NASA-CR-202572

SDL/96-032

Summary of Research: Study of Substrates in Microgravity NASA Cooperative Agreement NCC2-5039

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ABSTRACT

A nutrient delivery system (NDS) capable of operating in microgravity is an essential component of growing plants in space. A granular substrate-based NDS is a conventional but mechanically simple way to grow plants in microgravity, especially when a nutrient impregnated substrate is used. A properly designed substrate-based NDS should be easier to implement, maintain, and exhibit a higher long-term reliability than a mechanically complex NDS. A key element of the control of a substrate NDS is a reliable moisture sensor. Lack of ideal moisture conditions in the NDS of existing systems may have contributed to the wide range of plant responses that have been observed in space experiments to date.

An upcoming series of joint U.S. - Russian plant experiments will use the granular substrate NDS equipment developed by Russian and Bulgarian scientists for the Mir Space Station's Svet greenhouse. The purpose of this study was to develop a better understanding of granular substrate water relations and to provide the ability to document water distribution in the Svet NDS during the space experiments. To this end, we conducted a study to expanded our understanding of substrate water behavior in granular substrates in microgravity.

This report documents the results of our experiments with the Svet substrate water content sensor; explains the results observed in the Svet NDS during the 1990 Greenhouse experiment; describes the development of a miniature version of the Svet type (heat pulse) sensor that has been used to measure the distribution of water content inside the Svet NDS in space; and documents the calibration of these sensors and measurements conducted in both ground and space experiments.

INTRODUCTION

Water is essential for the growth and development of plants and also serves as the pathway through which most nutrients are delivered to the plants. An adequate water supply is necessary to allow normal stomatal functioning. Most of the heat delivered to the plant leaves by the sun or other radiant energy source should be transferred back to the environment by transpirational cooling. This process prevents the plant from overheating and the leaves from being damaged under intense radiation loads. The water content of the root support medium strongly affects the fluxes of water and gases to the roots and should be a known component of a plant growth system. The use of moisture sensors within the root environment provides critical information about the stresses faced by plants in microgravity and allows an informed response to irrigation control.

In current designs, the substrate of the NDS serves three purposes: holding the plant in place, moving water to the root surfaces, and infusing the water with essential nutrients required by the plant. The movement of water to the plant is bounded by the need to provide freely moving water at low energy levels. It is well understood that water moves more freely in a granular substrate as the thickness of the water layer around the particles increases. However, when the water layer thickness becomes too great, the free air space in the matrix becomes limited and the plant roots cannot acquire the oxygen needed to support respiration. Therefore, the balance between water and air must be carefully considered. These relationships have been fully researched under earth's strong gravitational acceleration. In microgravity, however, our understanding of the behavior of water and oxygen in porous media is incomplete.

OPTIMIZATION OF SUBSTRATE WATER AND GAS TRANSFER RELATIONS IN MICROGRAVITY

To provide a good theoretical basis for this study, we began by developing a physically sound understanding of the forces that influence the movement of water in a porous substrate in microgravity. Based on these results, we developed a procedure to optimize the substrate water relations of porous media for use in microgravity. First, we characterized the various media currently used in space plant experiments (da Silva et al., 1993). The media evaluated include Balkanine (Bulgaria), Vion 312 (Belarus), and Zioponics (USA); however, this report concentrates on our experience with Balkanine.

MEDIA CHARACTERIZATION

The intricate geometry of the substrate and the large surface area induce capillary forces between the water and the matrix. The substrate-water characteristic (SWC) is a functional relationship between water content (ψ) and substrate-matrix potential (θ). Balkanine, a zeolite, was characterized using three different size ranges of particles, as shown in Figure 1.

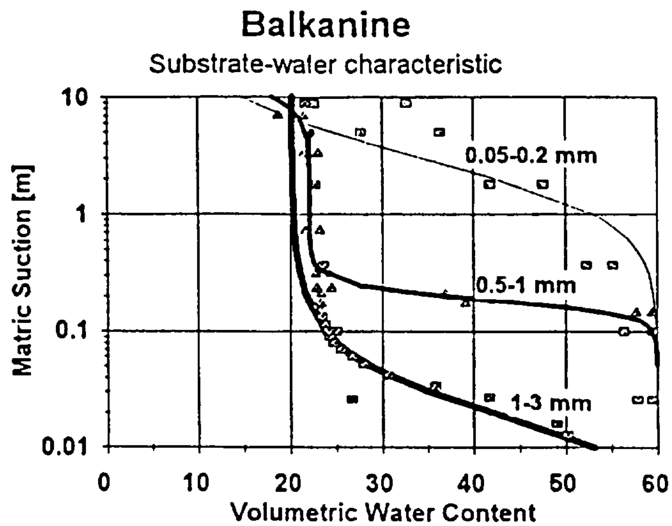

Figure 1. Substrate-water characteristic for three particle size ranges of Balkanine (zeolite). The symbols represent measured values; the lines represent the fitted van Genuchten model.

These three particle sizes show an order of magnitude difference in the suction values at which water drains from the matrix. The rapid desaturation of the 1-3 mm particles occurs for matric potentials less than 10 cm (1 kPa), while the 0.05-0.2 mm size remains saturated well beyond this same potential. The extreme change in matric suction for the two larger particle sizes between 20 and 25% water content is caused by the complete desaturation of the macropores. Water contents below this level represent inner-aggregate porosity, a characteristic of zeolites. The substrate-water retention data were obtained using methods including a hanging water column, pressure plate, and thermocouple psychrometry (Phene, Hoffman, and Rawlins, 1973). Models have been developed that can be fit to the characteristic data of a wide variety of porous media. A widely used parametric model for SWC was proposed by van Genuchten (1980). The van Genuchten model for matric potential (ψ) as a function of water content (θ) is given as:

$$\Psi = \frac{\left[\Theta^{\left(-\frac{n}{n-1}\right)} - 1\right]^{\frac{1}{n}}}{\alpha} \; ; \quad \Theta = \left(\frac{\Theta - \Theta_r}{\Theta_s - \Theta_r}\right) \qquad (1)$$

where $_s$ and $_r$ refer to saturated and residual water content, and α and n are empirical parameters. Recent studies characterizing different plant growth media have used the van Genuchten model (Luekov, 1978; Krichevski, 1980; Blackwell, 1954; Baker and Lascano, 1989). The parameters of this model are also meaningful when expressing the unsaturated hydraulic conductivity of the media.

Predictions of liquid fluxes in a substrate require knowledge of the unsaturated hydraulic conductivity function before any mathematical models may be applied. The conductivity is a function of the water content and may also be expressed with matric potential. The unsaturated hydraulic conductivity may be inferred using a measurement of saturated conductivity, K_s, and applying van Genuchten's model, given as:

$$K(\Psi) = K_s \frac{\left[1-(\alpha\Psi)^{n-1}\left[1+(\alpha\Psi)^n\right]^{\frac{1-n}{n}}\right]^2}{\left[1+(\alpha\Psi)^n\right]^{\left(\frac{n-1}{2n}\right)}} \tag{2}$$

Techniques for measuring conductivity in the laboratory are described by Klute and Dirksen (1986). The unsaturated hydraulic conductivities for the three particle ranges of Balkanine were measured (Figure 2). The unsaturated conductivity of the larger particles is greater than the other two size ranges below a matric potential of 10 cm. As the matric suction increases up to about 25 cm, the 0.5-1 mm particle size has the largest conductivity; beyond 25 cm, the smallest size range has the highest unsaturated hydraulic conductivity. The difficulty in conducting water through two different media of distinctly different pore sizes (1-3 mm Balkanine and wick material) is illustrated by Figure 2. Assuming the unsaturated conductivity of the wick is similar to the 0.05-0.2 mm Balkanine, Figure 2 shows the wick controlling the rate of water movement below about 5 cm suction and the 1-3 mm media limiting water movement at higher suction values (drier conditions). Under the conditions of an initially dry medium, the unsaturated conductivity would be extremely low, but gradients would be very large (i.e., wet to dry). Under the scenario of the medium conductivity limiting water transfer, plant roots would tend to develop in the wick where water is more readily available.

Even though the conductivity is limiting, the flux may not be limited when a sufficient hydraulic gradient develops. The one-dimensional horizontal liquid flux, J_w, can be calculated by the Buckingham-Darcy expression given as:

$$J_w = -K(\Psi)\left[\frac{d\Psi}{dx}\right] \tag{3}$$

where x is the distance between two points where the matric suction is measured. From Equation 3, it is apparent that as the unsaturated conductivity decreases, the hydraulic gradient must increase to maintain a constant flux. The energy component in the system is maintained as long as hydraulic continuity is maintained (particles do not float freely and separate). Particle separation is one possible impediment to liquid movement within the medium and another is the extremely low hydraulic conductivities (below 25% water content) caused by the few contact points of large particles (1-3 mm) and reduced cross-sectional flow area when macropores empty. In this scenario, water must pass almost entirely through inner-aggregate pores and vapor phase movement, which is an extremely slow process. It may seem logical to maintain high water contents to maintain liquid fluxes; however, gas exchange within the medium must also be considered. Because gas diffusion reduces as water content increases, the optimal water content should be investigated.

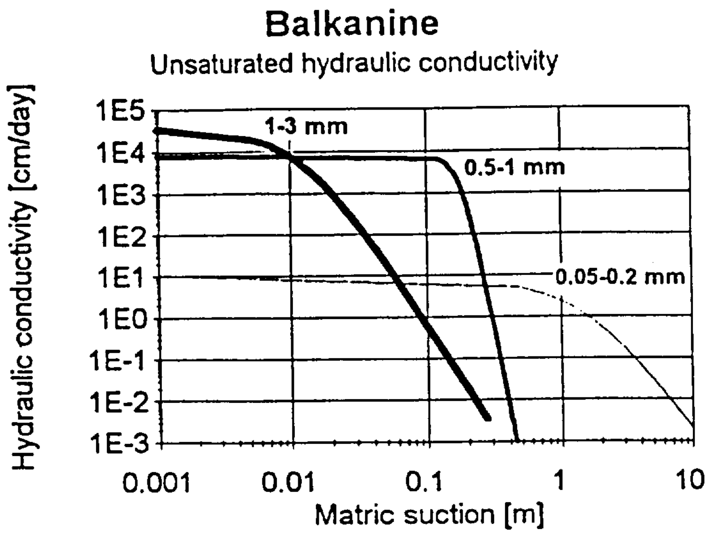

Figure 2. Unsaturated hydraulic conductivity of three particle sizes as a function of matric suction using Balkanine.

Diffusion is the most important component for gas flux within a substrate having negligible air pressure gradients (neglecting connective transport). The driving force for diffusion is a gas concentration or partial pressure gradient. Such gradients develop around plant roots as O_2 is being consumed for respiration and CO_2 is released. According to Fick's law for one-dimensional flow, the effective gas diffusion rate, J_D, in free air may be expressed as:

$$J_D = -D_G^A \frac{dC_G}{dx} \tag{4}$$

where D_G^A is the diffusion coefficient in free air and C_G is the gas concentration. The actual diffusion coefficient in the substrate is lower than in free air due to limited pathways caused by water-filled pores and the solid particles. Millington and Quirk (1961) derived an expression for the effective gas diffusion coefficient in the substrate, D_G^S, which is expressed in terms of water content as:

$$D_G^S = D_G^A \eta^{\frac{4}{3}} (1 - \Theta)^{\frac{10}{3}} \tag{5}$$

where η is the porosity or total pore space. The diffusion coefficient of gas in free air is about 10,000 times that in water; therefore, oxygen supply to roots is essentially cut off in waterlogged conditions.

The general equation for gas diffusion in porous media in the presence of sinks (e.g., O_2 consumption due to microorganisms or plant root activity) or sources (e.g., CO_2 production) is a combination of Fick's law with conservation of mass (continuity). Assuming steady-state conditions, van Bavel (1951) presented solutions for a constant and uniform production rate of CO_2 in a soil underlaid by a water table at x=L (an impervious boundary for CO_2 diffusion) and an atmospheric concentration (C_o) at the soil surface:

$$C_{G(L,\Theta)} = C_o + \frac{RL^2}{2D_G^s \eta^{\frac{4}{3}} (1-\Theta)^{\frac{10}{3}}} \tag{6}$$

where R is the production/consumption term. By solving Equation 1 for Θ and substituting it into Equation 6, a plot of the oxygen concentration profile as a function of matric potential at a depth of 10 cm in each of the three particle sizes is produced (Figure 3). As particle size increases, the matric potential for adequate aeration decreases (i.e., pores empty at lower matric suctions). Therefore, both adequate water content for liquid flux and adequate air-filled porosity for gas flux must be maintained. The ability to control water content or matric suction is a function of the slope of the SWC curve (particle size distribution). In Figure 1, a greater change occurs in matric suction over the range of water contents (30 to 50%) for the fine and coarse particle sizes than for the 0.5 to 1 mm particle size range. Thus, optimizing the particle size distribution to match the desired operating conditions is a key to controlling the root module environment (Wallach et al., 1992).

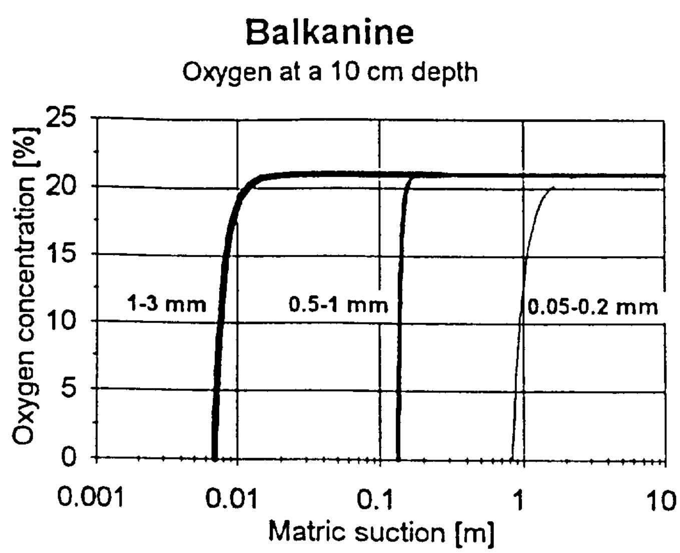

Figure 3. Oxygen concentration at a 10 cm depth in three particle sizes.

APPLICATION TO A PREVIOUS EXPERIMENT

The Bulgarian-built Svet (Russian for "light") plant growth unit has been onboard the Mir Space Station since 1989. The Svet NDS, which uses a granular substrate, will be used to grow two wheat crops during the Space Lab/Mir-1 experiments being conducted during 1995 and 1996. A description of Svet can be found in Ivanova and Dandolov (1992) and Ivanova et al. (1992). The Gas Exchange Measurement System (GEMS), developed for these experiments, is described by Bingham et al. (1995). The Svet system provides a single moisture sensor in each root zone container (cuvette) which controls the substrate water content. The GEMS includes an array of substrate moisture sensors that provide a distributed picture of moisture distribution, which significantly increases our understanding of water movement in porous media in microgravity.

The Svet root module consists of two identical cuvettes, one of which is depicted in Figure 4. Each cuvette is filled with the substrate Balkanine (naturally occurring zeolite impregnated with nutrients, 1-3 mm). Water delivery to the root module is controlled by signals from a single heat-pulse-type moisture sensor, referred to as the Svet moisture sensor (Svet MS). The system provides small pulses of water on an "on demand" basis. On a low-moisture signal from the sensor, water is pumped from the Svet water reservoir to a cylindrical, foam "hydroaccumulator" within the cuvette. Water moves passively from the hydroaccumulator into a system of highly conductive fabric wicks and then down the potential free energy gradient into the surrounding granular substrate. The Svet MS is surrounded by the wick material and responds to the water level in the wick.

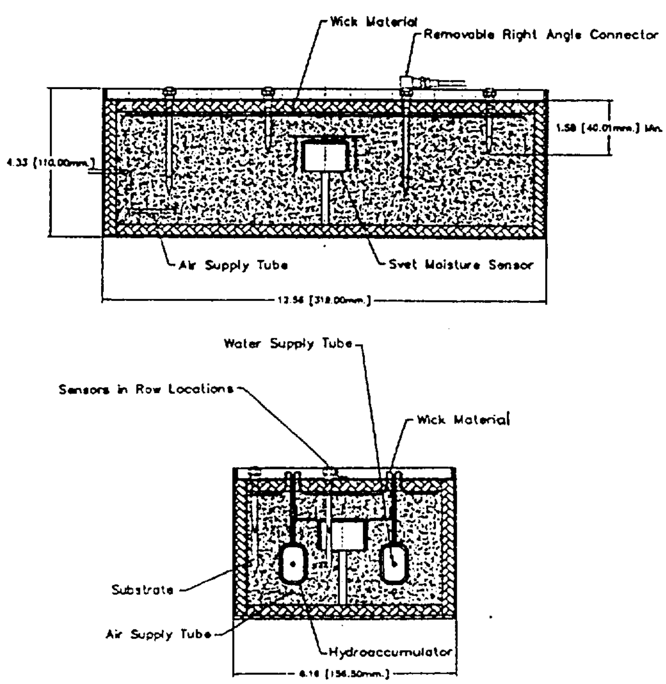

Figure 4. Physical layout of the Svet root module.

Tests using the ground-based Svet system have shown that the water delivery system is capable of maintaining a predetermined moisture level in the wick, under normal gravity conditions. The Svet MS was used in Greenhouse 1 space-based experiments in 1990. During these experiments, indicated wick water levels in microgravity were significantly different than those observed in a control unit on the ground. The space-based sensors showed high moisture levels with very little indicated capacitance. However, visual observations indicated that the plants were experiencing significant water stress. The number of irrigations recorded and the amount of water used indicated that water most likely was not moving from the wick into the substrate. To help us understand the behavior of the Svet root module system during the 1990 experiment, we conducted a study of the water relations of porous substrates in microgravity.

ANALYSIS OF GREENHOUSE 1 (1990) OBSERVATIONS

We applied our theoretical development to the analysis of the results from the 1990 Greenhouse 1 experiment. In this experiment, the two cuvettes were planted with Chinese cabbage and Radish. Each cuvette was packed with 3-5 mm granules of Balkanine. The large granule size was chosen (despite granule size optimization studies in flight), because scientists were extremely concerned about water logging and oxygen diffusion in the cuvettes . When the moisture sensor detects that the substrate and wick have dried below a programmed value, the controller injects additional water into the hydroaccumulator. The Svet takes hourly measurements of each cuvette's water content. On earth, the Svet root system seemed to work well. In the presence of gravity, water not only moved up to the root area, but also from the wick into the Balkanine surrounding it. Plant roots penetrated the fabric and entered the well-drained Balkanine, extracting water and nutrients.

The results observed in space were quite different. When the module was hydrated in microgravity, the sensors indicated saturation almost immediately and were maintained there with very little additional water. Figure 5 shows the early wetting phase of the two cuvettes in space; Figure 6 shows the responses of the two cuvettes in space (a and b) and one of the ground cuvettes (c) for the first 4 days. The continuous lines are the sensor output, and the bar graph shows water injections. Cuvette 1 has only five water pulses in the first 4 days, and Cuvette 2 only one, compared with 23 much more significant pulses on the ground. As soon as the flight sensors began to show an unsaturated condition, the water content indication dropped rapidly but was returned to saturation with only single pulses of water. The total amount of water injected into the approximately 4 kg of substrate in each cuvette was less than 400 ml over the entire period. The ground-based system on the other hand, required continual injections of water to keep the moisture level above the 75% set point. While the seeds planted in space germinated and started to grow normally, they began to lag behind the ground controls after only a few days. Harvested plants returned to earth were "dwarfed" and apparently "highly stressed" compared with ground controls. These results are described in some detail by Ivanova and Dandolov (1992) and by Ivanova et al. (1992). Physiological and chemical analysis of the plants were consistent with plants exposed to significant moisture and nutrient stress.

Based on our theoretical and laboratory research, we devised the following hypotheses about the 1990 experimental results:

1. In microgravity, the large difference in pore size between the wick and the 3-5 mm Balkanine caused the water to remain in the wicks. Water that was conducted into the Balkanine stayed in the internal pores of the aggregates, directly in contact with the wicks.
2. The Svet MS signal represents the water content of the wick system and does not adequately measure the status of the Balkanine.
3. Launch vibration could have broken corners and repacked the large Balkanine granules allowing the particles to move with respect to each other, further minimizing the transfer of water into the Balkanine.
4. Dry Balkanine cannot supply the roots with proper nutrients.

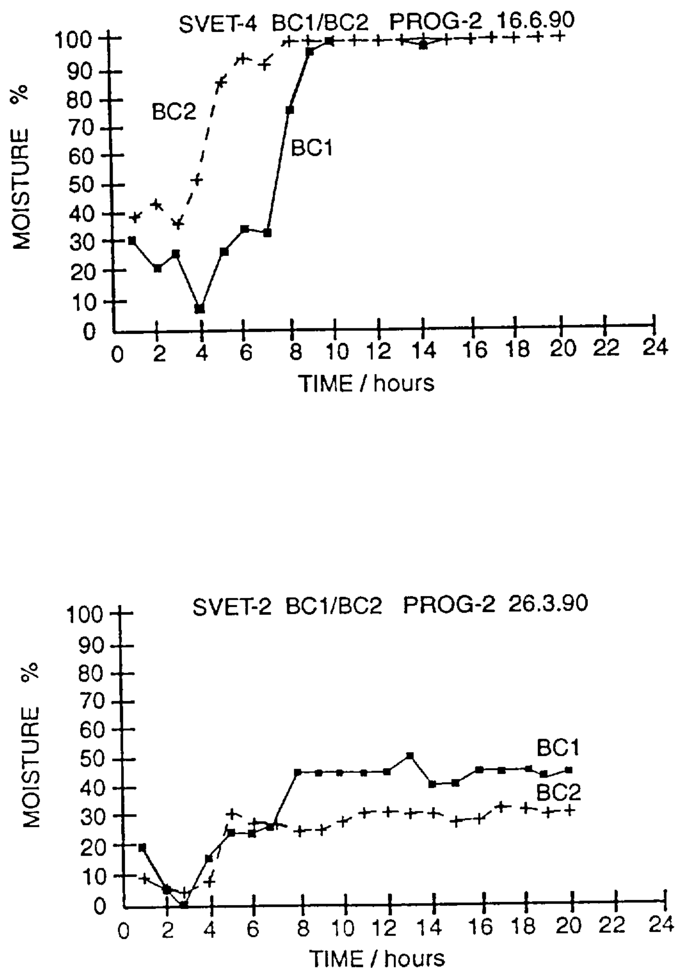

Figure 5. Initial wetting curves observed by the Svet MS during 1990 Greenhouse 1 experiment.

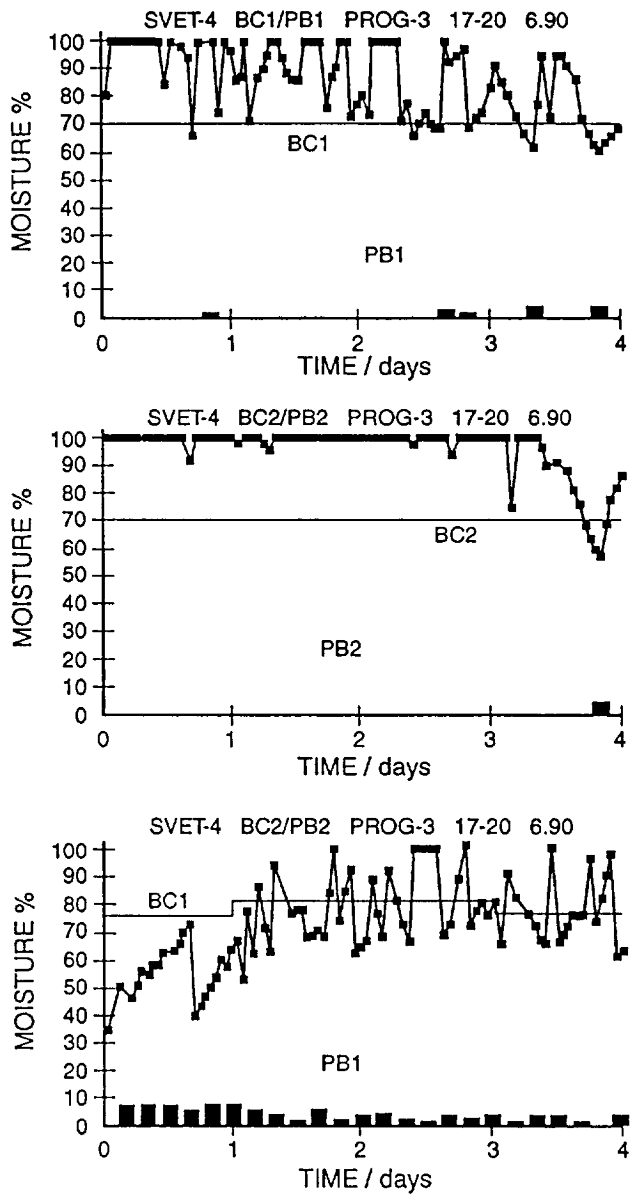

Figure 6. Water use dynamics for the 1990 Greenhouse 1 experiment.

Subsequent measurements on the ground confirmed that the Svet MS readings are dominated by the conditions in the wick. The range of sensitivity of the Svet MS was tested by placing three thermocouples at distances of 1, 2, and 3 mm from the Svet MS in dry, loosely packed substrate. In dry substrate, the heat-pulse amplitude dropped significantly across the wick and then dissipated in the substrate. The effectiveness of a dry wick as an insulator is also demonstrated by the temperature readings. The Svet MS surface temperature rise was 10°C; the temperature rise outside the wick in dry Balkanine was less than 1°C. With a wet wick, heat conduction down the wick was about 3 times greater than out into the Balkanine. Hence, the Svet MS cannot differentiate between a wet wick alone and a wet wick surrounded by wet Balkanine. At best, the area of sensitivity of the Svet MS is less than 1-2 mm. These results supported the need to supplement the single moisture sensor with additional sensors for the next experiment.

Examination of the flight backup root module, laboratory measurements, and our 1995 experience (Greenhouse 2) confirm our hypotheses about the problems observed during the 1990 experiment. We also discovered another significant condition necessary to fully understand the 1990 results. The 100% reading of the Svet MS, as calibrated for the 1990 experiment, is in percent of "field capacity" or about 22% g_w/g_s. Field capacity is by definition the most water that a substrate can sustain with the inter-particulate pore space drained by gravity. In microgravity, where the pore spaces can continue to fill, the actual 100% water content reading corresponds to about 2.5 times greater (~60 % g_w/g_s). Therefore, the 100% reading observed by the Svet MS is actually a very dry reading in space, and the wicks never became wet enough to develop a liquid film around the substrate granules. An examination of the 1990 flight backup root module indicated that the substrate was not tightly packed in the cuvette, and significant particulate movement could be expected in microgravity.

Based on our examination of the Svet root module, we concluded that a properly designed and managed granular matrix NDS could be highly successful. Proper management would include a system that determined the actual distribution of water content in the substrate.

MOISTURE MEASUREMENT DEVELOPMENTS

To maximize science development for long-term experiments on Mir, we concluded that a comprehensive environmental monitoring system was required to document plant growth conditions. For the Greenhouse 2 experiment, the Svet system was augmented with the U.S.-developed GEMS. An extremely important benefit of GEMS (Figure 7) is the ability to measure the distribution of water in each cuvette . The soil moisture sensors developed for use in GEMS supported this objective. The most important indication of water state, especially in microgravity, is the direct measurement of the free energy status of the water in the system. Given the free energy distribution of the water in a root module, movement and availability to plants could be easily calculated. Matrix potential (energy level) can be measured directly by a tensiometer, but these sensors are typically bulky, require significant care, and have not been proven in space (Gardner, 1986). Because moisture content and matrix potential are functions of one another, matrix potential is usually inferred from water content measurements (Figure 1).

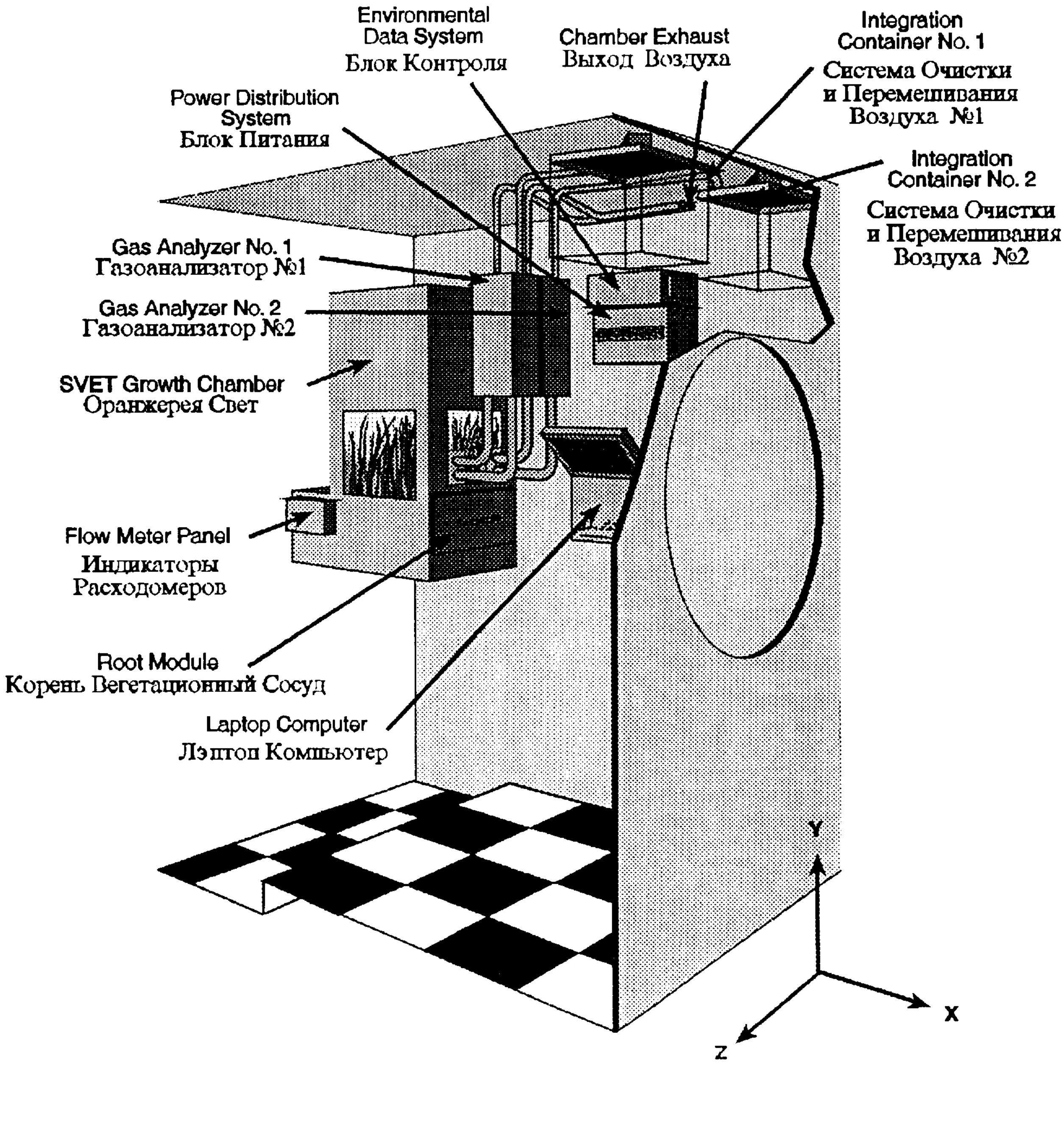

Figure 7. Svet-GEMS complex in the Krystl module of Mir.

Current state-of-the-art methods for determining substrate water content include neutron attenuation, gamma ray attenuation, gypsum blocks, time domain reflectometry (TDR), and heat pulse. Neutron attenuation and gamma ray attenuation pose a radiation hazard and tend to be bulky devices. Gypsum blocks have been available for terrestrial measurements for years, but they require high frequencies and have a lower sensitivity at the wet end of the scale. The TDR method has become popular because it is flexible, accurate, and measures rapidly. Traditional TDR requires complex circuitry, however, and uses high radio frequencies (2-3 GHz), which cause concern onboard a spacecraft. Smaller, more portable, capacitance-based TDR units are being developed but will require a significant development program.

Whereas, the gypsum block method relates electrical capacitance to water content, the heat-pulse method uses changes in thermal conductivity to infer moisture level (Gardner, 1986). The heat-pulse-type sensor has been widely used for moisture level measurements in substrates during plant experiments (Ivanova and Dandolov, 1992, 1992a; Ivanova et al., 1992). A TDR-type system was also investigated, but the cost and long qualification time required for acceptance negate its immediate application in space. Limitation in power requirements, electromagnetic emissions, and automation onboard a spacecraft place stringent constraints on available measurement techniques.

Based on the experience gained from these experiments and measurements from prototype sensors, the heat-pulse-type sensor was chosen for development in GEMS. While the heat-pulse approach has the advantages of low average power consumption and simplistic design, it also has the disadvantage of depending on heat conductivity for measurement, instead of a direct measurement of moisture content or matrix potential of the media. In small diameter heat-pulse-type sensors, where particle diameter of a substrate approaches the size of the sensor, the arrangement of the particles around the sensor can affect the resistance to heat flow between a moisture sensor and surrounding media. The effectiveness of this thermal contact, which is referred to as the contact resistance, can affect the calibration of a heat-pulse-type sensor by 3-5%.

Recently, heat-pulse sensors have been developed with a solid porous ceramic coating (Phene, Hoffman, and Rawlins, 1973). These sensors correlate the water content of the ceramic coating with the sensor temperature rise. Because the temperature rise of the sensor is dependent on the water content of the ceramic coating, other factors such as particle diameter cause less impact on the sensor readings. When placed in a soil medium, the water potential of the ceramic comes into equilibrium with the free energy level of the water in the medium. Hence, these sensors can be calibrated directly as a function of the water potential of the surrounding medium. Because the probe is in constant and rigid contact with the ceramic, the problems associated with the use of bare probes in varying sized media (contact resistance) are minimized. However, these sensors are limited by the movement of water from the media. Where fast response is required, the moisture transfer resistance between the sensor ceramic and the substrate can cause difficulties similar to those observed with the thermal contact resistance.

THEORETICAL BACKGROUND FOR THERMAL SENSOR DESIGN

The thermal conductivity of partially saturated substrate increases with water content. The temperature rise generated by constant energy injection depends on the rate at which heat is conducted away from the source. Therefore, the temperature rise depends on the moisture level in a substrate. Theoretical models of sensors based on this principle have been described by Phene, Hoffman, Rawlins (1973), Carslaw and Jaeger (1962), Luekov (1978), Krichevski (1980), and others. The temperature rise ($T - T_O$) on the probe surface for time t >> $b^2/4a$ can be approximated by (Blackwell, 1954):

$$T - T_O = [q/4pK]\ [ln(t) + c] \tag{7}$$

where $c = ln(4a/b^2)$ and 0.572 is a constant. In this relation, b is the probe radius, q is the heat produced per unit length of the source in unit time, K is the heat conductivity of the medium, a is the temperature diffusivity, and T_O is the temperature at $t = 0$. Equation 7 indicates that a plot of $(T - T_O)$ versus $ln(t)$ should be a straight line for large values of t.

DESIGN OF GEMS SUBSTRATE MOISTURE PROBE SENSORS

The design of the GEMS substrate moisture probe (SMP) sensor needed to accommodate the design of the Svet root module. The SMP sensors resemble large nails, as shown in Figure 8, to allow insertion through the existing vent holes in the top cover of the root module. The main components of the SMP sensor are a temperature transducer (AD-590) and a heater coil (~150 ohms), contained in a thermally conductive epoxy shell. The sensor is mounted in an insertion tube that can be made from different insulating materials, such as stainless steel or epoxy composite, or the tube can be eliminated.

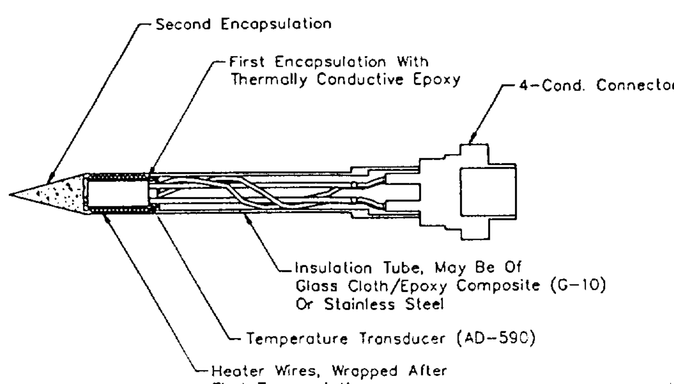

Figure 8. GEMS substrate moisture probe sensor.

The mounting tube (stainless in our case) was fabricated in three lengths for moisture measurements at three depths in the root module. The tube was made from an insulating material to minimize the effect of the mounting tube on the measurements. The sensor (without the mounting tube) is about 25 mm in length and 5 mm in diameter. The transducer has a linear temperature versus voltage output dependency. The sensor was activated in the GEMS unit by a 12 V power supply. The pulse length chosen for the GEMS unit was 20 seconds long, which dissipates about 0.5 W of heat into the medium. The pulse parameters reflect the requirement that the maximum surface temperature of the sensor should not exceed 10°C external to the sensor. This requirement prevents damage to the roots and reduces moisture capillary movement. Because water moves in response to a temperature gradient in the substrate, this phenomena could have a pronounced effect in microgravity if a large temperature gradient was allowed to be maintained in the substrate in the vicinity of the sensor due to sensor operation.

The difference between the temperature on the surface of the sensor and the temperature measured by the transducer inside the sensor is very small because the sensor's heat capacity is small. A temperature rise shown by the sensor is larger than the actual temperature rise in the medium due to the temperature jump on the sensor surface, which is a result of contact resistance.

Figure 9 gives a plot of $(T - T_O)$ versus $ln(t)$ for a pulse of 30 seconds, which demonstrates the linear dependence of temperature rise on the log of time for $t > 10$ seconds. It indicates that the sensor satisfies the large time approximation at times greater than about 10 seconds. When the temperature rise of the sensor is in the log-linear portion of the curve, the temperature rise is inversely proportional to the thermal conductivity of the medium and therefore sensitive to the water content of the substrate. Additional increases in temperature do not result in increased sensitivity.

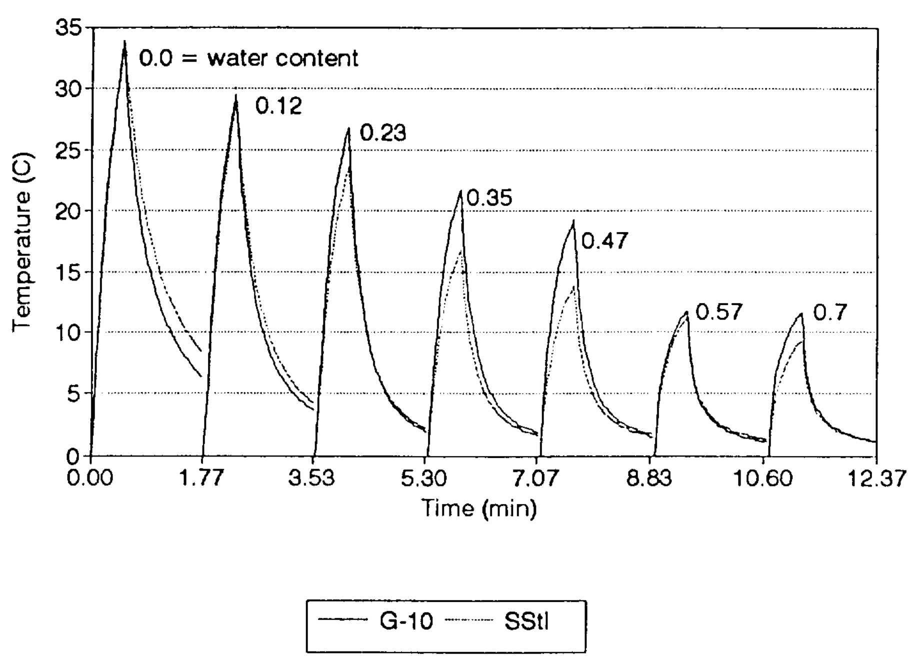

Figure 9. Time history of temperature rise for a GEMS substrate moisture probe sensor in 1-3 mm Balkanine at nine water contents.

CALIBRATION OF GEMS SUBSTRATE MOISTURE PROBE SENSORS

The SMP sensors were calibrated against both TDR and gravimetric standards. Weighed masses of oven-dry Balkanine were mixed with weighed amounts of water and allowed to equilibrate. The equated substrate-water mixture was packed firmly around the sensors. At saturation, a volume of 853 cm^3 was filled with 712 g of dry Balkanine and 386 g of water, giving a bulk density of 0.84 g/cm^3 and a porosity of 0.65. The particle density equaled 2.37 g/cm^3. Water content on a mass basis, obtained from the scale readings, was converted to a volume basis for comparison with TDR readings. After correcting for water content, the SMP sensor output was fit to the corresponding water content using linear regression.

Figure 10 shows calibration curves for three different sensors exhibiting similar dependency on water content. The variation in the maximum temperature rise of the different sensors is due to nonuniformity in fabrication. These arise from small variations in the resistivity of the heater coils and the distance between the heater coil and the sensor. This difference is accounted for in the calibration coefficients assigned to each sensor. Moisture level was measured as the per cent of mass of water per mass of dry substrate. In space experiments, the range of moisture level is wider than on earth. Saturation moisture level will be different in microgravity than in terrestrial conditions, because all of the pore space can be filled with water in microgravity.

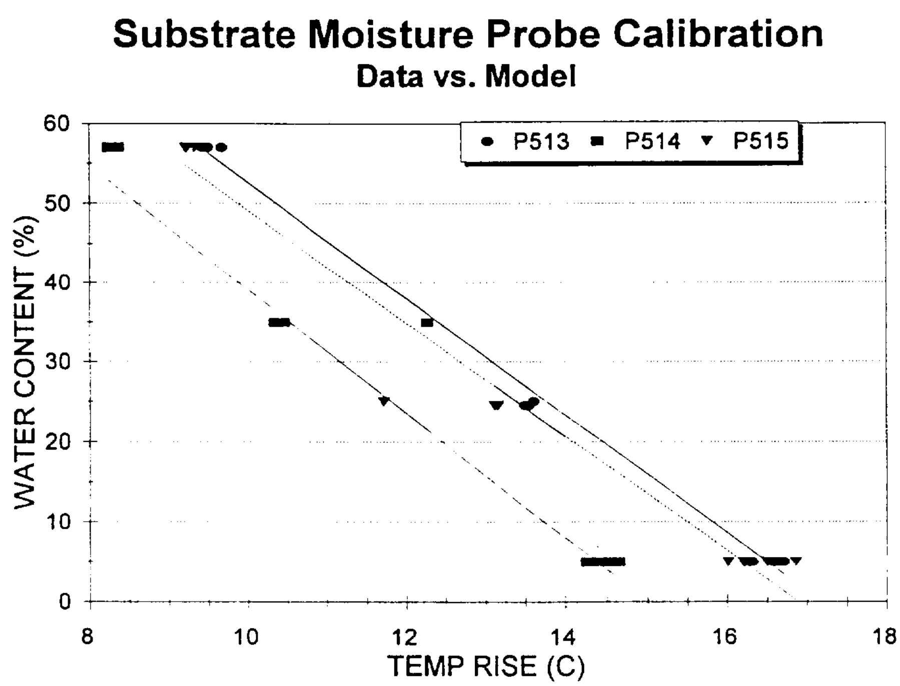

Figure 10. Calibration curves of three GEMS substrate moisture probe sensors in 1-3 mm Balkanine.

Experience with the GEMS SMP sensor showed that the sensor calibration was sensitive to particulate size distribution and the bulk density of the granular mixture being measured. One of the reasons for this shift of calibration is the existence of contact resistance for heat transfer between the substrate and the sensor surface. The contact resistance results from the change in the molecular level contact between the sensor and the substrate through which heat can flow. Clearly, heat flowing outward from the heater through the conductive epoxy shell of the sensor moves quite rapidly. Where the sensor ends and the porous matrix material starts, an air/substrate boundary exists through which the heat must flow. Because air is a good insulator and circulation is blocked by the aggregate, heat loss from the sensor is entirely by conduction in the matrix. Changes in the actual contact area between sensor surface and substrate can result from several causes. One cause is air entrapment on the sensor surface (Nagpal, 1973). Changes in the spatial orientation of particle contact points is another factor contributing to a variable contact resistance between calibration and use in flight. It has been observed that contact resistance changes slightly after a sensor is inserted and used a few times.

Taking into account the contact resistance, the large time approximation shown in Equation 7 becomes:

$$T-T^{o} = [q/4pK]\,[c + ln(t) + 2K/bH] \qquad (8)$$

where H is the heat transfer coefficient. A high heat transfer coefficient corresponds to good contact (conductance) between the sensor surface and the surrounding medium, which leads to a corresponding reduction in temperature rise. Equation 8 was used to determine the effect of contact resistance on the maximum temperature rise at conditions similar to ours; namely, the substrate heat conductivity is 1 W/km, the sensor diameter is 2 mm, the length is 25 mm, and the heat pulse of 0.625 W lasts for 30 seconds. The calculations have shown that at high heat transfer coefficient, 50 W/km^2 and higher, the temperature rise is the smallest and is determined by the substrate heat conductivity. The maximum temperature rise increases significantly when the heat transfer coefficient becomes less than 10 W/km^2.

Any substrate is a mixture of particles of different sizes and shapes. However, after a launch, the substrate becomes stratified due to vibrations and accelerations during liftoff. This leads to a spatial redistribution of particles of different sizes and shapes than was present at calibration. To correctly interpret the data obtained from orbit, the effect of substrate particle realignment must be quantified. The most important and encouraging facts obtained from these studies are that factors like contact resistance lead to only a small shift in calibration curves and the slope of the curve is not changed. The offset in the calibration curve can be determined if the measurements made at another contact resistance include measurements made at one known moisture level. For example, consider the situation in which a sensor that is calibrated using a sample of substrate is then used to determine the moisture content of the substrate in another device, such as a root module. The calibration curve corresponds to a contact resistance established during calibration. A new contact resistance will be established when the sensor is inserted into the root module. Therefore, the calibration curve in a plot, maximum temperature rise versus moisture content, can be shifted to a new position corresponding to the new contact resistance. This new position can be found by taking the measurement at a known moisture level, such as when the substrate is dry.

UTILIZATION OF GEMS SUBSTRATE MOISTURE PROBE SENSORS

Ground Results

Several ground experiments have been conducted in the Svet system using the SMP sensors presented in this paper. Long and short probes have been built to detect moisture distribution along the height of the cuvette. Long probes are used to measure the moisture level below the hydroaccumulator, and short probes are used to measure the moisture level above the hydroaccumulator (see Figure 4). The moisture level is expected to be higher below the hydroaccumulator than above the hydroaccumulator due to the effect of gravity on water distribution under terrestrial conditions. This phenomenon is not expected in microgravity. Figure 11 shows the effect of gravity on the time dependent distribution of water within the cuvette. During priming, the long probes show a faster rise in moisture content than the short probes. Water leaving the hydroaccumulator is initially driven downward by gravity. It then spreads horizontally around the long probes at a faster rate than capillary movement of water upward to the short probes in the cuvette. The data also indicate that moisture level below the hydroaccumulator is 5% higher than above the hydroaccumulator during plant growth. Such stratification of the moisture is due to gravity.

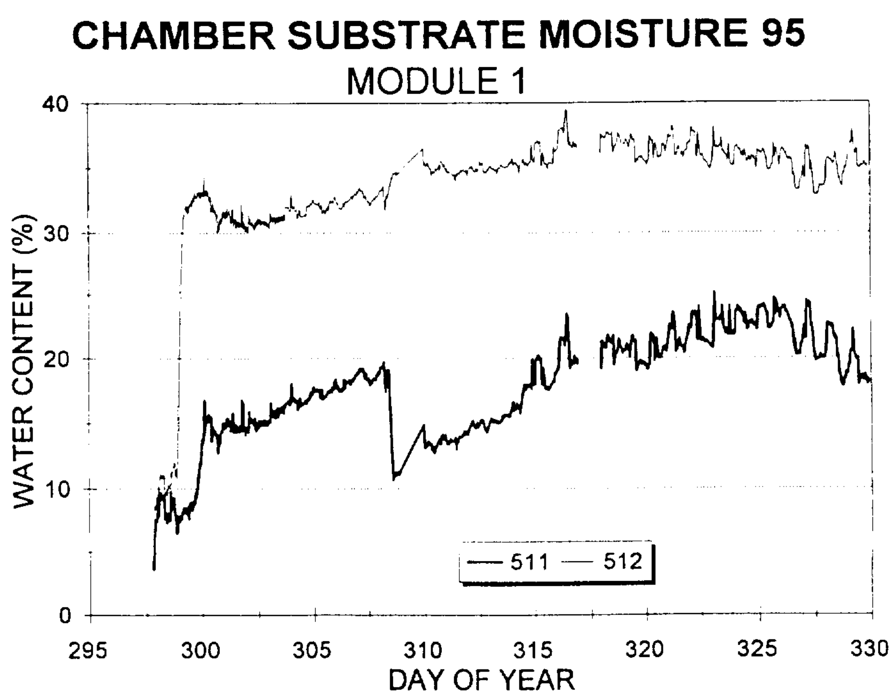

Figure 11. Effect of gravity on the time dependent distribution of water within the cuvette.

Figure 11 also demonstrates the problem of contact resistance. After inserting the SMP sensors into a dry root module, the readings observed in the dry Balkanine tend to change as the root module begins to wet up. Because the hydroaccumulators expand when they are wet, the arrangement of the particles around the sensors tends to shift as water is first injected into the hydroaccumulator. Because we know the water content of the dry matrix, we can adjust for any shift in the packing density due to this rearrangement. Adjusting the dry (starting) part of the curve to 8% water content allows the use of the ground calibration curve to be used effectively in interpreting the water content in the module. The resulting data show the expected water content stratification in the module due to the effect of gravity.

Flight Results

The GEMS equipment was launched to the Mir Station with the Specktr Module in June 1995 and used in a plant experiment between August and November 1995 (Greenhouse 2). Each cuvette contained eight SMP sensors, which were used to track water movement in the Balkanine. Unlike the 1990 experiment where the water remained in the wick, water was observed in the Balkanine in the 1995 experiment. However, the experiment was not without surprises.

The initial Balkanine wetup curves for each cuvette as recorded by two of the GEMS SMP sensors are shown in Figure 12. Figures 13 and 14 show time histories of the substrate moisture measurements recorded by two short sensors located near the center of each cuvette during the first 21 days of the 1995 experiment.

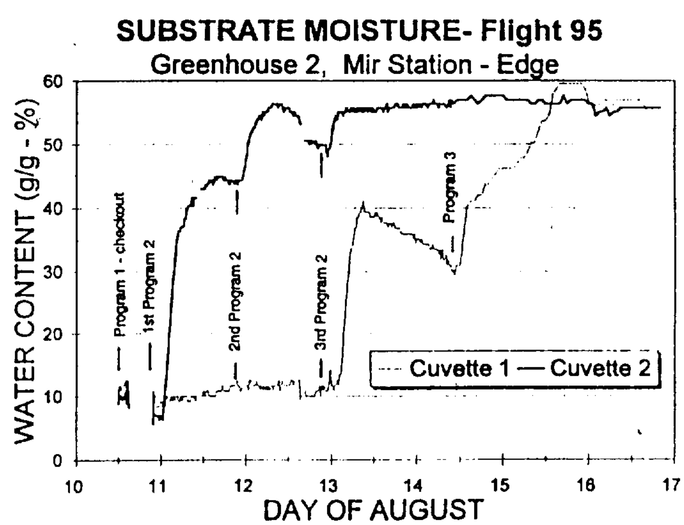

Figure 12. Wetup curves recorded by GEMS.

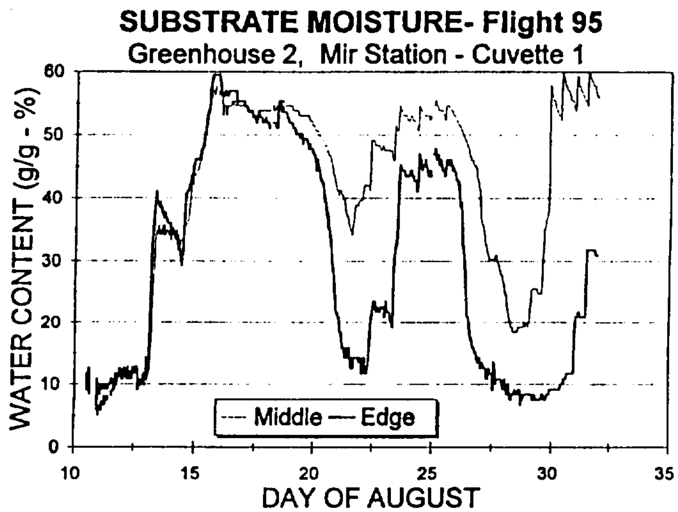

Figure 13. Time history of substrate moisture measurements for Cuvette 1.

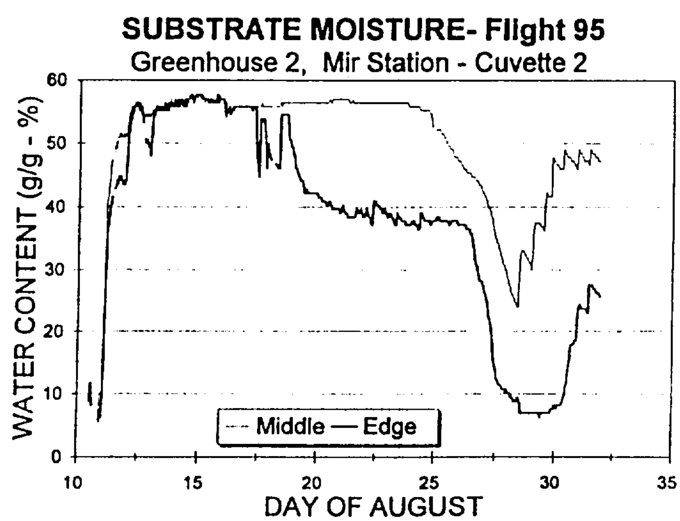

Figure 14. Time history of substrate moisture measurements for Cuvette 2.

At first glance, Figure 5 from the 1990 experiment and Figure 12 from the 1995 experiment look similar. In reality, they are quite different. The traces in Figure 5 are for the wick water content, while those in Figure 12 are for the Balkanine about 2 cm from the wick. The timing of the start of the rise in water content in the two figures is also significantly different. The full wetting period in 1990 occurred in the first 10 hours (one Program 2), while wetting both cuvettes in 1995 required running the initial wetting program three times, followed by maximum injection under automatic control (Program 3) for about 40 hours. This amount of water is consistent with the requirement for fully wetting the 4 kg of Balkanine contained in each cuvette. In both experiments, Cuvette 1 did not receive the same quantity of water per injection as Cuvette 2. Volume analysis and post-flight measurements indicate that, in 1995, Cuvette 2 received more than 3 times the water that Cuvette 1 received early in the experiment. The dose differential appears to have reduced as the experiment progressed to about 1.6 times near the end of the experiment. The differential appears to have been about 2 times during the 1990 experiment.

Communications with the flight experiment was a significant problem during Greenhouse 2. Neither the Svet telemetry system nor the NASA MIPS telemetry system that GEMS was designed to use were operational during Greenhouse 2. Because of these communications failures, ground controllers were forced to rely on voiced information to interpret data and make decisions about future actions. In addition, a calibration offset in the Svet root module, due to a misunderstanding of the Bulgarian calibration procedure, added further confusion to the initial results being reported by the cosmonaut. Because data were available on the ground only once per day, the level of discussion between the investigators during the first few days of the experiment was intense. The behavior of the system during the following few days, however, seemed to confirm the differential delivery hypothesis, which was fully confirmed when the first hard disk was returned to earth by the Mir 18 crew in early September 1995.

Lack of communications with the orbital system made it impossible to optimize the root module water content. Two problems continued to plague water management decisions throughout the 1995 experiment. The failure of the Svet control unit on August 16 made it mandatory that water injections be controlled manually, by the amount of time that the pump was turned on for each cuvette. This task was typically scheduled once per day, just after making a manual recording of the Balkanine water status for voice-down to the ground later in the day. Ground controllers, therefore, had only the previous day's data to use in suggesting the amount of pump time to be used for the following day's injection. Because water use varied significantly with cabin temperature, and oven use in the Krystl module caused significant variations in cabin temperature, smooth operations were difficult to establish. The biggest problem, however, was the Mir personnel's 5-day week schedule. Communications over the weekend are purposely limited. Therefore, it was necessary to anticipate the full weekend schedule on Thursday. The two large changes in water content in the middle of August (Figures 13 and 14) resulted from underestimating weekend water demands. These swings were probably hard on the plants, but they were useful for establishing substrate moisture dynamics.

During the first 21 days of the experiment, water loss from Cuvette 1 was by evaporation from the surfaces and wicks of the cuvette (see Figure 13). These measurements were made by two sensors located near the middle of the cuvette, but 2 cm from the wick toward the inside and outside of the cuvette. The sides of the cuvette have 1 mm holes on a 1 cm^2 pattern. The high wind velocity (~1.5

m/s) between the cuvettes induces a very high evaporation rate on the side wall. The evaporation from this surface dries this section of the cuvette much more rapidly than the middle. Evaporation from the middle of the cuvette is largely from the wick. Figure 14 shows the data collected from two sensors in Cuvette 2, but in the same positions as those shown in Figure 13. Again, the sensor located between the outside wall and the wick has much more dynamic movement than the one between the wicks. The amount of water in Cuvette 2 is obviously much greater than that in Cuvette 1, as the amount of drying observed over the first weekend is much less in Cuvette 2. The drying cycle around August 29, however, completely dries the layer of Balkanine outside the wick and substantially reduces the water content of the layer between the wicks.

The behavior of these sensors during these wetting and drying cycles validates the expressions that we have developed for the behavior of water in a granular substrate under microgravity. At 58% water content g/g, the substrate is fully saturated. That is, it is completely water logged, just as if someone had filled a cup with the substrate on earth and then filled the cup to the top with water. There is no air space left in the mixture. On August 15, the Balkanine around the sensors in both cuvettes was absolutely water logged. However, as soon as the source of water was reduced, the water was wicked away from these regions in a smoothly varying fashion. When the water input and evapotranspiration rates were similar, the water level in the Balkanine was well behaved and easily controlled.

CONCLUSIONS

We have developed an approach for accurately predicting water response of porous media systems in microgravity. For optimum plant development, the root support substrate must be able to transfer water efficiently from the source of liquid to the most distant root hair, without a substantial decrease in water potential. Figure 2 and Equation 2 show that for any given water flux through a substrate, the potential difference required decreases with increasing water content. With the still relatively large substrate that we chose to fly in Greenhouse 2, phase 1, it was necessary to maintain water content in the 35-40% range to provide adequate water fluxes to support root water uptake away from the wicks. Because oxygen diffusion in a substrate is a function of the air-filled porosity of the substrate (Figure 3 and Equation 6), water content should not have been increased above this value. The air-filled pore space in a substrate decreases linearly with the increase in water content. Figure 3 shows that moving to the region of most efficient water transfer in a substrate is a corresponding move into the region of limiting oxygen diffusion. In an oxygen limited environment, root vigor and water uptake capability decrease. Therefore, optimizing these two opposing functions is important in the operation of the root support system.

The procedure developed by Jones (1995), which was applied in the choice of Svet substrates used in the Greenhouse 2 (1995) experiment, was critical in helping to resolve the limited data available in the early days of this experiment. The data collected through three wetting and drying cycles show smoothly varying responses to changes in water balance and can be used to verify the coefficients used in the models we have developed. We are currently modeling the root module response observed to determine just how closely our ground-determined and flight-determined coefficients agree.

The substrate moisture sensors that we developed and deployed to the Mir Space Station for use in determining the distribution of water content in the substrate are currently being flown in the Greenhouse 2 experiment. Calibrations of the sensors on the ground allow moisture content to be determined in space within 3-5% relative water content. The effects of varying contact resistance when the SMP sensors are inserted in space result in an error of less than 5%, which can be corrected by using measurements made in the dry substrate before water is added. These sensors were extremely useful in understanding the differential behavior of the two cuvettes during the initial segment of the Greenhouse 2 experiment.

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