BLSS: A CONTRIBUTION TO FUTURE LIFE SUPPORT

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ABSTRACT

For extended duration missions in space the supply of basic life-supporting ingredients represents a formidable logistics problem. Storage volume and launch weight of water, oxygen and food in a conventional non-regenerable life support system are directly proportional to the crew size and the length of the mission. In view of spacecraft payload limitations this will require that the carbon, or food, recycling loop, the third and final part in the life support system, be closed to further reduce logistics cost. This will be practical only if advanced life support systems can be developed in which metabolic waste products are regenerated and food is produced.

Biological Life Support Systems (BLSS) satisfy the space station environmental control functions and close the food cycle. A Biological Life Support System has to be a balanced ecological system, biotechnical in nature and consisting of some combination of human beings, animals, plants and microorganisms integrated with mechanical and physico-chemical hardware.

Numerous scientific space experiments have been delineated in recent years, the results of which are applicable to the support of BLSS concepts. Furthermore ecological life support systems have become subject to intensified studies and experiments both in the U.S. and the U.S.S.R. The Japanese have also conducted detailed preliminary studies.

Dornier System has in recent years undertaken an effort to define requirements and concepts and to analyse the feasibility of BLSS for space applications. Analyses of the BLSS energy-mass relation have been performed, and the possibilities to influence it to achieve advantages for the BLSS (compared with physico-chemical systems) have been determined. The major problem areas which need immediate attention have been defined, and a programme for the development of BLSS has been proposed.

INTRODUCTION

A new era of space exploration, utilization, and research is developing as man extends his time in extraterrestrial activity. It is expected that orbital activities, such as research and satellite servicing, will become routine. Potential uses for manned space stations include facilities for space astronomy, materials processing, biological research, and earth resources research. In these and other future space station activities, man with his unique mobility, work dexterity and adaptive decision-making capabilities will play an essential role. However, for extended duration missions in space the practical supply of basic life-supporting ingredients represents a formidable logistics problem. The weight at launch and the storage volume in weightlessness of water, oxygen and food in a conventional non-regenerable life support system are directly proportional to the crew size and the length of the space mission. In view of spacecraft payload limitations, the inescapable conclusion is that extended-duration manned space missions will be practical only if advanced life support systems can be developed in which metabolic waste products are regenerated and food is produced.

Only a Biological Life Support System (BLSS)*, which not only satisfies the space station environmental control function requirements, but also closes the food cycle, can meet all the expected requirements. A BLSS must be a balanced ecological system, biotechnical in nature and consisting of some combination of human beings, animals, plants and microorganisms integrated with mechanical and physico-chemical hardware /2/.

*Biological Life Support System (BLSS) is synonymous to Controlled Ecological Life Support System (CELSS) in this paper.

The final BLSS functional requirements for space application can be summarized by:

- Atmosphere maintenance,
- Waste water reclamation,
- Solid waste reclamation, and
- Food production.

Some basic factors of human/plant/microorganism cohabitability are understood, but additional research to provide basic knowledge in a number of technologies remains necessary.

Numerous scientific space experiments have been delineated in recent years, the results of which are applicable to the BLSS concept. To ensure that the efforts expended by various international bodies aim toward a common goal, the coordination with existing Spacelab and Shuttle utilization programmes is of major importance to avoid duplication of effort, and to gain early access to valuable data as early as possible. The analysis reported here is a result of a cooperative effort undertaken by Dornier System and Hamilton Standard in recent years to define requirements and concepts, and to analyze the feasibility of BLSS for space applications.

STATE OF THE ART

The development of manned space activities will most likely continue along the evolutionary lines that have so successfully guided the space programme to date. Along with progressively growing crew sizes, mission duration and complexity have increased dramatically since the first orbital flights in 1961-1962. Mission duration has progressed from the one to three orbits of the first Vostok and Mercury flights to the 84 days of the third Skylab flight and the 211 days of Salyut. From the initial, single objective of survival, mission objectives have increased to the achievement of major experiments, and the accomplishment of major operational missions, such as satellite launch, deployment, capture, repair and redeployment.

The Space Transportation System (STS), Shuttle Orbiter and Spacelab, are opening up the future expansion of manned space activities. The baseline STS capability is a seven day on-orbit mission.

Future use of space stations and larger scale operations are forecasted to continue in a progressive manner /1/. In concert with the evolution of man's activities in space, the technology to support these activities will require progressive development of today's space systems. Of major importance is the life support system. The latest U.S. and European manned space vehicles, the Space Shuttle Orbiter and the Spacelab, contain the same life support systems with expendable supplies, such as the systems used on the earlier manned space flights. However, the next phases of manned space flight development will provide substantial impetus to improve life support technology, and to reduce the dependency upon these expendable technologies. Figure 1 shows how improvements in life support technology might be implemented in conjunction with the mission growth scenario.

The life support systems for pre-Shuttle space missions evolved very little from the initial systems of Mercury to the present ones; the evolution to today's systems was largely one of technology refinement, as opposed to the technology replacement forecasted for the future. The only exception to this generalization was the CO_2 control system of Skylab, in which a regenerable molecular sieve system was used due to the extended duration of the mission.

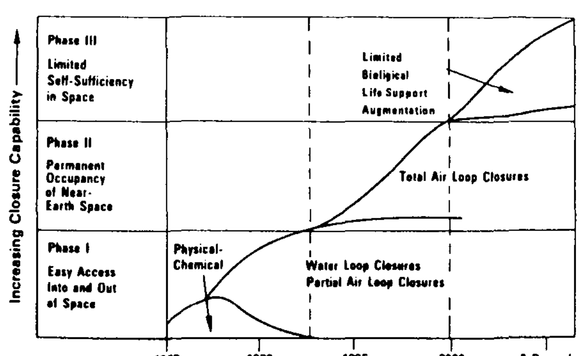

Fig. 1. Prospective evolution of life support systems /1/.

The next U.S. and European manned space objective is likely to be a space station. This permanently manned facility will presumably be resupplied on 90-day intervals and have a crew size of 4-8 astronauts. Such an on-orbit system is envisioned to have a large role in the commercialization of space activities, as well as playing a key role in continued development of space technology, primarily in the area of in-orbit operations. Because resupply from Earth of metabolic expendables (O_2, clean H_2O, food) incurs a high launch cost the space station life support system is expected to regenerate water and oxygen.

Beyond the initial space space station, future manned space missions include various missions that require large teams of humans working and living in space for extensive periods of time in permanently-inhabited large space stations. These space habitats will require the carbon loop to be closed to further reduce logistics costs. This recycling of carbon will only be partical if advanced life support systems can be developed in which metabolic waste products can be used to produce food (Figure 2).

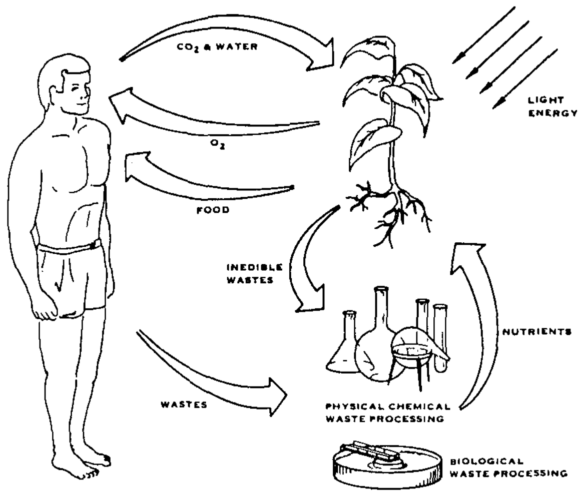

Fig. 2. Principal Biological Life Support System (BLSS).

Initial efforts to investigate advanced life support systems of the ecological/biological type to close the carbon loop (food supply), Figure 3, have been undertaken in the U.S. (Controlled Ecological Life Support Systems, CELSS) and in Europe (Biological Life Support Systems, BLSS) in recent years. During this decade, continuing efforts will concentrate on feasibility studies, investigations of specific development issues, and flight experiments to prove the viability of selected detailed designs or to provide basic scientific information in preparation for large scale testing on board a space station in the 1990's. As indicated in the literature, intensive experimental studies concerning BLSS are also being conducted in the U.S.S.R. and Japan as well. Both terrestrial and space experiments are being planned or performed.

The benefit of BLSS is primarily an economic one, because the cost of launching supplies into orbit to support manned space activities can be reduced by the use of a BLSS. The first, and relatively near potential application for BLSS is on a space station in a low earth orbit (LEO). An estimated systems trade-off between a non-biological (physico-chemical) regenerative system and a biological system with $\sim$ 80 % food closure is given in Figure 4.

Depending on the mission type and crew size the pay off varies from 6-7 years for a 4-man crew to about 1 1/2 year for a 100-man crew in LEO.

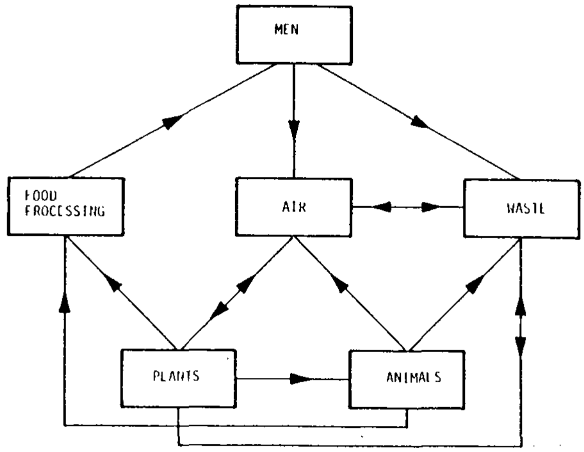

Fig. 3. Principle carbon mass flow in a closed system (BLSS).

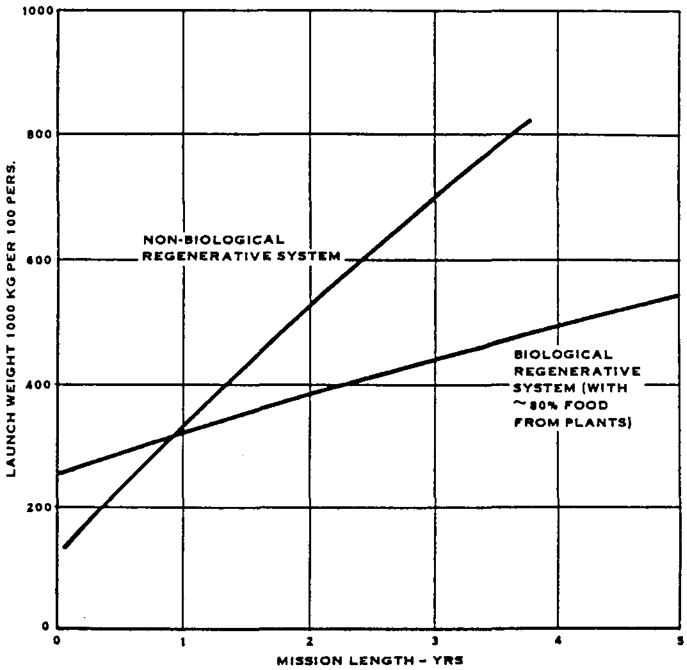

Fig. 4. Estimated systems trade-off for life support system alternatives.

BLSS REQUIREMENTS

In defining BLSS characteristics, it is important to consider potential space applications, which dictate BLSS functional requirements. A permanently manned space station or base has been used as the model for the following BLSS discussions, because this application embodies the essential complexities of most BLSS uses. As BLSS will represent only one of many subsystems integrated to form the space station, the BLSS design must take into account all potential inputs (e.g., gases, chemicals) from other subsystems if the resulting space station ecology is to be balanced and stable.

Space station life support functions can be more definitively specified as:

- Oxygen Production
- Carbon Dioxide Control and Reduction
- Contaminant Gas Control
- Two Gas Control and Pressure Regulation
- Humidity Control
- Thermal Control
- Solid Waste Reclamation
- Waste Water Reclamation

- Radiation Protection
- Illumination
- Artificial Gravity
- Food Supply (production and supply).

Ultimately, BLSS functional requirements for space application will be to supply oxygen, water and food for support of human life on a continuous basis, while maintaining a balanced, stable spacecraft ecology. The BLSS must satisfy both the Environmental Control and Food Production functional requirements of the space station listed above. While the precise BLSS components will be highly dependent on the space mission, it will probably consist of human, animal, plant and microorganisms integrated with other supporting physico-chemical components.

In an ideal scenario, a BLSS would be capable of perfect:

- metabolic balance between man's oxidative process and plants regenerative process,
- waste water reclamation, and
- mass-balanced regenerative food/waste cycle.

The closed system as presented in Figure 5 would represent this case. In a closed system, where the food supply might include both animal and plant species, no unusable residues would be produced. That is, a perfect regenerative balance of input and output quantities from human, animal and plant species would be maintained. In practice, however, total BLSS closure will not be achievable. At best, BLSS closure will be approached incrementally and only after intensive biological research effort. Representation of a partially closed BLSS is shown in Figure 6. Note the requirement for supplements to replace generated unusable waste products.

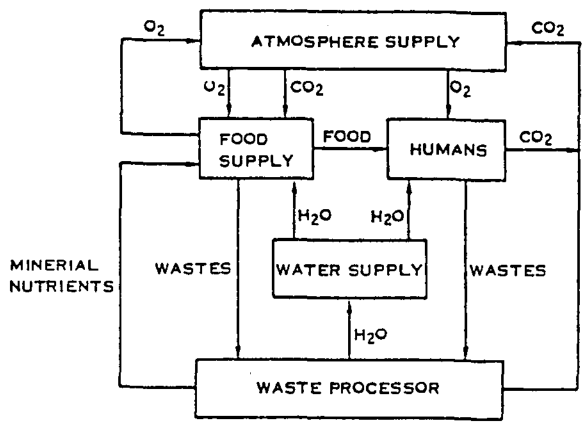

Fig. 5. Closed BLSS.

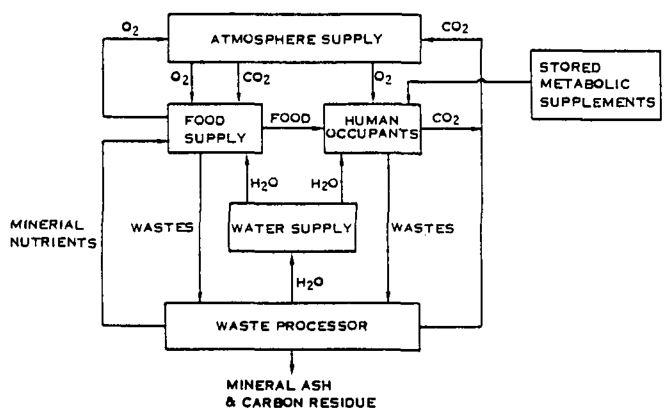

Fig. 6. Partially closed BLSS.

To expand upon the concepts introduced above, the BLSS must be balanced in the sense that proper proportions of CO_2, O_2, biomass, water, food reserves, etc., are maintained. The precise nature of this balance relates directly to BLSS's regenerative ability to convert waste products to usable products. In any practical BLSS, supplement additives to the system will periodically be required to maintain the desired ecological balance, because some unusable waste residues will always be produced. Such BLSS systems are said to be partially closed. Even if a closed BLSS could be achieved, the space station would still only exhibit limited self-sufficiency because resupply of consumables such as medicines, propellant fuels, clothing, replacement equipment, film, filters, etc., would be periodically required. Finally, even the simplest experimental closed biological systems, exposed to the same light and heat required by constituent species when in the earth's large open biosphere, eventually degrade in performance and die. Although this phenomenon is not entirely understood, it is believed to be linked to what has been defined as buffering capacity. Since space ecosystems are not expected to be self-regulating, an artificial buffering capacity, provided in the form of physico-chemical subsystems and a degree of human intervention, will be required to maintain stable biological processes.

Assessing the required life support functions (oxygen supply, food production and water reclamation) for a BLSS indicates that the food production requirement is the design driver for higher plants. A system sized for food production will be in the position to handle the other life support functions without an increase in size. Analyses of the BLSS energy-mass relation have been performed, and it appears possible to achieve advantages using the BLSS compared to physico-chemical systems. At equal energy consumption for a BLSS and a physico-chemical system, the break-even point of mass is in the order of 7 years. If the phototrophic efficiency could be increased over the 2 % used in this analysis the energy consumption would be higher for the BLSS, but it would show a weight advantage for shorter mission durations.

BLSS GENERAL DEVELOPMENT

The development of an operational biological life support system for space requires dual development paths /2/. In parallel to the selection of species plants and animals, the improvement of culturing methods and of waste treatment by experimental investigations, and mathematical models will be needed to decrease development risks of the prototype BLSS.

The development process (Figure 7) starts with the specification of the human diet and the vitamin and trace mineral requirements. Compatible with these human requirements and the environmental conditions of a space station, the next step would be to select the plant and animal species required. This selection will be reevaluated and retested as the development of a BLSS makes progress in the following areas:

- higher yield of cultures,
- waste treatment, and
- control mechanisms.

Many single experimental investigations in various disciplines will be necessary for the evaluation of the biological, chemical and technical basis for these areas before they can be integrated into subsystems, whose functional coupling and reliability under working conditions can be tested.

The theoretical approach, going hand in hand with the experimental one, will use mathematical models. These mathematical models should describe the functional couplings between all system components as well as their dynamic behaviour. The models should also define system stability and eventually form the basis for computerized control and management of the system, including problem prediction, trend analysis, crop forecasting, and logistical requirements predictions.

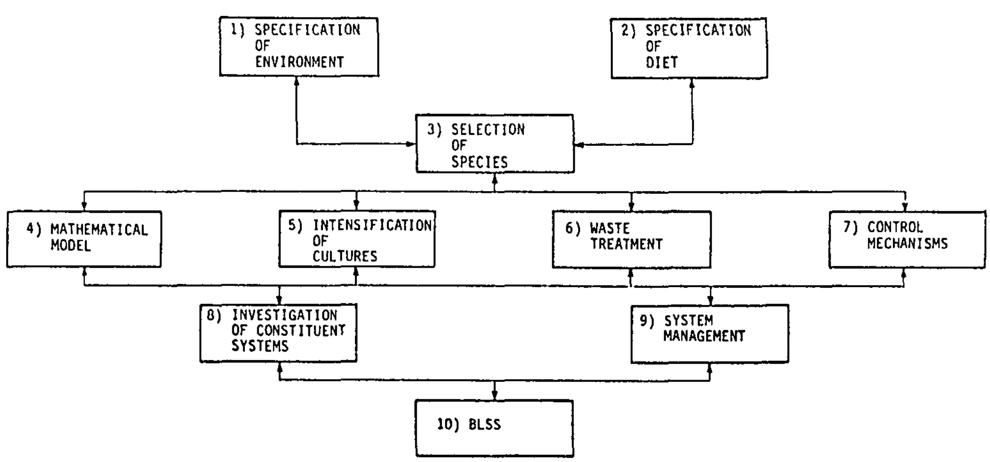

Fig. 7. Idea of the development process of a BLSS.

BLSS DEVELOPMENT APPROACH

The early state of development of the BLSS system is reflected by the large number of issues yet to be resolved in the definition of an operational system. Table 1 summarizes some basic developments yet to be undertaken in the areas of environment control, agriculture, aquaculture, food synthesis and processing, diets, and waste conversion. A development programme as outlined in Figure 7 is envisioned to sequentially address these issues in the development of a BLSS system /2, 3/.

TABLE 1 Basic BLSS Development Issues

REQUIRED BLSS SCIENTIFIC AND TECHNOLOGY DEVELOPMENTS
<u>Environment</u> - Materials selection - Atmosphere selection - Gravity selection - Radiation shielding requirements and methodology - Ecosystem tradeoff studies - Chemical analysis and control of contaminants and toxicants - Illumination requirements - Solar reflectors and filters
<u>Management and Control</u> - Critical biological performance parameters - Biological sensor development - Definition of biological stability criteria - BLSS mathematical models - BLSS management and control philosophy
<u>Agriculture</u> - Plant culture and physiology in space environments - Concepts to reduce spatial requirements - Equipment concepts for cultivation and harvesting - Radiation effect on genetic drift germination - Plant growth without soil - Forced growth effects on plants - Plant cycle photosynthesis efficiency - Plant hormone activity in micro-gravity - Plant production of toxic gases
<u>Aquaculture</u> - Food-producing ecologies based on waste conversion - High yield, high nutrition plant production and harvesting - Photosynthesis process
<u>Food Synthesis</u> - Acceptable microbiological sources and production methodology - Acceptable chemical synthetic production of protein and carbohydrates
<u>Food Processing</u> - New concepts for food preparation processing, storage, and distribution to reduce equipment and resource requirements - Improved food preservation and packaging methods
<u>Diet Planning</u> - Human nutritional requirements - Food and food-source selection criteria - Nutritional equivalency of various food sources - Physiological and psychological acceptability aspects of nonconventional diets and food sources - Definition of crop/plant scenarios - Digestive tract adaptability
<u>Waste Conversion and Resource Recovery</u> - Physico-chemical processes, particularly mineral separation and recovery - Microbiological processes - Regenerative chemical filters - Chemical separation methods - Auxiliary non-food products from wastes (e.g., paper and tools) - Plant waste byproduct processing.

Within the large list of BLSS issues to be resolved, there are a number of early technology tasks that can be performed in an initial test and development programme to lay a technological foundation for the eventual BLSS system evolution. These early key tasks are listed in Table 2.

These problems have to be subdivided into ones that absolutely require studies in space, and ones that can be studied and solved in terrestrial research programmes. Furthermore, priorities should be set as to whether the problem is relevant in the very near future (short-term relevance, pre-pilot type) or not (long-term relevance, pilot type).

TABLE 2 Problems to be Studied in Early BLSS Development

TASK	Pre-Pilot Type		Pilot Type	
	Terrestrial	Space	Terrestrial	Space
O-g influence during cultivation	x	x		x
O-g influence on culture-methods	x	x		x
Solar radiation in PAR region impact on biological material	x		x	x
Cosmic radiation	X	X		
Optimization of biological material	X	(X)	X	
Optimisation of cultivation methods	X	(X)	X	
Optimization of harvesting methods	(X)	(X)	X	X
Energy recycling	X		X	
Waste recycling	X		X	
Monitoring and Control	X	X	X	X
Improvement of mathematical modelling	X		X	
Selection of diet	X		X	
Development of large area windows for PAR and IR	X	X	X	X
Refined theoretical model	X		X	

( ) = need for exp. still to be defined
PAR = Photosynthetic Active Region
IR = Infrared

Generally speaking, only those problems need to be studied in space, which:

i) require a micro-gravity environment, and/or
ii) are cosmic radiation dependent.

As to i), perhaps problems arising in the micro-gravity environment of a BLSS may be solved on earth by studying the problems under increased g-force levels and directional attitudes of gravity, and then extrapolating the results to 0-g. This approach, in connection with sophisticated mathematical modelling, might be successful. If experiments have to be conducted under micro-gravity, it seems possible that only verification experiments may be necessary.

As to ii), it is clear that the simulation of cosmic radiation on earth is very difficult, and that appropriate experiments may have to be performed in space. However, the composition of cosmic radiation and its distribution in space is relatively well known, so that first order approximations are possible for certain experiments.

For all experimental activities, a prerequisite is that they focus on the applicability of certain biological features for BLSS. Therefore, questions concerning problems of basic life science are not to be studied, but results of such experiments might provide answers to certain questions relevant to BLSS.

Pre-Pilot Studies

Pre-pilot studies should center around the problem of providing the crew with a certain amount of fresh greens. The culture methods are characterized by the use of prepared beds or pots which contain a medium either in the form of solid fertile 'soil' (agar plate) or sponge-like substances. The interface of the BLSS with the spacecraft and with outer space (sunlight) should be as simple as possible. Direct sunlight would be preferred from an energy point-of-view, but because of multiple light-dark periods during each 24-hour day in low earth orbit, solar powered artificial light may be required.

The harvesting process should take place by cutting plants during their vegetative period. Species able to perform vegetative reproduction should be selected to shorten the duration between the harvesting periods; that is, the generative period during growth should be bypassed. Vegetative reproduction is usually supported by the method of stem-cutting. This method is also less crew-time consuming than sprouting from seed.

Below is a suggested listing of pre-pilot studies aimed at providing fresh greens:

Terrestrial activities.
(a) Test of stem-cut method for the following species:leek, dill, cabbage, endive, chicory, cress, parsley, and spinach.
All of these species grow leaves, which constitute the edible part of the biomass, hence the generative phase of growth can be bypassed.

(b) Optimization of the fertile soil with respect to the production of large amounts of biomass.

(c) Studies of the growth (orientation and propagation) of roots and sprouts under different intensities and directions of gravity forces.

(d) Studies of the effect of very high PAR (photosynthetic active region) intensities (up to 600 Wm^{-2} as is the case in low earth orbit) on photosynthetic efficiency and yield.

(e) Studies of the compatibility of species when cultivated simultaneously in the same greenhouse-like facility.

(f) Studies concerning the possibility of stimulating growth (yield) by hormones.

Activities in space.
(a) Verification of the results obtained in terrestrial growth studies if no unique interpretation of terrestrial experiments is possible.

(b) Study of the impact of cosmic radiation on biological material. BIOSTACK-like experiments with a window-like shielding of a material thought to be optimal for greenhouse windows in space.

(c) Production of certain species of edible greens in small scale to gain experience in cultivation and harvesting. These experiments will also fulfill the purpose of providing a certain diet variety by fresh vegetables.

Pilot Studies

Pilot studies focus on the design and testing of a terrestrial reference system which simulates the life support system with its biological subsystems intended for flight application. Reference systems have in the past been designed and tested along with the development of physico-chemical subsystems.

Whereas in pre-pilot studies principle aspects of BLSS are experimentally investigated, the aims of pilot design and testing of a reference system is to verify the selected principles for the closure of the water, atmosphere and carbon loops as a system. The successful experimental work performed to date with such systems led to the conclusion that the concept of a reference system is valid. Pilot studies should include both terrestrial and space activities.

Terrestrial activities. The major part of the work should only begin after careful analytical studies of subsystems and the complete system. On the other hand, with the broad spectrum of problems in mind, the terrestrial reference system should, as far as practical, be designed as a multipurpose and multi-user facility to allow the study of different approaches suggested by various disciplines of science and engineering before the determination of the flight configuration of the BLSS. The terrestrial investigations performed with a reference system constitute the indispensable basis for the development of a BLSS for flight application.

Activities in space. Although pilot studies are fairly well advanced in character, space activities in connection with these studies are to a certain extent equivalent with prepilot activities already defined. A typical example may be the micro-gravity testing of new promising species.

It is only in the final stage of the development of BLSS that pilot studies will occur in space. At this stage of development, complete biological subsystems are flown, possibly as some kind of parallel system to physico-chemical subsystems, activated only during a certain phase of the mission. Such a mission will occur before complete BLSS are implemented as the main life support system.

DEVELOPMENT OF BLSS EXPERIMENTS

The BLSS studies have indicated two blocks (pre-pilot and pilot type) of experiments and analysis which are required for the support and promotion of the development of BLSS (Table 2). The development of specific flight experiments should follow the generalized flow diagram (Figure 8). This approach takes into account the known typical BLSS design parameters for different types of species, and can also be used for the definition of new BLSS flight experiments and to evaluate modifications to planned experiments. A preliminary programme has been proposed indicating some potential BLSS experiments. These experiments investigate those areas with immediate impact upon the successful integration of a regenerable life support system into future manned space activities.

Tasks of immediate importance from a life support system development point-of-view are:

- investigations concerning micro-gravity,
- investigations concerning cosmic radiation,
- development of large area windows for radiation in the PAR-region,
- investigations concerning harvesting and cultivation in micro-gravity,
- monitoring, control and sensor technology, and
- waste processing.

Cosmic radiation studies are already planned, but those experiments dealing with micro-gravity and PAR-windows are only partly defined. Any efforts related to the PAR-windows should include systems analysis studies in the areas of:

- the correct wavelength needed for optimum growing conditions,
- avoidance of excessive heat load into the spacecraft, and
- use of day/night growing cycles.

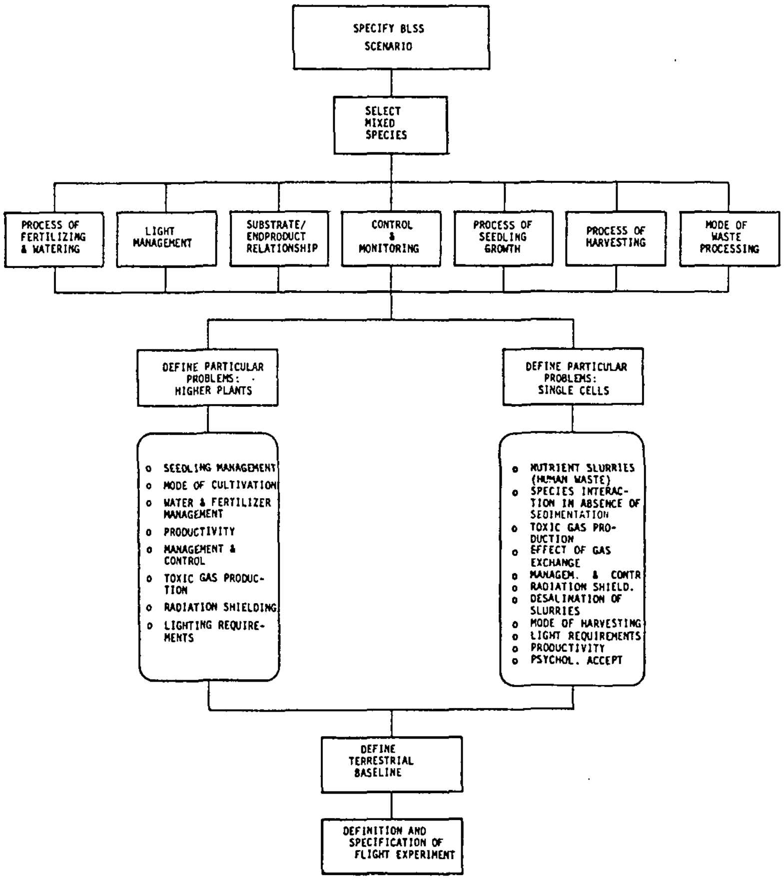

Fig. 8. Development of flight experiments for BLSS.

Concerning the cosmic radiation investigations, advanced experiments are planned and, in this case, the interpretation of results, and the subsequent influence on species selection are the major tasks in the BLSS development.

New experiments should have the dual goal of advancing the basic scientific research while meeting the BLSS requirements.

EUROPEAN ROLE

Due to the interdisciplinary character of BLSS, it will be necessary to engage many scientists of various disciplines in research and basic development of BLSS. The disciplines required, but not limited to, include:

- all kinds of biology,
- biochemistry,
- chemical engineering,
- ecology,
- cybernetics,
- physiology,
- medicine, and
- agriculture.

The development of new advanced life support systems on an ecological basis has just been initiated in different parts of the world (U.S., U.S.S.R., Europe, Japan). These systems can be tested and implemented on a space station towards the end of this century. The present life sciences and life support activities in Europe permit a projection of future activities until the end of the century (Figure 9). Europe has a strong position in many of the scientific disciplines relevant to this development activity (e.g. agriculture, botany, genetic engineering, biochemistry, physiology, ecology) and could become an important partner in the development of future life support systems for a permanent human presence in space.

The scientific and technology tasks to be performed to establish the basis for the design of an ecological life support system for space applications are very extensive and also well suited for international cooperation.

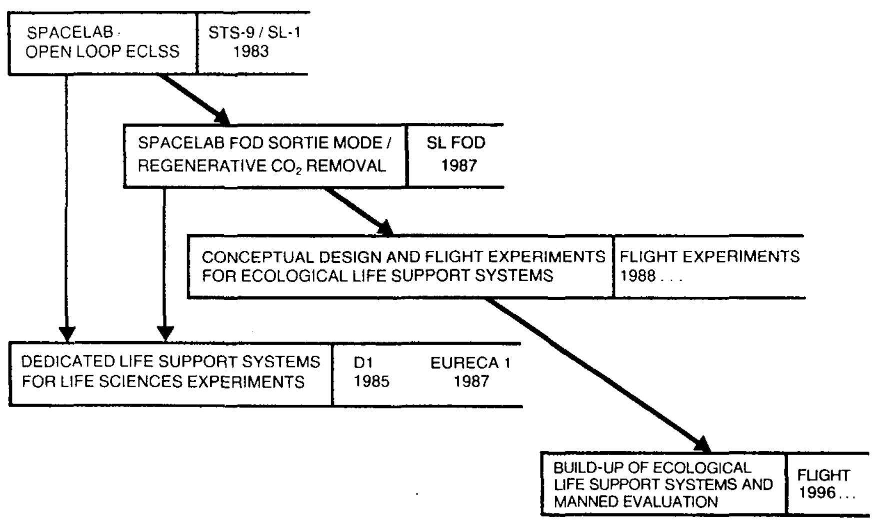

Fig. 9. Anticipated life support system development activities in Europe. (D1 refers to the first West German Spacelab flight; Eureca is an unmanned retrievable carrier.)

CONCLUSIONS

Several studies have revealed the benefits of a biological life support system to a space station by food production on-orbit from metabolic waste products. Problem areas requiring experimental and analytical investigations necessary for the development of BLSS have been identified. The nature of these problems allows for the classification into near-term (pre-pilot) and long-term (pilot) studies, and into terrestrial and space research programmes.

The knowledge of planned European and U.S. space experiments allows for a coordination with existing Spacelab and Shuttle programmes to avoid duplication of research efforts. The Japanese also plan biological experiments on Spacelab in 1988. Coordinating our efforts should provide answers to certain BLSS relevant questions.

Major areas which need immediate attention are:

- micro-gravity effects,
- cosmic radiation effects,
- use of PAR-radiation and high energy particle radiation protection, and
- monitoring and control (including sensor technology).

Relevant problem definitions and potential contacts with advisers in the scientific community are available. This allows for detailed definitions, tasks descriptions and programme planning as the next step in the development of BLSS.

ACKNOWLEDGEMENT

The work reported on in this paper has been performed as a cooperative effort between Dornier System and Hamilton Standard. Valuable support in preparing this paper has been given by A.O. Brouillet of Hamilton Standard and Dr. H.P. Leiseifer of Dornier System.

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