed - despite the energy needed to melt subsurface ice. For the extraction of salt (MgSO₄) alone, the power demand is ~ 1.1 GW if water is recycled in a daily cycle, but increases to 7.5 GW in the absence of recycling. The MOXIE-based carbon production method demonstrates comparatively low power requirements, while the acid-based leaching method requires < 1 GW.

For the acid-based method, using all metals does not reduce power demand appreciably. This is because it only reduces the power demand associated with acid production and leaching, while the most energy-intensive stage, the oxygen reduction process, remains unchanged. Nevertheless, the mixed-metal approach does lower the required system mass, as the total mass is dominated by hardware rather than the power system.

These results suggest that extracting a single material offers no clear efficiency advantage; gains are in-

stead achieved by utilizing all metals recovered during the extraction process. Other factors — such as location constraints and system complexity — favor MRE and MOXIE-based approaches, while other architectures may be disadvantaged by these considerations.

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