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CELSS AND REGENERATIVE LIFE SUPPORT FOR MANNED MISSIONS TO MARS

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ABSTRACT

In the mid 1990's, the Space Station will become a point from which inter-planetary vehicles can be launched. The practicalities of a manned Mars mission are now being studied, along with some newer concepts for human life support. Specifically, the use of organisms such as plants and algae as the basis for life support systems is now being actively considered. A Controlled Ecological Life Support System (CELSS) is composed of several facilities: (a) to grow photosynthetic plants or algae which will produce food, oxygen and potable water, and remove carbon dioxide exhaled by a crew; (b) to process biomass into food; (c) to oxidize organic wastes into CO_2; and (d) to maintain system operation and stability. Such a system, when compared to using materials stored at launch, may have distinct weight and cost advantages, depending upon crew size and mission duration, as well as phychological benefits for the crew. The use of the system during transit, as well as in establishing a re-visitable surface camp, will increase the attractiveness of the CELSS concept for life support on interplanetary missions.

INTRODUCTION

A manned mission to Mars has been a human dream ever since Percival Lowell (1) first began to popularize the planet as a place where highly advanced civilizations built canals to bring water from the polar regions to service cities at the equator. Unfortunately, no evidence of the "canali" sketched by Schaparelli in 1877 and by Lowell were revealed during the intensive, planet-wide scanning performed by the Viking orbiters; and no evidences for life, or even significant amounts of organic carbon, were detected by the Viking landers. Nevertheless, the Red Planet will probably be the first object that humans will visit outside of the Earth-Moon system.

Life support considerations for manned missions to Mars should include transit to and from the planet, the period of visit on the surface, and the possibility of leaving behind structures and equipment for subsequent visits, thus eventually making colonies easier to achieve. For these reasons, life support systems based on the use of biological components (primarily plants and algae) are discussed in this paper. These systems are generally termed Controlled (or Closed) Ecological Life Support Systems (CELSS).

CELSS CONCEPTS

The concept of CELSS is to provide for humans in space by regenerating life support materials as they are needed. A CELSS relies on photosynthetic organisms to regenerate food and oxygen from carbon dioxide and other waste materials. The reason for using such a system is to decrease the amount of material that must be launched from Earth for life suport purposes.

Biogeneration depends on the absortion of energy (light) by photosynthetic organisms (e.g. higher plants or algae). In the presence of light, plants absorb the principal human metabolic waste product, carbon dioxide, and elaborate it into materials that can be used as human food (Figure 1). At the same time, plants produce oxygen. For simplicity, the system is usually described as involving only plants or algae, however, the use of animals, ranging from shellfish through fish, birds and other small vertebrates, is not excluded.

The development of a CELSS solely for use on the Martian surface for a short (60 day) residence period is not likely to be economically justifiable. However, it is reasonable to expect that by the time a manned Mars mission is scheduled, a CELSS will have been developed independently for use on a "growth" Space Station (2), a second space platform, or for a Lunar Base (3). Moreover, if a CELSS were to be used in transit to and from Mars, and if a CELSS system were left in place for subsequent missions and visits, the economics of a CELSS system for a manned Mars mission would be positive.

CELSS FUNCTIONS

The major human life support requirements are well known. Figure 2 lists tha major input/output masses for one person (4). Food requirements are not just caloric, but must include specific nutrients: carbohydrates, protein, lipids, fibre, minerals and vitamins in acceptable ratios (5). Requirements for water include low salt content, as well as freedom from toxic materials and microorganisms. The demands for food

FIGURE 1. THE MAJOR MATERIAL FLOWS IN A CELSS.

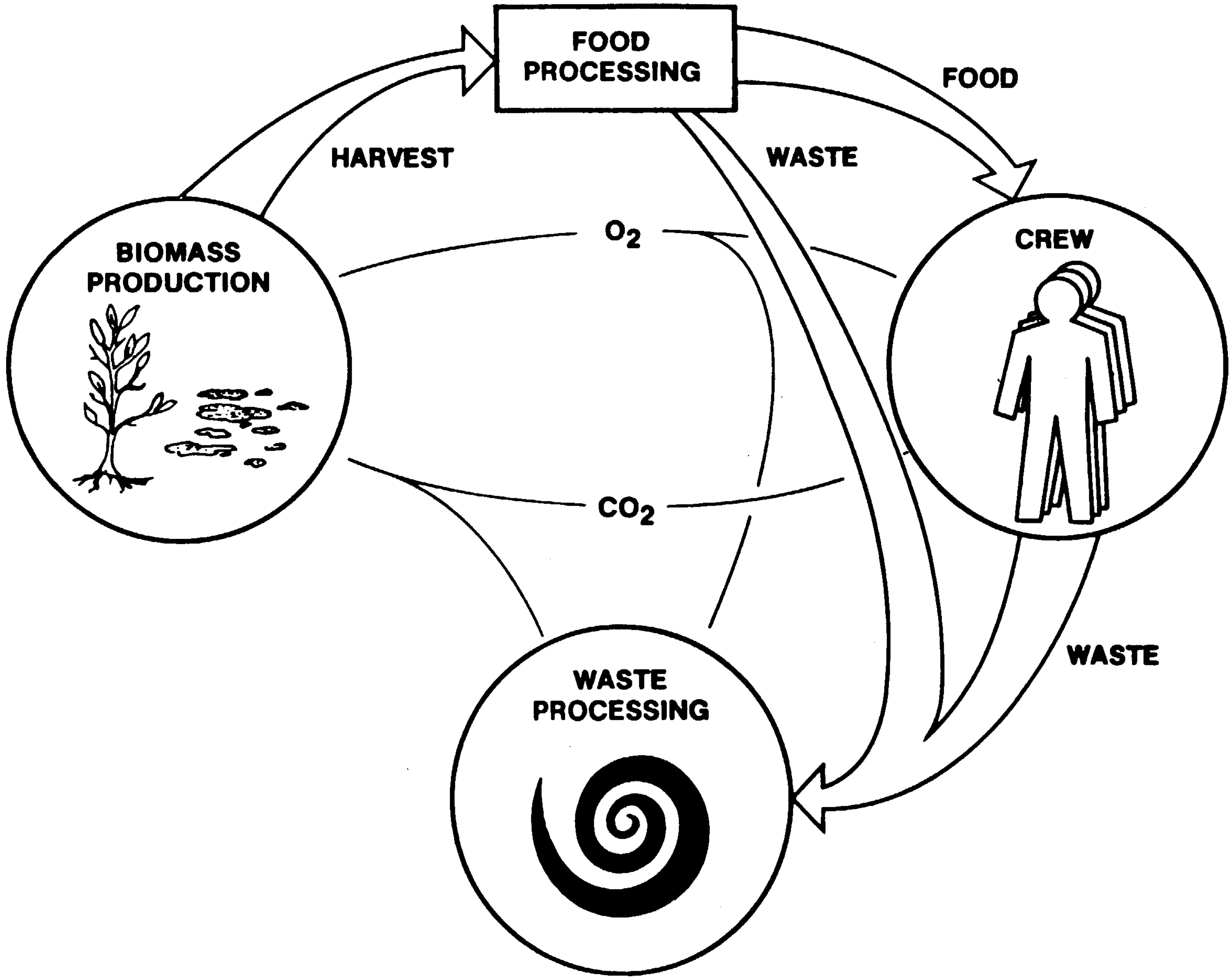
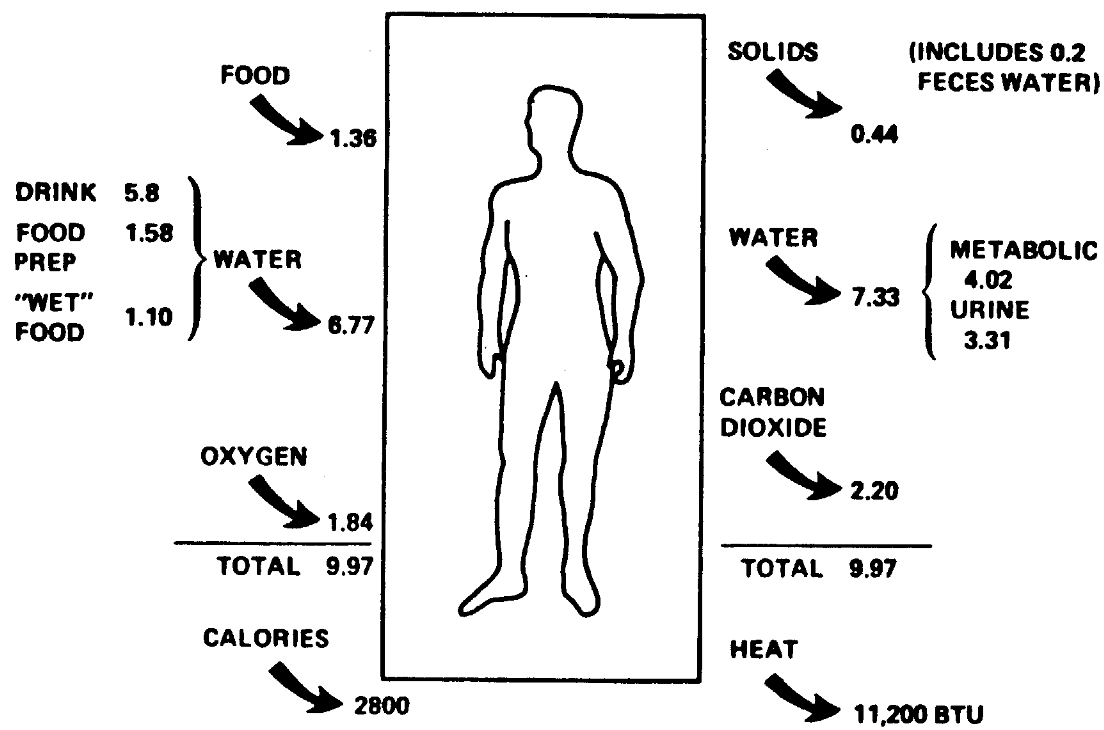


FIGURE 2. THE PRIMARY INPUT/OUTPUT MASSES OF A PERSON UNDER A MODERATE WORKLOAD, REQUIRING APPROXIMATELY 2800 CAL/DAY (AFTER OLSEN, ET AL., 1982, p 2). THE OXIDATION OF FOOD RESULTS IN THE PRODUCTION OF WATER AS WELL AS ENERGY.

HUMAN METABOLIC REQUIREMENTS (POUND/MAN-DAY)



FROM: GUSTAN, E. AND VINOPAL, T., CONTROLLED ECOLOGICAL LIFE SUPPORT SYSTEM: A TRANSPORTATION ANALYSIS. NASA-CR-166420. NASA-Ames Research Center MOFFETT FIELD, CA (1982) and water, as well as for oxygen, will vary according to the amount of crew activity.

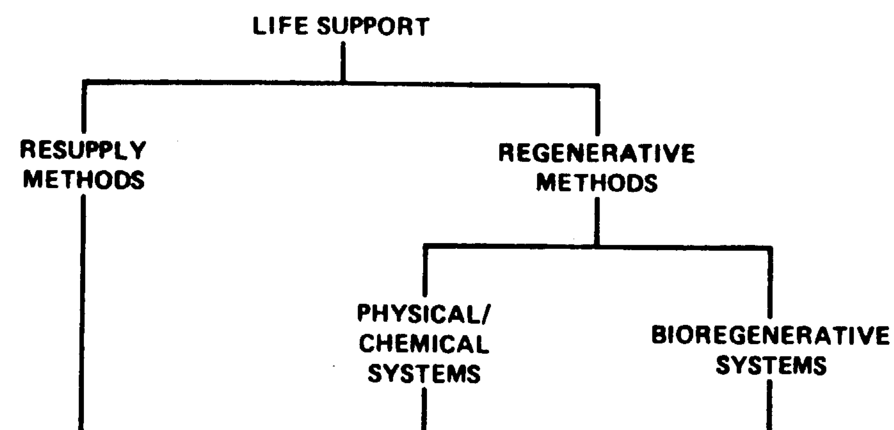
At the present time, life support requirements for Shuttle crews are met by taking as cargo the necessary materials: Food, water, and oxygen. Liquid and solid waste materials are collected in various ways and stored. Carbon dioxide is absorbed by lithium hydroxide and stored. This method of life support is very appropriate for small crews which are in space for relatively short periods of time. As crew sizes and/or mission durations grow, the cost of life support will become an increasingly significant fraction of total launch costs (6). Further, materials intended for life support will compete in weight and volume with other essentials such as equipment and fuel.

There are two options available to meet crew life support requirements (Figure 3). The first option ("resupply") allows for including all of the required materials at launch, or the establishment of unmanned resupply depots containing life support materials, a scenario that is unlikely on the first voyages to Mars. The second option is to regenerate the necessary materials partially or fully from waste materials. Depending upon the extent of recycling and regeneration, the last option can offer considerable savings in launch costs and in space habitat volumes.

Life support technology presently under development uses physical and chemical techniques to partially regenerate oxygen and potable water from waste materials. The carbon dioxide produced by the crew, instead of being absorbed by lithium hydroxide as it is at present, will be concentrated and processed to release the oxygen it contains. Used water, particularly wash water and exhaled vapor, will be reclaimed by removing materials dissolved or suspended in it. The equipment necessary for these processes has been developed under programs operating through NASA/Ames and NASA/Johnson, (see Quattrone (7), 1984 for a thorough review), and by several private companies (8).

Recycling part of the water and regenerating part of the oxygen needed for life suport will go a long way to decrease the mass and volume of materials required for life support. However, because the recycling of materials is incomplete, and because food is not regenerated, a significant mass of life support material will have to be launched from Earth.

FIGURE 3. CLASSIFICATION OF VARIOUS LIFE–SUPPORT TECHNIQUES.



O_2	STORED	FROM CO_2	FROM PLANTS
CO_2	LiOH ADSORBED	1. AMINE ADSORBED 2. CONC./REDUCED	TO PLANTS
H_2O	STORED	1. DISTILLATION 2. MEMBRANE/EVAP.	PLANT TRANSPIRATION
FOOD	STORED	STORED	PRODUCED
WASTE	STORED	STORED	RECYCLED

Methods that rely solely on chemical or physical means for regenerating food are unlikely to be practicable before the turn of the century, and may never supply all human nutritional needs. It is of interest, therefore, to use methods that were evolved by the photosynthetic organisms that are the fundamental suppliers of all of the food and oxygen that we use on Earth. Photosynthesis has the advantage that it simultaneously accomplishes three tasks necessary for human sustenance. (1) It directly uses the major human metabolic waste product, carbon dioxide; (2) it chemically reacts CO_2 with water to create the organic materials that we use as food; and (3) it produces essential oxygen. In addition, since water is the transporter of materials in vascular plants, and is rapidly passed from the plant to the atmosphere, higher plants can act to purify water.

SYSTEM CONTROL

An engineered, biogenerative life support system, such as CELSS, will depend upon the same biological processes that support life on Earth. However, it is obvious that the collection of plants, bacteria and animals on Earth are controlled in some way, so that there is a regulation of the abundance of different kinds of organisms, and consequently, in the concentrations of gases in the atmosphere and of solutes in the water. In essence, there are controls that maintain the stability of the environment. The kinds of controls that are operative in the natural environment are the objects of study of the discipline of ecology.

The distinction between the functioning of Earth's life support system and that of a smaller-scale, engineered life support system is primarily complexity. Each living organism in the natural system is "connected" with many others through a large number of interfaces, and controlled by activities such as access to nutrient supplies, competition for light, space or nutrients, predation, etc. A CELSS in space will have some of the same interrelationships, and many of the same physical structures and processes as the massive terrestrial life support system. But to a significant extent, the interfaces and system processes will have to be identified and stringently controlled. The reason is that an engineered bioregenerative system will be very small compared to terrestrial systems, and it will have to operate productively at a much higher rate, yet it will have to be at least as stable as a terrestrial system. Achievement of long-term stable and productive CELSS operation will require system control at levels not yet generally practiced (9, 10). This is a primary engineering problem for CELSS, and one which many Soviet scientists and technicians have been working on steadily for the past decade in their human-scale BIOS series of experimental life support systems.

CELSS COMPONENTS

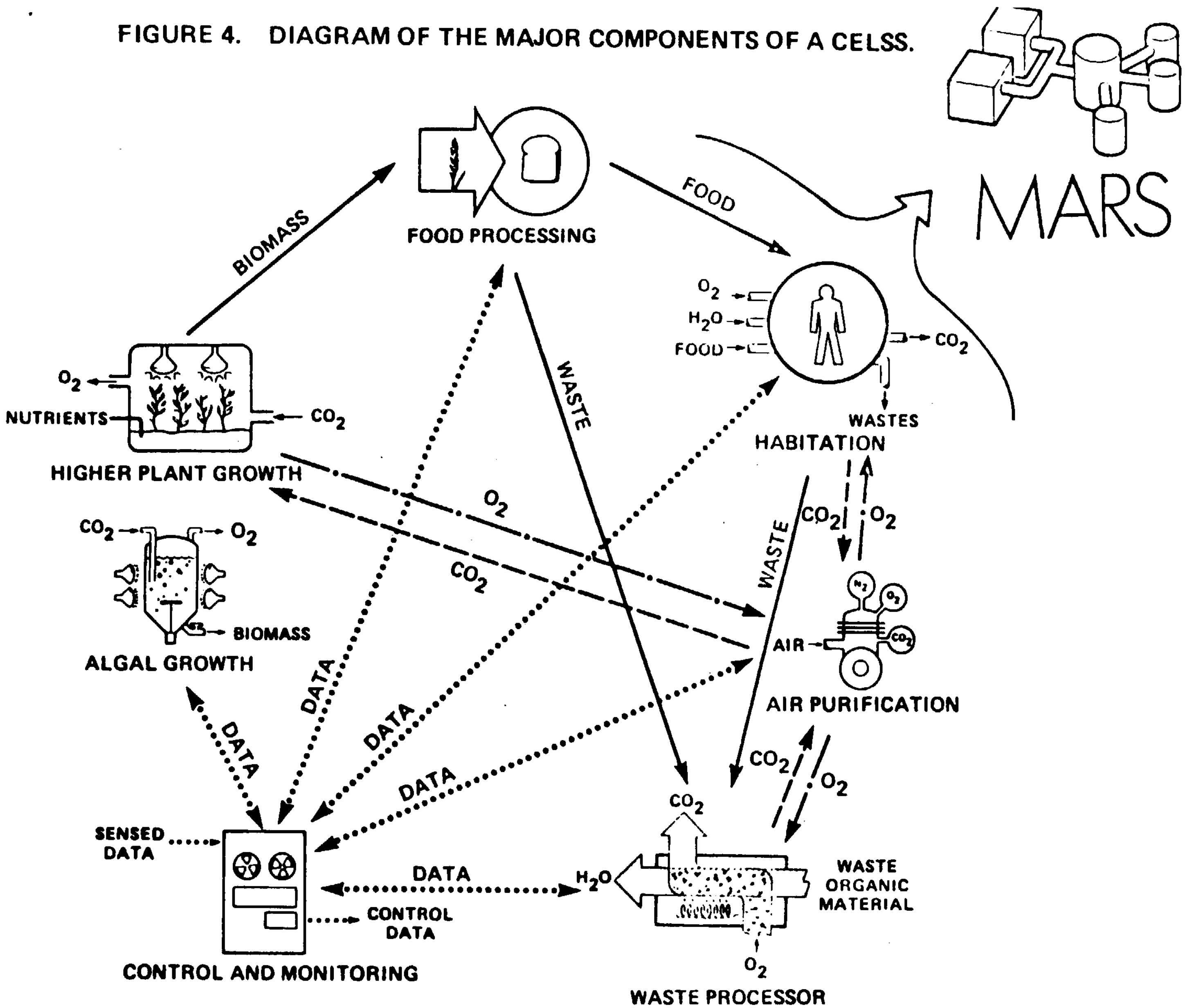
Figure 4 is a diagram of the components of a CELSS. The system will require modules for growing photosynthetic organisms, for processing food from plants, for processing waste materials, for treating water (removal of salts and micro-organisms), for separating gases, for storage of gases, liquids and solids, and for computer control of the system.

Of these components, the largest and the one requiring most power, is the plant or algal growth system. A plant growth system will require lighting with intensities between 10 and 1200 micro-Einsteins/m^2/sec, over a wavelength range from 400 nm to 800 nm. Because, in practice, less than 20% of incident radiation is utilized for chemical reactions, 80% of the incident energy must be removed as heat. Therefore, cooling devices must be incorporated into the growth systems. Cooling surfaces are also needed to maintain humidity between 60 and 95% (relative), as well as to collect water transpired by the plants.

Plant roots will be supplied with nutrients dissolved in water, and maintained at required levels by automated machinery. The plants' roots must be supplied with oxygen, and the stem portions of the plants must be supplied with carbon dioxide. Since during photosynthesis the plants produce oxygen, a gas separation system must be developed to "harvest" O_2 and supply to the plant growth units concentrations of CO_2 higher than is comfortable for a crew. Automated plant cultivation techniques will be required, as will automated food harvesting and food processing techniques, to conserve valuable crew time.

Between 20% and 60% of a plant's mass (depending on the species, and the plant's age) is material that is normally considered to be inedible. However, this material contains nutrients valuable in the human diet, if extracted properly. Cellulose can be converted to sugars, and high

FIGURE 4. DIAGRAM OF THE MAJOR COMPONENTS OF A CELSS.



quality protein can be easily extracted. The remainder of the material can be considered waste, and along with solid and liquid human waste, can be completely oxidized to produce CO_2. Several kinds of waste processors have been investigated: the one that is apparently most efficient (the super-critical water reactor) operates continuously to raise the temperature of a very small volume (about 10 ml) of waste slurry to about 500 C at a pressure of about 250 kg/cm^2 (about 3500 psi). Oxidation is complete in less than 1 second.

PHYSICAL REQUIREMENTS: MASS, POWER, VOLUME

The largest mass requirements in a CELSS are for water, and for plant growth and food processing equipment. Recycling machinery, such as waste and gas processors, constitute a smaller fraction of the total required mass. The masses involved have relatively low densities and will pose no problems for terrestrial lift-off vehicles.

More significant than mass is the volume required for the placement and operation of a CELSS. Volume is dependent on the biological productivity of the system. At the present time, sufficient food can be produced by higher plants, growing and being harvested continously, in an area of about 20 m^2/person. Such a cultivated area is able to supply 2800 calories/day. A mix of plant species can provide the variety of nutrients required in the human diet, but it is likely that preserved foods, such as meats, will supplement diets. An area 20 m^2 will require a height that is dependent on the species and on the growth phase of the plant. Young plants are short, and can be grown in smaller volumes than mature plants; wheat, particularly the short cultivars, can be grown in smaller volumes than soybeans or potatoes. Based upon current area requirements, and assuming dynamic changes in the growth support structures and equipment as the plants mature, a total volume estimate has been made.

PACKING

Recent work by Mel Oleson of Boeing Aerospace (11) has involved the packing of some unique designs for CELSS plant growth equipment within a "standard" Space Station module. The concept is that the system is an experimental one which would be used to investigate micro-gravity effects on all of the component's operations, including the plants. The sizing of the system is based on laboratory data for continuous production of sufficient wheat to meet daily caloric requirements (20 m^2 per person). The plant growth units, waste processing system and the storage reservoirs, sufficient to support 100% of all food requirements for 2.5 crew members, would occupy 4.6 to 5.2 meters of a module 4.5 meters in diameter (72 to 81.7 m^3).

DISCUSSION

It is anticipated that NASA's CELSS program will construct a series of increasingly automated and closed ecological systems during the next decade. It is further anticipated that a small experimental CELSS will be flown on the Space Station to determine the effects of fractional and micro-gravity on both the organisms and the devices that compose the system. Similar directions have been followed by Russian space scientists for the past two decades (12), and European (13) and Japanese (14) scientists have evidenced considerable interest in the problem. The literature in the field is growing rapidly, and the assumption is readily made that practical development of a system is based on sound theoretical grounds. The problems remaining are primarily technological, and their solution appears to be well within grasp.

The critical issues that must be addressed are: The production by organisms of sufficient food, water and oxygen for crews within the mass, power and volume constraints posed by space flight; the stability of a large system whose dynamics are dependent on a variety of organisms; the effects of fractional- and micro-gravity on the higher plants (see, for example, 15) that will probably form the primary source of food; and the extent to which human involvement will be required for system maintenance, or can be effectively replaced by automation and robotics.

The use of a CELSS for human life support during a flight to Mars appears to be within the constraints of the mission, particularly if it were designed to be functional during transit, and was then dropped for use on the Mars surface. Although it would be useful on the surface only for the short period of the human visit, it is one of the major items, requiring many years of lead-time for development unique to manned missions. Once on the Martian surface, it can be re-used by subsequent landing parties.

The existence of a CELSS on the surface would stimulate extensive scientific investigation of the utility of Martian materials in supporting terrestrial organisms. The most abundant gas in the martian atmosphere is CO_2, which is required by a CELSS. One of the least abundant gases is oxygen, which is produced by a CELSS. With properly developed scenarios, an automated CELSS, operating even after the departure of the human crew, might function to accumulate stores of oxygen and biomass useful to crews on subsequent visits to the Martian surface.

Long-term planning and international coordination by life science researchers can efficiently distribute the effort of developing a CELSS among technologically advanced nations, and can create a spirit of co-operation in an essentially non-sensitive area of technology development. Such a cooperation is a logical first step to synchronize a common human effort to visit, for the first time, another planet-the Red Planet, Mars.

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