Apr 23rd, 1:00 PM

Paper Session III-B - Closed Ecological Life Support System (CELSS) Modeling

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Scholarly Commons Citation
Drysdale, Alan; Thomas, Mark; Fresa, Mark; and Wheeler, Ray, "Paper Session III-B - Closed Ecological Life Support System (CELSS) Modeling" (1992). *The Space Congress® Proceedings*. 10.
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Controlled Ecological Life Support System (CELSS) Modeling

1/20/92

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ABSTRACT

A CELSS is a critical technology for the Space Exploration Initiative. NASA KSC has been performing CELSS research for several years, developing data related to CELSS design and operation.

MDSSC-KSC has recently developed OCAM, a CELSS modeling tool, and has been using this tool to evaluate CELSS concepts. The tool models carbon, hydrogen, and oxygen recycling. Multiple crops and plant types can be simulated. Resource recovery options from inedible biomass include leaching, enzyme treatment, aerobic digestion and mushroom and fish growth.

Data for the models has been taken primarily from the KSC CELSS Breadboard project. Results include time-history graphs of biomass, carbon dioxide, and oxygen; energy consumption; and manpower requirements.

Expected results that were demonstrated include the benefit of using many small crops overlapping in time, instead of a single large crop. Unanticipated results include startup transients which reduce the benefit of multiple small crops.

The relative contributions of mass, energy, and manpower to system cost have been analyzed in order to determine appropriate research directions.

CELSS CONCEPT AND BACKGROUND

A Controlled Ecological Life Support System (CELSS) is an environmental control and life support system which uses living organisms to sustain human life in space; producing oxygen, water, and food, and removing wastes. A block diagram of a CELSS is shown as Figure 1.

CELSS is an enabling technology for the Space Exploration Initiative (SEI), as shown in Figure 2. There are several reasons for its importance. SEI involves long flight times and high logistics costs. The high cost of resupply requires us to evaluate options for reducing resupply mass. The long flight times mean that we may not be able to supply a nutritionally adequate and satisfying diet through stored food.

Delivery of a pound of mass to the Moon's surface is estimated as costing about $30K. (For comparison, delivery costs to LEO are an order of magnitude lower.) Thus CELSS becomes attractive when the total mass for supply of food, water, and oxygen, and removal of wastes such as carbon dioxide, becomes less for a CELSS than for an alternative physico-chemical system option (which cannot for the foreseeable future provide food).

However, this simplistic comparison which is usually used to justify a CELSS is only part of the picture. The total mission cost, including hardware design, development and test, and energy cost as well as mass, must be considered. In addition, manpower will be required and must be factored into the analysis.

Early CELSS work focused on using microscopic algae, which have high productivity, and can be designed into a compact continuous process system. However, algae is not a good staple diet for humans, being too high in nucleic acids

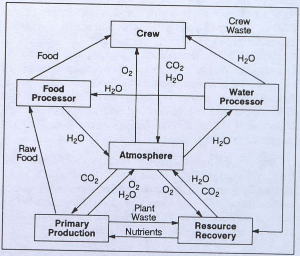

Figure 1 Components of CELSS

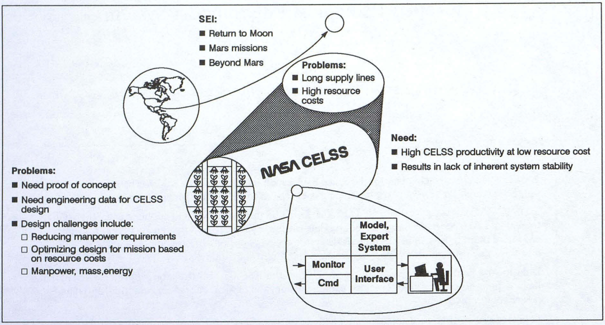

Figure 2 CELSS is an Enabling Technology for Long Duration Manned Space Missions

and protein. In addition, it is difficult to maintain sterility, to separate the algae from the nutrient solution, and to turn it into palatable food.

In view of the limitations of algae, current work focuses on more typical crop plants and animals. In addition to the increased availability of information on agriculture and use with familiar crops, a familiar diet reduces crew stress: an unfamiliar food is an unnecessary stress on flight crew in an already stressful environment.

Concerns about the adequacy of long term food storage are based on the fact that there are still things we do not know about nutrition. For many years, nutrition was a largely ignored facet of human biology, and nutrition research was almost non-existent. In recent years, the availability of sophisticated biochemical analysis techniques has changed that. It is no longer considered easy to specify an adequate diet, particularly for long missions and when using exotic foods and unusual mixtures. The novel zero gravity environment interacts with diet in ways we do not fully understand, and some of the changes undergone by the human body during long duration spaceflight may be aggravated or alleviated by diet.

Certainly, our food technology is inadequate for providing long term storage of some food items, such as salads, which we take for granted in America. Even on short missions such as the current NSTS missions, fresh food is gone well before the end of the mission. This is bearable for short missions, but much less acceptable for long missions

In addition to the physiological consequences of diet, food is a major component in the psychological welfare of the crew. Even on the relatively short Skylab missions, psychological stress was evident and of concern. Inadequate or different diets would add stress in an already difficult situation.

A practical CELSS does not have to completely close the loop for all human requirements. The benefits of recycling are well documented, and in fact the shuttle does not have a completely open loop life support system: air is regenerated by removal of carbon dioxide, water vapor and trace gasses. Additional recycling, such as regeneration of oxygen from carbon dioxide and of potable water from waste water, provide near term options. As we look at providing other commodities required for life, the payback time for regeneration increases. The biggest variable driving payback is the mission duration. System size is also significant, due to economies of scale. For the purpose of this paper, a system is assumed to be a CELSS when significant recycling is performed by biological components.

Most likely, CELSS technology will evolve gradually. The first step may be the production of small quantities of salads, and is being investigated by the NASA Ames Research Center in California. Their Salad Machine project has a goal of producing 4 servings of salads 3 times per week. The next step will probably be the purification of water, which results from transpiration by growing plants. Purification by plants is especially appropriate for water containing biological contaminants. Additional research in needed regarding the ability of plants to grow and reliably produce food using different grades of waste water.

Plants producing food and water inevitably remove carbon dioxide and produce oxygen. As the percentage of food produced by a CELSS increases, so does the percentage of carbon dioxide removal and oxygen production. Tissue respiration and photosynthesis are essentially equal and opposite processes.

CELSS systems may never become 100% closed. We may always import into them small quantities of vitamins and minerals or some reagent grade chemicals, simply because it is more cost effective to do so. Furthermore, complete closure also implies producing complex manufactured items such as new light bulbs, fans, pumps, and computer parts. Probably no community on the Earth is now totally self sufficient over long periods of time, although some are still close. We envisage any future large base off the Earth will remain part of the global economy unless forced to be self sufficient by catastrophe.

NASA KSC CELSS BREADBOARD PROJECT

NASA's Kennedy Space Center has been performing CELSS research for several years, developing data related to CELSS design. The initial concept developed in the late 70s was to use the large Apollo vacuum chambers in the O&C building to contain all CELSS components. This concept is still extremely attractive technically but may be hard to fund in the current fiscal environment. The current CELSS Breadboard Project is in Hanger L, CCAFS. This project uses a smaller Project Mercury vacuum chamber, shown in Figure 3, for plant growth. Other components of the system are housed in laboratories in Hanger L.

For the last five years, the plant chamber, the Biomass Production Chamber (BPC), has been the only large closed chamber in the world to provide a well controlled environment for plant growth, although JSC is now close to having a comparable facility. The BPC provides about 200 square feet of plant growth area with controlled light levels, temperature, humidity, air flow, air composition, nutrient solution temperature, pH, electrical conductivity, and chemical composition. Environmental monitoring is mostly automated, logging data every few minutes day and night. Additional measurements such as microbial load are made manually.

The upper and lower halves of the chamber have separate air loops with a small amount of leakage between the levels. Air is recirculated through heat exchangers which control air temperature and humidity. Carbon dioxide is added to the air to maintain a constant level, usually 1000ppm (0.1%). This is three times the proportion of carbon dioxide in the outside air and increases the plant growth rates. Efforts have been made to reduce leakage of the chamber, particularly around the doors, external blower shafts, and ducts. The rate of air exchange with the outside air is now 5 to 10% per day, driven by changes in pressure.

Each half of the chamber contains two levels of trays for plants as shown in Figure 4. Each level has independent lights and nutrient supply. Nutrient solution is stored in tanks and circulated to the plant growth trays, where it trickles across the roots. This type of hydroponics is called nutrient film technique. After passing over the roots, the nutrient drains back to the tanks and is recirculated.

Crops have been produced almost continuously in the BPC since the chamber was commissioned in 1987, including wheat, potatoes, lettuce, and soybean. Additional plant work has been done in smaller plant growth chambers in Hanger L, including work on sweet potatoes, raddishes, and peanuts.

In addition to the plant growth effort, major work has also been done on resource recovery – a redefinition of waste management. Much of the work has focused on converting waste biomass, which is as much as half the crop, into human food. For example, wheat straw can be ground up, soluble material extracted with water, digested, and used as food for mushrooms, fish, or other sources of human food. The fish used are

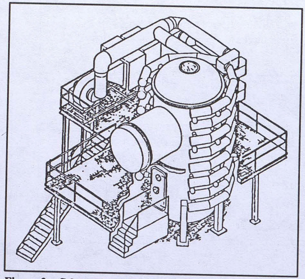

Figure 3 Schematic of the Biomass Production Chamber

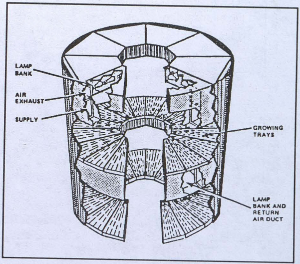

Figure 4 Schematic of One-half of the Biomass Production Chamber

Tilapia, an African fish which is adaptable to crowded living conditions and one that is becoming common in American grocery stores. One mushroom being investigated is the oyster mushroom, Pleurotus, which provides better nutritional value than the common white mushroom.

Resource recovery is important for several reasons. Converting inedible biomass into edible food reduces the plant growth area required, and thus the system mass and cost. The increased variety in the diet is beneficial both nutritionally and psychologically. Also, even if this mass cannot be used by the crew, it must be recovered or resupplied.

At KSC, little work has been done as yet with food processing, but this is expected to increase over the next few years. Sample menus have been cooked using the food produced, demonstrating that a wide range of palatable meals can be produced with the few types of food produced to date.

GOALS OF CELSS MODELING

Modeling is generally useful in understanding and controling systems. A CELSS is a complex system, too complex to understand without modeling. We are using computer modeling to understand the large scale dynamics of the system, in particular to predict system performance for specific mission scenarios. A longer term goal is to develop monitor and control capability. This is likely to require detailed modeling of component interactions.

OCAM – OBJECT-ORIENTED CELSS ANALYSIS AND MODELING

The tool we have developed for CELSS modeling is OCAM: Object-oriented CELSS Analysis and Modeling. OCAM is an extension of the MDSSC-developed GOST (Ground Operations Simulation Technique) object-oriented modeling and discrete-event simulation tool. It runs on a Symbolics workstation or an equivalent machine such as a MAC II with an Ivory board. GOST has been rehosted to run in C++ under UNIX on a 386, and we plan to port OCAM to a UNIX workstation.

OCAM has been under development for over a year and is now quite sophisticated. It allows the user to specify the CELSS configuration and attributes, define the mission, and set initial conditions using a graphics interface. It typically takes about half an hour to simulate a year's operation.

OCAM models carbon, hydrogen, and oxygen recycling, calculating on a daily basis the form taken, the quantities in each form, and other system resource impacts such as equipment mass, power requirements, and manpower requirements.

Results from the model include time-history graphs of biomass, carbon dioxide, and oxygen; energy consumption; and manpower requirements. Two examples are shown as Figures 5 and 6. Mass in kilograms is plotted against days.

Multiple crops and plant types can be simulated. For example, four potato crops can be planted at 30 day intervals, harvested at the end of each 120 day growth cycle. Growth and transpiration rates, consumption of nutrient, light require-

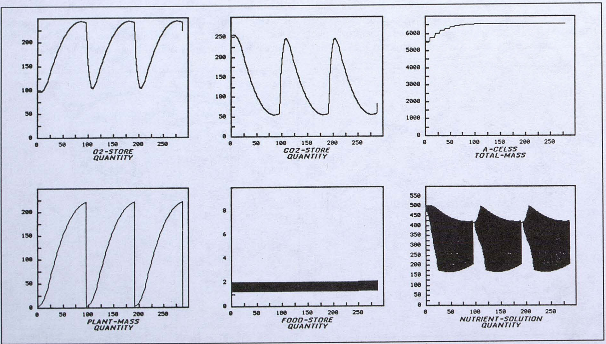

Figure 5 Wheat: 1 Crop – 1 Crew

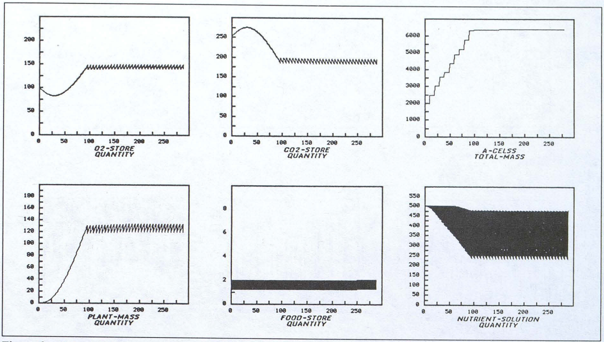

Figure 6 **Wheat: 16 Crops - 1 Crew**

ments, crew number and mass, and crew metabolic rates are examples of data used or produced.

Instead of four potato crops, a mixture of potato, wheat, soy, and lettuce could be used. Other crops could be simulated, but only these four crop plants have been entered into the system to date.

There are many options for resource recovery/waste treatment. Resource recovery options modeled include leaching, enzyme treatment, aerobic and anaerobic digestion and mushroom and fish growth. These options are currently hard coded, but OCAM is being modified to make them operator selectable.

Data for the models are taken primarily from the KSC CELSS Breadboard Project. This is the main worldwide source of data on crop level closed chamber plant physiology, while extensive data are available for open but controlled environments (e.g. studies with wheat at Utah State University).

STATUS AND RESULTS

The model was validated by a number of runs which were made to demonstrate anticipated results. Several authors have identified an expected reduction in system mass by using many small crops overlapping in time instead of a single large crop. As shown in Figure 7, which is derived from the data shown in Figures 5 and 6, the ranges of variation of masses of various commodities are reduced with multiple crops.

However, another effect was observed which, while unpredicted, is obvious in retrospect. If the system is balanced for average production, a system with multiple small crops will have a slower startup, requiring larger initial stores of consumables and producing a startup transient which reduces the benefit of multiple small crops. As a result of both of these processes, system mass with 16 overlapping crops was 1% lower than with a single crop. If a strategy is adopted to suppress the startup transient, such as growing a short term initial crop to produce water and remove carbon dioxide, this mass reduction was increased to about 6%.

Most of the simulations were done with a single species of plant, which produces a simpler picture. However, a more realistic situation would include several crops. Figure 8 shows a scenario with only four crop types, yet the outputs are no

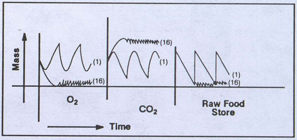

Figure 7 **Effects of Multiple Overlapping Crops (KSC Wheat: 1 Crop vs 16 Crops)**

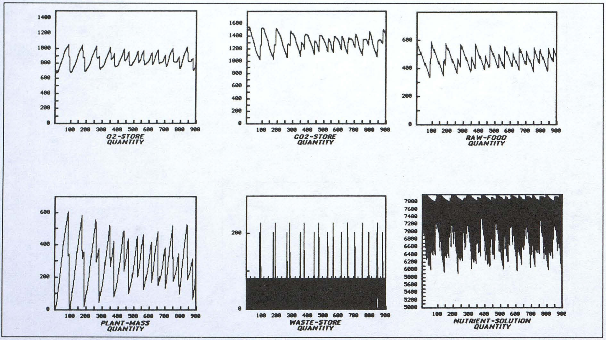

Figure 8 Mixed Crops Will Drive Irregular System Fluctuations

longer regular and will repeat at intervals equal to the least common multiple of the crop cycle times (about 85000 years).

A further interesting result was that the largest mass component is the system structure. Figure 9 and Table 1 show the distribution of system mass based on Space Station and Spacelab data. The water separator mass is based on Spacelab hardware and is excessively massive for this application.

The mission we have modeled most intensively was a 10-year, 4-Man Lunar Base. The major resource costs for this scenario are manpower, mass, and energy. To date most CELSS work has assumed that energy is the primary driver, followed by mass; manpower has not been addressed. In the absence of published cost factors for these three primary resource costs, we collected data from a variety of sources. The results are shown in Table 2. While we cannot claim these

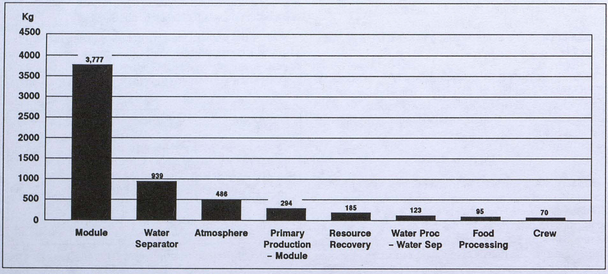

Figure 9 CELSS Component Masses (1 Wheat Crop, 1 Crew Member)

Table 1 Related Results: Distribution of Mass

Component	Mass Per Crewman (Kg)	Percent Mass
Module	3,777	63
Water Separator	939	16
Atmosphere	486	8
Primary production minus module	294	5
Resource recovery	185	3
Water processing minus water sep	123	2
Food processing	95	1.6
Crew	70	1.2
Total	5,969	99.8

numbers to be definitive, they do quantify resource costs in a way that allows them to be compared.

The results of our analysis showed that manpower is the most important cost factor, followed by mass, as shown in Table 3. Despite the uncertainty of the numbers, the ranking of these cost factors is not likely to be changed except by technological breakthroughs.

Table 2 Cost Factors Used in Mission Analysis

Mass	Energy	Manpower
Dollars per pound delivered to the Moon's surface	KWH per KG mass at the Moon's surface (nuclear power)	MH per KG mass at the Moon's surface (based on support costs)
$30K/Kg	3888 KWH per Kg	0.24 MH per Kg

Based on the masses, mass distributions, plant area and energy requirements produced by OCAM, we are developing a Lunar Base CELSS conceptual design. The initial configuration shown in Figure 10 is based on use of Space Station Freedom modules. It is sized to support four people and attaches to the Lunar Base at two points to provide two egress routes in emergencies.

FUTURE WORK

An important implication of this work is to throw into question the assumption by CELSS researchers that energy is the most important resource cost. In consequence, we expect to continue to refine our estimates on mission costs. Manpower cost is heavily dependent on configuration and automation. We are evaluating the conceptual design to identify tasks which can be effectively automated.

Table 3 Relative Importance of Resource Cost Factors

Manpower	Mass	Energy
9.4	2.6	1

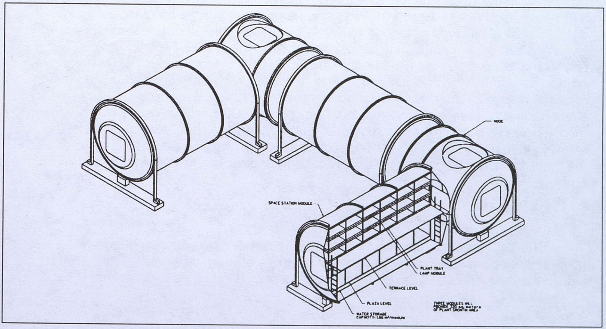

Figure 10 Lunar Base CELSS Design