CELSS. The technology to grow plants, microorganisms, and possibly animals in a space environment is in a primitive state compared with the need. However, scientific and technical progress in documenting plant characteristics and productivity can help overcome some of the current facility constraints. Visualizing future space farms supporting human populations in orbit and on moons and planets is no longer science fiction. The reality lies in determining what form the facilities to support CELSS operations will take.

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Challenges to Plant Growing in Space

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Picture yourself a million miles from earth; it's lunch time. What will you eat: meat, fish, bread, fresh vegetables (cooked or uncooked), or food from a tube? What will happen to the waste products from the processed food or even from yourself? What will you breathe? These and hundreds of detailed questions must be answered. At present, we have little knowledge about a totally closed environment life support system (CELSS). We have developed in this paper a list of references that are pertinent to the problem. It is divided into subject areas and listed chronologically, rather than alphabetically.

Perhaps we should ask whether food production will be a necessity. Others in this symposium series, specifically D. Olson and J. Bredt, have addressed the problem more directly. W. Mendell, in his opening address to this International Horticultural Congress, mentioned the importance of food production in the space program. It appears a colonization of the moon could become a reality. It would be a true colony, however, only if food could be produced. It would be too expensive to ship food that great a distance for a large number of people with current space transportation technology. Without food production, it would be an outpost, with people there for only short periods of time. Plant growing has the asset of the CO_2, O_2, and water relationships that are beneficial to man. The concepts have been known for a long time. Research support from NASA to this point has not been great. The techniques necessary to produce food in space may not be developed rapidly and technology may not be transferable from earth to space. Those of us who have thought about this problem have worried that when CELSS is needed to go into space, it will not be ready. A review of the literature will show that space biologists have been working on some of the problems of plant growing in space. What has not been investigated extensively is what we call cultural problems of growing plants. The opportunities are exciting and almost unlimited in scope, and the information obtained will, in many instances, be applicable to crop production on earth.

The major biological question is whether plants will grow in hypogravity. When we say "grow", we are referring to horticultural quality. Most of the space experiments have been carried out in very low irradiance flux, which would not produce quality plants on earth, so better results should not be expected in space. There are a number of reasons why the irradiance flux has been low in these studies, and they generally have to do with basic limitations of the space systems. These limitations do not help the results of the study, however, especially if one is trying to draw conclusions and say "plants grow in hypogravity". Another biological question is what effect will long- or short-term ionizing radiation levels have on the plants? These effects in the short-term, include perhaps plant injury, and, in the long-term, the potential of genetic aberrations, especially to the propagation materials for the next generation of plants.

NASA is building a ground-based demonstrator to study some of the problems involved in a large, closed plant-growing system. The demonstrator is located at the Kennedy Space Center in Florida, under the direction of William Knott.

The immensity of the problem is difficult to comprehend. In a limited space and with limited supplies, the plant-growing system has to produce a continuous supply of food, regulate the O_2 and CO_2, and purify water for the inhabitants. On Earth, a person, on average, consumes 750 kg of grain from 2.5 ha or 25,000 m^2 of land per year. Each square meter of land has 1250 m^3 of air above it that serves as supply, dilution, or buffer. We will describe the complexity of the systems, indicate the state of our present knowledge, and propose the challenges to the scientists.

1) Space Biology

A) Radiation—There have been numerous reports that the radiation levels in space are high. The exact levels and kinds of radiation are available through NASA literature. The spacecraft was not designed with a radiation shield, so this problem is not unexpected. The short- and/or long-term effects on plant growth should be investigated. If the radiation levels and types are known, they would appear to be relatively easy to mimic on earth, including radiation storms. This information is necessary, as it can affect the whole scenario of cultural planning. For example, it may not be possible to propagate plants either vegetatively or sexually because of the genetic changes in the next generation.

B) Hypogravity—Some experiments have been performed that have not, at least from a horticultural perspective, indicated that plants can be grown in hypogravity. We will make the assumption, for our discussions, that these problems will be solved or they are not real problems.

2) Plant Growing

NASA, and specifically CELSS, has determined that a balanced human diet, which includes all the essential elements, carbohydrates, oils, amino acids, etc., can be achieved with eight species of plants (vitamins can be supplemented), including wheat, rice, white potato, sweet potato, soy bean, peanut, lettuce, and sugar beet. This species selection can be researched further. Although a great deal is known about human nutrition, it appears that there are very few controlled examples of humans living for extended periods on a purely vegetable diet, and no studies to show they can live on these eight selected species. It will be necessary to know the quantity of the eight species required in the diet in order to determine the growth area needed. We will not discuss the arguments for using animal proteins, but there have been some thoughts of obtaining them from fish or insects.

Three major points are needed to understand the growth of these eight crops, and they are area required for growth, cultural requirements, and cultural selection.

A) Area required for growth—Frank Salisbury discusses this subject in greater detail. We just want to put it into perspective. We need production yields for each of these crops, so a total production area can be calculated. At present, the area for food production per astronaut is really very suspect. It has been calculated on a dry-weight basis and extrapolated, sometimes from field data. As horticulturists, we know there can be an appreciable difference between calculated and achieved, especially for small plots, with many outside rows, in rooms with walls.

B) Cultural requirements—It will be necessary to develop crop models for each of the eight crops. It will not be correct to find just the optimum for production or dry weight. At this time, we do not know the driving force or the limitations of the system. If, for example, electric power is limited, then irradiance flux will be limited, and all other factors will have to be optimized to that irradiance level. It could be possible that gas exchange and storage of CO_2 and O_2 are very critical to the overall spacecraft system; then, the regulation of photosynthesis and respiration rates would be the driving force. Listening to spacecraft design engineers, we would suspect irradiance will be the limiting factor. Similar to our growth chambers, the higher the irradiance, the more cooling that must be engineered into the system, and both require increased energy consumption and reduce the efficiency of the system.

It will be necessary for various horticulturists to become expert in growing each species, similar to our expertise for horticultural crops on earth. Some have started—Tibbitts with white potatoes, a group from Tuskegee Institute with sweet potatoes, Salisbury with wheat, and Mitchell with lettuce.

C) Cultivar selection—Once the systems are designed and the environmental conditions defined by the horticulturist and the engineer, the plant breeders should customize or optimize the crop to these special conditions. The objectives include plant size, production efficiency, speed of growth, resistance to radiation, etc.

3) Physical Systems

The plant-growing systems will have to be a cooperative design effort between the horticulturist and the engineer. First, the horticulturist must have sufficient information available to answer the design questions of the engineer, such as optimum irradiance, temperature, CO_2, and humidity levels. We should not use the same procedures most of us use when we ask for specifications for growth chambers (i.e., ask for wide ranges of environmental conditions with minimum variations and then proceed to use a single setting for the life of the chamber).

A) Light—Irradiance will be most important and probably the limiting factor. It generally is on earth, especially in growth chambers. It will be expensive in energy consumption terms to have an unlimited amount of irradiance.

1) Irradiance—If we had our wish, irradiance flux would be very high. This would enable us to increase production and give a greater opportunity to control the gases and transpiration. If irradiance is the limiting factor, then the whole scenario will be limited. It would be useful if we knew the effect of increasing irradiance on food production (assuming that is the bottom line), then optimum irradiance level vs. energy needs could be determined. We do not have this information for the eight selected crops.

2) Irradiance source—Another interesting question is whether the irradiance will be from lamps, such as HIDs or fiber optics. The fiber optics would seem a good prospect because it requires no energy, but apparently it has limitations. The engineers have indicated the energy loss through fiber optics is great, and the irradiance flux would be low. A second problem with fiber optics is that the spacecraft would have to be positioned so that the fiber optics face toward the sun. This requirement would be a driving force for the whole spacecraft and may not be desirable. On the lunar surface, it would not be very practical with the 2-week night.

B) Temperature—Temperature is a very controllable environmental factor, and crop models should be determined so that the regulation of food production, quality, and O_2–CO_2 production is known for all eight crops. The temperature requirement must be known for all stages of growth.

C) Relative humidity—Water management of the entire space craft environment may be very critical. Conservation of water is important. Water is the heaviest single item taken into space. Condensation coils probably will be an important part of the water recovery system, and the relative humidity range of the environment will have to be known. Large condensation coils in combination with high irradiance flux in the plant-growing units could create a desert-like condition. Conversely, it probably will be possible to have any relative humidity desired in the plant-growing units. We need to know what relative humidity is optimum for the eight species.

D) Gases—On earth, with its relatively constant ratio of gases (oxygen, O_2, CO_2, N_2, etc.), it is difficult and not very practical to change the ratio. In the space environment, where everything must be added, the gas ratio can be optimized. Research has shown that a reduced O_2 pressure has resulted in increased photosynthesis. In a space craft's plant-growing unit, it would be possible to have any pressure desired—a real opportunity for creative research. Another problem is the mismatches in the rates of production and uptake of O_2 and CO_2 between the plants and humans. The respiratory quotient (RQ) (moles of CO_2 produced/mole of O_2 consumed) for animals is ≈ 0.85 and the assimilatory quotient (AQ), moles of CO_2 consumed/mole of O_2 produced, for plants is ≈ 0.95. Thus, a loss of 0.1 vol of O_2 per cycle, creates a potential problem that must be solved.

E) Plant support, maintenance, and harvest systems—As the physical system of the space craft becomes known, it will be necessary to design the growing area—a great research potential for the agricultural engineer and the horticulturist. Many of the crops will have some type of support, not only to physically support the plant, but to obtain maximum exposure to light. The system will have to allow for maintenance on the plants during the growth process. The system will have to include harvesting. In most instances, the plants will be harvested at one time for efficient use of space. The opportunities for robotic harvest would appear to be very real, and this area should be investigated.

F) Nutrient/water distribution systems—We assumed hypogravity would not be a problem, i.e., would not inhibit plant growth. Hypogravity, however, will be a major consideration in space plant-growing units. One of the areas of concern is that of the water distribution system. In weightlessness, the nutrient/water distribution system will be critical. The problem is difficult to solve. How can water and nutrients be moved uniformly from a source to the plant and the excess returned to the source. In the one-sixth gravity of the moon, the problem should be greatly reduced and earth-designed systems should work.

The nutrient requirements of each of the eight species must be known. The use of waste water as a nutrient solution could be useful and should be investigated. Monitoring systems for both the nutrient solutions and the nutrient status of the plants must be designed so the distribution system can be computerized.

G) Water recovery systems—It appears plant transpiration can serve as an excellent way to purify water. The quality of the water used for the nutrient solution could be poor, and yet the transpiration water recovered could be potable. The questions are: how much water can be obtained from a square meter of plants? what are the relationships of transpiration to irradiance flux and temperature? and how do they affect food production or gas exchange?

H) Toxic management systems—There has not been a great deal of research on the production of toxic materials in a closed system. In the closed systems I have seen, no toxic materials were observed. It is true these systems have not been closed for very long periods of time (4 weeks). We assume that, after months of use, the nutrient system would contain foreign materials toxic to plants (yet to be determined). The same would be true of the air. Why materials like ethylene would not accumulate, we do not know. The problem appears to be, first to find if toxic materials are present and then find filters or other ways to remove them.

4) Food

A) Efficiency of food production—Food probably will be the driving force in the CELSS program, so maximum food production will be a major objective. The limiting environmental factors (irradiance, CO_2, temperature) then will determine the rate of food production in the limited area. Crop models will be needed for each of the eight species. The engineers will have to determine how feasible (energy consumption) it will be to increase any limiting factor and compare that to the value of added food production.

B) Processing of food—Food scientists will have to look at the eight selected crop species and determine the best way to process these plants to obtain the maximum amount of food. The greater the percentage of the plant that can be used, the less waste there will be to process. Energy will be limited on the spacecraft. Many food processes take a lot of energy, and ways to reduce energy consumption will be necessary.

C) Quality of food—One of the reasons this work should be done by horticulturists is that we recognize plant quality; many of our colleagues in plant physiology, botany, etc., do not have this expertise. The astronauts will have to live with this food production system for a long time, so it should be palatable. NASA has a program to study the feasibility of growing algae and can make a number of arguments for the production of algae. It is easy to grow and is very productive, doubling itself every 24 hr. They do have a problem selling it to the astronauts who have to eat the algae three times a day, or to the food nutritionists who must supply a complete balanced diet.

1) Essential elements, carbohydrates, amino acids, etc.—The food scientists should confirm that the diet of the space traveler contains the essential materials for human consumption and health.

2) Palatability—This is an important factor and should not be ignored. If the space traveler is to be in space for a few days, anything that will keep him or her alive is acceptable, but when the discussion is of lunar colonization, then the lunites should look forward to their meals. There are some interesting opportunities for the food scientist with the eight crops selected to supply a balanced and interesting diet.

3) Storage—The whole scenario of how the food chain will develop has not been determined, but we would suspect that storage of food will be important. At this time, it is not known whether the food will be grown on a continuous basis or cropped, i.e., one harvest at a time and stored for later use. Again, I would assume it will be a combination of both, just as it is here on earth.

5) Miscellaneous Systems

A) Toxic materials—As we indicated before, we assume there will be some toxic materials produced in this closed environment, if not by the plants, then by the humans or the waste or the food processing.

1) Air—It would appear that a filtering system of some type will have to be incorporated into the unit. Studies should be made to determine what materials are present. It will be difficult because it should be done with all the interrelated parts together, i.e., food production, humans, and waste processing.

2) Liquid—The liquid phase of the growing system will have to be filtered and monitored for toxic materials. On earth, we can dispose of the nutrient solutions every few weeks or allow enough leakage to dilute any problems. This disposal will not be possible in space.

B) Waste processing—NASA is studying the processing of the unused plant material and human waste. It is a very complex process; the end product has to be reusable, there are space restrictions for the process, and a limited amount of energy.

1) Plant—The selection of the plants is important to reduce the amount of waste or unused plant parts. The waste must be reduced to a reusable form, most likely to the salt form, with no waste or toxic materials as a residue.

2) Human—Human waste, the urine and feces, must be reduced to a reusable form.

C) Microbial management—It is impossible to produce a sterile situation in space travel, especially if humans are involved. A number of studies indicate that some microbial interaction is beneficial for both plants and humans. Like the rest of this complex program, it is a matter of a controlled balance. There are numerous cases of a single microbe species in a sterile situation causing major problems. In a balanced population of microbes, there is less danger of "contamination".

1) Air—In a closed small environment, some understanding of microbial populations is necessary. After an understanding is obtained, then a scenario can be constructed.

2) Liquid—There is a real danger that a disease could enter into the plant-growing system. It is our assumption that the plant-growing system will be some form of hydroponics with a central system for nutrient recharging, etc. It is easy to imagine a disease organism getting into the system and causing damage. A monitoring system to evaluate the microbial populations will have to be devised. A redundancy in the whole system will have to be designed to avoid a total catastrophe. This redundancy will be necessary for any number of problems, including insect infestations, or a mechanical breakdown of the environmental or hydroponic system.

We visualize a computerized, robotized, automated plant-growing unit, with the systems monitored by the human inhabitants of the spacecraft. The total system will be too complex for a person to control individually, and the limited manpower will probably not allow for a trained horticulturist—at least in the first CELSS space project.

We hope we have been able to give you some ideas about the potential for research in this field. There are literally thousands of bits of information that must be integrated into the total system to make the whole CELSS work.

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Plant Productivity in Controlled Environments

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To assess the cost and area/volume requirements of a farm in a space station or Lunar or Martian base, a few laboratories in the United States, the Soviet Union, France, and Japan are studying optimum controlled environments for the production of selected crops. Temperature, light, photoperiod, CO_2, humidity, the root-zone environment, and cultivars are the primary factors being manipulated to increase yields and harvest index. Our best wheat yields on a *time* basis (24 $g \cdot m^{-2} \cdot day^{-1}$ of edible biomass) are five times good field yields and twice the world record. Similar yields have been obtained in other laboratories with potatoes and lettuce; soybeans are also promising. These figures suggest that ≈ 30 m^2 under continuous production could support an astronaut with sufficient protein and about 2800 $kcal \cdot day^{-1}$. Scientists under Iosif Gitelzon in Krasnoyarsk, Siberia, have lived in a closed system for up to 5 months, producing 80% of their own food. Thirty square meters for crops were allotted to each of the two men taking part in the experiment.

A functional controlled-environment life-support system (CELSS) will require the refined application of several disciplines: controlled-environment agriculture, food preparation, waste disposal, and control-systems technology, to list only the broadest categories. It has seemed intuitively evident that ways could be found to prepare food, regenerate plant nutrients from wastes, and even control and integrate the several subsystems of a CELSS. But could sufficient food be produced in the limited areas and with the limited energy that might be available? Clearly, detailed studies of food production were necessary.

Soviet scientists have been engaged in such studies for more than a quarter of a century, and NASA supported a limited effort with algae and with higher plants in the early 1960s. NASA-supported studies with higher plants were soon terminated, but the research was reinitiated in the late 1970s. Recent planning for permanent colonies on the moon or Mars and for permanent manned space stations has led to an increased conviction within NASA that such work is essential (8). Related studies are being done in France and in Japan. The discussion here is arbitrarily limited to work with higher plants.

In spite of their recognized importance, only a few token studies have been supported by NASA so far: our own with wheat, studies with potatoes at the Univ. of Wisconsin, lettuce at Purdue Univ., soybeans at the Univ. of North Carolina, and some studies with algae. During the past 5 years, only about 4 million dollars have been allocated to these studies. This seems pitifully small when one

Work reported in this paper was supported by NASA–Ames Cooperative Agreement no. NCC 2-139 and by the Utah Agricultural Experiment Station. This is UAES paper no. 3556.