Dust as a hazard to human exploration: For nearly 20 years, the scientific exploration of Mars under NASA’s Science Mission Directorate (SMD) has been augmented by experiments sponsored by the human exploration directorates, with the objective of paving the way for crewed missions. Four themes have consistently been featured: Hazards associated with radiation; safe landing of large payloads; in-situ resource utilization (ISRU); and hazards associated with dust and soil. This talk addresses the latter two concerns and, in particular, their confluence in the Mars Oxygen ISRU Experiment (MOXIE) under development for the upcoming Mars 2020 Lander [1].

The first significant investment in flight payloads was provided by what was then called the Human Exploration and Development of Space (HEDS) program, a collaboration among two NASA codes responsible for human space flight. Under this program, three in situ payloads were developed and delivered for the Mars 2001 Surveyor Lander, which was eventually cancelled in the wake of the loss of Mars Polar Lander. These were: The Mars Radiation Environment Experiment (MARIE) [2], which had a counterpart on the Mars Odyssey orbiter; The Mars Environmental Compatibility Assessment (MECA), a multi-technique exploration of dust and soil hazards [3]; and the Mars ISPP Precursor (MIP), a demonstration of what is was then called In Situ Propellant Production (ISPP) and is now captured under the umbrella of ISRU. Reflecting the intimate link between ISRU and dust hazards, MIP also carried a capable diagnostic payload that included the Dust Accumulation and Repulsion Test (DART) [4].

Concerns about dust are associated with abrasion, toxicity, inhalation, and corrosion, as well as triboelectricity and corresponding obscuration and clogging of surfaces that might result. Much of this concern stemmed from Apollo experience on the moon, where abrasion threatened the integrity of space suits and, despite the lack of atmosphere, clouds of dust coated visors and other surfaces during mobility activities. Dust on the moon was found to be starkly different from Earth dust, more like highly charged, finely ground glass than the generally benign, electrically neutral, weathered, and aqueously eroded material typically found on Earth. The closest terrestrial analogy might be the silica fines produced in coal mining and responsible for life-threatening silicosis. MECA in particular was motivated by the question of whether dust on Mars would be more like that on Earth or the moon.

Mars 2001 HEDS payload objectives were eventually to be realized despite the cancellation of the mission. MECA flew under a different name but the same acronym on the 2007 Phoenix mission. MARIE scientific objectives were realized and extended by the RAD instrument on MSL [5]. The MOXIE instrument scheduled for Mars 2020 will capture the ISRU objective of MIP, producing ~200 times as much oxygen with comparable mass and volume, reflecting a much greater power allocation; some of the DART objectives will be realized by a dust experiment that is part of the MEDA meteorological investigation on Mars 2020 [6].

Phoenix 2007: The Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) on the 2007 Phoenix mission was the successor to the 2001 MECA experiment, featuring several minor improvements in its basic microscopy and wet chemistry systems while replacing a 2001 electrostatics experiment on the end of the robotic arm with a thermal and electrical conductivity probe (TECP) [7].

The microscopy experiment, with its fixed optical bench, returned the highest resolution images of surface martian dust and silt to date or planned (Fig. 1). The optical resolution was limited by the pixel size, 4 µm, with an attached Atomic Force Microscope (AFM) extending that range to ~0.1 µm. The taxonomy of the particles [8] prominently features small, ill-formed reddish particles, presumably nanophase iron oxide, that dominate the overall color of the sample (and, presumably the planet!), and larger particles, of order 20-100 µm, that appear polished and sub-rounded, presumably transported by saltation. Occasional white flakes are presumably salts, likely either carbonates or perchlorates. From a human exploration standpoint, it is reasonable to conclude that the iron oxide dust represents an airborne hazard, while the larger particles could represent chemical or toxic hazards and are likely to dominate (by mass) accumulation directly on the surface.

By individually identifying particles in optical and atomic force micrographs, it was possible to construct a particle size distribution (PSD), Fig. 2. [9]. The result strikingly demonstrated that the sampled soil was deficient in clay-sized particles compared either to Earth or the moon. On Earth, these particles are formed by aqueous alteration, suggesting that the martian soil has been
exposed to a negligible amount of water. On the moon, small particles can be formed by meteoritic gardening. On Mars, apparently, comminution alone is responsible for the distribution of fine particles.

MECA also performed wet chemistry analysis on surface soil samples, with the notable finding that the dominant source of chlorine in the soil is perchlorate, not chloride [10]. Chemically, the soil was otherwise unremarkable, though the finding of a neutral pH, apparently due to a carbonate component, was surprising [11].

Adding to the microscopy and chemistry findings were results from the TECP, observations from the excavation and handling of the regolith, and conclusions from other Phoenix experiments. From the standpoint of dust hazards to human exploration, the key findings from Phoenix were:

- The bulk properties of the regolith pose no particular hazards; It is structurally competent, not easily dispersed, and deficient in the finest particles that would pose inhalation hazards
- Perchlorate posed the only notable toxicity hazard. The primary adverse effect is suppression of thyroid function, which can be severe but is treatable and reversible.

**Magnet Experiments:** Much of what we know about the interaction of airborne dust with surfaces on Mars comes from experiments with magnets placed on landers for that purpose. The Viking landers were the first to show that both airborne dust and surface soil have a magnetic susceptibility [12]. The soils were inferred to contain 1 – 7 wt.% of a strongly magnetic phase [13]. A “sweep magnet” experiment on the Mars Exploration Rovers subsequently showed that most airborne particles have an appreciable magnetic susceptibility [14]. Mössbauer spectra of the airborne dust showed that the magnetic susceptibility is caused by the mineral magnetite [15]. APXS spectra indicated that, apart from Si, Fe is the most abundant element in the dust. Ti and to a lesser extent Cr are associated with Fe in the most strongly magnetic phase, which points to a basaltic origin of this phase and therefore that the magnetic particles were not formed by precipitation in or primarily by interaction with water [16].

**MOXIE:** MOXIE is a technology demonstration on the Mars 2020 Lander (M2020) to demonstrate In Situ Resource Utilization (ISRU) in the form of converting atmospheric CO$_2$ into O$_2$ [1]. On a future human mission, such a process will be used to autonomously provide up to 30 metric tons of liquid oxygen (LOx) for ascent vehicle propellant in the 16 months preceding launch of a human crew to Mars.
Fig. 3 describes the major MOXIE subsystems and shows how they are arranged in the body of the M2020 rover. The CO₂ Acquisition and Compression (CAC) system collects Martian atmosphere, filters it, and pressurizes it to ~1 atmosphere using a mechanical scroll compressor under development by Air Squared, Inc.; the Solid OXide Electrolyzer (SOXE), developed by Ceramtec, Inc., electrochemically converts the compressed CO₂ into the product O₂ and waste CO at ~800°C. The process monitor and control (PMC) subsystem provides the means to optimize and evaluate the efficacy of operation.

For MOXIE, filtering occurs both upstream (HEPA) and downstream (sintered metal) of the mechanical compressor. While the latter protects the more critical components, it is the former that poses the greater challenge. That is because, following Darcy’s law, pressure drop ΔP across a filter scales with gas velocity but not with total pressure (with the exception of the slip correction discussed below). As a result, ΔP of a few millibar that would barely be noticeable on the high-pressure outlet of the compressor could effectively throttle the low-pressure flow at the compressor intake. Moreover, the lower the ambient pressure, the faster the flow velocity must be to maintain a particular mass flow, exacerbating ΔP.

Studies of HEPA filter performance are typically performed at a flow rate of a few cm/s on particles of order 0.1-0.3 μm, a range that defines HEPA performance but is poorly characterized for Mars. Laboratory experiments in this range consistently find that pressure drops of a few mbar (a few hundred Pa) begin to appear at dust coverages as small as 1 g/m² of filter media area (e.g., Fig. 4).

The principal means to increase filtering capacity is to increase the filter surface area, often by making deep pleats within a given face area. For MOXIE, the face area of the filter is 264 cm², but the pleats increase that area by a factor of 19.2.

The optical depth in the martian atmosphere scales primarily with particle cross section, and the cross-section weighted mean radius has been reported to be in the 1.5 μm range [17], though it should be noted that optical measurements become increasingly unreliable as particle sizes become significantly smaller than 1 micron. Optical depth studies also don’t discriminate well between particles close to the ground and those far above the surface.

There is little data to determine how to translate filter dust loading to exposure to larger particles likely to be experienced on Mars, but it would be a reasonable assumption that, like the optical depth, the obstruction should be cross-section weighted. Following this logic, the critical dust mass loading might be expected to scale inversely with particle diameter, such that the threshold of ~1 g/m² for 0.15 μm particles in Fig. 4 might be expected to increase to ~10 g/m² for the 1.5 μm particles expected on Mars.

For the planned MOXIE operation for ~100 hrs on Mars, with air being drawn through the filter at a few cm/s, MOXIE is expected to accumulate ~50 mg dust, which corresponds to ~2 g/m² of face area but less than 0.1 g/m² per unit filter area. However, the MOXIE filter is exposed to incident dust even when it is not operating, and the incident velocity (i.e. the ambient Mars wind) is

MOXIE dust mitigation: While martian dust could conceivably compromise the CAC mechanical pump, it is primarily a hazard for the SOXE. Sulfates, which are common in Martian soil, can poison the cathode. Other constituents of dust might act more subtly, by coating surfaces with glassy materials or by obstructing the gas flow fields.
of order a few m/s, ~100x more than the velocity imparted by the compressor. Over 10,000 hours of the primary M2020 mission, at an estimated arrival rate of $10^6 \text{g/m}^2\cdot\text{s}$ (derived from Mars Global Climate Models), the filter would be expected to accumulate ~2 g/m² of filter area in the pleated configuration. This level might be expected to be measurable, but without causing significant impairment of MOXIE operation. Moreover, the MOXIE filter is baffled to prevent pebble strikes and saltation exposure, which may further limit the exposure to ambient dust. For comparison, a full scale system producing oxygen at a rate of 2 kg/hr might be expected to accumulate ~500g of dust over 10,000 hours.

![Diagram](image)

**Fig. 4:** Laboratory measurements of pressure resistance across a HEPA filter for incident particle velocity $v_0=5 \text{ cm/s}$ and particle diameter $d_p=0.15 \mu\text{m}$. [21]

An additional mitigating factor for operation in the Mars environment is the fact that the mean free path of gas molecules is comparable to the HEPA pore filter size (i.e. the Knudsen number is of order 1). In this circumstance, a “slip correction” needs to be applied because of the non-zero fluid velocity at the fiber surface. This is illustrated qualitatively in Fig. 5; an accurate analysis depends on improved knowledge of both the atmospheric conditions and the filter construction.

![Diagram](image)

**Fig. 5:** Pressure drop of fluid with a viscosity $1.1\times10^{-6} \text{ Pa-s}$, typical of martian CO₂, through a 0.4 mm long, 1 µm radius tube typical of a HEPA filter, using slip friction coefficients from 1 to $10^2$ and inlet velocities of 0-5 cm/s, comparable to the MOXIE compressor.

**Wind tunnel testing:** A prototype MOXIE filter and scroll compressor were tested under ambient Mars conditions in the Aarhus Wind Tunnel Simulator II (AWTSII) in the Mars Simulation Laboratory at the University of Aarhus, Denmark [18] for five days in 2016 [19]. Sections of filter media were connected via a feedthrough to a scroll pump (Air Squared V10T016A-01) and the pressure drop across the filter, $\Delta P$, was monitored by a differential pressure sensor. The inlet face velocity was determined with a Laser Doppler Anemometer, which measured the vertical component of the velocity of dust particles ~1 cm below the filter inlet. To monitor passive dust accumulation, a second filter media section was mounted adjacent to the first but without any connection to the pump. By varying the compressor speed, it was verified that the expected pressure drop was seen to scale with inlet velocity (Fig. 6) even at Mars ambient pressure.

Salten Skov dust simulant [20] was then injected into the tunnel. In an accelerated simulation of the MOXIE mission, three one-hour runs used average dust particle number densities of $n_0 = 40, 400,$ and $800 \text{ cm}^{-3}$, compared to the expected background of ~4 cm$^{-3}$ on Mars. After the runs were completed, dust loading $m$ was determined by weighing the filter media.

After all three dust exposure runs, the mass of the filter media increased to 65.600(5) g, corresponding to a dust loading $m = 0.03(2) \text{ g/m}^2$. Dust accumulation was evident in the color change of the exposed filters (Fig. 7). However, neither a measurable increase in pressure drop $\Delta P$ nor a decrease in inlet face velocity $v_0$, was seen after the three dust exposure runs. Microscopic analysis of filter loading is underway. An incidental conclusion of this analysis is that *in situ* color monitoring of the filters is likely to be the most sensitive way to detect filter degradation. Nothing in these results, however, suggest that dust loading is likely to pose a problem for MOXIE.

![Diagram](image)

**Figure 6.** Pressure drop, $\Delta P$, across the HEPA filter as a function of inlet face velocity, $v_0$.  

$\Delta P$ was determined with a Laser Doppler Anemometer, which measured the vertical component of the velocity of dust particles ~1 cm below the filter inlet.
Further testing has been proposed that will focus on basic dust-filter interactions. Emphasis will be on understanding:

- Pressure drop vs. dust loading at Mars-like conditions for particles of different (sieved) sizes ranging from 0.1 micron to 100 microns.
- Pressure drop vs. dust loading as a function of chamber pressure from 1-1000 mbar to understand slip factors.
- Differences in the above properties among commercially available HEPA materials.
- Filter uptake rates for sieved particles of particular sizes, 0.1 micron to 100 microns.
- Active (i.e. drawn on by pump) and passive dust uptake in different orientations relative to the airflow, in pleated vs. flat filters, and in baffled vs. open filter configurations.

![Figure 7. Clean (left), passive (center) and active (right) filter after dust exposure runs.](image)

**Future solutions:** HEPA filters are designed to trap and retain particles, particularly at the low coverages that we have seen can cause significant pressure drops on Mars. For this reason, attempts to clean or backflush filters are likely to be futile, and the only improvement possible over massive, heavily pleated, consumable filter assemblies will be to use other methods of dust mitigation. Efforts both within and outside NASA have focused on electrostatic methods that trap particles before they get to an inlet. Cyclonic mitigation is also possible.

For MOXIE and similar systems that actively collect martian atmosphere, another possible approach will be to filter dust at the high-pressure outlet of a compressor where small pressure drops can be tolerated. While this would require a dust-tolerant first pumping stage, it is conceivable that even the MOXIE scroll pump, if preceded by a commercial 25 µm mesh screen, would be insensitive to smaller particles. Such an assessment may be undertaken as part of the ground support aspect of the MOXIE investigation on Mars.

**Conclusions:** A great deal has been learned in the 20 years since NASA’s Human Exploration programs undertook the exploration of dust hazards on Mars. MER rovers completed much of the basic characterization of surface soils beginning in 2004, and the Phoenix mission specifically addressed both physical and chemical properties of the soil that could impact human exploration. MSL has further increased our understanding of mineralogical properties of the soil, and both experimental and theoretical progress has been made with respect to the airborne component. The upcoming MOXIE experiment will be the first to ingest large volumes of dust-laden martian atmosphere for processing, and will serve as a test case for translating our understanding into mitigation practices.

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**References:**