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PERFORMANCE OF THE CELSS ANTARCTIC ANALOG PROJECT (CAAP) CROP PRODUCTION SYSTEM

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ABSTRACT

Regenerative life support systems potentially offer a level of self-sufficiency and a decrease in logistics and associated costs in support of space exploration and habitation missions. Current state-of-the-art in plant-based, regenerative life support requires resources in excess of allocation proposed for candidate mission scenarios. Feasibility thresholds have been identified for candidate exploration missions. The goal of this paper is to review recent advances in performance achieved in the CELSS Antarctic Analog Project (CAAP) in light of the likely resource constraints. A prototype CAAP crop production chamber has been constructed and operated at the Ames Research Center. The chamber includes a number of unique hardware and software components focused on attempts to increase production efficiency, increase energy efficiency, and control the flow of energy and mass through the system. Both single crop, batch production and continuous cultivation of mixed crops production studies have been completed. The crop productivity as well as engineering performance of the chamber are described. For each scenario, energy required and partitioned for lighting, cooling, pumping, fans, etc. is quantified. Crop production and the resulting lighting efficiency and energy conversion efficiencies are presented. In the mixed-crop scenario, with 27 different crops under cultivation, 17 m^2 of crop area provided a mean of 515g edible biomass per day (85% of the approximate 620 g required for one person). Enhanced engineering and crop production performance achieved with the CAAP chamber, compared with current state-of-the-art, places plant-based life support systems at the threshold of feasibility.

INTRODUCTION

Renewed interest in Mars exploration has resulted in identification of candidate scenarios for Mars missions. As requirements for conduct of these missions are defined, consideration of technologies necessary to realize these missions occurs. Life support is an obvious necessity in any human mission. Regenerative Life Support (RLS), with features of self-sufficiency, mass recycle and reduced logistics support, have often been cited as valuable for exploration missions. However, the resource requirements to implement a full RLS exceed candidate mission resources. The goal of the design and operation of the CAAP chamber is to lessen RLS resource requirements and so make RLS feasible for inclusion in future exploration and habitation missions.

It is important to determine that the cost of utilizing RLS is practical compared with current practices and that RLS can be accommodated within a set of realistic resource constraints. Flynn (1997) determined that current RLS practices, when applied to NASA's Mars reference mission, would require twice the mass as carrying along equivalent life support materials. Since a final Mars mission schedule and configuration have not been determined, a final decision on approach and technologies is not yet

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appropriate. It is appropriate now, however, to review the feasibility of RLS in supporting candidate missions.

Green plants provide the focus for RLS functions. Plants are the only known method for production of food and supplying a diet that could maintain a healthy and happy crew for long-duration mission when these crew members will be required to perform strenuous work. In addition to food production, plants accomplish atmospheric regeneration, via CO_2 removal and O_2 production during photosynthesis, and water production, via transpiration. Full utilization of these processes for life support function has been slow to be realized. The complexity of the multiple processes, all occurring within a single physical processor, the plant community, presents a challenge to life support design. The guiding principles for controlling these processes have been provided by plant physiology and agricultural research; however, the notion of engineering a crop plant community system to manage and control these processes in a predictable and reliable way is a very new endeavor.

This paper provides a review of the state-of-the-art in plant-based RLS performance and resource requirements compared with resource limitations identified for candidate space exploration missions. Recent advanced in addressing areas of performance deficiencies in RLS realized in the research program associated with the National Science Foundation (NSF) supported Controlled Ecological Life Support System (CELSS) Antarctic Analog Project (CAAP) are discussed. These results aid in demonstrating the road map to feasible RLS.

DETERMINING SYSTEM FEASIBILITY

Two issues will determine the feasibility of plant-based RLS: cost of the system and performance or productivity. Several recent analyses have attempted to account for the cost factors associated with the RLS system and place them on a common equivalent cost or mass basis (Drysdale, 1996; Flynn, 1997). In addition to determining cost factors for RLS as currently practiced, Flynn considered two additional issues. First, he identified specific cost areas leading to the conclusion that RLS is not currently feasible, and second, identified target threshold performance levels that RLS must minimally meet in specific areas to become feasible. Primary system deficiencies or resource constraints identified were power and mass.

STATE-OF-THE-ART

The state-of-the art in plant based RLS is presented by the plans and performance expectations identified for the NASA Advanced Life Support Testbed, the Bioregenerative Planetary Life Support systems Test Complex (Bio-Plex) (Hanford, 1997). Performance targets for the Bio-Plex are listed in Table 1.

Table 1. Bio-Plex Crop Production Performance Estimates and Energy Requirements (Hanford (1997)

Parameter	NASA State-of-the-art
% food	90%
m^2 $person^{-1}$	43 m^2
Power - plant lighting	28 kW $person^{-1}$
Power - total plant system	52 kW $person^{-1}$
Mass Equivalent*	6,200 kg $person^{-1}$

*Calculated by Flynn (1991) using Hanford (1997) and Schwartzkopf (1991) data.

The mass equivalent values calculated in Table 1 assume an inflatable structure as included in the Schwartzkopf (1991) analysis. The Hanford analysis (1997) utilized a space station module and found the high-mass penalty would increase the total plant production system equivalent mass to 7,950 kg $person^{-1}$.

MISSION SCENARIOS AND CURRENT FEASIBILITY

Candidate mission scenarios were developed by Volosin (1995); they include a well documented set of support information (Table 2). These scenarios were defined for the purpose of quantifying constraints and resources within some range and to identify the common as well as any unique features of the range of missions proposed.

If we consider the current state of performance for plant-based RLS, as defined in Table 1, in light of power constraints identified for each scenario, we see that RLS is not currently feasible (Table 2). The only mission that could be considered is the short-term Mars mission and a 50% allocation of total mission power to accomplish the 10% food supply contribution seems unlikely.

Table 2. Candidate Mission Scenarios and Power Resources (Volosin, 1995) Compared with Bio-Plex Predicted Crop Production System Requirement

Mission Scenario	Crew Size	Diet (%)	Total Mission Power (kW)	Bio-Plex Predicted (kW)
Lunar (short-term)	4	10	25	23
Mars (short-term)	4	10	50	23
Lunar (long-term)	30	85	500	1474
Mars (long-term)	6	85	200	295

An analysis of the NASA Mars "Refence Mission" (1994), which is almost identical to the Volosin Mars long-term mission concluded that it is less expensive to ship stored food than to produce it using current RLS performance. The mass of stored food (including the penalty for volume and structure to house the stored food) is equivalent to approximately 3,170 kg person^{-1}, compared with the best current case of 6,200 kg person^{-1} for plant-based RLS. If RLS is to be considered seriously in the future to support exploration, the system must clearly become more energy and mass efficient.

CELSS ANTARCTIC ANALOG PROJECT

The CELSS Antarctic Analog Project (CAAP) is a joint NASA and NSF project to utilize the U.S. South Pole Station as an analog for understanding planetary base operation (Straight, et al., 1994, 1995; Bubenheim et al., 1994, 1995, Bubenheim and Flynn, 1996; Flynn et al., 1994). CAAP is specifically focused on the high degree of functional equivalency among application of advanced RLS systems at the South Pole Station and analogous operations in a future space mission. The goal is to take advantage of the real and relevant constraints that are present at the South Pole Station to aid in development of effective RLS.

NASA Headquarters sponsored a Space Analogs workshop for the purpose of reviewing the range of analogs potentially available to address development efforts around the four space exploration mission scenarios listed in Table 2. The Antarctic mission and CAAP analog ranked highest in addressing short-term and long-term Mars missions and the long-term Lunar mission (Logsdon, 1996; Shepanick and Volosin, 1996). Only Space Station ranked higher as an analog for the short-term lunar mission scenario. More detailed discussions regarding CAAP and efforts to design, install and operate a remote, complex human habitat supported by RLS technologies are available (Bubenheim et al., 199, 1995, 1996; Flynn et al., 1994; Rummel, 1994; Roberts et al., 1992; Straight et al., 1994, 1995).

The constraints for design and development at the South Pole Station are analogous to those for space flight. Energy is extremely limited. South Pole Station currently operates with less than 70% of the power resource planned for the long-term Mars mission scenario and supports the same size crew, 30 people. Planned upgrades will increase power to 500 kW, however, there is a concomitant increase in crew size to 50 people. Fitting plant-based, RLS within a constraint of 10 kW person^{-1} or less total mission power is more demanding than the 16 kW person^{-1} total power for the long-term Mars mission scenario. Just as is the case for NASA, the constraints of area, volume, and mass are important and related. The cost of habitat volume (area) and the cost of re-supply mass to maintain that environment is large. A detailed discussion of those limitations and constraints can be found elsewhere (Bubenheim and Flynn, 1996).

Faced with the real-life and relevant constraints of power, mass and volume imposed by South Pole Station, CAAP has provided a real measure of performance capability and limitations not possible to appreciate in laboratory exercises. Steps to address these limitations are developed during system design and analysis with the initial technology and system configuration performance being tested in the CAAP Testbed at Ames Research center (Bubenheim and Flynn, 1996). While the Testbed addresses the integrated nature of the South Pole Station, only performance of the crop production system will be discussed.

The developmental efforts associated with CAAP and validated through performance in the CAAP Testbed have resulted in recent advancements in crop productivity and system efficiency. The advances, while representing only the initial application of a small number of technologies and system design approaches planned for implementation in CAAP, have yielded large improvements in RLS performance and are directly related to achieving feasibility for future space mission.

RECENT ADVANCES IN CROP SYSTEM PERFORMANCE

Initial systems installed in the CAAP Testbed Crop Production Chamber were focused on increased energy efficiency, area utilization efficiency, and production efficiency. Advances in these areas have a large impact on mass requirements. Direct efforts to decrease system component mass or address volume optimization have not yet been included in the chamber.

Since the purpose of crop production at the South Pole Station is the regular production of crops for consumption by the crew, long-term stability and supply of predictable amounts of crop on a schedule is important. Crops are being selected which are desirable, provide nutrition, require little or no processing, and are versatile for use in several different menu options. The method utilized for selecting specific crops based on human nutrition requirements, production efficiency, and menu options is described by Cenci-McGrody and Quay (1997). The areas of hardware performance, candidate-crop performance and validation of long-term production schedules were initiated first.

Two of the crop production studies conducted in the CAAP Crop Production Chamber are discussed here to illustrate the level of performance achieved. These studies were: 1) a lettuce crop produced in a batch production schedule, and 2) a 90-day continuous production trail including mixed crops. There were 27 crops grown simultaneously in the chamber during the 90-day trial (Table 3).

Table 3. Crop and Cultivar List for the CAAP 90-Day, Multiple Crops, Continuous Production Trial

Lettuce	Spinach	Oregeno
'Waldmans Green'	'Tyee'	Perilla
'Jericho Boston'	'Melody'	Chicory
'Lollo Rosa Red'	Basil	Endive
'Ostinata'	Lemon	Catalonia
'Red Oak Leaf'	Purple	Cilantro
Brassicas	Tomatoes	Cucumber
'Jade Pagoda'	'Micro'	'Picobello'
'S. Stem Mustard'	'Beefsteak'	Long type
'Tah Tsai'	Bell Peppers	Beans
'Mizuna'	Wheat	Peas, Sugar Snap
Shungiku	'Yecora Rojo'	

In both studies, crops were grown using a recirculating hydroponic system including pH and nutrient composition monitoring and control. Plant spacing was adjusted, on average, four times during a particular crop cycle to maintain high photosynthetic radiation absorbance. Crop and engineered system performance are listed for each study in Table 4. Productivity for the batch lettuce production is averaged over the life cycle duration to achieve a daily performance value.

Table 4. CAAP Testbed Crop Production Chamber Performance: Lettuce Production and Continuous Mixed Crop Production

Parameter	Lettuce Production	Continuous Mixed Crop Production
Production Features		
Photoperiod	24 h	15 h
Daily PPF	38.3 mol d^{-1}	48.2 mol d^{-1}
Production Area	15 m^2	17 m^2
Production Duration	15 d	94 d
Yields		
Biomass Production	503 g d^{-1}	630 g d^{-1}
Harvest Index	95%	82%
Food Produced	478 g d^{-1}	517 g d^{-1}
Biomass m^{-2}	33.5 g d^{-1}	37.1 g d^{-1}
Edible Yield m^{-2}	31.8 g d^{-1}	30.3 g d^{-1}
Chamber Lighting Power	8.6 kW	11.5 kW
Emission Efficiency	35%	35%
Delivery Efficiency	32%	48%
Chamber HVAC Power	5.3 kW	5.6 kW
Fans	1.5	1.5
Pumps	0.9	0.9
Cooling Loop	1.9	2.2
Reheat	1	1
Total Chamber Power	13.9 kW	17.1 kW
One Person Food Equivalent Correction (620 g edible)	18.0 kW 19.5 m^2	20.5 kW 20.5 m^2

Production efficiency was greatest for the batch lettuce study; but of course, lettuce does not provide adequate nutrition for a full human diet. The mixed crop production study shows that the penalty for diversity in crop production, designed to provide specific amounts of each crop to support a menu based on nutritional needs, is not severe. The power and area requirements to produce 620 g edible d^{-1} for the mixed crop study was only 14% and 5%, respectively, higher than for the lettuce study. The dietary contribution of the mixed crop study was 68% of the daily caloric requirement (2,900 Calories) with a distribution of 65% carbohydrates, 21% protein, and 14% fat.

The engineered systems of the crop production chamber were also very energy efficient. Performance of the chamber (and component subsystems) matched goals for resource demands. The significance of the efficiency realized in these studies, with just the initial steps toward increasing efficiency, can be best appreciated when compared with state-of-the-art below.

IMPACT OF CAAP CHAMBER PERFORMANCE ON FEASIBILITY OF PLANT-BASED RLS

Considerable improvement in both crop production and energy efficiencies was demonstrated in the 90-day continuous production study and showed positive impact on plant-based RLS feasibility. Compared with NASA state-of-the-art being used to predict crop performance in controlled environment production, there is tremendous improvement to system performance (Tables 5 and 6). It is important to point out that the CAAP chamber performance reported here does not include any energy reuse. Additional reduction in overall total power requirements will be possible in the future with energy reuse.

Table 5. Crop Production and Power Efficiencies for RLS Projected Crop Performance Compared with CAAP Crop Production Chamber Performance

Parameter	RLS Projected Production	CAAP Production
Crop Production: g m^{-2} d^{-1}	12.4	30.3
Lighting Efficiency: moles of photons kWh^{-1}	1.6	3.9
Light Conversion efficiency: g biomass kW^{-1}	20	45
Total System Efficiency: g biomass kW^{-1} total	11	30

The lighting system of a crop production chamber will be a sink for electricity. Efficiently converting electrical power to photosynthetic radiation and delivery to the crop to drive photosynthesis and productivity is critical to feasibility of RLS. The lighting system of the CAAP Testbed Crop Production Chamber has two features important to achieving energy efficiency in a plant-based RLS. First, the efficiency of production and delivery of photosynthetic radiation to the crop has been significantly improved (Bubenheim and Flynn, 1996). The second feature is a recirculating water jacket around the lamps that absorbs and removes non-photosynthetic energy and provides a mechanism for transferring that energy for reuse to perform work currently accomplished with electricity. The issue of energy recovery and the importance to overall mission efficiency is addressed in another paper (Bubenheim and Flynn, 1996).

Table 6. Area and Energy Requirements to Produce a One Person Equivalent Food Portion (620 g) Using Current RLS Projected and CAAP Performance

Parameter	RLS Projected	CAAP Performance
area $person^{-1}$	50 m^2	20.5 m^2
lighting energy	31 kW $person^{-1}$	13.9 kW $person^{-1}$
total energy	57.8 kW $person^{-1}$	20.5 kW $person^{-1}$

The increases in crop performance realized in the CAAP chamber thus far significantly change the feasibility evaluation of plant-based RLS. Table 7 provides a summary of information regarding mission scenarios introduced in Table 2, but includes values utilizing CAAP performance.

Table 7. Characteristics of Candidate Mission Scenarios and Power Resources (Volosin, 1995): Current RLS Projections for Crop Performance Compared with CAAP Performance

Mission Scenario	Crew Size	Diet (%)	Mission Total Power (kW)	RLS Projected Production Power Requirement (kW)		CAAP Production Power Requirement (kW)	
Lunar: short-term	4	10%	25	23	92%	8.2	33%
Mars: short-term	4	10%	50	23	46%	8.2	16%
Lunar: long-term	30	85%	500	1474	295%	523	105%
Mars: long-term	6	85%	200	295	148%	105	52%

The percentage of total mission power required to employ plant-based RLS has been significantly decreased (Table 7). It remains difficult to assess what is a reasonable fraction of total power to expect to be available for life support. Addressing this very issue, Flynn (1997) determined target levels of performance representing threshold feasibility performance standards (Table 8). Plant-based RLS must meet or better these threshold performance targets to be considered feasible.

Table 8. CAAP Crop Production Performance Compared With Threshold Feasibility Performance Targets for Plant-Based RLS (Flynn, 1997)

Crop Production Parameter	Feasibility Threshold Target	CAAP Performance
Area	20 m^2 $person^{-1}$	20.5 m^2 $person^{-1}$
Power	20 kW $person^{-1}$	20.5 kW $person^{-1}$
Water	8 kg m^{-2}	16 kg m^{-2}

CONCLUSIONS

CAAP performance shows that plant-based RLS can be feasible. It further shows that crop production practices and technologies currently embraced as state-of-the-art by NASA are not adequate to meet requirements for future missions. The results of the CAAP project studies provides evidence that with proper consideration of technologies and system design, it is possible to achieve improved RLS performance. CAAP results presented here only represent the initial steps towards increasing efficiency. We are confident that performance can be improved still further with directed efforts to decrease system component mass, increase volume optimization, and further refine the production methods.

REFERENCES

Bates, M.E., and D.L. Bubenheim, Application of Process Control to Plant-Based Regenerative Life Support, 27th ICES, SAE Technical Paper #972359, 1997.

Bubenheim, D.L., M.E. Bates, and M. Flynn, An Approach for Development of Regenerative Life Support Systems for Human Habitats in Space, 25th ICES, SAE Technical Paper # 951730, 1995.

Bubenheim, D.L., C.L. Straight, M. Flynn, and R. Lamparter, Remote Sites as Analogs for Lunar and Mars Habitat Pilot Studies, 24th ICES, SAE Technical Paper #91455, 1994.

Cenci-McGrody, M., and C. Quay, A"Six-Step" Approach to Crop Selection and Menu Design in a Regenerative Life Support System, 27th ICES, SAE Technical Paper #972358, 1997.

Drysdale, A., Performance Measurements and Bioregenerative Life-Support System Performance: How Close Are We to Achieving Cost-Effectiveness? *Advances in Space Research*, 1996.

Flynn, M., The influence of Power Limitations on Closed Environment Life support System Applications. 27th ICES, SAE Technical Paper #972356, 1997.

Flynn, M.T., D.L. Bubenheim, C.L. Straight, and M. Bates, Analysis of wastewater from the South Pole Station, Antarctica, NASA Technical Paper (108836), 1994.

Hanford, A.J., Advanced Regenerative Life Support System Study, CTSD-ADV-287, Lockheed Martin Space Mission Systems and Services, 1997.

Human Exploration of Mars, The Reference Mission of the NASA Mars Exploration Study Team, NASA SP-6107, 1992-1994.

Longdon, J., Long-term Human Space Exploration: Ratings the Analogs, The Space Policy Institute, George Washington University, 1996.

Roberts, C.A., E. Chaing, J.T. Lynch, and P.D. Smith, Challenges to the U.S. Antarctic Program in the Decade of the 90's, SAE Technical Paper Series # 921128, 1992.

Rummel, J.D., Planetary Surface Exploration: Recent Results and Analog Environments, SAE Technical Paper # 932246, 1993.

Schwartzkopf, S., Lunar Base controlled Ecological Life Support System, Preliminary conceptual Design Study, LMSC/F280196, Lockheed Missiles and Space Company, 1991.

Shepanick, M., and J. Volosin, The Role of Analogs in Designing Space Habitats, 26th ICES, SAE Technical Paper #961396, 1996.

Striaght, C.L., D.L. Bubenehim, M.T. Flynn, M. Bates, and G. Schlick, The CELSS Antarctic Analog Project Pilot Studies, 25th ICES, SAE Technical Paper #951694, 1994.

Striaght, C.L., L. Kohout, D.L. Bubenehim, M.T. Flynn, and M. Bates, Energy Systems for The CAAP, 24th ICES, SAE Technical Paper #941353, 1994.

Volosin, J., Development of Recommendations for Advanced Life Support Program Requirements and R&D Priorities, NASA Document, 1995.