

NEAR-TERM LANDER EXPERIMENTS FOR GROWING PLANTS ON MARS: REQUIREMENTS FOR INFORMATION ON CHEMICAL AND PHYSICAL PROPERTIES OF MARS REGOLITH

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In order to support humans for long-duration missions to Mars, bioregenerative Advanced Life Support (ALS) systems have been proposed that would use higher plants as the primary candidates for photosynthesis. Hydroponic technologies have been suggested as the primary method of plant production in ALS systems, but the use of Mars regolith as a plant growth medium may have several advantages over hydroponic systems. The advantages for using Mars regolith include the likely bioavailability of plant-essential ions, mechanical support for plants, and easy access of the material once on the surface. We propose that plant biology experiments must be included in near-term Mars lander missions in order to begin defining the optimum approach for growing plants on Mars. Second, we discuss a range of soil chemistry and soil physics tests that must be conducted prior to, or in concert with, a plant biology experiment in order to properly interpret the results of plant growth studies in Mars regolith. The recommended chemical tests include measurements on soil pH, electrical conductivity and soluble salts, redox potential, bioavailability of essential plant nutrients, and bioavailability of phytotoxic elements. In addition, a future plant growth experiment should include procedures for determining the buffering and leaching requirements of Mars regolith prior to planting. Soil physical tests useful for plant biology studies in Mars regolith include bulk density, particle size distribution, porosity, water retention, and hydraulic conductivity.

Mars Mars lander Astrobiology Soil chemistry Plant biology

INTRODUCTION

Advanced Life Support (ALS) systems based on bioregenerative processes have been proposed for space

bases to regenerate oxygen, water, and food from human and industrial wastes (35,52). Biological processes will be combined with physical and chemical technologies to provide life support systems that will reduce

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requirements for the resupply of materials from Earth. Higher plants (e.g., wheat, rice, potatoes, peanuts, vegetables, and herbs) are considered the primary candidates for photosynthesis in ALS systems (27,52,61).

Various methods of plant production in ALS modules have been proposed (12,52), but the precise method to be used will depend on specific mission objectives. For example, a plant production system in a microgravity environment may require more stringent controls for the containment of nutrient solution than a plant production system might require on a planetary surface like Mars. Aeroponic nutrient delivery systems, nutrient film technique (NFT), porous ceramic tubes or plates, and substrate-based nutriculture systems have been proposed for plant production in ALS (12,19,52,63). In addition, in situ regolith or synthetically manufactured zeolites have been proposed as solid substrates for plant production on Mars (37,40). Although hydroponic systems have several advantages over substrate-based materials (12,55), the complexity of hydroponic systems (e.g., use of purified salts, acid and base buffers, nutrient delivery and monitoring systems, etc.) might make their use less attractive for missions in which in situ materials are readily accessible. In addition, the use of Mars regolith for ALS plant growth media may have several advantages over hydroponic systems including the immediate bioavailability of plant essential ions, low-tech mechanical support for plants, and easy access of in situ materials once on the surface.

Based on Viking, Pathfinder, and terrestrial-based spectroscopic studies (17,54,57,60), the Martian regolith appears to have undergone oxidative weathering and aqueous alteration. These processes would likely produce Martian fines that are similar to weathered terrestrial soils. Furthermore, most of the essential plant nutrients appear to be present in Martian regolith (37,39,40). The composition of the atmosphere of Mars (53) clearly indicates that CO₂ is abundant, and that O₂ and H₂O are present in trace amounts and may be collected and concentrated for use in an ALS module. However, other studies have suggested the presence of potentially phytotoxic materials in Martian regolith including peroxides (13) and heavy metals (25). If high levels of peroxides, heavy metals, or other phytotoxic factors are confirmed for Martian regolith, then the use of local resources for ALS systems on Mars might not be possible. *Thus, a key question in the design of an ALS system for human exploration of Mars will be*

whether the Martian regolith is capable of supporting plant growth in a robust and long-term manner. It is the objective of the current discussion to address practical horticultural considerations required for growing plants in Mars regolith with emphasis on soil chemistry and physical factors.

The terms "regolith" and "dust" are used here to refer to the unconsolidated and fine-textured surficial materials on Mars prior to any interactions with plants. The term "soil" will be used to refer to the Martian fine-textured surface materials placed in contact with water, nutrients, buffers, or plants. The distinction is similar to that used for describing "lunar regolith" and "lunar-derived soils" (41). For the discussions below, it is assumed that environmental and nutritional factors required for plant growth will be provided within small, automated plant growth systems on robotic missions or larger ALS modules during piloted Mars surface missions. We do not discuss the possibilities of growing terrestrial plants out on the open surface of Mars.

SIGNIFICANCE OF PLANT BIOLOGY EXPERIMENTS ON MARS TO NASA STRATEGIC PLANS

The growth of plants in space and on planetary bodies remains a priority for the development of NASA's strategic plans, especially for long-term exploration of space and Mars. However, even though plants will be an integral part of long-term bioregenerative ALS systems, the exact timing of initial plant biology experiments on near-term Mars lander missions is still under debate. We suggest that there are at least three key reasons to accelerate the planning of near-term plant biology experiments for Mars surface missions. First, the primary justification for sending plant biology experiments to Mars in the near-term is to confirm that plants can grow in Mars regolith, and to obtain the necessary baseline data for modeling plant growth on Mars. Near-term plant growth experiments in Mars regolith will drive many of the design criteria for ALS research and development over the next 20 years. Second, plant growth experiments are essential on near-term Mars landers because there will not be adequate amounts of Mars regolith returned in any near-term sample-return mission that will provide enough material to conduct comprehensive plant biology experiments with Mars regolith. At best, plant biologists are likely to receive no more than a few

milligrams of Martian regolith to screen for the "biosafety" of the soil. Plant biology experiments aimed at defining how plants might grow in Mars soils require that the plants are actually grown in Mars soils. In other words, plant biology experiments in which trace amounts of Mars regolith are added to root systems act only to test whether there is a catastrophic biocidal effect on plants from small amounts of Mars materials. These experiments cannot be easily extrapolated to modeling the overall effects of Mars soil on plant growth and development. Furthermore, consider that 382 kg of rock and soil samples were returned to Earth during the six Apollo landings (4), and yet, during the intervening 33 years, no plant experiments have been conducted in which plants were grown in 100% lunar regolith. And lastly, a plant biology experiment on a near-term Mars surface mission can be used to confirm the biosafety of the Mars regolith prior to the return of samples to Earth. This is critical for building confidence that nothing unexpected is present in Mars regolith that might be of concern for back contamination of Earth. The scientific community is in general agreement that the biological hazards from any extant Mars microbiota are extremely unlikely (47,48). And, we propose that the greatest challenge for the success of any plant biology experiment on a Mars lander will be managing the chemistry of Martian soils.

REQUIREMENTS FOR PLANT GROWTH ON MARS

On Earth, plants have adapted to diverse environments with wide extremes of temperature, moisture, and nutrition including Arctic and alpine tundra, temperate zones, and lush tropical ecosystems. However, most plants that have been proposed for ALS systems (e.g., wheat, soybean, rice, potatoes, vegetables, and herbs; sensu) (27,61) require a more moderate set of environmental and nutritional conditions. In general, higher plants proposed for ALS systems require temperatures between 25 and 18°C (day/night cycle), soil moisture adequate for mobilizing essential plant nutrients and hydrating plant roots, a soil pH between 5.5 and 7.0, ambient humidity above 50% at 20°C, and adequate photosynthetically active radiation (PAR) (defined as the photon flux between 400 and 700 nm). In general, PAR levels of between 300 and 500 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (65–110 W m^{-2}) are required for reasonable plant productivity, but low-light-adapted plants can grow effectively

at lower PAR levels. The light regime on Mars is likely to be sufficient in both intensity and spectral quality for the nominal growth of most plant species, as long as UV irradiation below 340 nm is attenuated within ALS plant growth modules. Plants generally do not require short UV photons, and irradiation below 340 nm can be detrimental to leaf tissues (26). All of these environmental factors must be provided or mitigated by the use of artificial life support systems within small lander payloads or full-scale ALS modules on Mars.

In addition, plants require 13 essential ions from soils or nutrient solutions (e.g., N, P, K, Mg, Ca, S, Fe, Mn, Cu, B, Cl, Zn, and Mo) (Tables 1 and 2); hydrogen from water; and the atmospheric gases O_2 and CO_2 for normal growth and development. Although N_2 gas is utilized by some bacterial species alone or in symbiosis with plants to fix nitrogen into a form that can be utilized by plants (i.e., NH_3), N_2 gas is not an absolute requirement for plant growth. As will be discussed below, many of the plant-essential elements have been identified on Mars (Table 1) (10,16,21,50).

Table 1. Plant Essential and Potentially Phytotoxic Elements Identified in the Shergotty Meteorite, at the Viking Lander 1 Site, and Pathfinder Landing Site

Element	Shergotty Meteorite*	Viking Lander 1*	Pathfinder†
Plant-essential elements			
N	132–794 ppb		
P	0.24–0.35%		0.4%
K	0.11–0.16%	<0.4%	0.4%
Ca	6.80–7.15%	4.1%	4.2%
Mg	5.40–5.7%	3.6%	5.8%
S	0.13–0.16%	2.7%	2.4%
Fe	15.1–15.6%	12.2%	14.5%
Cu	26–54 ppm		
Mn	0.40–0.42%		0.4%
B	ND	ND	ND
Zn	62–83 ppm		
Mo	0.37 ppm		
Cl	108 ppm	0.8%	0.7%
Potentially phytotoxic elements			
Al	3.60–4.02%	3.9%	5.2%
Na	0.95–1.09%		3.0%
Cr	0.12–0.16		0.2%
Co	27.2–45 ppm		
Ni	56–88 ppm		
As	0.025 ppm		
Cd	0.014–0.34 ppm		

ND, not detected.

*From Stoker et al. (58).

†From Foley et al. (22).

Table 2. Plant Essential and Potential Phytotoxic Elements, Effect of Soil pH on Bioavailability, and Recommended Soil Test to Determine Bioavailability of the Mars Regolith

Plant Nutrient	Effect of Soil pH on Bioavailability	Recommended Soil Test	Reference for Soil Test
Primary			
Nitrogen	Biological oxidation/reduction are affected by pH, inorganic $\text{NH}_4\text{-N}$, and $\text{NO}_3\text{-N}$; mostly unaffected by pH.	Potassium chloride extraction method for inorganic $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$.	Keeney & Nelson (30)
Phosphorus	Increases with decreasing pH.	Mehlich III method, Olsen method.	Mehlich (38), Olsen et al. (51)
Potassium	Mostly unaffected by pH.	Ammonium acetate and Mehlich III method.	Haby et al. (24), Mehlich (38)
Secondary			
Calcium & magnesium	Mostly unaffected by pH.	Ammonium acetate and Mehlich III method.	Haby et al. (24), Mehlich (38)
Sulfur	Mostly unaffected by pH.	Mehlich III method.	Mehlich (38)
Micronutrients			
Iron, manganese, copper, & zinc	Increase with decreasing pH.	AB-DTPA method for alkaline soils; Mehlich III for alkaline and acid soils.	Soltanpour & Schwab (58), Mehlich (38)
Boron	Mostly unaffected by pH.	Mehlich III method.	Mehlich (38)
Molybdenum	Increases with increasing pH.	Ammonium oxalate method.	Griggs (23)
Chlorine	Mostly unaffected by pH.	Potentiometric titration method.	Adriano & Doner (1)
Potential phytotoxic heavy metals			
Lead, mercury, nickel, cadmium, chromium, etc.	Increases with decreasing pH.	AB-DTPA method for alkaline soils; Mehlich III for alkaline and acid soils.	Soltanpour & Schwab (58), Mehlich (38)

NATURE AND ORIGIN OF THE MARTIAN REGOLITH

Chemical information about the major and minor elemental composition of Martian regolith was provided by the X-ray fluorescence (XRF) analyses on the two Viking landers in widely separated locations (17) and by the Alpha Proton X-ray Spectrometer (APXS) analyses on the Pathfinder's Sojourner rover at a third surface location (11,22,54) (Table 1). Although minor differences occur between the different landing sites, the results suggest that the regolith is a globally mixed aeolian deposit consisting of a basaltic silicate component similar to the basaltic Martian meteorites, but enriched in a "salt" component containing S, Cl, K, and probably Br (6,11,15-17,54). The silicate or "basaltic" component of the regolith probably consists mainly of amorphous silicates (6). Although Bishop et al. (9) have shown that the reflectance spectra of ferrihydrite and ferric sulfate-bearing montmorillonite resemble Martian bright regions, the mineralogy of the Martian regolith is generally characterized by the lack of spectral evidence for well-crystallized clay minerals. Furthermore, the absence of evidence for abundant clay min-

erals has led to alteration models for Martian fines involving palagonitization (36,43,44,56), the formation of amorphous alteration material due to an "acid-fog" mechanism (7), and/or alteration under different kinds of transient conditions involving impact cratering with very low water/rock ratios (31,50). In addition, the period of time over which the present Martian regolith has accumulated is unknown. The present low erosion rates could indicate that the regolith has been accumulating over several billion years (20,21).

Substantial efforts have been made to constrain the iron mineralogy of the regolith. The presence of poorly crystalline or nanophase ferric oxides that may include goethite, akaganeite, schwertmanite, and maghemite have been inferred from spectroscopic and surface measurements (8,14,43,45). From the Fe content of the regolith (approximately 18 wt% Fe_2O_3), Hviid et al. (28) suggested that approximately 6 wt% of the Fe is in the form of maghemite. Recently, Morris et al. (44) have suggested that magnetite/titanomagnetite derived from glass altered by palagonitization could explain the magnetic component of the regolith.

The Viking experiments showed that the regolith contains oxidants, possibly hydrogen peroxide (H_2O_2)

or superoxide radical ions (O_2^- or O^-) (29,32,34), which for the peroxide hypothesis could amount to a few parts per billion to a few parts per million H_2O_2 equivalents of peroxides in the most active samples (5,64,65). These oxidants may be formed by the interactions of UV photons and atmospheric gases (64). If oxidizing compounds are present in the regolith at moderate or high levels, they will efficiently oxidize any hydrocarbons in the regolith (29,32,34,64). This is consistent with the results from Viking and Pathfinder missions in which the carbon content of Mars regolith was below the detection limits of the Pathfinder APXS of 0.3 wt%, and below the detection limits of the gas chromatograph-mass spectrometer (GCMS) on the Viking landers (33). Therefore, significant quantities of hydrocarbons are not expected in the regolith. Furthermore, an excess of oxygen is present in the regolith after accounting for the stoichiometric oxygen for the other elements detected, with an abundance much greater than can be explained by the regolith oxidant alone, as described above. This excess oxygen may suggest the presence of a small amount of bound water ranging from 0.2 to 3.3 wt% (22). This result is consistent with the Viking GCMS experiment that semiquantitatively determined a water abundance of about 1–2 wt% after pyrolysis to 500°C (5).

RECOMMENDED SOIL TESTING FOR NEAR-TERM MARS LANDER MISSIONS

There are at least four primary functions of a rooting medium or soil that should be evaluated for plant growth, including: nutrient retention, aeration, water retention, and mechanical support. No doubt, Mars regolith will provide mechanical support and likely be adequately aerated; however, it is more difficult to predict what the capabilities of the regolith are for nutrient composition and water retention. Several experiments on Viking and Pathfinder landers have determined the elemental compositions of the regolith (Table 1). In contrast, little is known about the mineralogy of the Martian regolith, although we can surmise certain phases from the Viking and Pathfinder chemical data, analyses of SNC meteorites, and spectral reflectance data. In the following sections, we discuss what is generally known about the chemical and physical properties of Mars regolith with respect to plant production and what soil tests should be conducted on regolith materials prior to implementation of plant growth ex-

periments on Mars. The recommended chemical tests include measurements on soil pH, electrical conductivity and soluble salts, redox potential, bioavailability of essential plant nutrients, and bioavailability of phytotoxic elements. Soil physical tests useful for plant biology studies in Mars regolith include bulk density, particle size distribution, porosity, water retention, and hydraulic conductivity.

Soil pH

The hydrogen ion concentration (pH) of soil is probably the most important chemical property of any plant growth medium. Chemical processes that will affect the soil pH are precipitation and dissolution reactions, ion mobility (e.g., ion exchange), and oxidation-reduction reactions. The soil pH will provide information on mineralogy, chemistry, and reactivity of Martian regolith materials as they come in contact with water. Whether a regolith material is acidic, neutral, or basic depends on the reactivity of components in the regolith. For example, a soil pH of 4 may indicate the presence of free acids, generally from oxidation of sulfides; a pH of <5.5 may enhance the exchangeable Al^{3+} in soils and thus may increase the phytotoxicity of the soil; a pH of 7.8–8.2 may indicate the presence of calcium carbonate; and a pH of 10 may indicate an alkaline metal carbonate system (e.g., evaporite-type materials). In addition, knowledge about the pH of Martian soil is required to understand nutrient bioavailability and potential elemental toxicities for plant growth. Soil pH has a significant effect on several of the plant-essential nutrients. Trends in bioavailabilities of essential plant nutrients versus pH are listed in Table 2.

The pH of the Martian soil is not known, but it is likely buffered by either the dissolution of basaltic materials or slightly soluble Fe sulfates. Most basalt-rich materials, such as those on Mauna Kea Volcano in Hawaii, have soil pH values around 7, although non-sulfur-rich basaltic materials range from pH 5.9 to 7.8 on Mauna Kea (Ming et al., 2000, unpublished data). The basalt-rich materials from Mauna Kea have been proposed as Mars simulants for plant biology and soil chemistry studies (2,3,46). If Fe-rich sulfates, such as jarosite, exist in the regolith, it will likely buffer the pH of the soil solution around 4.5 to 5.0 (39). Another possibility is that regolith materials have undergone acidic volatile weathering by interaction with sulfuric, hydrochloric, and possibly nitric acids produced by volcanic

emissions (7). Although much of the acidity is "neutralized" by reacting with basaltic materials, some sulfuric and/or hydrochloric acid may be present and result in acidic soil pH values. Ming et al. (2000, unpublished data) found acidic pH values of 3.1 to 4.8 for basaltic materials from the Southwestern Rift Zone near the Kilauea Volcano that had been exposed to acidic volatiles from the volcano. As might be expected, basaltic materials immediately next to gas fissures on the caldera's rim were extremely acidic with soil pH values near 2.

Soil Electrical Conductivity and Soluble Salts

Additional information on the mineralogy, chemistry, and reactivity of the regolith and dust can be provided by the measurement of the electrical conductivity (EC) (i.e., salinity) and soluble elemental species of the soils. We expect that soluble or slightly soluble salts, such as chlorides and sulfates, exist in the Mars regolith and the EC measurements will provide a quantitative value on the degree of soluble salts in the soil. The measurement of specific species in solution, such as SO_4^{2-} , Cl^- , Fe^{3+} , and Fe^{2+} , will demarcate the possible solid phases from which these ions may have been dissolved. Although cation exchange capacity (CEC) of the Martian soil would be a challenging measurement on a robotic mission, CEC would provide information on the capacity of the soil to maintain various equilibria with elemental species at specific pH levels over long periods of time.

Mars regolith will likely have soluble salts, such as Mg and Ca sulfates and/or halides, that will rapidly dissolve once exposed to water. If all of the S and Cl are tied up as Mg and/or Ca sulfates and chlorides, then there is a very good possibility that solutions, which come in contact with Martian regolith, will have high salinities. In fact, if the regolith is not adequately leached with water, plants initially grown in Martian soil may encounter a salinity hazard. Salinity is usually determined by measuring the specific EC of a saturated soil extract, and soils that possess an EC of 4 dS m^{-1} or higher are classified as saline soils, although soils with EC of 2 dS m^{-1} and higher are toxic to some plants (59). Volcanic tephra Mars analog materials from Mauna Kea Volcano have an EC of 1.6 dS m^{-1} or less and most are below 1 dS m^{-1} (Ming, 2000, unpublished). However, specific tephra materials from Kilauea Volcano that have been exposed to recent acidic aerosols

or "fog" have very high salinities, several as high as 20 dS m^{-1} , which is toxic to most plants. Here again, because we do not know the mineralogy of the Martian regolith, we can only surmise the salinity effects of Martian soil on plants.

Soil Redox Potential

The measurement of the redox potential (Eh) will help identify and possibly quantify the component responsible for the highly oxidative nature of the Mars soil. The Eh of a chemical system is the measure of the potential rate of electron donation versus the rate of electron acceptance. It is probable that several reactions (i.e., electrochemical couples) are controlling the redox potential in the regolith materials and, thereby, limit the ability to quantitatively interpret the value. The oxidizing species with the highest oxidation potential will control the oxidation potential in a system. Sometimes, kinetics of the redox reactions in natural waters is slow and equilibrium is not achieved (i.e., disequilibrium); however, we expect that the oxidant in Martian "soils" will react quickly, as indicated during the Viking mission. For example, if H_2O_2 (or a metal peroxide) is present in the Martian surface materials, we anticipate that it will react quickly with water upon hydration of the regolith. Initially, the $\text{H}_2\text{O}_2/\text{H}_2\text{O}$ couple will control the redox potential. As H_2O_2 breaks down into H_2O , oxygen will be generated. In this example, depending on the quantity and intensity relationships, we anticipate that eventually the $\text{O}_2/\text{H}_2\text{O}$ couple will control the redox potential (e.g., see Fig. 1). However, as pointed out by Zent and McKay (65), the concentration of the oxidant in the regolith may be less than 1 ppm, and thus may not contribute significantly to the Eh.

An important aspect of the redox measurement will be the establishment of redox stability fields for Martian soils via Eh-pH diagrams. These diagrams can give an excellent perspective on the relative stabilities of several minerals in a single diagram. Again, we realize that these materials will not be at equilibrium; however, these data will delineate the types of reactions occurring when water is first introduced to the regolith and dust. An Eh-pH diagram for possible phases in Mars surface materials is shown in Figure 1. The range for terrestrial soils is illustrated on the diagram for a point of reference. Again, if we use the example of H_2O_2 as the oxidizing component in the regolith and dust, we would expect the redox potential to initially fall

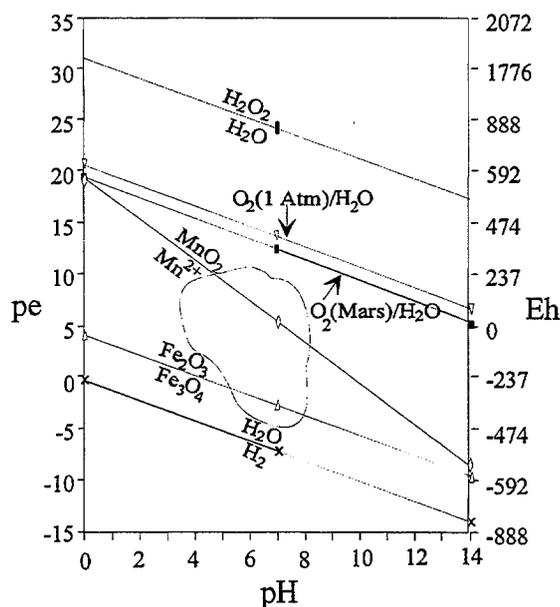


Figure 1. Eh-pH diagram for possible phases in Mars surface materials. The diagram was constructed for the environmental conditions at the surface of Mars (e.g., atmospheric partial pressures). The closed-curve shape shows the ranges for terrestrial soils (39). (Eh, redox potential; pH, hydrogen ion concentration; pe, $-\log$ of electron activity.)

somewhere on the H_2O_2/H_2O couple line, depending on the solution pH.

Bioavailability of Plant-Essential Nutrients and Potential Phytotoxic Elements

The bioavailability of plant-essential nutrients is controlled by the chemical, physical, and biological properties of the soil. A simple measurement of water-soluble species does not reflect the bioavailability of nutrients; therefore, a variety of soil tests have been developed to address bioavailability of these elements in terrestrial soils. We recommend including a multinutrient extracting solution, such as the Mehlich III extracting solution (38), as a basic soil test to determine bioavailability of both plant essential nutrients and potential phytotoxic elements in the Mars regolith. There is essentially no information on the nutrient and phytotoxic element bioavailability of Martian regolith and dust.

The key elements that must be assayed include the plant-essential nutrients N, P, K, Mg, Ca, S, Fe, Mn,

Cu, B, Cl, Zn, and Mo, and potential phytotoxic elements like Al, As, Cr, Cd, Na, Ni, and Pb. In Table 1, the concentrations of these elements on Mars are presented from data from the Shergotty meteorite, Viking Lander 1 site, and Pathfinder site (22,60). However, it currently is not known which specific forms of these elements would be available to plants in hydrated Mars soils, but it is likely that soil solutions will contain fairly high concentrations of K^+ , Ca^{2+} , Mg^{2+} , SO_4^{2-} , Cl^- , Mn^{2+} , and, depending on the soil pH and Eh, Fe^{2+} may be fairly high. In contrast, it seems likely that forms of N that can be utilized by plants (i.e., NO_3^- or NH_4^+) likely will not be present in hydrated Mars soils (Table 1).

Physical Properties

Physical properties of the Martian regolith including bulk density, particle size distribution, porosity, water retention, and hydraulic conductivity should be measured in order to determine how plants might interact with Mars regolith on purely a physical basis. For example, sandy soils (i.e., 50–2000 μm) have very little ability to retain water, and water flow through sandy soils is usually unrestricted. On the other hand, a clay soil (particle sizes $<2 \mu m$) may be able to retain more water, but if the soil is too fine O_2 diffusion may become limiting for normal plant growth and development. The parameter to measure flow through soil is hydraulic conductivity, which is dependent on the soil's water retention function. Hydraulic conductivity can be measured for either saturated flow (i.e., soil pores are entirely filled with water) or unsaturated flow (i.e., flow through a soil when soil pores are not entirely filled with water and the flow gradient is usually vertical). The hydraulic conductivity and water retention are dependent on soil texture and structure. The parameters bulk density, particle size distribution, and porosity likely will be readily measurable in robotic surface missions. However, hydraulic conductivity and water retention likely will be more difficult to directly measure on a robotic mission and, thus, may have to be inferred from particle size and bulk density measurements.

The "soil-like" surficial regolith materials on Mars can be described as drift materials (i.e., aeolian deposits), crusty to cloddy materials, and blocky materials (5,42). These materials are thought to consist of fine-grained particles in the size range of 0.1–10 μm . Bulk densities of the drift materials, crusty to cloddy materials, and blocky materials have been estimated to be

1.15 ± 0.15 , 1.40 ± 0.20 , and 1.60 ± 0.40 g/cm³, respectively (5,42). Most terrestrial soils have bulk densities between 1.1 and 1.8 g/cm³. Soils with bulk densities around 1.1 generally have lower hydraulic conductivities and high aeration porosities. The Mars "soil" particles (e.g., drift materials) once placed inside a plant growth chamber likely will exhibit good hydraulic conductivity (i.e., water infiltration) and aeration. However, it may be necessary to size the regolith materials to achieve the optimum soil physical conditions for plant growth.

Potentially Phytotoxic Toxic Chemical Factors in Martian Regolith

The most toxic materials on Mars are probably present in the mobile-element component of the regolith. These materials are likely to be composed of mainly sulfur and chlorine and are probably present as (Mg-Na-Ca) sulfates and chlorides. Sulfates are likely in the regolith based on new spectral data and the lack of evidence for sulfides (62). Recently, the Thermal Emission Spectrometer (TES) on the Mars Global Surveyor has been used to determine the distribution of sulfate (SO₄) cemented regolith (18). The sulfate is not located in topographic lows, arguing that the regolith was cemented by an atmospherically driven process. A number of other salts could be present at relatively low abundances, including carbonates (e.g. calcite, siderite), nitrates, and chlorides (e.g. halite) (6).

Because the abundances in the Martian regolith of the mobile elements sulfur and chlorine (potentially toxic themselves) have been measured (62), they can be used to estimate the abundances of mobile elements with potentially phytotoxic properties that should have been enriched along with the S and Cl (49,50). For example, the model abundances of some toxic elements are estimated to range up to 100 mg/kg for As, and up to hundreds of mg/kg for Cd, Pb, Br, and Zn, if the mobile-element component was contributed largely by volcanic aerosols. The abundances of S, Cl, and heavy metals are sufficiently high as to pose a possible toxic threat to humans (25), and may pose a significant threat to plants and microorganisms. Therefore, it will be necessary to assess the potential bioavailability of phytotoxic ions prior to any plant growth experiments in Mars regolith (see Table 2 for candidate soil tests for determining bioavailability of phytotoxic elements).

CONCLUSIONS

Future near-term Mars landers will include experiments that will examine various components of Mars regolith including basic soil chemistry and mineralogy, soil physics, organic detection, characterization of soil oxidants, and life-detection experiments. All of these experiments will produce information that will assist in understanding the evolution and history of Mars in general, and in Mars regolith in particular. In addition, these experiments will provide the basic knowledge required to grow plants in Mars soils. Although the debate is not over on whether to use regolith or hydroponic technologies to grow plants in a bioregenerative ALS module on Mars, the knowledge that plants can be grown in Mars soils will help determine the design of any future bioregenerative ALS system.

The recommended chemical tests include measurements on soil pH, electrical conductivity, redox potential, and bioavailability of essential plant nutrients and phytotoxic elements. In addition, future plant growth experiments should include procedures for determining the buffering and leaching requirements of Mars regolith prior to plant growth studies. Soil physical tests useful for plant biology studies in Mars regolith include measuring particle size, bulk density, porosity, water retention, and hydraulic conductivity.

Plant biology experiments on near-term Mars landers are strongly recommended for three basic reasons. First, the primary justification for sending plant biology experiments to Mars in the near-term is to confirm that plants can grow in Mars regolith, and to obtain the necessary baseline data for modeling plant growth on Mars. Such knowledge will directly impact the research agenda and design of bioregenerative systems over the next 20 years. Second, there will not be an adequate amount of Mars regolith returned to Earth in currently proposed sample-return missions that will provide enough material to conduct reasonable plant biology experiments. Thus, in order to accurately model plant growth in Mars soils, it is important that plants are actually grown in Mars soils. And third, a plant biology experiment on a near-term Mars surface mission can be used to confirm the biosafety of the Mars regolith prior to the return of samples to Earth.

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REFERENCES

- Adriano, D. C.; Doner, H. E. Bromine, chlorine, and fluorine. In: Page, A. L.; Miller, R. H.; Keeney, D. R., eds. *Methods of soil analysis, Part 2: Chemical and microbiological properties*, 2nd ed. Madison, WI: Amer. Soc. Agron.; 1982:449-483.
- Allen, C. C.; Gooding, J. L.; Jercinovic, M.; Keil, K. Altered basaltic glass: A terrestrial analog to the soil of Mars. *Icarus* 45:347-369; 1981.
- Allen, C. C.; Jager, K. M.; Morris, R. V.; Lindstrom, D. J.; Lindstrom, M. M.; Lockwood, J. P. JSC Mars-1: A Martian soil simulant. *Proc. Conf. Amer. Soc. Civil Eng., Albuquerque, NM*; 1998:469-476.
- Alton, J. H.; Bagby, J. R.; Stabekis, P. D. Lessons learned during Apollo Lunar sample quarantine and sample curation. *Adv. Space Res.* 22:373-382; 1998.
- Arvidson, R. E.; Gooding, J. L.; Moore, H. J. The Martian surface as imaged, sampled, and analyzed by the Viking landers. *Rev. Geophys.* 27:39-60; 1989.
- Banin, A.; Clark, B. C.; Wänke, H. Surface chemistry and mineralogy. In: Kieffer, H. H., ed., *Mars*. Tucson, AZ: University of Arizona Press; 1992:594-625.
- Banin, A.; Han, F. X.; Kan, I.; Cicelsky, A. Acidic volatiles and the Mars soil. *J. Geophys. Res.* 102(E6):13341-13356; 1997.
- Bell, J. F., III; McSween, H. Y.; Crisp, J. A.; Morris, R. V.; Murchie, S. L.; Bridges, N. T.; Johnson, J. R.; Britt, D. T.; Golombek, M. T.; Moore, H. J.; Ghosh, A.; Bishop, J. L.; Anderson, R. C.; Brückner, J.; Economou, T.; Greenwood, J. P.; Gunnlaugsson, H. P.; Hargraves, R. M.; Hviid, S.; Knudsen, J. M.; Madsen, M. B.; Reid, R.; Rieder, R.; Soderblom, L. Mineralogic and compositional properties of Martian soil and dust: Results from Mars Pathfinder. *J. Geophys. Res. E Planets* 105:1721-1755; 2000.
- Bishop, J. L.; Pieters, C. M.; Burns, R. G.; Edwards, J. O.; Mancinelli, R. L.; Froschl, H. Reflectance spectroscopy of ferric sulfate-bearing montmorillonites as Mars soil analog materials. *Icarus* 117:101-119; 1995.
- Boston, P. J. Low-pressure greenhouses and plants for a manned research station on Mars. *J. Br. Interplanet. Soc.* 54:189-192; 1981.
- Brückner, J.; Dreibus, G.; Rieder, R.; Wänke, H. Revised data of the Mars Pathfinder alpha proton X-ray spectrometer: Geochemical behavior of major and minor elements. *32nd Lunar and Planetary Sci., Abst. #1293*; 2001.
- Bugbee, B. G.; Salisbury, F. B. Controlled environment crop production: Hydroponics vs. lunar regolith. In: Ming, D. W.; Henninger, D. L., eds. *Lunar base agriculture: Soils for plant growth*. Madison, WI: Amer. Soc. Agron., Crop Sci. Soc. Amer., and Soil Sci. Soc. Amer.; 1989:107-129.
- Bullock, M. A.; Stoker, C. R.; McKay, C. P.; Zent, A. P. A coupled soil-atmosphere model of H₂O₂ on Mars. *Icarus* 107:142-154; 1994.
- Burns, R. G.; Fisher, D. S. Rates of oxidative weathering on the surface of Mars. *J. Geophys. Res.* 98:3365-3372; 1993.
- Clark, B. C. Geochemical components in Martian soil. *Geochim. Cosmochim. Acta* 57:4575-4581; 1993.
- Clark, B. C.; Baird, A. K. Is the Martian lithosphere sulfur rich? *J. Geophys. Res.* 84:8395-8403; 1979.
- Clark, B. C.; Baird, A. K.; Weldon, R. J.; Tsusaki, D. M.; Schnabel, L.; Candelaria, M. Chemical composition of Martian fines. *J. Geophys. Res.* 87:10059-10067; 1982.
- Cooper, C. D.; Mustard, J. F. TES observations of the global distribution of sulfate on Mars. *32nd Lunar and Planetary Science, Abst. # 2048*; 2001.
- Dreschel, T. W.; Sager, J. C. Control of water and nutrients using a porous tube: A method for growing plants in space. *Hortscience* 24:944-947; 1989.
- Flynn, G. J. The contribution by interplanetary dust to noble gases in the atmosphere of Mars. *J. Geophys. Res.* 102:9175-9182; 1997.
- Flynn, G. J.; McKay, D. S. An assessment of the meteoritic contribution to the Martian soil. *J. Geophys. Res.* 95:14497-14509; 1990.
- Foley, C. N.; Economou, T. E.; Clayton, R. N. Chemistry of Mars Pathfinder samples determined by the APXS. *32nd Lunar and Planetary Science, Abst. # 1979*; 2001.
- Griggs, J. L. Determination of the available molybdenum of soils. *N. Zeal. J. Sci. Technol.* 34:405-414; 1953.
- Haby, V. A.; Russelle, M. P.; Skogley, E. O. Testing soils for potassium, calcium, and magnesium. In: Westerman, R. L., ed., *Soil testing and plant analysis*, 3rd ed. Madison, WI: Soil Sci. Soc. Amer.; 1990:181-227.
- Hagerty, J. J.; Newsom, H. E. Potential toxicity of the Martian soil. *29th Lunar and Planetary Science, Abst. #1697*; 1998.
- Hashimoto, T. Requirements of blue, UV-A, and UV-B light for normal growth of higher plants, as assessed by action spectra for growth and related phenomena. In: Tibbitts, T. W., ed., *International lighting in controlled environments workshop*. NASA Publication NASA-CP-95-3309, Washington, DC; 1994:143-157.
- Hoff, J. E.; Howe, J. M.; Mitchell, C. A. Nutritional and cultural aspects of plant species selection in a controlled ecological life support system. *NASA Contractor Report 166324*, Ames Research Center, Moffett Field, CA; 1982.
- Hviid, S. F.; Madsen, M. B.; Gunnlaugsson, H. P.; Goetz, W.; Knudsen, J. M.; Hargraves, R. B.; Smith, P.; Britt, D.; Dinesen, A. R.; Morgensen, C. T.; Olsen, M.; Pedersen, C. T.; Vistisen L. Magnetic properties experiments on the Mars Pathfinder Lander: Preliminary results. *Science* 278:1768-1770; 1997.
- Hunten, D. Possible oxidant sources in the atmosphere and surface of Mars. *J. Mol. Evol.* 14:57-64; 1979.
- Keeney, D. R.; Nelson, D. W. Nitrogen-inorganic forms. In: Page, A. L.; Miller, R. H.; Keeney, D. R., eds. *Method of soil analysis. Part 2: Chemical and microbiological properties*, 2nd ed. Madison, WI: Amer. Soc. Agron.; 1982:643-698.

31. Kieffer, S. W.; Simonds, C. H. The role of volatiles and lithology in the impact cratering process. *Rev. Geophys. Space Phys.* 18:143; 1980.
32. Klein, H. P. The search of life on Mars. *Rev. Geophys. Space Phys.* 17:1655-1662; 1979.
33. Klein, H. P.; Horowitz, N. H.; Biemann, K. The search for extant life on Mars. In: Kieffer, H. H.; Jakosky, B. M.; Snyder, C. W.; Matthews, M. S., eds. *Mars*. Tucson, AZ: University of Arizona Press; 1992:1221-1233.
34. Klein, H. P.; Horowitz, N. H.; Levin, G. V.; Oyama, V. I.; Lederberg, J.; Rich, A.; Hubbard, J. S.; Hobby, G. L.; Straat, P. A.; Berdahl, B. U.; Carle, G. C.; Brown, F. S.; Johnson, R. D. Viking biological investigation: Preliminary results. *Science* 194:99-105; 1976.
35. MacElroy, R. D.; Klein, H. P. The evolution of CELSS for Lunar bases. In: Mendell, W. W., ed. *Lunar bases and space activities of the 21st century*. Houston, TX: Lunar & Planetary Institute; 1985:623-633.
36. McSween, H. Y.; Keil, K. Mixing relationships in the Martian regolith and the composition of globally homogeneous dust. *Geochim. Cosmochim. Acta* 64:2155-2166; 2000.
37. McKay, C. P.; Meyer, T. R.; Boston, P. J.; Nelson, M.; Maccallum, T.; Gwynne, O. Utilizing Martian resources for life support. In: Lewis, J. S.; Matthews, M. S.; Guerriere, M. L., eds. *Resources of near-Earth space*. Tucson, AZ: University of Arizona Press; 1993:819-843.
38. Mehlich, A. Mehlich III soil extractant: A modification of Mehlich II extractant. *Comm. Soil Plant Anal.* 15:1409-1416; 1984.
39. Ming, D. W.; Golden, D. C.; Liu, C. C.; Dawson, A. D.; Hedgecock, J. C. PHEEMS: A Mars soil reactivity experiment. 29th Lunar Planet. Sci. Conf., Abst. # 1232; 1998.
40. Ming, D. W.; Golden, D. C.; Henninger, D. L. Utilization of on-site resources for regenerative life support systems at Lunar and Martian outposts. SAE Technical Paper 932091, 23rd International Conference on Environmental Systems, Colorado Springs, CO; 1993.
41. Ming, D. W.; Henninger, D. L. Lunar base agriculture: Soils for plant growth. Madison, WI: Soil Sci. Soc. Amer.; 1989.
42. Moore, H. J.; Clow, J. D.; Hutton, R. E. A summary of Viking sample-trench analyses for angles of internal friction and cohesion. *J. Geophys. Res.* 87:10043-10050; 1982.
43. Morris, R. V.; Golden, D. C.; Bell, J. F., III; Shelfer, T. D.; Scheinost, A. C.; Hinman, N. W.; Furniss, G.; Mertzman, S. A.; Bishop, J. L.; Ming, D. W.; Allen, C. C.; Britt, D. T. Mineralogy, composition, and alteration of Mars Pathfinder rocks and soils; evidence from multispectral, elemental, and magnetic data on terrestrial analogue, SNC Meteorite, and Pathfinder samples. *J. Geophys. Res.* 105(E):757-818; 2000.
44. Morris, R. V.; Golden, D. C.; Ming, D. W.; Shelfer, T. D.; Jorgensen, L. C.; Bell, J. F., III; Graff, T. G.; Mertzman, S. A. Phyllosilicate-poor palagonitic dust from Mauna Kea Volcano (Hawaii): A mineralogical analogue for magnetic Martian dust? *J. Geophys. Res.* 106(E):5057-5083; 2001.
45. Morris, R.; Golden, D. C.; Shelfer, T. D.; Lauer, H. V., Jr. Lepidocrocite to maghemite: A pathway to magnetic and hematitic Martian soil. *Meteoritics Planetary Sci.* 33:743-751; 1998.
46. Morris, R. V.; Ming, D. W.; Golden, D. C.; Bell, J. F., III. An occurrence of jarositic tephra on Mauna Kea, Hawaii: Implications for the ferric mineralogy of the Martian surface. In: Dyar, M. D.; McCammon, C.; Schaefer, M. W., eds. *Mineral spectroscopy: A tribute to Roger G. Burns*. The Geochemical Society, Special Publication No. 5; 1996:327-336.
47. Neelson, K. H., ed. *Mars sample return: Issues and recommendations*. Washington, DC: Space Studies Board, National Research Council, National Academy Press; 1992.
48. Neelson, K. H., ed. *Biological contamination of Mars: Issues and recommendations*. Washington, DC: Space Studies Board, National Research Council, National Academy Press; 1997.
49. Newsom, H. E.; Hagerty, J. J. Chemical components of the Martian soil: Melt degassing, hydrothermal alteration, and chondritic debris. *J. Geophys. Res.* 102(E):19345-19355; 1997.
50. Newsom, H. E.; Hagerty, J. J.; Goff, F. Mixed hydrothermal fluids and the origin of the Martian soil. *J. Geophys. Res.* 104(E):8717-8728; 1999.
51. Olsen, S. R.; Cole, C. V.; Watanabe, F. S.; Dean, L. A. Estimation of available P in soils by extraction with sodium bicarbonate. *USDA Circ.* 939; 1954.
52. Olson, R. L.; Oleson, M. W.; Slavin, T. J. CELSS for advanced manned mission. *Hortscience* 23:275-286; 1988.
53. Owen, T. The composition and early history of the atmosphere of Mars. In: Kieffer, H. H.; Jakosky, B. M.; Snyder, C. W.; Matthews, M. S., eds. *Mars*. Tucson, AZ: University of Arizona Press; 1992:818-834.
54. Rieder, R. H.; Economou, T.; Wänke, H.; Turkevich, A.; Crisp, J.; Brückner, J.; Dreibus, G.; McSween, H. Y. The chemical composition of Martian soil and rocks returned by the mobile alpha proton X-ray spectrometer: Preliminary results from the X-ray mode. *Science* 278:1771-1774; 1997.
55. Schuerger, A. C. Microbial contamination of Advanced Life Support (ALS) systems poses a moderate threat to the long-term stability of space-based bioregenerative systems. *Life Support Biosphere Sci.* 5:325-337; 1998.
56. Singer, R. B. Spectral evidence for the mineralogy of high-albedo soils and dust on Mars. *J. Geophys. Res.* 87:10159-10168; 1982.
57. Singer, R. B.; McCord, T. B.; Clark, R. N.; Adams, J. B.; Huguenin, R. L. Mars surface composition from reflectance spectroscopy: A summary. *J. Geophys. Res.* 84(B14):8415-8426; 1979.
58. Soltanpour, P. N.; Schwab, P. A. A new soil test for simultaneous extraction of macro- and micronutrients in alkaline soils. *Comm. Soil Plant Anal.* 8:195-207; 1977.
59. SSSA. *Glossary of soil science terms*. Madison, WI: Soil Science Society of America; 1997.
60. Stoker, C. R.; Gooding, J. L.; Roush, T.; Banin, A.; Burt, D.; Clark, B. C.; Flynn, G.; Gwynne, O. 1993. The physical and chemical properties and resource potential of Martian surface soils. In: Lewis, J.; Matthews, M. S.; Guerriere,

- M. L., eds. Resources of near-Earth space. Tucson, AZ: University of Arizona Press; 1993:659-707.
61. Tibbits, T. W.; Alford, D. K. Controlled ecological life support systems: Use of higher plants. NASA Conference Publication 3321, Ames Research Center, Moffet Field, CA; 1982.
 62. Toulmin, P., III; Baird, A. K.; Clark, B. C.; Keil, K.; Rose, H. J., Jr.; Christian, R. P.; Evans, P. H.; Kelliher, W. C. Geochemical and mineralogical interpretation of the Viking inorganic chemical results. *J. Geophys. Res.* 82:4625-4634; 1977.
 63. Wright, B. D.; Bausch, W. C.; Knott, W. M. A hydroponic system for microgravity plant experiments. *Trans. ASAE* 31:440-446; 1988.
 64. Yen, A. S.; Kim, S. S.; Hecht, M. H.; Frant, M. S.; Murray, B. Evidence that the reactivity of the Martian soil is due to superoxide ions. *Science* 289:1909-1912; 2000.
 65. Zent, A. P.; McKay, C. P. The chemical reactivity of the Martian soil and implications for future missions. *Icarus* 108:146-157; 1994.