Chapter 11

Use of Plants to Control the Atmosphere in Spacecraft

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Introduction

In order to construct habitable modules for spaceflight, one must build a vessel that is well sealed against the space environment. The National Aeronautics and Space Administration (NASA) has constructed and launched into space numerous sealed spacecrafts that have successfully supported humans in the harsh environment of space. These spacecraft have been atmospherically sealed to extremely low leak rates.The space shuttle is the current vehicle that is actively taking people in space for the United States, and the Space Station will be the next major human inhabited vessel to be launched into space. Previous vehicles included various capsules and the Skylab Space Station.

With these atmospherically sealed vessels, NASA has been, and continues to be, interested in gases that are found in the spacecraft, and in both the influence that the humans have on the atmosphere and that the atmosphere has on the humans. The primary gases that have been controlled in these spacecraft are, CO_2 and O_2. Filters that regulate organic gases are often included, as are monitoring capabilities to identify the gaseous and particulate constituents of the cabin atmosphere.

NASA recently initiated a program that has as its goal the development of a bioregenerative life support system that will sustain humans during long duration spaceflight. This program, the Controlled Ecological Life Support System (CELSS) program, has as one of its primary objectives the maintenance of the atmosphere of a chamber under atmospherically recycling conditions acceptable for humans by using plants.The CELSS Breadboard Project is NASA's first attempt to construct and operate such a large atmospherically sealed chamber facility on Earth that will grow plants in a manner that simulates a functioning biomass production module in a bioregenerative life support system.

The purposes of this paper are to summarize briefly some of the results from analyses made of gas samples collected in the shuttle, to review research that has provided baseline data on atmospheric gases in sealed recycling chambers, to present results that document the influence that plants may have on these gases, and to describe briefly the capabilities of the newly constructed large sealed plant growth chamber of the CELSS Breadboard Project.The implications that this research may have for problems of indoor air pollution within closed facilities on earth will be discussed.

Characteristics of the Shuttle Atmosphere

The primary gases, O_2, N_2, and CO_2, are controlled in the shuttle and their fluctuations are partially minimized. O_2 and N_2 are maintained through the addition of make-up gases. Both are kept within ambient levels generally with a fluctuation of less than 1%. CO_2 is removed from the airstream by lithium hydroxide canisters which are periodically changed.This gas generally fluctuates from 300 ppm to 5,000 ppm, with the highest excursion recorded to date being approximately 10,000 ppm.The atmosphere of the shuttle cabin is monitored continuously for CO_2 and O_2 and is sampled often for trace contaminants. Samples have been taken in bottles or on resin filled tubes and identified later in ground laboratories by Gas Chromatography and Mass Spectrometry (GC/MS). Special samples have also been taken to identify particulate contaminants. These samples have revealed a large number of contaminants in the atmosphere of this sealed vessel.

Methane is a common gas found in the shuttle. Dimethyl benezene (toluene) has been identified on all shuttle flights. In one flight, it exceeded the shuttle maximum allowable limit–probably due to an uncapped marking pen. Such a result indicates the potential for contamination in atmospheres that are confined with little or no ventilation. A large number of silicone compounds have been observed in fairly high concentrations in the Shuttle. Two that may be toxic are propylfluorosilane and propyldifluorosilane. On several occasions, relatively large amounts of bromotrifluoromethane have been observed–possibly from leaky fire extinguishers. Twenty-three other halocarbons found, probably originated from outgassing of solvents. Dichloroethene has been detected and may have originated from trichloroethene, a common solvent used in the shuttle. In all, over 150 different compounds have been identified as trace contaminates in the Shuttle (Garavelli, 1986).

Airborne bacteria ranging between 100 and 350 culture forming units per cubic meter have been observed in the shuttle, and include both aerobic and anaerobic organisms. Spores from one fungus, *Candida albicans*, was found. However, fungal growth in the shuttle does not appear to be a problem.

These data indicate that a large array of contaminants can accumulate within the atmosphere of a space vessel that contains humans, even in one that is maintained under stringent cleanliness conditions until it is sealed. Many of the substances are from solvents and cleaning agents, aging synthetic polymers that are used in most facilities, and the interaction between gases outgassed from both of these to produce a secondary product. The secondary products may be toxic, even though the reactants are not. Tibbetts (1978) discussed the occurance of atmospheric contaminants in seaed plant growth chamber which influenced the growth of plants contained within these vessels.

Plant and Atmospheric Interactions

Plants in a confined space influence the composition of atmospheric gases in more ways than just by absorbing carbon dioxide and releasing oxygen. Both United States and Soviet scientists have found that plants release numerous compounds to the air. Several researchers have documented the emission of organic gases including ethylene, alcohols, terpenoids, terpenes and aromatics from various plant species. Soviet researchers (Dadykin, Stepanov & Ryzhkova, 1967) have detected many contaminant gases being emitted into spacecraft-type environments from plants. These compounds included methane, ethane, propane, butane, propionic aldehyde, and ethanol. In a comparison of five crop plants as to gaseous emissions, the maximum number of compounds detected were from tomato, the minimum number from potato, and in-between amounts were from radish and carrot. The amount of contaminants that may build up in a confined atmosphere from plant emissions and the rate of build-up are dependent on the types of plants present and the volume and degree of closure of the air. A recent review article (Metcalf, 1987) listed over 150 organic compounds that were emitted by plants and also indicated that differences existed for emissions from different plant organs and growth stages.

In contrast to plants generating contaminants, they may also clean the air of selected compounds. Wolverton, McDonald & Walkins, 1984; Wolverton, Johnson & Bounds, 1989) found that house plants remove formaldehyde, benzene, and trichoroethylene from an air stream, and they report that some plants are more efficient at removal than others.They found that the common house spider plant (*Chlorophytum*), is one of the most efficient by removing approximately 4 μg of formaldehyde per cm^2 of leaf area per 24 hours. Golden pothos (*Scindapsus*) was almost as efficien–removing 3.2 μg/cm^2/24 hrs. Other plants ranged from 2.3 to 0.7 μg/cm^2/24 hrs. Plants may be used in a sealed atmospheric environment as a waste-processing agent to rid the air of contaminants.

Controlled Ecological Life Support System Program

The Controlled Ecological Life Support System (CELSS) Program is a NASA effort begun in 1978 to develop a bioregenerative life support system by combining biological and physico-chemical processes capable of recycling the food, air, and water needed to support long-term missions with humans in space. Using a bioregenerative system involving the products of plant and

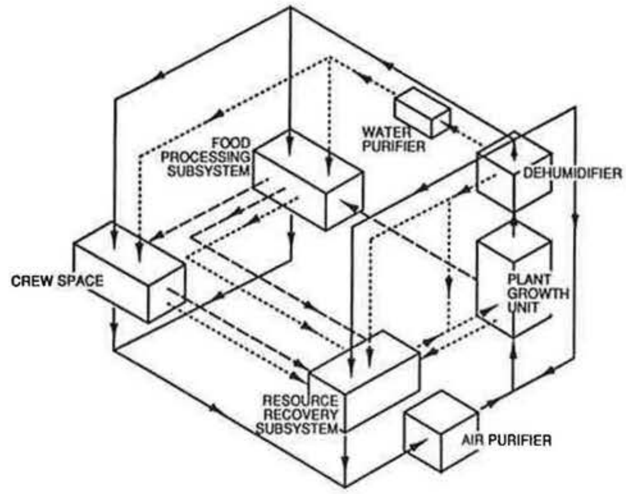

Figure 1. Schematic CELSS system diagram.

humans, CELSS will include three major units: a biomass production system to grow plants for food and oxygen under controlled conditions; a biomass processing system to derive maximum edible content from all plant parts; and a resource recovery system to recover and recycle all solid, liquid, and gaseous components necessary to support life. Such a system will simulate the earth, the only example of a stable bioregenerative life support system, by combining the processes of photosynthesis, respiration, and remineralization into system components. Since mission requirements impose stringent constraints on system design, physico-chemical system components and computer control will be substituted for bioregenerative processes as required. The requirements for long duration spaceflight and extraterrestrial habitation may demand that technology development for a CELSS be completed within the next 15 years to support NASA's plans. The CELSS Program staff recognized in 1986 the need to proceed with development and implementation of an operational facility. In response to this requirement, a phased program plan, the CELSS "Breadboard" Facility Project Plan, was written at Kennedy Space Center and accepted at NASA headquarters (Koller, 1986). Such a phased program with scaled component testing and with supporting research from Ames Research Center can provide the necessary technology to develop a CELSS in such a timeframe. The first component of the Breadboard Project is the construction

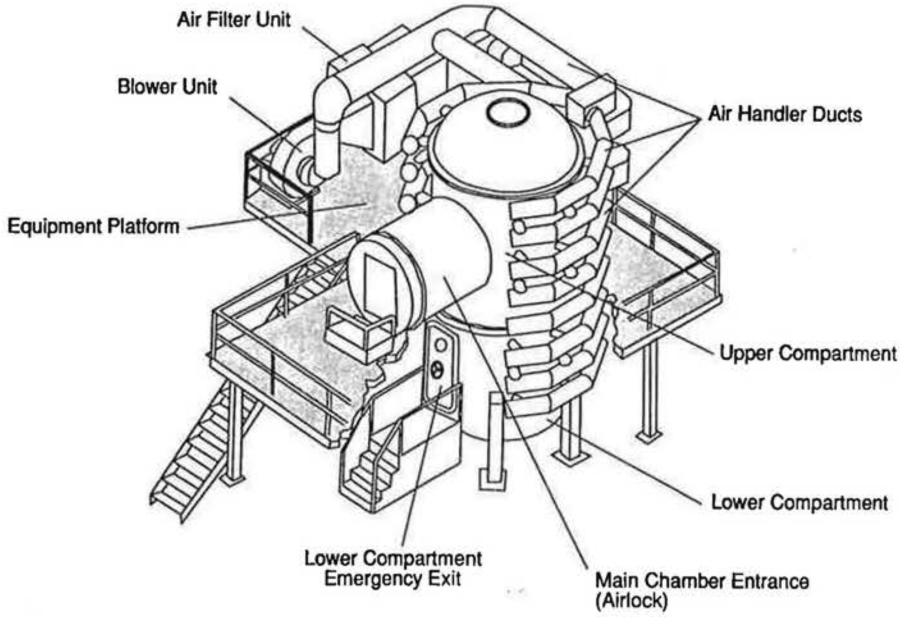

Figure 2. Schematic of the biomass production chamber.

of a special Biomass Production Chamber (BPC) where scientific studies can be conducted on topics unique to a sealed vessel. Biomass production was chosen as the first component to be evaluated because of its importance in recycling. With the BPC, the fluxes of energy and mass into and out of a closed system can be quantified. In addition to the physical parameters, biological parameters can be raised to levels not required in normal agriculture production practice.These parameters include: plant/crop physiology, plant/crop pathology, microbiology, nutrient chemistry, and gaseous and liquid contaminants.

CELSS Breadboard Project

To accomplish the goals and objectives of the CELSS Breadboard Project, laboratory scale and production level tests must be conducted. Disciplines such as biology, ecology, chemistry, pathology, genetics, engineering, nutrition, pharmacology, physics, etc. must be integrated into a team to investigate the different components. The components identified include: (1) Biomass production, (2) Food processing, (3) Product storage, (4) Atmospheric regeneration, (5) Resource recovery, (6) Crew habitability, (7) Analytical monitoring, and (8) Engineering and control.

To understand the complex nature of integrating these components, it is necessary to visualize compressing many of the basic ecological processes that routinely occur on this planet into an average set of rooms. Figure 1 (cf. Appendix A) shows the major essential life support components arranged in one possible pattern. It is a requirement that all essential minerals, gases, and liquids remain on the space vehicle along with the crew. Another requirement is that the recycle time for liquids, solids, and gases be understood; the limited volume and short recycl-ing time demands that the system be completely managed.

The CELSS Breadboard Project will address each component in detail and in relation to each other. Much of this effort will take place simultaneously because of the nature of the interactions and because of the sophistication needed in the monitoring and control components.The current focus of this project is the Biomass Production Chamber (Fig. 2).

Biomass Production Chamber

The Biomass Production Chamber (BPC) is approximately 3.5 m diameter by 7.5 m high. It is mounted in a vertical position with access on the second level through an air lock. The chamber consists of two floors with eight racks fitted onto each floor and each rack supporting two lamp banks and two adjustable platforms for a total chamber plant growing area of 20 m^2. The lamp banks and platforms are shaped like an isosceles trapezoid. The Biomass Production Chamber was designed so that it could satisfy a set of operational requirements that meet a wide range of plant growing objectives (see Table 1). The five physical subsystems identified within the BPC are: heating, ventilation, and air conditioning (HVAC); irradiance (light); nutrient delivery; control and monitoring; and atmospheric.

Heating, Ventilation, and Air Conditioning

Heating and cooling are through coils with modulating valves controlling circulating hot and cold water, respectively. Two air handling units, one on each level, move the volume of the system (the chamber and air circulation ducts), one complete air change every 17 sec. Condensate is collected in stainless-steel tanks and will eventually be recycled to the nutrient delivery system if it is determined that no contaminants are present. All eight shelf units on each shelf are connected by inlet and outlet ducts. Air diffusers provide uniform air distribution across each shelf unit, the planted surface. Air exists in the chamber through the lamp banks, passes through the air handlers, across the coils, through absolute filters, and back to the chamber.

Table 1. Subsystem control and monitoring parameter requirements for the biomass production chamber.

Subsystem	Range for Type
Heating, Ventilating, and Air conditioning	
Controlled:	
Air temperature	18° to 30°C
Relative humidity	60 to 70% RH
Ventilation rate	0.5 to 1 m s^{-1}
Monitored:	
Condensate water	100 to 200 1 day^{-1}
Atmospheric leak rate*	1.0% vol/24 hr
Air filtration	99.97% at 0.3 µm
Gas and Pressure	
Controlled:	
Oxygen	20.9%
Carbon dioxide	300 to 2000 ppm
Chamber operating pressure	0.10 to 0.25 kPa
Monitored:	
Ethylene	5 ppb
Radiation (Light)	
Controlled:	
Radiation (light)	300 to 1000 µmol m^{-2} s^{-1}
Photoperiod	0 to 24 hours
Nutrient Delivery	
Controlled:	
Nutrient temperature	15° to 30° C
pH	5.5 - 6.0 pH controlled
Conductivity	1000 to 2500 µS cm^{-1}
Flow rate	11 min^{-1} tray^{-1}

*Spacelab was designed for a leak rate of 1.3% of volume in 24 hours in the space environment. Banks and platforms are shaped like an isosceles trapezoid.

Irradiance (Light)

Photosynthetically Active Radiation (PAR) between 400 and 700 nm wavelength is provided by high pressure sodium (HPS) lamps. Three 400 W

HPS lamps are located in each of the 32 lamp banks to obtain 1000 μmol m^{-2} s^{-1} of photosynethetic photon flux (PPF) 0.5 m below the lamps. Each lamp bank has three parabolic reflectors, one per lamp, to provide uniform irradiance. One dimming ballast for each lamp is located outside the BPC.Two dimming controls are used on each of the 4 shelves, 12 ballasts per control, and can reduce the PPF to about 300 μmol m^{-2} s^{-1} at 0.5 m. A pyrex glass plate covering the lamp bank serves to confine the return air flow and direct air across the lamps with minimum spectral interference.

Nutrient Delivery

A thin film continuous flow nutrient delivery system has been installed. Shape of the plant growth trays was influenced by the circular layout of the BPC. All parts in contact with the solution are plastic. Space for sixty-four 0.245 m^2 plant growth trays are provided in the BPC; two per shelf unit, 16 per shelf. The plant growth trays were made to accommodate more than one crop with minor modifications. For example, a wheat tray set consists of 50 mm deep tray bottom, a tray top to cover the tray and support the seed for germination and growth, a germination hood, and cage for support of the mature plant. Approximately 400 wheat plants are grown in each tray, resulting in 6400 plants per shelf, and about 25 plants per liter of solution. Other configurations and operating procedures will be required for other crops.

Control and Monitoring

This subsystem is made up of monitoring, control, and data acquisition sections. It is configured to control with one set of sensors and to use a separate and more exhaustive set for experimental monitoring.This chosen hardware configuration permits expansion and flexibility as required when atmospheric and liquid regeneration processes are added and is designed to permit communication with other computers.

Atmospheric

The atmospheric control system provides continuous control of the carbon dioxide and oxygen concentrations in the BPC, and the pressure relative to the atmosphere. Separate monitoring and control systems, with redundant control systems for the upper and lower compartments of the BPC, are provided. Initially, control is being accomplished with bottled CO_2 and bottled breathing air which contains oxygen (20.8%) and nitrogen (79.2%). A continuous stream of BPC air from each level is analyzed by oxygen and carbon dioxide analyzers and returned to the chamber.Excesses are exhausted and deficiencies are made up from the bottled gas.