Paper Session II-B - The Whys, Wherefores and Whims of a CELSS

Ray Wheeler

Whys , Wherefores, and Whims of A CELSS

Raymond M. Wheeler
NASA Biomedical Operations and Research
Kennedy Space Center, FL 32899 USA

Introduction

When one thinks of what is required to provide life support in space, several things come to mind: First, is some sort of sheltered habitat to protect the humans from the extreme conditions of space, including high-energy radiation. Second, is a supply of life support consumables, including food, clean water, and oxygen (O_2) for breathing. The third is some means of dealing with waste products that build up in the habitat, including solid and liquid wastes, and carbon dioxide (CO_2) gas.

A aimple way to approach this is through stowage, where all the food, water, O_2, and materials for treating and containing wastes are brought along from Earth. Stowage is generally safe and reliable, but becomes more and more costly the farther one goes and the longer one stays. For example, traveling to and from Mars could take two years, depending on the propulsion systems available, and that does not include any time spent at the planet. Studies on the life support needs for the international space station indicate that each person requires about 31 kg of life support consumables each day (Table 1); thus a 2-year trip would require 22 metric tons per person, and this does not account for materials needed to deal with wastes! Clearly, relying only on stowage in this situation would be far too costly, and some sort of regenerative systems would be needed to recycle materials.

The most obvious step to reduce stowage is regeneration of clean water from waste water, since this represents over 95% of the mass requirements (Mitchell et al., 1994). But even if water is totally recycled, each person would still require 300 kg of O_2 per year, 225 kg of food (dried), and perhaps several hundred kg of materials for CO_2 removal, or nearly 1 metric ton per person. Physical/chemical processes for scrubbing CO_2 and retrieving O_2, such as the Sabatier reaction combined with water electrolysis, have been proposed for atmospheric regeneration

(Jones and Ingelfinger, 1973; Mitchell et al., 1994). But these systems add mass to the launch payload, as well as increased energy requirements, and no purely physical/chemical processes are available to provide food.

Table 1. Human life support requirements*

Inputs

	Daily Rqmt.	(% total mass)
Oxygen	0.83 kg	2.7%
Food**	0.62 kg	2.0%
Drink Food Water Prep Water	3.56 kg	11.4%
Water	26.0 kg	83.9%
(Hygiene/Flush	8.10)	
(Laundry/Dish	17.91)	
Total	**31.0 kg**	

Outputs

	Daily	(% total mass)
Carbon Dioxide	1.00 kg	3.2%
Metabolic Solids	0.11 kg	0.35%
Water	29.95 kg	96.5%
(Metabolic/Urine	12.3)	
(Hygiene/Flush	24.7)	
(Laundry/Dish	55.7)	
(Latent	3.6)	
Total	**31.0 kg**	

** Source: NASA SPP 30262 Space Station ECLSS Architectural Control Document*
*** Food assumed to be dry except for chemically-bound water.*

Instead of physical / chemical approaches, various biological processes such as photosynthesis might also be considered for life support. This concept is not new (Myers, 1954), and extensive testing was conducted in the early 1960s to study algae for atmospheric regeneration in closed life support systems (Miller and Ward, 1966). Through photosynthesis, the algae would fix the CO_2 into their tissue, while releasing O_2 as a reaction waste product. Beginning in the 1970s, bioregenerative testing using was expanded to include higher plants, since plants are generally more palatable and adaptable to food processing. Moreover, waste water could be used to grow the plants and the water that evaporates from the leaf canopy then condensed to provide a source of pure water. Thus plants could provide four essential functions for a life support habitat: O_2 production, CO_2 removal, food production, and water purification.

NASA's CELSS Program

The concept of incorporating biological components into a life support has come to be known as a Controlled Ecological Life Support System, or CELSS. Since the early 1980s, NASA has been sponsoring university-based research to explore CELSS concepts, with the major emphasis directed at defining growing requirements and yield potential of different plant species under controlled environments. This included studies with wheat at Utah State University (Bugbee and Salisbury, 1988), soybean at North Carolina State University (Raper et al., 1991), potatoes at the University of Wisconsin (Wheeler and Tibbitts, 1988), lettuce at Purdue University (Knight and Mitchell, 1985), and sweetpotato at Tuskegee University (Hill et al., 1989). The fundamental information from these studies was then used to conduct baseline tests in a large, Biomass Production Chamber located at Kennedy Space Center (Prince et al., 1987) (Fig. 1). The objective of Biomass Production Chamber testing was to determine the feasibility of growing the crops on a large scale and define the resources required for operating a bioregenerative system. In addition, the tightly closed atmosphere of the chamber provided the opportunity to precisely measure rates of CO_2 removal, O_2 production, water purification by the plants, as well as build-up of any atmospheric contaminants (Wheeler, 1992). This information was then used to begin to assess the overall economics of a CELSS (Drysdale et al., 1993).

What Have We Learned About Plants as Life Support "Machines" ?

Test results to date from the CELSS Biomass Production Chamber have shown that each of the candidate crops tested, viz., wheat, soybean, lettuce, and potato, can be grown successfully on a large scale in a closed chamber and that yields are close to those predicted from university studies (Wheeler et al., 1995). Edible yields obtained from the crops have varied, depending on the environmental conditions used and the inherent ability of the crops to partition their growth into edible structures (Table 2). For example, lettuce biomass yields were generally low because low to moderate lighting is best for growing lettuce. In contrast, wheat yields were high because wheat tolerates high light intensity and long photoperiods (even continuous light).

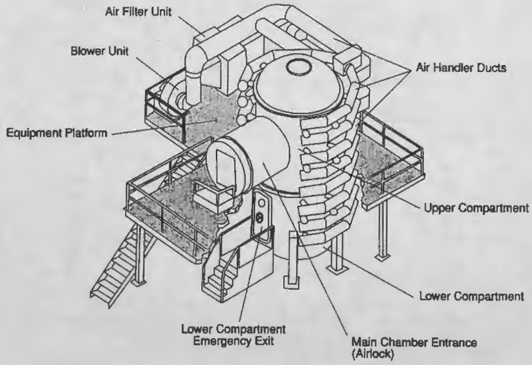

Figure 1. NASA's Controlled Ecological Life Support System (CELSS) Biomass Production Chamber located at Kennedy Space Center, FL, USA.

Potato yields also were high because potatoes tolerate high lighting (although they do best with a long dark cycle) and are capable of partitioning over 70% of their total biomass into edible tubers (Wheeler and Tibbitts, 1987). Soybeans also do well with high light and a dark period each day, but yields were lower than potato because soybeans typically partition only 30 to 40% of their biomass into seed. In all cases, the total and edible biomass yields were strongly dependent on the lighting provided to the plants, suggesting that increased yields can be obtained with higher lighting (Fig. 2). The best yields to date from the Biomass Production Chamber were obtained from potato and indicate that about 35 m^2 of continuously-cropped area would be required to sustain the dietary caloric needs of one person.

Table 2. Yield, gas exchenge, and water flux rates from different crops grown in NASA Biomass Production Chamber at Kennedy Space Center, FL.*

Crop	Total Light **	Total Biomass	Edible Biomass	Oxygen Production	Carbon Dioxide Removal	Water Production
	(mol m^{-2} d^{-1})	*(g m^{-2} d^{-1})*	*(g m^{-2} d^{-1})*	*(g m^{-2} d^{-1})*	*(g m^{-2} d^{-1})*	*(kg m^{-2} d^{-1})*
Wheat	58	32	13	34	46	4.7
Soybean	35	15	5	18	25	4.3
Lettuce	17	8	7	7	9	1.8
Potato	42	27	18	29	40	3.8

* Data gathered from a 20-m^2 stand but but expressed on a unit area, unit time basis.
** Daily photosynthetically active radiation (400 - 700 nm)

In all cases, the crops were grown using a recirculating hydroponic approach (nutrient film technique or NFT), which helped conserve water and minerals. Growth cycles varied depending on the species: wheat, 70 to 85 days; soybean, 90 to 97 days; potatoes, 90 to 105 days; and lettuce, 28 days. Optimal temperatures also varied with species: soybeans preferring warm--26°C light/20°C dark; lettuce intermediate--23°C; and wheat and potatoes cool--20°C light/16°C dark. In addition to these four species, other crops being considered for testing in the Biomass Production Chamber, include sweetpotato, rice, peanut, and rice. This range of species will provide a nutritionally balanced diet using highly productive crops, that have storage, processing, and palatability advantages (Tibbitts and Alford, 1982).

For water production, the planted area required for one human's needs would be far less than for food. Studies in the Biomass Production Chamber showed that once the plant canopies have filled in, rates of water transpiration can average 4 to 5 kg m^{-2} day^{-1} (Table 2). Rates for lettuce were somewhat less because the leaf canopy is not complete for a large portion of its growth cycle, i.e., there was less evaporating surface. To meet the water needs of one person (Table 1), a conservative estimate of 6 to 7 m^2 of continuously cropped area would be required. It is interesting to note that the water flux can be throttled up or down, depending on the humidity around the plants (Corey and Wheeler, 1992). If more water is needed, the humidity set point can be lowered to drive evaporation faster. Of course, this would require that more water from the waste processing streams be provided to the plant roots. Because most of the studies to date have used nutrient solutions from reagent-grade chemicals, the effect of adding waste-stream effluent to the plant growing system hes become an ective area of research (Mackowiak et al., 1995).

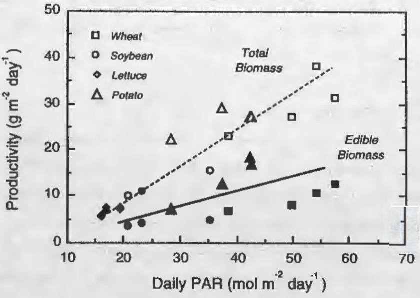

Fig. 2. Productivity of CELSS crops in NASA's Biomass Production Chamber (BPC) as a function of daily photosynthetically active radiation (PAR).

Although direct measurements of CO_2 uptake and O_2 production were taken throughout the growth and development of the different crops, an easy way to determine the average gas balances is to use the percentage carbon in the biomass, which could then be used to calculate total CO_2 removed and O_2 produced. Other than a small amount from the planted seed, all the carbon in the plants comes from photosynthetically-fixed CO_2, and the O_2 released is about 1:1 (molar basis) with the CO_2 fixed. Analyses of plant tissue from harvests have shown the following: lettuce--40% C, potatoes--41% C, wheat--42% C, and soybean--46% C. Thus conversions of biomass yields (Table 2) indicate that about 20 to 25 m^2 of continuously cropped area would be required to sustein atmospheric regeneration needs of one person, or slightly more than half of the area needed for food. As with water flux, this too could be throttled up or down as needed, but in this case by modulating tha light intensity instead of the humidity (Wheeler et al. 1993). It is important to note that if the inedible biomass (e.g., leaves, stems, and roots) are converted back to CO_2, this would consume soma of the O_2 produced during photosynthesis and the planted area requirements for atmospheric regeneration would be similar to that for food. In any case, system reservoirs of consumables would be required to buffer oscillations in fluxes, as well as a safeguard against system failures.

Are Plants Reliable for Life Support?

As meny of us have experienced in backyard gardens, plant yields are not always what we hope for! This leads one to ask whether plants are reliable life support machines. However, if one looks closely at garden failures, invariably they can be explained by environmantal stresses or suboptimal conditions on the plants. For example, if the plants dry out, or they do not receive enough nutrients (fertilizer), or it is too cold, yields will suffer. In addition, plants in natural settings are subject to insect pests and diseeses. In controlled environments, environmental factors can be maintained at optimal levels and insects and meny diseases can be excluded. After 6 years of operating the Biomass Production Chamber, we have not seen any insects nor experienced any plant diseases. We do not know conclusively whether any disease organisms were present, but simple precautions, such as keeping sources of disease inocula out of the chamber and maintaining healthy plants, appear to prevent disease outbreaks. Obviously, the plants do have environmental tolerance limits, and the hardware to provide the lighting, temperature control, water circulation, etc., must be reliable. Yet this requirement holds for any life support machine, and redundancy and alarms to initiate corrective actions are essential for any system. Perhaps one of the most important lessons we have learned to date is that most failures have been related to the system controls and hardware, and that the plants hava been very resilient and predictable.

Continuing Challenges

Is a CELSS feasible for a future Lunar or Martian colony? The results from studies at universities and our Biomass Production Chamber suggest that it is. Ultimately, the exact approach for life support must be determined after rigorous economic analyses. Mass, energy, and manpower requirements to operate and maintain a bioregenerative system will need to be determined, as will system reliability and risks. The letter may entail extensive failure mode testing and analysis, which represents a relatively unexplored area of horticulture. Another important consideration is that plants may provide some psychological benefits to humans who are forced to live in a confined habitat, and future testing should be expanded to study this.

Clearly, more testing for many of the aspects of bioregenerative systems is required, particularly to assess the long-term sustainability and stability. In addition, testing of biological waste treatment and resource recycling concepts must keep pace with the plant production tests, and the CELSS Breadboard Project at Kennedy Space Center has begun to look at integrated, closed system tests with plants and waste treatment systems.

The earliest applications of a CELSS concept will very likely rely heavily on stowage of consumables and regenerative physical/chemical schemes for life support, e.g., initial steps at colonizing Mars. As the colony becomes more autonomous over time, in my opinion, bioregenaretive approaches will become more and more prevalent, particularly for food production and waste recycling. Yet much remains unknown and further research is needed. Clearly, leaving the safety of our home Earth will be a complex and daunting task, but as we learn more about operating closed ecological life support systems, we in turn will learn much more about our Earth and its life support system.

References

Bugbee, B.G. and F.B. Salisbury. 1988. Exploring the limits of crop productivity. I. Photosynthetic efficiency of wheat in high irradiance environments. *Plant Physiology* 88:869-878.

Corey, K.A. and R.M. Wheeler. 1992. Gas exchange in NASA's biomass production chamber. *BioScience* 42:503-509.

Drysdale, A, J. Sager, R. Wheeler, R. Fortson, and P. Chetirkin. 1993. CELSS engineering parameters. *Society of Automotive Engineers Technical Paper Series 932130.*

Hill, W.A., P.A. Loretan, C.K. Bonsi, C.E. Morris, J.Y. Lu, and C.R. Ogbuehi. 1989. Utilization of sweetpotatoes in controlled ecological life support systems (CELSS). *Advances in Space Research* 9(8):22-25.

Jones, W.L. and A.L Ingelfinger. 1973. Atmosphere control. In: J.F. Parker and V.R. West (eds.) Bioastronautics Data Book. 2nd Edition, NASA, Washington, DC.

Knight, S.L. and C.A. Mitchell. 1988. Effects of CO_2 and photosynthetic photon flux on yield gas exchange and growth rate of *Lactuca sativa* L. Waldmann's Green. *Journal of Experimental Botany* 39:317-328.

Mackowiak, C.L., J.L. Garland, R.F. Strayer, B.W. Finger, and R.M. Wheeler. 1995. Comparison of aerobically-treated and untreated crop residue as a source of recycled nutrients in a recirculating hydroponic system. *Advances in Space Research* (in press).

Mitchell, K.L, R.M. Bagdigian, R.L. Carrasquillo, D.L. Carter, G.D. Franks, D.W. Holder, C.F. Hutchens, K.Y. Ogle, J.L. Perry, and C.D. Ray. 1994. Technical assessment of MIR-1 life support hardware for the International Space Station. *NASA Technical Memorandum* 108441.

Miller, R.L. and C.H. Ward. 1988. Algal bioregenerative systems. *In:* K Kemmermeyer (ed.) Atmosphere in space cabins and closed environments. Appleton-Century-Crofts, New York.

Myers, J. 1954. Basic remarks on the use of plants as biological gas exchangers in a closed system. *Journal of Aviation Medicine* 25:407-411.

Prince, R.P., W.M. Knott, J.C. Sager, and S.E. Hilding. 1987. Design and performance of the KSC biomass production chamber. *Society of Automotive Engineers Tech. Paper Series* 871437.

Raper, C.D., K. Vessey, and L.T. Henry. 1991. Increase in nitrate uptake by soybean plants during interruption of the dark period with low intensity light. *Physiologia Plantarum* 81:183-189.

Tibbitts, T.W. and D.K. Alford. 1982. Controlled ecological life support systems. Use of higher plants. *NASA Conference Publication* 2231.

Wheeler, R.M. and T.W. Tibbitts. 1987. Utilization of potatoes for life support systems in space. III. Productivity at successive harvest dates under 12-h and 24-h photoperiods. *American Potato Journal* 64:311-320.

Wheeler, R.M., T.W. Tibbitts, and A.H. Fitzpatrick. 1991. Carbon dioxide effects on potato growth under different photoperiods and irradiance. *Crop Science* 31:1209-1213.

Wheeler, R.M. 1992. Gas exchange measurements in a large, closed plant growth chamber. *HortScience* 27:777-780.

Wheeler, R.M., K.A. Corey, J.C. Sager, and W.M. Knott. 1993. Gas exchange characteristics of wheat stands grown in a closed, controlled environment. *Crop Science* 33:161-168.

Wheeler, R.M., C.L. Mackowiak, G.W. Stutte, J.C. Sager, N.C. Yorio, L.M. Ruffe, R.E. Fortson, T.W. Dreschel, W.M. Knott, and K.A. Corey. 1995. NASA's biomass production chamber: A testbed for bioregenerative life support studies. *Advances in Space Research* (in press).