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BIOREGENERATIVE LIFE SUPPORT

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Bioregenerative Life Support

Abstract

Bioregenerative life support systems utilize plant growth for food, water, and atmospheric revitalization. Simulation studies of a simplified model suggest survivability in the face of partial plant growth chamber failure.

Introduction

The degree of closure for a life support system has been recognized to be mission dependent [Doll, 1990]. Each spaceflight mission may be characterized by four sets of parameters: available resources, resupply capability, crew size and mission duration. Resources such as energy and material are location dependent: is the mission near a body with a surface or atmosphere which may be mined for necessary resources? Does the mission trajectory allow for solar energy absorption? Resupply may be relatively inexpensive for low earth orbit missions and much more expensive, say, for a mars colony.

For a given set of parameters which would characterize a particular mission, finding the optimum degree of closure involves minimizing a specific combination of total power consumption, mass and volume. The weights of the minimized variables depended on the mission parameters. At the same time, the life support system must be optimized for maximum reliability and probability of survival.

Elements of a life support system include subsystems for the continuous supply of food, air and water as well as a waste management subsystem. A bioregenerative life support system would integrate biological materials within each subsystem, and may also operate in conjunction with an environmental control and life support system (ECLSS) such as that planned for Space Station Freedom. Alternatively, ECLSS may be seen as a back-up safety resource.

Simplifying Assumptions

Considered here are those missions which would necessitate an on-board capacity for the complete regeneration of the crew's food supply. The effect on the air and water supplies will be examined also. This analysis involves a series of simplifications in an attempt to discover the fundamental or primary dynamics of a closed biological life support system.

The growth of plant matter includes both inedible and edible fractions. The crew, of course, consumes the edible matter as well as a portion of the inedible fraction. Waste material from the crew and the inedible plant matter fraction extracted at harvest are oxidized together, yielding carbon dioxide and fertilizing plant nutrients. The crew produces also carbon dioxide and metabolic water.

The first simplification here limits the discussion of food stuffs to edible plant matter. The overall empirical reaction [Volk, 1987] may be expressed as,

$$31.29\ CO_2 + 27.81\ H_2O + 1.74\ HNO_3 \longrightarrow 1.74\ C_4H_5ON + 3.82\ C_6H_{12}O_6 + 0.09\ C_{16}H_{32}O_2 + 35.39\ O_2 \qquad (1)$$

Since carbohydrate is the dominant foodstuff, limiting discussion to carbohydrate $(CH_2O)_x$ only, provides a key simplifying assumption. Were this the case, oxygen and carbon dioxide each would be produced and consumed on an equal molar basis. This is equivalent to assuming a unity respiratory quotient (RQ), whereas, the nominal crew RQ is usually taken to be about 0.89. The simplified plant growth equation thus becomes,

$$CO_2 + H_2O \longrightarrow CH_2O + O_2 \qquad (2)$$

Carbohydrates are completely oxidized by the crew. All oxidation of waste material will be assumed to happen at about the same time. The simplified oxidation equation then becomes,

$$CH_2O + O_2 \longrightarrow CO_2 + H_2O \qquad (3)$$

Not only is there molar equivalence between oxygen and carbon dioxide, but also of carbohydrate (and metabolic water). That is, each mole of CO_2 absorbed by plants is assumed to produce one mole of CH_2O and one mole of O_2, while each mole of CH_2O is metabolized with one mole of O_2 and produces exactly one mole of CO_2.

Since the life support system is closed the total mass of each element (carbon, hydrogen and oxygen) must remain constant under the assumption of no cabin leakage. Therefore,

$$mCO_2 + mCH_2O = \text{constant no. of moles} \qquad (4)$$

Model Development

In order to investigate the dynamics of the simplified model of a bioregenerative life support system, the following design parameters apply: The metabolic demand of a crew of eight is $\delta Q_{crew} = 209$ moles per day of carbohydrate consumed (or oxygen consumed, or carbon dioxide produced). The nominal food storage will be 6 kmol, approximately a four week's supply of 22.5 kg per man. On the other hand, the cabin atmosphere will be assumed to contain, nominally, 528 kg (18 kmol) carbon dioxide.

Plant growth is assumed to take 80 days to harvest. No CO_2 uptake will be assumed to occur during a 10 day germination stage. During the next thirty days there would be a linear increase in the growth rate followed by 20 days of constant growth and 20 days of maturation having a linear decrease in the plant growth rate, or

CH_2O production. The daily increase in food is proportional to the number of plants, N_i, at each stage of growth, or,

$$\delta Q_{plant} = r\ (\Sigma_{i=1:30} i N_{i+10} + 30\Sigma_{j=1:20} N_{j+40} + \Sigma_{k=1:20}(30-k) N_{k+60}\ ) \qquad (5)$$

where, $r = 0.0001436$ mole/plant-day^2.

Some authors have proposed multiple growth chambers [Babcock and Auslander, 1984] while others have proposed a system of continuous (daily) planting in a single plant growth chamber [Rummel and Volk, 1987]. The chaotic behavior observed under some conditions for the multiple chambered model may be due to the necessary multiplicity of state variables, whereas a single chamber non-linear model may be described by a single state variable.

An arbitrary, nominal planting rate of 1000 plants/day was chosen for a series of simulation studies. A maximum planting rate of 1500 and a minimum rate of 0 was set, with the planting rate adjusted by negative feedback with daily sampling of the total food storage. The system is simplified greatly by the view that CO_2 uptake by the plants results in foodstuff $(CH_2O)_x$ produced which immediately becomes part of the available food storage. This approach will not be valid, of course, in the event of the total depletion of the food supply and the immature plants are consumed. The model system is shown in Figure 1.

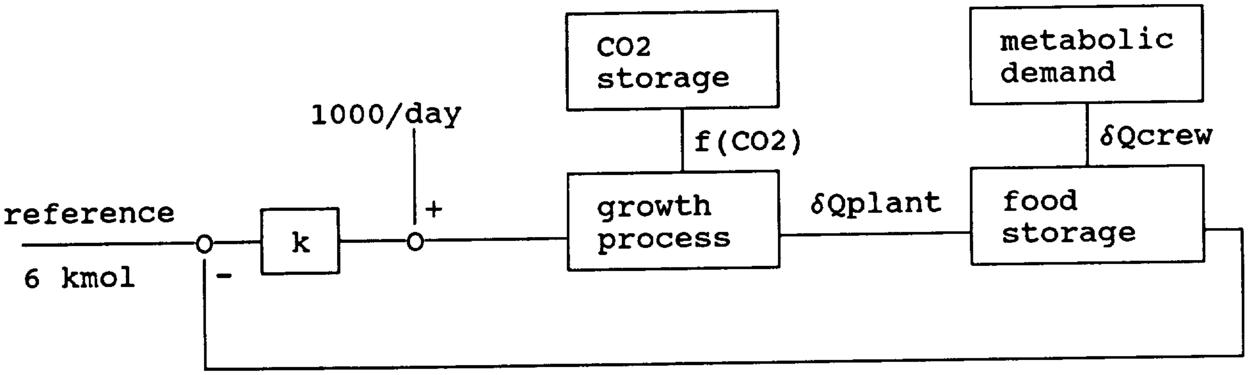

Figure 1. A block diagram of the planting control system.

Simulation Studies

A gain of 90 plants/kmol was found to provide good system response to a 30 day planting hiatus (≈1.0 yr settling time) and survivability of a 50% crop loss. The growth-inducing effects of carbon dioxide in the atmosphere can be studied by assuming a linear CO_2 activation function, $f(CO_2)$. Under this assumption and a gain of 90 plants/kmol, the model predicted survival in the face of a 75% crop loss. In order to survive a 100% crop loss the food stores would have to be increased in order to insure the food supply during the entire 80 day plant growth phase.

These simulation studies demonstrate the potential for a bioregenerative life support system on an extended mission. In addition to robustness and survivability in terms of the food supply, the plant growth chamber produces exactly the right amount of oxygen for the crew's metabolic needs. The amount of water taken up by the plants during food production is balanced by the crew's metabolic water production. However, this water would be overshadowed by the transpiration water in the plant growth chamber which is expected surpass the crew's demand several fold [MacElroy, 1989]. The excess water could be used for bathing and hygiene. There may be realized important psychological benefits which would result from passing purified waste water through the plant's transpiration system before introducing it into the crew's potable water supply.

References

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