DUST STORM IMPACTS ON HUMAN MARS MISSION EQUIPMENT AND OPERATIONS.

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Introduction: Although it is tempting to use dust impacts on Apollo lunar exploration mission equipment and operations [1] as an analog for human Mars exploration, there are a number of important differences to consider. Apollo missions were about a week long; a human Mars mission will start *at least* two years before crew depart from Earth, when cargo is pre-deployed, and crewed mission duration may be over 800 days. Each Apollo mission landed at a different site; although no decisions have been made, NASA is investigating multiple human missions to a single Mars landing site, building up capability over time and lowering costs by re-using surface infrastructure. Apollo missions used two, single-use spacecraft; a human Mars mission may require as many as six craft for different phases of the mission, most of which would be re-used by subsequent crews. Apollo crews never ventured more than a few kilometers from their lander; Mars crews may take "camping trips" a hundred kilometers or more from their landing site, utilizing pressurized rovers to explore far from their base. Apollo mission designers weren't constrained by human forward contamination of the Moon; if we plan to search for evidence of life on Mars we'll have to be more careful. These differences all impact how we will mitigate and manage dust on our human Mars mission equipment and operations.

Impacts to Equipment: Martian dust is expected to influence the design of Mars surface power systems, habitats, rovers, Extravehicular Activity (EVA) spacesuits and tools, and Mars Ascent Vehicle (MAV).

Surface Power Systems. A key decision facing Mars mission designers is whether to rely on solar power for surface operations. Atmospheric dust and accumulated dust on the arrays can both reduce array efficiency [2]. Unlike NASA's Mars Exploration Rovers (MER) that could retreat to a very low-power state to conserve energy [3], human Mars missions are estimated to require at least 15 kW "keep-alive" power simply to keep critical life support and spacecraft functions on-line [4]. Landing sites far from the equator or along seasonal dust storm tracks will be even more difficult to support with solar power. To reduce risk, designers must over-size solar arrays or expand energy storage capability (both of which add landed mass), or consider alternatives such as nuclear power. Although nuclear power systems would allow full power even during a severe dust storm, provisions for clearing accumulated dust from thermal radiators must be considered. Regardless of power source selected, power cable connections between multiple surface assets will have to be made, driving the need for dust-resistant connectors. To further complicate matters, some of these connections may be made by robots before the crew arrives.

Surface Habitat. Two-person Apollo crews accessed the lunar surface via an EVA hatch. With the hatch open and no airlock to serve as a "mud room," lunar dust migrated into the cabin, quickly becoming a nuisance [1]. For the longer-duration Mars missions, alternative crew ingress/egress methods are being studied, including airlocks, suitports [5], and hybrid combinations of these. Ingress/egress systems will all require dust-resistant pressure seals and locking mechanisms, perhaps with retractable covers to protect against dust while exposed to the surface.

In spite of best efforts some dust is likely to migrate into the habitat, with implications to critical life support system hardware. For example, cabin fans and filters must be sized to remove airborne dust, and regenerative air and water systems must be compatible with chemical compounds in the dust that find their way into these systems. Softgoods in the cabin, such as Velcro® fasteners, may be very difficult to rid of dust once contaminated. A portable vacuum cleaner may be needed to reach dust in crevices; note that even small vacuum cleaners require high peak power, with implications to power system mass, which in turn has implications to thermal system mass. Dust mitigation is likely to play a role in a disposable vs. washable crew clothing decision, with implications to cargo mass and volume. Planetary protection considerations will influence trash disposal; cleaning materials that have been exposed to both Martian dust and the internal cabin environment may require special handling or containment. The surface mission lengthy duration, combined with repeated habitat use by subsequent crews, will drive the need for creative dust mitigation and remediation to ensure the habitat is able to complete its intended life cycle.

Outside the cabin, dust accumulation on windows, handrails, and radiator panels must be addressed, with implications to crew maintenance time vs. the mass and power of autonomous cleaning systems.

Rovers. Unpressurized, robotic rovers may be used to ferry tools or samples between various work sites, or used to scout crew excursion routes. As demonstrated by the MER rovers, solar-powered rover operation can be affected by dust storms but even the Apollo batterypowered rover ran into trouble when dust accumulation on the battery case caused overheating [1]. Telerobotic systems that allow crew to operate a rover remotely must be resistant to dust and scratched optical surfaces.

To explore more than a few kilometers beyond the landing site, a pressurized crew rover capable of serving as a mobile habitat will be required. Unlike the robotic rovers, a crewed rover will need substantial power for life support function. One of the worst-case scenarios would be a solar-powered crew rover caught in a lengthy, severe dust storm, unable to generate enough power to return to the habitat. Even with alternate power sources such as fuel cells or batteries, poor visibility could make driving in a storm treacherous through boulder fields and hidden sand pits. Such a scenario may drive the need for crew rescue schemes, remote safe havens, better storm prediction, or surface navigation and hazard avoidance provisions.

Storm concerns aside, a pressurized rover will have many of the same dust-related issues as the surface habitat: crew ingress/egress dust mitigation, seal and mechanism integrity, and managing dust accumulation on windows, handrails, and radiator panels. Optical elements critical for surface navigation, such as the windscreen or externally mounted camera lenses, must be dust and scratch-resistant to ensure safe negotiation of visible terrain hazards.

EVA Spacesuits and Tools. An EVA spacesuit is essentially a one-person spacecraft, subject to the same dust concerns as the habitat and pressurized rover: crew ingress/egress dust mitigation, seal and mechanism integrity, and managing dust accumulation on the helmet visor, backpack, boots, gloves, and thermal components. Sharp dust particles may cause abrasion damage to seals and helmet visors. Once embedded in softgoods, such as suit fabrics, it may be difficult to shed dust.

EVA suits were re-used to support multiple Space Shuttle and International Space Station crews but planetary protection considerations make returning dusty Mars spacesuits to Earth problematic. Potentially, each crew must dispose of their EVA suits on Mars and return to Earth in their Intravehicular Activity (IVA) suits. This will require the suit customization that is normally performed by specialists on Earth (to accommodate different crew members' height, girth, arm length, etc.) to be performed by the crew on Mars instead (higher risk), or alternatively manufacture new EVA suits for each mission (higher cost).

One area of particular concern is how to perform routine maintenance on dusty spacesuits. Maintenance of small, intricate parts would be difficult while wearing EVA gloves, so the preference is to bring suits into a pressurized cabin where maintenance could be performed in a shirt-sleeve environment. The question is: which pressurized cabin? Crews will eat and sleep in both the habitat and pressurized rover, making them unsuitable for dusty suit maintenance. Adding a purpose-built maintenance module is a solution, but would increase landed mass (and cost). Other options include partitioning the pressurized rover or habitat (though this may drive additional complication, such as a separate environmental control system for the maintenance compartment) or utilizing an ingress/egress airlock as a maintenance space. Personnel protective clothing to work on dusty suits may add to consumables mass and volume.

EVA tools—particularly power tools—have many of the same dust concerns outlined above: overheating, grit abrasion on seals or mechanisms, and maintenance or repair of dusty tools. EVA cameras will require dust-resistant housings, with scratch-resistant optical panes.

Mars Ascent Vehicle. The MAV will transport crew from the Mars surface to an Earth transit vehicle loitering in Mars orbit. The MAV plays a key role in Earth planetary protection because the amount of dust returning with the crew to Earth will be limited to what migrates into the MAV. As a one to three day-duration vehicle, the MAV cabin will be much smaller than either the surface habitat or pressurized rover, but will share many of the same dust concerns: airborne dust in the cabin, grit abrasion on seals and mechanisms, reduced visibility due to accumulation on windows, and thermal system malfunction due to dust accumulation.

The key to minimizing dust inside the MAV may be to use it as little as possible while on the surface and never open the hatch to the Mars environment. As noted above, leaving dusty EVA suits behind and ascending in pristine IVA suits is helpful, but how will crew transfer from their habitat to the MAV without going outside? One option is to change suits inside the pressurized rover, then tunnel from the rover to the MAV [6]. This virtually eliminates dust migration into the MAV, then to Earth, but at a landed mass, complication, and cost penalty for a retractable tunnel.

Preliminary study has not identified any reason the MAV could not launch during a dust storm. However, limited visibility and dust accumulation could make pre-launch preparations (likely performed by EVA crew) more difficult and risky.

Impacts to Operations: Martian dust is expected to influence landing, surface operations, and crew ascent in several ways.

Landing. The prevalence of seasonal dust storms along well-worn tracks [7] may influence landing site selection and potentially even timing. Landing on Mars during a dust storm could make it difficult to detect and avoid hazards such as boulders and sand dunes, or other mission surface assets such as rovers or the surface habitat. Mitigation might include advanced hazard detection and avoidance systems--or simply waiting for the dust to clear. Once in Mars orbit, landers will have some flexibility to delay landing, but a storm lasting months could affect overall mission timeline and cut into schedule margins for critical surface operations, such as manufacturing in situ propellant for crew departure on the MAV. Note that the landers themselves may generate dust plumes as the descent engines interact with loose regolith during approach and touchdown. The equipment previously noted as sensitive to dust accumulation would be equally affected by these man-made dust storms, but with the added complication of potentially unburned propellants or propellant byproducts mixed with the dust. Descent flight paths that avoid surface infrastructure overflight will be desirable.

Habitat Operations. Long crew surface stays and the possibility of reusing the surface habitat for multiple crews will require robust housekeeping. The most significant dust-related impact to habitat operations is likely to be crew housekeeping time, either maintaining equipment to keep dust out of the habitat, or cleaning dust that migrates inside. Housekeeping on the International Space Station involves disposable wet wipes but the high cost of shipping consumables to Mars makes reusable cleaning tools desirable, in spite of the added time penalties to clean the cleaning tools for reuse.

Keeping dust out of the habitat is likely to involve special operational procedures that could add time getting EVA crew back inside. This would be a problem in an emergency, such as an EVA crewmember requiring immediate medical care.

Reduced visibility through habitat windows due to dust accumulation or storm conditions could disrupt telerobotic operations such as cargo handling or robotic sample collection.

Rover Excursions. The potential for reduced driving visibility and solar power availability during a storm could influence surface exploration planning. Exploration close to the landing site may be scheduled during storm season, with excursions farther from the landing site planned when the risk of dusts storms is lower.

As with the habitat, special operational procedures could add time getting EVA crew back into the rover, potentially delaying emergency medical care.

EVA Operations. Ideally, equipment will be designed to shed dust, or will include autonomous dust clearing provisions. If not, EVA crews could spend a considerable portion of their day maintaining outdoor equipment, leaving less time for science or exploration. As with the habitat, time will likely be devoted to cleaning dust from EVA suit components, or repairing grit-damaged seals and mechanisms.

MAV Operations. Like the lander's descent engines, the MAV's ascent engine could create a man-made dust storm resulting in lofted dust—potentially mixed with ascent propellants or residues—settling on the habitat or rovers. Ascent flight paths that avoid surface infrastructure overflight will be desirable.

Conclusions: NASA has accumulated a wealth of experience operating in dusty environments between the Apollo program and robotic Mars rover programs. However, there are key differences between those missions and a human Mars mission that will require unique approaches to mitigate potential dust storm concerns.

References:

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