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SOLID-SUPPORT SUBSTRATES FOR PLANT GROWTH AT A LUNAR BASE

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ABSTRACT

A variety of in situ materials could be used as solid-support substrates for plant growth at planetary bases (primarily lunar bases); including 1) native lunar "soils", 2) sized lunar regolith amended with synthetic materials (e.g., zeolites, smectites) that provide nutrient and water retention, 3) synthetic, inorganic, highly-reactive substrates (e.g., zeoponics), and 4) sized lunar materials or industrial by-products used as inert, solid-support substrates in nutriculture systems. Research at NASA/JSC is being conducted in several areas of plant growth in solid-support substrates; including 1) behavior of lunar materials as "soils"; 2) zeoponic systems for plant growth; and 3) production of lunar simulants to use in plant growth experiments. Presently, most of our attention is being directed toward zeoponic systems and lunar simulants. Zeoponics is only in its developmental stages at JSC and is defined as the cultivation of plants in zeolite substrates that 1) contain essential, plant-growth cations on their exchange sites, and 2) have minor amounts of mineral phases (e.g., apatite) and/or anion-exchange resins (e.g., activated aluminum resins) that supply essential, plant-growth anions. Zeolites are hydrated aluminosilicates of alkali and alkaline earth cations with the ability to exchange most of their constituent exchange cations as well as hydrate/dehydrate without change to their structural framework. Because zeolites have extremely high cation exchange capacities, they are very attractive media for plant growth. It is possible to partially or fully saturate plant-essential cations on zeolites. The apparent selectivity of plant-essential cations and Na for the terrestrial zeolite clinoptilolite is:

$$K^{+} > NH_4^{+} >> Na^{+} > Mn^{2+} = Cu^{2+} = Fe^{2+} > Zn^{2+} > Ca^{2+} > Mg^{2+}.$$

Zeoponic systems will probably have their greatest applications at planetary bases (e.g., lunar bases). Lunar raw materials will have to be located that are best suited for the syntheses of zeolites and other exchange resins; however, we have previously shown that zeolites can be synthesized from lunar analog glass subjected to mild hydrothermal conditions. Lunar "soil" simulants have been or are being prepared for zeolite/smectite syntheses and "soil" dissolution studies.

INTRODUCTION

The newly created Office of Exploration at NASA Headquarters is considering several missions that the Agency may undertake as part of the human exploration of our inner solar system. These scenarios include: 1) expeditions to establish the first human presence on another planet (e.g., Mars); 2) lunar outposts to conduct extraterrestrial science; and 3) evolutionary expansion to establish self-sufficient human presence beyond low Earth orbit. Evolutionary expansion is a step-by-step program away from low Earth orbit. The first step will probably be the establishment of a lunar outpost that will lead to a self-sufficient lunar base. A self-sufficient lunar base will require the utilization of in situ resources for construction materials, propellants, life-support systems, etc. The growth of plants at a lunar base will be essential to sustain a self-sufficient human colony, and there are several systems in which to grow plants, e.g., hydroponics, aeroponics, and solid-support substrates. Most of the plant-growth research in controlled ecological life support systems (CELSS) has been aimed toward hydroponic systems. Soils may also be viable plant-growth systems, however, our knowledge of how lunar materials will react as soil is virtually unknown.

BACKGROUND

Controlled Ecological Life Support Systems (CELSS)

A bioregenerative Controlled Ecological Life Support System (CELSS) is a system where the crew is supplied with water, food and oxygen that is produced by photosynthesis of living plants. The photosynthetic organisms (primarily plants and algae) consume carbon dioxide (CO_2), the major metabolic human waste, and combine it with water converting these materials into food as well as producing the essential gas oxygen. Development of such a CELSS is needed not only to allow for self sufficiency but to reduce the transportation costs of resupply when the numbers of crew members rise above those required for an initial outpost.

Growing plants at a lunar base has other attractive features beyond supply of food to lunar crews. Instead of re-supplying food to Space Station Freedom (or other space stations) from Earth, resupplying through lunar base agricultural production could reduce the transportation costs. Furthermore, industrial and human wastes from space stations could be transported to the lunar surface where they could be re-cycled; thus they become a resource available to lunar base expansion rather than a liability for Shuttle to return to Earth. Manned interplanetary spacecraft will be extremely large vehicles requiring on-orbit assembly and supply due to their long-duration missions. Initial supplies of food could be provided from lunar base agricultural production. Waste products from the returning manned interplanetary spacecraft could be sent to the lunar surface for renovation and use.

In fact, a true bioregenerative CELSS will have its greatest application at a lunar base rather than a space station or other space vehicle simply because of the tight mass, volume, power, and thermal requirements associated with space vehicles. The Moon also offers a gravity gradient which will make the engineering of systems involving fluid flow much easier. The 1/6th g of the moon might also be ideal for breeding varieties of food plants to maximize fruit production over stem rigidity, for example.

Assuming the growth of plants at a lunar base is inevitable, the question of the required technology arises. Terrestrial agricultural practices are well developed, and it seems fitting that as humans seek to establish a colony on the Moon that they take a familiar practice with them.

Terrestrial Soil

On Earth, in addition to the absence of plant disease and insect pests, there are six external factors that affect the growth of all plants. These factors are: (1) light, (2) mechanical support, (3) heat, (4) air, (5) water, and (6) nutrients [1]. Soil is integral to each of these factors except light. Robust plant growth is dependent on a favorable combination of these factors; and if one is out of balance, plant growth can be restricted or even totally inhibited. Furthermore, whichever factor is least optimum determines the maximum level of plant growth; this is especially true with respect to nutrients. Five of these six plant growth factors are influenced to some degree by both physical and chemical properties of the soil. For example, soil texture and structure influence air, water and heat gradients within the soil profile. Soil solution pH, ion concentration, ion balance, and activity are important chemical properties.

The sixteen essential nutritive elements needed by plants and their sources are listed in Table 1. Of the elements obtained from the soil by plants, six are used in relatively large quantities (macronutrients): nitrogen, phosphorous, potassium, calcium, magnesium, and sulfur. Plant growth can be limited by a deficiency of any one or a combination of these elements in the soil. Each nutrient must exist in a form available to the plant; and each nutrient must be balanced with respect to the others. The remaining nutrients, while essential to plant growth, are used in much smaller quantities, and are called micronutrients or trace elements (Table 1).

Four areas must be examined with respect to plant growth nutrients and their potential deficiencies. They are: (1) the macronutrient content of the mineral portion of the soil, (2) the ionic form of the nutrient in soil solution, (3) the process by which nutrients become available to plants, and (4) the soil solution and its pH. The mineral portion is established geologically and weathers to yield the various compounds and ions. The ionic form of the plant growth nutrients that are in the soil solution or on the soil colloids (Table 2) are important from the standpoint of being available for uptake into the plant. Some ionic forms of the elements are preferentially absorbed by plants. In addition to physical weathering of soil minerals and those derived from the atmosphere, plant growth nutrients are supplied by microbiological degradation of organic matter (nutrients are also added via commercial fertilizers).

TABLE 1. Essential plant growth elements and their sources [1].

Elements Used in Relatively Large Amounts		Elements Used in Relatively Small Amounts	
Mostly from			
Air and Water	Soil Solids	Soil Solids	
Carbon	Nitrogen	Iron	Copper
Hydrogen	Phosphorous	Manganese	Zinc
Oxygen	Potassium	Boron	Chlorine
	Calcium	Molybdenum	
	Magnesium		
	Sulfur		

TABLE 2. Important ions present in the soil solution or on the soil colloids [1].

Element	Solution Species	Element	Solution Species
N	NH_4^+, NO_2^-, NO_3^-	Ca	Ca^{2+}
P	$H_2PO_4^{2-}$, $H_2PO_4^-$	Mg	Mg^{2+}
K	K^+	S	SO_3^{2-}, SO_4^{2-}
Fe	Fe^{2+}, Fe^{3+}	Zn	Zn^{2+}
Mo	MoO_4^{2-}	B	$H_2BO_3^-$, H_3BO_3
Mn	Mn^{4+}, Mn^{2+}	Cl	Cl^-
Cu	Cu^+, Cu^{2+}	water	H^+, OH^-

The soil solution is the water in which the dissolved ionic forms of plant nutrients reside. The concentration of ions in the soil solution changes as the volume of water changes and also as the nutrients are added or removed. Another important aspect of the soil solution is its pH. Soil pH ranges from 5 to 7 in humid region soils, and 7 to 9 in arid region soils with extremes near 3.5 to over 10. The importance of pH rests with its effect on the availability of several of the essential nutrients as well as the solubility of certain elements toxic to plant growth. Iron, manganese, and zinc tend to become less available as the pH rises from 5.0 to 8.0. Conversely, molybdenum is increasingly available at these higher pH's. At pH values below approximately 5.0, aluminum, chromium, iron, and manganese are often soluble in quantities sufficient to be toxic to the growth of some plants.

Lunar Regolith

Both the lunar regolith and its parent bedrock are composed (like Earth rocks) mainly of small crystals (minerals) that are chemical compounds formed by the combination of metal elements with oxygen (see Table 3). These minerals are of two principal types: (1) silicates in which various metals (calcium, iron, aluminum, magnesium) are combined with networks of oxygen and silicon atoms; and, (2) oxides in which metal (titanium and iron, primarily) are combined directly with oxygen atoms. The lunar regolith also contains free iron metal (0.1 to 1.0 percent) and iron sulfides. These substances occur as small particles derived from both the lunar bedrock and from impacting meteorites. This metal also contains significant amounts of nickel, cobalt and chromium.

The most common components of the lunar regolith are minerals (and glasses) made of silicates (see Table 3). These minerals are identified as: pyroxene (calcium-iron-magnesium aluminosilicates, e.g., enstatite,

TABLE 3. Lunar minerals [2].

Major Minerals[a]	**Minor Minerals**[b]
Olivine $(Mg,Fe)_2SiO_4$	Spinels $(Fe,Mg,Al,Cr,Ti)O_4$
Pyroxene $(Ca,Mg,Fe)SiO_3$	Armalcolite (Fe_2TiO_5)
Plagioclase feldspars $(Ca,Na)Al_2Si_2O_8$	Silica (quartz, tridymite cristobalite) SiO_2
	Iron Fe (variable amounts of Ni and Co)
	Troilite FeS
	Ilmenite $FeTiO_3$

Trace Minerals[c]	
Phosphates	**Oxides**
[d]Apatite $Ca_5(PO_4)_3(F,Cl)_3$	Rutile TiO_2
[d]Whitlockite $Ca_9(Mg,Fe)(PO_4)_7(F,Cl)$	Corrundum (?) Al_2O_3
	Hematite (?) Fe_2O_3
	Magnetite Fe_3O_4
Zr Minerals	Goethite (?) FeO(OH)
[d]Zircon $ZrSiO_4$	
Baddeleyite ZrO_4	**Metals**
	Copper (?) Cu
Silicates	Brass (?)
Pyroxferroite $(Fe,Mg,Ca)SiO_3$	Tin (?) Sn
Amphibole $(Ca,Mg,Fe)(Si,Al)_8)_{22}F$	
Garnet (?)	
[d]Tranquilletyite $Fe_8Zr_2Ti_3Si_3O_4$	**Zr-rich Minerals**
	[d]Zirkilite or zirconolite $CuZrTi_2O_7$
Sulfides	**Meteoritic Minerals**
Mackinawite $(Fe,Ni)_9S_8$	Schreibernite $(Fe,Ni)_3P$
Pentlandite $(Fe,Ni)_9S_8$	Cohenite (Fe,Ni,Co),C
Chalcopyrite $CuFeS_2$	Niningerite (Mg,Fe,Mn)S
Cubanite $CuFe_2S_3$	Lawrencite (?) $(Fe,Ni,)Cl_2$
Sphalerite (Zn,Fe)S	

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[a] Major minerals may occur in concentrations up to 100%.

[b] Minor minerals generally occur at less than 2 percent.

[c] Trace minerals never exceed a few tenths of a percent.

[d] These minerals are known to exhibit complete substitution, particularly of elements like Y, Nb, Hf, U, and the rare earth elements that are concentrated in these minerals.

? Controversial with respect to indigenous lunar origin.

wollastonite, ferrosilite), feldspar (calcium aluminosilicates, anorthite or plagioclase), and olivine (iron-magnesium aluminosilicates, forsterite or fayalite). These different materials occur in the lunar regolith as fine particles. While the regolith does contain boulder, cobble, and chip sized materials, the average grain size of the portion of the lunar regolith that passes through a 1 mm sieve is only about 0.045 to 0.1 millimeters [2].

Most of the particles in the lunar regolith are complex, composed of mixed glasses and mineral fragments. These particles are called agglutinates and are produced by the melting and mixing caused by micrometeorite impacts. Agglutinates are frequently porous. Embedded in them are small quantities of gas (volatiles) implanted by the solar wind. The small size and irregular shape of these agglutinate particles are largely responsible for the strongly cohesive character of the lunar regolith.

Since individual particles in the lunar regolith have chemical compositions that vary more widely than does that of the bulk regolith itself, it may be possible to obtain several chemically different feedstocks by processing the regolith to separate out and concentrate particular components. Such processes may be pre-treatments to the formation of a viable agricultural substrate. A feldspar-rich concentrate would have a higher proportion of calcium and aluminum than would the bulk soil. Similarly, an ilmenite-rich concentrate from a basalt lava would be an improved source of iron for soil development and a source of titanium, as a by-product, for other lunar applications. The traces of iron metal in the soil might be directly concentrated by magnetic methods or other innovative techniques. Agglutinate particles might be concentrated as a source of volatile materials, although their content of solar wind gases is relatively small [2].

On the basis of chemical composition and available tonnages, lunar resources could well form the basis of an extensive manufacturing technology and similarly promote the formation of an agricultural enterprise to support man's endeavors in space. What is now lacking is the technology needed to extract the essential chemical elements for these manufacturing and agricultural undertakings.

Comparison of Terrestrial Soil and Lunar Regolith

A comparison of the concentration of the sixteen essential plant growth nutrients in terrestrial soils, plants, and in the lunar regolith is shown in Table 4. Carbon, hydrogen, and oxygen are obtained by plants from the Earth's atmosphere and water; these primary plant-essential elements are very abundant in the Earth's air and water. Carbon and hydrogen are in very short supply on the Moon; however, there is approximately 40% oxygen by weight in the lunar regolith.

The lunar regolith contains much more Ca, Mg, and S than do terrestrial soils and with exposure to a moist, aerobic environment, dissolution of these macronutrients should take place quite easily and in sufficient quantities for plant growth. High levels of P are contained in the lunar regolith in the mineral apatite; however, this mineral has a low solubility in the near-neutral pH of the lunar soil (pH of 7.38 in deionized water and 6.32 in CO_2 - charged water; [3]) and dissolution rates are likely to be slow. The lunar regolith contains about half as much K as do terrestrial soils and might require the addition of fertilizer K to insure good plant growth. Of

TABLE 4. Comparison of essential plant growth nutrients in terrestrial soils, plants, and lunar regolith [1, 11].

Element	Terrestrial[a]		Plants	Lunar[b]	
			Macronutrients		
	wt. %	kg m^{-3}	wt. %	wt. %	kg m^{-3}
Carbon[c]	atm	atm	18	0.011	0.18
Hydrogen[c]	atm	atm	8	0.0055	0.09
Oxygen[c]	atm	atm	70	40	664
Nitrogen	0.14	2.0	0.3	0.01	0.17
Phosphorous	0.06	0.8	0.07	0.4	6.64
Potassium	0.83	11.6	0.3	0.4	6.64
Calcium	1.4	20	0.5	9.0	149
Magnesium	0.5	7	0.04	6.0	99.6
Sulfur	0.07	1	0.07	0.5	8.3
			Micronutrients		
	ppm	kg m^{-3}	ppm	ppm	kg m^{-3}
Iron	38000	53	100	90000	149
Manganese	800	1.1	10	2000	3.3
Boron	10	0.014	10	20	0.03
Molybdenum	3	0.004	0.1	1	0.002
Copper	20	0.03	2	13	0.022
Zinc	50	0.07	5	28	0.046
Chlorine	100	0.14	200	26	0.043

[a] Average density of cropped soils taken to be 1.4 g cm^{-3}
[b] Average density of lunar regolith in the 0-60 cm depth taken to be 1.66 g cm^{-3}
[c] Plants obtain these nutrients mainly from air and water; the other nutrients are obtained from the soil.

the micronutrients, only Cl is present in appreciably lower concentrations on the Moon than in terrestrial soils but since it is one of the micronutrients required by plants in quite small quantities it should not represent a serious problem.

Factors such as pH, Eh, and mineralogical composition will affect concentration and ionic species of elements potentially toxic to plants. Table 5 lists thirteen elements that have been shown to be toxic to plants and their total soil and soil solution concentrations. A high total concentration does not necessarily mean that the element will be toxic. Other factors such as mineral or ionic form of the element and the plant species grown, along with soil factors such as composition, pH, Eh, and moisture status all affect the element's ability to be absorbed by the plant [4].

Of the toxic elements listed in Table 5, only Cr and Ni are present in the lunar regolith in concentrations appreciably higher than in terrestrial soils. Terrestrial concentrations of Cr and Ni are approximately 20 and 40 ppm (or mg/kg), respectively, while lunar concentrations of Cr range from 479 to 6705 ppm and Ni from 55 to 720 ppm [5]. Within the normal range of pH and Eh in terrestrial soils, chromium can exist as the Cr^{3+} cation and the CrO^- anion, and two hexavalent states, the $Cr_2O_7^{2-}$ and CrO_4^{2-} anions [6]. The hexavalent state appears to be more toxic to plants than the trivalent state [7]. Trivalent chromium is more common in soils than is Cr(VI) since chromium is quite easily reduced; however, Bartlett and James [8] have shown that oxidation of Cr(III) to Cr(VI) does take place in aerobic, non-acid soils. According to Bohn et al. [9], Cr(VI) stability increases with increasing pH. Since the chromium content is high in the lunar regolith and the pH is near neutral, chromium toxicity will have to be addressed.

Nickel toxicity in lunar soils is less likely than chromium toxicity, but the potential exists in those lunar soils containing the higher levels of nickel. In some areas nickel toxicity has been shown where concentrations as high as 8000 ppm total Ni have been measured. Slingsbury and Brown [10] have suggested that increasing

TABLE 5. Concentrations of plant toxic elements in terrestrial soils and plants [9].

Element	Total Soil Typical Value	Total Soil Range	Soil Solution	Plants Range
	$mg\ kg^{-1}$	$mg\ kg^{-1}$	$mg\ L^{-1}$	$mg\ kg^{-1}$
Al	50,000	10,000-200,000	0.1-0.6	---
As	5	1-50	0.1	---
Be	1	0.2-10	0.001	---
Cd	0.06	0.01-7	0.001	0.1-0.8
Cr	20	5-1000	0.001	---
Co	8	1-40	0.01	0.05-0.5
Cu	20	2-100	0.03-0.3	4-15
Pb	10	2-200	0.001	0.1-10
Mn	850	100-4000	0.1-10	15-100
Hg	0.05	0.02-0.2	0.001	---
Ni	40	10-1000	0.05	1
Se	0.5	0.1-2.0	0.001-0.01	---
Zn	50	10-300	<0.005	8-15

the soil pH and organic matter content might reduce the nickel availability to plants. With respect to use of lunar regolith as a plant growth medium, nickel toxicity may be a problem only if the pH of the soils decreases over time and nickel concentrations are high.

SOLID-SUPPORT SUBSTRATES

Native Lunar "Soils"

Weathering is the action of the elements in altering the color, texture, composition, or form of exposed objects; specifically, the physical disintegration and chemical decomposition of Earth materials at or near the Earth's surface. Weathering is basically a combination of destruction and synthesis. Rock fragments and the minerals contained in them are attacked by weathering forces and are changed into new minerals (secondary minerals) either by minor modifications (alterations) or by complete chemical changes [1]. These changes are accompanied by a release of soluble constituents into the soil solution. The minerals which are synthesized are in two groups: 1) the silicate clays, and 2) the very resistant end products, including iron and aluminum oxides. Two basic processes are involved in the weathering process: mechanical and chemical. Mechanical or disintegration takes place as a result of temperature fluctuations (differential expansion, frost action, and exfoliation), erosion and deposition by water or wind, and plant or animal influences. Chemical processes include hydrolysis, hydration, carbonation and related acidity processes, oxidation, and solution.

Mechanical forces of major impact events were once very active on the moon. Micrometeorite impacts still play an important role in mechanically altering lunar surface materials. Since the Moon is essentially devoid of water, the chemical processes of terrestrial weathering are not at work. However, when we establish an Earth-like environment we can introduce and control an environment of our choosing. This presents a host of questions concerning the lunar regolith's response to such Earth-like envionments which we can impose, control and change. Parameters such as temperature, atmospheric composition and pressure, and weathering solvents can be controlled as a function of time. Specific environments can be introduced to perform certain functions and then changed to perform another function; eventually getting to the point of having a true lunar "soil" capable of growing plants.

In work currently underway at the Johnson Space Center, experiments are being conducted to examine the effects of various solvents on simulated lunar regolith as a function of time. Solvents range from water to solvents representing a range of complexing abilities and include humic and fulvic acids extracted from terrestrial soil samples. Humic and fulvic acids are complex organic acids common in the root zone environment of plants and promote good soil structure, increase cation exchange capacity, improve pH buffering, and increase water holding capacities [11]. Since hydrolysis, the reaction of a substance with dissociated ions of water (H^+ and OH^-), is the most important terrestrial weathering reaction, special emphasis is being placed on it.

Simulated lunar material (and later actual lunar material) is being subjected to a complement of weathering environments ranging from relatively mild conditions such as those under a growing crop to much harsher conditions of low pH, high temperature, and increased pressures. Weathering products and the leachates are being analyzed to determine modifications induced by such environments.

Workshop

A workshop entitled "Lunar Derived `Soils' for the Growth of Higher Plants" was held at the Johnson Space Center in Houston, Texas on June 1-2, 1987. The workshop was sponsored by the Solar System Exploration Division at JSC and the NASA-Headquarters CELSS Program within the Life Sciences Division. The more than 100 participants represented over 25 different universities, companies and federal agencies with a diverse range of agricultural and related disciplines. Soil and crop science, microbiology, biology, geology and lunar science, and engineering disciplines were well represented. A book describing the results of the workshop is currently in preparation and will be published by the American Society of Agronomy in the summer of 1989 [12]. Soil scientists were in general agreement that lunar material "has the potential to be an excellent medium for the growth of higher plants" and that the lunar regolith "when exposed to a moist, aerobic, Earth-like environment, can be the source for many of the plant essential nutrients" [13]. One reservation that both the soil scientists and soil microbiologists had was potential plant toxicities due to chromium and nickel. Microbiologists were of the opinion that microbial species could play an important role in beneficiation of the regolith. Recovery of useful constituents (ranging from oxygen and hydrogen to chromium and nickel), removal of materials potentially toxic to plants and other microbial species, and development of a highly productive soil for food production were discussed [14].

Only one major unanticipated item surfaced during the workshop; the emphasis placed on the need for simulated lunar regolith. The shared opinion was that a set of lunar simulants with varying degrees of fidelity was needed in order to carry out this complex line of research. Lunar samples returned during the Apollo missions are an extremely valuable resource and can only be expected to be made available in extremely small amounts for specific experiments after the experimental procedure has been fully verified. Thus, initial experiments and experiments requiring relatively large amounts of material (say, larger than 5 grams) must be conducted with simulated lunar material.

Lunar "Soil" Simulants

The lunar samples returned during the Apollo program represent an extremely valuable resource and are made available to researchers only in very small quantities. Even then, researchers are usually required to fully verify their experimental procedures with some substitute material before using actual lunar material. Typical allocations of lunar sample are in the tens of milligrams quantities. Thus, experiments requiring sample material of greater than say 5 grams are forced to resort to use of some sort of simulated material. At this time, the only known source of simulated lunar material is from Drs. Paul Weiblen and Ken Reid of the University of Minnesota [15]. They have been preparing relatively large amounts of lunar soil simulant from a fine-grained basaltic rock that closely resembles the Apollo 11 high-titanium basalts in mineralogy and bulk chemistry. The crushed and ground material has the size distribution of the Apollo 11 soil samples. They have also successfully produced agglutinate-like material using a plasma arc melting technique. At present, this is the only source of any type of lunar simulant.

There are limitations to the degree of fidelity any simulant can achieve. Even the returned Apollo samples were altered when they were removed from the lunar surface; most notably, in terms of the in situ characteristics of bulk density and stratigraphy. The least physically disturbing method of sampling the lunar soil was with the large diameter core tubes used on Apollo 15, 16, and 17 [16]. The lunar samples undergo further changes in the laboratory since the lunar conditions of hard vacuum and freedom of water molecules and other atmospheric gases cannot be maintained on Earth. In the lunar sample curatorial facility `pristine' samples are stored and handled only under dry nitrogen. Despite this, small amounts of water and other gases are probably adsorbed on the highly reactive surfaces of lunar soil grains.

Simulating the lunar soil for laboratory experimentation is approached from three aspects: soil grain size distribution, soil particle type distribution, and particle chemistry [17]. Grain size distribution curves have been determined for most Apollo soils [18]. The grain size distribution of simulants should be prepared with the fewest sieve sizes that adequately characterize the grain size distribution curve and yet are practical to use. For example, simulant composition should be defined as 90 percent finer than 1 mm, 75 percent finer than 0.25 mm, and 50 percent finer than 0.075 mm.

Most particles comprising the lunar soil are igneous or breccia lithic grains, mineral grains, glass fragments, and agglutinates. A simulant could be prepared with crushed basalt or minerals to substitute for the lithic and mineral fragments and by using crushed glass to substitute for the glass fragments and agglutinates. Glasseous basaltic melts have been prepared in small quantities in the laboratory using a formula or recipe developed by Williams (personal communication, 1987). These glasses are difficult and time consuming to prepare and can be made only in small quantities (20 - 30 grams) since high temperature furnaces and Platinum crucibles must be used. Large quantities of glass can be made by commercial glass companies. Approximately 90 kilograms of 11-component glass can be produced under controlled conditions in one company's laboratory. The 11 lunar components are: silicon, iron, aluminum, calcium, magnesium, titanium, sodium, phosphorous, manganese, potassium, and chromium. Each will be added as the oxide in the correct proportions based on actual analyses of selected lunar glasses. Two glass starting materials have been prepared by a commercial glass company for our lunar "soil" dissolution studies at JSC. Chemical compositions of the glass (see Table 6) prepared by the glass company have not yet achieved the analogous compositions of lunar glasses; however, we are working with the company to improve the fidelity of the lunar simulant.

For lunar soil dissolution studies, we are using the fine-grained basaltic rock simulant (along with the agglutinate-like melt which will be obtained from the University of Minnesota) and the 11-component glasseous melt obtained from the research laboratory of the commercial glass company. The material has been ground to a selected particle size distribution (one matching an actual measured lunar size distribution) and mixed in the appropriate proportions. This mixture will represent the `baseline simulant' for current and future research and will allow for comparability of results between experiments. Simulants representing other lunar samples and other degrees of fidelity (such as solar wind implanted ions) will be addressed on an as-needed basis.

TABLE 6. Chemical compositions of lunar analog glasses prepared by commercial glass company. Lunar glass simulants B-1, B-2D, and B-2P are being stored at the Johnson Space Center in environmental glove boxes.

Oxides	Requested[a]	B-1	B-2D	B-2P
	------ wt. % ------			
SiO_2	42.1	45.75	47.93	50.47
Al_2O_3	13.9	10.18	12.99	12.35
TiO_2	7.52	5.37	6.62	6.43
FeO	15.7	22.84	12.81	12.09
MnO	0.20	0.16	0.16	0.14
MgO	7.92	5.78	6.89	6.51
CaO	12.1	8.57	10.39	9.94
Na_2O	0	0.04	0.03	0.03
K_2O	0	0.03	0.05	0.04
Cr_2O_3	0.30	0.21	0.22	0.27
P_2O_5	0.10	0.12	0.15	0.15
Total	99.84	99.05	98.24	98.36

[a] Oxide compositions requested by JSC to commercial glass company. Chemical compositions were determined by electron microprobe analysis.

Synthetic or Manufactured "Soils" at a Lunar Base

Lunar materials as they now exist may not provide an adequate growth medium for higher plants for several reasons. The poor physical structure of lunar regolith may prevent proper aeration and water movement through the lunar materials. Minerals and materials that comprise the lunar surface may have little nutrient supplying power or retention capacity for plant-essential elements. Also, the toxicity of lunar materials to plants is not well known. For example, high Cr and Ni contents in lunar materials may be toxic to plants. It may be necessary therefore to alter lunar materials or prepare "soils" that will be productive for plant growth.

Advantages and Disadvantages of a Synthetic "soil"

Synthetic soils are attractive because the physical, chemical, and mineralogical properties of lunar materials may be altered to best suit plant growth. Lunar regolith is a fine-grained deposit, which is primarily a result of meteorite impacts on the surface. The mean grain size of lunar "soils" ranges between 0.04 and 8 mm, however, the majority of the particles fall between 0.045 and 0.1 mm (vide supra). The regolith is poorly sorted with no "soil" structure and average bulk densities range from 1.50 to 1.74 Mg m^{-3}. These "soil" physical conditions may not be suited for plant growth due to the high bulk density of the regolith. A synthetic or manufactured soil could be sized and prepared to best suit the physical and chemical properties necessary to maximize plant growth.

Lunar regolith consists of mineral (e.g., plagioclase feldspar, pyroxene, olivine, ilmenite) and glass phases. The glass phases have formed primarily by meteorite impact melting and should be the most reactive regolith phases in water. Elements toxic to plants may exist in high enough concentrations in glasses to be detrimental to plant growth. Lunar materials may be found that do not contain high levels of plant-toxic elements on the surface. However, the easiest way to avoid toxicity problems may be to synthesize a soil without these elements. One of the first resources to be extracted lunar from materials will be oxygen, which will be used for rocket propellent and in life-support systems. A number of by-products will be produced during oxygen production that may not contain plant-toxic elements; therefore, these by-products may be desirable materials to use as a solid-support substrates for plant growth.

Minerals that exhibit cation exchange as a result of isomorphic substitution (e.g., phyllosilicates) do not exist on the Moon. The lunar regolith therefore lacks retention for plant-essential cations. It may be possible to alter regolith glasses to form minerals with cation exchange capacities (CECs). With this problem in mind, Ming and Lofgren [19] have synthesized minerals with CECs (e.g., smectites, zeolites, tobermorites) from lunar-analog glasses (Fig. 1). These reactive minerals may be added to other regolith materials to create a soil that will have a retention capacity for plant-essential elements.

There are drawbacks to manufacturing a soil at a lunar base. Special equipment to synthesize soils may need to be shipped to the moon. Initially, the cost of shipping equipment and resources required to produce a

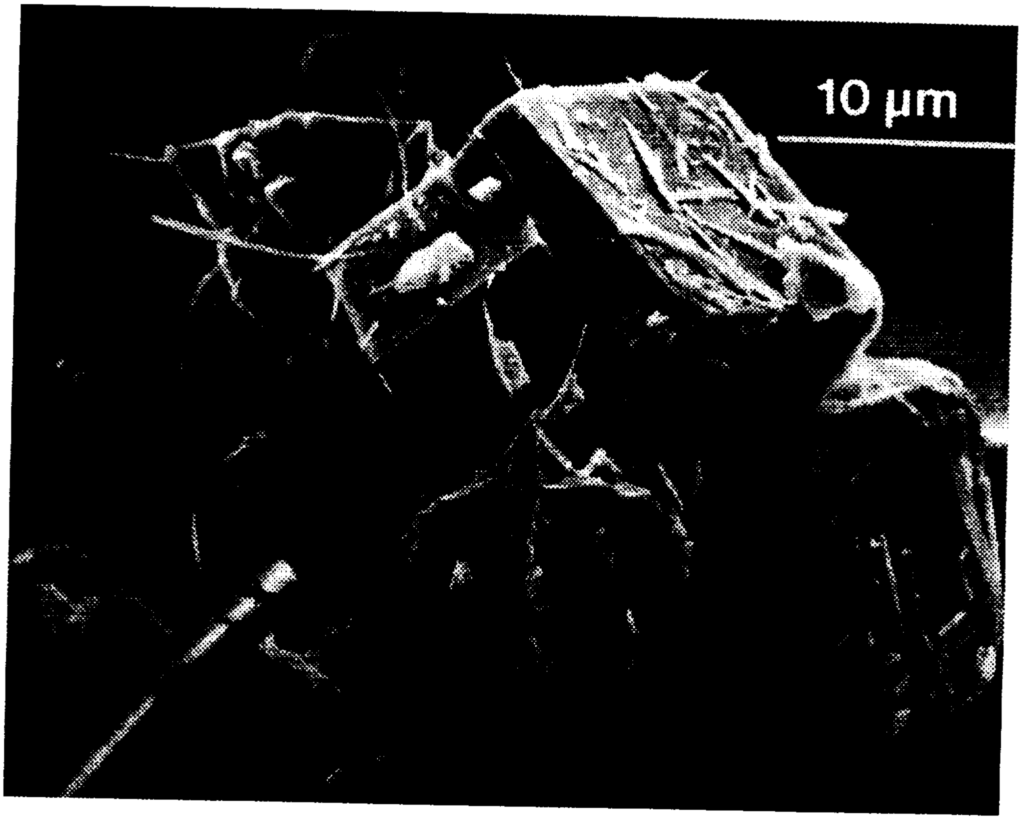

FIGURE 1. Scanning electron micrograph of Zeolite A (twinned cubes in upper center of micrograph) and Zeolite P_t (bipyramidal-like crystals in lower center of micrograph). These zeolites were synthesized under mild hydrothermal conditions from synthetic basaltic glass with chemical compositions analogous to basaltic glass of the lunar highlands. (Hydrothermal conditions: temp. = 150 C, solution = 0.1 M $Na_2SiO_3 \cdot 5H_2O$, duration = 76 h, press. = ~0.3 MPa, glass/solution mass ratio = 0.015). See Ming and Lofgren [19] for experimental procedures.

soil may not be economically feasible. The synthesis of most minerals that exhibit CECs will require water as a solvent; however, there are potential methods to synthesize minerals that exhibit CEC without water as a solvent (vide infra). Because the moon is devoid of water, materials to make water (e.g., H) may have to be shipped to the moon; or water will have to be made on the lunar surface from regolith oxygen and solar wind implanted hydrogen. Oxygen production on the lunar surface should not be a problem; however, small concentrations of hydrogen in lunar materials (generally < 50 ppm) could preclude the economical production of water using solar-implanted hydrogen.

No doubt, the samples returned by the Apollo missions have provided us with a wealth of information on the physical, chemical, and mineralogical properties of lunar materials. However, finding the starting materials best suited for synthetic soils may have to wait until we go back to the Moon and conduct a thorough survey of lunar resources. Until then, we will have to use existing chemical and mineralogical data on lunar materials to design synthetic soil systems.

Synthetic "Soils"

Four primary functions of a root media should be considered when developing a synthetic lunar soil--nutrient retention, aeration, moisture retention, and mechanical support. Most terrestrial potting media have organic matter that provides nutrient and water retention. The production of organic components for a root media at a lunar base will be difficult because of the very small quantities of organic compounds present in the regolith. Therefore, several hypothetical, plant-growth systems in inorganic, solid-support substrates have been proposed by the authors in this paper; however, a considerable amount of basic research is necessary before these systems can be used to their fullest potential at a lunar base or even in terrestrial applications.

Zeoponics

The term "zeoponics" was first used by Parham [20] to describe an artificial soil that consisted of zeolites, peat, and vermiculite used by Bulgarian researchers. Zeolites are hydrated aluminosilicates of alkali and alkaline-earth cations (e.g., K^+, Na^+, Ca^{2+}, Mg^{2+}) that possess infinite, three-dimensional crystal structures (i.e., tektosilicates). The primary building units of the zeolite crystal structure are $(Al,Si)O_4$ tetrahedra. When Al^{3+} and sometimes Fe^{3+} substitute for Si^{4+} in the central cation position of the tetrahedron, a net-negative charge is generated. This negative charge is counterbalanced primarily by monovalent and divalent cations (generally called "exchange cations"). Zeolites have the ability to exchange most of their constituent exchange cations as well as hydrate/dehydrate without major change of the structural framework. There have been about 50 zeolites found in nature, and several hundred synthetic species have been made in the laboratory. Natural zeolites can have CECs of 200 to 300 $cmol_c\ kg^{-1}$, whereas some synthetic zeolites have CECs as high as 600 $cmol_c\ kg^{-1}$ (see Table 7). The chemical and mineralogical properties of zeolites have been reviewed by Ming and Mumpton [21], Gottardi and Galli [22], and Breck [23].

Most zeolites have large channels and/or cages which allow easy access of exchange cations, including plant-essential cations, to sites of charge (Fig. 2). Zeolites have unique cation selectivities that depend upon a number of factors: 1) framework topology (channel configuration and dimensions), 2) size and shape of the exchange ion(s), 3) charge density in the channels and cages, 4) valence and charge density of the exchange ion(s), and 5) electrolyte composition and concentration in the external solution [24].

Based upon these unique properties of natural and synthetic zeolites, a number of agricultural scientists have examined potential uses of zeolites, including 1) slow-release fertilizers (see Table 8), 2) traps for heavy metal ions (e.g., Cd, Pb, Zn) in soils [25, 26, 27, 28, 29], 3) dietary supplements in animal nutrition [30, 31];

TABLE 7. Representative unit cell formulae and selected physical and chemical properties of minerals that exhibit cation exchange.

Special Purpose Minerals	Representative Unit-cell Formulae[a]	Typical Void Volume	Theoretical Cation Exchange Capacity
Zeolites		(%)	$\mathrm{cmol_c\ kg^{-1}}$
Analcime	$Na_{16}\{Al_{16}Si_{32}O_{96}\}\cdot 16H_2O$	18	460
Chabazite	$(Na_2,Ca)_6\{Al_{12}Si_{24}O_{72}\}\cdot 40H_2O$	47	420
Clinoptilolite	$(Na_3K_3)\{Al_6Si_{30}O_{72}\}\cdot 24H_2O$	34	220
Mordenite	$Na_8\{Al_8Si_{40}O_{96}\}\cdot 24H_2O$	28	220
Phillipsite	$(Na,K)_5\{Al_5Si_{11}O_{32}\}\cdot 20H_2O$	31	380
Linde Type A	$Na_{96}\{Al_{96}Si_{96}O_{384}\}\cdot 216H_2O$	47	540
Linde Type X	$Na_{86}\{Al_{86}Si_{106}O_{384}\}\cdot 264H_2O$	50	470
Phyllosilicates			
Vermiculite	$Mg_{0.4}(Mg,Fe^{2+})_3(Al_{0.8}Si_{3.2})O_{10}(OH)_2\cdot nH_2O$	--	160[c]
Smectite[b]	$Ca_{0.25}(Al_{1.5}Mg_{0.5})Si_4O_{10}(OH)_2\cdot nH_2O$	--	110[c]

[a] Taken mainly from Breck [23]
[b] Montmorillonite
[c] Alexaides and Jackson [56]

4) nutrient retention and odor control in animal manures [32, 33; P. van Straaten, 1985, personal communication]; and 5) other agricultural uses [31, 34].

Zeolites were first suggested as major components of soils in the mid-1800s. This misconception was based upon the similar exchange behavior of zeolites and soils. In fact, Breazeale [35] showed how K-zeolites and soil exchange complexes behaved in a similar fashion. Breazeale's experiments were probably the first conducted on plant growth in a zeoponic system. However, the introduction of modern X-ray diffraction in the late 1920s disproved the hypothesis that zeolites were major components of soils and, in fact, proved that phyllosilicates, primarily smectites, were responsible for the CEC in soils. Plant growth in zeolite substrates was essentially ignored until the 1980s. Recently, several studies have investigated the potential use of zeolites as slow-release fertilizers or in-soil reservoirs for NH_4^+ and K^+ (see Table 8); however, little has been done

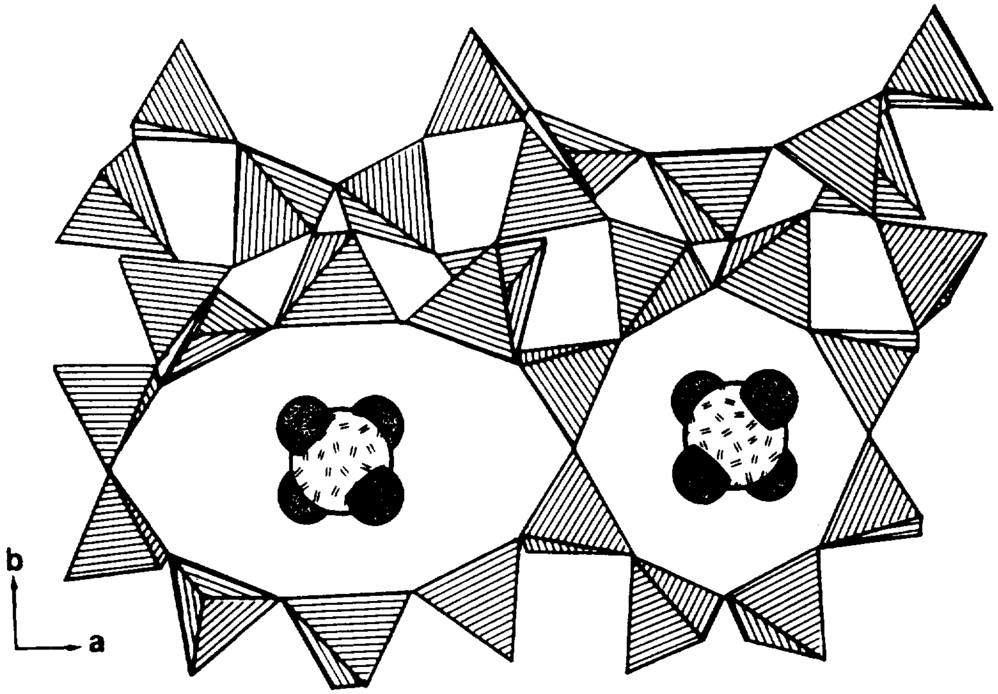

FIGURE 2. Clinoptilolite structure showing 10- and 8-ring channels (modified from Koyama and Takeuchi, [67]). Ammonium ions readily access channels.

using zeolites as a substrate by themselves. Although little information is available, Bulgarian researchers [36] reported the use of clinoptilolite (a highly-siliceous natural zeolite with a CEC around 200 $cmol_c\ kg^{-1}$) as a raw material for plant substrates. The zeolitic substrate was found to act as a reservoir for nutrient cations, to have desirable strength and other physical properties, to be sterile with respect to pathogenic microorganisms, and to be aesthetically pleasing. Depending on the plant variety, 20-150% increases in yields over control plots were observed for tomatoes, strawberries, peppers, and rice. Also, the ripening of rice, cotton, and tomatoes was accelerated in the zeolite substrate.

Zeoponics is only in its developmental stages at the NASA Johnson Space Center. In this work, zeoponics has been defined as the cultivation of plants in zeolite substrates that 1) contain essential, plant-growth cations on their exchange sites, and 2) have minor amounts of mineral phases (e.g., apatite) and/or anion-exchange resins (e.g., activated aluminum resins) that supply essential, plant-growth anions (e.g., $H_2PO_4^-$). A zeoponics system is illustrated in Fig. 3. It is possible to saturate partially or wholly plant-essential cations (e.g., NH_4^+, K^+, Mn^{2+}, Cu^{2+}, Fe^{2+}, Zn^{2+}, Ca^{2+}, Mg^{2+}) on clinoptilolite. Ming et al. [37] have determined the apparent selectivity of plant-essential cations and Na for native cations in clinoptilolite from Oregon and Wyoming to be:

$$K^+ > NH_4^+ >> Na^+ > Mn^{2+} = Cu^{2+} = Fe^{2+} > Zn^{2+} > Ca^{2+} > Mg^{2+}.$$

The dissolution of apatite is accelerated in a zeolite system [38, 39, 40, 41]. Apparently, the zeolitic exchange sites act as sinks for Ca^{2+} released into solution by the dissolution of apatite. Once Ca^{2+} is removed

TABLE 8. Recent studies using zeolites as slow release fertilizers or in-soil reservoirs for several plant essential cations.

Cation(s)/Zeolite-Mineral	Reference
NH_4/clinoptilolite	Pirela et al. [57] Mackown and Tucker [58] Ferguson et al. [59] Ferguson and Pepper [60] Bartz and Jones [61] Lewis et al. [62] Weber et al. [63]
NH_4,K/clinoptilolite	Iskenderov and Mamedova [64]
K/zeolites	Hershey et al. [65]
NH_4,K,Zn/clinoptilolite	Lewis [66]
NH_4/clinoptilolite-apatite NH_4/zeolites-apatite K,NH_4/clinoptilolite-apatite	Lai and Eberl [38], Barbarick et al. [39] Chesworth et al. [40] Allen and Hossner [41]
NH_4,K,Mn,Cu,Fe,Zn,Ca,Mg/clinoptilolite	Ming et al. [37]
Zeolitic substrates	Stoilov and Popov [36]

from solution by the zeolite, the dissolution of apatite proceeds, thereby causing the release of phosphate into solution. In zeoponic systems, Ca^{2+} released from apatite should compete with plant-essential cations located at zeolitic sites. Once released into solutions, these plant-essential cations become available for plant uptake.

A NASA Graduate Student Fellow at Texas A&M Unversity has been conducting research in our laboratories at JSC on the zeolite/apatite system [41]. Chemical equilibrium relationships between the zeolite clinoptilolite and apatite have been investigated using batch equilibrium experiments. Sufficient levels of N, P, K, and Ca were supplied to solution in the zeolite/apatite system. The concentrations of nutrients can be adjusted by changing the type of apatite, varying the ratio of clinoptilolite to apatite, or by varying the ratio of exchangeable K^+ to exchangeable NH_4^+ on the zeolitic exchange sites. The equilibrium solution P concentrations were from 1 to 2 orders of magnitude greater for the zeolite/apatite mixtures than for apatite alone, indicating that the addition of the zeolite increased the solubility of apatite (see Fig. 4).

Since most sulfur compounds are more soluble than phosphorus compounds, it should not be difficult to find a sulfur-containing material to supply necessary sulfur for plant growth in a zeoponic system.

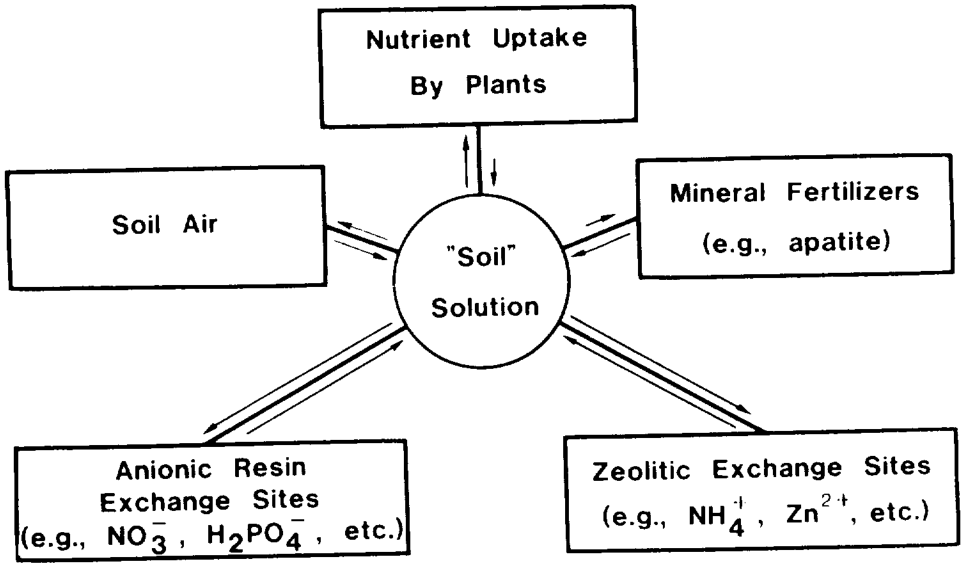

FIGURE 3. Dynamic equilibria for a zeoponics system. The reactions in soil solution should (theoretically) be driven towards the root-soil interface by the uptake of nutrients by the plant.

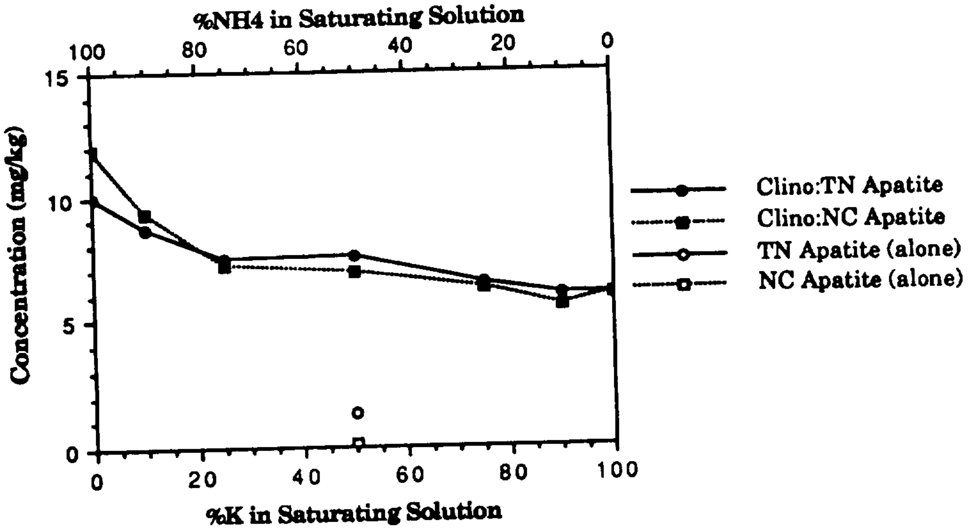

FIGURE 4. Solution Phosphorus concentrations as a function of the composition of the saturating solution for a clinoptilolite (zeolite)/apatite system (Clino = clinoptilolite; TN = Tennessee, NC = North Carolina).

Undoubtedly, the redox potential of the system will have an important role in selecting the sulfur compound best suited for a zeoponic system.

Alternatively, anion-exchange materials may be used to supply plant essential anionic elements (e.g., $H_2PO_4^-$, SO_4^{2-}, NO_3^-). For example, Checkai et al. [42] developed a mixed-resin hydroponic system that buffered the activities of cations and phosphate in solution without appreciably affecting pH or ionic strength. The P content was controlled by a cation-exchange resin (Dowex 50W-X4) containing adsorbed polynuclear hydroxyaluminum. Even though this resin was designed for hydroponic systems, similar resins may provide anion sinks in solid-support substrates.

Zeoponic systems have the potential to be regenerated with plant-essential nutrients and reused over and over. Nutrient solutions that contain experimentally-determined concentrations of the plant-growth elements will be passed through zeoponic materials until the desired type and amount of each nutrient has been adsorbed on zeolitic-exchange sites and anion-exchange resins.

Several problems may develop in zeoponic systems. First, the plant requirements for essential, plant-growth elements may not be completely satisfied by a single ionic phase. For example, plants are known to take up N in the form of NH_4^+ as well as NO_3^-. However, it is not well known to what extent plants will take up and utilize NH_4^+ and/or NO_3^-. Because the zeolite substrate will supply NH_4-N, it may be necessary to amend the zeoponic system with nitrates (possibly by anion-exchange resins saturated with NO_3^-) to facilitate maximum yields. Another problem may be in establishing a buffered pH that will best suit the growth of a particular plant species. Because of the abundance of exchange reactions occurring in a zeoponic system, it may be difficult to maintain a constant pH and ionic strength of solution; however, the addition of a mineral phase (e.g., apatite) will help buffer the solution pH and ionic strength.

It will be essential to understand the exchange behavior for zeolites and/or anion-exchange resins used in zeoponic systems; therefore, it will be necessary to establish ion-exchange isotherms for these exchange resins at specific electrolyte concentrations. Zeoponics must have the ability to buffer ionic strength and pH. Once the exchange behavior of plant-essential elements for the synthetic or natural zeolites and anion exchange materials is understood, plant-growth experiments must be conducted to determine economic feasibility and how plant production in zeoponics compares to other plant-growth systems (e.g., hydroponics).

Preparation of zeoponic systems at a lunar base will not be an easy task. Raw materials will have to be found on the lunar surface that will be best suited for the syntheses of zeolites and other exchange resins. However, Ming and Lofgren [19] have shown that zeolites can be synthesized from lunar analog glass subjected to mild hydrothermal conditions. Plant-essential elements will have to be extracted from the regolith or transported from Earth as may be the case for N. Because small traces of apatite and metal sulfides occur in the regolith [2], the extraction of PO_4 and S should not be a major problem.

The use of synthetic zeolites at lunar bases should not be limited to agricultural purposes. Based on their unique adsorption, hydration/dehydration, molecular-sieving, ion-exchange, and catalytic properties, synthetic zeolites may be used 1) as adsorption media for the separtation of various gases, 2) as catalysts, 3) as molecular sieves, and 4) as cation exchangers in sewage-effluent treatment, in radioactive-waste disposal, and in pollution control [43].

Other Cation-Exchange Materials

Smectite, vermiculite, and organic matter are a few of the materials used in terrestrial greenhouses to increase the cation exchange capacity and nutrient retention in plant-growth substrates. The addition of organic matter to a lunar soil will be nearly impossible due to the low abundance of organic molecules in the regolith. However, wastes from various processes (e.g., crop by-products, composted garbage) may be used as organic additives to lunar soils. A more likely candidate for increasing the CEC of these lunar soils will be the addition of inorganic phases which exhibit cation exchange.

Expanded vermiculites are in wide spread use as terrestrial potting media. Water between vermiculite particles (or quasi-crystals) causes permenant expansion between particles upon heating. The expanded volume of the vermiculite can be up to 16 times larger than the original material. Expanded vermiculites are desirable solid-support substrates for plant growth because of their nutrient and water retention, good root aeration, and low bulk densities. Lunar regolith amended with expanded vermiculite could act as excellent soils for plant growth at a lunar base; however, it may be difficult to synthesize vermiculites from lunar materials. In nature, vermiculites are thought to be alteration products of micas [44]. In the laboratory, vermiculization of chlorite can be readily achieved by thermal treatments of chlorite [45, 46, 47]. The direct synthesis of vermiculite from solution however is rather difficult to achieve in the laboratory. However, it may be possible to synthesize high-charged vermiculite-type silicates in the absence of water by heating lunar starting materials (e.g., pyroxenes) and NaF, MgF_2, or CaF_2, then allow the melt to slowly cool to promote crystallization. Gregorkiewitz and Rausell-Colom [48] synthesized a high-charged, mica-type silicate from the reaction of augite in NaF-MgF_2 melts, which were allowed to slowly cool. The interlayer of the mica-type silicate, $Na_{4.0}(Mg_{6.0}Ti_{0.05})[Fe_{0.1}Al_{3.4}Si_{4.5}O_{20.7}F_{3.3}]$, readily hydrated and Na^+ in the interlayer was easily replaced by K^+ in solution, indicating that the product exhibited cation-exchange properties.

Smectites, which are responsible for a large portion of the CEC in terrestrial soils [49], may be a more realistic material to amend lunar soils than vermiculites in order to increase the CEC. Smectites may be easier to synthesize from lunar regolith than chlorites and micas. Ming and Lofgren [19] have synthesized smectites from hydrothermally-altered glass, which has a chemical composition similar to lunar basaltic glasses. In terrestrial soils, smectitic cation-exchange sites create sinks to hold fertilizer cations such as K^+, NH_4^+, Ca^{2+}, Mg^{2+}, Zn^{2+}, and Fe^{2+}. The addition of smectite to lunar regolith will increase the nutrient and water-retention capacity of the manufactured soil. Calcined smectites (i.e., aggregates of smectite particles heated to high temperatures) forms hardened particles, and when mixed with other components (e.g., quartz sand, soil, peat moss) make a productive terestrial root medium. The irregular shape of particles creates large pores for aeration and drainage. Calcined smectites also have sizable CECs (e.g., as high as 25 $cmol_c\ kg^{-1}$), which results in good nutrient retention. A productive lunar soil could consist of calcined smectite combined with lunar materials (e.g., sand-sized feldspar).

As with zeolites, the use of synthetic smectites at lunar bases should not be limited to agricultural purposes. Smectites could be used as 1) adsorption media for waste renovation, 2) cation exchangers, and 3) adsorption media for organic molecules (Ming, 1989).

Nutriculture

Nutriculture is the cultivation of plants in inert substrates (e.g., water, sand, air). Hydroponics (cultivation of plants in water) has been considered by plant physiologists as a leading candidate for plant-growth systems in controlled ecological life support systems (CELSS). Since hydroponic systems for CELSS have been discussed elsewhere [50, 51, 52, 53], only solid-support substrates used in nutriculture will be discussed.

Nutriculture systems using a solid-support substrate have been suggested as viable growth system for potatoes in CELSS. Tibbitts and Wheeler [54] found that tuberization was normal when recirculating nutrient solutions were passed through calcined clay particles or sphagnum moss; however, when solution was recirculated through containers filled with nutrient solution and the plant roots immersed, tuberization was delayed and the plants failed to tuberize normally. If potatoes and other edible tubers are to be grown in CELSS, it may be necessary to have a solid-support substrate to promote tuberization.

Several inorganic materials and plastics are used terrestrially as inert, solid-support substrates, including perlite (crushed siliceous volcanic rock that expands to a lightweight cellular material 10 to 20 times the original volume when heated to high temperatures), rockwool (mass of fine, intertwined fibers formed by passing molten coke, basalt, limestone, and possibly slag through a high-speed rotor), and polystyrenes (plastic made by polymerization of the hydrocarbon styrene). These materials, unless they are chemically altered, e.g., chloromethylation of polystyrene, should not contribute to or alter plant nutrients. Unfortunately, these materials do not exist on the Moon, or could be very difficult to synthesize on the lunar surface; the synthesis of polystrene would be difficult because of the lack of organic molecules in lunar materials. However, other materials produced from lunar materials may serve as excellent, inert, solid-support substrates for nutriculture.

A resource-processing pilot plant will probably be the first industry to be built on the Moon that will utilize in situ resources [55]. The primary products of a lunar processing plant will include 1) oxygen for rocket propellent and life-support systems, 2) construction materials (e.g, concrete, ceramics, glasses), 3) volatiles (e.g., H_2, CO_2) for life-support systems, and 4) metals for construction. Undoubtedly, a number of useful by-products will be produced by a resource-processing pilot plant. Some of these products and by-products (e.g., ceramics, concrete) may provide excellent solid-support substrates for plant growth. For nutriculture systems, special attention will have to be given to the particle size and the reactivity of the substrate. Ideally, the substrate in nutriculture systems should be inert and have a particle size that allows proper root aeration and drainage between the addition of the nutrient solution. With the addition of a nutrient solution (e.g., Hoaglands solution), plant-growth systems using inert, solid-support substrates are productive and fairly well understood; thereby, these systems should become attractive for use as solid-support substrates for plant growth at a lunar base.

SUMMARY

It appears that a "soil" capable of growing plants can be produced from lunar materials. However, the synthesis of a lunar soil is only the beginning of a very complex and advanced research effort. Many factors (e.g., source of water, source of plant nutrients, growth modules, effects of radiation, plant varieties, microbial populations, reduced gravity) must be thoroughly examined before plants can be grown in lunar materials.

There are a variety of materials that could be used as solid-support substrates at lunar bases; some of the more likely candidates include 1) native lunar "soils", 2) sized lunar regolith amended with synthetic materials (e.g., zeolites, smectites) that provide nutrient and water retention, 3) synthetic, inorganic, highly-reactive substrates (e.g., zeoponics), and 4) sized lunar materials or industrial by-products used as inert, solid-support substrates with nutriculture systems. The design of new, plant-growth substrates could have tremendous terrestrial applications; for example, zeoponic systems could be used in commercial greenhouses. These systems are only in their research stages and will require much more research before they can be used to their fullest potential.

The success of a permanently human-occupied lunar base will be insured if it is viewed as an integral part of the Earth's space infrastructure. That is, it will represent a piece of the overall, long-term efforts of humans to explore our Solar System. Lunar base can become a supplier of many necessary items in this complex scenario while at the same time contributing significantly to answering scientific questions through research conducted at a lunar base.

One of the key long-term technologies to human exploration is the reliable supply of consumables through regeneration of wastes and production of food. Without a reliable and economical supply, the ability of humans to venture very far from Earth will be severely limited. The lunar regolith represents a valuable resource which can supply many things to space explorers, not the least of which is a major role in providing a reliable long term supply of food to sustain those efforts.

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16. Abstract

In February 1989, NASA's Controlled Ecological Life Support Systems (CELSS) program assembled a diverse group of investigators in Orlando, Florida, to discuss a variety of topics which must be addressed in order to develop bioregenerative systems for use during piloted missions early in the next century. The meeting was attended by investigators from several NASA centers (Ames, Johnson, JPL, and Kennedy) as well as scientists from universities and private industries from around the United States. These proceedings contain the 25 papers presented during the two days of the conference. Topics concerning the production of edible biomass range from studies on the efficiency of plant growth, to the conversion of inedible plant material to edible food, to the use of plant tissue culture techniques. Models of plant growth, and of whole CELSS systems, are also included. The use of algae to supplement and improve dietary requirements is addressed. Several papers discuss the development of CELSS technology, both ground-based and flight-qualified. Work at Kennedy's Breadboard Facility and Ames' Crop Growth Research Chamber is described. Flight experimentation is covered in topics ranging from a Salad Machine for use on Space Station *Freedom* to conceptual designs for a Lunar Base CELSS. Control issues are reviewed and recommendations made concerning a strategy for development of a robust control system. Processing of waste materials is covered, including analysis of physical/chemical, biological, and hybrid systems, and how source characterization affects design criteria.

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