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Development of Space Technology for Ecological Habitats

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Introduction

NASA's announcement that it will develop a Space Station over the next decade initiates a new phase of human evolution into space. When the Space Station becomes operational, it will permit continuous human presence in the space environment well into the next century. Scientific experiments that require long periods of time in the space environment will then become possible. Among the many aerospace technologies that make the long term presence of humans in space possible is the technology of life support.

Because of current life support technology, astronauts can work in shirt sleeves inside of pressurized spacecraft, and survive in sealed suits surrounded by the vacuum of space. Life support on spaceflights conducted by the U.S. and the U.S.S.R. over the past 25 years was possible because enough air, water and food was carried from Earth to maintain life. Longer missions have involved replacing supplies of oxygen and food from Earth, in the case of the Soviet cosmonauts on the Salyut orbital station, or electrolyzing water to produce oxygen, in the case of the U.S. Skylab mission. For the most part, however, the regeneration of life support supplies has had limited use.

As flight duration and crew size increase, resupply of life support materials from Earth becomes noticeably expensive. Recycling of spent life support supplies reduces payload weight and the cost of resupply from Earth. On Salyut for example, water vapor from human respiration and perspiration was condensed from the cabin atmosphere on cooling coils. This condensate, along with used wash water was passed through ion exchange columns and activated charcoal filters, sterilized by heat, and stored.

Both the U.S. and the U.S.S.R. have expressed interest in, and actively support research in a variety of techniques to regenerate life support materials in space. The American program has explored two approaches to the problem. One is based on physical-chemical techniques that show promise in regenerating oxygen and clean water; the other makes use of those mechanical technologies with aspects of biotechnology to integrate photosynthetic organisms into the system. The American program is called Controlled Ecological Life Support System (CELSS) research. There is considerable evidence from the open literature that the U.S.S.R. space program is following similar lines of research. Material cycling in a CELSS (Figure 1) could sustain life in space for an indefinite period, while reducing the cost of human space operations.

The technology of CELSS includes physical-chemical-mechanical systems that use heat, pressure and chemical reactants to process food, oxidize wastes, separate and store gases, as well as biological systems that use either micro-algae or angiosperms (higher plants) to produce food, potable water and oxygen, and to remove carbon dioxide. CELSS may be an enabling technology for long-term missions on the Moon and to Mars and the outer planets. A sample scenario is first to develop CELSS technology for use on later Space Stations, then

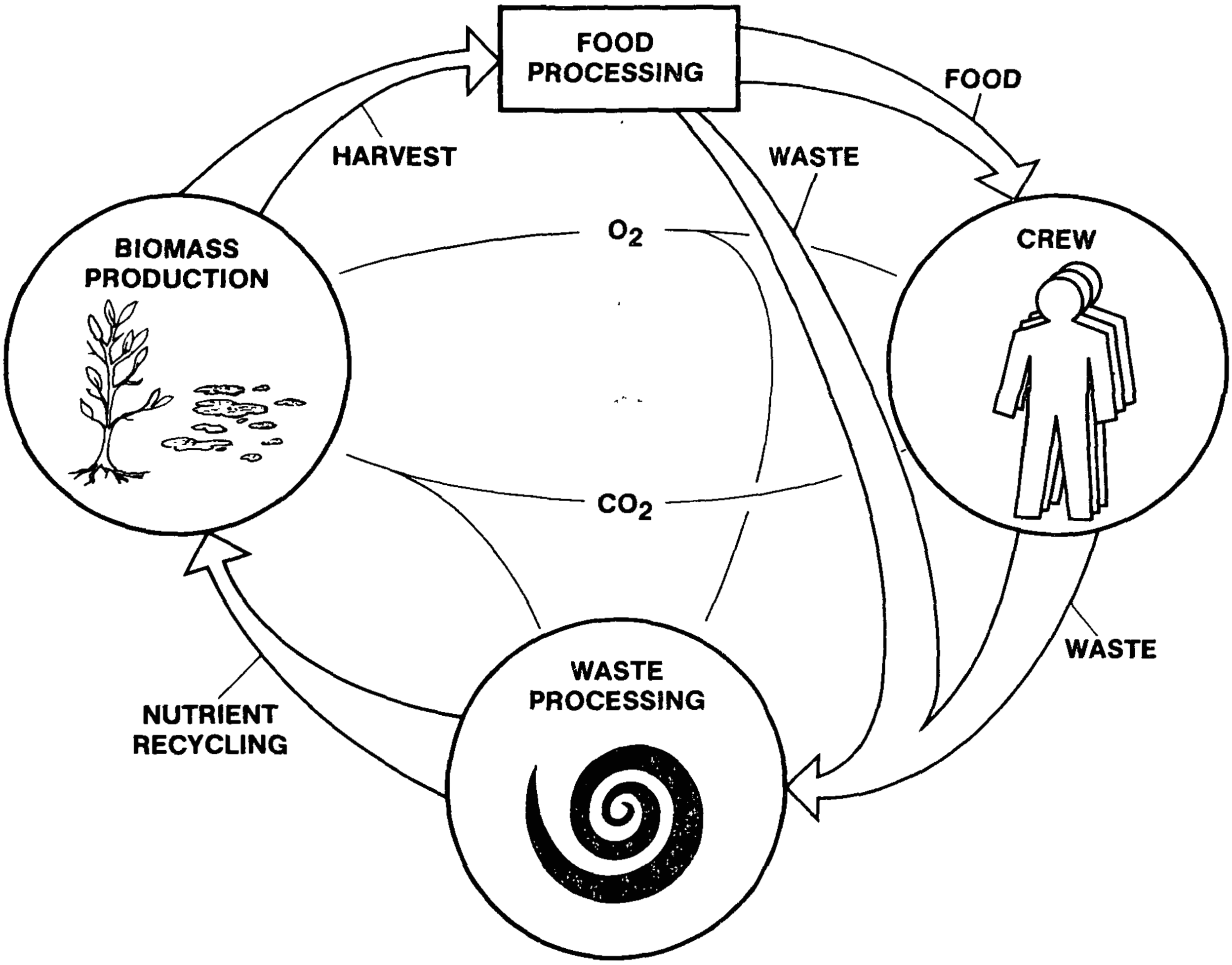

Figure 1. Pathways of material cycling within a CELSS

using CELSS technology on the lunar surface, or to establish a habitat on the Martian moon Phobos. The experience gained with habitats on these moons would be essential for the establishment of a habitat on the Martian surface, which has its own unique environmental conditions and design problems for habitation. Space Station experience would also be invaluable in developing scenarios using CELSS technology for transit to Mars or elsewhere in the solar system.

Biological Space Research Relevant to CELSS

Two approaches to developing a CELSS have been suggested. A holistic method involves enclosing an ecosystem, altering the species content, and manipulating environmental conditions until long-term stability and productivity is achieved. Another approach is a reductionist method that divides the system into several subsystems, develops separate controls for the complete system as well as for each subsystem, and links the subsystems and their controls together. Generally speaking, researchers in the U.S.S.R. have chosen the holistic strategy, while those in the U.S. have chosen the latter. Although in some respects their approaches are different, both the Soviet and American space programs have made considerable advances in bioregenerative life support research.

One of the central research tools of bioregenerative research is the tightly-sealed plant growth chamber. This kind of device, several of which have been built in France (see papers by M. André, these proceedings), and in the U.S. (see paper by Schwartzkopf, these proceedings), provide an opportunity to examine the metabolism of plants while they are growing and to experimentally manipulate environmental conditions to increase (or decrease) growth rates, oxygen production, etc. Typically, a chamber contains separate compartments for the roots and shoots. The stem compartment allows the leaves to grow in higher than normal levels carbon dioxide, lower oxygen tensions, or both to promote photosynthesis and plant growth, to stimulate flowering, and to produce higher crop yields. A separate compartment for roots growing hydroponically or aeroponically (misting the roots) allows manipulation of the rhizosphere (root zone), as well as studies of nutrient uptake. The Schwartzkopf chamber is diagrammed in Figure 2.

Only recently with the advent of computer control systems has it been possible to achieve in enclosed chambers the necessary manipulation of air movement, water, humidity, and temperature and the removal of contaminants to maintain long-term plant growth. Although these chambers are a specialized requirement for research and development of a CELSS, they can also have terrestrial applications. This new technology expands the resources available for research by the botanist and agronomist. In addition they can be used for the study of ecosystem effects on new organisms produced by recombinant DNA techniques, or on chemical products (pesticides, herbicides, etc.) before releasing them into the environment.

The missions of the Soviet Salyut space station provided for the first time an opportunity for many long-term experiments using plants in space. Starting in the 1970's, Soviet researchers experimented with both partially and totally controlled environments for plants in space using a series of chambers, which were gradually upgraded to suit the unique environmental conditions of microgravity. Problems of water and nutrient delivery, and aeration of

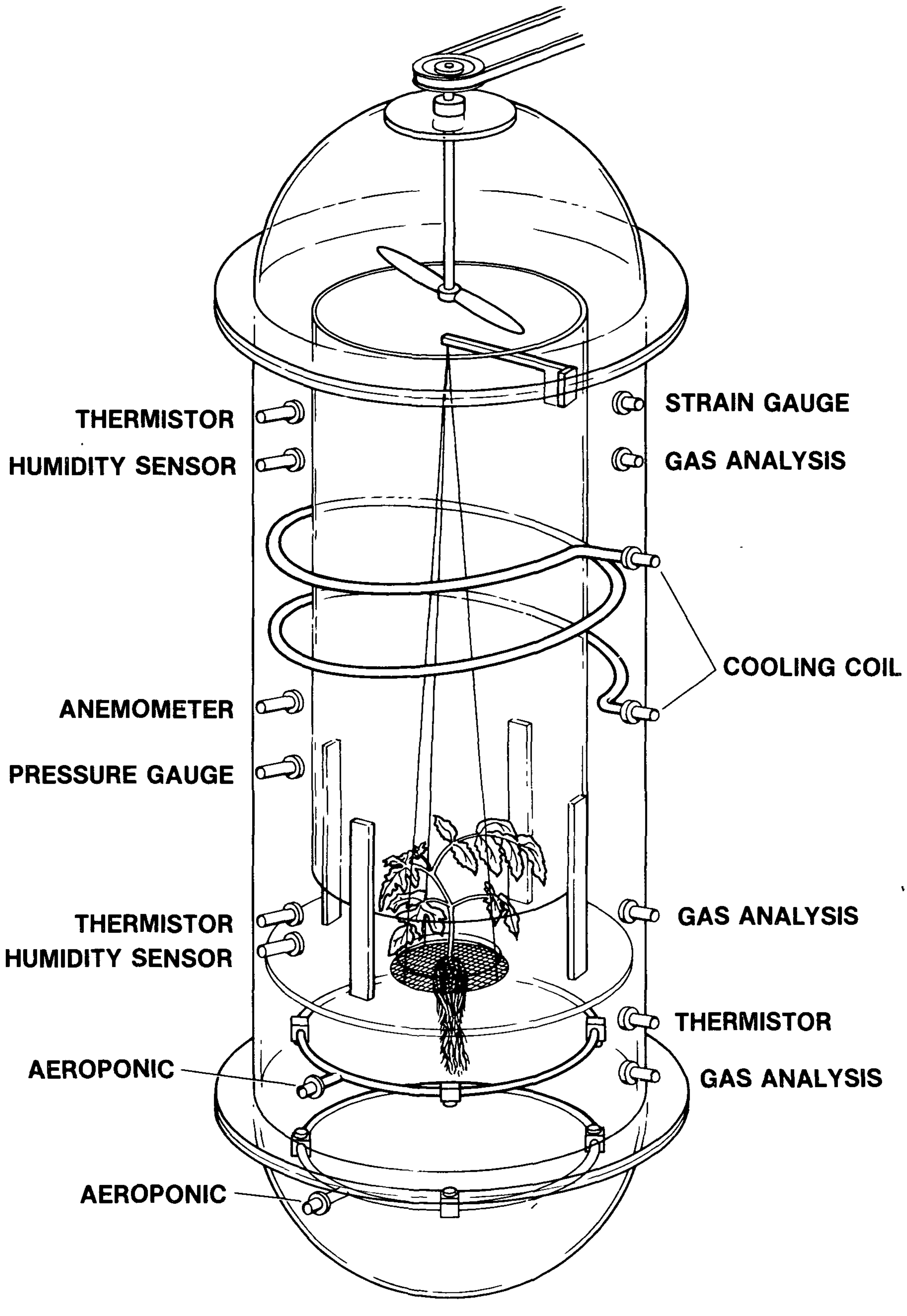

Figure 2. Closed plant chamber design that supported plant growth continuously for two months (Schwartzkopf 1985).

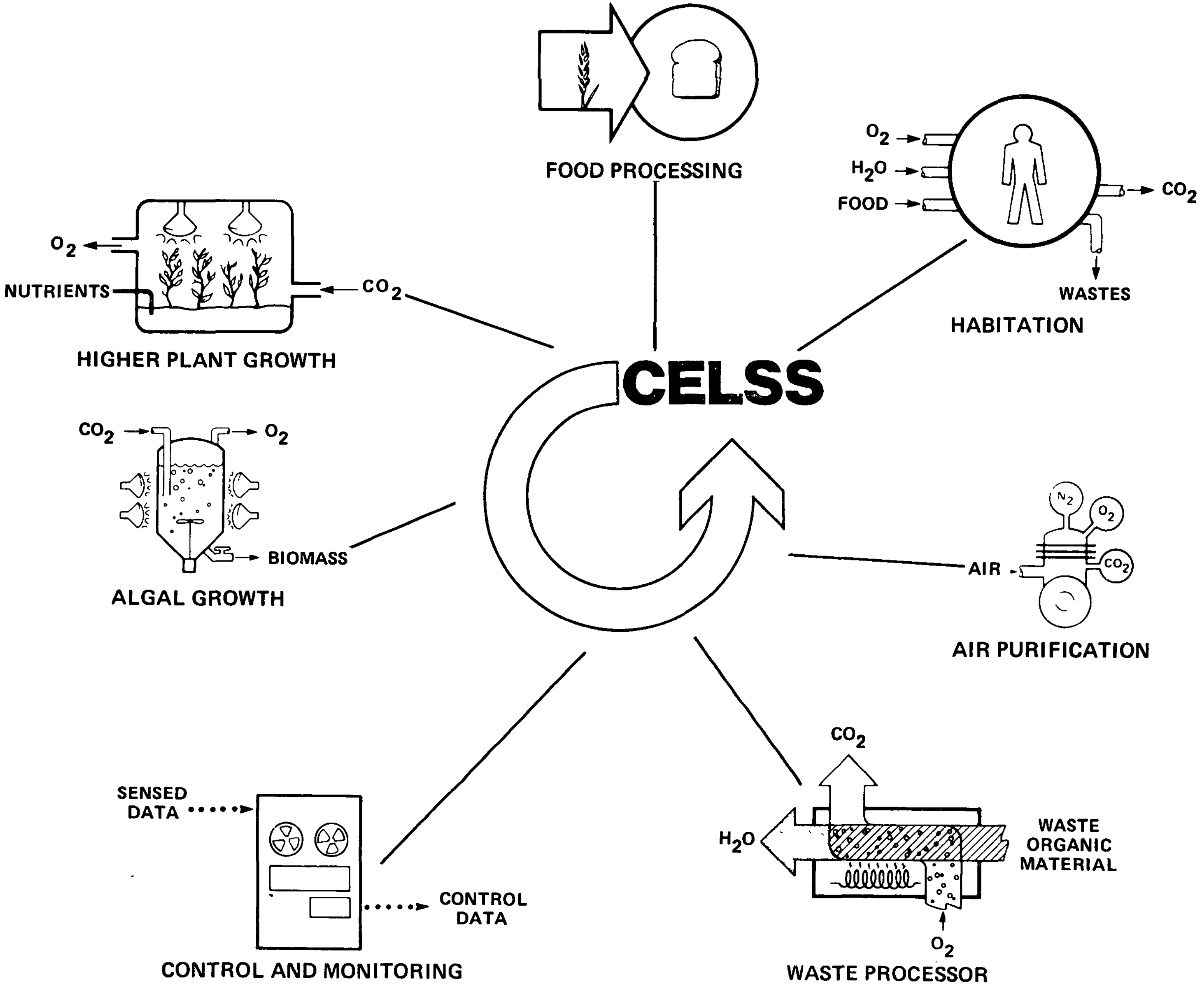

Figure 3. The various subsystems that comprise a CELSS are a mix of living and non-living components.

roots in weightlessness were apparently solved. On Salyut the growth of onion, radish, dill, cucumber, and carrot was achieved, but the plants died at the flowering stage. In 1982 flowering and seed formation in space was achieved through the efforts of Lithuanian botanists. Intense illumination and filtering impurities from the plants' air supply finally resulted in growth through an entire life cycle (fertilization, embryogenesis, maturation, and new seed formation) of the test-tube size angiosperm *Arabidopsis thaliana* (L.) Heynh. Light intensity and photoperiod apparently must be adjusted for reliable plant productivity in space, as on Earth. Some of this data is already available in the literature for input into computer data bases and models. This information is of consequence because different plant species have different lighting requirements to ensure their growth and flowering. In space, plants also developed at a slower rate and it is unknown if this effect is due to lack of convection for heat and gas exchange, or to altered plant physiology in microgravity.

Soviet researchers have conducted botanical studies on Earth continuously for 20 years in their Bios program. Using the 'Bios' series of chambers, researchers started with 12 cubic meters, which has evolved into 315 cubic meters. In recent years a team of about 20 Soviet scientists used this chamber to supply two engineers with fresh air and water, and four-fifths of their foodstuffs for five months, the length of a round trip to Mars.

Soviet experiments with food crops in space show every sign of continuing at an aggressive pace to provide cosmonauts fresh food, psychological enjoyment, and increased life support capabilities. As recently as late 1985, cosmonauts on Salyut were investigating the growth of pepper, onion, and lettuce in different nutrients in at least two different plant growth chambers. A 'Biogravistat' also provided various spin rates to affect the growth rate of seeds in space.

Stability in Controlled Ecosystems

The stability of any ecosystem demands the orderly flow of nutrients between the living and non-living components of the system. Non-living components in the Earth's biosphere include the gigantic reservoirs of clay and humus in the soil, and the water and the atmosphere that are set in motion by the light and heat of the sun, producing the planet's weather and the cycling of elements. In a CELSS the non-living components will be mechanical units to process crops into foodstuffs and to breakdown the excess waste and extract the nutrients, and chemical units to purify the air (Figure 3). On Earth as well as in space, the living members of the system are the same: plants, animals (including humans) and microorganisms. On Earth microbes perform most of the recycling of elements in the biosphere.

With the addition of plants for food and for air and water regeneration, a life support system begins to resemble a terrestrial ecosystem, although the large size of the terrestrial system permits life processes to continue even with some perturbations in the system. On the other hand, a small interruption, if not considered during the design of controls for the system, could be a weak link in CELSS stability and, depending on the cause of the perturbation, could cause the system to become unstable and "crash". Maintaining system stability, especially when a single factor may affect the operation of the whole system, is an issue. For this reason it is important to understand ecosystem behavior and to integrate ecological concepts into the design of a CELSS.

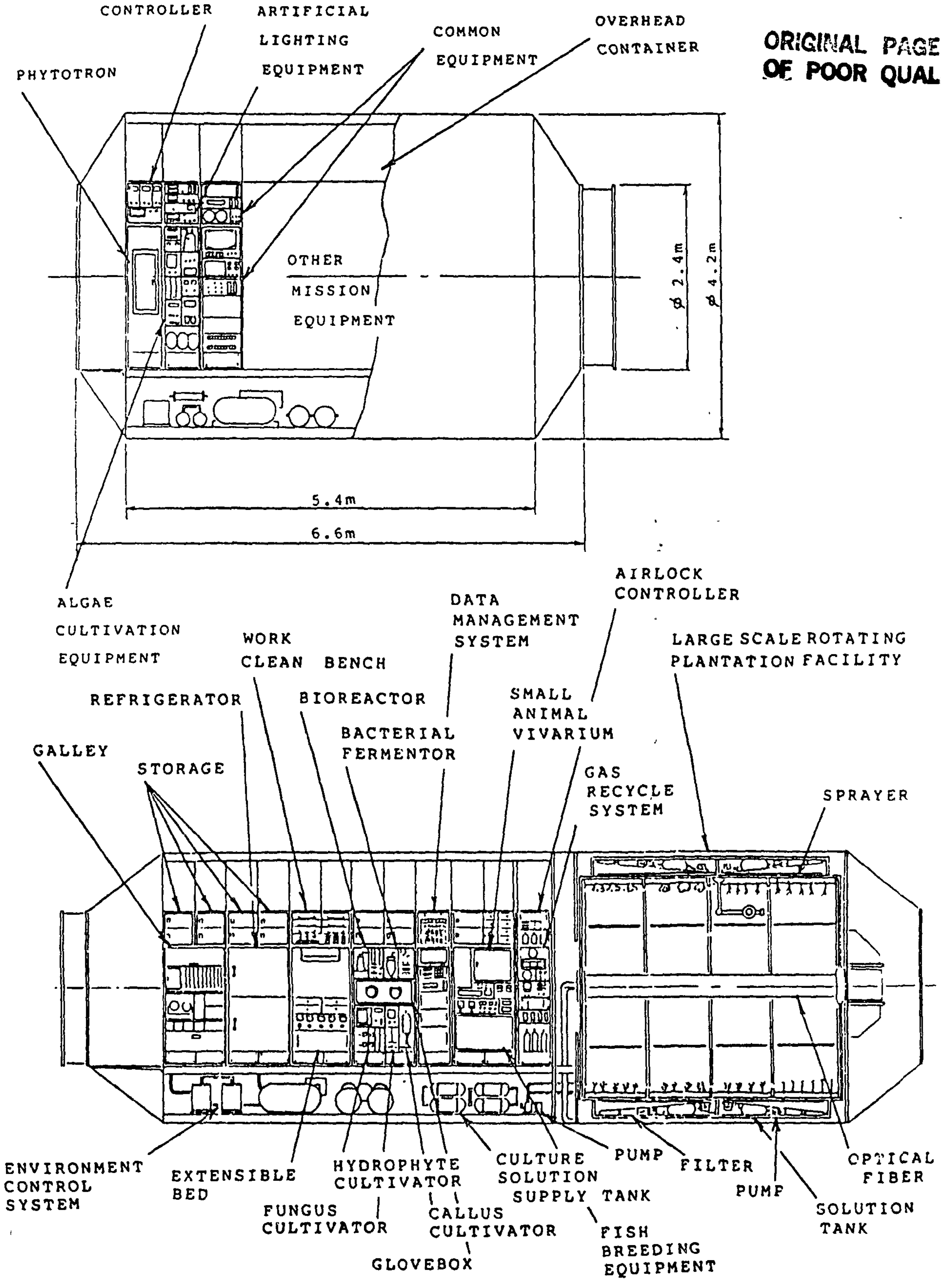

Figure 4. Japanese concept showing the evolutionary growth of a CELSS Space Station module. The first mission (top) would be based on a phytotron (plant chamber) and algal cultivator to study food production and gas conversion of carbon dioxide to oxygen through photosynthesis. A CELSS-dedicated module (bottom) eventually could be used to study a variety of organisms.

Ecological design, that is, design that incorporates principals of the natural world to sustain human settlement for a long period of time, is used successfully on Earth to maintain stability in the natural environment. One ecological design principal is the use of a variety of organisms to aid stability. For example, farms in Java have produced continuously for centuries by constant use and regeneration of water and nutrients, managed by a balanced mix of trees, livestock, grains, grasses, vegetables, and fish. No single crop type dominates the system, so if a single crop performs less than optimally, the proper flow of nutrients, and hence the whole system, will not collapse. The economy of size in a CELSS requires a limited number of specific species, carefully chosen to ensure stability and productivity. More than on crop species may even be grown in a chamber simultaneously, once studies are conducted to determine optimal species mix.

An aquaculture system has been suggested as part of a detailed design study by Japanese aerospace scientists to establish a CELSS module in space in evolutionary steps (Figure 4). To increase the complexity, and perhaps the stability, of the ecosystem 'loop' in a CELSS, bacteria could be added to transform toxic ammonia and nitrogenous waste from the fish into nitrates, which would act as a fertilizer for algae, which in turn would be a major source of food for fish. The first source of animal protein for human consumption in a bioregenerative life support system is likely to be an aquatic creature. Traditional livestock would be inappropriate in a CELSS because of their very low food conversion efficiencies. However, small animals, such as fowl and rabbits have higher efficiencies of conversion and may be of interest.

Techniques of ecological design and controlled-environment agriculture can be useful in land reclamation on Earth, as well as making permanent habitats easier to achieve in space. Recently, the University of Arizona, the New York Botanical Garden, the Smithsonian Institution and other groups proposed a seven-year venture to create an isolated, enclosed biosphere (86,000 square feet) outside of Tucson, Arizona. Such technology could be used to restore damaged ecosystems and as a research tool for studying complex ecological interactions.

Designing a CELSS for Spaceflight

Of paramount importance in a Space Station environment is the conservation of volume inside of the pressurized modules. The first CELSS for use in space must be economical, taking up as little volume as possible on the spacecraft, and recycling as much material as possible over its lifetime to minimize the launch weight of resupply from Earth. To conserve volume, the size of 'holding tanks', which act as buffers or reservoirs between the CELSS subsystems must be reduced as much as possible, and therefore material processing through the system must be rapid. Crops should produce predetermined yields in a short time. Waste materials (primarily from crop plants, but also from humans) should be quickly processed into reusable nutrients. The human control of system size and the rate of nutrient flows throughout is a major distinguishing feature of CELSS compared to the gigantic terrestrial ecosystems, their nutrient flows, reservoirs and buffers, which may require hundreds of years to completely recycle and remix elements.

If lack of normal gravity actually affects plant physiology, perhaps centrifuged chambers will be required to provide artificial gravity. If plant physiology is not the real problem in

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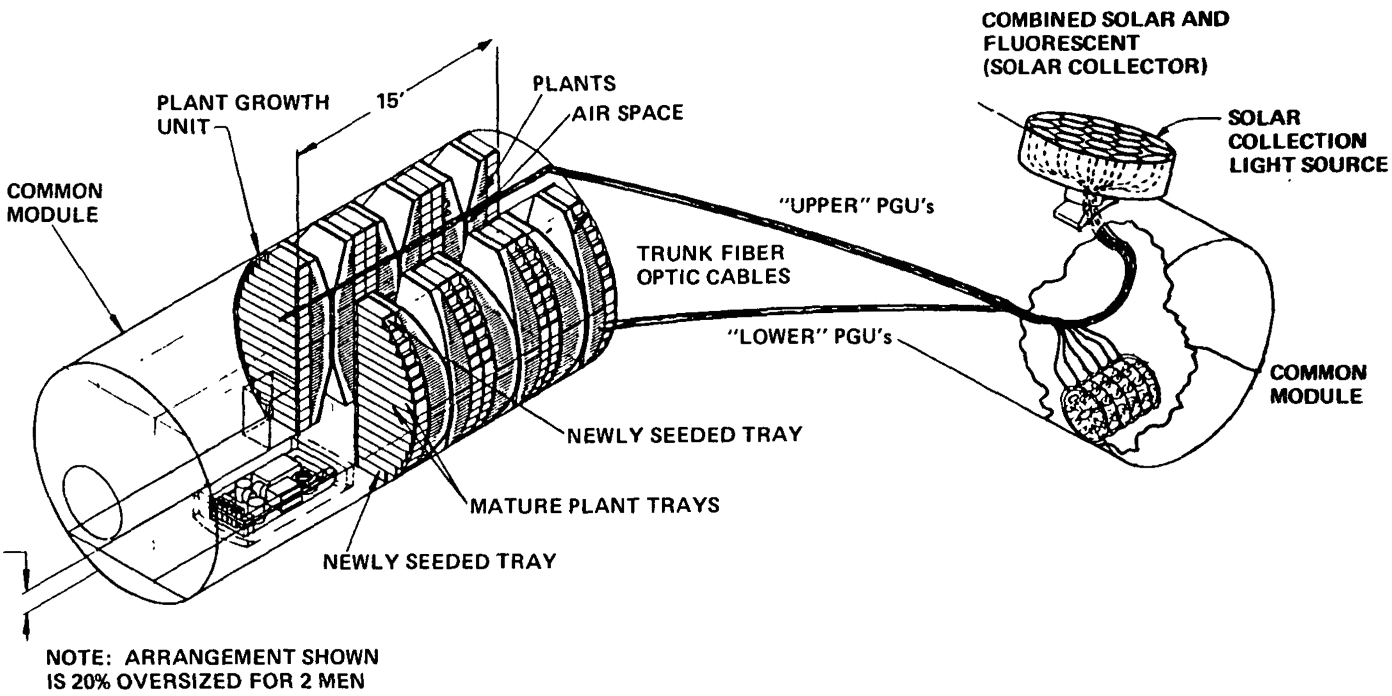

Figure 5. A combined solar and artificial lighting system delivers light to plant growth units (PGU's) via fiber optic cables.

weightlessness, more efficiently designed plant chambers will be required. In microgravity the absence of normal convection, to aid in circulation of heat and metabolic gases for the leaves, and altered behavior of fluids in the root area, may be the critical factor. The nutrient solution for the roots, easy to aerate with oxygen and drain on Earth, will be heavily influenced by the behavior of gas-liquid interfaces and the strong influence of liquids' surface tension under microgravity. On the other hand lack of response to density differences in microgravity may actually aid in the mixing of oxygen and mineral nutrients in solution. Pumps will be required just to maintain air exchange to the leaves, and water/nutrient exchange to the roots.

A particular problem in spaceflight will be the spectral quality and periodicity of light as the Space Station orbits the Earth, or the Lunar Base moves from sunlight into shadow and back. During its lifecycle a plant requires certain changes in wavelength, intensity and photoperiod to maintain normal productivity. Light must be provided in the wavelengths most usable by plants: the visible wavelengths with emphasis on red and blue, the absorption peaks of the two major chlorophyll components of plants. Existing data on the effects of light on various plant crops should be studied in this regard. New experiments should examine the unique limitations of lighting in the man-made space environment. Although maximum control can be achieved by the exclusive use of artificial lighting, this method consumes the most energy and generates the most waste heat. A mix of natural and artificial light sources may prove optimal.

To achieve energy efficiency in these space systems, natural sunlight could be collected on the outside of a CELSS module. A solar collector would remove both harmful ultraviolet light and ineffective wavelengths, such as the infrared. An extensive discussion of this approach, first proposed by a Japanese company (Himawari) has been published as a NASA report by Boeing Aerospace. A schematic design of the device is presented in Figure 5.

To ensure adequate nutrition for space crews, a minimum variety of crop species suggested for a CELSS includes soybean, peanut, wheat, rice, potato, carrot, spinach, cabbage, and lettuce. This list could be expanded to include root crops like sweet potatoes, red beets and sugar beets; vegetables like broccoli, cauliflower chard and other greens; and additional grain crops. Tomato, green bean and sugar pea may also be included. Cantaloupe and the everbearing (perennial) strawberry are suitable fruit species. To prepare the harvest for storage and consumption, automated methods must be chosen and adapted from those already in use in the food processing industries. Threshing, hulling and milling of grains and seeds; pressing, centrifugation and filtration of oils and juices; evaporation of sugars; pickling and fermentation to preserve certain foods; and dehydration of some products to minimize storage space and maximize 'shelf life' will all be required.

In a CELSS module it may be necessary to process the largest variety of foodstuffs from a few major crops that are good producers in microgravity. Some of these so-called fabricated foods are quite acceptable in the diet; some may be less so. Such foods include imitation cheeses and the traditional Oriental meat analogues of tofu, tempeh and seitan (gluten). Seasonings and flavorings for foods may best be provided from Earth by essential oils or their analogues, which are so concentrated that their payload weight may be negligible. By not growing herbs and spices in space, valuable space and energy would be conserved in a CELSS module for food crops that are essential. This strategy would also avoid a whole new class

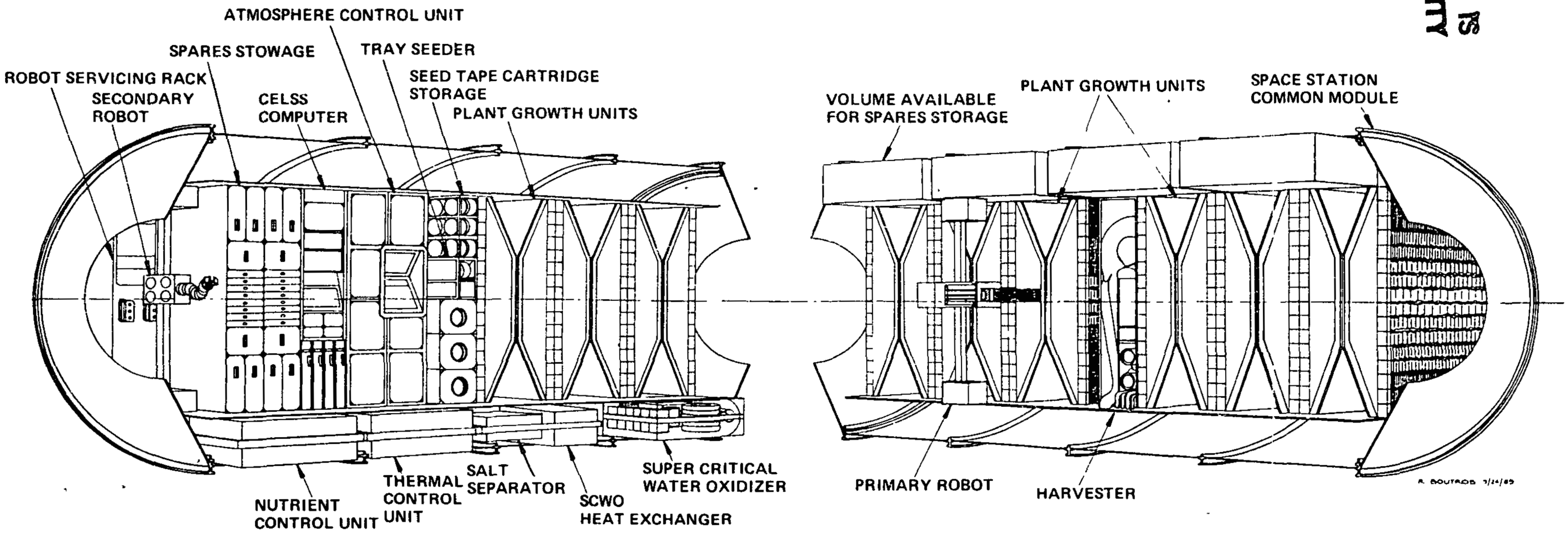

Figure 6. Layout of an operational CELSS module from a Boeing study. Operations are fully automated with robots moving plant trays from the seeding station to the growth chambers and to the harvest equipment. A super critical water oxidizer (SCWO) processes small batches of waste biomass at high speed.

of aromatic trace contaminants from the growing of some flavoring herbs.

A major consideration in the design of a CELSS module is waste processing, particularly *of the large amount of inedible plant biomass. A non-microbiological process may be most* efficient. A promising unit for the waste processing subsystem is a Super Critical Water Oxidation (SCWO) reactor. Water is heated up to 700oC, pressurized with air or oxygen to 3000 psi and injected into small batches of ground waste slurry, which is then oxidized within seconds into carbon dioxide, nitrogen, water, and mineral salts. Plant nutrients may then be reclaimed and recycled.

When subsystem units for food production, waste regeneration, computer control and automation are finally linked to outfit an operational CELSS module, it may look somewhat like the artist's conception in Figure 6. This accomplishment may be only a decade away with appropriate, continuous research support, and the pooling of information among biologists and bioengineers working in related projects.

The U.S. announcement to establish a Space Station provides an opportunity for cooperation with other national space agencies, laboratories and industries. Such opportunities are especially promising for CELSS research because of the expertise that exists around the world in related ventures. The most efficient development of CELSS would probably result from careful pooling of international resources. If stable and productive materially-closed ecosystems can be made to function on Earth, they could probably be made to work in space. Increased international cooperation will enhance the progressive, logical development of bioregenerative life support systems for use in future space missions.

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