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The Role of Plant Pathology in Development of Controlled Ecological Life Support Systems

The exploration and utilization of the space frontier is one of the most challenging of human adventures. The engineering sophistication of the manned space programs of the United States and the Soviet Union has now made it possible for humans to plan for a permanent presence in space. The United States is firmly committed to a manned space program. President Reagan in his State of the Union message in 1984 stated that the United States will proceed with the development of a permanent space station to begin initial operation in 1994. The National Commission on Space, charged by the president and Congress to propose civilian space goals for 21st-century America, recently completed a report titled *Pioneering the Space Frontier*, which is a critical evaluation of our next 50 years in space (16). The report outlines a program that will result in a network of spaceports between Earth, the moon, and Mars, with permanent bases on the moon and Mars. The commission foresees vast expansion in space travel and commercial development in the 21st century. The National Aeronautics and Space Administration (NASA), Congress, and the president have reiterated their commitment to construction of a space station (Fig. 1) and a vigorous space program following the loss of the space shuttle Challenger in 1986. Possibly within a decade the first permanent presence of Americans in space will begin.

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Controlled Ecological Life Support Systems (CELSS)

Life support systems are necessary for humans to live in the inhospitable environment of space. NASA has determined that for permanent manned space stations and long-duration space flights, regenerating systems are necessary to reduce the high cost of continuous resupply from Earth associated with nonregenerating systems (14). The regenerating systems being promoted by NASA are termed "controlled ecological life support systems," commonly referred to as CELSS. The National Commission on Space has identified CELSS as a critical technology needed for the United States space program. CELSS uses living organisms to revitalize life support materials (i.e., production of oxygen and removal of carbon dioxide from the air) and produce the basic foods essential for human life. The prime candidates for the photoautotrophic components of CELSS are edible higher plants. CELSS resembles a terrestrial ecosystem, but because it is a life support system isolated from Earth and cannot rely on the same kinds of reservoirs and buffering mechanisms as in Earth ecosystems, the environment must be controlled through physical, chemical, and mechanical means. NASA is developing a ground-based experimental CELSS at the John F. Kennedy Space Center in Florida. The Soviet Union has an operational ground-based CELSS in which people have lived for several months.

A primary concern in the design and operation of a CELSS based on the use of higher plants is maintaining plant health and maximizing plant growth rates. Without continuous growth of healthy plants, perturbations would occur in the life support system. Maintaining stability is an important concept in CELSS design, and unplanned perturbations adversely affect stability and thus the operation of the entire system. Although many aspects of plant growth are being studied by scientists working in CELSS research, a subject that has received minor consideration is plant disease. Indeed, the literature on CELSS before 1985 contains only one NASA contractor report (15) and one APS meeting abstract (17) identifying plant disease as a potential problem.

Plant Disease in CELSS?

The production of higher plants for food and other uses on Earth requires a constant and coordinated effort to control diseases, especially in intensive agricultural systems. When plant diseases are not controlled, their effects can be dramatic and costly. Could diseases of higher plants occur and be of similar importance in CELSS? I believe the answer is yes and that plant disease control should be an important consideration in the design and operation of CELSS. Noninfectious and infectious diseases could cause major perturbations in CELSS, such as destroying plants, reducing the efficiency of plant growth, affecting the storage of plant products, and contaminating the plant growth systems. In a closed life support system, these are all highly undesirable and probably unacceptable if severe. Most noninfectious diseases may be controlled through properly designed plant growth systems, cultivation methods, and environmental controls. Infectious diseases, however, could be more

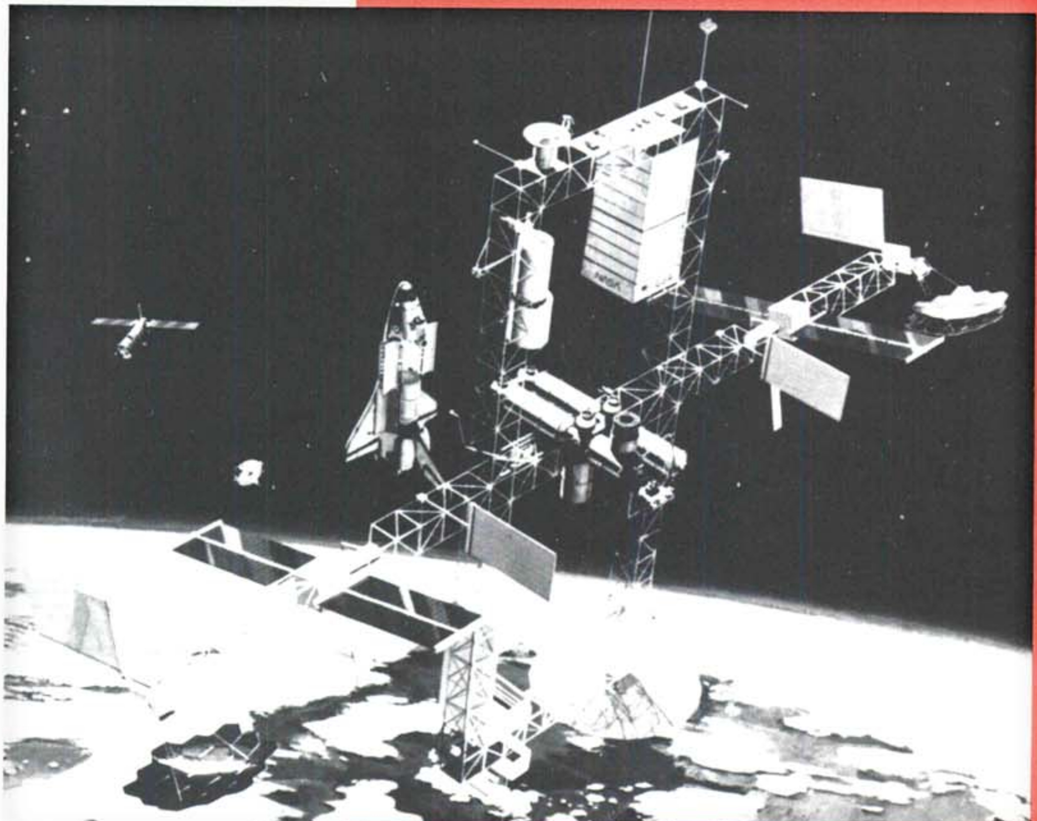

Fig. 1. Drawing of NASA's permanently manned space station that will be assembled in space in the 1990s. The design is termed the dual keel configuration because of the two vertical keels (5-m square erectable trusses) 361 ft long connected by upper and lower horizontal booms 146 ft long. (Courtesy NASA's Office of Space Station)

difficult to control. A wide variety of microorganisms cause plant disease, and they are highly diverse in their means of survival, reproduction, dissemination, and pathogenicity. Preventing their introduction into, and eradicating them from, plant growth environments is notoriously difficult.

Consider the evidence from the following four topics as support for the statement that diseases could occur and be important in CELSS.

Pathogen-infected seed and vegetative stock. The importance of pathogen-infected or pathogen-infested seed or vegetative stock in the dissemination of pathogens and the outbreak of disease is well documented. This is the principal reason for clean seed programs, plant quarantine regulations, and virus indexing procedures—all designed to help control diseases. This means of introducing pathogens into CELSS cannot be underestimated.

Microbial contamination of spacecraft. A wide variety of fungi and bacteria have been detected aboard spacecraft, either on the external and internal hardware or on the human passengers. Most micro-organisms detected inside spacecraft are indigenous to humans, but contamination by soil and dust has occurred. Taylor et al (26) reported that 112 species of fungi (yeasts and filamentous fungi) belonging to 57 genera were isolated from six astronauts in the Apollo 14 and 15 lunar exploration missions. From the interior and exterior surfaces of six of the Apollo spacecraft (missions 10 through 15) 33 species of bacteria and 24 genera of filamentous fungi were identified (20,21). Organisms associated with soil and dust increased with each successive Apollo spaceflight. On the Apollo 16 spacecraft, numerous fungi representing 50 genera were isolated from the instrument unit and the Saturn S4 booster (9). Some fungi were considered to be common plant pathogens, although the researchers did not specify if pathogenicity was confirmed. Within the Skylab spacecraft, manned by three different astronaut crews in th 1970s, 29 species of fungi were isolated from equipment and surfaces (3). The number of species increased with each flight, and each mission was characterized by an essentially different microflora.

Studies on the microbial contamination of the space shuttle (officially known as the space transportation system) have demonstrated a variety of bacteria and fungi associated with the crew, air, spacecraft surfaces, water, and food (19). Approximately 30 species of fungi (14 genera) and 14 species of bacteria (eight genera) were detected in the air and on the spacecraft surfaces of the crew compartment of the space shuttle Columbia. Although the shuttle is thoroughly cleaned before each mission, there is no decontamination procedure to eliminate all microbial contamination in the crew compartments or cargo area. Also, astronauts are not subjected to a decontamination procedure before flight (NASA personnel, *personal communication*).

Table 1. Genera of phytopathogenic fungi and bacteria detected in or on spacecraft and astronauts

Fungi	Bacteria
Ascomycetes	*Bacillus*
Leptosphaeria	*Corynebacterium*
Deuteromycetes	*Pseudomonas*
Alternaria	
Aspergillus	
Asperisporium	
Bipolaris	
Cephalosporium	
Cladosporium	
Coniothyrium	
Curvularia	
Cytospora	
Cytosporella	
Drechslera	
Fusarium	
Helminthosporium	
Hyalodendron	
Kabatiella	
Nigrospora	
Penicillium	
Periconia	
Periconiella	
Pestalotia	
Phialophora	
Phoma	
Piggotia	
Pyrenochaeta	
Sphaeropsis	
Zygomycetes	
Mucor	
Rhizopus	

Many of the genera of fungi found in spacecraft contain plant pathogens (Table 1). The potential for introducing specific plant-pathogenic fungi into a spacecraft was demonstrated in a ground-based Skylab simulation test where *Helminthosporium maydis, Botrytis allii, Fusarium lateritium, F. conglutinans (F. oxysporum)*, and *Aspergillus flavus* were isolated from the human participants (8). Of the genera of bacteria that contain plant pathogens, three have been detected in spacecraft (Table 1). Human-carried bacteria that cause disease on both plants and humans (23) could be potential problems in CELSS (15). Whether phytopathogenic microorganisms have been part of the microbial contamination aboard launched spacecraft is unknown. It should be remembered, however, that microbiological studies of spacecraft have concentrated on human health and not plant health. The only study relating to the detection of plant pathogens from space is by Walkinshaw et al (27), who demonstrated that lunar material had no harmful effects on plants.

Survival of microorganisms in the space environment. Bacteria, fungi, nematodes, and viruses survive direct exposure to the space environment, some for extended periods if shielded from direct solar irradiation (10,11,24,25). Spores of *Bacillus subtilis* survived 10 days of exposure to space when shielded from solar irradiation, and tobacco mosaic virus survived a 6-hour exposure. The long-term survival of microorganisms in space was indicated by the isolation of *Streptococcus mitis* from within a camera body from the American Surveyor III spacecraft that had resided on the moon for 2.5 years until retrieved by the Apollo 12 mission (24). On the basis of these studies, it is conceivable that microbial contamination of spacecraft and cargo outside of the crew compartments (i.e., exposed to the space environment) could result in the introduction of plant pathogens into a space station. It is important to remember that two characteristics of the space environment, deep cold and vacuum, are used in the lyophilization process to preserve plant pathogens.

Vulnerability of plants in CELSS to disease. The novel hydroponic plant growth systems proposed for CELSS, such as aeroponics (13,14), would be highly vulnerable to certain plant diseases. Hydroponic systems lack the diverse microbial community common in soil and thus, when compared with soil culture, have a reduced microbiological buffer that could inhibit establishment and spread of pathogens. The rapid and destructive disease development that can occur with reduced microbiological buffers, as, for example, in soil after fumigation, is a well-known phenomenon. Furthermore, hydroponic systems, especially recirculating types, provide a favorable means for dissemination of, and an ideal environment for, many root-infecting pathogens. The occurrence of destructive root diseases in hydroponically grown vegetables is well documented and has resulted in yield loss and temporary or permanent abandonment of hydroponic culture of these crops (2,4,12,22). *Pythium, Phytophthora*, and *Fusarium* are some of the destructive root pathogens reported in hydroponics. Other disease problems such as unexplained root death and difficulty with chemical control have also occurred.

In the completely controlled environment process of vegetable production of PhytoFarms of America, Inc. (5), one of the most advanced commercial hydroponic systems in the United States, diseases caused by *Pythium* and *Erwinia* stopped production for up to 2 weeks, and rigorous sanitation procedures followed by chemical control were required to return to normal operations (N. Davis, PhytoFarms of America, Inc., *personal communication*). One of the major problems in commercial hydroponic vegetable production has been the implementation of effective sanitation procedures after a disease outbreak.

The plant growth systems proposed for CELSS also may be vulnerable to diseases induced by exopathogens. Microorganisms growing in the nutrient solution could adversely affect plant growth through competition for rooting substrate and/or liberation of toxins that inhibit normal plant growth. In the Russian ground-based experimental CELSS, scientists reported that plant growth rate, especially of wheat, steadily deteriorated, resulting in a crop failure (6). Although the reasons for this were not clearly identified, researchers speculated that it was due to metabolites from the accompanying microflora in the nutrient medium.

Plant Research in Space

Plant research in space began in 1960, and plants have grown and completed their life cycle in microgravity (7). Such problems as chromosomal disturbances, changes in cell metabolism, and perturbed orientation of shoots and roots have occurred, however, and even unexplained plant deaths have been reported. Many of these problems appear to have been associated specifically with microgravity or inadequacies in the plant growth systems. There are no confirmed reports of infectious plant diseases occurring during plant experiments in orbiting spacecraft, but experiments with an infectious plant disease, crown gall, were performed aboard a Soviet Cosmos satellite (1).

Plant Species for CELSS

Eight higher plant species have been recommended for prime consideration in CELSS: wheat, rice, potato, sweet potato, soybean, peanut, lettuce, and sugar beet (28). All of these plants, however, are susceptible to a wide variety of plant-pathogenic microorganisms. Furthermore, with the exception of lettuce, these plants are not normally grown in hydroponic culture except on an experimental basis, so disease problems associated with hydroponics are poorly studied.

Plant Disease Control in CELSS: A Proposal

With the movement of people, plants, and cargo into space, contamination of CELSS with terrestrial microorganisms appears inevitable. Plant pathogens, therefore, could inadvertently be introduced into CELSS plant growth systems. Indeed, scientists are already considering control of microbiological contamination in the design of the first NASA space station, specifically to maintain crew health. To maintain plant health and prevent perturbations in CELSS, a disease control program is necessary. It should be implemented during the design of CELSS to ensure that methods of disease control are incorporated into CELSS operation before actual use in a space station. This approach to plant disease control is essentially no different from what is being considered to maintain human health in space.

I propose that NASA consider an integrated plant disease control program for CELSS (18) (Fig. 2). The controls should be aimed principally at 1) preventing the introduction, reproduction, and spread of pathogens and 2) destroying and removing disease inoculum from plant growth systems. These can be achieved by the following means.

Quarantine. Plant quarantine regulations that permit the introduction of only pathogen-free plants (including seed and vegetative stock) into CELSS should be established and judiciously enforced. The regulations should be written by plant pathologists and should state the specific procedures required to detect plant pathogens in or on plants. Furthermore, they should state, for each crop, the specific type of plant material permitted into CELSS (i.e., seeds, tubers, plants derived from tissue cultures, etc.). For example, it might be wise to permit the introduction of potato plants derived from meristem cuttings but not from tubers, since many pathogens are tuberborne. Evaluation of plants for pathogens could be conducted by plant pathologists in state, federal, or private institutions through the normal NASA contract process. However, one agency, possibly the proposed National Space Lab (16), should coordinate the quarantine program. The regulations could be based on those of the United States Department of Agriculture. Strictly enforced plant quarantine regulations offer a unique opportunity to restrict movement of plant pathogens from Earth to space. It is the responsibility of plant pathologists to insist on this.

Sanitation. The most efficient means of controlling diseases after their detection in controlled environments is by destruction of inoculum. It is imperative, therefore, that effective and rapid methods for sanitizing plant growth systems be incorporated into CELSS operation. Without such methods, infested systems would be prone to continuous disease problems. Plant growth systems cannot be abandoned in CELSS, and it would be undesirable to remove them from production for extended periods. It is especially important during the design of plant growth systems to consider sanitation procedures, not only for the rooting areas but also for the nutrient solution and transport system and other parts where inoculum could survive. The complexity of the system would be an important factor affecting these procedures. The method for disposal of plant debris, particularly after harvest and cleaning of rooting areas, is also important in eliminating sources of inoculum.

Traditionally, steam or chemical means of sanitation are used in soilless culture for disease control. Their appropriateness in CELSS, however, will need to be critically evaluated. Certainly fumigants and other chemicals that are human poisons would be unacceptable in a closed ecosystem. Indeed, chemical control in general may be highly undesirable because of possible air and water contamination in a recycling system. Ultraviolet irradiation may be one potentially useful technique for disinfecting hydroponic systems (22). In addition to sanitizing plant growth systems, general sanitation procedures to prevent the introduction of pathogens on

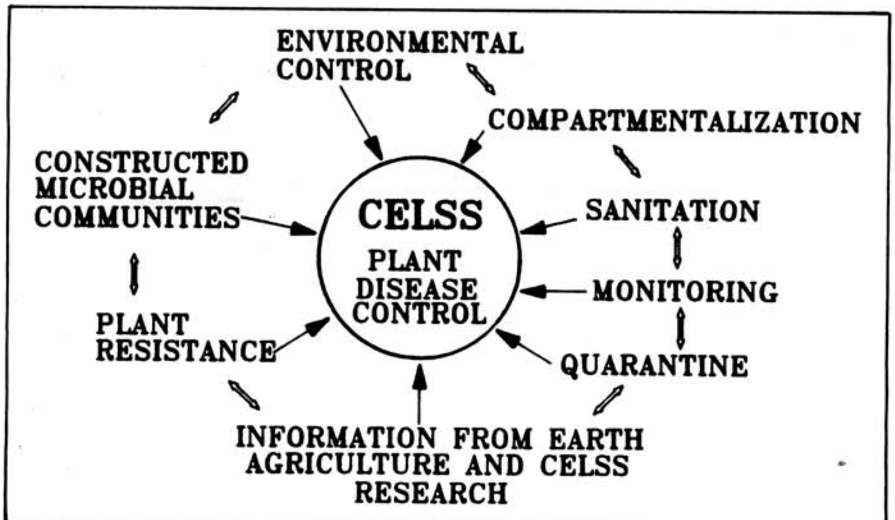

Fig. 2. Conceptual integrated plant disease control program for CELSS. Small arrows indicate interactions between components.

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equipment and humans should be instigated.

Compartmentalization of plant growth systems. Compartmentalization of plant growth systems would reduce the possibility of pathogen infestations, minimize dissemination of pathogens within CELSS, reduce potential damage from plant disease, and greatly facilitate sanitation procedures. Each plant growth compartment (e.g., for a group of food crops needed to be harvested at a certain date) should contain its own nutrient solutions plus delivery system, plant handling and harvesting equipment, and air circulation and filtering system, with no direct air connection with another compartment. Although compartmentalization may be difficult to achieve in small space stations with few people, it becomes a more important and realistic goal as space stations increase in size and population.

Constructed microbial communities. An unusual opportunity exists in CELSS development to construct microbial communities that promote plant growth and protect plants from pathogens and exopathogens (15). Such communities would act as a buffer against establishment, spread, and reproduction of undesirable microorganisms in plant growth systems. Mycorrhizal fungi and rhizosphere and phylloplane bacteria and fungi antagonistic to pathogens are examples of potential members of constructed communities. Although many beneficial microorganisms associated with plants live in the soil environment, they probably can be used in hydroponic systems. In a closed ecosystem, biological control with microbial agents is a wise alternative to chemical control because effects last longer and the environment is less contaminated.

Other controls. Several other controls would be important in an integrated program. Disease monitoring would be necessary and could detect the onset of disease and allow early implementation of control procedures. Automated monitoring, possibly by sensors measuring reflected radiation in specific infrared wavelengths, could be advantageous in CELSS plant growth systems. Rapid, sensitive, and specific methods for disease diagnosis, such as antibody-based diagnostics, would be highly desirable. Plant resistance could be used for the most serious or common diseases, and environmental control would allow adjustment of such factors as temperature and humidity to stop or slow disease development. Advances in biotechnology may offer other controls in the future. Also, a thorough review of plant diseases in hydroponic culture, an understanding of microbial contamination of spacecraft and astronauts, and the importance of human-carried bacteria as plant pathogens (23), plus experience from land-based CELSS, would provide a foundation of information from which intelligent decisions could be made on disease control in a space-based CELSS.

Summary

Plant pathology has an important role in the exploration and utilization of the space frontier. Plants will be an essential part of CELSS for manned space stations and spaceships designed for long-duration flights. Maintaining healthy plants for production of food and oxygen will be one of the major factors that will permit human habitation and colonization of space. To accomplish this, an integrated plant disease control program should be an integral part of CELSS design and operation.

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