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Nutritional and Cultural Aspects of Plant Species Selection for a Controlled Ecological Life Support System

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CELSS

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I. Introduction

As space missions become of progressively longer duration, it will eventually become necessary to recycle many or all nutrients required for sustenance of the crew. Estimation of "break-even", the point in time when it becomes more cost efficient to recycle rather than to transport required supplies, has been the subject of previous studies (30,33,67,68). Such estimates in terms of flight duration have ranged from five to twenty-five years and are based on assumptions and extrapolated projections involving factors with which we have little experience.

Several different recycling systems have been considered (9,12,19,20,25,30, 33,34,46,48,51,57,62,67,68,73,78) ranging from synthetic reconstitution of nutrients from waste materials to an ecological system incorporating a range of organisms including animals, higher plants, algae, yeast, other microbes, and ultimately, humans.

With input of energy, living organisms can convert biological waste materials into nutrients in forms and quantities adequate for maintenance of humans in a pyramidal food chain. Such a system would be a miniature ecosystem in which homeostasis is achieved, not by interplay of "natural" forces, but by human management. The number and seriousness of problems associated with maintaining balance in a "managed" ecosystem are considered to increase exponentially with number of participating organisms, while the overall utilization efficiency of materials and energy decreases exponentially with number of steps in the food chain (63). For these reasons, it is desirable to simplify a regenerating system as much as possible, to keep the number of participating species to a minimum, while achieving adequate physical and psychological maintenance of humans.

We explore in this report the feasibility of a system composed of autotrophic organisms (higher plants) and one heterotroph (humans) in fulfilling the life support needs of that heterotroph. This concept envisions humans existing on a strictly vegetarian diet and has been proposed by a number of investigators (6,9,20,33,46,67,78). A recent report on the use of higher plants in regenerative life support systems discusses several aspects of nutritional importance in such a scenario and suggests plant species that most likely should be included (68). The feasibility of such a system is continually demonstrated on Earth by various ethnic and religious groups which sustain life on such diets (1,5,6,61,81,82).

But space travel brings about constraints not present on Earth. Space, energy, and mass will be limited onboard spacecraft; the number of plant species that can be grown at any one time will severly limit their selection relative to the number available to vegetarians on Earth. Furthermore, the absence of gravitational force may create problems of plant culture and development.

We originally felt that our task was to disregard theoretical limitations and to select plant species that would best fulfill human nutritional needs. However, we were soon persuaded that considerations of limited energy, space, and mass cannot be disregarded, and that problems relating to cultivation and management of plants, food processing, the psychological impact of vegetarian diets, and plant propagation must influence the selection procedure. We became convinced that our efforts would be futile in the absence of such considerations and our report would have been irrelevant in the context of reality.

In view of the present vagueness of defined parameters for long duration space flight, one also cannot presume that the assumptions included herein will escape the test of time. As more concrete concepts concerning energy, space, and mass constraints evolve, and as present voids in knowledge are filled in by ongoing research, it is to be expected that further modification of present ideas will be necessary. Thus, one cannot exclude the possiblity that systems involving animals as well as plants eventually will prove economical, fulfilling, and will be more easily managed than are systems considered here.

II. Human Nutritional Concerns in CELSS

A controlled ecology life support system (CELSS) will constitute a unique environment for its human inhabitants, and can be anticipated to have profound implications for many aspects of human nutrition. On the one hand, inhabitants will be faced with the psychological impact of confinement, isolation, crowding, monotony, anxiety, and boredom, with their consequent influences on food preference and intake. On the other hand, our ability to cope with food preferences, with normal or aberrant appetites, is severely limited by the absence of animal-derived foods. The resulting problems can be expected to provide great challenges for food scientists.

We will in this section discuss the subject of human nutritional requirements in the context of the CELSS environment and provide, when considered necessary for general understanding, some background of common nutritional nature. At the same time, one also must consider human nutritional requirements in the context of psychological stress, as well as abnormal physical activity (inactivity vs. strenuous exercise), abnormal temperature, disease, or extraterrestrial activity (hypogravity).

The Daily Recommended Allowances (RDA) (53) of essential nutrients constitute the major reference point for dietary considerations in this country, and has been used in planning diets for previous space missions (Table 1). In the context of CELSS, one must realize that the RDA is assumed to be provided by "as varied a selection of foods as practicable", and that dietary needs of still unrecognized nutrients, or of nutrients for which requirements still have not been established, may not necessarily be met if foods are derived from sources substantially different than those ordinarily consumed by Americans. Dietary recommendations issued by FAO/WHO (16) differ from those of the RDA due to variation in food availability and composition throughout the world (39).

Table 1. Dietary Recommendations vs. Practices

Nutrient	NRC[1] (RDA)	FAO/WHO[2]	SKYLAB[3]	VEGETARIAN[4]
Energy kcal	2700(2300-3100)	3000	RDA	1970
Protein g	56	37-62	90-125±10	65.4
Vit. A μg	1000	750	RDA	2102
Vit. D μg	5 (200 I.U.)	100 I.U.	RDA	-
Vit. E mg	10	-	RDA	-
Vit. C mg	60	30	RDA	180
Thiamin mg	1.4	1.2	RDA	1.9
Riboflavin mg	1.6	1.7	RDA	1.2
Niacin mg	18	19.8	RDA	18
Vit. B_6 mg	2.2	-	RDA	-
Folacin μg	400	200	RDA	-
Vit. B_{12} μg	3	2	RDA	0
Calcium mg	800	400-500	750-850±16	594
Phosphorus mg	800	-	1500-1700±120	1368
Magnesium mg	350	-	300-400±100	-
Iron mg	10 (man)	9 (man)	RDA	19
	18 (woman)	28 (woman)	-	-
Zinc mg	15	-	RDA	-
Iodine μg	150	-	RDA	-
Sodium g	1.1-3.3	-	3.0-6.0±0.5	2.2
Potassium mg	1525-4575	-	2740 min.	4100

[1]Ref. 53

[2]Ref. 16

[3]Ref. 41, 52

[4]VEG.: Average calculated values of a 14-day vegetarian cycle menu developed from communication with practicing strict vegetarians and other sources (15, 64).

Food Energy:

The caloric needs of a person are determined by body weight and height (or total surface area), as well as by physical activity and environmental conditions (e.g., temperature). It is not likely that these basic relationships will be altered in a CELSS. Fats and carbohydrates are the main contributors of calories in most diets, although if the diet contains excess of proteins, these also will contribute significantly to total caloric intake. Caloric contribution by hemicelluloses, pectins, and "fibrous" materials occurring in substantial quantities in plants is very small due to the inability of the human digestive system to utilize them. Fats and carbohydrates most likely will continue to be the mainstay of caloric needs in CELSS. Of course, caloric requirements are greatly influenced by physical activity (Table 2). The RDA is intended for people that lead a relatively sedentary life, with only moderate to low levels of physical exertion. If we assume that the inhabitants of CELSS will live under similar circumstances, then it is obvious that the RDA level should be adequate. If, however, one visualizes CELSS in a space setting, where extravehicular activity in terms of strenuous construction work might take place over extended periods of time, additional caloric input might be required (66).

Low ambient temperature in the absence of protective clothing will enhance the caloric requirement to maintain body temperature. In the absence of stipulations to the contrary, we assume that temperature and humidity will be in the comfort range and that abnormal conditions will not have to be considered. Other stress factors such as anxiety, boredom, tension, and disease generally have negative effects on appetite, and may result in a temporary decrease of caloric intake, following which there may be a recuperative period with gradually increasing caloric intake that eventually may exceed the norm

Table 2. Energy Expenditure and Physical Activity*

Activity	$kcal \cdot hr^{-1}$
Sleeping	65
Sitting	100
Walking	250
Running	570
Dishwashing	144
Carpentry	240
Sawing wood	480

*For a 70-kg male subject. From ref. 23.

until weight loss has been regained. Means must be present in CELSS to provide for such exigencies, namely foods composed and processed according to requirements for convalescence. These foods generally are characterized by ease of digestibility, low in fiber and fat, and high in protein.

Protein:

The minimum RDA is based on the assumption that it will be supplied as "good quality" protein, and is 30% above the average requirement to cover minimal needs (Table 3). It also is corrected for incomplete utilization by assigning a factor of 75% to the digestibility of dietary protein. Both assumptions may have to be modified for CELSS. Protein quality is an imprecise term which cannot be easily quantified. More meaningful is the concept of "Biological Value" (BV), at least when considering adults (Table 4), and "Nitrogen Balance" (NB), both of which are applicable to mixtures of proteins and to complete diets. The proteins in the average American diet are to a major extent derived from animal sources, and generally have high BV and digestibility relative to plant proteins (Table 5). Another difference between animal and plant proteins involves their essential amino acid content (Table 6). Plant proteins generally are deficient in one or more essential amino acids. Since all essential amino acids must be present simultaneously and in the correct proportions in tissues when protein synthesis takes place, deficiencies of particular amino acid will correspondingly affect the extent of tissue maintenance and repair.

The "most limiting amino acid" (underlined in Table 6) in cereal proteins usually is lysine, whereas that of legume seed most often is methionine or total sulfur amino acids (methionine plus cysteine). If a vegetarian meal is composed of cereal and legume seeds, there occurs a "complementation" whereby any deficiencies of amino acids in one component are to some degree overcome by

Table 3. Protein Allowance vs. Protein Requirement

	$g \cdot kg^{-1} \cdot day^{-1}$*
Requirement	0.47
Individual variation (+ 30%)	0.60
Utilization efficiency (75%)	0.80

70-kg man: $56 g \cdot day^{-1}$
58-kg woman: $46 g \cdot day^{-1}$

*high quality protein assumed. From ref. 53

Table 4. Biological Value and Protein Efficiency Ratio of Food Proteins.*

Food	BV[1]	PER[2]
Maize	59	1.12
Oats	65	2.25
Rice	64	2.18
Wheat	65	1.53
Beans	58	1.48
Peanuts	55	1.65
Peas	64	1.57
Beef	74	2.30
Egg	94	3.92
Fish	74	3.55
Milk	85	3.09
Casein	80	2.88

[1]BV = Biological Value: (nitrogen retained/nitrogen absorbed) x 100

[2]PER = Protein Efficiency Ratio: weight gain/protein intake

*Data from ref. 4

Table 5. Digestibility of Food Proteins.*

Food	Coefficient of Digestibility %	Food	Coefficient of Digestibility %
Eggs	97	Rice, brown	75
Fish, meat	97	Rye flour	67
Milk	97	Sorghum	20
Cornmeal	60	Wheat	79
Oatmeal	76	Potatoes	74
Legumes: (soybeans, drybeans cowpeas, peas)	78	Leafy vegetables	65

*Data from ref. 79

Table 6. Essential Amino Acid Composition of Food Proteins (grams per 100 g protein)*

Amino Acid	White potato	Sweet potato	Oats	Rice	Wheat	Corn	Peanut	Soybean	Rye	Sorghum	Barley	Grass Leaves	Casein
Histidine	2.2	1.4	2.3	1.7	2.1	2.5	2.1	2.9	2.3	1.9	1.9	2.0	3.2
Lysine	8.3	4.3	3.6	3.2	2.7	2.3	3.0	6.8	4.1	2.7	3.4	5.5	8.5
Tryptophan	2.1	1.8	1.3	1.3	1.2	0.6	1.0	1.4	1.1	1.1	1.2	2.2	1.3
Phenylalanine	5.9	4.3	5.1	5.0	5.1	5.0	5.1	5.3	4.7	5.0	5.2	5.6	6.3
Methione	2.5	1.7	2.0	3.0	2.5	3.1	1.0	1.7	1.6	1.7	1.5	2.5	3.5
Threonine	6.9	3.8	3.6	3.8	3.3	3.7	1.6	3.9	3.7	3.6	3.4	5.4	4.5
Leucine	9.6	4.8	8.0	8.2	7.0	15.0	6.7	8.0	6.7	16.1	7.0	10.0	10.0
Isoleucine	3.7	3.6	4.9	5.2	4.0	6.4	4.6	6.0	4.3	5.4	4.3	5.0	7.5
Valine	5.3	5.6	5.4	6.2	4.3	5.3	4.4	5.3	5.2	5.7	5.0	5.0	7.7

*Data from ref. 3

contributions from the other component (Table 7). The resulting mixture therefore has a higher BV and NB than does either component alone. Protein complementation can overcome to some measure the inferiority of plant proteins, and should be given due consideration in selecting candidate species and in composing meals for CELSS.

The digestibility of plant proteins is as a rule inferior to that of animal protein. There is no single cause for this phenomenon. Contributing factors include poor solubility of plant proteins in stomach juices, presence of substances such as tannin and fiber that interfere with digestion, and unique peptide bonds in plant proteins that are resistant to attack by human digestive enzymes. Some of these factors may be reduced by proper food processing before consumption. Removal of excess fiber by milling and sifting cereal grains, or fermenting soy products, are examples of processing methods that have this effect.

Fats:

The dietary intake of fats in current practice in this country, in terms of energy, exceeds that of carbohydrates (Table 8). The majority of dietary fat comes from animal (meat and dairy) sources, and has a high proportion of saturated fatty acids. The high proportion of saturated fatty acids and consequent low levels of polyunsaturated fatty acids in the American diet are of concern with reference to degenerative blood and heart diseases. However, sources of fats for CELSS will be plants, and the composition of dietary fats is therefore likely to be much different (Table 9). Excessive intake of saturated fatty acid is easily prevented if care is used in plant selection and meal planning. The high saturated fatty acid content of coconut oil and palm kernel oil represent the exception rather than the rule in fatty acid composition within the plant kingdom (Table 9). A more likely concern will be

Table 7. Lysine Complementation by Supplementations of Soy Flour or Peanut Flour to Cereals*

	Chemical Score[1]		
	Supplement		
	None	Soy flour[2]	Peanut flour[2]
Wheat	45	88	72
Corn	49	86	70
Sorghum	38	86	67
Rice	69	96	78

[1]Chemical score: a "calculated biological value" based on amino acid composition data.

[2]Supplemented with 0.7 kg per kg cereal

*Data from ref. 31

Table 8. U. S. Dietary Practice vs. Dietary Goals*

	Percent of total caloric intake		
	Natural carbohydrate	Refined sugar	Fat
Current practice	28	18	40
Dietary goals	48	10	30**

*Data from ref. 71

**To be composed of approximately equal quantities of saturated, monounsaturated, and polyunsaturated fatty acids.

Table 9. Fatty Acid Composition of Fats and Oils[1]

Sources	Fatty acids, g per 100 g			
	saturated	oleic*	linoleic	linolenic
Beef tallow	44.8	41.8	4.0	3.1
Lard (pork)	39.2	45.1	11.2	10.2
Butterfat	61.9	28.7	2.3	1.5
Coconut	86.5	5.8	1.8	-
Corn	12.7	24.2	58.0	0.7
Palm	49.3	37.0	9.1	0.2
Palm kernel	81.4	11.4	1.6	-
Peanut	16.9	46.2	32.0	-
Soybean	14.4	23.3	51.0	6.8
Sunflower	10.3	19.5	65.7	-
Wheat germ	18.8	15.1	54.8	6.9

*Includes some palmitoleic acid

[1]Data from ref. 60

excessive intake of polyunsaturated fatty acids. The susceptibility of such fatty acids to peroxidation may increase human demand for vitamin E. This is an area of research which is as yet relatively unexplored, but much concern has been raised with respect to the faddist overuse of unsaturated fats, a practice that may possibly accelerate aging and negatively affect maintenance of epithelial tissues.

It is generally agreed that the average American consumes too much fat and too many calories which lead to adiposity. An educational program (13,71) has been launched by the federal government in hopes of decreasing fat consumption (Table 8). Such concerns are not warranted for CELSS. As will be presented in more detail in Chapter III, the importance of fats in CELSS is accentuated by their role as a heat transfer medium in food processing and food preparation, as well as to enhance palatability. It is likely that the CELSS diet will contain a higher proportion of fats than is present in crude plant materials, which implies that certain plant species may be grown specifically for providing oil, whereas the residue (carbohydrate, protein, fiber) may not necessarily find its way into the diet.

Minerals and Trace Elements:

The minerals required to maintain life processes are with few exceptions the same for plants as for animals. There is, therefore, little qualitative difference in mineral composition between members of the two kingdoms, but large quantitative differences may exist between plants and animals, between individual species, and even between different organs of the same species. When composing diets, due consideration must be given to such differences, which is one reason why the NRC stresses the importance of meeting the RDA by selection from a wide variety of foods. A number of U.S. dietary plans (10) are based on the "Basic Four" concept, which specifies that the daily intake is to be comprised of a number of servings in the proportions 2:2:4:4 from the meat, milk, fruit and vegetable, and cereal and bread groups, respectively (44).

The meat and milk groups will not be available in CELSS, and a major challenge will be to adequately substitute plant species rich in the minerals for which these groups are major contributors. The meat group is a major source of iron, copper, and zinc to the average American diet. Adequate compensation may be obtained from such sources as legume and cereal seed (wheat germ), as well as green leafy vegetables, but the bioavailability of these metals is poor from plant materials, and it is questionable whether functional adequacy can be achieved without supplementation.

The milk group (milk, cheese, ice cream) is a major contributor of calcium and phosphorus in a well composed American diet. Furthermore, the ratio of Ca to P (weight basis), is close to ideal in this group. Plant materials vary greatly in calcium content, and in the Ca/P ratio (Table 10). The common staples (soybean, beans, potatoes, wheat, and rice) have a calcium content roughly inversely related to moisture content, and a Ca/P ratio that is rather low. When the foods illustrated in Table 10 are compared on a moisture-free basis (Table 11) it is observed that green, leafy vegetables (e.g. kale) have the highest calcium content, and that they also possess a favorable Ca/P ratio. The cereal grains (e.g. wheat and rice) contain, in contrast, rather low levels of Ca and low Ca/P ratios. Dehydrated cabbage and lettuce also are good sources of iron (Table 11) and zinc, and could contribute significant quantities of protein, vitamins C and A, and have specific energy values comparable to that of the cereal grains.

<u>Vitamins</u>:

A well-balanced American diet composed according to the "basic four"

Table 10. Mineral Composition of Selected Foods (Data from ref. 75)

	mg per 100g fresh weight						Ratio	Percent
Meats	Ca	P	Mg	Fe	Na	K	Ca/P	Moistur
Beef	8	136	22	2.2	65	355	0.05	48
Pork	10	193	22	2.6	70	285	0.04	57
Chicken	11	214	23	1.2	50	320	0.05	76
Dairy Products								
Milk	118	93	13	tr.	50	144	1.31	87
Cheese	750	478	45	1.0	700	82	1.54	37
Vegetables and cereals								
Soybean	226	554	265	8.4	5	1677	0.40	10
Dry bean	144	425	170	7.8	19	1200	0.34	11
Cabbage, head	49	29	13	0.4	20	233	1.70	92
Kale	179	73	37	2.2	75	378	2.20	83
Lettuce, looseleaf	68	25	11	1.4	9	264	2.72	94
Broccoli	103	78	24	1.1	15	382	1.32	89
Potato	7	53	34	0.6	3	407	0.13	80
Wheat flour, whole	41	372	113	3.3	3	370	0.13	12
Rice, brown	32	221	88	1.6	9	214	0.15	12
Fruits								
Banana	8	26	33	0.7	1	370	0.29	76
Grape	16	12	13	0.4	3	158	1.33	82
Strawberry	21	21	12	1.0	1	164	1.00	90

Table 11. Mineral Composition of Selected Foods (dry weight basis) (Data derived from ref. 75)

	mg per 100g						ratio
Meats	Ca	P	Mg	Fe	Na	K	Ca/P
Beef	15	262	42	4.2	125	683	0.05
Pork	23	449	51	6.0	163	663	0.04
Chicken	49	892	96	5.0	208	1333	0.05
Dairy Products							
Milk	908	715	100	trace	385	1108	1.31
Cheese	1190	759	71	1.6	1111	130	1.54
Vegetables and cereals							
Soybean	251	616	294	9.3	6	1863	0.40
Dry bean	162	478	191	8.8	21	1348	0.34
Cabbage, head	613	363	163	5.0	250	2913	1.70
Kale	1053	429	218	12.9	441	2224	2.30
Lettuce, looseleaf	1133	417	183	23.0	150	4400	2.72
Broccoli	936	709	218	10.0	136	3473	1.32
Potato	35	265	170	3.0	15	2035	0.13
Wheat flour, whole	47	423	128	3.8	3	420	0.13
Rice, brown	36	251	100	1.8	10	420	0.15
Fruits							
Banana	33	108	138	2.9	4	1542	0.29
Grape	89	67	72	2.2	17	878	1.33
Strawberry	210	210	120	10.0	10	1640	1.00

concept is considered adequate in vitamin content and no vitamin supplementation is required. However, strict vegetarians must exercise great care in composing their diet to avoid vitamin deficiencies, particularly if vitamin supplementation is not practiced.

When comparing the vitamin content of foods of animal origin with those of plant origin (Table 12), one finds large differences between the two groups. These differences are further accentuated when actual intake pattens are considered. Thus, legumes (soybeans or dry beans) are not consumed in the dry form listed in the table, but only after having been soaked and fully rehydrated with consequent dilution of their vitamin content. Kale and broccoli, which are rich in riboflavin, are not likely to be consumed in quantities that will make major contributions to vitamin intake.

When vitamin content of the two groups is compared on a moisture free basis (Table 13), it is observed that the contents of the various B vitamins become roughly similar. This suggests that vegetarians should practice food preparation methods that remove moisture and thereby enhance the vitamin B content in the diet.

Vitamins A and C (ascorbic acid) occur rather uniquely in photosynthesizing plant tissues. As will be further discussed in the following section, overdosage can be of concern with respect to these vitamins.

In CELSS it is not likely that vitamin deficiencies will be a problem since vitamin supplementation is so easily practiced.

Table 12. Vitamin Content of Selected Foods (Data derived from ref. 75)

	(mg per 100g fresh weight)				
Meats	Vitamin A	Thiamine	Riboflavin	Niacin	Ascorbic Acid
Beef	70	0.06	0.13	3.6	-
Pork	0	0.83	0.20	4.4	-
Chicken	80	0.05	0.16	7.9	-
Dairy Products					
Milk	140	0.03	0.17	0.1	1
Cheese	1,310	0.03	0.46	0.1	-
Vegetables and Cereals					
Soybean	80	1.10	0.31	2.2	-
Dry bean	0	0.65	0.22	2.4	-
Cabbage, head	130	0.05	0.05	0.3	47
Kale	10,000	0.16	0.26	2.1	186
Lettuce, looseleaf	1,900	0.05	0.08	0.4	18
Broccoli	2,500	0.10	0.23	0.9	113
Potato	trace	0.10	0.04	1.5	20
Wheat flour, whole	-	0.55	0.12	4.3	-
Rice, brown	-	0.34	0.05	4.7	-
Fruits					
Banana	190	0.05	0.06	0.7	10
Grapes	100	0.05	0.03	0.3	4
Strawberry	60	0.03	0.07	0.6	59

Table 13. Vitamin Content of Selected Foods (Data derived from ref. 75)

	(mg per 100g dry weight)				
Meats	Vitamin A	Thiamine	Riboflavin	Niacin	Ascorbic Acid
Beef	135	0.12	0.25	6.9	-
Pork	0	1.93	0.47	10.2	-
Chicken	333	0.21	0.67	32.9	-
Dairy Products					
Milk	1,077	0.23	1.31	0.8	8
Cheese	2,079	0.05	0.73	0.2	-
Vegetables and Cereals					
Soybean	89	1.22	0.34	2.4	-
Dry Bean	0	0.73	0.25	2.7	-
Cabbage, head	1,625	0.63	0.63	3.8	588
Kale	59,000	0.94	1.53	12.4	1,094
Lettuce, looseleaf	32,000	0.83	1.33	6.7	300
Broccoli	23,000	0.91	2.09	8.2	1,027
Potato	trace	0.50	0.20	7.5	100
Wheat flour, whole	-	0.63	0.14	4.9	-
Rice, brown	-	0.39	0.06	5.3	-
Fruits					
Banana	792	0.21	0.25	2.9	42
Grape	555	0.28	0.17	1.7	22
Strawberry	600	0.30	0.70	6.0	590

III. Guidelines for Composing Pure Vegetarian Diets

Plant materials contain all nutrients required by humans with the exception of vitamin B_{12}, and often iodine. However, the proportions in which nutrients occur are not necessarily well suited for balanced intake, nor do they necessarily occur in suitable concentrations. The task of composing diets is, therefore, to correct imbalance problems and overcome deficiencies, or in some cases, to avoid excessive intake while maintaining or improving palatability and variety. In the following, we discuss common problems encountered with pure vegetarian diets and ways by which they may be overcome:

1. Specific energy value. Many edible plant parts (leaves, fruits, tubers, etc.) naturally contain so much moisture that their energy value per unit weight (specific energy value, or SEV) is very low. It thus becomes difficult to satisfy the human energy requirement with reasonable meal size in terms of weight or volume of intake. As an example, cooked potatoes have a SEV of 0.76 kcal g^{-1} fr. wt. To obtain 900 kcal (one third of the daily energy requirement), intake would have to be 1.2 kg, an amount exceeding the capacity of the human stomach. In contrast, animal foods such as meats or cheeses may have SEV's ranging from 1.8 to 6.0 Kcal g-1, depending on their fat and water content. Plant seeds (legume, cereal) have a high SEV in dry form, but after imbibing water, such as occurs during meal preparation by boiling or steaming, the SEV again becomes fairly low. Rice in dry form has a value of 3.6 kcal g^{-1}, but steamed or boiled rice has a value of only 1.1.

There are essentially two means of overcoming the problem of bulk volume in the diet: 1) Food energy can be provided by supplementation of oils or fats (SEV of 8.8) to the meal; or, 2) water can be removed from raw materials before they are consumed. The latter approach is provided by food processing methods that make foods with lowered moisture content available, and also by cooking procedures that inherently remove moisture by evaporation. Roasting, baking, and deep frying are examples of such procedures. Cooked, rolled wheat has an SEV of 0.75, whereas wheat in the highly processed form of bread has a value of 2.7.

2. Calcium content. The calcium content of plant materials is not unusually low relative to meats, especially on a dry matter basis, but dietary intake from plant sources is hampered by high bulk volume and moisture content, and by the quantities that are normally accepted as a "serving" in a meal. Kale, mustard greens, and turnip greens are exceptionally good soures of calcium, but a vegetarian meal does not normally contain large quantities of such materials, and it is likely that exaggerated portions would meet with resistance by the consumer. Nor does it appear likely that dehydrated forms of these vegetables would be readily accepted. Beans contain appreciable amounts of calcium, but calcium bioavailability would be limited by their phytic acid content. The average American diet derives much of its calcium from dairy products, but these will not be available in any strict vegetarian scenario. It is likely, therefore, that pure vegetarian diets somehow must be fortified with calcium. The severity of this problem in a CELSS would likely be accentuated by abberations of calcium metabolism that seem to be a consequence of low gravity (81). Fortification with calcium eventually would lead to accumulation of calcium as a result of waste recycling, and would cause problems unless steps were taken to remove excess calcium and recycle it back to humans through a special loop.

3. Ca/P ratio. The main energy sources of a vegetarian diet, which of necessity will constitute the major portion of such diets, are legume seeds and cereal grains. Unfortunately, these sources all have a very low Ca/P ratio ranging from 0.09 for corn and wheat to 0.40 for soybean, whereas a human diet

ideally should maintain a ratio of 0.67 (11). Green leafy vegetables, on the other hand, have Ca/P ratios far in excess of 1.0. Mustard and turnip greens, for instance, have ratios close to 4.0. It should, therefore, be possible to correct the deficiency of seed foods by composing a diet consisting of grain and legume seed on the one hand, and dehydrated leafy vegetables on the other. For the reasons discussed, such a dietary regime seems hardly possible. We are therefore, forced to supplement calcium in such diets to maintain a reasonable Ca/P ratio. Fortification of bread with calcium carbonate, for instance, is required by law in several European countries. It should be noted that the importance of the Ca/P ratio as a nutrition indicator has been de-emphasized in recent times (10). In the special circumstances of practicing strict vegetarianism, particularly when combined with the observed abberations in the Ca metabolism associated with low gravity we feel, however, that it is warranted to hold the Ca/P ratio within reasonable limits.

4. Low content of sodium and chlorine. Edible plants normally are very low in both elements and cannot provide anywhere near the tentatively accepted level of 3.2 g NaCl day^{-1} $person^{-1}$ as recommended by the NRC (53). NaCl must, therefore, enter the human system in substantial quantities as an additive to food. Problems created by recycling waste would become inevitable unless means are found to separate salt from the waste stream for recycling through a special loop back to the food preparation stage.

5. Fortification with vitamins. Vitamin B_{12} does not occur in higher plant tissues. Vitamin B_2 is generally low, and human requirements may be difficult to meet with pure vegetarian diets. Fortification with both vitamins will not pose any particular problem since only small amounts are required and the vitamins will not accumulate in the system. Vitamin D, which occurs very sparingly in plant materials, also must supplement the diet unless a source can

be generated within the system. Irradiation with ultraviolet light, of either green leaves or yeast cells, will convert ergosterol to calciferol, one of the active forms of this vitamin. Even simpler would be exposure of human inhabitants to ultraviolet light, resulting in "endogenous" generation of vitamin D.

6. Vitamin Overdosage. Green leaves and certain storage tissues (e.g. carrot roots) contain large quantities of provitamin A in the form of various carotenoid compounds, mainly β-carotene. If a major portion of dietary intake contains such materials, the possibility of a vitamin A overdosage exists. Provitamin A toxicity has been less studied than that of vitamin A, and clear guidelines are lacking with respect to tolerable limits (24). Excessive amounts of the provitamin evidently are stored in the liver and in fatty tissues, and we surmise that prolonged overdosage may have deleterious effects.

IV. Candidate Species

Plant species grown in a CELSS must provide a nutritionally and psychologically adequate diet for human inhabitants, as well as controlled air revitalization. The ultimate selection of suitable crops will depend on species performance within the unique restrictions imposed by recycling ecosystems, and on the ability of harvested parts to meet human needs (69). We have identified two general categories of selection criteria which can be used to select promising species upon which future research effort should be focused: i.e., cultural and use criteria (Table 14). As will become evident in the following sections, certain criteria included under each major category are incompletely known for many species, and therefore introduce elements of uncertainty into the selection process.

Scoring System

The problem is further complicated by present uncertainties regarding the relative weight to attach to individual selection criteria. Three of nine "use" criteria and two of eleven "cultural" criteria were identified as being of major importance, and were therefore weighted double the value of the remaining 16 criteria. A crude scoring system was adopted, giving a score of 2 if a given species seemed to be compatible with a particular scoring criterion, a score of 1 if minor problems must be solved before a species would be compatible, and a score of 0 if difficult problems would have to be overcome. Utilizing this system, then, we proceed with caution toward preliminary selection, realizing that future research may change relative rank as scientific data become available. It also should be pointed out that species occurring further down in the ranking are not necessarily disqualified from future selection, especially if the relative importance of selection criteria should change as new information becomes available.

Table 14. Candidate Species Selection Criteria

Criterion No.	Use (or nutritional) Criteria
1	Energy concentration
2	Nutritional composition
3	Palatability
4	Serving size and frequency
5	Processing requirements
6	Use flexibility
7	Storage stability
8	Toxicity
9	Human use experience

Criterion No.	Cultural Criteria
10	Proportion of edible biomass
11	Yield of edible plant biomass
12	Continuous vs. determinate harvestability
13	Growth habit and morphology
14	Environmental tolerance
15	Photoperiodic and temperature requirements
16	Symbiotic requirements and restrictions
17	Carbon dioxide - light intensity response
18	Suitability for soilless culture
19	Disease resistance
20	Familiarity with species
21	Pollination and propagation

Selection Criteria

The criteria used for candidate species selected are listed in Table 14. The order of listing does not indicate relative importance. The first nine items fall into the realm of human nutriton, wellbeing and convenience (the so-called "use" criteria), whereas the remaining 11 items are predominantly cultural considerations. Selection criteria numbers 1, 2, 5, 10, and 11 were considered to be of great importance to the selection of plant species for a CELSS and were therefore given double weight relative to the remaining criteria.

Use Criteria

1. Energy concentration. This category considers the concentration of the major nutrients, particularly energy (calories), in the food consumed. Certain foods, (e.g., lettuce) may be of such low biomass density that they contribute insignificantly to caloric requirements due to volume restrictions of intake. The human stomach can accept about 700 ml per meal without discomfort. With three meals per day, the minimum caloric bulk density requirement will be 1.3 Cal per ml. As will become evident, strict vegetarian diets have difficulty fulfilling this requirement, and it may be necessary to schedule at least four equicaloric meals per day to cover energy needs.

2. Nutritional composition. Plant materials contain many components important in human nutrition. The question addressed here is: how many of these contribute significantly to human rquirements in an average meal? Plant species may be nutritionally mono- or poly-functional. For instance, taro is essentially a nutritionally mono-functional species (for carbohydrate), whereas soybean is poly-functional (for protein, minerals, B vitamins).

3. Palatability. To derive benefits from meals, one must desire to

consume them. Palatability is one of the major factors (hunger is another) in determining appetite. Culinary art plays an important role in creating palatability, but the extent to which it can be exercised and the extent to which culinary input is required are determined by inherent properties of the plant species. Kale is likely to be ranked low in this regard, while strawberry or peanut most likely would be ranked high.

4. Serving size and frequency. The nutritional benefits obtained from a specific food item depend in part on the amount consumed. Serving size is a measure of the amount of a food that can be comfortabley eaten without developing psychological resistance to it. This is a factor that varies widely among individuals, but is, on the average, uniform enough to be a useful concept practiced widely in institutional meal planning. Similarly, the frequency with which a menu item can be tolerated will determine its relative contribution to the nutritional status of the consumer. Again, this tolerance varies among individuals, but the variability is not sufficient to obviate its usefulness in menu planning. Certain plant species (e.g., wheat in the form of baked items) can be served frequently, whereas other species (e.g., spinach) much less so.

5. Processing requirements. Raw plant material usually requires some form of processing to become acceptable as a food. Processing serves several purposes, chief of which are enhancement of palatability, destruction or removal of toxic substances, and enhancement of nutritional value. The degree of processing required to achieve these ends varies greatly among species. Thus, strawberries and lettuce require no processing at all, whereas wheat and soybeans are rather demanding in that respect.

6. Use flexibility. A plant product that can be introduced into meals in multiple ways, as an active ingredient in unrelated dishes, or in a

variety of forms for different occasions, would seem to be of more value in a CELSS than would a more restricted product. If milling can be made permissible as a processing operation in a closed environment, then wheat would be an excellent example of such a multiple use plant material. Leafy plant materials would, on the other hand, seem to have a much more restricted range of application.

7. Storage stability. If a plant product cannot be stored without suffering quality loss or spoilage, consumption will have to be closely coordinated with production. Such imposed operational restrictions seem undesirable. Edible plant materials in the form of seeds, and to a lesser extent roots and tubers, would therefore seem to be preferred candidates, whereas leaves, flowers, and fruits would require greater post-harvest handling, run a greater risk of substantial losses, or demand more sophisticated methods of preservation (freezing, freeze drying, canning, controlled atmosphere storage).

8. Toxicity. Many plants contain substances that may be classified either as toxic or as antimetabolites, depending on the severity of effects when ingested by humans. Potato foliage, for instance, contains solanins at concentrations high enough to exclude the use of this material as food for humans or animals. The tuber contains much less solanine, but the amounts are variable and depend upon cultivar and growing conditions. Legume seed contains relatively large amounts of proteinase inhibitors that will interfere with protein digestion in the intestinal tract and lead to pancreatic hypertrophy, fatty liver, etc. In contrast to the solanins, proteinase inhibitors usually are inactivated by ordinary heat processing (cooking). With respect to this criterion, it may be convenient to classify plants according to: a) those which are virtually free of toxic or antimetabolite substances, b) those that contain significant amounts of such substances in the raw state, but not in the

processed form which is consumed, and c) those that contain residual amounts of toxins not removed or destroyed by processing.

9. Human experience. Most food crops have been cultivated for hundreds or thousands of years. During this time, man has gained a thorough knowledge of these plants, not only in cultural terms, but also their effects on the human organism when consumed as food. It is, therefore, likely that fewer unexpected reactions will be manifested if "known" species are used in the CELSS environment rather than species of more recent vintage or of an exotic nature. The winged bean has been suggested as a food crop suitable for CELSS since it offers several very attractive attributes: virtually the entire plant body is edible, including the tuber which has a high protein content of good nutritional value. However, we know very little about possible long-term effects of winged bean simply because its cultivation outside of small, primitive societies has not occurred until recently.

Cultural Criteria

10. Proportion of edible biomass. Partitioning of dry matter between edible and inedible plant parts could be such an important selection criterion that it has been weighted double among the cultural criteria used to score various species. However, strict selection for minimum inedible biomass, such as might occur with dwarf or determinate cultivars, admittedly conflicts with the desirability of sustained photosynthetic activity and continuous harvestability characteristic of some indeterminate cultivars. Arguments in favor of minimizing accumulation of inedible dry matter include the effective utilization of available carbon and oxygen. Inedible plant residues tie up carbon in a reduced form unavailable to the carbon cycle until reoxidized to gaseous CO_2. Release of fixed carbon requires the consumption of just as much O_2 as was

liberated during its original fixation, so undigestible plant residues represent wasted calories and inefficiency within the system. Therefore, species such as garden beet, whose parts are all potentially edible, would score high in this category, whereas woody perennials, which tie up valuable carbon (and calories) in inedible biomass, would score low.

11. Yield of edible plant biomass. This is another selection criterion of such importance to a regenerative life support system that it also was given double weight. Potential yield was estimated as the amount of edible dry weight produced per unit growing area (or volume) per unit time, based upon available data for field crops. Many field crops have rather impressive yield figures on a fresh weight basis (leaf lettuce, etc.), but if the harvest is expressed on a dry weight basis, the figures often shrink by more than an order of magnitude. Although the figures used to score yield per harvest and production cycle time are based upon field performance, it is uncertain how yield potential of different species will respond to controlled-environment agriculture until tested.

12. Continuous vs. determinate harvestability. Ideal crops for a CELSS according to this criterion might be everbearing perennials, or at least those that permit multiple harvests throughout the life cycle of the plant. On the other hand, crops having natural dormant periods and environmental requirements for relieving dormancy (e.g., chilling) would receive low scores, as would crops requiring high management input. Penalties associated with raising regular-harvest crops (e.g., indeterminate tomato) include accumulation of inedible biomass, senescence of older parts, and gradual decline of photosynthetic efficiency. On the other hand, once-over mass harvest would interrupt the O_2-regenerating capacity of an annual crop. Furthermore, many nutritious food crops are annuals which undergo rapid decline and death soon after the

onset of reproductive development (e.g., soybean, wheat). However, it seems reasonable that gas exchange equilibrium could be preserved, even with annual crops, by staggering planting schedules, sufficient iteration, and judicious crop management.

13. Growth habit and morphology. Growth habits which are undemanding of either lateral or vertical space would permit maximum plant density while minimizing mutual shading within the foliar canopy. Coffee trees, for instance, would be impractical from the point of view of height, spread, length of juvenile period, etc., whereas leaves can be picked on a regular basis from the diminutive tea shrub. Vining cultivars might be trained vertically without sacrificing lateral area, but would then require aerial support, especially for solution culture. Small, bushy, highly-productive perennial species would score highest in this category.

14. Environmental tolerance. It would be important for the plant components of a CELSS to tolerate the range of environmental fluctuations that may be required to maintain the overall homeostasis of a closed system, or that may occur due to temporary loss of environmental control, without suffering catastrophic stress. In addition to screening candidate species for a broad range of tolerance to factors such as temperature, humidity, water status, and light intensity, it may be necessary to select for tolerance of organic and inorganic pollutants that may accumulate within a closed system. Sugar beet, for instance, proves to be a rather hardy sugar crop, tolerating a wide range of temperatures and soil water conditions, whereas date palm is very narrow in its range of tolerances. However, the present state of knowledge in this category is spotty for most species, and overall environmental tolerance cannot yet be used as a determining factor for selecting candidate species in most cases, although it remains a highly important criterion to be researched.

15. Photoperiod and temperature requirements. Another set of trade-offs will involve the diurnal fluctuations of lighting and temperature that may be required for plants in a CELSS. Although long photoperiods approaching continuous illumination would be highly desirable for O_2 regeneration and biomass production, and has proved to be feasible for controlled-environment production of leaf lettuce, the edible parts of many crops require short photoperiods for their induction or development. Soybeans and potatoes, for instance, tend to be short-day plants for flowering or tuberization, respectively, although these requirements tend to be more quantitative than qualitative. Selection of day-neutral or long-day photoperiodic classes (for development of the desired, edible part) certainly would be preferable for maximizing primary productivity. Leafy vegetable crops such as lettuce or kale are almost ideal from the point of view of maximizing productivity, since photosynthetic tissue itself is the desired harvest. Even though crops such as lettuce may be long-day for flowering (undesirable), it is possible to maintain them vegetative under continuous illumination by lowering ambient temperature.

Species should be selected which have flexible temperature requirements for flowering, seed set, maturation, etc. Species which are highly productive at elevated temperatures would be desirable (tropical fruits, vines), whereas species which require long cold treatments to relieve their natural rest periods (temperate fruits) would be highly undesirable. Once beyond the seedling stage, most species seem to prefer a day-night temperature differential, or at least a temperature alternation, even if light is continuous. In fact, species such as tomato are "thermoperiodic" under some conditions, requiring a diurnal temperature shift for best development. This category also must remain somewhat speculative until appropriate optimization studies can be done under defined environments.

16. Symbiotic requirements and restrictions. Various types of self- and cross-interactions are possible which could impact on the stability of particular plant species in a CELSS. One potential restriction to the use of a particular species would be its sensitivity to substances leached or secreted from tissues of the same or different species sharing a common nutrient solution (allelopathy). There presently are so many unknowns regarding the productivity of corps in mixed-culture that it would be impossible to select or reject any species based upon this criterion until much more research is done. Other species may require symbiotic association with microorganisms in order to realize their potential productivity. Associations with mycorrhizal and nitrogen-fixing organisms are widespread in nature and are known to enhance the growth vigor of both herbaceous and woody plants. However, species not known to depend upon microorganisms for normal growth and development would score highest in this category. In general, it was difficult to separate species according to this criterion based upon current knowledge.

17. Carbon dioxide - light intensity response. Combined manipulation of CO_2 and light levels probably have greater potential for boosting crop productivity in a CELSS than does optimization of any other envrionmental parameter. Although the photosynthetic apparatus of C-4 species (tropical grasses, maize, sugar cane, etc.) is inherently more efficient in terms of CO_2 fixation and response to increasing light intensity than that of C-3 species (temperate dicots, soybean, wheat, etc.), there should be no particular advantage of one photosynthetic type over another in a controlled environment if ambient CO_2 and illumination are enhanced. Nevertheless, based upon field performance, C-4 species outscore C-3 species in this category. Lack of data in this area is so evident that it will become a good selection criterion only after sufficient research has been done on cultural optimization.

18. Suitability for soilless culture. Soil as we know it probably will not be used in a CELSS since it would: (a) be heavy and costly to transport into space, (b) tend to break down and become depleted with repeated use, (c) be difficult to sterilize. Similar arguments might be made against inert root support media such as gravel, sand, vermiculite, perlite, calcined clays, polystyrene beads, etc. Even solution culture might require transportation of large volumes of water into space. Therefore, aeroponic (nutrient mist) or flowing nutrient film culture might be suitable alternatives to other cultural methods, but they lack extensive root support capabilities, and certain species might be less adaptable to this type of culture than are others. Top heavy shoots would require special aerial support. Certain root or tuber crops (beet, potato, etc.) also may not adapt well to solution culture, and they would not score well in this category. However, aquatic types (rice, taro, etc.) should adapt easily to this type of culture and would score very well.

19. Disease resistance. Although space-bound propagules undoubtedly will be disinfested and quarantined prior to launch, it may be impossible or impractical to maintain an aseptic CELSS environment, particularly if symbiotic relationships are desired. Even if non-pathogenic microorganisms (e.g., N_2-fixing bacteria) are allowed (or inoculated) into the system, there always would be the possibility that a given strain could mutate to a virulent form. Therefore, as a safeguard, selected species at least should be screened for their resistance to the diseases that threaten that species in the field. Most food crops are plagued by one or more diseases, so this category did not prove to be a particularly useful criterion for separating candidate species.

20. Familiarity with species. In order to progress efficiently with optimization of plant culture conditions for a CELSS, it would be a distinct advantage to have already available background knowledge in the field or

controlled-environment production of that species. There may be many under-exploited plant species in the world that are as nutritious and productive as our best cultivated crops, but if experience in their cultivation is lacking, much more background research is required to learn how to maximize their production. Therefore, highly domesticated crops of a technological society (e.g., soybean) would score highest in this category, whereas even highly promising crops of developing societies (e.g., winged bean) would score lower.

21. Pollination and propagation. Most candidate crop species can be propagated from seed, although cloning procedures (cuttings, cell cultures) could be adopted (or developed) to eliminate unwanted variability. Vegetative propagation also could be used to regenerate root and tuber crops (Jerusalem Artichoke, potato, etc.). It was assumed that all seeds have finite viability, and therefore specific storage requirements. Hence, seed-propagated crops received an intermediate score. However, if pollination of these species was other than by selfing, those species were scored down, since hand, wind, or insect pollination are all less feasible in a CELSS. Species easily propagated by vegetative means (dandelion, grape, etc.) scored highest in this category.

Selection Criteria Lists

The selection criteria list (Tables 15-24) contains 115 plant species. Since there are believed to exist thousands of edible plant species and Bailey's Manual (2) lists only several hundred of them, it is evident that drastic selection already has been made. Our list is drawn from species that are known and appreciated as world food crops, most of which also are grown in the United States and its territories (43). We have further reduced the number by application of criteria No. 13 and 20 (growth habit, familiarity) by excluding species that seem impractical for reasons of size, rarity, or infrequent utilization as food. The remaining species form the basis for further selection by full application of selection criteria 1 through 21 (Tables 15 through 24).

The selected species were given one of three scores for each criterion. The scores reflect whether a species rates high "2", medium "1", or low "0" in desirability with respect to a particular criterion.

No integration of individual scores into a total rating for individual species has been attempted beyond a summation of the 21 "use" and "cultural" scores. There are so many remaining unknowns that it is difficult to assign scenario-dependent "weighing factors" at this time. The total scores as listed should therefore be regarded as highly tentative.

Leguminous species (Table 15).

The edible part of most legumes is the seed, although some species and cultivars also have edible pods (Pisum sativum: snowpea), leaves, stems, and tubers (Psophocarpus tetragonolobus: winged bean). Most species exist in the field symbiotically with nodule-forming, nitrogen-fixing, bacteria, a feature of interest in connection with operation of the nitrogen cycle in a CELSS. Raw legume seeds, as a rule, cannot be consumed in significant quantities due to the presence of several toxic substances (proteinase inhibitors, lectins, etc.). These generally are rendered harmless by cooking. The seeds, when allowed to develop to maturity, are harvested dry and then have excellent storage stability. The legumes under consideration are annual species, but further propagation should pose no serious problem since the edible harvest also may serve as propagules.

Leguminous species include many warm season crops which require adequate moisture particularly during early reproductive growth, but prefer an environment that allows the seed to dry for ease of harvesting. A number of different

Table 15. Selection Criteria: Leguminous Crops

	Nutritional Criteria										Cultural Criteria													
Common Name	1*	2*	3	4	5*	6	7	8	9	Total	10*	11*	12	13	(14)	(15)	(16)	(17)	18	19	20	21	Total	Grand Total
Bean, broad	2	2	1	1	2	0	2	0	1	11	2	2	1	1	1	1	1	1	2	1	1	1	15	26
Bean, dry or field	2	2	1	1	2	0	2	1	2	13	2	2	1	1	1	1	1	1	2	1	2	1	16	29
Bean, goa, winged	4	4	1	1	0	0	2	1	0	13	4	2	1	0	1	1	1	1	2	1	0	1	15	28
Bean, green or snap	0	4	1	1	2	1	0	1	2	12	2	2	2	1	1	1	1	1	2	1	2	1	17	29
Bean, lima	2	2	1	1	2	0	2	1	1	12	2	2	1	1	1	1	1	1	2	1	1	1	15	27
Bean, mung	2	2	1	1	2	1	2	1	2	14	2	2	1	1	1	1	1	1	2	1	1	1	15	29
Garbanzo	2	2	1	1	2	0	2	1	2	13	2	2	1	1	1	1	1	1	2	1	1	1	15	28
Pea, garden	2	2	1	1	2	1	2	1	2	14	2	2	1	1	1	1	1	1	2	1	2	1	16	30
Pea, grass	2	2	1	1	2	0	2	0	1	11	2	2	1	1	1	1	1	1	2	1	1	1	15	26
Pea, pigeon	2	2	1	1	2	0	2	1	2	13	2	2	1	1	1	1	1	1	2	1	1	1	15	28
Pea, southern, cow	2	2	1	1	2	1	2	1	2	14	2	2	1	1	1	1	1	1	2	1	1	1	15	29
Pea (sugar, Chinese)	0	4	2	1	2	1	0	1	2	13	2	2	2	1	1	1	1	1	2	1	1	1	16	29
Peanut	4	4	2	1	2	2	2	1	2	20	2	2	2	1	1	1	1	1	0	1	2	1	15	35
Soybean	4	4	1	2	0	2	2	1	2	18	2	2	1	1	1	1	1	1	2	1	2	1	16	34

* Assigned a weighting factor twice that of other criteria.

( ) ≅ largely unknown

bean diseases (e.g., anthracnose) are carried on or in the seeds, and vigorous indexing procedures will be required to assure that only disease-free seed are carried on board spacecraft.

Soybean (Glycine max (L.) Merr.). In terms of the nine use criteria soybean ranks high. Its protein content, biological value, caloric content, polyfunctional nutritional character, use flexibility, and storage stability suggest that it would be one of the primary candidate species for a CELSS. However, it also possesses certain negative attributes. Palatability may be a problem, depending on the product desired and type of processing. Flavor defects occur due to the rapid action of lipoxygenase (47), which takes place when broken bean tissues contact moisture. Although the resulting fatty acid oxidation products are not necessarily considered objectionable by people accustomed to soy products, they are not easily tolerated by others. However, there are ways to alleviate this problem, such as by suitable selection of processing conditions (49,50). Although soybean may be consumed in a form and following cooking procedures similar to those used for dry beans in general, it may be considered rather demanding in processing sophistication if full advantage is to be taken of its use flexibility. For instance, the manufacture of tofu (26), a gelatinous curd, which has multiple uses as a Japanese meal ingredient, requires the following unit processes: cleaning, soaking, wet grinding, cooking, filtering, precipitation with calcium sulfate, filtering, and washing. Each unit process creates problems of waste, water consumption, and for precipitation of curd, it also introduces a foreign substance - calcium sulfate - into the system. The use of this compound probably cannot be tolerated because of recycling complications. Some substitute in the form of a recyclable compound, such as acetic acid or other carboxylic acid, may have to be used (42).

Another negative attribute of soybean is its carbohydrate, which is largely nonutilizable by the human digestive tract (29,59). Some low molecular weight forms, such as cellobiose and stachyose, are further believed to be responsible for the digestive upset and flatulence that are commonly associated with ingestion of large amounts of unrefined soybean products (59). These ingredients usually are removed with more elaborate processing methods.

High protein cultivars are preferred on the Japanese market, and such cultivars also should be preferred for a CELSS. The 'Harosoy' and 'Hawkeye' are examples of suitable American cultivars.

Soybean is a warm-season C-3 crop that responds favorably to both high light and elevated CO_2 (7) for its reproductive and vegetative growth. One potential disadvantage is that it tends to be a short-day species, although cultivars differ markedly in this regard (35). If it proves desirable for soybean to operate in the N_2-fixing mode in a CELSS, technical problems may have to be worked out relative to soilless culture of this species. Optimum soil pH for soybean is about 6.5. Moisture content of soybean seeds is critical to their storage life. For example, at 14% moisture, viability of soybean seeds lasts only about a month, whereas at 12% moisture they may remain viable for as long as 3 years (7). Also, mechanical damage to soybean seeds occurs easily and can retard growth and development for its entire life cycle. Thus, special handling and storage of seeds is in order for this species.

Mung bean (<u>Phaseolus aureus</u> Roxb.). The main attribute of this species lies in the palatability and nutritional value of the sprouted seedling. If used extensively, it would contribute significantly to riboflavin intake.

Lima bean (<u>Phaseolus lunatus</u> L.). This species has limited palatability, serving size and frequency, and there may be questions regarding its toxicity in long-term feeding programs due to low levels of the cyanogenic glycoside phaseolunatin (8).

Green or snap bean (Phaseolus vulgaris L.). The edible pod contributes to the nutritionally polyfunctional nature of this species. It is a likely contributor of Ca, B-vitamin complex, A, and C vitamins, and adds significant amounts of protein and calories if served frequently. Its value is diminished by relatively high moisture content of the seed and limited storage stability. Some of the most productive cultivars per unit area are of pole rather than bush types, and if used, would require additional mechanical support, especially in hydroponic culture. This may not be true on a unit volume basis.

Dry, (common, navy) bean (Phaseolus vulgaris L.). Dry beans have an advantage over soybeans in being more readily acceptable. The white types (peabean, navybean) contain less tannin, their hull is softer, need not be separated from the cotyledons, and off-flavor formation is much less pronounced since the lipoxygenase - lipid system is significantly less active. They lend themselves well to protein complementation with cereal proteins, a fact which is demonstrated by large population groups (Brazil, India) subsisting on such diets. Yields are by necessity much lower than for green bean since the pods are not utilized, and the time required from bloom to maturity is approximately three times longer. It might be advantageous to try to select for CELSS cultivars that produce edible pods as well as dry seed.

Green pea (Pisum sativum L.). This species, similar to Phaseolus vulgaris, has cultivars that produce either edible pods or dry seed. Combination cultivars are known. Its attributes are similar to those of bean with the following differences: palatability is probably somewhat greater, its protein and starch have higher digestibility, but the sulfur amino acid content is lower (4). Therefore, it will benefit more from complementation with cereals, but the biological value of the mixture will be less.

Unlike many leguminous species, pea is a hardy, cool-season crop. The fact that humus or barnyard manure favor satisfactory production in clay soils suggests that pea tolerates recycled organic wastes. Peas grow best at pH 5.5 to 6.5. Whether or not hydroponic culture will pose serious problems for inoculation of seeds with N_2- fixing bacteria remains to be determined. Vining types will require some sort of shoot support (trellising) in hydroponic culture.

Winged bean, Goa (Psophocarpus tetragonolobus (L.) D.C.). The composition and nutritive value of the seed is similar to that of soybean (72). It has relatively high protein content, but an amino acid composition deficient in sulfur amino acids, and a fairly high lipid content. However, the fatty acid composition is less dominated by polyunsaturated acids, and it is likely that products of this species will be less susceptible to development of off-flavors. The tuber is unusually rich in good-quality protein. Although the winged bean appears to have many attributes desirable for a CELSS candidate species, not the least of which is that virtually the entire plant could be utilized under the proper circumstances, it probably has not yet been sufficiently evaluated and developed to be recommended for this purpose. Long-term toxicity effects need to be evaluated. Many horticultural characteristics also need to be improved. In particular, it would seem that the short-day requirement for seed set and development would hinder high photosynthetic productivity in controlled environments. The fact that pods of this perennial ripen continuously would hamper the use of winged bean for mass commercial harvest, but might make it ideal as a reliable protein source for a small space colony.

Peanut (Arachis hypogaea L.). Peanuts constitute a high energy food source with almost 50% fat and 26% protein in the edible portion. The protein is one of the more digestible seed proteins, but its biological value is limited by rather low values for lysine, threonine, and the sulfur amino acids. Its palatability is generally high, and it can be consumed in a variety of forms and as an ingredient of many food preparations. The shell may find applications in the CELSS environment as a raw material for charcoal manufacture or as a filter medium. The oil can be expressed hydraulically and does not need to be further processed to be suitable for consumption as a salad oil, frying medium, bakery ingredient, or for other uses. Peanut will pose unique challenges for hydroponic culture, not only because it has potential for N_2 fixation, but also because pegs normally develop underground. A split-root technique utilizing some solid support medium may be necessary for successful nutrient culture of this species.

Several other leguminous candidate species to consider include the following:

- Garbanzo bean, chick pea (*Cicer arietinum* L.)
- Broad bean (*Vicia faba* L.)
- Cowpea (*Vigna sinensis* L.)
- Pigeon pea (*Cajanus cajan*, Millsp.)
- Grass pea (*Lathyrus sativus* L.)

These legumes are similar to *Phaseolus vulgaris* in seed composition and find similar applications as food. Two of them (*Vicia faba* and *Lathyrus sativus*) have a history of causing toxic reactions (favism and lathyrism, respectively), and probably should not be considered as viable candidate species. The other three, the garbanzo, the pigeon pea, and the cowpea, may substitute for *Phaseolus* or be preferred for purely horticultural reasons.

Root and Tuber Crops (Table 16).

Edible roots and tubers have, in contrast to the seed crops, water as a main component, which creates some storage problems. Their dry matter content differs substantially among species, some containing two or three times as much as others. Some owe their high dry matter content mainly to accumulation of

Table 16. Selection Criteria: Root and Tuber Crops

	Nutritional Criteria										Cultural Criteria													
Common Name	1*	2*	3	4	5*	6	7	8	9	Total	10*	11*	12	13	(14)	(15)	(16)	(17)	(18)	19	20	21	Total	Grand Total
Artichoke, Jerusalem	4	0	1	0	2	0	0	1	1	9	2	2	1	1	1	1	1	1	0	1	1	1	13	22
Beet, garden	2	0	1	0	2	1	1	1	2	10	4	4	1	2	1	1	1	1	0	1	2	1	19	29
Carrot	2	2	2	1	2	1	2	1	2	15	4	4	1	2	1	1	1	1	0	1	2	1	19	34
Kohlrabi	2	2	1	0	2	0	2	1	2	12	2	2	1	1	1	1	1	1	1	1	1	1	14	26
Manioc	4	0	1	1	0	1	1	0	1	9	2	2	1	0	1	1	1	1	0	1	0	1	11	20
Parsnip	4	0	1	0	2	0	1	1	1	10	2	2	1	1	1	1	1	1	0	1	0	0	11	21
Potato	4	2	1	2	2	2	2	1	2	18	2	4	1	1	1	1	1	1	1	1	2	1	17	35
Radish	0	0	1	0	4	0	1	1	1	8	2	2	1	2	1	1	1	1	0	1	1	1	14	22
Rutabaga	2	2	1	0	2	0	1	1	1	10	2	2	1	2	1	1	1	1	0	1	1	1	14	24
Sweet Potato	4	4	1	1	2	1	2	1	2	18	2	2	1	1	1	1	1	1	0	1	2	1	14	32
Taro	4	0	1	1	2	1	1	1	1	12	2	4	1	1	1	1	1	(2)	2	1	1	1	18	30
Turnip	2	2	1	0	2	0	1	1	1	10	2	2	1	2	1	1	1	1	0	1	1	1	14	24
Yam	4	2	1	0	2	1	1	1	1	13	2	2	1	1	1	1	1	1	0	1	1	1	13	26

* Assigned a weighting factor twice that of other criteria.

( ) $\cong$ largely unknown

starch (e.g. potato and taro), but others appear also to accumulate protein (winged bean). Tubers with high starch content are good energy sources, particularly since they may be usually consumed without further addition of water, or even after some moisture has been removed (e.g., chips, french fries). Most species contain rather little protein (turnip, cassava), but others have a protein content that on a dry weight basis, is equivalent to or higher than that of most cereal grains. This protein appears, in most cases, to possess a biological value considerably higher than that of cereal proteins and legume seeds. Some species (75) are significant sources of ascorbic acid and/or vitamin A. Storage stability is fair to good, depending on species and storage conditions. Proteinase inhibitors and lectins are usually present, but are rendered harmless by ordinary cooking procedures.

White (Irish) Potato (*Solanum tuberosum* L.). The potato tuber has a dry matter content of about 20%, most of which is highly-digestible starch. The protein content is low (2%), but the protein has fairly high biological value in spite of being deficient in sulfur amino acids. In nitrogen balance studies with human adults, mixtures of potato and animal protein maintained a positive balance with lower total protein intake than with animal (egg or meat) protein provided alone (36). Fiber content is low, but has good physiological characteristics (28). The potato is an important source of ascorbic acid, is fairly palatable in its various forms of usage, can be served in substantial portions, has good storage stability, and toxic proteinase inhibitors are easily inactiviated by normal cooking procedures. Toxic glyco-alkaloids such as solanine are not affected by processing. It is therefore important that low-alkaloid cultivars be selected, and that the tubers be grown and stored under conditions that do not favor glyco-alkaloid development (i.e., absence of bright light). Foliage contains high levels of these substances, and this may become an environmental problem in a CELSS, as well as put an undue burden on the waste recycling system. Special systems must be developed for growing potatoes in hydroponic culture since stolons and tubers require a non-aqueous environment shielded from light. Tuberization in potato is favored by short photoperiods, cool temperatures, and an abundant supply of nitrogen. Potato also requires adequate moisture and is a heavy user of fertilizer. Drought and heat-resistant cultivars are available.

Sweetpotato (Ipomoea batatas (L.) Lam.). The tuberous root has a dry matter content averaging 27%, which is higher than that of the white potato. The main constituent is starch, but certain varieties also have the ability to accumulate considerable amounts of sucrose and reducing sugars. These are derived from starch and the amounts can be accentuated by "curing" prior to consumption. The tuberous root is a rich source of vitamin A, mainly β-carotene, and a moderate source of ascorbic acid. The protein content is similar to that of the white potato. The protein has a tendency to undergo rather extensive hydrolysis during curing, but this does not appear to affect its nutritional value. The root is an item of fair palatability, but does not lend itself readily to multiple usage. It stores well under proper conditions. Heat-stable trypsin and chymotrypsin inhibitors are known, but these apparently do not occur in concentrations sufficient to be of much concern. The plant may not be easily adaptable to hydroponic culture since the tuberous root seems to require a solid, moist medium for its development. Unlike white potato, sweet potato is a warm-weather crop and is considered to be drought- resistant, even though it can be grown under irrigation.

Taro (Colocasia esculenta (L). Schott.). The edible, underground corms have a dry matter content of about 27%, wich consists mainly of starch. The palatability is similar to that of the white potato, but it has a sweeter, more bland taste. Use flexibility appears to be more limited than for potato, but this may be due mainly to lack of commercial exploitation of its potential. A fermented product, poi, is a popular item in Hawaii. Calcium oxalate crystals occur and may limit its serving frequency. The variety 'Dasheen' is reputed to be largely free of this substance. Taro has extremely high productivity rates and should be adaptable to some kind of hydroponic culture since it is often grown in flooded paddy culture. Taro leaves also are edible when cooked, and provide protein, calcium, phosphorus, iron, potassium, and vitamin A, several B vitamins and ascorbic acid (75). This species responds well to intensive agriculture.

Cassava, Manihoc (Manihot esculenta Crantz). The large underground tubers are rich in starch, but rather poor in protein. The protein content is further reduced when the sliced tubers are leached with water in order to remove the toxic cyanogenic glycoside linamarin. The plant grows to considerable height, which might limit its usefulness for CELSS. The size of the underground tubers would appear to pose problems for hydroponic culture.

Yam (Dioscorea batatas Deene). The edible tubers are similar to the two foregoing species in food value, but develop deeper in the ground. The plant is viny and may grow to great heights (30 ft.).

Jerusalem artichoke (Helianthus tuberosus L.). The edible tubers accumulate inulin, not starch. Inulin, which releases fructose when digested, may be of value to diabetics. The tubers have poor storage stability.

Carrot (Daucus carota L.). In contrast to the tuber crops, this species has a lower nutrient concentration. The dry matter content is usually less than half that of white potato. The carrot is of value as a source of vitamin A and has considerable use flexibility, although it can cause vitamin A toxicity if consumed in large amounts. It can be consumed raw, although digestibility is very limited in that form. Carrots generally require deep, loose, well-drained, sandy loam or loam for best development, and it is uncertain how they would perform in soilless culture.

Garden beet (Beta vulgaris). The main value of this species is as a "decorative" ingredient in meals. The intense red color, due to high concentration of the pigment betanin, adds interest and variety, and therefore appeal, to any meal. The fact that beets are commonly grown in well-drained soils, including muck-types dressed with high rates of rotted manure, suggest that they, along with other root crops, may do well in "soils" created by composting treated, recycled wastes in a CELSS. Beets, like carrots, thrive best at relatively cool temperatures. One of the most appealing features of beets for CELSS is that the greens as well as roots can be eaten, which means that virtually all plant biomass is edible, leaving no unused residue.

Other root crops also have value as salad ingredients due to their "spicy" flavor, or as cooked vegetables to create variety and interest. Some, such as beet and turnip, also have edible leaves of considerable nutritional value. These crops include the following:

Rutabaga (Brassica nupus L.)
Kohlrabi (Brassica oleracea L.)
Parsnip (Pastinaca sativa L.)
Radish (Raphinus sativus L.)
Turnip (Brassica campestris L.)

Leaf and Flower Crops (Table 17).

This group comprises a great variety of species and edible plant parts, including the pot herbs, green leafy vegetables (lettuce is included under the salad crops) that are usually consumed after cooking (collards, mustard greens), edible flower tissues (broccoli, cauliflower), leafy cluster tissues (cabbage, brussel sprouts), starch fruits (squash, eggplant), and some edible

Table 17. Selection Criteria: Leaf and Flower Crops

Common Name	Nutritional Criteria										Cultural Criteria													Grand Total
	1*	2*	3	4	5*	6	7	8	9	Total	10*	11*	12	13	(14)	(15)	(16)	(17)	18	19	20	21	Total	
Broccoli	0	4	2	1	2	0	0	1	2	12	2	2	0	2	1	1	2	1	1	1	2	1	16	28
Brussel Sprouts	0	2	1	1	2	0	0	1	2	9	2	2	1	1	1	1	2	1	0	1	2	1	15	24
Cabbage, Chinese	0	0	1	1	2	1	0	1	2	8	4	2	1	2	1	1	2	1	1	1	2	1	19	27
Cabbage, head	0	2	1	1	2	1	1	1	2	11	4	2	0	2	1	1	2	1	1	1	2	1	18	29
Cauliflower	0	2	2	1	2	1	0	1	2	11	2	2	0	2	1	1	2	1	1	1	2	1	16	27
Chard	0	4	1	1	2	0	0	1	2	11	4	2	2	2	2	2	2	1	2	1	2	1	23	34
Collards	0	4	1	1	2	0	0	1	2	11	4	2	2	2	2	2	2	1	2	1	1	1	22	33
Corn, sweet	2	0	2	1	2	1	0	1	2	11	0	2	0	1	1	1	2	1	0	1	2	1	12	23
Dandelion	0	4	1	1	2	0	0	1	1	10	2	2	2	2	1	1	2	1	1	1	1	2	18	28
Eggplant	0	0	1	1	2	0	0	1	2	7	2	2	0	1	1	1	2	1	1	1	2	1	15	22
Kale	0	4	1	1	2	0	0	1	2	11	4	2	2	2	2	2	2	1	2	1	2	1	23	34
Mustard greens	0	4	1	1	2	0	0	1	2	11	4	2	2	2	1	1	2	1	2	1	1	1	20	31
Okra	2	2	1	0	2	0	0	1	2	10	2	2	0	1	1	1	2	1	1	1	2	1	15	25
Spinach	0	4	1	1	2	0	0	0	2	10	4	2	1	2	1	1	2	1	2	1	2	1	20	30
Squash, summer	0	2	1	0	2	0	0	1	2	8	0	2	1	0	1	1	2	1	0	1	2	0	11	19
Squash, winter	2	2	1	0	2	0	1	1	2	11	0	2	1	0	1	1	2	1	0	1	2	0	11	22

* Assigned a weighting factor twice that of other criteria.

( ) ≅ largely unknown

seeds and pods (sweet corn, okra). The main ingredient in all of them is water. A few provide significant energy, but their main appeal is variety and, from a nutritional point of view, their vitamin and mineral content. These are particularly concentrated in dark green photosynthetically active tissues. They contain high concentrations of Vitamin A, ascorbic acid, various B vitamins in significant amounts, and minerals such as iron, zinc, and calcium. These vegetables have limited storage stability due to their high moisture content. They often are rather inflexible in usage because of their pronounced flavor and intense coloration. Some tend to accumulate oxalic acid (spinach, beet leaves), and others, particularly the Brassica species, contain varying amounts of goitrogens (glucosinolates). The presence of these toxic compounds in many of our common vegetables (72) constitutes one of the main arugments for avoiding monotonous diets and unusually large intake of single species.

The nutritionally-important species in this category are:

Chard (Beta vulgaris L.)
Collards (Brassica oleracea L.)
Kale (Brassica oleracea L.)
Brussel sprouts (Brassica oleracea L.)
Broccoli (Brassica oleracea L.)
Spinach (Spinacia oleracea L.)
Dandelion (Taraxacum officinale Webber ex Wigg)
Mustard greens (Brassica juncea (L.) Coss.)

As evaluated by our scoring system, these species are very similar in use characteristics. Outstanding candidate species in this category are collards and kale. Both contribute significantly to the supply of several minerals (Ca, Fe, Zn, Cu) and vitamins (A, riboflavin, ascorbic acid) if served at least once daily. Spinach is less favored because of its oxalic acid content, which is likely to reduce the bioavailability of calcium in the diet. Broccoli has an advantage over the leafy vegetables in being more readily acceptable, particularly when served frequently, but its specific biomass productivity is much lower. Swiss chard is a type of beet that has been developed for its tops rather than its roots. Leaves can be harvested continually without a build-up of inedible biomass. The plants are vigorous and extremely cold hardy, easily withstanding hard frosts. Kale is another nutritious leaf vegetable crop that is winter hardy and likely hardy to other environmental stresses besides cold.

Spinach is a cool-season crop that bolts when exposed to long days and/or high temperatures, both of which environmental conditions may be desirable for maximizing primary productivity in a CELSS.

A number of species which have sprawling or vining growth habits would appear to be undesirable for a high productivity, intensive culture situation. Dwarf or bush-type selections, or chemical control of growth habit, might make some of these species more acceptable.

The remaining species in the cooked vegetable category that should be considered are:

Cabbage, Chinese (*Brassica campestris* L.)
Cabbage, head (*Brassica oleracea* L.)
Eggplant (*Solanum melongena* L.)
Sweetcorn (*Zea mays* L.)
Squash, winter (*Cucurbita mosschata* Duch, ex Poir)
Squash, Summer (*Curcurbita pepo* L.)
Okra (*Hibiscus esculentus* L.)
Cauliflower (*Brassica oleracea* L.)

These species range from high (sweet corn) to low (eggplant) in nutrient concentration, from medium (squash) to low (sweetcorn) in nutritional polyfunctionality, and with the exception of head cabbage and winter squash, suffer from poor storage stability. Their main function as diet ingredients is to provide variety of taste, texture, and appearance.

Salad Crops (Table 18).

Grouped in this category are species that are predominantly consumed raw,

Table 18. Selection Criteria: Salad Crops

	Nutritional Criteria										Cultural Criteria													
Common Name	1*	2*	3	4	5*	6	7	8	9	Total	10*	11*	12	13	(14)	(15)	(16)	(17)	18	19	20	21	Total	Grand Total
Celery	0	2	1	0	4	1	0	2	1	11	4	2	1	2	1	1	2	1	2	1	2	1	20	31
Cucumber	0	0	2	1	4	1	1	2	2	13	2	2	2	1	1	1	2	1	1	1	2	0	16	29
Endive, Excarole	0	2	1	1	2	0	0	1	0	7	4	2	1	2	1	1	2	1	2	1	1	1	19	26
Leek	0	0	1	0	4	0	1	1	0	7	4	2	1	2	1	1	2	1	1	1	1	1	18	25
Lettuce, leaf	0	4	2	2	4	1	0	2	2	17	4	2	2	2	1	1	2	1	2	1	2	1	21	38
Mushroom	0	0	2	1	4	1	0	2	2	12	4	2	2	2	1	1	0	0	0	1	2	1	16	28
Onion	0	0	2	1	4	2	2	1	2	14	4	2	1	2	1	1	2	1	1	1	2	1	19	33
Parsley	0	0	1	0	4	0	0	2	0	7	4	2	2	2	1	1	2	1	2	1	2	1	21	28
Peppers	0	0	1	1	4	1	1	1	1	10	2	2	2	1	1	1	2	1	1	1	2	1	17	27
Shallot	0	0	1	0	4	1	0	1	1	8	4	2	1	2	1	1	2	1	1	1	1	1	18	26
Tomato	0	4	2	2	4	2	1	2	2	19	2	2	2	1	1	1	2	2	1	1	2	1	18	37

* Assigned a weighting factor twice that of other criteria.

( ) $\cong$ largely unknown

as for instance in tossed salads, or garnishings for other prepared food items. Some of these species, however, also may be consumed following some form of processing (fried onions, cooked tomatoes), but none are usually consumed in quantities sufficient to make a significant contribution to caloric intake. A few such species may add significantly to intake of vitamin A and ascorbic acid (tomato, lettuce), and to dietary fiber (celery, cucumber), but their main value is their culinary and psychological appeal. The species considered in this category include:

Mushroom (Agaricus campestris L.)
Onion (Allium cepa L.)
Shallot (Allium cepa L.)
Celery (Apium graveolens L.)
Pepper (Capsicum annuum L.)
Cucumber (Cucumis sativus L.)
Lettuce, leaf (Lactuca sativa var. crispa L.)
Tomato (Lycopersicon esculentum Mill.)
Parsley (Petroselinum crispum Mill. Nym)
Endive, escarole (Chicorium endivia L.)
Leek (Allium ampeloprasum L.)

Mushrooms recently have received consideration as a nutritious human food, particularly with respect to their favorable amino acid and vitamin content (75). Although nonphotosynthetic, mushroom also may prove useful in degrading certain wastes in the regenerative system. High moisture content (85-92%) remains a serious storage problem.

Tomato, lettuce, and onion probably are the more important species in this category. Tomato has great flexibility of usage, being well accepted both in raw and cooked forms, and gives rise to vitamin A and C-rich juice products. As a crop, tomato requires high fertility levels for best productivity, and has been grown very successfully in hydroponic culture. Indeterminate cultivars will provide a regular supply of fruits at the cost of accumulating inedible biomass, although this can be minimized by pruning off and recycling lower, senescing branches and leaves. Shorter, determinate cultivars also are available, but sacrifice continuity of fruit supply. Culturally, tomato reponds well to high light and CO_2 enhancement, and is day-neutral with respect to flower initiation. Tomato is a warm-weather crop, has its share of pests and diseases, and is very sensitive to all kinds of envrionmental stresses.

Lettuce usually is the major constituent of salads, and as such contributes to vitamin A and C intake. Looseleaf or bunching cultivars would appear to be best, both from the point of view of human nutrition, as well as that of photosynthetic productivity. Lettuce thrives at relatively cool temperatures, but bolts at high temperatures. However, if root temperature (in hydroponics) is maintained at $65^{o}F$, the crop will tolerate rather high air temperature (32). Lettuce is a long-day plant for flowering, but vegetative lettuce is produced commercially under continuous illumination by keeping ambient temperature low. Among the advantages of lettuce include demonstrated suitability for hydroponic culture, a positive response to controlled-environment production (shortened production cycle, increased yield), and a favorable ratio of edible-to-inedible biomass which does not have to be harvested all at once (loose-leaf cultivars).

Onions add their distinctive and commonly accepted flavor to many foods. It is a cool season crop but will grow well over a wide range of temperatures. The edibility ratio is favorable (in some types both tops and bulbs are eaten), but the crop may not adapt well to conventional forms of solution culture, preferring moist, well-drained soils high in organic matter. Onions might adapt well to growth in artificial soil created by composting plant and human wastes in a recycling ecosystem.

Grain Crops (Table 19).

The cereal grains are among the oldest cultivated food crops and form the basis upon which all major civilizations have been built. Their value lies in

Table 19. Selection Criteria: Grain Crops

	Nutritional Criteria										Cultural Criteria													
Common Name	1*	2*	3	4	5*	6	7	8	9	Total	10*	11*	12	13	(14)	(15)	(16)	(17)	18	19	20	21	Total	Grand Total
Barley	4	2	1	0	0	0	2	2	2	13	2	2	0	2	2	1	2	1	(1)	1	2	1	17	30
Corn	4	2	1	1	0	0	2	2	2	14	2	4	0	2	1	1	2	2	0	1	2	1	18	32
Japanese Buckwheat	4	2	1	0	0	0	2	2	1	12	2	2	0	1	1	1	2	1	(1)	1	1	1	14	26
Oats	4	2	1	0	0	0	2	2	2	13	2	2	0	2	1	1	2	1	(1)	1	2	1	16	29
Rice	4	2	2	2	0	2	2	2	2	18	2	2	0	2	1	1	2	(2)	2	1	2	1	18	36
Rye	4	2	1	0	2	0	2	2	2	15	2	2	0	2	2	1	2	1	(1)	1	2	1	17	32
Wheat	4	2	2	2	2	2	2	2	2	20	2	2	0	2	1	1	2	(2)	2	1	2	1	18	38

* Assigned a weighting factor twice that of other criteria.

( ) ≅ largely unknown

their high energy concentration, storage stability of the harvested grain, their significant contribution to protein requirements, and their appreciable content of B vitamins. All of the small grains, but particularly wheat, can be processed and served in numerous forms and combinations, thus providing culinary variety from a monotonous base. However, they differ greatly in the type and extent of processing required to convert the harvested kernels to usable products. Oats, barley, and rice all have hulls that adhere to the kernels, whereas wheat and rye have hulls that separate easily in a simple threshing operation. Some grain products retain distinctive flavors which limit their use flexibility. Corn, barley, and oats fall into this category, whereas wheat and rice have a bland flavor which allows expression of other flavor ingredients.

Wheat (Triticum aesitivum L., T. durum Desf.). Wheat is probably the most versatile of the grain crops as a food. It is found as an ingredient, and often as the major component, of hundreds of processed food items. Like all small grains, its major constituent is starch (70-75%). Its protein (11-14%) is deficient in lysine and tryptophan, and therefore complementation with proteins higher in these amino acids is required for good nutrition. The wheat protein (gluten) is unique among cereal proteins in its elastic and gas retention properties. These characteristics are responsible for the ability of wheat to form leavened products (bread, rolls, cakes) and extruded pasta products (spaghetti, noodles). Vitamin and lipid content depends upon degree of refining. Highly refined flour contains much less of these components. The commonly accepted products made from wheat (bread, crackers, cakes) contain a relatively low level of moisture. These products are, therefore, high energy sources and are undemanding in terms of consumption volume needed to cover human energy needs. The minimum processing requirement for wheat is threshing or winnowing. The whole grain can then be consumed after parboiling. Further processing in the form of cracking or grinding the whole kernel will, depending on the extent of grinding and the fineness of the resulting particles, open up many more applications as a whole wheat coarsely-ground flour. If sifting is used to remove germ and fiber, the full gamut of applications becomes available.

Different varieties of wheat can be selected which are adapted to almost any type of climate. Dwarf varieties of spring wheat would appear to be most appropriate for a highly efficient ecological system. Winter wheat requires a long period of low temperature vernalization in order to continue growth and set grain, whereas spring wheat can proceed through its entire life cycle under optimum growing conditions. It is fortunate that wheat is self-fertilizing in that hand pollination would be totally impractical on a large scale. On the other hand, it is unfortunate in terms of efficient space utilization for CO_2-O_2 conversions that wheat undergoes a sharp, irreversible decline in photosynthetic activity soon after the onset of reproductive development.

Rye (<u>Secale cereale</u> L.). Rye has characteristics that are in many ways similar to those of wheat: hulls are easily removed, and milling operations can be made rather simple. However, the kernel usually has a grayish bran layer wich carries its color over to the milled flour. A characteristic flavor associated with rye products makes this species less desirable than wheat as a food ingredient. Culturally, rye scores similar to wheat, although it tends to be much taller and possess more inedible biomass than does wheat. Rye is the most cold hardy of all small grain cereal crops, and does the best on low-fertility soils.

Rice (<u>Oryza sativa</u> L.). Rice contains considerbly less protein than do the other cereal crops (7.5 vs. 12%), but its protein has a somewhat higher biological value. The hull clings to the seed, which requires more refining than does wheat or rye. The refined kernel has a bland flavor which allows rice to be used as an ingredient of numerous meal combinations. Rice is the only major crop species that is aquatic, and as such should be easily adaptable to hydroponic culture. It is a warm-season short-day crop, although cultivars differ in their sensitivity to photoperiod.

Other grain crops falling within this general category include the following:

Barley (Hordeum vulgare L.)
Buckwheat, Japanese (Fagopyrum esculentum Moench)
Corn (Zea mays L.)
Oats (Avena sativa L.)

All have hulls which are removed only with difficulty. Distinct flavors limit their use in combination with other food items. Of the cereal grain crops, corn has the greatest yield potential under field conditions, probably because it is the only C-4 species in this category.

Fruit Crops (Table 20).

The nutritional significance of fruit in the diet essentially is limited to their contribution of vitamin C and fiber. The importance of this contribution is considerably diminished in dietary regimes containing fresh salad crops, freshly-harvested pot herbs, and other vegetables. Under such circumstances, the only argument for including fruits is to create variety, interest, and avoidance of monotony. These psychological factors appear to be important for a strict vegetarian lifestyle, but not essential. Many woody fruit species have prolonged juvenility, require a dormant period and chilling to relieve it, have a very unfavorable ratio of edible-to-inedible biomass, and remove carbon from the carbon cycle for long periods of time. Herbaceous fruit species such

Table 20. Selection Criteria: Fruit Crops

Common Name	Nutritional Criteria										Cultural Criteria													Grand Total
	1*	2*	3	4	5*	6	7	8	9	Total	10*	11*	12	13	(14)	(15)	(16)	(17)	18	19	20	21	Total	
Apple	2	0	2	2	4	1	1	2	2	16	0	0	1	0	1	0	2	1	0	1	2	1	9	25
Apricot	2	0	1	0	4	1	0	1	2	11	0	2	1	0	1	0	2	1	0	1	2	0	10	21
Banana	4	0	2	2	4	1	1	2	2	18	0	2	2	1	1	2	2	2	0	1	2	2	17	35
Blueberry	2	0	2	1	4	0	0	2	2	13	2	2	1	1	1	0	2	1	1	1	2	0	14	27
Cantaloupe	2	2	2	1	4	0	0	2	2	15	4	4	1	1	1	2	2	1	1	1	2	1	21	36
Cherry, sweet	2	0	1	0	4	0	0	2	2	11	0	0	1	0	1	0	2	1	0	1	2	0	8	19
Cranberry	0	0	1	0	2	0	0	2	2	7	2	2	1	1	1	0	2	1	1	1	1	0	13	20
Currant	0	0	1	0	4	0	0	2	1	8	2	2	1	1	1	0	2	1	1	1	1	0	13	21
Gooseberry	0	0	1	0	4	0	0	2	1	8	2	2	1	1	1	0	2	1	1	1	1	0	13	21
Grape, European	4	0	2	1	4	1	0	2	2	16	4	2	1	1	1	0	2	1	1	1	2	2	18	34
Grapefruit	2	2	1	1	4	1	0	2	2	15	0	2	1	0	1	0	2	1	0	1	2	1	11	26
Orange, sweet	2	2	2	1	4	1	0	2	2	16	0	2	1	0	1	0	2	1	0	1	2	1	11	27
Papaya	2	2	1	0	4	0	0	2	1	12	0	2	2	0	1	2	2	1	0	1	1	1	13	25
Peach and Nectarine	0	0	2	0	4	0	0	2	2	10	0	0	1	0	1	0	2	1	0	1	2	0	8	18
Pineapple	2	0	2	1	4	1	0	2	2	14	2	2	1	1	1	2	2	1	1	1	2	2	18	32
Plum, American	2	0	1	0	4	1	0	1	2	11	0	0	1	0	1	0	2	1	0	1	2	0	8	19
Raspberry	2	0	2	1	4	1	0	2	2	14	2	2	1	1	1	0	2	1	1	1	2	0	14	28
Strawberry	2	2	2	1	4	0	0	2	2	15	4	4	2	2	1	2	2	1	2	1	2	1	24	39
Tangelo	2	2	2	0	4	0	0	2	2	14	0	2	1	0	1	0	2	1	0	1	2	1	11	25
Tangerine	2	2	2	0	4	0	0	2	2	14	0	2	1	0	1	0	2	1	0	1	2	1	11	25
Watermelon	0	0	1	0	4	0	0	2	2	9	2	4	1	1	1	2	2	1	1	1	2	1	19	28

* Assigned a weighting factor twice that of other criteria.

( ) ≅ largely unknown

as the everbearing strawberry (Fragaria chilensis L.) and cantaloupe (Cucumis melo L.) would appear to be much more suitable. Numerous other species have been listed and evaluated. It would be particularly desirable to eventually include banana and grape in a CELSS if cultural difficulties associated with these species could be overcome.

Nut crops (Table 21).

Nuts are excellent sources of energy, having a high fat content and low moisture level. They also generally contain fairly high levels of riboflavin and iron, two nutrients likely to be marginal in strict vegetarian diets. However, since nuts usually are not consumed in large quantities (except by squirrels), their nutritional importance is not really significant. Their main value would be in alleviating monotony in the diet. Although nuts come from woody species, which generally seem inappropriate for a small regenerating system, some attention might be given to almond (Prunus dulcis Mill.) and hazelnut (Corylus avellana L.), both of which can be small trees with minimal dormancy requirements and very nutritious nuts.

Sugar Crops (Table 22).

Sugar (sucrose) in the diet recently has come under attack due to its demonstrated caries-promoting effect and alleged aggravation of various degenerative diseases, including heart ailments, diabetic conditions, arteriosclerosis, and adiposity. However, all of these conditions are the result of abuse and misuse due to excessive intake. In a CELSS, sugar can play two significant roles: it can enhance palatability, and it can serve as an energy supplement if caloric intake is marginal or deficient. There are several potential sources, the choice of which for the CELSS environment depends

Table 21. Selection Criteria: Nut Crops

	Nutritional Criteria										Cultural Criteria													
Common Name	1*	2*	3	4	5*	6	7	8	9	Total	10*	11*	12	13	(14)	(15)	(16)	(17)	(18)	19	20	21	Total	Grand Total
Almond	4	4	2	0	4	1	2	2	2	21	0	0	1	0	1	0	1	1	0	1	2	0	7	28
Filbert	4	4	2	0	4	1	2	2	2	21	0	0	1	0	2	0	1	1	0	1	2	1	9	30

* Assigned a weighting factor twice that of other selection criteria.

( ) ≅ largely unknown

Table 22. Selection Criteria: Sugar Crops

	Nutritional Criteria										Cultural Criteria													
Common Name	1*	2*	3	4	5*	6	7	8	9	Total	10*	11*	12	13	(14)	(15)	(16)	(17)	(18)	19	20	21	Total	Grand Total
Date palm	4	0	2	1	4	2	1	2	1	17	0	0	1	0	0	1	2	1	0	1	1	0	7	24
Sorghum	4	0	1	1	0	1	1	1	1	10	2	2	1	1	2	1	2	2	1	1	2	1	18	28
Sugar beets	4	0	2	1	0	2	1	1	2	13	4	4	1	2	2	2	2	2	1	1	2	1	24	37
Sugar cane	4	0	2	1	2	2	1	2	2	16	2	4	1	1	1	1	2	2	0	1	2	1	18	34

* Assigned a weighting factor twice that of other selection criteria.

( ) ≅ largely unknown

less upon the quality of the final product than upon the culture requirements of the species and the degree and complexity of processing necessary to obtain an acceptable product.

Sugar cane (Saccharum officinalis L.). Sugar cane can grow to great heights, although dwarf cultivars exist, but even "tall" cane can be harvested with sufficient sugar content at early stages of development. The juice is expressed from stalks by crushing and centrifugation. If these operations are done carefully and under mild conditions (sacrificing yield to some extent), the juice will be light colored and have an acceptable flavor. Depending on the final product desired, juice must be condensed to syrup by evaporation with intermittent skimming to remove coagulated protein, or allowed to crystallize to form crude, raw sugar. A higher degree of purity is obtained by repeating the crystallization process. Commerical refining involves the use of lime and phosphate, but these additives would be hardly acceptable in a CELSS. Sugarcane is a tropical or subtropical C-4 species with high productivity rates. It is a perennial crop which, in Hawaii, is grown as a virtual monoculture where there is essentially no rotation with other crops. The cane is harvested two or three times before a field is replanted. The fact that cane is propagated vegetatively circumvents problems associated with reproductive growth, pollination, etc., but one still has the problem of storing propagules.

Sugar beet (Beta vulgaris L.). Commercial extraction of sugar from beets involves diffusion from tiny V-shaped slices (cosettes) of root tissue to avoid extraction of large amounts of impurities which would occur with crushing or grinding. However, diffusional extraction requires large amounts of water and it is doubtful whether this approach would be suitable for a CELSS. Further conventional refining requires the use of lime and carbon dioxide or sulfur dioxide, all of which hardly would be possible in a small, closed ecosystem. The final product (syrup or crystalline sugar) is likely to be less acceptable than that from sugarcane in the absence of such means of refining. If hydroponic systems are to be used, there is a need to develop special growing systems to accommodate proper development of the tuberous root. One favorable attribute of sugar beet is that it maintains a much more highly favorable root/shoot ratio than does sugarcane, and a very reduced foliar canopy of only one or two leaves can support maximum root development under optimum environmental conditions. Sugar beet is a warm-season crop which is day-neutral for root development but long-day for seed production. However, the regional distribution of its production throughout the United States and Canada indicate that it tolerates a wide range of environmental conditions.

Sorghum, sorgo, sweet sorghum (*Sorghum bicolor* (L.) Moench). Harvesting and processing of this species would be similar to that of sugarcane. The final product (syrup) contains polyphenolic substances (tannins) which give it a certain astrigent taste appreciated by few. Its use flexibility is likely to suffer for this reason. In terms of cultural considerations, sorghum is among the most heat and drought tolerant of the cereals, and dwarf forms although not necessarily of the syrup type are available that would minimize the proportion of inedible biomass and suggest that it may be adaptable to hydroponic culture. Sorghum scored competitively among the cultivation criteria, but poorly among the nutritional use criteria.

Date palm (*Phoenix sylvestris*). The sap of the date palm may be harvested in a manner similar to that used for maple trees. Evaporation of the sap yields a sugar which is acceptable with respect to color and flavor. Although the date palm competes favorably with the other sugar crops in terms of use criteria, the fact that it is a tropical tree growing to heights of 50 feet would create so many cultural problems that it almost certainly would preclude selection of this species.

Stimulant crops (Table 23).

The use of certain stimulants, particularly in the form of beverages, is by now thoroguhly ingrained in Western culture. Coffee, tea, and cacao all contain caffeine as well as other alkaloids. These stimulants function as anti-depressants and combat fatigue and drowsiness in users. As such, they serve a useful function in a stressful society, and it is likely they would serve a similar function in a CELSS.

Coffee (Coffee arabica L.). The shrub can be maintained at a height of 6 feet by pruning, but probably could be reduced still further if necessary. Coffee is a perennial evergreen that has a short-day requirement for flower bud initiation, but then goes into a dormancy that can be broken by drought followed by irrigation. The berries must be fermented to remove the pulp, and are roasted to prepare the final product. This process develops a considerable amount of noxious gas which would pose an environmental problem within a closed system.

Tea (Camellia sinensis (L.) Kuntze). This evergreen shrub produces harvestable leaves continuously. Its height is kept to approximately 3 feet in commercial production, but, as with coffee, this height probably can be reduced still further to suit circumstances. Tea requires only minor processing to obtain the final product. Steamed, rolled, and dried leaves yield the green tea of the Orient, whereas rolling and 'fermentation' followed by drying yields black tea. In cultural terms, tea would appear to have fewer problems associated with its production than would other stimulants.

Cacao, cocoa (Theobroma cacao L.). The cacao tree is an evergreen, commonly 25 or more feet in height. Although its cultural characteristics would appear to preclude its inculsion in a CELSS, the recent development of

Table 23. Selection Criteria: Stimulant Crops

	Nutritional Criteria										Cultural Criteria													
Common Name	1*	2*	3	4	5*	6	7	8	9	Total	10*	11*	12	13	14	15	(16)	(17)	18	19	20	21	Total	Grand Total
Cacao	4	0	2	1	0	1	1	1	1	11	0	0	1	0	0	1	1	1	0	1	1	0	6	17
Coffee	0	0	2	2	2	0	2	1	2	11	0	2	1	0	0	1	1	1	0	1	2	0	8	19
Tea	0	0	2	2	4	0	2	1	2	13	2	4	2	1	1	2	1	1	1	1	2	2	17	30

* Assigned a weighting factor twice that of other selection criteria.

( ) ≅ largely unknown

proliferating cacao cotyledons in tissue culture (56) could make it possible to produce cacao without the plant in the future. This would require a source of sucrose, but could be carried out in darkness. Cacao products (cocoa powder, cocoa fat, chocolate) are rather demanding in terms of processing requirements.

Herbs and Spices (Table 24).

A great number of herbs and spices are commonly used to provide a variety of interesting flavors in our diets, and to make certain bland foods more palatable. The necessity of incorporating such species into CELSS is highly debatable and individualistic. Since the incorporation of a few species into a CELSS cultivation plan would not appear to be demanding in terms of space, nor pose any large cultural problems, a listing of species that logically should be considered appears without rank according to score.

Table 24. Herbs and Spices

Common Name	Botanical Name
Anis	*Pimpinella anisum* L.
Basil	*Ocimum basilicum* L.
Cardamom	*Elettaria cardamomum* (L.) Maton. Amomum Cardamomum L.
Caraway	*Carum carui* L.
Chicory	*Cichorium intybus* L.
Chili peppers	*Capsicum annuum* L.
Chives	*Allium schoenoprasum* L.
Coriander	*Coriandrum sativum* L.
Cumin	*Cuninum cyminum* L.
Dill	*Anethum graveolens* L.
Garlic	*Allium sativum* L.
Ginger	*Zingiber officinale* Roscoe
Lavender	*Lavendula officinalis* Chaix. in Vill.
Marjoram, sweet	*Origanum majorana* L.
Mint	*Mentha* sp.
Mustard, white	*Brassica juncea* (L.) Coss., B. japonica Sieb, B. campestris L.
Nasturtium, garden	*Tropaeolum majus* L.
Parsley	*Petroselinum crispum* (Mill.) Nym.
Pepper	*Piper nigrum* L.
Peppers, Pimiento type	*Capsicum annuum* L.
Peppers, small fruited	*Capsicum annuum* L.
Sage	*Salvia officinalis* L.
Sesame	*Sesamum indicum* L.
Thyme	*Thymus serpyllum* L.
Tumeric	*Curcuma longa* L.
Vanilla	*Vanilla planifolia* Andr.

V. Human Life Support Scenarios

It has been taken as a matter of course that man will eventually expand his territory beyond the limits of Earth and ultimately occupy through settlements and colonization the entire solar system (33). Provided such expansion will take place, it is further assumed that space settlements will incorporate elements of the Earth's biosphere deemed essential for human survival and well-being. The number of living components (plant, animal, and microbial species) required to maintain long-term physical and mental health in a society existing under conditions so remote from any previous human experience cannot be envisioned without a gradual and stepwise progression of experimentation. Speculations abound, but the areas of insufficient information concerning human interaction with nature, both physical and psychological, are so vast that detailed "theoretical" probing seems rather tenuous.

We also assume that plants will play as vital a role in space as they do on Earth, and that experimentation should begin now as we make our first steps into space. We will further assume that plants will play useful roles at intermediate levels of space exploration and utilization. Justification for incorporation of plant agriculture at these levels must be given not only on economic grounds, but also as required for nutritional and psychological purposes. The relative imortance of these considerations probably will depend upon the magnitude and duration of space missions.

We will in the following attempt to define the scope and time scale for the anticipated utilization of plant agriculture in space. In so doing, we hope to clarify the extent and character of research needed. However, the probability of achieving a meaningful analysis is low considering the current lack of data and knowledge in this area.

We hope, however, that such an excercise will be useful in providing a degree of realism in planning future research investment and in focusing attention to problem areas that otherwise may be overlooked.

We will do the analysis by considering various circumstances and scenarios. These scenarios will be compared on the bases of qualities and quantities about which reasonable opinions can be formulated. The simplest of these is one that has been used for this purpose several times previously, namely, payload cost. This approach consists of comparing given scenarios on the basis of payload weight; the weight being, to a first approximation, equivalent to cost of launching, and viewing it in relation to duration of the mission. The point in time at which two given scenarios result in equal transportation costs is termed the break-even point (67). No consideration is given by this method of analysis to psychological factors (diet monotony, variety in work assignments, attractiveness of surroundings, similiarity with Earth-like scenery) or to the value of a given scenario as an experiment. It is furthermore obvious that this method of analysis breaks down when the duration of the mission becomes for all practical purposes indefinite (i.e. permanent settlements).

The importance of psychological factors presently cannot be evaluated quantitatively. That they are likely to be of importance, and perhaps of overriding importance in the long-term, seems demonstrated by experiences obtained by people living for long periods of time in confined structures such as nuclear submarines (80).

That the ultimate (or at least foreseeable) goal, a permanent space settlement, will require a high degree of Earth-like living conditions and Earth-like surroundings, appears, in the absence of evidence to the contrary, to be a reasonable assumption. That plants will occupy a similar and equally important position in the scheme of things in such settlements as they do on Earth therefore seems a natural consequence. At this early stage, we know little about how plants will perform in space, the effect of hypogravity or zero gravity, their behavior in closed systems, their susceptibility to radiation damage at various stages of growth and development, etc. Our ignorance only can be remedied by experimentation, and this experimentation ought to take place at every stage in the conquest of space. This implies that each involvement of plants in the development of self-sustaining and self-renewing systems constitutes experiences for which there are no substitutes. In that sense, any life support system based on plant life cannot be compared on the basis of costs with "alternatives" which do not incorporate plants, and the value of such an excercise becomes limited to answering questions of how and when to utilize available research funds and not in deciding which scenario is to be preferred.

Break-Even Calculations. In the past (33), the implicit assumption has been made that agriculturally-based, regenerative systems would become cost effective in terms of payload weight only in relation to very large missions of long duration (populations in excess of 10^4 persons and durations approaching a lifetime). Others (67,68) have more ambitiously attempted to make comparisons between scenarios by calculating break- even points of cost in terms of launch payloads. Results of such calculations indicate that plant regenerative systems may become cost effective in a much shorter time. That such calculations are presently difficult was discussed previously. That they also are at best very approximate, due to vast uncertainties of assumptions, will be demonstrated.

Any life support system launched into space will consist of components of fixed mass independent of mission duration, as well as components consumed during the mission, whose mass is therefore proportional to time. The expendable components may be incorporated either at the outset of the mission in quantities sufficient for the anticipated duration or be resupplied from

Earth at regular intervals. The two payload penalties are, for the purpose of the following argument, considered equivalent. According to this simple model, the total mass to be launched for any particular scenario is then

$$\text{Total Payload} = PE + YR \times T$$

where PE (payload excess) is the mass of the time-independent components in excess of that common to all scenarios (mass of crew quarters, flight and navigational instrumentation, equipment needed for the intended purpose of the mision, etc.), and YR (yearly resupply) is the yearly requirement of expendable components, while T represents time in years. The break-even point (BEP) in comparing two scenarios for a given mission is then the time (mission duration) when the two payloads are equal, or

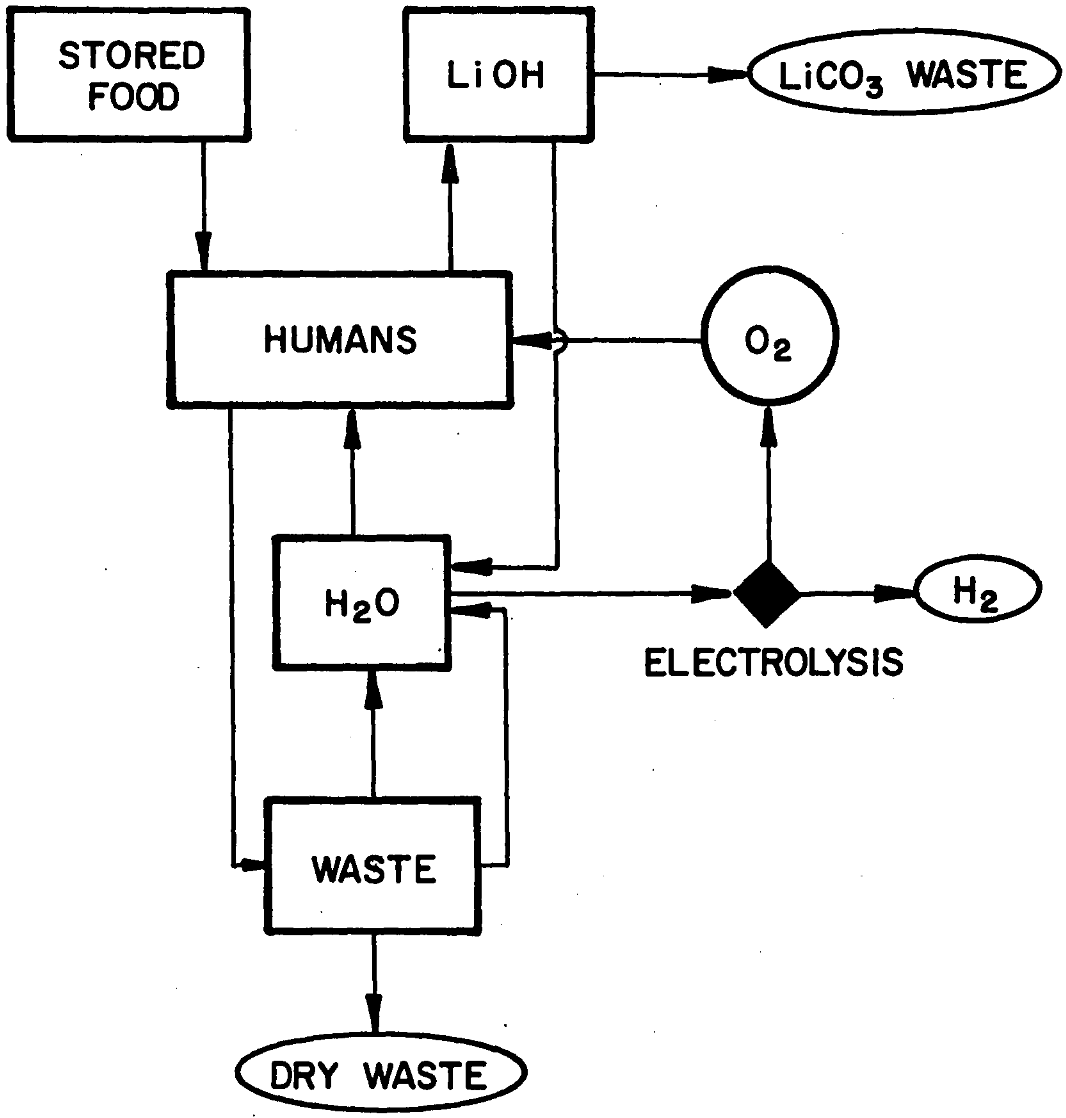
$$BEP = \frac{PE_2 - PE_1}{YR_1 - YR_2} = \frac{\Delta PE}{\Delta YR} \quad \text{(eq. 1)}$$

where the subscripts refer to scenarios 1 and 2, respectively. It is worthwhile to note that the difference in PE and/or YR determines the BEP. A small BEP value is obtained by minimizing ΔPE and/or maximizing ΔYR. If scenario 1 represents a non-regenerative system and scenario 2 a regenerative system, then it is obvious that BEP decreases as both PE_2 and YR_2 decrease.

The potential value of such calculations lies in the reliability of the BEP estimate, but it is precisely here that the difficulty resides. We will in the following illustrate this by an example:

We are comparing two scenarios, one of which is a non-regenerative system based upon ample yearly resupply, whereas the other is a CELSS incorporating controlled-environment agriculture. Scenario 1 could, for example, include a system that eliminates respiratory CO_2 by trapping with LiOH and generates O_2 from H_2O (Fig. 1), or one of the systems illustrated in Figure 2, utilizing either the Bosch or Sabatier process for eliminating CO_2, and electrolysis for

Fig. 1. A Non-Regenerative Life Support System Utilizing CO_2 Trapping.



generating O_2 from H_2O. The stoichiometry for these alternatives is as follows:

Alternative 1: CO_2 trapping: $2LiOH + CO_2 = Li_2CO_3 + H_2O$

H_2O electrolysis: $2H_2O = 2H_2 + O_2$

Total balance: $2LiOH + CO_2 + H_2O = Li_2CO_3 + O_2 + 2H_2$

If a person produces 386 kg CO_2 per year (Table 27), the total consumption of LiOH and H_2O in maintaining this process will be 580 kg/person.

Alternative 2 (Bosch Process, Fig. 2):

CO_2 reduction: $CO_2 + 2H_2 = C + 2H_2O$

H_2O electrolysis: $2H_2O = 2H_2 + O_2$

Total balance: $CO_2 = C + O_2$

Thus, no supplementary materials will be consumed in this process.

Alternative 3 (Sabatier Process):

CO_2 reduction: $CO_2 + 4H_2 = CH_4 + 2H_2O$

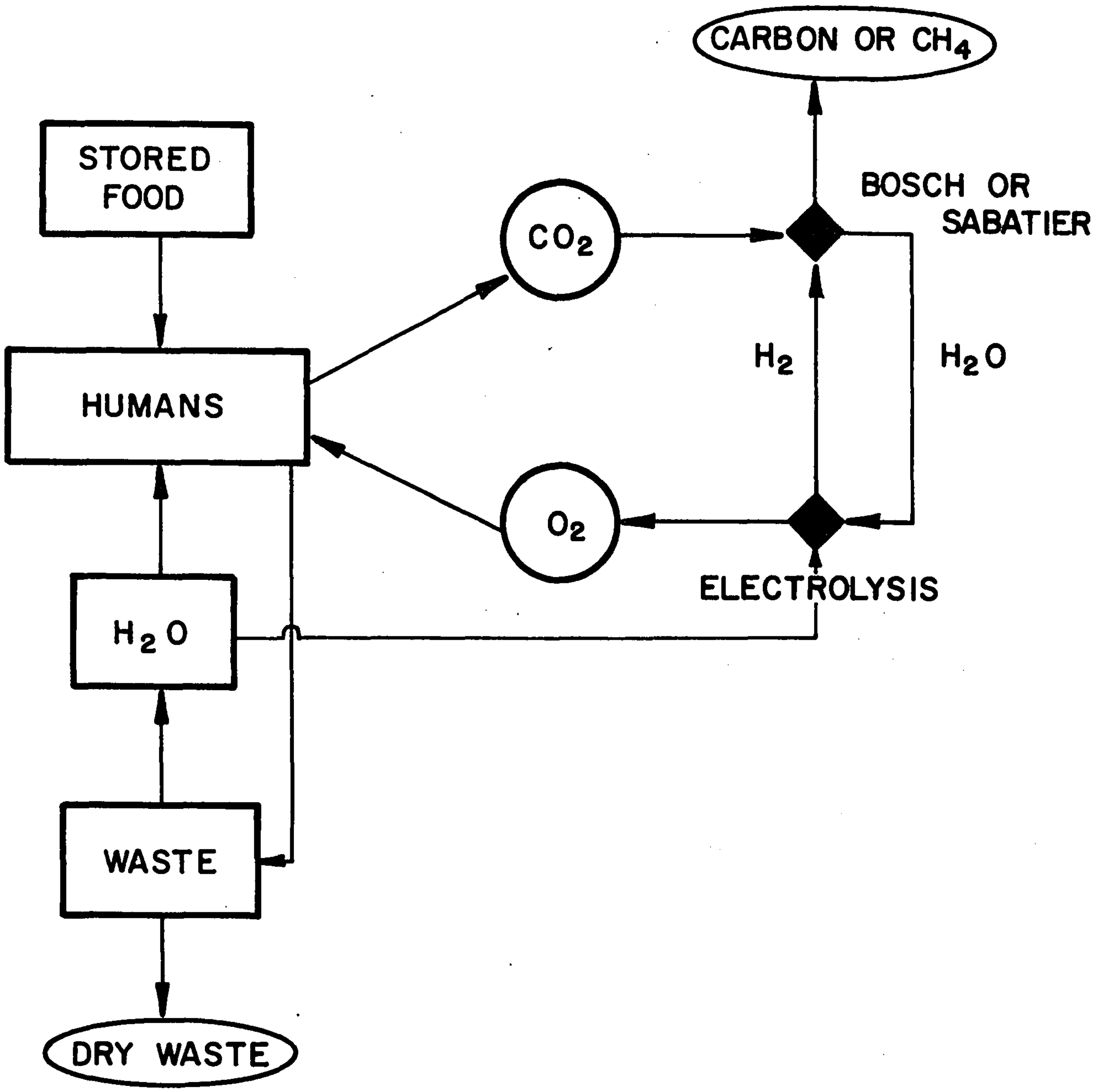
H_2O electrolysis: $4H_2O = 4H_2 + 2O_2$

Total balance: $CO_2 + 2H_2O = CH_4 + 2O_2$

To maintain this process, 342 kg of H_2O will be expended per year per person.

The Bosch-electrolysis process is clearly superior in terms of YR weight reduction, but inherent difficulties in maintaining high yield of an intermediate reduction product (C, graphite) while avoiding formation of a variety of toxic substances (formaldehyde, methanol) apparently makes this process of questionable value (22). The Sabatier process suffers from similar technical difficulties in separating CO_2 and H_2 from the reaction mixture. The alternative based upon CO_2 trapping is clearly the simplest and least hazardous

Fig. 2. A Non-Regenerative Life Support System Utilizing Catalytic O_2 Regeneration.



process, but carries the heaviest weight penalty.

We will assume that the Bosch process eventually will be perfected and choose to adopt this process for Scenario 1.

For Scenario 2 we visualize a closed, regenerative system comprised of plants and humans as the biological elements (Fig. 3). The plants are assumed to provide sufficient and wholesome food for the personnel as well as air revitalization.

In comparing the two scenarios, one requires weight estimates for the time-independent (PE) and time-dependent (YR) components (Table 25). Table 26 indicates the scenarios to which the various components are to be charged. It is clear from equation 1, that if we stipulate a maximal BEP value of 10 years for Scenario 2 to become an economically-viable consideration for intermediate steps in space development, the ratio $\Delta PE/\Delta YR$ must be less than 10. It is further obvious that ΔYR must have a positive value, and thus $YR_1 > YR_2$. The feasibility of providing an acceptable BEP is therefore constrained by the value of YR_1. Inspection of Table 26 shows that YR_1 is composed of two items only: stored food and spare parts. The first item can be estimated as follows: If food is provided as pure nutrients (a purely theoretical and limiting case) (Tables 27 and 28), an approximate value of 0.22 ton person^{-1} year^{-1} is required. If dehydrated natural foods are provided similar to those used during Apollo missions (37), the requirement becomes 0.48 tons person^{-1} year^{-1}. Lastly, by providing a substantial amount of intermediate-moisture food for greater palatability, one can assume a value of 0.65 tons person^{-1} year^{-1}. Spare parts for operation of the Bosch process is the only other item to be charged to YR_1. A value of 0.2 tons person^{-1} year^{-1} seems ample for this purpose. Thus, a total of 0.42 to 0.85 tons can be estimated for YR_1. This rather wide range probably can be narrowed considerably by further advances in

Fig. 3. A Regenerative Life Support System Based on Higher Plants for Food Production and Air Revitalization.

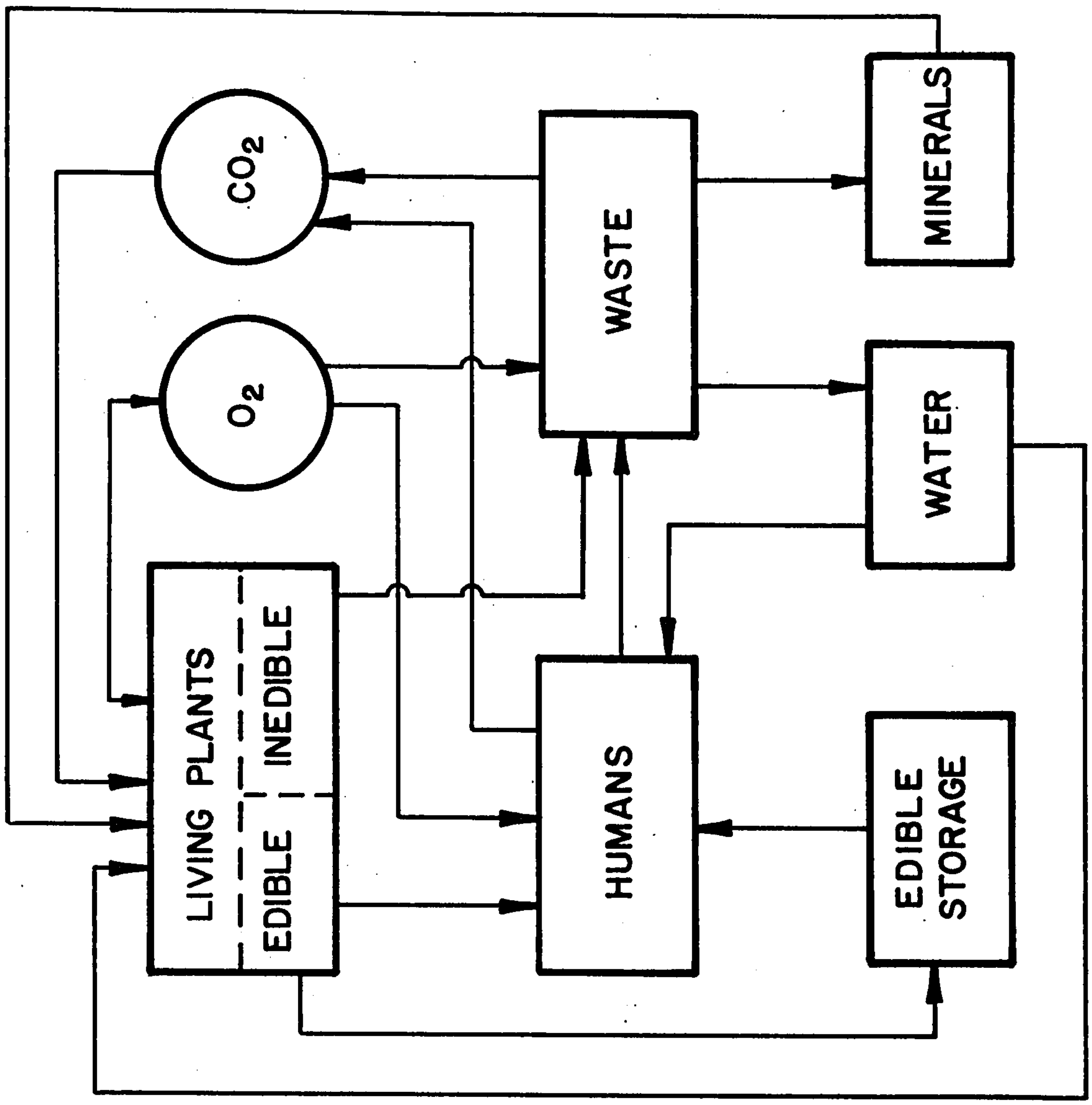


Table 25. Components Affecting Payload Excess (PE)and Yearly Resupply (YR).

Payload Excess.

Agricultural Housing: The physical structure incorporating agricultural production.

Agricultural Power: Solar panels and support structures for operation of agricultural activities, including illuminaiton of plant-growing area.

Agricultural Structures: Structures for support of plants and root media, containers and conduits for nutrient solutions, circulation equipment, motors, pumps, fans, light sources and fixtures, conveyors.

Agricultural Water: Water present in the agricultural production area, in growing plants, in stored plant materials, in plant waste, in agricultural waste treatment plant, in nutrient solutions, concentrates, and reservoirs.

Biomass Hold-up: Total mass of plant dry matter in all forms in the system.

Cooling Equipment: Air conditioning of the agricultural production area, including condensors, evaporators, compressors, motors, pipelines.

Food Processing: Equipment for drying, milling, grinding, extracting, cooking, including support structures and housing.

Machine Shop: Tools and machinery for repair and manufacture of defective parts. Hardware storage area for replacement parts, structures, etc.

Oxygen Power: Solar power panels and accessories for regeneration of oxygen from carbon dioxide and water.

Oxygen Regeneration: Equipment for regeneration of oxygen from carbon dioxide and water. Bosch or Sabatier process.

Waste Treatment: Waste treatment plant for agricultural wastes or the excess capacity of such a plant due to agricultural wastes. Includes furnaces, pressure vessels, filters, gas purification, compressors.

Yearly Resupply

Biomass Resupply: Biomass in storage to compensate for that lost due to agricultural operations by seepage from spacecraft, mainly in the form of gases. Stored as food, water, and nitrogen.

Stored Food: Food prepared, packaged, and preserved on Earth and present at launch.

Spare Parts: Spare parts storage for replacing defective equipment and structures.

Stored Water: Water for generation of oxygen, including items such as tanks, pipelines, etc.

Table 26. Items Affecting PE (Payload Excess) and YR (Yearly Resupply) Scenarios 1 and 2 (Tons person^{-1}).

Time-independent Components	Scenario 1 (Total Resupply)	Scenario 2 (Regenerating)
	PE_1	PE_2
Agricultural Housing		x
Agricultural Power		x
Agricultural Structures		x
Agricultural Water		x
Biomass Holdup		x
Heat Dissipation Equipment		x
Food Processing		x
Machine Shop		x
Waste Treatment		x
Oxygen Power	x	
Oxygen Regeneration	x	
Food Storage	x	
Time-dependent Components	YR_1	YR_2
Biomass Resupply		x
Stored Food	x	
Spare Parts	(x)	x

Table 27. Mass input-output for a ten-year ten-person space mission.*

	Fat	Protein	Carbohydrate	Total
Input				
a) Daily, per person				
Food, g	60	101	439	600
Water, g				540
Oxygen, g	170	110	260	1,356
b) Yearly, per person				
Food, kg	22	39	160	221
Water, kg				820
Oxygen, kg	62	40	95	197
c) Total mission				
Food, kg	2,200	3,900	11,600	22,100
Water, kg				82,000
Oxygen, kg	6,200	4,000	9,500	19,700
Output**				
a) Daily per person				
Carbon dioxide, g	170	172	715	1,057
Metabolic water, g	67	42	244	353
Urea, g		34		34
b) Yearly, per person				
Carbon dioxide, kg	62	63	261	386
Metabolic water, kg	24	15	89	128
Urea, kg		13		13
c) Total mission				
Carbon dioxide, kg	6,200	6,300	26,100	38,600
Metabolic water, kg	2,400	1,500	8,900	12,800
Urea, kg		1,300		1,300

* The caloric distribution of the diet was assumed to be 20% from fat, 15% from protein, and 65% from carbohydrates. Caloric values were calculated on the basis of 4 kcal g^{-1} for protein and carbohydrates, 9 kcal g^{-1} for fat. A total of 2,700 kcal was taken as the daily requirement of a 70 kg adult male (RDA). Protein composition was assumed to be $C_{.53}H_{.07}N_{.16}O_{.23}S_{.01}$ were the decimals indicate weight fractions. Fat was calculated as tristearin and carbohydrate as glycosyl monomers. Sulfur from protein was considered insignificant and omitted from calculations.

** Values for carbon dioxide and metabolic water include quantities contributed by combustion of wastes (including feces, etc.).

Table 28. Vitamin and mineral requirements for a 10-year 10-person space mission.*

	Daily, per person mg	Yearly, per person g	Mission total kg
Vitamin A	1	0.4	0.040
Vitamin C	60	20	2.000
Vitamin D	0.005	0.002	0.001
Vitamin E	10	4	0.400
Vitamin K	—	—	—
Vitamin B6	2.2	0.8	0.080
Vitamin B_{12}	0.003	0.001	0.001
Thiamin	1.4	0.5	0.050
Riboflavin	1.6	0.6	0.060
Niacin	18	7	0.700
Folic acid	0.4	0.2	0.020
Biotin	0.15	0.05	0.005
Pantothenic acid	8	3	3.857
Choline	500	180	19.000
Iron	14	5	0.500
Zinc	15	5	0.500
Copper	3	1	0.100
Molybdenum	0.3	0.1	0.010
Iodine	0.15	0.05	0.005
Fluorine	3	1	0.100
Selenium	0.1	0.04	1.219
Calcium	800	300	30.000
Phosphorus	800	300	30.000
Magnesium	350	100	10.000
Sodium	1,500	500	50.000
Potassium	4,000	1,500	150.000
Chlorine	1,700	600	60.000
Sulfur (tentative)	1,000	300	30.000
Totals (approx.)	10,000	3,500	350.00

*Data from ref. 75

food science. Utilization of high vacuum and storage temperatures approaching absolute zero, which would be available in the space environment, would substantially enhance the storage stability of dehydrated foods. Assuming that such progress will be made, one can accept a total value of 0.7 tons for YR_1. As indicated previously, YR_2 cannot exceed this value.

YR_2 contains the following items: biomass resupply (loss of biomass as gases from compartments associated with agricultural activities), and spare parts required to maintain all equipment and structures connected with agricultural production (Table 26). An optimistic value for the first item has been given as 0.1 tons $person^{-1}$ $year^{-1}$ (67), and we will adopt that value. Spare parts of a wide variety will be needed to maintain agricultural activity, including tools, parts for motors, pumps, compressors, materials for the machine shop, photovoltaic cells, and lighting fixtures and sources (if direct sunlight is not used), etc. Until a detailed design of a regenerative system has been made, it is impossible to estimate the weight penalty associated with these items. However, it is possible to approximate what the maximum mass of YR_2 would be. The divisor in equation 1 should have a reasonable minimum value for BEP not to exceed 10 years. As will be shown later, ΔPE is likely to have a magnitude of several tons. If this is tentatively accepted as being 3 tons, the divisor must have a value of at least 0.3 to meet our stipulated requirement (BEP=10). The corresponding value for YR_2 is then:

$$YR_2 = YR_1 - 0.3$$

$$YR_2 = 0.7 - 0.3 = 0.4 \text{ tons}$$

This value does not appear to be an unreasonable quantity since all equipment and spare parts must be designed for long life and be made of lightweight materials.

It may be more difficult to meet the requirement of a maximum of 3 tons for the dividend of equation 1 (ΔPE). The three major components of PE_2 (Table 26) are likely to be agricultural housing, agricultural power, and heat dissipation equipment. None of these today can be estimated within a reasonable degree of reliability because there are too many unknowns. Do plants require shielding against the radiation of space? Must artificial gravity be provided (by rotation of large structures) for normal plant development? How will light and energy for plant growth be furnished (direct solar irradiance, photovoltaic cells, nuclear reactor)? The problem can be approached only by making assumptions concerning these factors. Thus, we assume that radiation shielding is not required, that photovoltaic energy will be used, and that plants do well in zero gravity. Under these stipulations, we can make a rough estimate of the mass required for agricultural housing.

The area required for plant growth to maintain 10 people (nutritionally) was estimated at $236 m^2$ (Table 29). If we arrange the plant production area as six levels 1 m apart in the shape of a cube, provide for 1 m free space on the sides, and construct the housing from 0.25 inch aluminum (required to resist a pressure of 1 atm against a vacuum on the outside), we arrive at a total weight of approximately 7 tons or 0.7 tons $person^{-1}$. A similar calculation for a 100-man mission yields approximately 0.25 tons $person^{-1}$. The area conversion factor for solar energy to electrically generated illumination, from a solar constant of 1.4 kw m^{-2} (Earth orbit) to 0.7 kw m^{-2} (Earth surface, noon), is approximately 0.02 using state-of-the-art technology. The energy-harvesting area should, therefore, be approximately $23.6/0.02 = 1180\ m^2 \times person^{-1}$. This area is not dependent on size of the mission. To estimate realistically the mass of supporting structures, electrical converters, light fixtures, light sources, and photovoltaic cells is clearly beyond our present capabilities, but it would seem that a total mass of one ton per person easily could be exceeded.

Table 29. Growing Area Requirements for Producing a "Minimum" Vegetarian Diet

	Yield of edible dry matter $g\ m^{-2}\ day^{-1}$			Consumption rate	Area required $m^2\ person^{-1}$		
	OFA*	CEA*	CEA,proj.	(g $person^{-1}$ day^{-1})	OFA	CEA	CEA,proj.
Plant Species							
Soybean	4	14	25	104	26	7.4	4.2
Peanut	2	9	15	71	36	7.9	4.7
Wheat	3	16	25	119	40	7.4	4.8
Rice	4	8	25	116	29	14.5	4.6
Potato	7	19	30	121	17	6.4	4.0
Carrot	9	(10)	30	3	0.3	0.3	0.1
Chard	(3)	(5)	40	3	1	0.6	0.1
Cabbage	(3)	9	40	9	3	1	0.3
Lettuce	4	16	40	3	1	0.2	0.1
Tomato	5	17	40	13	2.6	0.8	0.7
			Total area		155.9	46.5	23.6

*Data from ref. 48 and other sources.

We have similar difficulties estimating the mass of the heat dissipation system (refrigeration, air conditioning). Such a system probably would have to be designed rather unconventionally by taking advantage of radiant heat dissipation toward a black body (space) at temperatures approaching $0^{o}K$, and therefore achieve much higher efficiencies than are normally possible. However, it is difficult to imagine a mechanical system comprised of compressors, metallic tubing, cooling coils, fins, and radiant surfaces that would weigh less than a few hundred kilograms per person. Adding to this the various other items in Table 26, it would seem difficult to meet our stipulated goal of a maximum mass of 3 tons per person.

One factor that could materially change this picture is an improvement in crop yield figures used to make these calculations (Table 29). Yield ($g\ m^{-2}\ day^{-1}$) ultimately determines the extent of growing area required per person, and therefore also the magnitude of supporting structures. The yield data used (for these calculations) are "Projected CEA" values. These have not yet been attained, but are considered to be achievable within the scope of present agricultural technology. Further developments in cultivar selection, including breeding cultivars designed for rapid growth rates under the specific conditions of CEA can be expected to have the effect of making CEA an increasingly attractive proposition for intermediate-to-short-term space missions.

We have in the foregoing attempted to calculate the "break-even" point between two scenarios, one based on total food resupply and the other a CELSS based on plant regeneration of food and revitalization of the atmosphere. It should be evident that such calculations are subject to uncertain assumptions, and therefore yield results of questionable value. On the other hand, we believe that the excercise has been useful in pointing out areas where information is required to make the assumptions less tenuous. Paramount among these are questions regarding the gravity dependence of plant growth and development, the radiation sensitivity of plants, and ultimate yield of plant biomass per unit area of production per unit time. As also was pointed out, break-even calculations have little bearing on the final goal of establishing independence from Earth. To that end, there is no alternative to the CELSS scenario. Application of partially-closed CELSS at intermediate levels of space exploration should be justifiable on the grounds of representing experimental efforts needed to achieve that final goal. Justification of CELSS on the basis of economics at these intermediate levels cannot be made at the present time due to missing background information.

VI. Plant Scenarios

We are in the following exploring the consequences of using scenarios involving regeneration (Scenario 2) as briefly delineated in the preceding section. These scenarios are based on the premise that plants will provide adequate nutrition for the personnel as well as function as the exclusive means for air rejuvenation.

Plant scenarios obviously will require a special attitude by personnel that subsist on a pure vegetarian diet. A certain dedication to the goals of the mission must be inherent in these people. The magnitude of the acceptance and palatability problem will depend upon the diversity of plant species and the extent and sophistication of food processing methods (40).

The following discussion emphasizes application of plant scenarios at intermediate levels of space exploration. We have, therefore, assumed that energy, space, and weight were constrained, and that plant species would be chosen from those favored by the evaluation presented in Chapter IV. These constraints were dominant factors in the ratings used there.

In selecting various combinations of plant species to constitute a particular diet, we have paid particular attention to sufficiency and balance of proteins, adequacy of calories, and proper ratios of protein, carbohydrate, and fat. Adequacy of vitamins and minerals has been deemphasized, since we have reasoned that any deficiency in these can be remedied without difficulty by supplementation. As indicated in Table 28, vitamins are required in amounts that will not add significantly to payload weight. State-of-the-art technology in the field of industrial pharmacy also should alleviate any concerns with regard to stability of vitamins. For instance, multivitamin pills are available that maintain 90% of original potency after 5 years at room temperature. Similar considerations also are valid for certain minerals that may be provided in less-than-adequate amounts by plants. But one must recognize that mineral supplementation would inevitably add to the inventory of recycling minerals and eventually could pose new problems of waste treatment and toxic effects in plant culture. These aspects will be discussed further under specific diets.

We will present two versions of the plant scenario: The "modest" version represents an attempt to simplify the system as much as possible. This implies that the number of species has been dictated strictly by nutritional needs without regard for palatability and diversity. The extent of food processing similarly has been limited to nutritional rather than organoleptic concerns. In the "generous" scenario we pay attention to these factors and the resulting diet should be met with a considerably greater enthusiasm by CELSS personnel than would the former. This advantage is not achieved without penalty. The complexity of the system is considerably greater, and the scenario puts greater demands on space, weight, and power.

The Modest Scenario

We referred earlier (Table 30) to a "minimum" diet which may be considered as one example of this scenario. This diet is composed of components from ten species, and these are consumed in proportions indicated by the number of servings. Eight of the ten species produce edible parts that can be stored under appropriate conditions, while two of them (chard and tomato) must be consumed shortly after harvest. The latter species are nutritionally the least important. Harvest failure among these would therefore not have catastrophic consequences. The remaining species, being storable, would buffer against production hazards, provided adequate stores were maintained.

To make an extreme point of simplicity, we have assumed that processing is virtually absent in this scenario. With the exception of roasting peanuts, no

Table 30. An Example of a "Modest" Diet Scenario, the so-called "Minimum" Diet (Quantities per person per day).

Species	No. of Servings	Weight as served, g	Food Energy, kcal	Protein, g	Fat, g	Carbohydrate, g	Calcium, mg	Magnesium, mg	Phosphorus, mg	Sodium, mg	Potassium, mg	Iron, mg	Vitamin A, IU	Thiamin, mg	Riboflavin, mg	Niacin, mg	Ascorbic Acid, mg
Soybean	2	180	234	19.8	10.2	19.4	131	58	322	4	971	4.9	50	0.38	0.16	1.1	-
Dry bean	2	190	212	14.0	1.0	38.2	90	72	265	12	746	4.9	-	0.41	0.14	1.5	-
Peanut	2	72	419	18.9	35.1	14.9	54	126	293	2	504	1.6	-	0.23	0.10	12.3	-
Wheat	6	405	681	25.2	2.7	141.9	81	326	810	-	351	5.4	-	0.21	0.12	9.6	-
Rice	4	390	464	9.8	2.4	99.4	46	113	284	-	274	2.0	-	0.36	0.08	5.4	-
Potato	4	600	416	11.6	0.4	93.2	40	132	282	8	2224	3.2	-	0.48	0.20	0.8	88
Carrot	1/4	19	6	0.2	0.1	1.3	6	5	6	6	41	0.1	1903	0.01	0.01	0.1	1
Chard	1/4	22	4	0.4	0.1	0.8	16	15	5	19	70	0.4	1182	0.02	0.05	0.1	4
Cabbage	1	145	29	1.6	0.3	6.2	64	19	29	20	336	0.4	180	0.06	0.06	0.4	48
Tomato	2	200	40	2.0	0.4	8.6	24	28	50	6	444	1.0	1640	0.10	0.08	1.2	42
Totals		2223	2505	103.5	52.7	324.1	552	762	2346	77	4999	23.9	4955	2.26	1.00	32.5	183
Percent of RDA			93	185			69	218	293	5	(150)	170	100	101	63	181	305
Caloric Distribution, %				15	20	65											

postharvest processing is performed besides that required to make the items edible. This is essentially limited to boiling in water. A simple system such as this may be suitable for initial short-term experiments of closure involving human subjects.

The nutritional consequences of the proposed diet are illustrated in Table 30. The difficulty in meeting caloric requirements with a diet of this type is apparent. Only 93% of RDA caloric needs for a 70 kg (ca. 154 lb) human male undergoing moderate physical activity is met by this diet, although a person of lesser body weight would be satisfied. Total daily intake amounts to 2.2 kg (ca. 4.8 lb). It should be possible to consume such a quantity divided between three meals, provided personnel have undergone an adaptation period to rather voluminous meals.

The low specific energy value of the diet (1.13 kcal g^{-1}) is a consequence of lack of elaborate processing. All food items, as consumed, have a moisture content in excess of 70%, and some as high as 94%. This aspect of vegetarian diets can be changed and associated problems overcome by introducing processing methods such as grinding (flour milling), drying, oil extraction, and deep-frying. The "generous" scenario will implement these considerations.

Two nutrients indicated as being deficient (Table 30) are calcium and riboflavin. The major sources of the former are legumes, and it would seem difficult to increase calcium content appreciably without increasing the proportion of these. The deficiency in relation to RDA is probably not significant under normal conditions, but may become so in space under zero-gravity conditions where serious problems of calcium retention have been noted (81). Riboflavin may need supplementation; it generally is recognized as being deficient in vegetarian diets (see Chapter III).

While the calcium level of this list is rather low, the phosphorus level appears too high. The Ca/P ratio which ideally should be 0.67 (11), is, for this diet 0.24. However, one must consider that phosphorus occurs in seeds in the form of phytic acid, and has very low bioavailability. We estimate that no more than 1000 mg phosphorus per day is available from this diet. Further complications result from the interaction of calcium with phytic acid in the gut, resulting in formation of insoluble calcium phytate. The extent to which this occurs in humans is not known, but it can be inferred from animal data (55) that this phenomenon has no major effect on calcium bioavailability. These considerations lead to an estimated Ca/P ratio of 0.55, but it is difficult to conclude whether this diet would be harmful or lead to calcium deficiency.

Several nutrients appear to be in considerable excess in this diet (Table 30). Excesses of protein, thiamine, niacin, and ascorbic acid compensate for unavoidable daily variations in the intake of the species, as well as cooking losses, and variations in the raw material quality. A certain degree of flexibility is introduced which, in the absence of these surpluses, would not be available.

The "excess" of iron is more difficult to evaluate. It is again necessary to emphasize that the RDA is based on an average American diet in which a major portion of the iron occurs as heme iron. This is not so in a vegetarian diet. The bioavailability of non-heme iron is considerably lower than that of heme iron. Plant materials contain, furthermore, compounds that may chelate with or otherwise interfere with iron uptake. Recent reports (76) indicate that plant (soy) proteins may have an adverse effect on absorption of inorganic iron. It is not possible to predict the iron bioavailability of this "minimum" diet within the framework of present knowledge, but it is probably safe to state that a real excess may not occur.

An all-plant diet is severely lacking in Na and probably also in Cl although there are no available data for the latter element. Cultivated plants generally are low in sodium, which in the plant kingdom is found in concentrations suitable for human dietary needs only in non-edible species adapted to brackish marsh lands or arid regions with high salt levels in the soil (21). Whether a reduced level of NaCl in the diet will create health problems is not altogether certain. RDA values are very tentative, and it is possible that humans can adapt, presumably by developing a more efficient resorption process, to considerably lower levels of intake than normally occurs. Certain primates (gorillas) apparently have succeeded in doing this (65).

Daily supplementation of the so-called "required" amounts of sodium and chloride in the form of table salt would increase the amount of these elements being recycled within a CELSS to 1.1 kg per person by the end of one year. Clearly, the potential for harmful effects of salt build-up on plant growth and development does exist. Continuous removal or regeneration of pure salt from the effluent of the waste treatment plant might be required, but would seem to pose rather formidable technical problems.

Available data for Cu and Zn are incomplete for this diet (Table 31), but are sufficient to suggest that the RDA may be satisfied, provided bioavailability is not a problem with these elements.

A second example of the "Modest" scenario is illustrated in Table 32. A total of 15 plant species are included in this scenario. They are partitioned into five groups containing three species each in such a manner that each group constitutes a fairly well balanced meal. The daily intake comprises a combination of any three of the five meals. If all meals are consumed with equal frequency, the growing area (Table 33) required for each species is dictated by the need to provide 60% of the quantities listed in Table 32. The total area

Table 31. Copper and Zinc Content of Species in the "Minimum" Diet.

	mg per 100 g edible, raw portion	
Species	Cu	Zn
Soybean	(0.50)	-
Dry bean	0.85	0.20
Peanut	0.27	3.0
Wheat	0.20	-
Rice	-	-
Potato	0.15	0.3
Carrot	-	-
Chard	-	-
Cabbage	-	-

Table 32. A 15-Species Version of the "Modest" Scenario

Meal No.	Species	Servings per meal	Weight as served, g	Moisture, g	Food energy, kcal	Protein, g	Fat, g	Carbohydrate, g	Calcium, mg	Magnesium, mg	Phosphorus, mg	Sodium, mg	Potassium, mg	Iron, mg	Vitamin A, IU	Thiamin, mg	Riboflavin, mg	Niacin, mg	Ascorbic acid, mg
1	Soybeans	4	360	256	468	39.6	20.8	38.8	262	116	644	9	1942	9.8	100	0.76	0.32	2.2	-
	Potato	4	600	474	416	11.6	0.4	93.2	40	132	282	8	2224	3.2	-	0.48	0.20	0.8	88
	Mustard green	¼	18	16	4	0.5	-	0.2	32	14	9	6	66	0.5	1225	0.02	0.04	0.1	55
	TOTAL		976	730	888	51.7	21.2	132.2	334	262	935	23	3232	13.5	1325	1.26	0.56	3.1	143
2	Peanuts	2	54	1	419	18.9	35.1	14.9	54	126	293	4	504	1.6	-	0.23	(0.10)	(12.3)	-
	Rice	4	390	274	464	9.8	2.4	99.4	5	113	284	-	274	2.0	-	0.36	0.08	6.4	-
	Pea pod	½	50	41	26	1.7	0.1	6.0	31	17	45	-	85	0.4	340	0.14	0.06	-	11
	TOTAL		494	316	909	37.4	37.6	120.3	89	239	622	4	863	4.0	340	0.73	(0.24)	(18.7)	11
3	Split pea	4	400	280	472	37.2	2.0	96.0	89	141	472	49	1395	7.1	167	1.03	0.04	4.2	-
	Corn	2	226	157	272	6.8	2.4	52.0	17	115	209	-	221	1.6	382	0.29	0.09	1.7	-
	Kale	¼	18	15	4	0.7	0.5	0.7	31	7	13	13	66	0.4	1558	-	-	-	22
	TOTAL		644	452	748	44.7	4.9	148.7	137	263	694	62	1682	9.1	2107	1.31	0.49	5.9	22
4	Dry bean	4	380	262	424	27.8	2.0	76.3	178	212	530	24	1491	9.7	-	0.81	0.27	3.0	-
	Wheat	4	227	152	456	16.8	2.0	96.0	50	192	529	4	511	4.3	-	0.79	0.17	5.9	-
	Turnip green	¼	18	16	5	0.5	-	-	44	9	10	-	85	0.3	1368	0.04	0.07	0.1	25
	TOTAL		670	430	885	45.1	4.0	172.3	272	413	1069	28	1087	14.3	1368	1.64	0.51	9.0	25
5	Chickpea	4	380	255	452	25.7	6.0	76.6	188	200	416	33	1000	8.7	63	0.39	0.19	2.5	-
	Oats	2	360	292	264	9.6	5.0	46.1	36	173	274	1	238	3.0	-	0.41	0.09	0.7	-
	Broccoli	½	75	67	24	2.7	0.2	4.4	77	12	59	11	287	0.8	1875	0.08	0.17	0.7	85
	TOTAL		815	614	740	38.0	11.2	127.1	301	385	749	45	1525	12.5	1938	0.88	0.45	3.9	85
	Average daily intake comprising three of the five meals will provide (percent of RDA):																		
					93	227			85	268	305	3	100+	228	106	249	84	136	287

Table 33. Growing Area requirements for a 15-species vegetarian diet

Species	Yield, edible D.M. $g \cdot m^{-2} \cdot day^{-1}$ (Projected CEA)	Consumption rate $g \cdot person^{-1} \cdot day^{-1}$	Area required $m^2 \cdot person^{-1}$
Soybean	25	62	2.3
Potato	30	76	2.5
Mustard greens	40	1.2	0.03
Peanuts	15	32	2.1
Rice	25	70	2.8
Pea pod	30	5.4	0.18
Split pea	25	72	2.9
Corn	25	41	1.6
Kale	40	1.8	0.05
Dry bean	25	71	2.8
Wheat	25	72	2.9
Turnip greens	40	1.2	0.03
Chickpea	25	75	3.0
Oats	25	41	1.6
Broccoli	30	4.8	0.16
		Total	25.00

required for all 15 species is approximatly 25 $m^2 person^{-1}$, which is very similar to that found for the "minimum" diet (Table 29). The similarity extends to several other characteristics of this diet. Thus, the specific energy value (1.16 vs. 1.13 kcal g^{-1}) is again very low, as is the Ca/P ratio (0.28 vs. 0.24), and the sodium content is negligible (3 vs. 5% of RDA). The levels of calcium and riboflavin are again marginal, whereas the remaining nutrients are adequately supplied. The caloric intake is slightly lower than that required for a 70 kg adult male (93% of RDA), in spite of consumption of voluminous meals. As indicated previously, this difficulty is a consequence of the low specific energy value and is overcome by more elaborate processing.

This version of the "modest" plant scenario offers certain advantages over the "minimum" version. The larger number of species in the second version makes for less monotony in the dietary regime: the three meals in any one day are different, and the daily menus can be varied by changing meal combinations. As a result, this dietary regime should be suitable for closure experiments of somewhat longer duration than that discussed previously.

However, some attention must then be given to the defective characteristics of the diet that were briefly discussed above. Supplementation with small amounts of vitamins (riboflavin, B_{12}) would seem to pose no particular problem since vitamins would not accumulate in the system. Supplementation with minerals would lead to such accumulation and eventually cause difficulties elsewhere in the system. One simple way of raising the calcium level in the diet and at the same time achieve an amelioration of the skewed Ca/P ratio would involve use of plant nutrient solutions as cooking water in preparation of meals. Hoagland's solution (27) has a Ca/P ratio of 6.5/1. The daily intake of cooking water in the proposed diet amounts 1.5 L. If Hoagland's solution was used instead of water, the average daily intake of calcium would be equivalent to 123% of the RDA and the Ca/P ratio would increase to 0.39. Trace mineral levels at the same time would be raised to assure adequate intake without causing excesses and toxic reactions. The levels of sodium and chlorine only can be made adequate by direct supplementation of the meals with NaCl. Complications in the recycling system are therefore unavoidable with this diet.

The Generous Scenario. This plant scenario is considerably more elaborate than the previously discussed "modest" scenario. The number of plant species has been increased to 43 (Table 34) to allow for greater flexibility in menu planning and to avoid the monotony that characterizes the "modest" scenario. Processing is more sophisticated and includes such items as milling, oil extraction, extrusion, evaporative crystllization of sugar, fermentation, etc., (Table 35). The additional plant species were selected according to the scores developed in Tables 15 through 24.

We will not describe this scenario in great detail. It should be obvious that the consequences of introducing a large number of new plant species and a considerable amount of processing technology will result in improved palatability as well as nutrition and general well-being by the CELSS personnel. The difficulties associated with providing meals with sufficiently high SEV's will be overcome, and there should be opportunities for improving the Ca/P ratio and enhance protein biological values and vitamin intakes that were marginal under the "modest" scenario.

On the other hand, the agricultural system has been rendered much more complex, and proper integration and control of such a large number of plant species will require a new dimension of plant management practices.

Table 34. Plant Species Recommended for the "Generous" Scenario

Leguminous crops:
- Dry bean (navy, pea)
- Green bean (garden)
- Mung bean
- Garbanzo (chickpea)
- Dry pea (split)
- Sugar pea (podded, chinese)
- Peanut
- Soybean

Grains crops:
- Barley
- Corn (maize)
- Oats
- Rice
- Rye
- Wheat

Root and Tuber crops:
- Garden beet (red)
- Carrot
- Potato
- Sweet potato
- Taro

Leaf and flower crops:
- Broccoli
- Chinese cabbage
- Head cabbage
- Cauliflower
- Chard
- Kale
- Spinach

Salad crops:
- Celery
- Leaf lettuce
- Onion
- Tomato

Fruit crops:
- Banana
- Grape
- Strawberry
- Cantaloupe

Sugar Crops:
- Sugar beets
- Sugar cane

Stimulant crop:
- Tea

Herbs and spices:
- Chives
- Garlic
- Mint
- Parsley
- Pimiento peppers

Table 35. Unit Operations and Processes Recommended for Food Processing in the "Generous" Scenario

Operations	Crops or Raw Material	Products or Purpose
Threshing	Cereal crops	Cereal grain, straw, glume
Hulling	Barley, oats, rice, legume seed	Dehulled grain, seed, glume
Milling	All cereal crops	Flour, grits, hulls and fiber, bran
Grinding	Legume seed, herbs and spices	Meals and spice powders
Shelling	Peanuts	Shelled peanuts, shells
Dry Heating	Meals of oil seed	Facilitate oil extraction
Pressing	Oilseed meals, cane sugar beet	Low-fat flour, oil, juices
Centrifugation	Crude oils, juices	Clarification
Filtration	Crude oils, juices	Clarification
Evaporation	Clarified juices, treated waste stream	Crude sugar, syrups, NaCL+Ca
Drying	Herbs and spices, tea sugar grapes	Dried leaves, raisins, granula sugar
Fermentation	Crude juices, molasses	Yeast, acetic acid, lactic acid
Germination	Mung bean, soybean	Germinated seed sprouts

Food Preparation Methods: Volatiles Produced

Roasting	Steam	Organics
Boiling	Steam	
Frying	Steam	Organics
Baking	Steam	Organics
Deep Frying	Steam	Organics

VII. Controlled Environment Agriculture in CELSS

Maintaining homeostasis in a CELSS with limited buffer size will require close control of environmental conditions for all component biosystems. This is particularly true for photoautotrophic components, whose efficiency of air revitalization and carbohydrate synthesis is quite responsive to environmental manipulation. Available evidence indicates that crop production cycles can be shortened and yields enhanced if the cardinal factors of plant growth (light, temperature, water, nutrients, and atmosphere) are provided in proper combinations. However, specific information regarding environmental optimation of plant growth and development largely is lacking, especially for species usually grown by "extensive" rather than "intensive" culture.

If photosynthetic higher plants are to comprise a vital link in a manned CELSS, it is essential that limits of crop performance be defined for candidate species. Environmental optimization studies are needed to realize this goal, and will require inprovement of present growth chamber capabilities. The following discussion summarizes topic areas in which improvements to controlled environment facilities are needed to realize the research objectives of the food production group in the CELSS program.

Illumination

The level of photosynthetically-active radiation (PAR, 400-700nm) provided by most reach-in and walk-in CE facilities seldom exceeds 25-40% of full daylight, and more often is in the range of 16-20% (70). Thus, whereas photon flux density usually is not the factor most often limiting photosynthesis in the field under summer growing conditions, it may well be the limiting factor in plant growth chambers, especially when other environmental parameters are controlled. Nevertheless, it may not be necessary to provide PAR equivalent to full sunlight in order to saturate photosynthesis, because relative growth rates of several crops apparently do not increase further when light is raised above half-sunlight level (74). Factors such as leaf geometry and plant spacing within a stand may be equally important in making the most efficient use of available light, and should be carefully considered when designing CE cropping systems for CELSS. It should be noted, however, that capabilities for high irradiance lighting to stimulate photosynthesis under conditions of elevated carbon dioxide and temperature have not yet been fully exploited. Present lighting technology for plant growth should be able to provide the quality and level of artificial illumination required for optimizing primary productivity of any given crop species, given time and resources needed for this type of research. High intensity discharge (HID) lighting fixtures combined with incandescent sources should be incorporated into future CE facilities dedicated to the food production aspect of this program. Flexibility also should be retained so that new types of lighting fixtures can be introducted into such facilities as they are developed.

Atmospheric Composition

Control of air composition is another important part of growth optimization efforts for candidate species. Most of the world's most important food crops, including the prime candidate species, are low efficiency C-3 plants (38). But the photorespiration that reduces efficiency of net CO_2 fixation in C-3 species can be overcome either by raising ambient CO_2 levels or lowering ambient O_2 levels around the shoot of the plant (45). Since it is more practical to manipulate CO_2 (0.03%) than O_2 (21%), and because O_2 appears to be important for reproductive development (58) and root growth, initial optimization studies probably will involve mainly CO_2 enhancement. Dose-response curves for photosynthesis and growth rates should be obtained as a function of variable CO_2 concentration, and these curves should be obtained at several levels of light and temperature, so that growth modelers will be able to construct appropriate "response surfaces" with predictive capabilities. Furthermore, it may prove desirable to "program" CO_2 enhancement into the production cycle of a given crop so as to minimize production of nonedible biomass but maximize yield by injecting CO_2 only during critical phases of crop development. Leafy vegetables, for instance, may benefit from elevated CO_2 through the production cycle (at least during the photoperiod), whereas cereal and pulse crops may benefit from CO_2 most during grain or pod-filling periods of development, particularly if we learn how to defer the monocarpic senescence of leaves often associated with flowering and fruiting of annual crops.

In the event that reduced atmospheric pressure (hypobaric) conditions (e.g., 0.2 atm) are found to be desirable for minimizing gas diffusion rates through the hull of a space-deployed CELSS, it still would be possible to compensate O_2 and CO_2 to their equivalent partial pressures at sea level (although this also would be an easy way to lower O_2 partial pressure and minimize inhibition of photosynthesis by the Warburg effect (18)). However, plants growing in such an environment would be almost entirely devoid of N_2 gas, which normally is thought of as an inert gas as far as plant growth is concerned (except for N_2 fixation). The presumed non-essential function of nitrogen deserves testing during long-term hypobaric growth. Replacement of water vapor as an atmospheric constituent also would become critical to the gas exchange and water status properties of the hypobarically grown plant.

Outgassing of ethylene and other organic constituents from plants in a closed system will be yet another area of major concern to the program, and may be a reason for filtering or otherwise purifying air that flows between compartments within a closed system.

Mineral Nutrition

Mineral nutrition of plants will likely provide unique challenges in a CELSS. If human wastes are to be recycled and plants are to be part of the processing system, not only must potential toxicants (accumulated sodium, heavy metals, organic toxins) be removed, but even essential inorganic elements (e.g., Ca, Mg, K) in waste materials may have be be resolubilized, separated, and recombined in the proper proportions so as to allow normal plant development. Depending on what approach to waste treatment (incineration, wet oxidation, biological oxidation) is developed, procedures will have to be developed to handle unprocessed residues or to resolubilize unavailable minerals from ash before partially processed waste could be used to nourish plant systems.

Nitrogen is an element often limiting plant growth because of the large quantities that are accumulated and assimilated when it is available. Most crop species seem to prefer nitrogen provided to the root medium as NO_3^-, although treated wastes probably will supply nitrogen mainly as NH_4^+. A number of crops will tolerate some NH_4^+, but the presence of some nitrogen as NO_3^- will greatly alleviate NH_4^+ toxicity (17). Thus, nitrification of NH_4^+ to NO_3^- by microbial activity may be important for maintaining high productivity rates by crops growing on recycled wastes. Loss of nitrogen as N_2 during waste treatment may require imput from free-living or symbiotic N_2-fixing organisms, which will add still another dimension of complexity to the closed system.

Other problems expected to be associated with mineral nutrition in soilless culture include providing inorganic elements at optimum levels, adequate aeration and pH, control of microbial contamination, root sloughing, and leaching of nutrients and allelochemicals from roots. Rapid circulation of nutrient solution should minimize problems of aeration and boundary layer nutrient depletion, but could encourage microbial contamination, allelopathy, etc., unless nutrient solutions are filtered or otherwise decontaminated. Ion selective and pH electrodes inserted into the reservoir of a recirculating hydroponic system should be used as part of an automated injection system to help maintain pH and nutrients (by injection) at nonlimiting levels. Conductivity of nutrient solutions also should be measured and adjusted as needed by injection of water or nutrient concentrates. Selection of compatible species for mixed nutriculture also may contribute to the solution of those potential problems.

Temperature

Optimization of temperature in high-productivity cropping systems also will provide unique challenges. Tissue temperature, for instance, may rise far above ambient air temperature, particularly under conditions of high irradiance lighting and high humidity. It may be necessary to do any or all of the following to prevent supraoptimal leaf temperatures under these conditions: decrease ambient air temperature, reduce relative humidity to increase transpirational cooling, and provide a dark surface within the growing area to absorb thermal re-radiation from plant tissue. In any case, it will be important to monitor tissue temperature as well as air temperature in a high irradiance growth environment. Studies with cultivated species indicate that shoots can be maintained at rather high temperatures, provided that roots are cooled (32). High photosynthetic rates can be achieved in this way, especially in combination with CO_2 enhancement and high irradiance lighting. Thus, it may prove useful to control the temperature of the circulating nutrient solution (hydroponics) or mist (aeroponics) independently of ambient temperature, and determine experimentally the root zone temperature giving highest productivity under a given set of environmental conditions. A prevailing assumption of plant culture based upon relatively few observations (77) seems to be that ambient air temperature should be somewhat lower during the dark cycle of the day for best growth performance. However, given that plants are reputed to undergo most of their cell expansion growth and hydrolyze photosynthetic reserves during the night, both of which are temperature dependent, day/night temperature differentials should be totally re-examined in light of optimization objectives.

Flexibility and Tolerance

Although combinations of environmental parameters undoubtedly will be found to maximize photosynthetic rates and yields of candidate species, it also will be advisable to select conditions within the crop compartments of CELSS for intermediate rates of performance. This would retain the potential for greater regulatory control by plant components of the regenerative system. If, for instance, increased human respiratory activity were to challenge the gas equilibrium capacity of CELSS reservoirs, photosynthesizing plants could respond by fixing more CO_2 and releasing more O_2, provided they were not already operating at maximum capacity.

Once optimization of crop performance has been achieved to practical limits by environmental manipulation, it will be important to determine how well candidate species perform under sub-optimal, or even stressful, environmental conditions. Although favorable growth conditions always would be a first choice for crop production, in the event that cost, power, payload limitations, or technological factors become limiting in a space-deployed CELSS, species and cultivars should be selected (or developed) that not only are stress tolerant, but perform well even under suboptimal conditions. Tolerance to suboptimal levels of light and humidity, as well as to supraoptimal levels of CO_2 and temperature, and tolerance to pollutants and toxicants may be additional traits that should be emphasized in selecting candidate species.

Human nutritional value as well as yield considerations should be used as a criterion to evaluate various environmental regimes to be used for crop production. It is anticipated that favorable growth conditions will improve the nutritional value of crops such as leafy vegetables, because the more rapidly they grow, the more succulent they become, the less fiber they should develop, and the more digestible they should be. Thus, nutrient absorption and bioavailability should be greatest from foods grown under optimizing conditions, and less from foods grown under suboptimal or stressful conditions. This hypothesis must be verified because the literature is totally inadequate in providing this type of information, other than for reports of a few preliminary Russian studies (19).

VIII. Recommendations for Further Research

We list in the following a series of recommendations for research required in the continuing development of the CELSS program. These are items that emerged during the process of analyzing the problems addressed in this report. Our recommendations follow the sequence of the 21 selection criteria given in chapter IV and are listed without attempting to assign relative importance to them. We feel that logical priority of research problems can be assigned only after a clearer understanding is achieved concerning the availability of energy and the degree to which gravity will be present in the production and food processing areas of CELSS.

1. Energy concentration studies. Diets composed from plant materials that have undergone little or no processing are bulky and have low specific energy value. Attention should be focused on the need to establish simple processing methods that will reduce bulk and lower the water content of the raw materials.

2. Nutrient optimization. The chemical composition of plants is influenced by environmental factors. Levels of nutrients, such as vitamins, carbohydrates, proteins, and levels of non-nutrients such as fiber and water (moisture) are commonly affected. Bioavailability is furthermore indirectly affected by such altered chemical composition. Nutrient optimization, rather than mere biomass optimization, should therefore be the aim of future CEA studies.

3. Engineered foods. Strict vegetarian (vegan) diets suffer from lack of palatability except to persons who by long familiarization have become accustomed to them. Plant selection should emphasize species that can find multiple uses and be altered in appearance, texture, and flavor. These species would constitute edible raw materials that are bland in taste, relatively colorless, and have no pronounced textural characteristics. An effort should be made to

initiate "engineered foods" by use of additives to alter various quality parameters to achieve simulation of various animal foods (meat, dairy products).

4. Determination of serving size and frequency. Consumption of many edible plants is limited in quantity and serving frequency due to their pronounced quality characteristics (strong and characteristic color, flavor, unique texture). To be able to estimate dietary composition and thereby also production parameters, there is need to establish tolerable limits of serving size and frequency.

5. Conversion of inedible to edible biomass. Inedible plant structures (foliage, stalks, roots) contain materials that are potentially useful as food. Can a portion of these be recovered by use of simple processing techniques?

6. Increasing use flexibility. Certain nutritious plants (e.g., sweet potato) have limited use flexibility due to pronounced quality characteristics. Effort should be made to extend their usefulness by developing new products through processing and formulation with other edible plant materials.

7. Increasing storage stability. Effort should be made to increase the storage life of perishable commodities. The use of controlled atmosphere storage, perhaps combined with subatmospheric techniques, might be particularly suitable for space-deployed missions.

8. Studies of wholesomeness. A diet composed of a drastically reduced number of raw materials, as compared with the number that enters into the average American diet, may have long-term unanticipated consequences. Thus, deficiencies of as yet unidentified essential nutrients could feasibly occur, or toxic reactions eventually could become apparent due to the presence of small amounts of unrecognized substances. Proposed diets must therefore be evaluated first with long-term animal studies (life-time of rats, approx. two

years) and subsequently by human studies of reasonable duration.

9. Familiarization with promising species. Some species appear to be sufficiently promising to be considered for CELSS if more were known about them. The winged bean may be one of these. An effort should be made to study such species for better definition of their nutritional criteria.

10. Proportion of edible biomass. Production of non-edible biomass would appear to provide no particular benefit to a regenerating system, and in fact, probably represents wasted energy and space in amounts proportional to the extent to which it occurs. This consideration favors selection or development of cultivars which minimize the proportion of non-edible biomass. Selection and plant breeding, as well as molecular genetic engineering, would be appropriate, as would approaches maximizing proportion of edible biomass by cultural, environmental, or chemical means.

11. Yield of edible biomass. Energy constraints within a space-deployed CELSS will require that the yield rate (e.g., dry weight of edible biomass per unit growing area per unit time) be higher than that for conventional open-field agriculture. Therefore, research must be conducted to define the yield potential of a given crop. Also, selection and development of superior-yielding types, as well as cultural and environmental optimization studies, will be essential for defining the limits of edible biomass production.

12. Indeterminate vs. determinate harvestability. The ideal CELSS crop should be highly nutritious and continuously productive without accumulating unwanted biomass. Therefore, species and cultivars should be sought which are everbearing, determinate in growth, and which experience delayed senescence so that they continue to revitalize air during maturation. Most candidate species do not presently possess these attributes. Genetic manipulation may be required to develop desired types. Physiological research also should be carried

out to learn how to break the link between maturation and monocarpic senescence of vegetative parts, which occurs in many economic crops (e.g., wheat, soybean, etc.).

13. Growth habit and morphology. The same experimental approaches should be used to develop plant types having desirable growth habit and morphology. Compact plants with minimal stem tissue and with leaf geometry conducive to maximum light interception in a dense stand will be preferred. If breeding proves unsuccessful, research should be conducted to determine the potential of plant growth regulators (phytohormones, growth retardants, etc.) to produce desired plant types.

14. Environmental stress tolerance. Environmental tolerance is a characteristic that is unexplored for most candidate species. It should be investigated as soon as the limits of certain environmental variables within CELSS are defined. One area of particular concern regards the maximum permissible levels of air and water pollutants that will be tolerated. This information will aid in determining the degree of control and monitoring required to maintain homeostasis in the plant compartments of CELSS. Simultaneous selection of cultivars for productivity and environmental tolerance (to heavy metals, salts, outgassed organics, etc.) is be required to assure stability of biological components in a recycling system. Long-term tolerance of candidate species to ionizing radiation and high intensity illumination also must be determined.

15. Photoperiod and temperature requirements. Candidate species should be evaluated for their temperature and photoperiod requirements, and types selected which are compatible with projected CELSS conditions. Selected crops should be able to withstand expected perturbations of ambient temperature without suffering irreversible damage. Since long photoperiods (approaching

continuous illumination) are desirable for air revitalization, either long-day or photoperiod-insensitive types should be developed. For instance, many soybean varieties are short-day plants for reproductive development, whereas loose-leaf lettuce tends to bolt and flower under long days.

16. Symbiotic interaction. Symbiotic requirements, restrictions, and limitations are largely unknown at present for most crop species growing in highly controlled and defined environments. Crops which normally grow with microbial associations (mycorrhizae, rhizobia, etc.) must be evaluated in soilless culture to determine whether these species can remain productive. Candidate species must also be tested for compatibility as well as allelopathy, especially if several species share a nutrient solution. Genetic selection against such limitations could be attempted to obviate the need for monoculture and separate compartmentation.

17. Carbon dioxide - light interaction. One of the most promising research areas for improving photosynthetic productivity and crop yield involves optimizing simultaneously levels of CO_2 and light. The photosynthetic apparatus responds readily to changes in these environmental variables. It is necessary to establish dose-response curves for photosynthetic rate, production cycle time, and crop yield for elevated levels of light and CO_2 together. Carbon dioxide at supraoptimal levels can inhibit productivity by inducing stomatal closure and CO_2 narcosis, but it is expected that the inhibitory CO_2 level will be pushed upward by each increment of higher light intensity until a limit is reached. Different light sources, including high intensity discharge fixtures and extra-terrestrial (filtered) sunlight, should be evaluated for their effects on plant growth and development.

18. Soilless culture. If solid growth media (soil, artificial substrates) prove to be impractical for plant culture in CELSS, investigation of candidate

species performance in soilless culture such as hydroponics, aeroponics, or flowing nutrient film is required. Hydroponic culture of candidate species such as soybean and wheat already has been proven feasible, but adoption of nutriculture systems for root or tuber crops will provide challenges. Aerial support will be required for certain species in the absence of root anchorage. If some degree of hypogravity will exist in the plant growth compartments of CELSS, novel nutriculture systems may be needed. Environmental optimization will create great demand for mineral nutrients by rapidly growing plants, and modified nutrient solutions may have be developed to prevent nutrient availability from becoming a limiting factor to crop production.

19. Disease resistance. Although candidate species undoubtedly will be screened and quarantined to assure absence of pathogens prior to enclosure in CELSS, it is unlikely that the CELSS environment will be totally free of microorganisms, and there is a finite possibility of mutation to pathogenic forms. Therefore, cultivars of candidate species need to be selected or developed for specific pathogen-resistant characters as well as general pathogen and stress resistance.

20. Familiarity with species. Research should be initiated or continued with promising underexploited species for which we have little information. For instance, the winged bean, which in many respects promises to make a significant contribution to CELSS diets, is yet relatively unexplored in terms of cultural approaches.

21. Pollination and propagation. Research should be initiated to develop artificial pollination techniques for species normally requiring cross-pollination vectors (wind, insects). In lieu of propagation by seed, unconventional techniques such as vegetative propagation (leaf, stem, root cuttings) should be developed to hasten plant development and reserve seeds for their intended use

as food. The potential for development of aseptic micropropagation techniques for maintenance of germplasm, cloning, muliplication, and for actual production of plant materials *in vitro* should be explored.

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16. Abstract

This report discusses the feasibility of using higher plants in a controlled ecological life support system (CELSS). Aspects of this system considered important in the use of higher plants include: limited energy, space, and mass, and problems relating to cultivation and management of plants, food processing, the psychological impact of vegetarian diets, and plant propagation. A total of 115 higher plant species are compared based on 21 selection criteria.

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