

# Porous Plant Growth Media Design Considerations for Lunar and Martian Habitats

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## ABSTRACT

Lunar- and Martian-based plant growth facilities pose novel challenges to design and management of porous medium-based root-zone environments. For example, to achieve similar equilibrium water content distribution using potting soil, a 10 cm tall root zone on earth needs to be 60 cm tall on the moon. We used analytical models to parameterize porous plant growth media for reduced gravity conditions. This approach is straight-forward because the equilibrium capillary potential scales linearly with gravity force. However, the highly non-linear water retention character is tied to particle size through the resulting pore-size distribution. Therefore interpreting the corresponding particle size and generating and evaluating the porous medium hydraulic properties remains a challenge. Soil physical principles can be applied to address the ultimate concern of controlling fluids ( $O_2$ ,  $H_2O$ ) within the plant root-zone in reduced gravity. Resulting gravel-sized particles for Lunar gravity would theoretically provide a rooting environment whose vertical extent is minimized to conserve energy, water and space resources while providing an optimal root zone for plant growth. However, issues relating to larger pores, thicker water films and reduced matric potentials may pose unforeseen problems for plant growth that will need to be addressed.

## INTRODUCTION

Plant growth facilities are in integral part of space exploration and a number of facilities have been tested in orbit [1-3] and proposed for lunar and Martian exploration [4]. The plant-rooting environment and physical processes governing fluid flow and distribution within porous plant growth media require a generalized design approach in order to address reduced gravity environments. Guidelines for selecting plant growth media are needed in order to prepare for both microgravity and reduced gravity opportunities [3, 5, 6]. Past studies in microgravity were focused on a few limited applications of liquid transfer at low matric potentials within different coarse-grained and porous materials, e.g., zeolite, arcillite, floral foam, agar gel, and perlite [2, 7-11]. These studies illustrate deficiencies in media selection and characterization because: (i) the “desirable” high liquid fluxes obtained at low matric potential ensure a commensurate reduction in the rates of gas transfer (e.g., oxygen) at the high water contents, and (ii) most of the results were not cast in general and transferable forms such as the hydraulic conductivity of the media and thus are of limited use for general inferences [12].

Questions regarding the applicability of Earth-based models to describe fluid behavior in porous media under reduced gravity conditions need to be addressed. Indications that liquid and gas fluxes in  $\mu g$  cannot be accurately predicted from conventional models arose due to concerns such as the equal buoyancy of fluids in microgravity. Data collection in microgravity ( $\mu g$ ) is a necessary step toward model testing and validation. Preliminary observations from parabolic flight experiments [13, 14] suggest that the impact of reduced gravity is manifest at meso-scale (cluster of pores) rather than at the single pore level. Reduced gravity accentuates the role of pre-wetted surfaces for transport, enhances liquid- or gas-phase entrapment, and affects macroscopic imbibition and drainage processes and sample scale hydraulic properties. Heinse et al. [13, 15] attempted to observe and quantify gravitational effects on water retention and saturated hydraulic conductivity on porous media samples during parabolic flight. Resulting comparisons of water retention in 1g vs.  $\mu g$  and variance in retention model parameters under repeated cycles at 1g indicated lower air entry values in  $\mu g$ . However, this may have been an artifact of the hyper-gravity phase accompanying parabolic flight. In recent measurements made aboard the International Space Station (ISS), data suggested minor differences on water retention in  $\mu g$  when compared to Earth-based measurements. Varied gravitational force did not seem to affect the measured saturated hydraulic conductivity ( $K_s$ ) of densely packed tubes in parabolic flight, while loose packing resulted in modified  $K_s$  during periods of  $\mu g$ . A recent microgravity review [16] summarized studies on fluid behavior in reduced gravity, suggesting that fluid displacement patterns become unstable and enhance phase entrapment in the absence of gravity, thereby modifying macroscopic transport properties.

Some of the more significant concerns for reduced and microgravity relate to gas diffusion and the exchange of gasses in the root zone. These concerns stem from early research efforts to grow plants on the Mir space station where there was evidence of root hypoxia. Results from recent ISS experiments of oxygen diffusion in partially saturated porous media indicate there may be enhancement of hysteresis in gas-diffusion/air-content characteristics. Diffusion coefficients obtained in smaller particle-sized media were significantly different from those measured on Earth. The observed trend was for the percolation threshold for gas diffusion to shift to larger air-filled porosities (lower water content). The air percolation threshold for  $\mu g$  may be greater than on Earth and likely depends on the intricacies of the pore structure and resulting capillary and viscous forces. As Or et al., [16] point out, the air imbibition front morphology may proceed during drainage bounded by two extreme processes of uniform flow or non-uniform fingering flow. A mixture of these is common with some air 'fingers' percolating the medium ahead of the advancing front. The consequence of this process in reduced gravity may be significant changes in

macroscopic transport properties, such as enhanced hysteresis or a shift in the percolation threshold.

While there is no optimal value of air-filled porosity, there is agreement that 10–20 percent is desirable [17]. The lack of an optimal air-filled porosity value is attributed to variability of different plant species tolerance to poor aeration, the effects of different environmental and management factors, and to the use of different methods of determining air-filled porosity. Indirect evidence suggests that air filled porosities of 20 to 30% provide optimal conditions to microbial activity in soils (i.e., balance between aqueous and gaseous fluxes within the same pore network [17, 18]). The increased air-filled porosity need for microbial activity may be linked to diffusion path length differences between the sub-millimeter scale of plant roots and the sub-micrometer scale of soil fauna where the associated water layer thickness varies with water content. These critical levels of air-filled porosity are related to the percolation threshold values associated with the initiation of transport [19, 20].

Access to water, oxygen and nutrients, as well as adequate fluxes to replenish consumption depends upon the pore-scale flow structure within the porous media. Physical characteristics of the growth medium must be characterized using general and transferable methods to allow some degree of predictability for future design and management. The presence of plant roots and their requirements for liquid and gaseous content and fluxes poses an important dynamic component for media selection and characterization. The intensive growth conditions in microgravity with small containers and desirable high efficiency of growth and gas exchange add to the complexity of the problem aboard orbiting or transient space craft.

With the current direction of NASA to look to Lunar and Martian manned space flight, there is an ongoing need to utilize parent materials on these planets as plant growth media. A significant challenge arises from the fact that as gravitational force varies, so may the need to

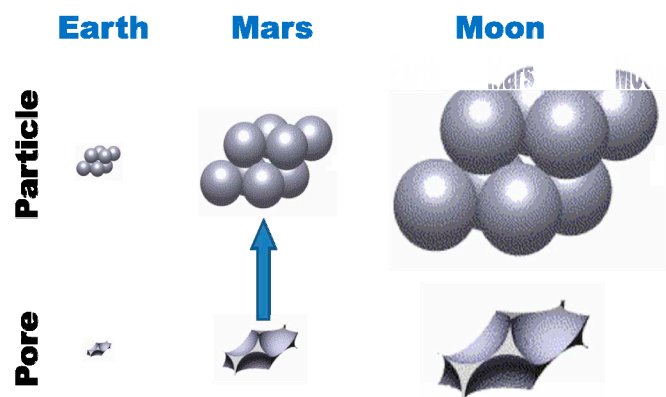


**Figure 1.** Conceptual illustration of rhombohedral packings of idealized particles and their resulting pore geometries, all scaled based on the reciprocal gravity forces (i.e., Earth = 1).

adjust plant growth medium properties, for example particle size (Figure 1) where reduced gravity warrants larger particles. This may be difficult on the moon where the mean particle size of the native surface grains is on the order of 0.1 mm [18] as illustrated in Figure 2. This represents not only a reduction in the growth medium pore size (water held tighter) but the reduced gravitational force complicates the problem by increasing the capillary rise (i.e., readily water logged conditions), thus the need for larger particles.

An optimized 10 cm tall root zone on Earth would require 60 cm to achieve the same relative water content distribution in a Lunar greenhouse using conventional media. For adapting Lunar gravity to the desired container height (e.g., 10 cm), one could theoretically scale the water retention character of the porous medium by increasing the particle sizes and perhaps distribution of sizes. We outline how this is done as the paper progresses, arriving at the proposed Lunar particle size distribution shown in Figure 2. However, while matric potential scales linearly, the highly non-linear water retention character is tied to particle size through the resulting complex pore-size distribution, leaving a significant challenge for generating and evaluating a porous medium with the ideal particle-size distribution. Beyond these simplistic concepts, effects of reduced gravity may manifest themselves in altered fluid distribution and transport, especially when considering a shift from sand-sized to gravel-sized particles. This has implications on water film thickness, unsaturated hydraulic conductivity and diffusion path lengths at pore-scales that we have little experience with. Soil physical principles can be applied to unlock these challenges of controlling fluids in porous rooting environments.

Our objectives here are to present concepts that could be used to design and construct a porous medium for plant growth in Lunar or Martian gravity environments.

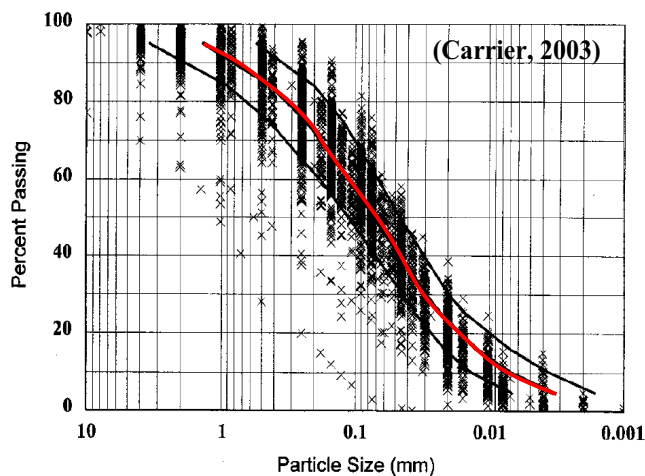


**Figure 2.** Measured particle size distributions (PSD) of Lunar surface regolith with the red ‘mean’ curve shown for all samples collected [18].

This design is based on equilibrium hydraulic properties and geared toward larger-scale systems that would require periodic removal of plant roots and replanting of seeds, making particulate media the preferred form of substrate. In this paper, we focus our attention on Lunar (0.163-g) and Martian (0.380-g) gravity levels and draw analogies to previously characterized Lunar simulant (JSC-1) assuming a 10 cm tall root zone.

## THEORETICAL CONSIDERATIONS

**CAPILLARITY** - Capillary rise in a porous medium is related to the water retention character of that medium with smaller particles (pores) resulting in higher capillary rise. An illustration of capillary rise is given for two different sized capillary tubes in Figure 3. Capillary forces are dominant in microgravity and dominate on Earth in fine-textured porous media (e.g., clays). The capillary rise equation is derived from a balance of capillary force,  $F_c$ , given as

$$F_c = 2\pi r \cdot \sigma \cdot \cos \gamma \quad (1)$$

and gravity force,  $F_g$ , as

$$F_g = \pi r^2 \cdot h \cdot \rho_w \cdot g \quad (2)$$

where,  $h$ , is the height of rise,  $r$ , is the radius of a capillary tube,  $\sigma$ , is the surface tension of liquid,  $\gamma$  is the contact angle of a solid-liquid interface,  $\rho_w$  is the density of liquid and  $g$  is the gravitational force. Rearranging Eqs. (1) and (2) in terms of  $h$  results in the capillary rise equation written in terms of an equivalent pore radius.

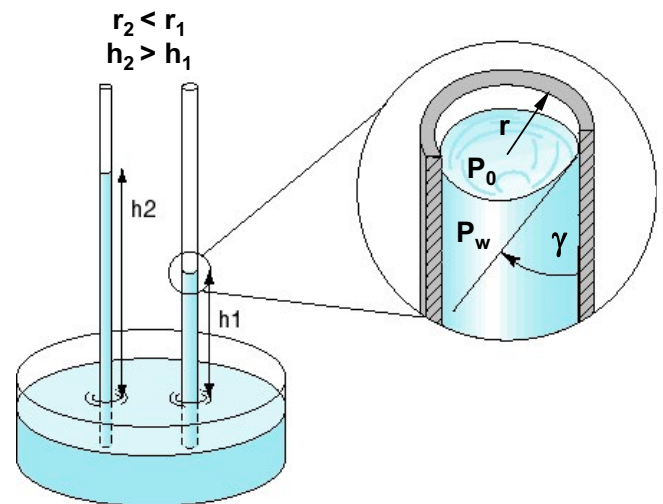


**Figure 3.** Heights of capillary rise,  $h_1$  and  $h_2$ , in vertical tubes balance liquid-solid surface tension induced pressure differences ( $P_w$ ,  $P_0$ ) with gravitational force.