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MODELING ADVANCE LIFE SUPPORT SYSTEMS

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ABSTRACT

Activities this summer consisted of two projects that involved computer simulation of bioregenerative life support systems for space habitats. Students in the *Space Life Science Training Program* (SLSTP) used the simulation, SpaceStation, to learn about relationships between humans, fish, plants and microorganisms in a closed environment. One student, Ed Eaton, completed a six week project to modify the simulation by converting the microbes from anaerobic to aerobic, and then balancing the simulation's life support system. A detailed computer simulation of a closed lunar station using bioregenerative life support was attempted, but there was not enough known about system restraints and constants in plant growth, bioreactor design for space habitats and food preparation to develop an integrated model with any confidence. Instead of a completed detailed model with broad assumptions concerning the unknown system parameters, a frame work for an integrated model was outlined, and work begun on plant and bioreactor simulations. The NASA sponsors and the summer Fellow were satisfied with progress made during the 10 weeks, and we have planned future cooperative work.

Modeling Advance Life Support Systems

Marvin Pitts

1. Introduction

Scientists and engineers within the National Aeronautics and Space Administration (NASA) are conducting research which will lead to the development of advanced life-support systems that use plants, and microbes to solve long term life-support problems in space (1). The Controlled Ecological Life-Support System (CELSS) is a complex, extensively-controlled, bioengineered system for human life support. It relies on plants, and microbes to perform gas exchange and food and potable water reclamation to supply principal elements needed for human existence.

Information on gas exchange of plants in controlled environments is vital for assessing the use of crops for human life-support in closed space habitats. Fortson et al. (2) studied gas exchange and biomass production for wheat stands (*Triticum aestivum* L. c.v. Yecora Rojo) grown from planting to maturity in a 20 m^2 canopy area closed growth chamber. They determined that more biomass is needed to produce oxygen than to produce food grain.

A single-person demonstration unit was developed by Owens and Hall (3) to evaluate ecological processes and hardware requirements necessary to assess feasibility and to define design criteria. The system consisted of a 1 m^2 plant growth area, a 500 l fish culture tank, and computerized monitoring and control hardware. Nutrients in the hydroponic solution were derived from fish metabolites and fish food leachate.

Strayer (4) characterized the microbial constituents of the CELSS Biomass Production Chamber during production tests of hydroponically-grown crops of wheat and soybeans. Bacterial and fungal viable counts were determined for the hydroponic solution, dehumidifier condensate water, and atmosphere.

Corey and Wheeler (5) measured gas exchange in the Biomass Production Chamber for various combinations of plants and fish. They described the life-support needs for humans in space in their manuscript.

The computer simulation, SpaceStation©, uses simplified relationships and typical steady-state values defined by the CELSS researchers cited above. SpaceStation© biology consists of the organisms— plants, fish, people and microbes— that share four quantities: oxygen, carbon dioxide, water and organic waste. The SpaceStation© biology modeled in the program is highly interrelated.

In the simulation, the people consume oxygen, fish protein and cereal grain, and they produce carbon dioxide and organic waste (in water passed to the fish). The fish consume oxygen and cereal grain, and they produce carbon dioxide, organic waste (in water passed to the microbes) and protein. The microbes consume carbon dioxide and organic waste and produce oxygen and plant nutrients (in water passed to the plants). The plants consume carbon dioxide and plant nutrients and produce oxygen and cereal grain. The growth and/or death of any organism depends on the state of the other organisms in the system.

People and fish share the oxygen and cereal grain in the station, and both produce carbon dioxide and organic waste. Both people and fish will suffer (slower growth or death) if the quantities of oxygen or grain decrease too far, or if carbon dioxide or organic waste accumulate excessively. The interaction between people and fish is complicated by the predator / prey relationship.

The interaction between plants and microbes is less complicated. The plants and microbes share the carbon dioxide in the station. The plants are dependent on the microbes to convert organic waste into plant nutrients, and the animals that produce the organic waste depend on the plants for food.

The stated goal of the simulation is for the station's life-support manager to change food and water allocations between people, fish and plants to keep the system in balance when disruptions occur due to human arrivals and departures from the station. The simulation objectives are to:
1. maintain a suitable environment for people on the station
2. maintain suitable environments for fish, microbes and plants, and
3. minimize changes in fish, microbe and plant populations.

2. PROJECT DESCRIPTIONS AND RESULTS

Project 1: Using SpaceStation with SLSTP students (with Colleen Loader)
The Advance Life Support section of Biomedical Operations hosted eleven college students in the Space Life Science Training Program (SLSTP). Our goal was to introduce concepts related to system dynamics and engineering design in biological systems to the students.

Early in the six week program, I presented a two hour workshop on the relationship between people, fish, plants and microbes in a closed environment, in the use of SpaceStation, and gave a design exercise to determine how much crew fluctuation the station could accommodate and remain in ecological balance. Teams of three students were tasked to determine the maximum number of people who could enter or leave the station, and needed changes to the environmental control system. We did not get a chance to meet again as a group to hear team reports.

I also mentored Edward Eaton, a ceramic engineering junior at Rutgers University, in his student project. Ed changed the SpaceStation simulation by converting the microbes from anaerobic to aerobic. This change meant that the microbes began to consume oxygen rather than produce the gas. In his presentation to the SLSTP students, Ed listed key concepts he gained during the project:
- Biological systems are complex, time variant and nonlinear
- Different time constants in various organisms made balancing life support difficult
- Negative feedback control stabilizes populations
- Need to infer the unobservable from what is observable

Project 2: Simulation of a Lunar Station (with Alan Drysdale)
The second project I was involved with was to write a computer simulation of the biomass and related energy flows through a bioregenerative life support system for a lunar station. A lunar station was selected over the International Space Station (ISS), a Mars transit vehicle or a Mars station because the lunar mission duration and distance from Earth would preclude frequent resupply as is possible with the ISS, and yet is not as far in the future as a Mars mission. The goal of the project was to understand the dynamics of biomass and related energy transport in a closed system.

To meet this goal, we planned to develop a model based on the science developed in the CELSS Breadboard project. We would consult with the engineers and scientists working on CELLS projects to determine system parameters and constants. Once the model was completed, its predictions would be compared to other models, and the differences in model predictions would then give direction to the assumptions made in developing the different models.

Once we began to implement this plan, I soon realized that the integrated model envisioned was not possible at this time. Critical relationships in Plant and Bioreactor systems intended for space are not defined, or system parameters are not known. The engineers and scientists involved with CELSS (as well as myself) were skeptical that the integrated model would accurately estimate system dynamics. Conversation with Russ Fortson, Lockheed Corp. based at JSC, indicated that a model that was used by design engineers at KSC and JSC would be most useful. Consultation with engineers and scientists at JSC was needed to gain their support of the simulation. In addition, expertise in crew requirements and physical-chemical systems was at Johnson Space Center. Every indication we had was that an integrated simulation developed using only CELSS expertise and current knowledge would not be accepted or used.

Clearly, I needed to redefine my goals for the summer. My long term goal is to develop an integrated computer simulation of a lunar station that uses a combination of bioregenerative and physical-chemical life support systems. My revised goal for this summer was to lay the groundwork needed to build the integrated simulation. To meet this goal, I completed the following activities:

- Sketched a framework for an integrated model using modules to simulation major life support systems
- Began to define Resource Recovery and Plants modules using CELSS expertise
- Began to define Crew module and physical-chemical devices using JSC expertise (met with JSC engineers and scientists August 8th and 9th)

The framework I outlined consists of the following major groupings: crew, plants, resource recovery, food preparation, energy (electrical, mechanical and heat), water and other liquids, air and associated gasses, physical - chemical units and environmental control. Additional parts of the simulation used for design are: flow of carbon, nitrogen, other elements and organic compounds, and data sets of system constants for various station operation assumptions.

Plant Module: Plant growth and grain production are influenced by the following factors: light source and intensity, CO_2 concentration in the air, NO_3 and NH_4 concentrations in the plant nutrient solution, other major nutrients, water and evapotranspiration. Based on these relationships, I built three models: one which modeled the growth of a single set of plants of the same age and under the same environmental conditions, a second model which simulated a series of eleven sets of plants grown at weekly intervals, and a model of a proportional control system used to meter NH_4 into the plant nutrient solution to regulate solution pH.

The single set plant model is based on the following equation defined by Volk et. al, (6):

$$CGR = K[H*P - (24-H)R] \qquad\qquad 2.1$$

where CGR = crop growth rate
K = unit conversion constant
H = hours per day that growth lights are on
P = biomass accumulated through photosynthesis
R = biomass consumed by respiration when the growth lights are not on

The photosynthesis term is a function of the light energy absorbed by the plants, the conversion of light energy into plant mass, and the age of the plant. The respiration term is a function of the same factors. Curve 1 in Figure 2.1 is a plot of the wheat growth under the environmental conditions used in the CELSS Biomass Production Chamber (BPC) (7). The second and third curve in Figure 2.1 is a modification of equation 2.1 which partitions the plant biomass into vegetation and grain. After antithesis, most of the additional plant mass is channeled into grain fill. Two terms were defined in the simulation which control the mass partition: day of antithesis and potential grain fill. Day of antithesis is self explanatory. Potential grain fill is a term used to model the significant effects of environmental conditions during antithesis on the ability

of the plant to produce grain. There is a qualitative understanding of the effect of some environmental conditions on grain fill, but additional study is needed to quantify these effects. Figure 2.2 demonstrates the significant reduction in grain yield from delaying antithesis. Figure 2.3 demonstrates significant reduction in grain yield due to lower grain potential constants.

I expanded the single plant model into eleven sets of plants, each containing producing a weekly ration of grain for a crew of 4. The oldest plants set was harvested each week, and a new set planted. This model was used to demonstrate the effect of various environmental factors in common with all eleven sets on grain production. For example, Figure 2.4 shows the reduction in harvest index following a light system failure of 5 days. Even though the light failed on days 10 through 15, the most severe grain shortage was five weeks after the light disruption, and 16 weeks until grain production reached normal levels.

The third plant–related model was a proportional control of plant nutrient solution pH via the addition of NH_4. Plant nutrient uptake uses an ion exchange in the absorption of nitrogen based molecules. The primary nitrogen source for plants grown in hydroponic systems is NO_3. For each mole of NO_3 the plant uptakes, it releases 2 moles of OH. Over time, the pH of the solution will increase to toxic levels due to the increasing concentration of OH ions. Traditionally, pH is corrected via the addition of nitric acid (7). Nitric acid is not produced in a closed system such as a lunar station, and must be supplied from external sources. In a closed system that includes animals, there is a constant source of ammonia from animal waste. Plants readily absorb ammonia, in fact at a rate twice that for nitrate (8). Ammonia uptake must be limited because plants release 4 moles of H ions per mole of ammonia (which would drive the nutrient solution pH down), and because excess absorption of ammonia is toxic to plants (maximum $NH_4 : NO_3$ ratio is 0.5). Figure 2.5 demonstrates that a proportional control based on pH levels can maintain the correct chemistry for plant growth without the addition of nitric acid to the plant nutrient solution.
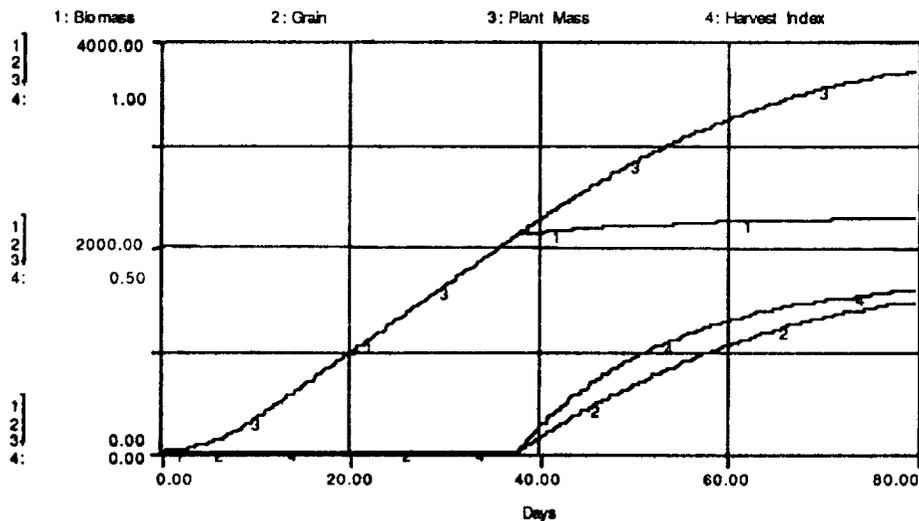
Figure 2.1 Graph of plant growth using equation developed by Volk et. al. for wheat grown under environmental conditions similar to the biomass production chamber used in the NASA CELSS project. Curve 1 is plant vegetative mass; Curve 2 is grain mass, Curve 3 is the total plant mass (vegetative and grain), and Curve 4 is the Harvest Index (grain mass / total plant mass).

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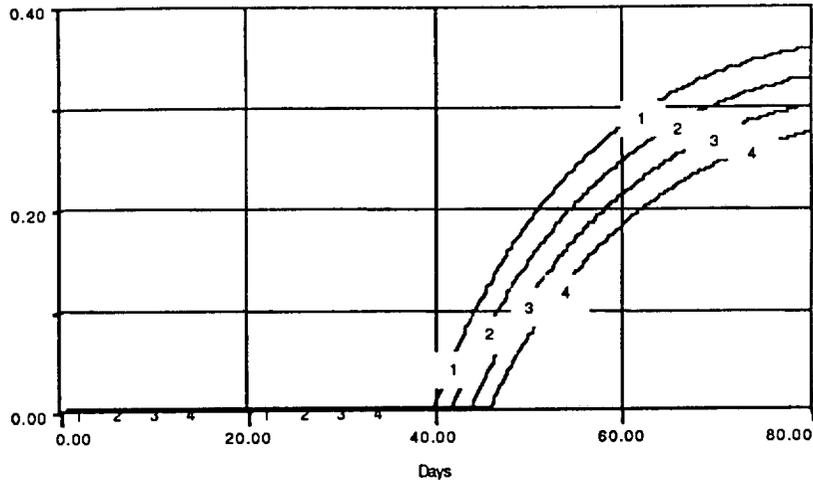
Figure 2.2. Effect of day of antithesis on Harvest Index using the equation developed by Volk et. al. for wheat grown under environmental conditions similar to the biomass production chamber used in the NASA CELSS project. Day of antithesis were 40 (Curve 1), 42 (Curve 2), 44 (Curve 3) and 46 (Curve 4).
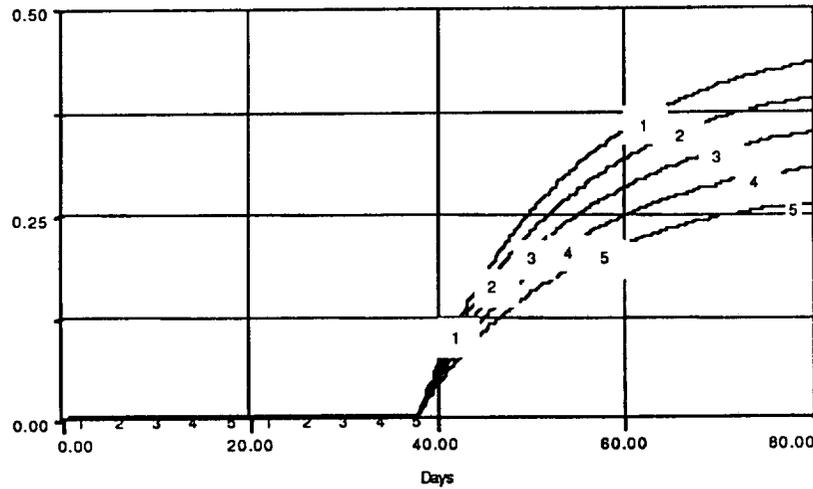
Figure 2.3. Effect of "potential grain fill" on Harvest Index using the equation developed by Volk et. al. for wheat grown under environmental conditions similar to the biomass production chamber used in the NASA CELSS project. Potential grain fill values were 1 (Curve 1), 0.9 (Curve 2), 0.8 (Curve 3), 0.7 (Curve 4) and 0.6 (Curve 5).

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0.40

0.20

0.00

0.00   30.00   60.00   90.00   120.00

Days
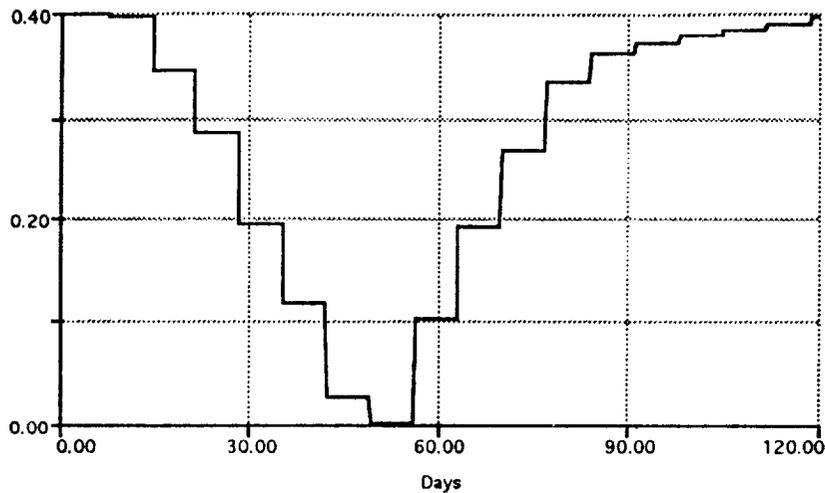
Figure 2.4. Effect of light failure in a staggered growing system on Harvest Index using the equation developed by Volk et. al. for wheat grown under environmental conditions similar to the biomass production chamber used in the NASA CELSS project. A weekly harvest based on eleven plant sets were modeled. Lights were off from Day 10 to Day 15.

Curve 1 shows a characteristic finite error in pH due to the proportional control. The rise in pH would not affect plant growth. The ratio of NH_4 : NO_3 remains below 0.50. Rising pH from OH produced by nitrate uptake is first controlled by the buffer in the solution, and as ammonia is released into the solution in response to the rise in pH, the H ions produced by the ammonia uptake combine with OH ions to produce water molecules.

Bioreactor modeling: Waste Recovery in a lunar station has different goals than existing wastewater treatment plants in regards to nitrogen. Terrestrial wastewater treatment encourages microbe growth because the microbes bind organic carbon and nitrogen, reducing BOD and nitrate levels in the effluent. The microbes are removed from the treatment plant and disposed via burial, incineration or spread onto agricultural fields (9). In a lunar station, these elements must be recycled. While incineration will release the carbon in the microbes in a useful form as carbon dioxide, the nitrogen in the microbes will be released as nitric oxides, requiring further treatment to convert the nitrogen into compounds suitable as plant nutrient. Thus, a design goal for waste recovery in a lunar station is to reduce organic carbon and nitrogen in waste streams without adding nitrogen to untreated biomass that will be incinerated.

Many of the constants needed to model a bioreactor are system specific, and there is not a design procedure which will estimate these parameters for a lunar-based bioreactor. However, I developed a fully-mixed, continuous flow bioreactor model using typical values for demonstration purposes to indicate how a lunar-bioreactor might be operated. Figure 2.6 indicates the effect of microbe mass on the amount of nitrogen that is in the untreated biomass (organic waste that was not treated plus microbes that were removed from the bioreactor). For this system, an optimum microbe mass is indicated by curves 2 and 3 which have the minimum amount of untreated nitrogen. Low microbe levels (curve 1) cannot consume all the organic matter in the waste, allowing untreated organic matter out of the bioreactor. High microbe levels (curves 4 and 5) result in a large amount of microbes removed from the bioreactor.

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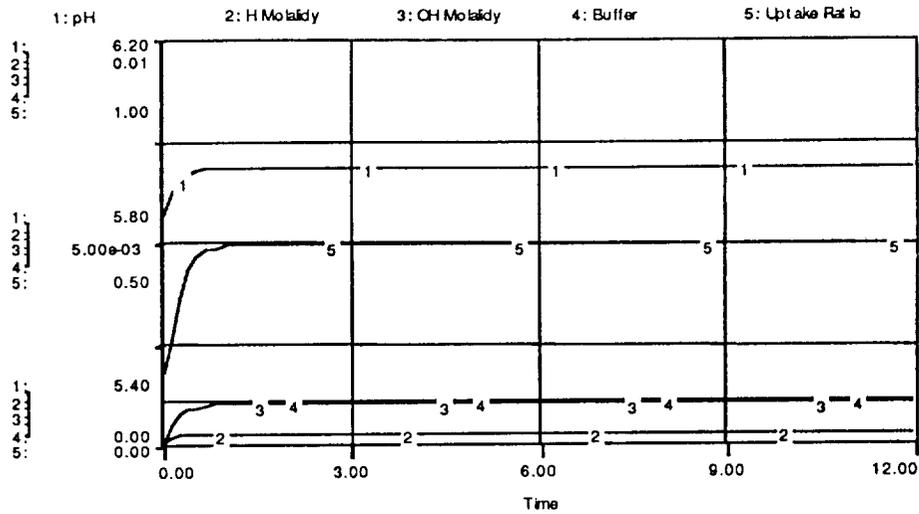
Figure 2.5 Modeled nutrient chemical response to proportional control of pH via the addition of ammonia.

Few Bioreactor design constants or processes exist for lunar station based waste recovery systems. Some of the unknown values I needed for modeling were:

- Microbe growth rate
- Substrate consumption
- How to maximize consumption while minimizing microbe growth?
- How to scale bioreactor volume and flow rate?
- How these values change in alternate bioreactor designs?
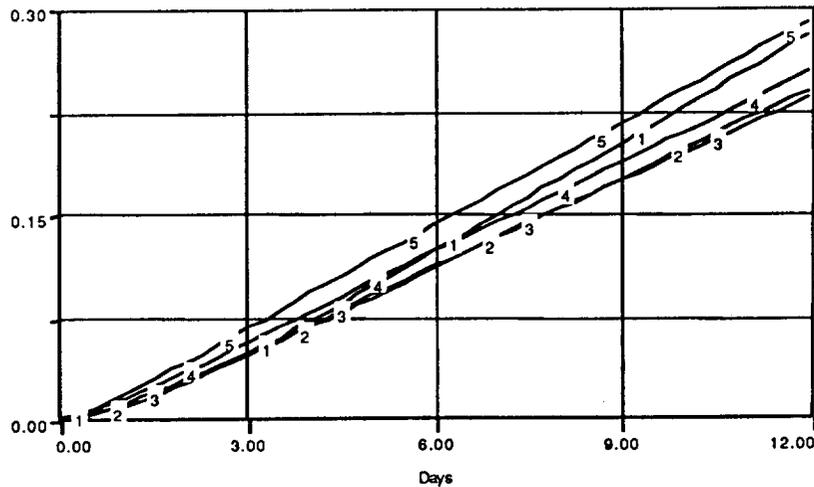
Figure 2.6 Effect of microbe mass in a continuous flow, fully mixed bioreactor on nitrogen level in effluent biomass (untreated organic carbon and microbes removed from the reactor). Microbe mass increases by a 0.1 kg from Curve 1 (0.1 kg) to Curve 5 (0.5 kg).

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3. CONCLUSIONS AND RECOMMENDATIONS

During the ten week summer program I developed the following products:

- An improved SpaceStation model
- Workshop task sheets for use with SpaceStation with emphasis on engineering design in biological systems
- Framework for a model of integrated life support systems, and
- Prototype Bioreactor and Plant modules

During the summer, a number of needs surfaced which require further cooperative work. The most urgent areas are to:

- Determine relationships that are oversimplified
- Verify trends pointed out in the prototype models, and
- Determine constants needed in the models

4. REFERENCES

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