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Report of the First Planning Workshop for CELSS Flight Experimentation

Workshop for CELSS Flight Experimentation
Ames Research Center,
Moffett Field, California
March 1987

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CELSS

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INTRODUCTION

The First Planning Workshop for CELSS Flight Experimentation was convened at Ames Research Center on March 23 and 24, 1987. Its aim was to establish a base upon which a CELSS Flight Experiment Program will be developed during the next several months. The charge given to the First Workshop participants was 1) to identify science requirements for CELSS flight experiments, and 2) to evaluate potential near-term CELSS flight experiment opportunities.

The meeting opened with a presentation by R.D. MacElroy of Ames of a brief overview of the CELSS program and a description of the rationales for CELSS flight experiments. In summary, the purpose of the CELSS program is to develop the scientific and technological base required for the construction and use of a bioregenerative life support system (BLSS) to support crews in extraterrestrial environments. A BLSS utilizes energy to grow photosynthetic organisms whose growth involves absorbtion of the crew's waste carbon dioxide, recycled water and mineral elements and the concommitant production of food, oxygen, and transpired water. A complete BLSS is capable of continuously recycling most life support materials through the use of waste-processing devices and of continuously regenerating consumed materials.

The potential uses of a BLSS include placement in a Growth Space Station on low Earth orbit (LEO), in a geosynchronous space station, on the surface of the Moon, in transit to Mars, and on the Martian surface. In each of these cases the gravitational and radiation environment is significantly different from that of Earth, where the plants and organisms useful in the BLSS evolved. It is therefore necessary to evaluate the response of higher plants and other organisms to be used in the BLSS, as well as some of the fluid handling machinery, to the space environment.

The gravity parameter is of greatest immediate significance to a space experimentation program. Space radiation, to some extent, can be simulated on the ground and, again to some extent, protected against in flight. Levels of gravity below unity can be achieved effectively only on flight missions. Knowledge of the behavior of systems in these microfields is essential for the design of a BLSS. The gravitational environment of the Space Station and possibly of a transit to Mars is in the microgravity range; lunar gravitational forces are about 1/6 g and Mars surface gravity about 38% of that of Earth.

In the case of Space Station, though it is relatively close to the Earth, costs of resupplying life support materials, including the logistics of resupply, have not been evaluated. It is therefore possible, particularly as the efficiency of a BLSS increases, that bioregeneration will supplement the more traditional life support systems. Transit to Mars may require, for reasons of human health, the imposition of artificial gravity on all or parts of the spacecraft. However, such a decision will not be made for some time. The usefulness of a BLSS, and its efficiency compared to other methods of life support, during a Mars transit has not been fully evaluated. However, the duration of the trip, and the potential need for psychological support of the crew through the supply of fresh food, increases the likelihood that a BLSS will be selected as part of the life support system.

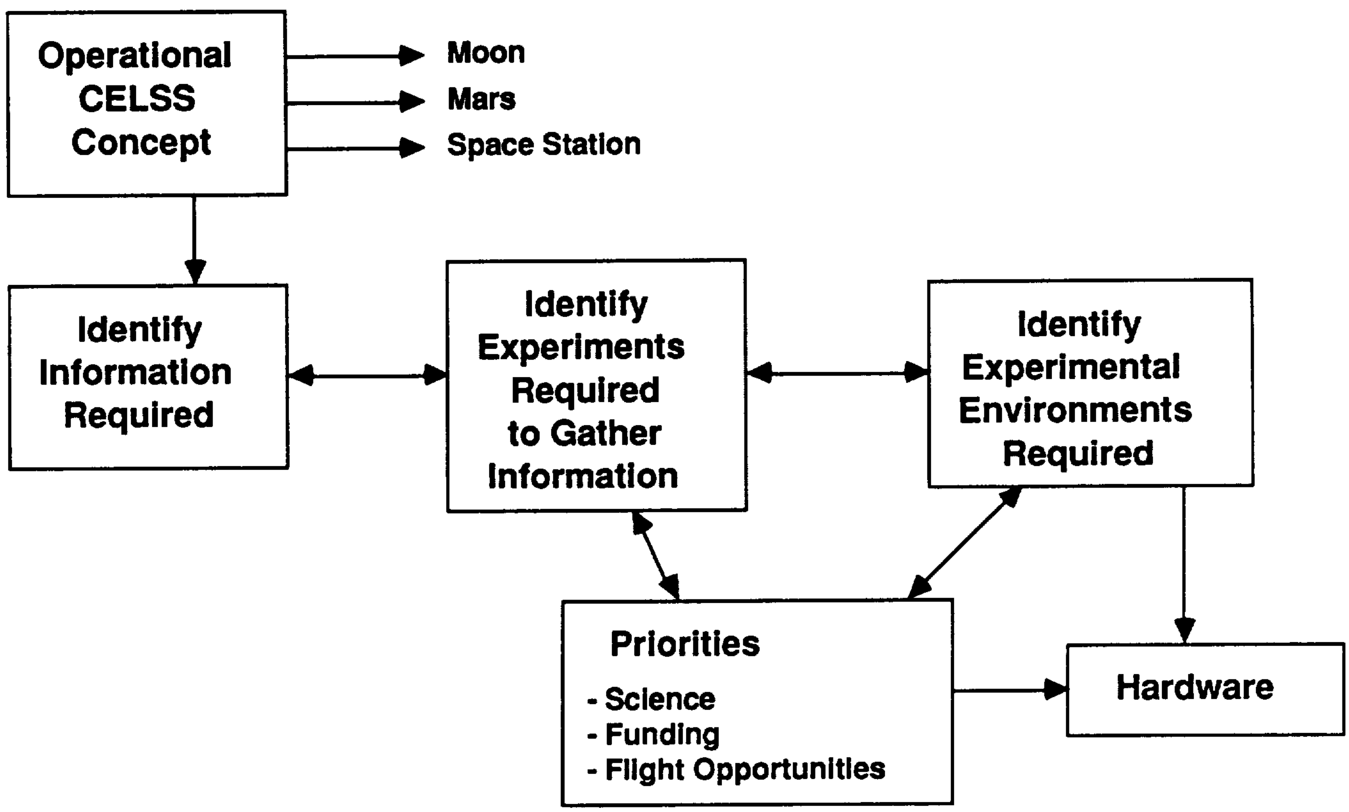

Figure 1.- Development of CELSS flight experiments science requirements.

elements; and initiating technology development. Phase B refines science justifications and requirements and yields a detailed option definition, including technology, costs, and schedules. The Phase C/D sequences are the actual building, deployment, and operation of the experimental device. Reconciliation of science priorities with flight opportunities, budget cycles, equipment readiness, technology barriers, etc., leads to the determination of priorities and the actual costs and timetables required to complete the science objectives.

With the above as introduction and perspective, the participants were better prepared to discuss science requirements and possibilities for flight experimentation. These discussions were led, for the most part, by Frank Salisbury of Utah State University.

These discussions led to several propositions: 1) That perhaps flight-testing could help us answer questions not directly concerned with science; 2) that there were a number of problems– such as gas/liquid interface; 3) that a Detailed Test Objectives (DTO) program would be helpful (e.g., Brown's substrate moisture experiment); and 4) that convection vs. fan-driven air problems probably exist that can only be answered by flight-testing. (The comment was later made that propositions 2 and 4 require expert counsel.) These discussions prompted the agreed-with statement of Steven Schwartzkopf (U.C. Davis) that a flight program must consider two sets of questions: 1) Basic Science Issues and 2) Hardware Issues.

Satisfactory hardware support relates directly back to the concept expressed by Salisbury that, in order to maximize productivity, a stress-free environment must be provided. Therefore, constraining factors of flight must be overcome by hardware design and component flight-testing prior to conducting biological experimentation.

Defining the goal of experimentation to promote increased plant productivity, and in particular, to uncover the effects of flight conditions on productivity, led to a discussion centered around conditions which might affect experiment design and/or CELSS operation. Space radiation, both external (long-wave, ionizing) and internally provided (PAR), and microgravity (to 0.00001) were first considered; then other conditions of flight were regarded as influential, e.g., vibration and acceleration, fluid interfaces, and hardware requirements. The latter were considered in some detail during the second day.

With these considerations as background and the CELSS generic experiments as listed in the "Greenbook" (Addendum 3, not included in this Report) as constituting a kind of checklist, the group outlined a number of desirable end-points, the final product being an "ultimate experiment" unconstrained by limited flight opportunities and conditions of support. This list of CELSS flight experiments went through modifications influenced by subsequent discussion, expressed finally as a priority list of space experimentation important to the design of a CELSS operating with optimal productivity (Table 1).

The following list describes the highest-priority experiments in greater detail.

1. The measurement of possible micro-gravity-induced ethylene production as an indication of plant stress was considered to be important, perhaps vital, in interpreting response to the flight environment.

2. Photosynthesis and respiration studies are critical. They are primary measures of productivity and of gaseous interchange, two major categories of a BLSS (in addition to waste management).

3. Orientation response of stem and root under microgravity conditions is important, especially to hardware configuration and possible countermeasure design.

4. "Seed-to-seed" experiments with crop plants are necessary, especially where the edible product is a flowering vegetable. Production of nonflowering veg-

etables (e.g., lettuce) falls ultimately into this category since seed must be formed to ensure succession, vegetative propagation and exotic technologies (e.g., tissue culture) aside.

5. Partitioning of assimilates is related to the above. It is important to determine the quality and quantity of the major dietary constituents as influenced by growth in flight.

6. Microbial growth must be described because it may affect productivity and constitute a possible pathogenic hazard.

7. The study of reproductive development is important as it relates to fruit development. Flower initiation, pollination, and seed formation may be affected by microgravity. It is important to consider photo and thermal periodicism requirements or the artificial triggering of reproductive development.

8. Morphological development at all stages should be defined, including node elongation, tillering (in cereal grains), release of apical dominance, and tuber and root enlargement.

9. Algae or *lemna* experimentation was proposed as informative of basic productivity, organelle changes, genetic variation, and multigenerations of vegetative growth over relatively short-term studies.

In support of such experimentation, it was again emphasized that engineering tests assume a high priority in assuring satisfactory support of experimental material and in the development of components. Gale noted that, to supplement the effort of formally named PIs, it would be most efficient to have a team of plant physiologists from a variety of backgrounds prepared to analyze plants upon their return in order to extract the greatest amount of information from each experiment. Further, the importance of research on a number of different species as flight candidates for the above studies was mentioned as was a due consideration for acceleration, vibration, and other controls for providing standards of interpretation. This is critical because many plants, for one reason or another, may simply not grow well under flight conditions. Hence, a fair number (e.g., 12-15 species) of successfully ground-tested (in closed systems) plants should be made available.

Pearl Cheng of the Ames Life Sciences Project Office then gave a presentation on the proposed LifeSat reusable satellite. General consensus was that the power limitations of the vehicle would prohibit extensive use by the CELSS flight program, but that simple experiments, perhaps using the plant growth unit (PGU), would be appropriate and would offer the first realistic opportunity to begin addressing CELSS flight issues.

The prioritization of experiments was made with several constraints in mind. Lynn Griffiths spoke of flight opportunities and discussed approaches to minimizing constraints arising from competition for resources and flight time. For Space Station, a well-defined experimental protocol, including mass, power, and volume requirements, and equipment specifications and crew time, is essential. Such a protocol should be

TABLE 2: REQUIREMENTS FOR HARDWARE DEVELOPMENT

I. Basic Hardware Subsystems

A. Light System

1. 0 to 400-2000 μmoles/m^2/sec ± 5%
2. Controllable day/night cycle, set points
3. Uniform illumination
4. Wavelengths found in incandescent, fluorescent, and high-intensity discharge (HID) lamps
5. "Lights on/off" indication (intensity monitor optional)

B. Life Support System

1. Atmosphere constituent control (leaf and stem area)
   a. Total pressure control (P ±10%) (monitor within 1 mm Hg)
   b. Constituents (partial pressures??)
      1) O_2 — 23.8% ±5%
      2) CO_2 — 0 to 5000 ppm, ±0.2%
      3) H_2O (humidity) — 10-25 mm Hg ±5% ideal, ±10% acceptable; Controlled humidity; Day/night set points
      4) Ethylene — <5 ppb (control and monitor)
      5) N_2 — Makeup to obtain "P" pressure
   c. Integral gas chromatograph
   d. Scrubbing system for CO
   e. Scrubbing system for volatile organics
   f. Air flow — 0.1 to 1 m/sec; 100 to 400 vol/hr.; Mixed air (no "dead" areas in chambers)
   g. Air temperature — 10 to 35 °C ±5 °C; Day/night set points; 1 °C uniformity within chamber
2. Food/Nutrient Delivery (root zone)
   a. Liquid nutrient — Line-fed membrane/substrate; Use premixed makeup solution; Control pH (continuously); Monitor conductivity (continuously); Monitor and control specific elements in the nutrients (if possible/feasible); Monitor to trigger addition of pre-set amounts of nutrient
   b. Nutrient temperature 10 to 35 °C $\pm\frac{1}{2}$ °C at setpoints
   c. Pressure — Maintain slightly lower than growth pressure
   d. Gases — O_2 – nutrient > 80% saturated O_2 (7-8 ppm); CO_2 – $\leq$ 1% atm. above solution; N_2 – makeup to maintain pressure; Ethylene – < 5 ppb; H_2O – saturated

CONCLUSIONS

Certain summary conclusions can be drawn from the proceedings. There was general agreement that:

1. A CELSS Flight Experimentation Program is necessary based upon:
   a. the rationale of designing hardware functional in various space mission environments and ultimately in the microgravity and radiation environments of Lunar and Martian bases.
   b. the definition of science requirements arising from the need to optimize higher plant productivity in CELSS-supported missions.
2. The kind of information necessary for productivity assessment has been identified.
3. Generic experiments necessary to gather that information have been identified and prioritized.
4. General problems of hardware and equipment have been defined.
5. It is necessary for that hardware to provide a stress-free environment, not only to maximize productivity, but to also make more readily identifiable disturbing mission factors.

ADDENDUM 2

SCIENCE REQUIREMENTS

Facilitator: F. B. Salisbury
Utah State University

THE BASIC CELSS PROBLEMS:

1. PLANT PRODUCTION – this is the one that can use space experimentation.

   And that depends on where and how a CELSS is used: space station, long voyage, Lunar or Martian surface colony.

   But future development will determine how it might be used:

   > How big a problem is weightlessness?
   >
   > How expensive and how reliable can we make a CELSS?

   An important problem of plant production is that of CLOSURE; can we grow highly productive plants in a completely closed system?

2. FOOD PREPARATION – most important study, but probably does not need weightlessness experimentation for a while: only after we know whether plant production can be efficient in weightlessness.

3. WASTE DISPOSAL or RECYCLING – in the same catagory as food preparation.

4. CONTROL SYSTEMS – likewise, but this also involves question of closure.

THE BASIC FOOD-PRODUCTION PROBLEM: How will weightlessness affect productivity? All other problems are secondary, including all basic problems of the mechanisms of plant growth.

> If productivity is reduced (as seems quite possible, based on the few imperfect experiments that have been done), then we will ask why?
>
> Basic research might well be required to solve such a problem.
>
> But first we must see if there is a problem.
>
> SO FAR, PLANTS HAVE NEVER BEEN GROWN IN SPACE IN A RELATIVELY STRESS-FREE ENVIRONMENT!
>
> Actually, plants on Earth have never been grown in completely stress-free environment, although our plants come very close!

WHY DID WE FINALLY ACHIEVE SUCH HIGH YIELDS?

High CO2: 1200 μmol/mol. But this is "as usual."

Lower temperature than before (means longer life cycle): 20/15 °C.

A range of light levels: 400 to 2000 $\mu mol/m^2/s$.

Shorter photoperiod than before (also longer life cycle): 20 h.

Higher density than before: 2000 plants/m^2.

Rock wool, 5 to 10x field.

A bit higher phosphorus than before.

SOME MOST IMPORTANT CONCLUSIONS:

1. Yield is a straight-line function of irradiance! (NO SATURATION!)
2. Efficiency drops with increasing light.
3. At low light levels, efficiency is close to theoretical values.
4. The last tillers to form are not efficient (need uniculm).

SO WHAT ARE THE SCIENCE REQUIREMENTS FOR A GOOD CELSS EXPERIMENT IN SPACE?

1. Control of CO_2. (Too high quickly becomes toxic to plants.)
2. Control of temperature; should also cycle.
3. HIGH LIGHT LEVELS!!! (This is absolutely essential for CELSS test.)
4. Control of photoperiod. (Temperature might be more important.)
5. Control of humidity. (Not discussed much, but also important.)
6. A good support system that allows HIGH DENSITIES:
A CANOPY OF PLANTS!
7. TIME to complete a life cycle – or some significant portion of it.
8. Sufficient VOLUME for a mature crop.

WITH THAT AS A STARTER, LET THE COLLECTIVE MIND DETAIL FUTHER REQUIREMENTS.

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15. Supplementary Notes

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16. Abstract

This report summarizes a workshop held March 23 and 24, 1987 to establish a base upon which a CELSS flight experiment program will be developed. The kind of information necessary for productivity assessment was determined. In addition, generic experiments necessary to gather that information have been identified and prioritized. General problems of hardware and equipment have been defined. The need for the hardware to provide a stress-free environment, not only for productivity, but also to make more readily identifiable disturbing mission factors, was recognized.

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