GRO-SAT: THE DEVELOPMENT OF AN EXTENDED LIFE SUPPORT SYSTEM FOR PLANTS IN MICROGRAVITY

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Abstract

The effects of a microgravity environment on the entire life cycle of plants is not yet fully understood. A conceptual design for the payload of a Get Away Special canister has been developed to implement a complete life support system for plants. This small satellite is a closed system that must maintain plant life for at least three months. It consists of an innovative lighting system and a complete plant nutrient delivery system. The use of hardware to limit long-term contamination of the nutrient solution in the closed system as well as other considerations are discussed.

The design, based on the Northern Utah Satellite, considers control of both the thermal environment and the atmospheric composition. Levels of carbon dioxide, oxygen, and nitrogen in the atmosphere are optimized such that plant growth rate is increased. Control of additional environmental parameters is also considered. Proper monitoring of the system will increase knowledge of the effects of microgravity on plants in a closed system. Furthermore, information acquired from Gro-Sat will be used to improve the plant life support system for future Gro-Sat missions.

Introduction

Ever since the Eagle's lunar landing in 1969, the concept of space colonization has emerged from the pages of science fiction, making its way into scientific reality. Among the projects under consideration are a permanent lunar colony, a long-term mission to Mars, and an international space station. In order to meet economic and practical considerations, such environments must be self-supporting. To provide inhabitants with oxygen, clean water, and a fresh food supply, an ecological area for living plants is essential.

Through the years, many researchers have attempted to determine the parameters of such an ecological system. A major question remains unanswered: are plants actually capable of flourishing in a microgravity environment? Most microgravity experiments have been relatively unsuccessful due to poor growing conditions, especially low irradiation flux.[9]

NASA scientists have developed an extensive plan for a Controlled Ecological Life Support Systems (CELSS) intended for the space environment.[13] The plan relies on the assumption that microgravity will not be a limiting factor. If at some point, however, it turns out to be a problem, significant aspects of CELSS research may be put on hold.

Many botanical experiments intended for space shuttle missions have been delayed to make way for military and industrial payloads.[5] Even when such a project is finally flown, the duration of the experiment is usually less than one week, the length of the mission. This is clearly insufficient time for a thorough investigation.

To address this issue, four undergraduate students have combined their knowledge to initiate the development of Gro-Sat, a small satellite designed to house living plants. Its primary advantage is that it will not be restricted to a five-day mission. It will provide for the monitoring of the plants' growth in every stage of development through one complete life cycle. The mission will last an estimated period of three months.

Gro-Sat is designed with easily accessible materials and existing technology. Its basic design and launching device is patterned after NUSAT, a radar calibration satellite of similar volume and design which was launched on April 29, 1985 from the space shuttle cargo bay.[12]

The following proposal examines the major considerations of the Gro-Sat project. Included is a brief history of NUSAT, the basic satellite design, the plant selection process, payload specifications (plant environmental factors), and essential subsystems.

History of NUSAT

The Northern Utah Satellite (NUSAT) was the first satellite to be deployed from a Get Away Special (GAS) canister. "Its purpose was to provide a safer and more efficient means for the FAA [Federal Aviation Administration] to calibrate airport radar equipment."[10] It was designed and built as a Weber State College senior class project with the volunteer assistance of Utah State University, New Mexico State University, the FAA, Goddard Space Flight Center, the U.S. Air Force, and more than 26 private corporations.[10]

The spatial constraints of the GAS can were the limiting factors in the design of NUSAT. Realistically, it would have been too time consuming for the college students to design an attitude control system such that the receiver would always face the earth. For this reason, they simply allowed the satellite to freely tumble as it orbited the earth. Therefore, it was necessary to have a shape that would permit receiving of signals regardless of the satellite's orientation. NUSAT was designed with an eighteen-sided surface, as displayed in Figure 1. The satellite was 19 7/8 in. in diameter and weighed 130 lb. Twelve sides were covered with solar cells and six sides were antennae for the signals sent to and from the ground. This way, no matter how NUSAT was oriented, at least one receiver would face the earth and at least one solar cell would face the sun. Also, NUSAT was designed to be ejected by a mechanism the designers developed specifically for the GAS.[11] A photograph of it is displayed in Figure 2.

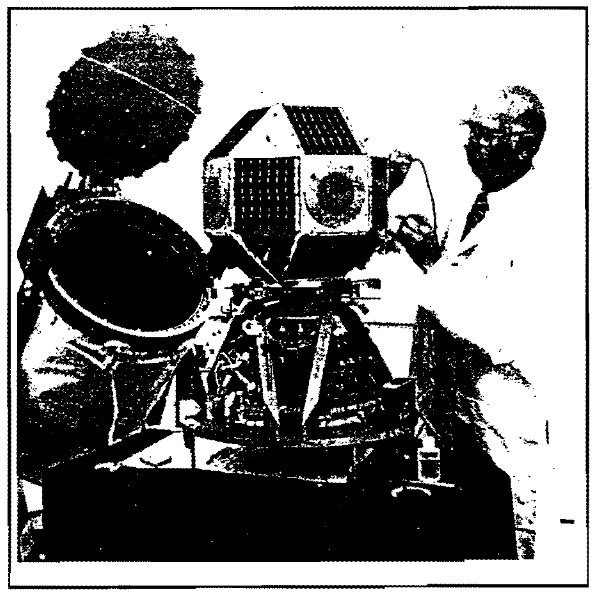
Figure 1 NUSAT. Source: NASA.

We have based many of our design considerations on the ideas used by NUSAT due to high launch costs, time, and volume constraints. These considerations include size, weight, launching device, shape, lack of an attitude control system, and general configuration of the solar panels and antennae. These will be explained in greater detail in the following sections.

Design Constraints

The size and weight requirements of the GAS can are the limiting constraints on Gro-Sat. The GAS can has a 20.00 in. diameter and is 29.00 in. high. Therefore, the NASA specifications require that the payload within the GAS does not exceed 19.75 in. in diameter and 28.25 in. in height. The maximum weight possible is 200 lbs.[12]

In considering the needs of our payload, we considered two shapes for our satellite. The first was a cylinder. This idea was considered in order to maximize the available space within the GAS can. However, we decided, as did the developers of NUSAT, not to have attitude control for Gro-Sat.

Without any attitude control, this design would be impractical since it would be difficult to orient the solar panels and windows.

A symmetric shape seemed a better choice for this reason, and we chose one similar to that of NUSAT. The outside surface will accommodate several solar panels, antennae, and three orthogonal pairs of diametrically opposed windows. The utilization of the windows to provide irradiation for the plants will be discussed later in the paper. Gro-Sat will also utilize isogrid as part of its structural design. Isogrid will decrease the total weight while providing the necessary support and component interfaces.

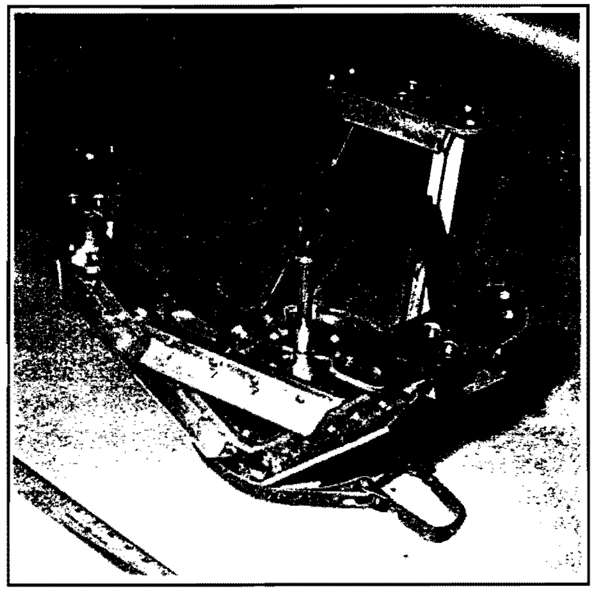

Figure 2 Ejection Mechanism for NUSAT. Source: NASA.

Plant Selection

Several factors were considered in determining which plants would be housed in the satellite. These factors include size, duration of life cycle, and ability to withstand a wide range of environmental conditions. A large variety of plants were initially examined. Some plants like cacti and succulents were rejected due to their slow growth. Others plants were discarded from the final list due to their inability to grow to maturity in 60 days or less. A mission duration of 90 days will allow for a complete life cycle even if adverse conditions slow plant growth. To ensure success, four different varieties of plants with a wide range of features will be placed inside the satellite. These plants and their characteristics are as follows:

- Arabidopsis Thalania - a small mustard-like plant used in many experiments because of its simple genetic code. Life cycle is approximately 45 days.

- Grape Hyacinth - a short, spiky plant similar to daffodils and irises. This type of plant sprouts from a bulb. Life cycle is about 60 days.

- Resurrection Plant - a variety of moss that can be completely dried and then revived by rehydration. Life cycle is irrelevant since it will be transported in its mature stage.

- Dwarf Pea - a smaller variety of a typical garden pea. Special features are its growing method and that it can be used as a possible food source. Since peas grow by physical contact, they will easily orient themselves in a microgravity environment. Life cycle is roughly 60 days.[7]

- Dwarf Brassica - a fast growing cabbage-like plant developed by the University of Wisconsin. It has the advantage of being a possible food source. Life cycle is approximately 40 days.[4]

The dwarf brassica is an alternative choice in an event that experiments prove one of the other plants impractical to use.

Payload Specifications

Lighting System

The most difficult requirement to meet is the amount of light necessary for living plants to grow. In orbit, the sun will shine on the satellite for approximately two-thirds of one trip around the earth, i.e., about sixty minutes. However, not all forms of this light are needed. Some of it is destructive to the plants' health. One type of harmful wavelengths is the ultraviolet (UV). UV light must be filtered out since it retards plant growth by actually changing the DNA structure of the plant, giving it "cancer".

Plants need all wavelengths in the visible spectrum, particularly the blue and far-red frequencies.[7] These frequencies are important since they promote photosynthesis in plants. The plants also require heat, so part of the infrared (IR) spectrum will be incorporated into the wavelength selection. The full IR spectrum is not included because it will cause the internal atmosphere to become too hot. Thus, the wavelengths between 400 and 750 nm will be used.

Earlier attempts to grow plants in microgravity have often failed due to insufficient lighting. To get enough light to the plants, several methods were considered. The obvious idea is a simple window allowing sunlight to shine directly onto the plants. This is not reasonable since the satellite will not have a specified orientation and will be slowly tumbling as it orbits the earth. The interior design of the satellite and the position of the plants within do not allow a window to be placed in the area where the nutrient supply system is contained. Therefore, even if several windows were used, the plants would receive no light if this area were facing the sun. This could result in an extended period of time during which little or no sunlight would enter the windows, and the plants would die.

A second idea involved implementing a set of mirrors that would reflect the light from several windows to the area where the plants are contained. However, mirrors are very fragile and difficult to align properly.

Similar to the mirror configuration was the idea of using fiber optics. First, light from the sun will be collected by six "windows" of Fresnel lenses on the outside of the satellite, as described earlier. A Fresnel lens is made by cutting the bulk out of a large convex lens and then collapsing it. The resulting lens is flat and thin with a short focal length. As stated, the satellite will be slowly tumbling, so not all of the windows will be collecting light simultaneously. This is the reason for placing them at various positions around the circumference of the satellite.

To restrict the wavelengths that reach the plants, the UV and far-IR wavelengths will be filtered out by the actual method of transporting the light. The natural properties of the glass will eliminate these undesired wavelengths.[14] Glass absorbs the short-UV wavelengths (10-280 nm) and by using yellow or orange glass, the near-UV wavelengths (280-400 nm) will also be absorbed[3]. Various coatings on the window, or perhaps on an additional piece of glass, can be used to reflect the IR rays. These may be multiple quarter-wavelength reflective coatings, metal, or composite coatings, or IR absorbing filters.

Another consideration is the intensity of the light that reaches the plants. They need a minimum of 25 W/m^2 in order to sustain life and about 87 W/m^2 for optimum photosynthesis. The light coming directly from the sun has an average intensity of 1388 W/m^2 and will not be filtered out by any atmosphere. Filtering the sunlight with fiber optics and lenses will reduce the intensity to about 578 W/m^2, which is the energy contained only in the visible spectrum. On earth, the light intensity reaches approximately 500 W/m^2 due to the filtering done by the atmosphere. Therefore, it is safe to assume that the plant will not be adversely affected by the light intensity within the satellite.

Nutrient and Water Distribution Systems

The circulation of nutrients and water is of paramount concern in any controlled life support system.[13] Design of such a system requires cooperation between the horticulturist and the engineer. To simplify the system, conditions must be such that each plant will be able to thrive in a similar environment.

The major components of the circulation system are the pump, pipe system, and growing area. The system provides the plants with water, nutrients, air, and physical support. Water use must be efficient and so containment of the nutrient solution is also an important function.[9]

These functions are fairly easily accomplished in earth-based designs, but complexity increases greatly in a microgravity environment. The solution must be contained and yet moved uniformly from the source to the plants and back to the source again. Because of the environmental conditions, familiar fluid transport systems which rely on gravity cannot be used. Liquid and gas states are no longer easily separable, so a system to control both states is necessary.[6]

Fritted plates may be utilized to control the flow of the nutrient solution. A fritted plate is a hydrophilic, microporous, ceramic disk. A small pump moves the solution from the storage reservoir into the pipe system which houses the growth units. A valve at the exit slows the flow, forcing the gases out and the water to fill the entire system. A fritted plate with a wick attached at each growing unit contains the bulk of the solution and transfers a certain amount outward to the growing platform. The wick contacts a multi-layer matrix which houses the seed or bulb. In this fashion, the solution is completely contained and the plant receives sufficient nourishment.

When the seed germinates, the plant will grow toward the light source and the roots will grow in the opposite direction,[2] into the airspace separating the growing platform and the fritted plate. This will allow sufficient room for the roots as well as for the plant itself. In this manner, the roots will not be completely submerged in the nutrient solution, yet the stem and roots will be supplied with both air and sufficient nutrient solution.

A few elements of the design require further research and possible experimentation. It is known that water will leave the plant through transpiration. As yet, the approximate amount that will be transpired from each plant is uncertain. If this amount is unduly large, a water recovery system will have to be designed. It is also uncertain how much water each plant will need as well as how quickly the wick can transfer water. Each of these will be found from further research and experimentation.

Thermal Management

The thermal environment of the satellite is very important to the success of the mission. In general, plants can tolerate a relatively small temperature range, 10°C to 40°C. Near the outer limits of the temperature range, the plants' growth is reduced. Optimum growth of a plant occurs in the temperature range from 20° to 25°C.[7] With this limited temperature range, the thermal model needs to be of utmost accuracy.

The lighting system makes temperature control more challenging. The fiber optics transport a large amount of energy to the inner vessel (approximately 578 W/m^2 is contained within the visible spectrum).[8] A part of this energy is transformed into heat, either through transmission efficiency losses or wavelength alteration as it exits the fiber optics. This excess energy coupled with the solar radiation on the outside surface of the satellite will produce an enormous amount of heat that will need to be dissipated. Some of this heat can be radiated off during the dark portion of the satellite's orbit. However, other methods of passive thermal control are still required.

Throughout the preliminary thermal design, the satellite is geometrically modelled as two concentric spheres. The inner sphere contains an atmosphere similar to the composition of typical air and therefore, the properties of air are used throughout the design. Between the outer and inner spheres, nitrogen gas is used as the insulator in this initial model. This insulator material will probably be changed if an intermediate pressure between the two vessels is undesirable or if a different conductance is required. The outside diameter, which was based on the NUSAT's dimensions, is 19 7/8 in. The outside diameter of the inner vessel is 12 in.[11] Both the outside and inside spheres are assumed to be made of an aluminum alloy with a 0.54 in. thickness.

Initial thermal modelling included finding the rate at which the temperature of the contained atmosphere increased once Gro-Sat is ejected from the space shuttle. The time required to heat the atmosphere to 27°C inside the satellite was approximately a minute, depending on the initial temperature of satellite and assuming that the satellite is released when the space shuttle is in view of the sun. The required time was determined using a general lumped capacitance assumption.

Other preliminary calculations included finding the steady-state temperatures of both the hot and cold cases and determining the final temperatures after each diurnal period. These calculations included the average fluxes from solar, albedo, and earth radiations and a point source equivalent to the incoming light energy.[1] The final temperatures were highly dependent on the surface properties of the satellite. If a "cold" surface were modelled, like white paint, the calculated temperatures of the satellite differed immensely when compared to the "warm" surface model. Equilibrium temperatures for some typical coatings are shown in Table 1.[1]

Surface	α	ϵ	$T_{E,h}$ (°C)	$T_{E,c}$ (°C)
White	0.2	0.9	-37	-178
Black	0.9	0.9	29	-134
Gold	0.2	0.06	192	-85

TABLE 1 Equilibrium Temperatures

The average temperature of the satellite can be somewhat specified by using different coatings on both the outside and inside surfaces. The average steady-state temperatures for the above surfaces are as follows: white paint -60°C, black paint 6°, and gold 146°C. Other methods of passive control, including radiators and thermal blankets, will probably need to be implemented in the final design to slow down the rate of temperature change.

The temperature change with respect to time is shown in Figure 3. This figure shows the ideal range (24°-36°C) that can be expected based on a surface with an absorptivity to emissivity ratio of 1.25. The actual rate of temperature change will be lower than indicated since the overall heat capacity will be greater due to the added weight of the water, plants, and equipment.

From these initial models, it is feasible to say that the satellite's equilibrium temperature will exist in the necessary range. However, a more detailed analysis using computer software like the Net Energy Verification And Determination Analyzer (NEVADA) will be required. With software, a more dynamic and exact thermal model can be created. This will provide a better transient model because it will consider the implications of the fiber optics and other components within the satellite.

Other Considerations

There are several secondary factors which must be considered in a closed system such as this. The major issues that must be examined further are the composition of the atmosphere, the transpiration of each plant, the pH of the nutrient solution, and the contaminants.

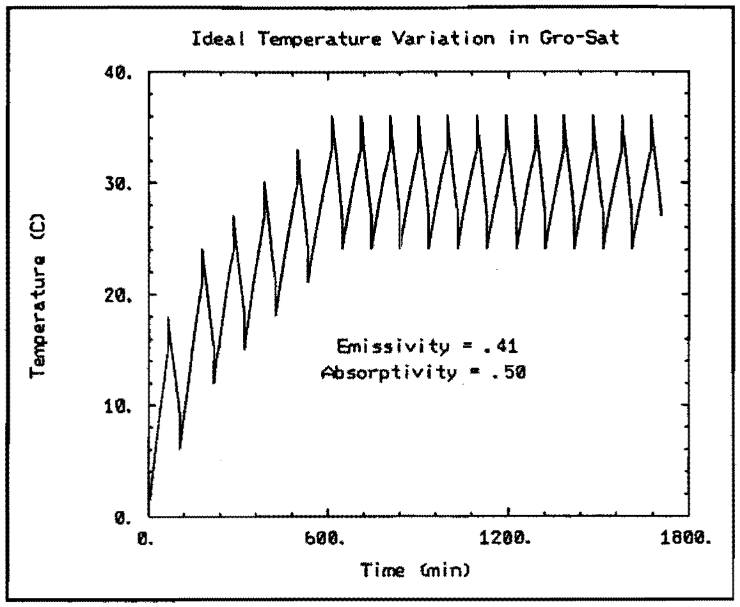

Figure 3 Satellite Temperature Variation

The major components of the closed atmosphere are nitrogen, oxygen, carbon dioxide, and water vapor. In particular, changes in the relative amount of carbon dioxide can have a significant effect on the system. Numerous studies have been conducted concerning the effect of varying levels of carbon dioxide on plant growth. The amount of carbon dioxide in typical air is about 0.03% by volume. It has been shown that plant growth can be sustained until the carbon dioxide level reaches approximately 0.2% by volume. Furthermore, optimum plant growth occurs at approximately 0.12% by volume.[4]

Another factor that will need to be determined is the atmospheric pressure inside the growth chamber. At Utah State University, the atmospheric pressure is approximately 85% of sea level pressure. Studies performed on plants with the pressure as low as 60% showed that plants can function normally at this reduced pressure. Little is known about the effect of pressures less than this on plants.[4]

Plants release water into the air by transpiration. This effect is amplified as the relative humidity of the air decreases. Therefore, the balance must be carefully controlled to decrease the amount of water lost into the air by transpiration. Transpiration rate also increases at lower atmospheric pressures due to the change in the diffusion gradient.[4]

The nutrient solution contains ammonium (NH_4^+) and nitrate (NO_3^-) ions. The plant releases an hydrogen ion (H^+) for each ammonium ion it absorbs and releases an hydroxide (OH^-) ion for each nitrate ion that is absorbed. Because plants use more ammonium than nitrate, more hydrogen ions are liberated than hydroxide ions. Therefore, the exchange between the nutrient solution and the roots of the plant causes an increase in the acidity of the solution. The pH of a solution can be balanced by adding ammonium or nitrate ions as necessary. Because the pH of such a closed system must remain between approximately 4.0 and 7.0, such control is critical.

There are fundamental differences between growing plants in a closed system and in an open system. One that will have to be examined further is that of trace contamination. Many common materials release trace amounts of contaminants that can become toxic to plants in a closed system after several months. Therefore, materials such as copper and aluminum cannot be used for transport of the nutrient solution. Materials such as chemically inert teflon tubing and chemically inert fittings will be used.

Detailed information about our particular system must be obtained through experimentation. The level of carbon dioxide necessary for optimum plant growth is well established. However, experiments to determine the amount of transpiration for varying levels of relative humidity and the effective change in the pH of the nutrient solution are currently underway.

Communications

There are two essential aspects of any satellite communication system. First, it is important to choose which data needs to be sent to earth. Secondly, the best method of data transmission must be determined. There are obviously numerous components to monitor in a life support payload such as Gro-Sat, including temperature, irradiation, air composition, water, nutrient delivery, pH, etc. It is unfeasible to attempt a communication system in this project that would continuously monitor each of these elements accurately. As more systems are monitored, the possibility of technical failure increases, as does the cost.

For these reasons, every possible aspect of the experiment will not be monitored. This does not, however, violate the major emphasis of Gro-Sat, which is to demonstrate that it is a working support system for plants. This will be accomplished with a camera in the satellite that transmits photographic data to one or more ground stations. These pictures will indicate the plants' general health at each stage of growth. Ideally the data base will also include information about a few of the most critical plant environmental factors, including light intensity, temperature, and carbon dioxide concentration. With this information, in addition to the pictures, we will be able to determine how well the plant grew, and if not, why.

The information transmitted from Gro-Sat will become the foundation for future Gro-Sat experiments. This data will indicate which adjustments can be made to make the system more effective. Future Gro-Sat missions will contain additional devices to more completely monitor the environment. Therefore, future missions will provide a more complete life support system.

Power

The power subsystem will rely on standard equipment and technology to operate the satellite's electronic components. It will consist of several solar panels positioned on the outer surface of the satellite, rechargeable batteries, and a power regulating bus. The solar panels will be connected to the bus which will regulate the recharging of the batteries and the voltage supplied to the various electronic components. The power requirement will depend on the specifications of the pump, the onboard computer, the transmitter/receiver, and various sensors.

Future Research

This paper is only the beginning of a tedious research process. The ideas proposed here are the foundation on which the remainder of our research will be based. In the coming months, we will be working to fill in the gaps and details of this basic design. To accomplish this, we have several tasks in mind.

Before Gro-Sat is constructed, we must be sure that the components of the plant containment system will accomplish the task(s) for which they were chosen. Several models of the system will be constructed to grow the plants we have selected. These experiments will resemble the actual environment as much as possible. Tests of the lighting system and the effect of the brief day-night cycle on the plants will be conducted. Additional tests on the water distribution system will be performed. Through these tests we hope to investigate the implementation of the theoretical model.

The most pressing concern is providing sufficient irradiation for the plants. Further research must be done on Fresnel lenses and how they can be interfaced with the optical fibers. This is a relatively new idea that is supported by the scientific community. We hope to contact other researchers who have some experience with this material.

As the design is finalized, a more precise thermal model will be completed. This model will include radiation transfer between the inside and outside surfaces of the satellite. It will be a complicated model due to the complexity of the satellite's structure and the various materials of which it will be composed. These calculations will be performed with the assistance of several thermal analysis software packages.

Once the data transmission capability is determined, a ground station to communicate with the satellite must be found. The station will be student operated, providing an opportunity for them to receive hands-on training in communications and tracking. It would be convenient to have the ground station here at Utah State University. However, the latitude here makes only limited communication possible. Therefore, we will likely work with another university so that data transmission will be less dependent on the satellite's orbit. Currently, the most likely candidate is the University of Mexico in Mexico City because of existing contacts there.

Conclusion

Knowledge gained from Gro-Sat will help to answer questions concerning plant growth in microgravity that NASA has not yet been able to answer. The majority of plant experiments up until this time have been for very short durations. The significance of this satellite is that it will allow scientists to conduct experiments on plants in a space environment for an extended period of time. Gro-Sat is based on small satellite technology which will allow for a lower overall cost for the researcher. NUSAT is the basis for its structural design, including shape, volume, and launch mechanism.

During Gro-Sat's mission, four different plant varieties will be studied for a period of at least 90 days. Growing four types of plants will provide a wide base of study, since each variety of plant was selected for its distinctive characteristics.

All environmental factors affecting plant growth must be considered and incorporated into the system. Some of the subsystems of the growing chamber include the lighting and nutrient-water distribution systems. The lighting system is founded on the recent technology of combining Fresnel lenses and fiber optics. The nutrient-water distribution system will provide the plants with the required nutrients that will be transported by capillary action to the roots. Other system components that will need to be determined in the final design are CO_2 regulation, pH maintenance of the nutrient solution, and temperature control.

The parameters of Gro-Sat, including plant selection, payload specifications, and the satellite design, are continually being developed with experimentation. The practicality of the satellite design has already been demonstrated by NUSAT. This design will be improved through the use of isogrid technology. Furthermore, the satellite will be considerably lighter and more cost effective than previous plant-growth missions. The inherent advantages of Gro-Sat are apparent and make its implementation promising to the small satellite community.

Bibliography

1. Agrawal, B. N. (1986). *Design of geosynchronous spacecraft*. Englewood Cliffs, NJ: Prentice-Hall, Inc.

2. Bickford, E. & Dunn, S. (1972). *Lighting for plant growth*. Kent, OH: Kent State University Press.

3. Brill, T. B. (1980). *Light: its interaction with art and antiquities*. New York: Plenum Press.

4. Bugbee, B., associate professor, Plants, Soils, and Biometeorology Department, Utah State University. (1993, June). [Interview].

5. Cox, R. (1988, March). Zero-G Mysteries and LifeSat. *Space World, Y-3-291*, pp. 13-15.

6. Dreschel, T. W. & Sager, J. C. (1989). Control of water and nutrients using a porous tube: a methods for growing plants in space. *HortScience, 24*(6), pp. 944-947.

7. Hood, E., assistant professor, Biology Department, assistant professor, Program in Molecular Biology. (1993, June). [Interview].

8. Incropera, F. P. & DeWitt, D. P. (1990). *Fundamentals of heat and mass transfer* (3rd ed.). New York: John Wiley & Sons.

9. Langhans, R. W. & Dreesen, D. R. (1988). Challenges to plant growing in space, *HortScience, 23*(2). pp. 286-293.

10. Moore, R. G., senior research associate, Physics Department, senior research associate, Space Dynamics Laboratory.

11. National Aeronautics and Space Administration. (1987). *Get Away Special (GAS) small self-contained payloads experimenter handbook*. Greenbelt, MD: Goddard Space Flight Center, Special Payloads Division.

12. National Aeronautics and Space Administration. (1989). *Get Away Special: the first ten years*. Greenbelt, MD: Goddard Space Flight Center.

13. Olson, R. L., Oleson, M. W., & Slavin, T. J. (1988). CELSS for Advanced Manned Mission, *HortScience, 23*(2). pp. 275-286.

14. Reese, H. M. (1924). *Light: a textbook for students who have had one year of physics*. Columbia, MO: Lucas Brothers.