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Nutritional Models for a Controlled Ecological Life Support System (CELSS): Linear Mathematical Modeling

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Dedication

James H. Bredt, Ph.D.

This publication is dedicated to the memory of James H. Bredt, Manager of NASA's Controlled Ecological Life Support System (CELSS) Program. Dr. Bredt's vision provided the impetus for this publication: to generate mathematical models for the convenient manipulation of human dietary and plant production requirements for use in a future CELSS on a long-duration spaceflight. His commitment to biological systems research will be long remembered.

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EXECUTIVE SUMMARY

Long-term space habitation by humans requires adequate supplies of food, air, and water. Transporting these supplies between earth and space is not a major concern for short-term missions but will be nearly impossible for long-term missions such as the 2 to 3 years projected for a Mars mission. The Controlled Ecological Life Support System (CELSS) program of the National Aeronautics and Space Administration (NASA) is in the process of developing a bioregenerative life support system that will supply food, air, and water to meet the needs of space crews for long-duration missions. CELSS activities to date have concentrated on establishing the feasibility of a system capable of performing such functions as gas regeneration, food production, waste utilization, food processing, and waste management.

Scope of the Report

An important goal of the CELSS program—one that will become increasingly important as this program evolves and as long-duration spaceflight approaches reality—is to develop the knowledge and technological capability to produce and process foods that can provide optimal diets for space crews. This is a complex issue involving such interrelated factors as determination of the diet itself, based on knowledge of nutrient needs of humans and adjustments in those needs that may become necessary as a result of the unique conditions of long-duration spaceflight; determination of the optimal mixture of crops required to provide nutrients at levels that are sufficient but that are not excessive or toxic; and due consideration of the critical issue of spacecraft space and power limitations which impose a phytomass minimization requirement on all food production calculations. A project was initiated to examine the complex interactions among these factors, with the goal of supplying a diet that will satisfy human needs while minimizing the total phytomass requirement. The approach taken has been to collect plant nutritional composition and phytomass production data, identify human nutritional needs and estimate the adjustments to the nutrient requirements likely to result from spaceflight factors (based on the limited data presently available), and then to generate mathematical models from these data to meet the above goal.

Nutrition and Spaceflight Effects

In order to develop the models as accurately as possible within the confines of our current knowledge base, an effort was made to determine the need to adjust dietary requirements due to conditions of spaceflight. To date NASA has not placed significant emphasis on such modifications, since the Recommended Dietary Allowances (RDAs) have basically proven to be adequate for the short-term missions that have constituted most of the U.S. space program. However, experience acquired during the Soviet space station and U.S. Skylab programs has indicated that terrestrial nutritional criteria may not be sufficient for extended space missions, particularly in light of the necessity for preventing or alleviating some of the adverse biomedical effects that result from spaceflight. Considerably more effort needs to be expended on determining nutrient requirements or ranges with respect to facilitating the human body's adaptation to spaceflight conditions and readaptation to gravity. Development of appropriate diets may be able to prevent or ameliorate some of these physiological disturbances. Therefore, adverse effects of spaceflight will need to be taken into account as guidelines for determining nutrient needs. There have been a number of metabolic studies that attempted to determine if spaceflight factors affect metabolism directly or if the adverse effects are secondary. The conclusions of these studies are incorporated into the models.

Other than the Skylab experiments, there is no western literature on nutritional effects of long-term spaceflight. The Soviet literature on this subject is somewhat more extensive. Some information can be taken directly from the literature on the biomedical effects encountered during the Salyut space station missions, while some will require further extrapolation. Determining nutritional guidelines from these data, in combination with data from the few available nutritional studies, can provide a reasonable starting point for devising a sound nutritional strategy in terms of satisfying basic nutritional needs and endeavoring to therapeutically resolve some of the adverse biomedical effects of spaceflight.

The major biomedical effects of spaceflight that are considered here are: bone demineralization, muscle atrophy, cardiovascular deconditioning, and fluid and electrolyte shifts. These are the most frequently investigated effects associated with spaceflight, and each needs to be considered in terms of the extent to which it is a "problem" or an adaptation necessary to the stress of spaceflight. Muscle and bone atrophy are clearly problems as their resulting adverse effects extend into the postflight period with some questions still remaining concerning their total reversibility. Some of the other effects are considered briefly in view of possible adaptive benefits. The usefulness of exercise in alleviating some of the effects of microgravity and the ensuing nutritional effects are also discussed here.

Model Development

In the original series of models developed by Linda Jones of General Electric Management and Technical Service Company (see Appendix A) an optimal diet was defined as one that satisfies a set of caloric, protein, fat, and carbohydrate constraints while requiring the minimum phytomass possible. Diets containing eggs and chickens were also considered in that series of models. For a number of reasons, plant-only diets have been projected to be considerably more practical than diets containing animal products even though animal diets would provide more variety. The models considered in this report deal only with plant-based foods.

Work on this project was continued and expanded in considerably greater detail and forms the basis for this report. In these expanded models, an optimal CELSS diet is defined as one that satisfies as nearly as possible a set of constraints including many of the vitamins and minerals known to be required, and that satisfies completely the constraints of protein, fat, and carbohydrate. In addition, many of the RDAs have been adjusted for spaceflight factors where modified needs are indicated (see section on Nutrition and Spaceflight Effects above).

The original CELSS models (see Appendix A) were based on the edible raw product of soybean, wheat, potatoes, peanuts and chicken and eggs, where applicable. The expanded models discussed in this report are based on products in their final edible form. The products included are tofu (soybean curd), tempeh, soymilk, baked sweet potatoes, cooked rice, soy sprouts, dry roasted soybeans, baked potatoes, boiled potatoes, boiled sweet potatoes, boiled onions, boiled green beans, sunflower seed, wheat meal, boiled spinach, lettuce, tomatoes, and wheat sprouts. The food products utilized in the models have been briefly investigated to determine the simplicity and practicality of their preparation in a CELSS. Peanuts as an oil crop have been replaced in the first expanded series of models by sunflower seed because of their lower cost of production (in terms of phytomass). Peanuts will be considered again in the product basis of the Model Building Utility which will be used to generate a later series of models.

The original series of models developed by Linda Jones demonstrated the feasibility of producing an optimal combination of the four base crops to meet energy, protein, carbohydrate, and fat needs. It suggested that in order to satisfy basic human needs, 925 g/person/day of dry weight phytomass would be required. Of this 925 g, 176.5 g of soybean and 747 g of potatoes would be required. This weight includes phytomass waste which could, if utilized, decrease the total phytomass requirement considerably.

The nutrient data used in the models have been obtained from a database which itself is derived from a number of sources. The major sources used were the United States Department of Agriculture's Handbook #8 Expanded Series and the Extended Table of Nutrient Values (ETNV), which includes much of the data available in Handbook #8, developed by Margaret C. Moore, M.D., Ph.D., for the International Dietary Information Foundation, Inc. in New Orleans, Louisiana. ETNV is the most complete source of nutrient composition data available. This database also possesses the capability to analyze recipes and determine the effect of preparation processes on the nutrient composition of the food.

Mathematical Modeling Approach

The primary objective of these models has been to establish the basic feasibility of a closed ecological system with the capability of meeting the basic human requirements for energy and essential nutrients. More specifically, the purpose is to demonstrate the feasibility of satisfying human nutritional requirements through combinations of the previously mentioned crops as determined via the final product composition.

The approach that has been followed is to first determine the specific dietary requirement whenever possible, and to determine ranges between toxicity and deficiency when this is not possible, and then to determine via the model the feasibility of meeting these requirements within the defined parameters of a CELSS. The need to prevent the dietary accumulation of certain heavy metals has been taken into consideration. The extent to which supplements will be required can be made from analysis of the models.

The technique of linear optimization is used in the creation of the models. This technique can be used to determine an optimal solution to a linear algebraic minimization/maximization problem. If the problem is extensive enough, as in the present case, there arises a need for a complex system of equations or models to state and define the problem. The linear models discussed here have been solved with a program developed by Lindo Systems, Inc. in Chicago, Illinois. The Linear, Interactive, and Discrete Optimizer (LINDO), an interactive linear, quadratic, and integer programming system, is one of three systems currently available that has the capability of solving these complex systems of equations. The program is available for MacIntosh and IBM personal computers as well as for mainframes.

The specific use of linear optimization in this project is to determine the total phytomass production requirements while meeting a number of nutritional constraints. The solution is the optimal combination and level of crop production that must be accomplished by a CELSS in order to meet the nutritional needs of the crewmembers. The primary basis for modification in this series of models has been to increase the variety of crops in the solution with minimal phytomass increases.

The series also demonstrates the changes in phytomass requirements that occur when constraints are expanded to include vitamins, minerals, and essential amino acids, in addition to basic nutrients.

It should also be mentioned that the nutrient data (coefficient), the constraints, and production values (used in the objective function) can be altered to change the model and the solution, but not with facility.

A number of problems and concerns have materialized during the creation of these models. One of these is the matter of dietary variety, which can only be improved by forcing certain items into the diet through additional constraining. Meeting certain nutrient requirements can result in a surplus of other nutrients that may also be a significant problem. Another concern is the effect of the unique spaceflight environment on various aspects of the model. Possible solutions to these problems are being considered. It should also be taken into consideration that the nutrient composition values are derived from terrestrially grown plants. Although there are not sufficient data at this time to suggest that there will be considerable differences in the compositional values for space-grown plants which despite their genetic constitition could result from modifications in the environment in which these plants customarily grow, this remains an open question awaiting additional spaceflight research.

In summary, the models developed in this project have yielded a CELSS nutritional scenario that is as realistic a representation as is possible at this time. The following specific accomplishments have been demonstrated:
1) optimal crop solution based on minimal phytomass and a system of nutrient and dietary constraints;
2) the marginal cost in terms of phytomass production if a crop is altered or substituted; and
3) the types of crops to be produced based on the nutrient composition of foods converted from those crops.

Model Building Utility

The results of these expanded series of models are indicative of the dynamic relationship between the different variables and suggest that because of this dynamism the models could become invalid whenever new data becomes available. The only effective method for alleviating this problem is through the development of a program with the capability of generating new models when data for any of the variables is modified. Such a program has been developed. This program known as the Model Building Utility (MBU) has the capability of accommodating any changes to the various elements of the model and of generating new models when needed. The need to develop new models when modifications are required will no longer exist. The only effort that will now be required is modification of the data within the databank, while the actual building of the model will be done by the program and solved by LINDO.

Conclusion

The many sample models and the Model Building Utility program that have been developed during the course of this study demonstrate the remarkable capability of mathematical and computer models as predictors of future spaceflight needs. Mathematical/computer modeling has many possible applications in terms of a CELSS because of its capacity to handle complex multivariate interactions that would be difficult if not impossible to simulate with other types of modeling. The models developed in this report represent a first effort in the type of analysis and approach that will have to be carried out in increasingly greater detail as long-duration spaceflight and use of a CELSS in space approaches reality.

I. INTRODUCTION

In a previous study (Appendix A), the feasibility of a Controlled Ecological Life Support System (CELSS) producing enough food to meet human nutrient needs was investigated via linear mathematical models. The levels of crop production required to meet basic human nutrient constraints were calculated in these models on the basis of nutrient composition of the raw products. The actual amounts of edible products that will result from the preparation/ processing of these raw products will differ significantly from the amount of edible product that will be consumed. Thus, a more realistic picture of crop production requirements can be obtained only if the actual products to be consumed are considered in terms of the amount of phytomass required to produce them.

The purpose of the expanded series of models described in this report is to demonstrate the feasibility of satisfying human nutritional requirements through combinations of the products of 13 crops: soybean, wheat, potatoes, sunflower, sweet potatoes, rice, soy sprouts, wheat sprouts, green beans, lettuce, tomatoes, onions, and spinach. These crops are either currently under investigation by NASA CELSS scientists or are being considered for investigation by the CELSS Program at a future date. The nutrient values used in this report are assessed from field-grown samples. At this time there is no reason to assume that the nutrient compositional values for space-grown crops will differ significantly from field-grown crops, unless nutrient values are manipulated via significant modifications of the growth media. This question awaits more detailed spaceflight research. The question that is addressed here is whether or not a CELSS, as defined in the preliminary planning phase, can meet the nutrient needs of humans during space voyages that eventually may be as long as two to three years, as would be the case with a Mars mission.

In order to demonstrate the degree of feasibility of meeting human nutritional requirements during long-duration space missions, it is first necessary to determine what these requirements will be. Nutrient guidelines for long-duration space missions must not only serve to maximize the health status of crewmembers by providing appropriate levels of essential nutrients but must also, if at all possible, contribute to the minimization of the adverse effects of spaceflight. Thus, spaceflight nutrient requirements become perhaps even more essential than terrestrial requirements. For the purposes of this report, nutrient guidelines that have been determined from the available Soviet and U.S. spaceflight biomedical data or that have been extrapolated from the results of other space-related studies are used as constraints in the models that are developed. These are the only possible sources of such data currently available and they will be utilized until specific nutrient data from long-term missions become available. The approach that has been taken has been to determine specific dietary requirements when possible, and safety ranges when this is not possible.

While the overall goal of this study, is to establish, to whatever degree possible, the feasibility of an artificial ecosystem meeting the basic requirements for energy and essential nutrients required for long-duration space missions, or a more direct goal A more specific goal is to determine an actual optimal CELSS diet based on the 13 potential crops mentioned earlier. To determine such a diet, linear mathematical models have been developed in conjunction with the Linear, Integer, and Nonlinear Discrete Optimizer (LINDO), a software program which uses the simplex method to select optimal solutions to complex systems of equations. The crops are selected by LINDO on the basis of how effectively their nutrient composition satisfies the nutrient constraints determined for spaceflight while minimizing the total phytomass production.

The feasibility of meeting the nutrient requirements within the suggested parameters of a CELSS by means of linear (and integer when required) mathematical models is discussed in Section III.

II. SPACEFLIGHT EFFECTS AND NUTRITION

Determining the baseline nutrient/metabolic needs of an individual who is to live in space is a task best performed prior to spaceflight, both for ground-based needs and for later inflight requirements. Synthesis of a space diet should then evolve through analysis of the individual ground-based nutrient requirements in combination with values taken directly from or extrapolated from the spaceflight literature. Though averages are adequate for modeling purposes, individual baseline data would be preferable for use in actual missions.

The basis for the following analysis is the Recommended Dietary Allowances (RDAs), which have been determined by the National Academy of Sciences. It should be noted that these allowances are averages only. They generally exceed an individual's nutrient needs but at the same time they tend to insure that the needs of most of the population will be met (1).

Not much emphasis has yet been placed on determining adjusted nutritional requirements for long-term spaceflight, or even on determining if a need exists for such adjusted requirements. This is because the RDAs have proven to be adequate for the short-term missions that have basically constituted the U.S. space program to date (2). Results from various Soviet Soyuz-Salyut flights and U.S. Skylab missions, however, have suggested that extended spaceflights produce previously unconsidered physiological and psychological stresses some of which may be moderated by nutrient intake. Similarly, nutrient deficiencies, as well as related disorders, that might compromise the health status of spaceflight crewmembers could easily be created which could result either directly or indirectly from the intake of nutrients that are inadequate for spaceflight needs. Therefore, increased efforts to determine nutritional ranges for long-duration space missions are essential, with the goals of facilitating the body's adaptation to spaceflight conditions and readaptation to normal gravity situations and avoiding any situations deriving from a condition of nutrient deficiency. Until actual flight data are available to address these specific nutritional issues, tentative nutritional guidelines will be suggested based on the general nutritional information available as well as the results of flight and bedrest studies that have considered nutritional modification as a plausible option in the alleviation of the adverse biomedical effects of spaceflight.

Experiments carried out by U.S. investigators have shown that physiological effects resulting from flights of approximately 90 days or less are reversible (3). Soviet space studies exceeding 90 days in duration have produced similar results. For example, it was possible to reverse degenerative effects after a 211-day mission, probably because of the nutritional and exercise precautions that were taken inflight (4). The fact that some currently projected missions extend well beyond the Soviet range of experience obtained in space to date will require that assumptions be made that countermeasures applied in shorter term spaceflights, in conjunction with inflight monitoring and some capacity to therapeutically treat problems of a more specific nature, will be as effective on longer flights.

Even though it is clear that spaceflight does have an effect on major body systems, it has not been conclusively demonstrated that spaceflight causes significant, direct metabolic changes. The results of Skylab and other space missions suggest there is a greater energy need in space than in normal gravity. It is highly possible that weightlessness alters metabolic rate by promoting muscle disuse atrophy and by altering protein metabolism, tissue hydration, and endocrine functions. When considering the Soviet results relevant to the subject of the actual effects of spaceflight on metabolism, it must be taken into consideration that Soviet crewmembers did not always consume their total diets. Because of this factor and because careful records were not kept of their actual consumption, nutritional deficiencies may have been the result of less than optimal consumption, rather than modifications in metabolism.

The general subject of adverse biomedical effects of spaceflight extends beyond the scope of this report, since there has been no clear indication that many of these effects are subject to improvement via nutritional modification. While both bone demineralization and muscle atrophy can be considered clearly adverse biomedical effects of spaceflight and as potentially good candidates for nutritional therapy; other spaceflight effects such as cardiovascular deconditioning and fluid/electrolyte shifts appear to be beneficial adaptations that quite possibly could not (and probably should not) be improved through nutritional modification. The extent to which spaceflight effects need to be considered as health problems inflight and/or postflight and the degree to which they need to be tolerated as normal adaptive strategies must be more clearly defined as a workable model continues to evolve.

To receive feedback on the appropriateness and effectiveness of the strategies employed, a monitoring system with the capability of frequently checking nutrient levels in plasma and other biochemical media, along with the availability of facilities to normalize the abnormalities that may occur, will likely be required. Such capabilities will have to be available during the course of long-term flights if major degenerative problems are to be prevented and if enough data are to be gathered to establish more precise nutrient guidelines for continued long-duration space missions.

The final, and possibly the most critical, spaceflight health maintenance tool to be considered is exercise. Exercise appears to be even more essential under spaceflight conditions than under terrestrial conditions. The most significant adverse effects of spaceflight, bone and muscle atrophy, seem to be more responsive to proper exercise than to any other single form of intervention. Thus, the direct effects of exercise as a countermeasure to general deconditioning and its possible effect of increasing nutrient requirements will also be taken into consideration in these models.

The major concerns with nutrient levels in a CELSS diet, as with any other specific diet, are that the levels will either be too high and cause toxic effects or be too low and cause deficiency syndromes. The variety inherent in a normal terrestrial diet contributes significantly to the prevention of toxicity/deficiency effects. But biomedical and physiological changes and the inherent limitations of natural food variety in a closed system will increase the possibility of toxicity/deficiency syndromes. As regards the question of variety, a definite correlation exists between toxicity/deficiency and limited variety. Such concerns are of greater importance in long-duration spaceflights since long duration and extreme conditions may make toxicity or deficiency syndromes more detrimental. The necessity of limiting and carefully combining food items in an effort to assure that all nutrients are received and that their absorption is not inhibited by interactions with other nutrients tends to create an inelasticity which may then inadvertently increase any of the diet's unsuspected deficiencies or toxicities to detrimental levels. Because of the limited opportunity to choose dietary variety under spaceflight conditions, efforts will have to be made to assure that such situations do not develop.

In view of the many deficiencies within the spaceflight nutrition database, the most promising approach to projecting provisional values for nutrient requirements for long-term spaceflight is to suggest ranges and, in some cases, actual values. The ranges and values suggested here have been extrapolated from the information available on the known adverse physiological effects of spaceflight, the terrestrial RDAs, and the toxic/deficient levels of each nutrient. It is understood that it is not possible at this time to make other than theoretically sound estimates when setting nutrient ranges at levels appropriate to long-term spaceflight and the amelioration of its more prominent biomedical problems.

The system of constraints that has been used in the mathematical models are the requirements for each nutrient, based on analysis of the spaceflight literature or, in cases where there is no clear indication of changes from terrestrial levels, use of the RDA. The objective function value of each model diet represents the amount of phytomass needed to meet the nutrient requirements for an individual. The discussion centers around the feasibility of the model solutions and the additional needs, or the composition of the supplement if it is determined that to meeting all nutrient needs via CELSS-produced food is nonfeasible.

A. SPECIFIC DIETARY COMPONENTS TO BE CONSIDERED

1. Energy

A CELSS diet must provide the quantities and variety of food sufficient to supply all of the required micro- and macronutrients and to provide the balance of energy necessary to maintain ideal weight. A major unanswered question is: do astronauts have a greater or lesser energy need in flight than they have on the ground? This question must be answered if energy needs for long-duration spaceflight are to be accurately determined. There are various approaches to the question of determining energy requirements during spaceflight. One possible method of predicting the energy needs of astronauts is by studying human subjects in an earth-based environment similar to that of a spacecraft. Bedrest studies may at present be the most effective simulation in determining basal energy needs and the increments of energy that occur as activity increases. For the purpose of this particular group of models, all pertinent data will be considered in determining the approximate energy needs of spaceflight.

The major goal of determining an adequate energy level for spaceflight is the prevention of the body weight loss that frequently occurs during spaceflight. The part of this weight loss that is caused by metabolic changes and the part that is due to inadequate energy intake is not yet clear. It appears that about 50% of the weight loss in Skylab astronauts was caused by loss of water early in the mission, while the other 50% occurred during the course of the flight as a result of both fat and protein tissue depletion (5, 6).

It has been reported that for comparable work at least as many kilocalories (kcal) are required in space as on earth (7). After 1-2 months in space, energy requirements appear to increase, possibly as a result of trying to do the same work with a diminished or qualitatively different muscle mass (8). Although it is clear that different crewmembers will experience different needs, depending on the specific tasks which they are performing, it is not clear how different these needs will be for a particular activity conducted in space, compared with the same activity performed on earth. Energy needs seem to be a function of duration of stay in space combined with the effect of this time on muscle quality and possibly other metabolic parameters (9, 10).

Caloric requirements of Skylab astronauts, as determined by least squares regression from Skylab data, were 49.5 kcal/day/kg body weight (bwt) (11). This is the level of energy that would be required to maintain body weight under the specific workload of Skylab astronauts. The specific workload of crewmembers of future flights may differ, but it seems that a caloric intake of approximately 50 kcal/day/kg bwt should be sufficient to maintain body weight during spaceflight (12), if the activity levels are similar to those of Skylab.

The average energy supply to Soviet crewmembers during Salyut space station missions of up to and beyond 211 days has been about 3000 to 3200 kcal/day/person (13). No problems were reported to be generated by this intake level. The estimate that Skylab astronauts could have prevented significant tissue loss by consuming between 46-50 kcal/day/kg bwt suggests an energy requirement of between 3220-3500 kcal/day/70 kg bwt calculated on the basis of a workload similar to that of Skylab 4.

Energy requirements can also be estimated by utilizing an average value for the basal metabolic requirement, 2250 kcal, and adding to it the approximate energy expenditure for the exercise that will be required for long-duration missions, ~1125 kcal. This value is derived from data which demonstrate that energy expenditures during exercise can be as high as 450 kcal/hr in cases of extremely rigorous exercise, which may well be the case during spaceflight (14). Using as a basis for calculation the 2.5 hr/day (minimum) of exercise suggested by the Soviets results in an additional 1125 kcal (450 kcal/hr x 2.5 exercise hr). This value when added to the basal requirement of 2250 kcal yields a total of approximately 3375 kcal that will be required to maintain body weight during spaceflight.

It is also possible that apart from the extra energy that will be required during spaceflight for exercise, there will be a general increased need for energy because of the increased effort required to maintain a desired upright position (15). This may help to clarify why the energy utilization rate for Skylab was 43.7 kcal/day/kg bwt, which increased 1.6%/month for 3 months to 3.7%/month by the final month inflight (16). These figures indicate either an increasing energy output or a decreasing metabolic efficiency. Increases in thyroxine measured postflight suggest that metabolic efficiency may have decreased during flight. If this is primarily a result of diminishing muscle mass, then it is possible that maintaining muscle mass within the normal preflight range may cause the energy requirements to remain at about the same level for similar activities. No provision for an increase in the energy allowance due to this possibility has been made in this study pending more complete data.

According to other analyses, Gemini, Apollo, and Skylab data all support the conclusion that the energy cost of life in space is higher than food consumption indicates, which may partially explain the weight loss. Therefore, to maintain body weight and to account for the usual 9% loss of calories in urine and feces, it can be concluded that at least 47.5 kcal/day/kg bwt, or about 3325 kcal/day/70 kg person is needed.

To summarize, calculations of energy required during spaceflight by the methods of summming workload calculations and basal metabolic requirements, and from the analysis of actual flight data as well, suggest a total energy requirement of between 3300 and 3400 kcal/day/70 kg individual. Based on these estimates, the energy constraint in the current CELSS models has been set at 3400 kcal/day.

It should also be pointed out that an adequate energy intake which yields a positive energy balance coupled with appropriate exercise can considerably reduce weight loss during spaceflight. But energy intake alone cannot prevent the fraction of loss of body mass that is associated with postural muscle atrophy and the extracellular fluid elimination that occurs as a result of rapid headward fluid shifts (17). This loss of body mass is more difficult to reverse than that from improper energy intake. To improve the overall condition of weight loss, exercise will be required in combination with proper energy intake.

2. Protein

There are two major considerations that form the basis for the modification of protein intake requirements unique to spaceflight. The first concerns the effect of protein levels on atrophied muscle, and the second, the effect of protein on calcium absorption. It has been postulated that the muscle atrophy that occurs during spaceflight is the result of a musculoskeletal load that is not sufficient to maintain the normal physiologic status of the musculature. With no gravity to actively oppose the muscles and no need to maintain normal posture, the effort for doing so is considerably reduced (18). If this description is accurate, then it follows that increasing the musculoskeletal load through exercise or weightbearing would be most effective, although it remains essential to evaluate the influence of protein intake levels as well.

a. Intake Criteria. Since protein may be the essential balancing macronutrient of the space diet, determining optimal protein intake is of primary importance. Protein intake affects a number of other nutrient factors including calcium balance, water retention levels, and vitamin and mineral metabolism. Adequate protein intake is essential if amino acid requirements are to be met; this is particularly true of leucine, which may take on added importance because of its possible effect on minimizing muscle atrophy and contributing to the maintenance of a positive nitrogen balance (19).

The need for all of the essential amino acids must be met, because deficiency of even a single amino acid will result in a negative nitrogen balance, even if total protein intake is high. To meet the needs for all of the amino acids, protein complementarity will have to be considered in a CELSS diet. For example, wheat is low in sulfur-containing amino acids but is high in lysine; soybeans are high in sulfur-containing amino acids yet are low in lysine. Neither plant alone is an adequate source of all of the essential amino acids, but a combination of the two results in a high net protein utilization value, which means that consuming the products of the two plants in combination will more closely approximate the human requirement for a specific complement of amino acids. This factor suggests that at least two crops will probably have to be produced in a CELSS to adequately meet protein needs.

In regard to meeting minimal protein requirements, it has been shown that nitrogen equilibrium is maintained in men consuming diets of 3150 kcal/day/70 kg bwt when the protein intake is less than 6% of total calories. The protein requirement decreases as the total energy intake increases. For example, 3.2% of total energy supplied as protein has been shown to result in a positive nitrogen balance when the total caloric intake is 3990 kcal (20).

Protein requirements are not normally defined in terms of percentage of total energy. But, because (1) the protein requirement normally calculated on the basis of the .8 g/kg of bwt intake level recommended by the National Academy of Sciences falls within the range of approximately 8-10% of total dietary energy for a 70 kg individual, (2) because the daily average protein intake falls within the range of 10-15% of total kcal; and (3) because it is more convenient for modeling purposes to set constraints for basic nutrients in terms of percentage of energy, for present purposes protein requirements will be defined in terms of percentages of total dietary energy.

Though a minimal intake level for protein is readily determined from available data, it is nearly impossible to determine a maximum intake level without more specific data. It is possible to derive a tentative upper level by considering a combination of the factors of cost to the system of lowering protein and the percentage of the terrestrial diet composed of protein. The .8g/kg recommended intake level of protein mentioned above is approximately equal to 10% of the total energy in the diet of a 70 kg individual. It appears that, since less protein is indicated for a space diet, a lower value rather than a higher value will be more desirable, even though at this time it is not known how much lower the protein requirement in space should be. Also, in terms of the economic considerations in a CELSS diet, it should be pointed out that a higher protein constraint is less of a cost to the system than a lower protein constraint; if the constraint is decreased to less than 10% of energy, the phytomass requirement is considerably greater than when it is increased to above 10%, so the nutritional gain may not offset the loss to the system in terms of cost of phytomass production. In a sense, 10% is an equilibrium level, at least in terms of the present models, if only from an economic standpoint. From a nutritional viewpoint, it appears that the protein requirement should decrease with increasing energy intake levels and that if, in a 2700-2800 kcal diet (average energy intake for men in terrestrial conditions) protein is about 9-10% of total energy for 70 kg bwt, that it should decrease both because of increased kcal and because of its effect on bone mineral. However, since it is not possible to determine a more specific level of protein, it is preferable at this time to choose a level primarily on an economic basis, and it is an added advantage that the level selected does not conflict with the nutritional indications.

b. Effects. High intake of protein, particularly animal protein, causes a significant increase in the urinary excretion of calcium, oxalate, and uric acid, the primary urinary risk factors for calcium stone formation. Intake of protein from sources that are primarily vegetable is associated with a low risk of calcium stone formation; the risk is lowered still further by decreased intake levels of total protein (21). Both of these criteria, vegetable protein and low protein intake, should be introduced into CELSS system design.

Relatively long-term, high protein intake may contribute to the development of low-grade metabolic acidosis, which may result in increased bone resorption, release of calcium from bone, increased urinary calcium excretion, and osteoporosis (22). High protein intake is generally considered high if equal to or greater than upper end of the protein average daily intake of about 10-15% of total energy. If levels of protein slightly less than or equal to the lower end of the protein average daily intake of 10% of total energy are consumed in a CELSS diet, additional bone mass loss due to high protein intake should not occur as a result of excess protein, unless future study demonstrates that bone loss can only be prevented by maintaining a protein intake even lower than this level.

As mentioned above, urinary calcium excretion is known to be directly correlated with the level of dietary protein intake. A decrease in the fractional reabsorption of calcium by the kidney seems to be the most likely cause of protein-induced hypercalciuria, and consuming high calcium diets is not likely to prevent the negative calcium balance and bone loss that is induced by the consumption of high protein diets (23). This suggests that a balance must be established between protein and calcium intake and absorption levels in order to effectively minimize this problem.

c. Prevention/Treatment. It has been suggested that several dietary components possess the capability of increasing protein synthesis and preventing protein degradation in muscle, both of which are essential in the maintenance of a positive nitrogen balance and in the prevention of muscle atrophy. Of these dietary components, probably the most feasible for manipulation in a CELSS are glucose and leucine, both of which have been shown to have beneficial effects on muscle when their intake is increased. According to preliminary analyses, it is expected that both will be plentiful in a CELSS. Glucose will be available primarily as the breakdown product of the cellulosic byproducts from the crop plants, while leucine will be available from plant protein (24).

There are no recommended intake ratios for glucose vs. other forms of carbohydrate. At this point, it appears that the intake range is the same for glucose as for carbohydrate, with the body making no significant distinction except perhaps in terms of an effect on protein synthesis/degradation. Unfortunately, at this time sufficient quantitative data on glucose intake effects are not available.

It has been shown that increased intake of leucine may contribute to the amelioration and prevention of muscle atrophy. A number of investigators have concluded that protein synthesis rates are increased with increased intake levels of leucine and other branched chain amino acids (BCAA) (25). These studies have also shown that leucine inhibits protein degradation, which would be valuable in maintaining a positive nitrogen balance during spaceflight. Since leucine is not toxic, even at very high levels (except in terms of its possible role in the induction of a pellagragenic syndrome, which specifies the need for isoleucine in levels greater than or equal to those of leucine in order to counter this effect), excessive leucine levels should not be a major point of concern. It should also be pointed out that in addition to the effectiveness of isoleucine in countering many of the biochemical abnormalities associated with induced-niacin deficiency (or pellagra), it is equally as effective as leucine in countering muscle atrophy (26).

A Soviet study which evaluated amino acid levels of cosmonauts who had flown in five Soyuz/Salyut flights indicated that most of the values were within the normal range. After a 211-day flight, most plasma amino acid levels were approximately within normal range; methionine and cystine, the sulfur-containing amino acids and the only two amino acids to show a decline, were only slightly below normal. The authors of the study recommended that the diet contain an excess of cystine and methionine, and also of aspartic acid, proline, and arginine (27). The extent to which the levels of these amino acids can be increased beyond the normal recommended levels is limited only by the total protein constraint, as neither of them has been shown to be toxic even at extremely high levels.

The immediate tendency when attempting to resolve the muscle atrophy problem is to increase protein intake, since the protein that is broken down at a rapid rate during muscle atrophy needs to be returned to the body. This is not a viable option, however, because, as mentioned earlier, high protein diets can affect calcium balance. They can also cause an increase in the need for zinc and vitamin B6 by altering their absorption and bioavailability (28). Protein intake must be kept in a range such that, at the upper limit it does not affect calcium excretion and at the lower limit it does not create an amino acid deficiency. It has been suggested that muscle mass in the calves, thighs, and back should be maintained by increasing protein intake and taking anabolic steroids (29). However, controlling protein, increasing exercise, and initiating some of the other strategies, such as increased leucine and glucose intake, may be sufficiently effective. While there are non-dietary approaches that have been suggested for the treatment of muscle atrophy, a dietary approach appears to be more desirable since the introduction of therapeutic drugs with possible adverse side effects would be particularly risky during long-term space missions.

d. Effects of Exercise. The beneficial effects of exercise on muscle disuse atrophy have been well documented in both the Soviet and U.S flight and bedrest literature. Studies on the restorative effects of exercise on bedrest subjects have indicated that 2.5 hr/day of exercise during long-term bedrest has the desired effect of retaining strength in the muscles exercised, thus allowing subjects to retain the ability to tolerate orthostatic actions, maintain mineral saturation of the bones, and retain adequate immunobiological defenses (30). The exercise performed on Skylab 4 seems to have contributed significantly to the stabilization of protein loss and to have significantly reduced the loss of total body protein (31). In any event, a likely approach to controlling muscle atrophy will be through a program of exercise and adequate nutrition. As mentioned earlier, one problem that may arise when attempting to maintain a positive nitrogen balance is the possibility of having to increase protein intake at the expense of calcium. A possible solution to maintaining both positive nitrogen and calcium balances may be to limit protein intake and to implement an exercise regimen that will help to maintain both bone and muscle mass (32). At this point, it is inevitable that an appropriate exercise program is essential to the establishment of an effective nutrition and health maintenance program in a CELSS.

e. Summary. In general, a diet in which protein constitutes 10% of total calories is considered sufficient to meet and exceed minimum protein requirements by an adequate safety margin. Though it appears at this time that spaceflight factors may decrease this requirement, to what extent is not yet known. Protein requirements should be based, at least in part, on the effect of protein intake on muscular deconditioning arising from spaceflight, and these requirements can only be determined accurately when sufficient quantitative data become available. Properly prescribed exercise is likely the most effective preventive approach to the muscle atrophy problem and, in combination with appropriate levels of protein intake, this problem may be brought under control.

Until studies are completed to demonstrate the optimal level of dietary protein needed to effectively prevent or minimize calcium loss, recommending protein intake at the lowest level required to maintain a positive nitrogen balance and that causes no adverse effect on other biochemical/nutritional parameters is not contraindicated. Therefore, based on the limited available information, it can be tentatively assumed that the minimal level of protein required in a 3400 kcal space diet is about 4%, an estimate based on data presented in reference 20. However, because of the high protein content of the CELSS-proposed crops, it is unlikely that such a lower limit will ever be approached. An upper level for protein is more difficult to determine. For the purpose of these models, an upper range of 10% will be sought because of the expense to the system of decreasing protein further. As described earlier each increase in protein lowers the phytomass requirement while, conversely, each decrease in protein increases the phytomass requirement. This subject is discussed further in Section III.

Based on the above assumptions and on preliminary runs of the models, the most practical approach therefore appears to be to set the total protein intake at 10%. In a 70 kg individual, this means about 340 kcal (10% of 3400 total kcal) from protein, or about 85 g/day.

3. Carbohydrate

There is no direct means for determining optimal carbohydrate intake for spaceflight conditions; therefore, specifications will have to be derived from the available data. A very specific need for carbohydrate exists in the diet: it stems from the requirement that although most body tissues can utilize any of the three major energy sources (protein, fat, carbohydrate), red blood cells and brain cells can only utilize energy from carbohydrate. Brain and red blood cells of an adult may utilize about 180 g or 720 kcal of glucose/day. More generally, slightly more than 2 g/kg bwt is the minimal daily intake required to prevent ketosis (33). It is not certain at this time whether the amount of carbohydrate required in a space diet will need to be increased or decreased. This will not be a problem, however, since excess carbohydrate levels will be obligatory in a CELSS diet due to its high yield from the plants.

Determining an upper limit for carbohydrate in a space diet is somewhat more complex than determining a lower limit. A specific maximum tolerance level for carbohydrate has not been determined for terrestrial conditions. It has been reported that blood lipid levels become undesirably high when carbohydrates are increased beyond 85-90% of total dietary energy intake. The type of carbohydrate consumed also plays an essential role in the maximum tolerance level (34). There appears to be no reason for increasing the carbohydrate intake in a CELSS diet to levels as high as the maximum (85-90%) since fat, the other major dietary component that is subject to adjustment, can be increased considerably without causing adverse effects.

The amino acid/protein content of the diet will also play a role in determining the level of carbohydrate intake. If, for example, maximum protein intake is set at 10% of total energy or 340 kcal, then the other 90% will have to be composed of carbohydrate and fat. The initial runs of the models have been partially responsible for determining what levels of each nutrient are most readily available at the lowest cost to the system. It could only be determined from the literature that the carbohydrate level can fall within the range of 720 to 2990 kcal (assuming a 2% minimum for fats) and still satisfy and not exceed the maximum safe level. The equilibrium level was determined to be 70% by preliminary runs of the models. As this level falls within the range considered to be safe for carbohydrate and as it approximates average daily intakes for individuals in a terrestrial environment this level will be tentatively defined as an appropriate level for current modeling needs (see Section III for a more detailed explanation).

Carbohydrate composition is another area requiring consideration. Most of the foods to be produced directly in a CELSS will be composed of carbohydrates in the form of starches and fiber. Dietary glucose intake may be required in the diet to counter protein degradation and the resulting muscle atrophy. The major source of glucose will be from byproduct conversion, and it may constitute as much as 90% of total carbohydrate for some of the crops. How much of the final dietary carbohydrate will be in the form of glucose depends on the crops that are finally selected. There is no known limit for glucose except in terms of limits for carbohydrate, and there is no indication that total carbohydrate intake in the form of glucose is harmful to healthy individuals. In any event, it is not likely that this the use of glucose as a sole form of carbohydrate would arise in a CELSS diet composed of products from the crops currently under consideration.

Lactose is a dietary component that has been shown to have a stimulatory effect on the absorption of key minerals, including calcium, magnesium, and manganese. It increases their absorption by up to 50% (35). There is no lactose present in the CELSS crops but, like glucose, certain microorganisms are capable of converting cellulosic/hemicellulosic byproducts to lactose if this becomes necessary. No significant consideration is currently being given to the specific production of lactose in a CELSS diet at this time; it is only mentioned as an option for countering some of the mineral deficiency problems that result from spaceflight.

A final consideration with respect to carbohydrates is fiber. Fiber is known to form complexes with minerals that can either prevent or interfere with their absorption, a situation to be avoided, particularly during long-term stays in space. Setting an intake level for fiber that would be adequate for spaceflight is not very feasible since such a level has not been established for terrestrial conditions to date.

Some fiber in the diet is believed to be beneficial in the prevention of certain types of cancer, but how much is a question that has no answer at this time (36).

4. Fat

Food sources composed primarily of fat are the most abundant in energy. While fat will be readily available in a CELSS diet, saturated fats and cholesterol will be quite low since the primary food sources will be plants, which produce mainly unsaturated fats. Polyunsaturated fats will predominate, with sunflower and soy oil the major potential sources.

There is no established need for fat in a terrestrial diet, other than the minimal need for essential fatty acids, which is quite low at about 1-2% of the total daily energy intake. The high level of fatty foods in the human diet can best be explained in terms of aesthetic appeal or, in some cases, by the energy value. The average combustion factor for 1 g of fat is about 9.0 kcal as compared to 4.0 kcal for protein and carbohydrate. The inflight absorption factor for fat is higher than for protein, at about 96.5% vs. 87%. Fat is therefore more efficient than protein in both absorption and as an energy source and compares as well with carbohydrate also (37, 38). These values, which are from Soviet studies, may require additional evaluation since supplements developed for spaceflight are generally employed during Soviet missions.

During recent Soviet flights, the average fat intake was approximately 33% of total calories, while in Skylab the total fat intake was only about 25% (39). Either of these levels will probably be safe and adequate for long-term spaceflight. Once again it is necessary to determine how low or how high intake of an essential nutrient can be without causing adverse effects. Since it will be a concern in a CELSS to determine acceptable ratios for fat:carbohydrate, it will be necessary to determine as accurately as possible the upper and lower limits for both components.

As mentioned above the lowest tolerable level of fat in the diet is 1-2% of total calories, and this must be in the form of essential fatty acids. There is evidence that suggests that the amount of fat in the diet significantly influences the absorption of key nutrients, including calcium, magnesium, and zinc. It has been demonstrated that diets as low as 40 g/day of fat resulted in much higher mineral absorption than a 100 g/day fat diet (40). If this is an indication of what fat levels should be in a CELSS, then they should be kept at lower levels. An appropriate ratio of saturated to unsaturated fats will not be significant in a CELSS, since most of the fats from CELSS-type crops are polyunsaturated.

Fat intake levels above 150 g/day cause acute toxic symptoms that can be tolerated by some individuals but not by others (41). If the potential toxicity of fats as well as its effects on absorption of key minerals is considered, it can be assumed that 150 g/day or 40% of total energy can be set as an upper limit for fat. Thus, it appears that 1-40% of total energy in a 3400-kcal diet can be fat without adverse deficiency or toxicity effects. Fat intake levels as high as 40% are not generally recommended, however, even for terrestrial conditions, because of the effects of high fat levels on cardiovascular and neoplastic diseases. Intakes of less than 30% of total energy are generally considered beneficial in preventing these types of diseases.

The levels of fat and carbohydrate constrained in the models have been determined by considering the information above, together with preliminary runs of the raw product models while varying the constraints at levels within the range of 1-40% of total energy. Carbohydrate was constrained at 70% and fat at 20% of total energy because they are the optimal levels when protein is set at 10% of total energy. The method used to determine these constraints is discussed further in Section III.

5. Calcium

A major area of focus in the space diet is calcium and the nutrients involved in maintaining calcium levels. Much effort in space biomedical research has focused on calcium loss and therapeutic approaches to treating the problem. Since calcium is the most critical mineral in cell and tissue function and in the body's structural support as well, it becomes even more critical in an organism faced with situations affecting its equilibrium, such as the weightless condition of spaceflight. Calcium loss and bone demineralization is a major concern when considering long-duration spaceflight. Skylab 4 results suggest that bone loss on flights of about 90 days is reversible, but what the effects will be beyond this period cannot yet be determined from U.S. data.

Spaceflight effects involving calcium include increased urinary and fecal calcium excretion, negative calcium balance, and loss of calcium from weight-bearing bone. The loss of calcium from the os calcis of weight-bearing bone is probably the most critical spaceflight effect with regard to the possibility of total recovery. Total body calcium loss of about 0.3-.4% per month occurs during spaceflight, while os calcis loses about 5% of its mass per month (42).

The continuing increase in fecal calcium loss throughout spaceflight indicates the major route of calcium loss. It may represent progressive malabsorption of calcium or losses in endogenous stores. It appears that the primary reason for the calcium loss during spaceflight is the lack of stress and strain on the bone. The mechanism apparently involves both increased resorption of bone, and decreased formation of new bone. Urinary calcium levels increase immediately upon exposure to weightlessness, as the body begins to unload calcium. The kidneys then increase calcium excretion up to a maximum level. With the increasing loss of bone calcium, less calcium is absorbed by the intestines from the food ingested, resulting in increased urinary calcium. The increased urinary calcium also contributes to the risk of renal stone formation.

Bone and total calcium loss during spaceflight are much like those of healthy bedrest subjects, that is, both urinary and fecal calcium increase, calcium balance is negative, and calcium loss is primarily from weight-bearing bone. Bedrest is therefore considered one of the more reliable models for the study of spaceflight effects on bone mass.

Three major manipulative methods have been employed to prevent or decrease the severity of bone demineralization during spaceflight: dietary manipulation, exercise/weight-bearing, and pharmacological intervention. The first two will be considered briefly here. Pharmacological intervention is not directly related to the purposes of this report and will not be further discussed.

a. Dietary Manipulation. Among the dietary approaches that have been considered in dealing with bone demineralization are control of the calcium:phosphorus ratio, fluorine; vitamins A, K, and D; protein; sugars; amino acids; and oxalates and phytates.

The recommended calcium:phosphorus ratio is 1:1, but this is difficult to achieve since most foods contain considerably more phosphorus than calcium, generally resulting in a ratio closer to 1:2. Simultaneously adding calcium and phosphorus may enhance the formation of renal stones (decreasing protein intake appears to decrease this propensity, however). A close interrelationship exists between calcium, phosphorus, and protein levels, one which requires careful balancing. Moderately low intakes of calcium and phosphorus and low intakes of protein permit calcium equilibrium to be achieved. For example, 800 mg/day of calcium and phosphorus each, coupled with a low protein intake (between 6-7% of total energy) results in a positive calcium balance (43). Use of phosphate taken orally as 1.3 g/day K_3PO_4 prevents hypercalciuria but it does not prevent a negative calcium balance, loss of os calcis mineral, or the possibility of renal stone formation (44). Other studies have suggested that treating bedrest subjects with K_3PO_4 entirely prevented the hypercalciuria of bedrest but that it also increased fecal calcium loss. Also, treatment with phosphate may increase the possibility of renal stone development. This condition would be even more undesirable in space than on earth (45, 46).

Studies conducted with fluoride suggest that it may have beneficial effects on bone calcium loss due to spaceflight. Fluoride can be used to help treat or reduce osteoporosis if it is taken in fairly large doses, for example, 40 mg/day. This amount has been shown to produce gastric irritation and bone pain, however. In lower doses, fluorine has been shown to improve calcium balance slightly in ambulatory subjects, although it seems to have no effect on significantly reducing total calcium loss during bedrest (47).

Recommended dietary allowances for fluorine have been set at levels between 1.5-4.0 mg/day. An intake level in the range 10-40 mg/day would likely be beneficial during spaceflight, although the upper level would have to be more carefully defined since toxicity has been reported at doses of about 40 mg/day. Only small amounts of fluorine will be available through the plants grown in a CELSS (unless larger quantities are added via the growth media and incorporated by the plants), so fluorine supplements will likely be required.

Certain vitamins affect calcium absorption. Vitamin A deficiency affects bone structure by altering glycosaminoglycan biosynthesis in the organic matrix and mineral deposition in bones and teeth. The exact mechanism of this process is not clear, but the effect indicates that vitamin A levels may be very important in a space diet. Vitamin A also influences calcium metabolism in tissues other than bone, which would affect overall calcium balance (48).

Vitamin K proteins appear to be ubiquitous, although their functions are still not fully elucidated. Osteocalcin vitamin K-dependent bone proteins probably play a role in bone mineral maturation, direct regulation of calcium metabolism in bone, and indirect hormonal mediation of bone mineral metabolism. Elevated osteocalcin levels have been observed in certain bone and calcium metabolism disorders, suggesting a possible association between vitamin K and vitamin D functions in bone metabolism (49).

The effect of vitamin D metabolism on calcium absorption is also relevant. Vitamin D is implicated in calcium absorption interactions because it is known to be involved in the maintenance of calcium homeostasis through the action of parathyroid hormone on bone. Altered vitamin D metabolism could impair intestinal calcium absorption and result in a negative calcium balance, which may contribute to the development of osteoporosis.

Studies have suggested that it is the action of vitamin D metabolizing to its active 1,25-dihydroxyvitamin D form, and not vitamin D itself, that is responsible for the increased intestinal calcium absorption and increased bone density observed in subjects treated with large doses of vitamin D and 1,25-dihydroxyvitamin D (50). For intestinal calcium absorption, though dependent on 1,25-dihydroxyvitamin D, it is the precursor vitamin D3 (which can be synthesized from 7-dehydrocholesterol) that is required. Plants that contain vitamin D also usually contain vitamin D2 precursors or ergocalciferol; vitamin D in animals usually contains D3 precursors or 7-dehydrocholesterol which must be present. Animals exposed to sunlight can use either of these forms to synthesize the active metabolite involved in calcium absorption (51).

The percent of calcium absorbed by adults decreases with age; not because their capacity to synthesize it is impaired, but because their intake of vitamin D-containing foods and their exposure to sunlight is decreased. Since the same situation may exist in space (though not necessarily by choice), it may contribute to the deterioration of the calcium:phosphorus equilibrium, since compromised vitamin D status can progressively deplete calcium and probably phosphorus stores also (52).

Vitamin D intake and calcium consumption may have to be increased above the RDAs, even in the presence of sunlight. In the absence of ultraviolet radiation, there is an even greater need for increased vitamin D intake. (At least 400 iu/day is required). Since amounts of vitamin D as small as 1000-3000 ius can cause toxic reactions (53) it is therefore essential that the level of intake not be in excess of 1000 ius, until it is conclusively demonstrated that spaceflight vitamin D requirements are higher (and thus toxicity levels are perhaps lower than terrestrial requirements). To summarize, a vitamin D level between 400 and 1000 ius should meet the requirement without approaching the toxic level.

The effects of protein intake on calcium levels in various tissues of the body and on the state of calcium excretion was discussed previously in the Protein section.

A number of dietary agents are known to improve calcium absorption. Among them are the amino acids arginine, tryptophan, and lysine and the sugars lactose and glucose (54, 55, 56). The glucose polymer increases calcium absorption 2-5 fold. The specific levels at which these compounds modify calcium absorption activity were not provided in these reports, however. Since none of these compounds are particularly toxic, increasing their levels should not present a problem as long as imbalances with other nutrients are not created. Arginine, tryptophan, and lysine could be increased to several times their RDA without any negative effect, as long as the other essential amino acids remain in balance and the protein constraint is not exceeded (57).

Glucose either would not be available or would be at a minimal level in most of the crops being considered. The ideal source for glucose in a CELSS would be from the conversion of agricultural byproducts from the crops produced. Conversion of the cellulosic fraction to 6-carbon sugars is generally the first step to be completed in the process and since the total waste phytomass could be in the range of 30-50%, depending on the crops selected. Since the conversion rate can be as high as 90%, the yield of glucose could be quite high.

A number of dietary factors may contribute to decreased calcium absorption. Primary among these are the presence of oxalates and phytates, substances found in some of the foods planned for a CELSS. Phytates may represent a significant problem if wheat products are to be a major component of the diet, since they complex with minerals and prevent their absorption. Since flight crews will probably ingest a large amount of calcium, both as food and as supplements, this may not be a significant problem. But if the intake of grain is large, it would be prudent to assure that these grain products are leavened, since leavening agents generally produce phytase enzymes that break down the phytate (58). Nevertheless, it is probably wise to minimize products in the diet that have a potential for contributing to the bone demineralization problem.

b. Exercise/Weight-bearing. A final possibility to be considered in terms of controlling spaceflight bone demineralization is exercise. Exercise may be the single most effective means for significantly reducing or eliminating bone mass loss. The Soviets report that they have successfully countered bone demineralization through the use of a diet high in calories, exercise on a bicycle ergometer and treadmill, and use of the penguin compression suit. Although no metabolic data have yet been provided to confirm these reports (59, 60), data from a number of Soviet flights indicate a significant decrease in calcium loss from weight-bearing bone when 1.3 to 3.0 hr/day of exercise is performed. These bone changes may be associated with changes in the contractile properties of corresponding muscle (61). It has also been demonstrated that calcaneal mineral density is maintained or improved by impact loading and compression of 80% of the body weight for 8 hr/day (62).

Results obtained during Skylab 4 also indicate the need for exercise to prevent calcium loss from bone as Skylab 4 astronauts experienced a lesser rate of decline in overall and bone calcium levels, despite the fact that this was the longest of the Skylab Missions, a result which is attributed to the incorporation of exercise into the daily activity schedule (63). This may be because they were the only Skylab crew that participated in exercise on a regular basis.

None of these approaches — increased calcium intake, balanced calcium and phosphorus ratios, fluorine supplementation, decreased protein intake, simulated weight-bearing, or exercise — appears to be capable alone of completely alleviating bone demineralization.

6. Vitamins and Minerals

Extreme environmental conditions are associated with increased utilization of vitamins and minerals, changes in their interstitial metabolism, and differential changes in vitamin requirements because of altered metabolism. The effects of spaceflight on vitamin and micromineral metabolism have not been clearly elucidated, though it does appear that certain vitamins and minerals are affected by the unique conditions of spaceflight. Soviet studies of vitamin metabolism during spaceflight have shown significant decreases in vitamin excretion in urine. Low levels of vitamins were observed in blood, which indicated a higher vitamin requirement during such times. Vitamin B12, vitamin E, and NAD all decreased. Levels of some other vitamins increased (64). This increase can be viewed as indicative of an increase in catabolism.

Because of the potency of certain vitamins and minerals, it is essential that they be carefully considered in the system design of a CELSS. In particular, their toxicity as well as deficiency levels need to be evaluated. Due to the bioregenerative nature of a CELSS, some nutrients will remain in the system, possibly resulting in difficulties in overaccumulation and accompanying toxicity. The general guideline is that it is safe to use water soluble vitamins in any dose desirable beyond the RDA, while the intake of fat soluble vitamins must be controlled because of their greater toxicity. This may be true in terms of direct effects of the vitamins, but when considering interactions between these vitamins and other nutrients, it becomes clear that the situation is not quite so simple, particularly in a closed system where levels of many nutrients that ordinarily would not be a concern need to be addressed.

a. Vitamin D. Vitamin D was discussed in some detail in the section on calcium.

b. Vitamin E. Vitamin E (alpha-tocopherol) is a relatively nontoxic agent. Its dose intake as a dietary component is determined by the intake of polyunsaturated fats (PUFA), since foods that are high in PUFA are also high in vitamin E. By terrestrial standards, a vitamin E intake that can insure a blood concentration of total tocopherols of 0.5 mg/100 ml is adequate to meet vitamin E needs. In balanced diets of 1800-3000 kcal, 7-13 mg/day of alpha-tocopherol (10-20 ius) can be expected to be obtained (65). Because of the wide range of vitamin E in foods, it is better to ingest the recommended level over a period of several days to a week, rather than to attempt to meet it on a daily basis. (In later stages of CELSS modeling, it will be better to do this with all nutrients).

Both vitamins E and A have been found by the Soviets to become deficient during spaceflight (66). Despite the fact that they interact metabolically (vitamin E preserves vitamin A), it is possible that the deficiency is not completely a result of metabolic changes resulting from spaceflight. Despite the availability of a balanced diet, the Soviet cosmonauts may have failed to consume all of the food, and therefore the deficiencies may have resulted from inadequate intake. But for for now it will be assumed that vitamin E requirements for spaceflight should be increased over terrestrial standards. The level to which they should be increased is unknown, but a level between the terrestrial requirement and the toxicity level should suffice. Vitamin E becomes indirectly toxic by causing a deficiency in vitamin K when it is present in levels that exceed 1200 ius. Conditions that may result in a vitamin E deficiency, or that may indicate an increased need for vitamin E, include high intake of protein or vitamin B_{12}, or a deficiency in folic acid, vitamin B_6, selenium, or methionine (67). In a diet that provides about 20-25% of total calories as PUFA, there will be no difficulty exceeding terrestrial vitamin E needs for short-term or extended spaceflight. Based on this information, the vitamin E range will tentatively be set at between 10 and 1200 ius/day.

c. Vitamin A. Specific requirements for vitamin A are based on a number of factors, including age, growth rate, sex, efficiency of absorption, general state of health, and deficiencies of other nutrients (68). Vitamin A has an effect on calcium metabolism as discussed earlier in the calcium section. Vitamin A becomes toxic at about 10 times the RDA when ingested on a regular basis over a period of several months (the RDA for vitamin A is 4000 ius for females and 5000 ius for males). The amount of vitamin A available in a CELSS diet could reach toxic levels and should be carefully monitored.

Since it is not yet clear what the requirement for vitamin A will be, a range between 5000 and 50,000 ius for adult males and between 4000 and 40,000 ius for adult females will be assumed to be acceptable. Since Soviet studies indicate increased vitamin A needs in space, and if there is indeed such an increased need, levels slightly in excess of the upper limit of the range should be no reason for concern.

d. Vitamin K. Vitamin K was also discussed earlier with respect to calcium balance. Vitamin K is produced by microorganisms in the gastrointestinal tract and, unless other nutrient imbalances interfere with its equilibrium, it should not occur at either deficient or toxic levels. If for some reason it cannot be produced endogeneously, the RDA of 1-2 ug could be met by introducing appropriate amounts of spinach and/or green beans into the diet.

e. Vitamin C. Vitamin C in amounts as small as 10 mg/day prevents scurvy. Using a range of 10-60 mg/day as a guideline, the amounts of vitamin C available from most combinations of CELSS crops should be sufficient to meet the requirement. The stressful conditions of spaceflight and the possible involvement of vitamin C in countering stress suggest that the requirement for vitamin C in space may be greater than it is on earth (69). Although vitamin C is not a toxic agent, it can have adverse effects if ingested in irregular doses, varying from very high to very low doses over extended periods of time. It is therefore preferable that the amounts ingested be kept constant over a period of time.

Amounts of vitamin C in excess of 500 mg/day can cause a deficiency of vitamin B12 by affecting its bioavailability (70). This would be a major factor limiting the use of vitamin C in a CELSS, since vitamin B12 will be in demand in an all-plant diet. If fermented products such as tempeh are employed in a CELSS, vitamin B12 requirements will be easily met, but if fermented products are not used, there may be a need to supplement B12. However, the storage capacity of the body for vitamin B12 is remarkable; studies indicate that the body can store enough to satisfy its needs for up to 13 years. Therefore, even if fermented products are not used, vitamin B12 deficiency may not be a problem, barring any interference in its metabolism or absorption which would result in a secondary deficiency. It is probably preferable to have some vitamin B12 in the diet to rule out any possibility of developing a deficiency. The RDA has been set at 3.0 ug/day by the National Academy of Sciences, 2.0 ug/day by the World Health Organization, and 1.0 ug/day by other sources (71).

Requirements for vitamin B1 (thiamin), vitamin B6 (pyridoxine), biotin, and pantothenic acid during long-term space missions will remain the same as the ground-based RDAs, since there is no indication at this time to suggest that their requirements should be altered.

f. Vitamin B3. Vitamin B3 (niacin) intake in space may require some modification over terrestrial intake since it interacts with some of the other nutrients that may be tailored for spaceflight. A primary concern will be its interaction with leucine, if leucine is chosen for use as a countermeasure against muscle atrophy. Leucine prevents the conversion of tryptophan to niacin, thus causing a niacin deficiency. If both niacin and pyridoxine are present in the diet in sufficient quantities, excess leucine should not be a problem. Four niacin equivalents (2 mg/1000 kcal) should meet most of the need for niacin. However, there are reports suggesting that even in the presence of sufficient niacin intake, niacin can still become deficient if leucine is increased considerably (72). There are also reports that suggest that isoleucine counters the effect of leucine on niacin. Since both of these branched-chain amino acids may have the same potential for countering muscle atrophy, it would probably be beneficial to keep a ratio of about 1:1 between them, or to have isoleucine in excess of leucine. The level to which these amino acids can be increased in the diet is not known. It does appear, though, that they can exist at any level that is within the protein constraint, provided all of the other essential amino acid requirements are satisfied.

g. Vitamin B2. Vitamin B2 (riboflavin) may present a problem in a plant-based CELSS since it is found predominantly in meat, meat products, and dairy products. The terrestrial requirement is 1.2-1.5 mg/day, which is generally met without difficulty. Exposure to light and cooking can result in considerable loss of this vitamin. Vitamin B2 is extremely sensitive to artificial light and, even though it is synthesized by intestinal bacteria, the use of artificial light in spacecraft may cause it to be insufficient to meet nutritional needs (73). It may therefore require supplementation in a CELSS, even if it is present at seemingly sufficient levels.

h. Folic Acid. The requirement for folic acid under terrestrial conditions is approximately 50 ug/day. This requirement can be affected by stressful conditions, however, and levels in excess of the terrestrial requirement may therefore be required in a CELSS. The level at which folic acid should be set in a space diet is not known. Since it is a relatively nontoxic substance, increasing its intake to levels somewhat in excess of the recommended level should not create any problems (74).

i. Magnesium. Magnesium depletion may have direct and indirect effects on cardiac function by virtue of secondary changes in potassium, sodium, and calcium concentrations in intracellular and extracellular fluids. A number of studies suggest there may be some correlation between coronary artery disease and magnesium deficiency, but deficiencies in magnesium are very rare. Another aspect that may be of concern in a CELSS diet is the role of magnesium in calcium and phosphorus metabolism. When the rare magnesium deficiency exists, there is concurrent incidence of hypocalcemia (75). Though there is no indication that the RDA will require adjustment in a space diet, magnesium should be monitored because of its possible effect on the cardiovascular deconditioned state that already exists as a result of the weightless condition.

j. Sodium. In a bioregenerative system, sodium will be one of the primary recycled nutrients. As such, it has the potential to become a problem since it is toxic and its excessive use is associated with various diseases. A range between 1100-3300 mg/day should be sufficient to meet sodium requirements and to prevent adverse side effects. It will be preferable to keep sodium closer to the lower end of the range since its capability of increasing blood pressure and causing fluid retention during spaceflight (76) may interfere in the adaptive mechanism of fluid loss balancing during spaceflight.

k. Copper. At this time, it appears that the requirement forcopper during spaceflight will be the same as for normal terrestrial conditions, that is, between 2-3 mg/day (77).

l. Zinc. Zinc is another nutrient involved in the growth and development of bone. Its use needs to be controlled in a CELSS diet, however, since large quantities of zinc can inhibit the absorption of calcium. Zinc requirements are based on the levels of phosphorus and nitrogen in the diet; its requirement is low when phosphorus and protein levels are low, and vice versa. It was suggested in the protein section that the requirement for protein in a CELSS diet will be rather low, about 10% or less of total energy. Because of this and because phosphorus will be in the normal range, the requirement for zinc in a CELSS will be somewhat less than the terrestrial requirement (78). It is not possible to determine how much less at this time.

m. Selenium. Selenium is available through some of the plants to be grown in a CELSS, but whether it will be available in an actual CELSS will depend on whether it is a component of the hydroponic solution which will be employed as the plant growth medium. Because it is an essential component of a glutathione peroxidase which is involved in degradation of cellular hydrogen peroxide, a selenium deficiency is to be avoided. If it is not available through the diet in a range between 50-200 ug/day, the level recommended for terrestrial conditions, it will have to be supplemented (79).

n. Fluoride. Fluoride requirements in a CELSS were discussed in the calcium section.

o. Manganese. There are no known cases of manganese toxicity, and it is rarely found to be deficient in vegetarian diets. Its requirement is 2.5-5.0 mg/day, a level that will be easily met and exceeded in a CELSS (80).

p. Iodine. Iodine is another nutrient that may be required at higher levels in the space diet. This is because it has been suggested that the adverse effects of continued exposure to ultraviolet radiation may be prevented or lessened to some degree by increased iodine intake. To determine the iodine requirement more specifically, more studies on its depletion rates by ultraviolet radiation need to be conducted. The RDA for iodine is 1-2 ug/kg bwt, or between 70-140 ug/day with a safe intake of up to about 150 ug/day. An amount in the upper part of the range may be an appropriate level for a CELSS until more specific information becomes available (81).

q. Molybdenum. Terrestrial molybdenum requirements have been set in the range of 0.15-0.5 mg/day. Levels higher than this can be quite detrimental. For example, levels as low as 0.54 mg/day, which is only .04 mg in excess of the .5 mg requirement, can compromise copper balance. This particular nutrient will have to be carefully monitored in a CELSS to prevent its causing additional complications by interacting with other minerals (82).

r. Potassium. Potassium in amounts between 90-100 mEq/day (3510-3900 mg) is required to meet various metabolic needs. The loss of water, sodium, and potassium during the course of spaceflight is a result of normal physiologic responses to headward shifts of fluid in zero gravity, a change which seems to be obligatory. This loss is likely an adaptation of the body and it may be better not to adjust it, although under normal conditions increasing potassium and sodium would help improve the condition of water loss (83). Since potassium will be available in considerable excess in a CELSS producing many of the 12 crops under consideration, it will be necessary to determine if this is beneficial or if potassium should be kept at a lower level. The latter approach would require constraining it at lower levels in the models to determine what effects this would have on crop selection and phytomass levels.

s. Iron. The RDA for iron is about 18 mg/day for females and about 10 mg/day for males. There are a number of factors associated with iron absorption that may have to be considered in a CELSS. The presence of vitamin C correlates positively with increased iron absorption (84). The interaction of iron with other substances, such as calcium and its salts, phytates, tannic acid, and antacids, may decrease its absorption. All of these substances can decrease iron absorption if they are ingested at high levels, particularly if the iron status of an individual is compromised. Despite these concerns, meeting iron needs should not be a problem in a CELSS.

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	Recommended Dietary Allowances	RDAs Adjusted to Spaceflight
Essential Amino Acids		
leucine	1120 mg/70 kg bwt	1120 mg/70 kg - no upper limit
isoleucine	840 mg/70 kg bwt	840 mg/70 kg - no upper limit
lysine	840 mg/70 kg bwt	840 mg/70 kg - no upper limit
threonine	560 mg/70 kg bwt	560 mg/70 kg - no upper limit
tryptophan	210 mg/70 kg bwt	210 mg/70 kg - no upper limit
valine	980 mg/70 kg bwt	980 mg/70 kg - no upper limit
aromatic amino acids	1120 mg/70 kg bwt	1120 mg/70 kg - no upper limit
sulfur containing amino acids	700 mg/70 kg bwt	700 mg/70 kg - no upper limit
fiber	none established	None established
essential fatty acids	1-2% of total energy	7.5-150 g
vitamin A	4000 ius (female) 5000 ius (male)	4-40000ius(female) 5-50000ius (male)
vitamin C	50-60 mg	50-500mg
vitamin E	10 ius	20-1200 ius
vitamin K	1-2 ug kg bwt (if not produced endogenously)	2 ug/kg bwt
vitamin D	400-1000 ius (if not produced endogenously)	400-1000 ius
riboflavin	.6 mg/1000 kcal	.6mg/1000 kcal
niacin	18 mg (male) 13 mg (female)	2.2mg/1000 kcal
pantothenic acid	4-7 mg	4-7 mg
pyridoxine	2.2 (males) 2.0 (females)	2.0 mg/100 grams of protein(about 1.87 mg)
folic acid	400 ug	400 ug
biotin	100-200 ug	100-200
cobalamin	3 ug	3 ug
thiamin	.5 mg/1000 kcal	.5 mg/1000 kcal
calcium	800 mg	1200-1500 mg
phosphorus	800 mg	1200-1500 mg
iron	10 mg (males) 18 mg (females)	10 mg
sodium	1100-3300 mg	1100-3300 mg
potassium	3510-3900 mg (90-100 mEq)	3510-3900 mg (90-100 mEq)
copper	2-3 mg	2-3 mg
fluorine	1.5-4.0 mg	10-40 mg
iodine	150 ug	70-150 ug
magnesium	350 (males) 300 (females)	300 mg (female) 350 mg (male)
manganese	2.5-5.0 mg	2.5-5.0 mg
molybdenum	.15-.5 mg	.15-.5 mg
selenium	50-200 ug	50-200 ug
zinc	15 mg	15 mg
kilocalories	2000 (females) 2800 (males)	3400 (70 kg male)
protein	224 (males) 176 (females) prevents - nitrogen	340 kcal or 10% of total energy
carbohydrate	200-400 kcal is minimal amount	2380 kcal or 70% of total energy
fats	135-225 kcal	680 kcal or 20% of total energy

Table 1. Nutrient Constraints for Space Flight. Recommended Dietary Allowances (RDAs) of essential human nutrients, and the RDAs adjusted for long-duration spaceflight, as described in the text.

B. Conclusion

The available literature suggests that the conditions of spaceflight do indeed affect the levels of some of the nutrients required in the human diet. In some cases, the modified need is quite obvious as, for example, with calcium, calcium:phosphorous, and protein. In many other cases, considerably more research will be required before specific spaceflight nutrient requirements can be determined.

What this section has attempted to do is to develop nutrient guidelines adjusted to the unique conditions of spaceflight as well as can be done at this time with the limitations of the database, so as to have reasonable estimates to use in the development of model CELSS diets. (Table I is a summary of these efforts.) The adjusted nutrient guidelines developed in this section are used as constraints in the models developed in Section III.

III. MODEL DEVELOPMENT AND ANALYSIS

A. Introduction

A number of linear algebraic models were developed to determine the optimal combination and production levels of crops selected from soybeans, wheat, potatoes, wheat sprouts, soy sprouts, sweet potatoes, rice, lettuce, tomatoes, onions, green beans, sunflower seed, and spinach. These models were solved using LINDO, a program with the capability of solving complex systems of linear equations using the simplex method. A combination of both raw and edible product models were developed, as well as models that incorporated byproducts. The system of constraints used in these models was the nutrient requirements, determined from analysis of the spaceflight literature, or, in the case of those nutrients where there is no clear indication that modifications should be made for spaceflight, the RDA was used. The solution values represent the total amount of phytomass needed to meet the nutrient requirements of an individual within the confines of the constraints utilized. The degree of feasibility of the model solutions are considered and the composition of the supplements required by each model diet to satisfy all spaceflight nutrient needs are determined.

The models that were developed can be classified into three major types. The first type consists of the Raw Product Models, diets labeled #1-3, these were derived from the nutrient composition values for the 13 crops in their raw form. The second type, which consists of Edible Product Models, diets #4-6, were derived from the nutrient composition values of 18 representative products of the 13 base crops. The third type, the Product/Byproduct Models (diets #7-9), were derived from the same products as the Edible Product Models, but include the kilocalorie values for the additional carbohydrate derived from the cellulosic glucose found in 16 of the 18 crops/products. The specific values from which the models have been derived are shown in Table 2 for the Raw Product Models and Table 3 for the Edible Product Models and the Product/Byproduct Models. The objective function coefficient—the value that represents the cost (loss) in inedible phytomass that is sustained in order to produce the crop—was derived from the harvest/production indices which are discussed in Appendix B.

TABLE 2. Nutrient composition of raw products proposed for a CELSS

	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13
	Spinach	Lettuce	Tomatoes	Sweet	Onions	Green	Rice	Soybeans	Wheat	Potatoes	Sunflow	Soy	Wheat
				potatoes		beans			meal		seed	sprouts	sprouts
Leucine (mg)	223	70	33	121	41	112	728	926	670	105	1659	664	R
Isoleucine (mg)	147	75	21	82	42	66	371	570	434	92	1139	394	R
Lysine (mg)	174	75	33	81	56	88	319	775	274	113	937	552	R
Threonine (mg)	122	53	22	52	28	79	293	516	288	83	928	458	R
Tryptophan (mg)	39	8	7	20	17	19	91	157	123	22	348	181	R
Valine (mg)	161	62	23	108	27	90	512	576	468	113	1351	442	R
Aromatic Amino Acids (mg)	237	78	38	167	59	109	712	1050	867	58	1835	576	R
Sulfur Amino Acids (mg)	88	28	20	54	31	40	323	275	373	46	945	130	R
Fiber (g)	0.9	0.53	0.5	0.9	0.44	1.1	0.3	2.05	1.8	0.5	4.16	2.3	2.2
Essential Fatty Acids (g)	0.1	0.035	0.1	0.1	0.037	0.1	0.4	4.445	2	0	41.98	3.7	0.5
Vitamin A (ius)	6715	330	1133	20063	0	668	0	180	0	0	50	11	0
Vitamin C (mg)	28	3.9	18	23	8.4	16.3	0	29	0	9	0	15	R
Vitamin E (ius)	1.8	0.4	0.34	4.5	0.31	0.02	0.35	R	0.89	0.01	32	0.03	R
Vitamin K (ug)	0.35	R	8	R	R	R	R	R	R	R	R	R	R
Vitamin D (ius)	0	R	0	0	R	R	0	R	0	0	0	0	0
Riboflavin (mg)	0.19	0.03	0.05	0.15	0.01	0.105	0.04	0.175	0.12	0.04	0.25	0.12	0.21
Niacin (mg)	0.7	0.187	0.6	0.7	0.674	0.752	1.5	1.65	4.4	1.5	4.5	1.1	0.9
Pantothenic Acid (mg)	0.07	0.046	0.25	0.56	0.132	0.094	0.55	0	1.1	0.2	0.7	0.93	R
Pyridoxine (mg)	0.2	0.04	0.05	0.26	0.157	0.074	0.17	R	0.39	0.39	0.8	0.18	R
Folic Acid (ug)	194	56	9.4	13.8	19.9	36.5	29	R	52	25	237	171.8	R
Biotin (ug)	6.9	R	1.5	4.3	R	R	3	R	9	0.1	R	R	R
Cobalamin (ug)	0	0	0	0	0	0	0	0	0	0	0	0	0
Thiamin (mg)	0.08	0.046	0.06	0.07	0.06	0.084	0.13	0.435	0.66	0.1	0.11	0.34	0.01
Calcium (mg)	99	19	7	22	25	37	32	197	37	7	116	67	22
Phosphorus (mg)	49	20	23	28	29	38	127	194	386	53	705	164	150
Iron (mg)	2.7	0.5	0.5	0.6	0.37	1.04	0.1	3.55	4.3	0.6	6.77	2.1	R
Sodium (mg)	79	9	8	13	2	6	8	R	3	3	3	14	R
Potassium (mg)	558	158	207	204	155	209	85	R	435	407	689	484	R
Copper (mg)	0.13	0.028	0.077	0.169	0.04	0.069	0.2	R	0.93	0.311	1.752	0.427	R
Fluorine (mg)	0.01	R	0.024	R	R	R	0.19	R	0.053	0.045	R	0	0.01
Iodine (mg)	0.012	R	0.003	0.0022	R	R	0.0018	R	0.0041	0.004	R	R	R
Magnesium (mg)	79	9	11	10	10	25	28	R	113	20	354	72	R
Manganese (mg)	0.9	0.151	0.12	0.37	0.133	0.214	1.5	R	3.4	0.63	2.02	0.7	0.08
Molybdenum (mg)	0.026	R	R	R	R	R	0.015	R	0.036	0.003	R	R	R
Selenium (mg)	0.0017	R	0.001	0.0061	R	R	0.0203	R	0.0627	0.001	R	1	1
Zinc (mg)	0.53	0.22	0.11	0.28	0.18	0.24	1.3	R	3.4	0.58	5.06	1.17	R
Kilocalories	28.7	14	27	106.7	36.7	36.5	354.3	157.2	353.3	77.7	621.6	157.5	188.3
Harvest Index	1.42	1.17	2.2	1.2	1.33	1.6	2.2	2	2.5	1.25	3	1	1
Protein (kcal)	11.6	4	3.6	6.8	4.8	7.2	33.6	51.8	50.8	8.4	77.2	52.4	28
Carbohydrate (kcal)	14.4	8.3	17.2	97.2	29.2	28.4	310.8	44.2	280	68.4	96.4	44.8	154
Fat (kcal)	2.7	1.71	6.3	2.7	2.7	0.9	9.9	61.2	22.5	0.9	448	60.3	6.3
Water %	91.6	95.8	94	72.8	90.8	90.2	12	67.5	13	79.8	5.3	69.1	53.1

All values are for 100 gram raw product. R = unknown value.

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Table 3. Nutrient composition of edible products proposed for a CELSS

	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16	x17	x18
	Soy	Tofu	Tempeh	Soy	Roast	Baked	Boiled	Baked	Boiled	Boiled	Cooked	Sunflow	Cooked	Wheat	Boiled	Lettuce	Tomatoes	Wheat
	milk			sprouts	Soybean	Potatoes	Potatoes	Sweetpot	Sweetpot	Onions	Grbeans	seed	Rice	meal	Spinach			sprouts
Leucine (mg)	295	61	1063	664	3220	138	103	126	121	32	118	1659	131	67	231	70	33	R
Isoleucine (mg)	181	355	1000	394	1920	93	7	86	82	32	69	1139	76	434	152	75	21	R
Lysine (mg)	207	454	1125	552	2630	140	104	85	81	43	91	937	54	274	182	75	33	R
Threonine (mg)	136	232	77	458	1710	840	62	86	82	22	82	928	58	288	127	53	22	R
Tryptophan (mg)	51	131	282	181	575	360	27	21	20	13	20	348	28	123	40	8	7	R
Valine (mg)	175	359	979	442	1970	130	96	112	108	21	93	1351	107	468	168	62	23	R
Aromatic Amino Acids (mg)	327	23	1733	576	3550	187	140	174	169	45	113	1835	166	867	247	78	38	R
Sulfur Amino Acids (mg)	113	214	584	130	1172	65	49	56	54	23	41	945	91	373	90	28	20	R
Fiber (g)	0	0.1	2.99	2.3	5.38	0.7	0.4	0.8	0.9	0.4	1.4	4.16	0.1	1.8	0.88	0.53	0.5	2.2
Essen. Fatty Acids (g)	1.2	3	5.93	3.7	16.97	0	0	0	0.1	0.1	0.2	41.98	0.2	2	0.111	0.035	0.1	0.5
Vitamin A (ius)	40	0	69	11	2	0	0	21822	17054	0	666	50	0	0	8190	330	1133	0
Vitamin C (mg)	0	0	R	15	4.6	13	7	25	17	6	10	0	0	0	9.8	3.9	18	R
Vitamin E (ius)	R	0.74	R	0.03	R	0.03	0.04	4	4.5	0.2	0.01	32	0.01	0.89	R	0.4	0.34	R
Vitamin K (ug)	R	R	R	R	R	R	R	R	R	R	0.25	R	0	R	R	R	8	R
Vitamin D (ius)	R	0	R	0	R	0	0	0	0	0	0	0	0	0	R	R	0	0
Riboflavin (mg)	0.03	0.03	0.111	0.12	0.755	0.035	0.02	0.13	0.14	0.01	0.1	0.25	0.01	0.12	0.236	0.03	0.05	0.21
Niacin (mg)	0.2	0.1	4.63	1.1	1	1.64	1.3	0.6	0.6	0.1	0.6	4.5	0.4	4.4	0.49	0.187	0.6	0.9
Pantothenic Acid (mg)	0.26	R	0.355	0.93	0.473	0.555	0.51	0.65	0.53	0.13	0.07	0.7	0.13	1.1	0.145	0.046	0.25	R
Pyridoxine (mg)	0.02	R	0.299	0.18	0.225	0.347	0.27	0.24	0.24	0.18	0.06	0.8	0.04	0.39	0.242	0.04	0.05	R
Folic Acid (ug)	10.3	R	52	171.8	204.6	11	8.9	22.6	11	12.7	33	237	6	52	145.8	56	9.4	R
Biotin (ug)	2.1	R	53	R	R	0	0	4.3	4.3	0.6	0.5	R	1	9	R	R	1.5	R
Cobalamin (ug)	0	0	0.84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thiamin (mg)	0.08	0.06	0.131	0.34	0.427	0.11	0.1	0.07	0.05	0.04	0.07	0.11	0.02	0.66	0.095	0.046	0.06	0.01
Calcium (mg)	21	128	93	67	270	10	8	28	21	27	46	116	10	37	136	19	7	22
Phosphorus (mg)	48	126	206	164	649	57	40	55	27	23	39	705	28	386	56	20	23	150
Iron (mg)	0.8	1.9	2.6	2.1	3.95	1.4	0.3	0.5	0.6	0.2	1.3	6.77	0.2	4.3	3.57	0.5	0.5	R
Sodium (mg)	0	7	6	14	2	9	5	10	13	8	3	3	374	3	70	9	8	R
Potassium (mg)	196	42	367	484	1364	418	328	348	184	152	299	689	28	435	466	158	207	R
Copper (mg)	0.72	R	0.67	0.427	1.07	0.305	0.167	0.208	0.16	0.04	0.103	1.752	0.02	0.93	0.174	0.028	0.077	R
Fluorine (mg)	R	0	70	0	0	0.062	0.045	0.01	0.01	0.096	0.013	R	0.077	0.053	R	R	0.024	0.01
Iodine (mg)	R	R	1.43	R	R	0.0056	0.0056	0.006	0.006	0.0019	0.003	R	0.0007	0.0041	R	R	0.0026	R
Magnesium (mg)	R	111	70	72	228	27	20	20	10	0.11	25	354	8	113	87	9	11	R
Manganese (mg)	R	R	1.43	0.7	2.18	0.23	0.14	0.56	0.34	R	0.29	2.02	0.47	3.4	0.935	0.151	0.12	0.08
Molybdenum (mg)	R	R	R	R	R	0.026	0.019	R	R	R	0.021	R	0.039	0.036	R	R	R	R
Selenium (ug)	R	R	R	1	R	9	9	0.7	0.7	1.2	0.7	R	5.3	62	R	R	1	1
Zinc (mg)	0.3	0.6	1.81	1.17	4.77	0.32	0.27	0.29	0.27	0.18	0.36	5.06	0.4	3.4	0.76	0.22	0.11	R
Kilocalories	35.9	78.6	216.6	157.5	483.5	110.9	87.7	104.9	106.7	30.6	41.9	612	106.7	353.3	29.2	14	22.6	188.3
Protein (kcal)	13.6	31.2	77.7	52.4	158.2	9.2	6.8	6.8	6.8	3.6	7.6	91.12	10.4	50.8	11.88	4	3.6	28
Carbohydrate (kcal)	8.8	9.6	69.8	44.8	130.8	100.8	80	97.2	97.2	25.2	31.6	75	93.6	280	15	8.36	17.2	154
Fat (kcal)	13.5	37.8	69.1	60.3	194.5	0.9	0.9	0.9	2.7	1.8	2.7	446	2.7	22.5	2.34	1.71	1.8	6.3
Water %	92.4	84.8	54.9	69.1	80	71.2	77.5	77.5	72.8	92.2	89.2	5.36	72.6	13	91.21	95.89	94	53.1
Harvest Index (products only)	0.375	0.5	1.14	1	2	1.25	1.25	1.2	1.2	1.33	1.6	3	1.15	2.5	1.42	1.17	2.2	1
Harvest Index (byproducts)	0.276	0.367	0.84	1	1.47	1.11	1.11	1.09	1.09	1.2	1.38	1.8	0.847	1.53	1.26	1.11	1.6161.	1
Kilocalories (byproducts)	106.5	142.5	287.1		554	148.3	125.1	138	139.8	61.4	91.2	694.7	174.4	454.3	66.2	35.5	90.48	
Carbohydrate (kcal) (byproducts)	79.36	80.16	140.36		201.3	138.2	117.4	130.2	130.2	56	80.9	157.7	161.3	381	52	26.8	85.08	

All values are for 100 g raw product. R = unknown value.

The nutrient values listed in Tables 2 and 3 for all of the products, raw and edible, are fresh weights. In contrast, dry weight values were used in the original (four-product) series of models (see Appendix A). This may cause the solution values to appear considerably higher for the expanded models, compared with the original models, but if adjustments are made for water content, the discrepancy between the original and current series is not as great as it initially appears. Water content is provided in Tables 1 and 2 so that dry weight calculations can be made; however, it was decided that for the series of models analyzed in this report, the use of fresh weights was more appropriate. There is also some discrepancy due to the fact that the constraints employed in the current series of models are considerably more stringent than those used in the original (Appendix A) series, and so the amount of phytomass required to satisfy them is greater.

B. Constraint Determination

Prior to the development of the Raw Product Series of models, a preliminary model was developed in which the levels of carbohydrate and fats were varied. This was done in an attempt to determine what the optimal levels should be for these two essential dietary components, since their requirements could not be readily determined from the literature. (A level for protein is more easily set because an approximate optimal level of 10% is suggested by preliminary runs of the models, and a minimal level of about 4% can be extrapolated from the literature). In a CELSS, protein will be satisfied more easily than the other essential nutrients since many of the crops under consideration are composed predominantly of protein.

Carbohydrate at a level of 70% and fat at a level of 20% were found to be optimal by "dual price" analysis. Dual price analysis is an index built into the LINDO program which indicates the relative sensitivity of a constraint. The 70% carbohydrate and 20% fat levels resulted in a near equilibrium in dual prices for these two components; this means that the effort of satisfying requirements for both is about the same at these levels. In a sense, these levels could be considered equilibrium levels or the levels at which the least phytomass is required.

The above analysis was based on raw product data and was used throughout the Edible Product and Product/Byproduct Models. The levels determined can be altered at any time however and if new data become available, this method can be used to derive new values to replace the current constraints.

The first model diet of the Raw Product Model series, Model Diet 1, was designed to demonstrate what the minimal phytomass production requirements of a CELSS would be if the only nutrients constrained were the energy-yielding components: 3400 total kilocalories, with 70% from carbohydrate, 10% from protein, and 20% from fat. Essential amino acids (EAA) were also constrained. Model Diet 1 (see Table 4) predicts that the total minimal phytomass required to meet these constraints is approximately 1926 g/person/day. The crops selected were spinach, sunflower seed, rice, wheat sprouts, and sweet potatoes. The selection was not totally spontaneous; crop variety contraints for two of the five crops were introduced/forced into the models, on a basis of least cost in terms of waste phytomass. This was done to control for crop/product numbers between models in the three series. In addition to this model, other Raw Product Models (Model Diets 2 and 3) were developed which constrained for some of the more essential vitamins and minerals.

It became obvious in the early stages of model development that as each additional nutrient was constrained, the cost for satisfying many of the nutrient needs would be extremely high and it would not be possible to satisfy all of them. In the models that constrained more extensively for nutrients (not included in the tables or analyses), including the EAA, vitamins E, A, and C, the B vitamins (except B12), calcium, phosphorus, magnesium, manganese, zinc, potassium, copper, iron, and sodium, the phytomass requirements were extremely high. For example, phytomass requirements were in excess of 10 times the feasible level (which is about 1 kg/person/day) or 10 kg/person/day, which far exceeds the expected limitations of a proposed CELSS. Despite this high level of phytomass, the nutrient requirements were still not completely satisfied. In addition, many of the nutrients were present in toxic or near toxic levels. Each additional intensification of the constraints caused considerable increases in the phytomass and finally yielded an infeasible solution when any of the nutrients (i.e. fluoride), that will be present at very low levels in a CELSS, were constrained.

Based on this analysis, it can be concluded that a CELSS cannot feasibly meet all of the nutrient needs of a crew solely by means of crop production, and thus the most practical approach to developing a feasible model or models for a CELSS would be through devising models that constrain for the basic nutrients only: protein, fat, carbohydrate, and EAA. (In some cases, additional nutrients may still have to be constrained, however). The use of this approach inadvertently causes many of the other nutrient needs to be satisfied; the vitamins and minerals that are present at deficient levels or not at all (e.g., vitamins B12 and D) can then be supplemented. Most of the vitamin and mineral nutrients are met or are nearly met by the model diets discussed below.

In general, modification of protein, fat, and carbohydrate constraints can affect the total phytomass considerably. For example, increasing protein levels from 10 to 15% of total energy in the second series of models, the Edible Product Models, can decrease the phytomass requirement by as much as 30%. It is thus essential to keep in mind the relative sensitivity of the constraints.

C. Development of Model Diets

The phytomass production figures yielded by the more extensively constrained models, as discussed above, are obviously not feasible for a CELSS. Ideally, levels of approximately 1 kg/person/day have been projected to be within the capacity of a proposed CELSS. Although this value may increase considerably during the period preceding CELSS flight, it will be used here as a tentative guideline so that the CELSS model diets developed in this study will fall within the feasibility range of projected CELSS phytomass production capabilities.

The Raw Product series of models (Model Diets 1-3) were developed primarily for the purpose of comparison with the Edible Product Model Diets, in an effort to demonstrate that the Edible Product models have the capability of more accurately projecting the crop production requirements of a CELSS. Thus, for the purposes of this report, the Raw Product models will not be analyzed for surplus, deficiency, or supplement projection.

The number of products/crops in the models were expanded on the basis of increased variety in the diet, rather than on the basis of general intensification of nutrient constraints. In Model Diets 4 and 7 the solutions were composed of five crops/products and were increased to six and seven components by introducing additional crops/products which resulted in Diets 5 and 8, and 6 and 9. However, the original Model Diet 1 solution included only three crops—sunflower seed, sweet potatoes, and rice—which made it necessary to introduce two additional crops in order to maintain an equal basis for comparison with the models of the other series. Increasing variety in the diet does not necessarily always result in considerable phytomass increase; that is, the increase in phytomass may be only slightly greater than for a simpler, less diverse diet. The benefits, once they are defined, of increasing the variety of crops grown may therefore far outweigh the slight increases in phytomass that result.

In Model Diets 4-9 only Vitamin A and phosphorus were constrained along with the energy components (protein, fat, and carbohydrate) and EAA. In the initial runs of models 4-9, vitamin A was present at levels in excess of 200,000 ius, which made it necessary to constrain it at < or = 50,000 ius. Phosphorus was also constrained, in an effort to maintain it in a near 1:1 ratio with calcium.

Model Diet 2 demonstrates the effects of increased variety on phytomass. The number of crops is increased from five (rice, spinach, soy sprouts, sunflower seed and sweet potatoes) to six (wheat sprouts are added). The total phytomass increases from 1926 g/person/day to 1950 g/person/day. Slightly more of the vitamin and mineral needs are satisfied by Model Diet 2 than by Model Diet 1; requirements for EFA, Vitamins A and E, riboflavin, niacin, folic acid, phosphorus, iron, potassium, copper, magnesium, and manganese are all fully met. Deficiencies ranging from slight to near total arise for most of the remaining nutrients, including biotin, thiamin, calcium, sodium, iodine, molybdenum, zinc and selenium. Vitamins K, D, and B12 and fluorine require complete supplementation in Model Diet 2.

Model Diet 3 introduces a seventh crop, wheat, into the diet. The phytomass increases slightly, from 1950 to 1981 g/person/day. There is very little effect on the nutrient composition of the diet: only a slight increase in the levels of some vitamins and minerals.

As was mentioned earlier, the Raw Product Models were derived for the purpose of demonstrating, through comparison, the differences in phytomass production requirements between raw and consumable products, differences which enhance the validity and feasibility of CELSS nutritional modeling. The consumable product models are based on representative foods that can be prepared from each of the products. They represent basic food preparation and processing methods, such as boiling and baking, that a food could be subjected to, regardless of its role in a composite product. Composite products are not considered here. For example, fried foods are not included since they are a composite product, requiring the products of two crops. While the foods prepared in an actual CELSS will not be restricted to this list (the actual list will undoubtedly be considerably more extensive), it is necessary to select a representative list to form a basis determining what crops should be grown in a CELSS. For example, soybeans will be one of the crops of choice because it yields much more net product on a gram per gram basis (tofu, soymilk, and tempeh; see Appendix B) than any of the other crops and consequently will be an item of low cost to the system.

Model Diets 4-9 include 18 major products selected from the many possible products that can be produced from the 13 crops under consideration. Based on a comparison between the Raw Product Models (Model Diets 1-3) and the Edible Product Models (Model Diets 4-6) each of which are controlled for the number of crops and constraints, it can be concluded that more phytomass is required to produce edible foods than raw products at levels sufficient to meet human nutrient requirements. However, the crops selected are not the same for both series of models because of the differences in cost to the system.

In Model Diet 4, 3469 g/person/day of total phytomass would have to be produced in order to prepare actual edible foods, whereas Model Diet 1 demonstrated that only 1926 g/person/day of phytomass would be required to meet nutrient needs if raw products were consumed. Thus, there is an increase of approximately 45% or 1543 g/person/day in phytomass production requirements between raw and consumable product models consisting of five products. This is a significant amount, particularly when gross production figures are considered over 45- to 90-day growing periods.

Edible Product Model Diet 5 (six crops) requires 3540 g total phytomass, to meet nutrient needs, an increase of 1590 g or 45% over the 1950 g required by Raw Product Model Diet 2 (also six crops). Edible Product Model Diet 6 requires 1669 g less phytomass (3650 g) to meet nutrient needs than the seven crop/product Model Diet 3 (1981 g) does. Therefore, a phytomass requirement increase of 45% is projected by the Edible Product Models compared with the

Raw Product Models, when controlled for.factors of variety and nutrient requirements.

The five crops selected in Model Diet 4 were selected spontaneously. They were expanded in Model Diet 5 to include one additional crop, onion. It was selected for introduction into the model on the basis of least marginal cost, as was the case with all of the models. Model Diet 5 was expanded on the same basis by adding lettuce which results in Model Diet 6. In summary the effect of introducing (forcing) these crops into the models was the increase in the phytomass requirement from 3469 g/person/day (Model Diet 4) to 3540 g (Model Diet 5) to 3650 g (Model Diet 6).

D. Improvement of Yields

The most practical, and possibly the only, approach to improving net energy yields and decreasing net phytomass production requirements in a CELSS is to convert cellulosic byproducts into edible glucose products. Incorporating the glucose from the cellulose fraction into the edible products can significantly improve the total yield while decreasing the overall cost to the system. The most favorable rates of saccharification for cellulose reported to date are approximately 90%, achieved with the Purdue Process developed by Michael Ladisch of Purdue University (see Appendix B).

Model Diets 7-9, the Product/Byproduct Models, include waste phytomass from the cellulosic fraction of each plant. These models have demonstrated the energy value of utilitarianism in a CELSS and the effect waste phytomass conversion can have in terms of increasing the feasibility of meeting human nutrient needs while minimizing phytomass. Waste phytomass conversion could be a significant benefit, probably the most significant in terms of attempying to economically meet human nutrient needs during long-term spaceflight. Whether or not it is technologically feasible is another question that will require additional research.

Actual cellulose composition values were available for soybeans, wheat, potatoes, and sweet potatoes. The other cellulosic values are averages, whose derivation is described in Appendix B. Incorporation of the cellulosic phytomass into the product models results in a considerable decrease in the total phytomass production requirement. Table 3 gives the increased carbohydrate and kilocalorie yield that results from incorporation of cellulosic glucose into the products. As can be seen in Table 3, the net edible carbohydrate yield increases by as much as nine times the level found originally in the products; a considerable contribution to the total energy in the diet can therefore be made by increasing the carbohydrate content. The amounts of total phytomass in Model Diets 7-9 show a decrease compared with Model Diets 4-6. The total amount of phytomass required in Model Diet 7 is 1226 g/person/day total crop production, for five spontaneously selected crops (soymilk, tofu, sweet potatoes, sunflower seed, and rice). This represents a decrease of approximately 282% in the total phytomass production requirement, compared with the five-crop Model Diet 4 requirement of 3469 g/person/day. Corresponding decreases of 276%, when comparing Model Diets 5 and 8 (six crops), and 283% when comparing Model Diets 6 and 9 (seven crops) are found.

A related subject is that of production yields, or the ratio of yield of raw product to edible product. The ratio of soybean to soymilk production on a gram per gram basis is 1:3.62 when the cellulosic fraction is included. Despite the fact that soybeans were selected in the solution of the Product/Byproduct Models on the basis of their capacity to produce as much as 3.62 times their raw yield in product, it should be possible, at least theoretically, to process and prepare the designated amount of soybeans in any way and still be able to provide nutrients at the same level as with soymilk. But, according to the nutrient compositional values that are used to construct these models, this is not quite true. This may be because the nutrient analyses that provided the data were performed by different sources; it may also be due to differences in composition from one plant to another and/or from one processing method to another.

It is clear that production yields should be factored into CELSS nutritional models since, despite any slight discrepancies that may develop, they are considerably more accurate than straight harvest indices. Cooking and processing methods do alter nutrient composition significantly, and an awareness of the extent to which this happens is essential when designing optimal CELSS diets.

E. Methods of Incorporating Variety

What actually constitutes a varied diet is relative by its very nature, and what constitutes a varied CELSS diet is even more relative. No real basis currently exists for determining or defining a varied diet. The initial solution selected by Model Diet 7 includes four crops and is based on five of the products that could be derived from those crops. Whether or not this combination of crops could provide enough variety to satisfy human aesthetic needs is not presently known as variety is a very subjective concept, and the question of food preference is even more subjective. The possibilities that could result from this combination of crops may be very limited or they may be nearly infinite. The purpose at this time is to establish the relationship that exists between increasing variety and increasing phytomass.

With each increment in crop number, the potential for dietary variety increases. The models represented here have been increased to include up to six crops, (seven products). The method of selecting the six crops was primarily designed to demonstrate the increased phytomass requirement that results from increasing variety. The actual phytomass increase that occurs in any given diet will depend on the particular crop selected, since each crop has different marginal costs and nutrient values. The number of crops that will eventually be determined to be optimal for a CELSS will depend on many factors, some of which are outside of the scope of this report.

Variety can be introduced into the model in a number of ways. The first method is by forcing additional products into the diet on the basis of random choice or preference. While this method basically defeats the purpose of spontaneous optimization and minimization of phytomass production by the simplex method (utilized in LINDO), it would be valuable in the sense that a projection of the cost in phytomass required to produce that particular crop/product can be made.

The most effective method for increasing dietary variety is by adding new products based on the least marginal cost; this indicates what products can be introduced into the solution while increasing the phytomass requirement as little as possible or not at all. The amount of new product can be and often is quite minimal and it may have to be increased considerably at some cost to the system, but by using the least marginal cost or reduced cost method, it is possible to introduce those crops that will be most economically feasible (those that increase the phytomass the least). It is also possible to introduce a constraint that designates the number of products (crops) required in the solution. This approach yields the same results as the aforementioned method. Model Diets 5, 6, 8, and 9 are based on the method of introducing additional constraints that increase the variety whereas Model Diets 4 and 7 are not; they are spontaneous, i.e., they were selected by LINDO without additional constraining.

All of the model diets demonstrate a positive correlation between increasing phytomass and increasing variety. For example, in Model Diet 5 the total phytomass requirement is increased slightly, compared with Model Diet 4, by introducing onion into the model. Variety is increased and the total required phytomass production increases by 71 g from 3469 to 3540 g (this includes 1537 g of total potato production, 292 g of sweet potatoes, 143 g of sunflower seed, 670 g of rice, and 50 g of onions). In both Diets 4 and 5 the constrained nutrients are satisfied with little surplus and there are only minor changes in the dietary composition of the vitamins and minerals. In Model Diet 6, lettuce is introduced on the same basis and the total phytomass requirement increases to 3650 g/person/day (1596 g is derived from potatoes, 291 g from sweet potatoes, 143 g from sunflower seed, and 433 g from wheat meal). The increase in variety that results from the addition of crops/products in the Product/Byproduct series of models (Diets 7-9) increases the total phytomass requirements from 1226 g/person/day (Model Diet 7, five crops/products), to 1281 g/person/day (Model Diet 8, six crops/products), to 1287 g/person/day (Model Diet 9, seven crops/products). These results show that the increased cost to the system when variety is increased is not considerable. In most cases it is less than 5% for each increment if measured in terms of energy. This suggests that if variety is determined to be necessary in a CELSS diet, the extra cost involved will not make its achievement unattainable.

The results also show that the Product/Byproduct models compare favorably with the Edible Product models in terms of variety as well as nutrient composition and total phytomass expenditure. It should be noted that the discrepancy that appears to result between the phytomass requirement and the total when the crops are added together is a result of the production costs in terms of waste phytomass. If the total waste from the plant could be utilized, the addition of crops would be equal to the predicted phytomass requirement.

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Table 4. Composition of model CELSS diets.

	Raw Product Models			Edible Product Models			Product/Byproduct Models		
	Model Diet 1	Model Diet 2	Model Diet 3	Model Diet 4	Model Diet 5	Model Diet 6	Model Diet 7	Model Diet 8	Model Diet 9
Selected Crops/Products	1 4 7 11 13	1 4 711 1213	147911 1213	6791213	679101213	67910121316	1281213	128121317	12812131417
Total Phytomass	1926	1950	1981	3469	3540	3650	1226	1281	1287
Ess. Amino Acids (mg)									
Leucine (mg)	2822	3070	3383	5418	5408	5420	6211	6217	5730
Isoleucine (mg)	1867	2006	2208	3043	2992	2880	3946	3954	3851
Lysine (mg)	1597		1955	3766	3766	3996	3838	3864	3633
Threonine (mg)	1791	1693	1825	7874	7323	6145	3062	3070	2996
Tryptophan (mg)	551	623	680	3284	3050	2538	1195	1196	1165
Valine (mg)	2244	2395	2611	4662	4649	4659	4377	4373	4296
Aromatic Amino Acids (mg)	3063	3257	3666	4689	6679	6690	7057	7057	6907
Sulfur Amino Acids (mg)	2219	2232	2406	2980	2978	2976	3070	3063	3044
Fiber (g)	35.4	35.9	34.7	17.3	17.3	17.3	6	6	7.1
Ess. Fatty Acids (g)	56.6	54	54.4	61.7	61.7	61.6	62.6	62.5	62.6
Vitamin A (ius)	32648	31727	31634	50000	50000	50000	38593	38021	38092
Vitamin C (mg)	36.5	46	46	195	194	190.8	12.5	21.5	21.5
Vitamin E (ius)	46.4		44.6	20	20	20	3	3.33	4
Vitamin K (ug)	3.13	3.5	3.48	0	0	0	0	40	40
Vitamin D (ius)	0	0	0	0	0	0	0	0	0
Riboflavin (mg)	3.18	3.2	3.06	7.33	7.32	7.31	5.59	5.59	5.74
Niacin (mg)	18.7	18.9	20.2	32.9	32.8	33	10.7	10.9	12.7
Pantothenic Acid (mg)	1.54	1.97	2.51	10.54	10.61	10.83	4.19	4.3	4.34
Pyridoxine (mg)	1.45	1.51	1.69	5.61	5.66	5.7	0.65	0.66	0.81
Folic Acid (ug)	509	600	622	222	227	256	167	171	178
Biotin (ug)	9.8	27.5	32	19.33	19.3	19	30.8	31.5	31.9
Cobalamin (ug)	0	0	0	0	0	0	0	0	0
Thiamin (mg)	0.4	0.6	0.92	2.23	2.25	2.31	1.35	1.39	1.57
Calcium (mg)	540	572	569	430	442	451	465	468	447
Phosphorus (mg)	2903	2912	2961	0	0	0	415	408	290
Iron (mg)	12.1	13	15	24.4	23.7	47.1	18.4	18.7	19.5
Sodium (mg)	85.2	100	101	2655	2640	2572	2921	2801	2685
Potassium (mg)	1557	1813	2019	7306	7343	7466	3328	3446	3323
Copper (mg)	2.6	2.7	3.1	6.3	6.2	6.1	10	10	9.2
Fluorine (mg)	trace	trace	trace	trace	trace	trace	trace	trace	trace
Iodine (mg)	12.7	14	16	130.5	131	134.2	34.2	34.2	33
Magnesium (mg)	559	544	596	941.8	942	945.5	484	486.7	550.4
Manganese (mg)	5.4	5.6	7.3	9.7	9.7	9.7	6.2	6.1	7.7
Molybdenum (mg)	8.03	0.03	0.05	0.59	0.59	0.59	0.3	0.29	0.29
Selenium (mg)	0.027	0.027	0.057	173	174	178.8	41.3	40	69.8
Zinc (mg)	7.9	8.2	9.9	14.4	14.4	14.5	12.3	12.3	13.5
Kilocalories	3577	3554	3553	3400	3400	3400	3400	3400	3400
Protein	477	494	493	340	340	340	340	340	340
Carbohydrate	2380	2380	2380	2380	2380	2380	2380	2380	2380
Fats	680	680	680	680	680	680	680	680	680

Crops/Products: Model Diets 1-3

1 Spinach
4 Sweet potatoe
7 Rice
11 Sunflower
12 Soy sprouts
13 Wheat sprouts

Crops/Products: Model Diets 4-9

1 Soymilk
2 Tofu
6 Baked potatoe
7 Boiled potatoe
8 Baked sweet potatoe
9 Boiled sweet potatoe
10 Boiled onions
12 Sunflower
13 Cooked rice
14 Wheat meal
16 Lettuce
17 Tomatoes

Table 5. Nutrient Surplus/Deficiency of Model CELSS Diets.

Nutrient	Adjusted RDA	Surplus/Deficiency Diet 4	Surplus/Deficiency Diet 5	Surplus/Deficiency Diet 6	Surplus/Deficiency Diet 7	Surplus/Deficiency Diet 8	Surplus/Deficie Diet 9
Leucine (mg)	1200 mg	na	na	na	na	na	
Isoleucine (mg)	840 mg	na	na	na	na	na	
Lysine (mg)	840 mg	na	na	na	na	na	
Threonine (mg)	560 mg	na	na	na	na	na	
Tryptophan (mg)	210 mg	na	na	na	na	na	
Valine (mg)	980 mg	na	na	na	na	na	
Aromatic Amino Acids	1100 mg	na	na	na	na	na	
Sulfur Amino Acids (m	700 mg	na	na	na	na	na	
Fiber	none	na	na	na	na	na	
Essential Fatty Acids	7.5-150 g	na	na	na	na	na	
Vitamin A	5000-50000 ius	na	na	na	na	na	
Vitamin C	50-60 mg	na	na	na	37.5 D	28.5D	28.
Vitamin E	10-2200 ius	na	na	na	7.02 D	6.67 D	6.0
Vitamin K	2ug/kg/bwt	140 D	140 D	140 D	140 D	100 D	10
Vitamin D	400-1000 ius	400 D	400 D	400 D	400 D	400 D	40
Riboflavin	.6mg/1000 kcal	1.13 D	1.05 D	1.03 D	na	na	
Niacin	4.4mg/1000 kcal	na	na	na	4.26 D	4.06 D	2.2
Pantothenic Acid	4-7mg/day	na	na	na	na	na	
Pyridoxine	2.0mg/100g/protein	na	na	na	1.05 D	1.04 D	.8
Folic Acid	50 ug	na	na	na	na	na	
Biotin	50 ug/1000 kcal	150.67 D	150.7 D	151 D	139.2 D	138.5 D	138.1
Cobalamin	1-3 ug	3 ug D	3 ug D	3 ug D	3 ug D	3 ug D	3 u
Thiamin	.5mg/1000 kcal	na	na	na	.35 D	.31 D	.1
					na		
Calcium	12-1500 mg	770 D	757.4 D	749 D	735 D	731.5 D	75
Phosphorous	" "	1200 D	1200 D	1200 D	785 D	791.4 D	909.
Iron	10 mg	na	na	na	na	na	
Sodium	100-3300 mg	na	na	na	na	na	
Potassium	3510-3900 mg	na	na	na	182 D	64 D	18
Copper	2-3 mg	3.31 S	3.22 S	3.1 S	6.93 S	7 S	3.2
Fluorine	10-40 mg	10 D	10 D	10 D	10 D	10 D	1
Iodine	70 ug	60.5 S	61 S	64.2 S	35.8 D	35.8 D	3
Magnesium	300-350 mg	591.85 S	592 S	595.5 S	134 S	136.7 S	200.
Managanese	2.5-5.0 ug	4.7 S	4.7 S	4.67 S	1.24 S	1.1 S	2.7
Molybdenum	.1-.5 mg	.09 S	.09 S	.09 S	na	na	
Selenium	50-200 ug	na	na	na	na	na	
Zinc	15 mg	.6 D	.6 D	.5 D	2.7 D	2.7 D	1.
Kilocalories	3400	na	na	na	na	na	
Protein (kcal)	340	na	na	na	na	na	
Carbohydrate (kcal)	2380	na	na	na	na	na	
Fat (kcal)	680	na	na	na	na	na	

S=surplus D=deficiency. na = not applicable, not D or S.

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F. Analysis of Diets

The most comprehensive approach to analyzing these model diets is to evaluate them in terms of surplus and deficiency of key nutrients. This approach can provide a more realistic picture of what a diet based primarily on CELSS-produced crops, will be, especially in terms of special nutrient considerations. Special considerations include such factors as the increased importance of the balance between calcium and phosphorus and the levels of Vitamin A, perhaps the most critical nutrient relationships in a CELSS diet. Nutrient composition of all of the model diets is given in Table 4 while nutrient surplus/deficiency values are listed in Table 5.

In all of the solutions, the basic nutrient constraints for protein, fat, and carbohydrate were satisfied. There were no deficiencies and virtually no surpluses. In Model Diets 4-6, the level of protein in the solution is slightly greater than what was constrained, but the difference is slight and is not considered significant and thus is not shown in Table 4.

The EAA values are necessarily high, because of the protein constraint. As discussed in Section II, 'Spaceflight Effects and Nutrition,' the EAA's are generally nontoxic, providing that none are deficient. It will be recalled that there may be unique spaceflight EAA requirements. Spaceflight requirements are basically the same as terrestrial requirements, with the exception of a possible increased need for sulfur-containing amino acids and a possible increased need for leucine, which may help counter spaceflight-associated muscle atrophy. Leucine needs to be in some degree of balance with isoleucine, that is, in as close to a 1:1 balance as possible, or with isoleucine present at higher levels than leucine. Since isoleucine considerably exceeds leucine in these six model diets, there is no need to supplement with additional isoleucine or to introduce further constraints.

There is no recommended allowance for fiber in either terrestrial conditions or in spaceflight. The major criteria for determining safe levels would be to determine the effects of various levels of fiber on the binding of mineral nutrients, primarily calcium. This is another area requiring further experimentation.

EFA's are at a safe level in all six of the model diets. They range from 59.6-62.6 g, which is well within the range of 7.5 to 150 g/person/day recommended to meet human requirements for this nutrient.

Vitamin A, as mentioned in Section III C, had to be constrained at an upper limit of 50,000 ius, which is the level present in Model Diets 4-6. It is present in levels of 38,593, 38,021, and 38,092 ius in Model Diets 7-9. The levels in Model Diets 7-9 are preferable to the borderline toxic levels present in Model Diets 4-6.

More than 300% of the minimum recommended level of vitamin C is present in Model Diets 4-6, but this is still well under the 500 mg level that may result in adverse interactions with vitamin B12. In Model Diets 7-9, Vitamin C is 37.5, 28.5, and 28.5 mg deficient, respectively, in relation to the minimum recommended level of 50 mg (Table 5). But vitamin C at these deficiency levels is not excessively low, and enough would be present to prevent the major Vitamin C deficiency disorders that can occur. Supplementation may be beneficial.

Vitamin E is adequate in Model Diets 4-6 at levels of 19.89, 19.96 and 20.26 ius. In Model Diets 7-9, it is deficient in amounts of 7.02, 6.67, and 6.03 ius.

Both Vitamins K and D will have to be totally supplemented in a CELSS diet if it is determined that a need for them exists (see Section II for discussion).

Riboflavin is deficient at levels of 1.13, 1.05, and 1.03 mg in Model Diets 4-6. It is present in sufficient levels in Model Diets 7-9.

Niacin is present in adequate amounts in Model Diets 4-6, but is deficient at levels of 4.26, 4.06, and 2.26 mg in Model Diets 7-9.

Pantothenic acid is present at adequate levels in all diets.

Pyridoxine is present at appropriate levels in Model Diets 4-6 and is deficient at 1.05, 1.04, and .89 mg levels in Model Diets 7-9.

Folic acid is present at appropriate levels in all diets.

Biotin is deficient in all six of the model diets. It will require supplementation in amounts of 150.7, 150.7, 151.0, 139.2, 138.5, and 138.1 ug in Model Diets 4-9.

Vitamin B12 is not present in any of the model diets. It could only be present in a CELSS diet if a product such as tempeh, which has been subjected to fermentation, is introduced into the diet, thereby providing a source of B12. Therefore, for each of these model diets, there would be a need for total supplementation of Vitamin B12, if indeed it is determined to be a nutrient required at levels above which the body stores it.

Thiamin is available in Model Diets 4-6 at appropriate levels, but is deficient in amounts of .35, .31, and .13 mg in Model Diets 7-9.

Calcium requires supplementation in amounts of 770.0, 757.4, 749.0, 735.0, 731.5, and 752.0 mg in Model Diets 4-9, in order to attain the minimum 1200 mg level that is recommended for spaceflight.

Phosphorus requires total supplementation in Model Diets 4-6 and supplements of 785.0, 791.4, and 909.8 mg in Model Diets 7-9. It will be recalled that phosphorous along with vitamin A was constrained in Diets 4-9. It is preferable to have phosphorus levels deficient prior to supplementation in a CELSS diet and then to supplement it (as opposed to having excess levels in the diet which can not be reduced) because of the importance of controlling its intake and maintaining a 1:1 phosphorus to calcium ratio and because foods generally contain considerably more phosphorus than calcium. It is therefore fortunate that phosphorus will be at deficient levels in these diets.

Iron and sodium are present in appropriate amounts in all of the model diets.

Potassium has generally not been considered toxic because of the body's mechanisms for preventing its toxicity, although some toxic effects on the intestine at high levels have been reported. At the levels at which it is present in the CELSS model diets, it should not pose any substantial problems. Surpluses are present in Model Diets 4-6, but the levels are not nearly high enough to cause any significant effects. In Model Diets 7-9 potassium is deficient and would require supplementation of 182, 64, and 187 mg. At this point it does not appear to be necessary to constrain potassium, and unless it is determined to be more toxic in a space diet than is currently suspected, it will remain unconstrained at levels below 10 g.

Copper is not known to be toxic to humans, especially at the levels present in potential CELSS crops. There is no reason to further constrain it in the models because it is present in surplus amounts in Model Diets 4-9 of only 3.31, 3.22, 3.1, 6.93, 7.0, and 3.24 mg.

Fluoride will require total supplementation in all of the diets.

Iodine is present at appropriate levels in Model Diets 4-6, but it will require supplementation of at least 35.8, 35.8, and 37 ug in Model Diets 7-9. The levels in Model Diets 4-6 are higher than the RDA, but they are not toxic and may be more appropriate for spaceflight needs.

Magnesium in amounts less than 3 g/day are not considered to be harmful. Although the amounts present in Model Diets 4-9 are in excess of the 300-350 mg recommended level, they are still considerably below the level that is considered toxic.

Manganese, though present at surplus levels ranging from 1.2 to 4.7 ug in six of the model diets, is still not at levels considered to be toxic, since manganese is generally not toxic when exposure is by oral ingestion.

Molybdenum, in daily amounts as low as .54 mg, has been associated with significant urinary loss of copper, and it is recommended that it should never be supplemented because of its extreme toxicity at very low surplus levels. Molybdenum is in excess of .09 mg in Model Diets 4-6, but is safely within the recommended range in Model Diets 7-9. If any of the Model Diets 4-6 were chosen, it would be necessary to constrain molybdenum to bring it out of the toxicity range.

Selenium is present at appropriate levels in all of the model diets.

Zinc is slightly deficient in all of the diets. Supplements of .6, .6, .5, 2.7, 2.7, and 1.5 mg would be required in Model Diets 4-9. However, it was suggested in Section II that zinc at levels less than the RDA's should not create any problems and supplementation may not be required.

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G. Composition of Supplements

The minimal daily supplements for each of the model diets based on the above analysis are as follows:

Table 6. Composition of nutrient supplement for CELSS model diets

Nutrient	Model Diet 4	Model Diet 5	Model Diet 6	Model Diet 7	Model Diet 8	Model Diet 9
Vitamin C (mg)				37.5	28.5	28.5
Vitamin E (ius)				7.02	6.67	6.03
Vitamin K (ug)	140	140	140	140	100	100
Vitamin D (ius)	400	400	400	400	400	400
Riboflavin (mg)	1.13	1.05	1.03			
Niacin (mg)				4.26	4.06	2.26
Pyridoxine (mg)				1.05	1.04	0.89
Thiamin (mg)				0.35	0.31	0.13
Biotin (ug)	150.7	150.7	151	139.2	138.5	138.1
Cobalamin (ug)	3	3	3	3	3	3
Calcium (mg)	770	757.4	749	735	731.5	752
Phosphorus (mg)	1200	1200	1200		791.4	909.8
Fluorine (mg)	10-40	10-40	10-40	10-40	10-40	10-40
Iodine (mg)				35.8	35.8	37
Zinc (mg)	0.6	0.6	0.5	2.7	2.7	1.5
Potassium (mg)				182	64	187

As can be seen, a number of surplus/deficiency problems exist in these representative CELSS diets, problems that are characteristic of diets with limited food choices. Deficiencies are more desirable than surpluses, particularly with regard to potentially toxic nutrients, for the simple reason that while a deficiency can be corrected by supplementation; a surplus cannot be corrected once the crops have been selected and produced. As a result, except for those cases where energy-yielding components (fats, protein, and carbohydrate) are deficient, deficiencies are more desirable. Unfortunately, in order to meet certain nutrient constraints, some nutrients may become excessive to the point of becoming toxic, primarily Vitamin A and phosphorus.

There may be some concern about the artificiality of these model diets. To some extent, the diets are artificial, a situation that is probably inevitable if the model is adapted to include variety. In this case the problem may become an integer programming problem rather than a linear programming model. The problem that results from integer models is that of crop levels, which may in many cases be extremely low as a result of the variables being forced into the solution when in reality they are not as optimal as the variables selected in solution to the spontaneous models. The lower the variable, the less the cost, and thus the increased minimization of phytomass. The numbers that result from such a model may represent a level of product that is too small to be included in the daily menu. In some cases, it is so small that even when multiplied in value over the course of the growth cycle of the plants, it is not large enough to be useful. The most effective approach to this problem is to constrain a minimal level of the crop/product in the diet. Fifty grams was used in this study; this is a level of any crop/product that would be significant on a daily basis. If this is done via integer programming, the final result is the same as in the other diets in which additional linear constraints were added, based on the sensitivity analysis, because these products were also constrained at 50 g/person/day.

In an effort to demonstrate the meaning of the solutions resulting from the integer models, models were developed which constrained for five, six, and seven variables in the solution at a minimal level of 50 g/crop of edible phytomass. The results of these models were compared with those of the byproduct models containing the same number of variables in the solution. The composition of the solutions were identical, as predicted.

IV. MODEL BUILDING UTILITY (MBU)

At this point, it is difficult to say how realistic CELSS production capability projections are. Resources currently available permit estimates to be made with some degree of accuracy, but it is important to realize that with the current state of knowledge, a number of unknown variables exist that must be considered. For example, as discussed in Section II, the constraints necessary to produce an optimal spaceflight diet that will satisfy specific spaceflight needs may change as our knowledge of spaceflight nutrition grows and may differ considerably from the established terrestrial standards. Another factor is that the nutrient composition of space-grown foods may vary considerably from terrestrial values. These two items alone can greatly alter projections made by the models. If other factors change also, for example, improvements in the harvest indices of crop plants causing a different selection of crops, the total phytomass requirement could be considerably altered. If per meter^2 production yields continue to improve, then this could possibly offset any deficits that might arise as a result of declining nutrient quality of space-grown plants, assuming that the problem of inferior quality does arise. If such a problem does not develop, then the effect of improved yields will be evident in a decrease in the amount of space required to grow crops. If none of the indices discussed above undergo any improvement, but rather deteriorate instead, then the models will require further modification.

The key point, then, is that all of the major components of these models and any other models that could be developed are subject to change: nutrient values, harvest indices, production indices, and nutrient requirements. As CELSS technology continues to evolve, such changes are inevitable. All of the relationships considered here are dynamic relationships, and in order to eventually realize a more accurate projection of CELSS phytomass production needs, this dynamicism will have to be addressed.

In an attempt to accommodate the ever-expanding knowledge base yielded by spaceflight, CELSS, and nutritional research, and to more readily address many of the problems that arose during the preliminary modeling, a software program has been developed that is capable of processing new data on a continuous basis and that automatically generates new models based on these data. All data, including nutrient composition values, objective function coefficient values, harvest and production indices, and nutritional constraint values, are subject to change and can be easily modified by the program. The models generated by the new program can then be easily solved for new phytomass requirement projections at any time. This program, in effect, generalizes the CELSS nutritional model so that it is not necessary to continually develop models; rather, it is only necessary to update the nutrient database to which the program is linked; and the models will be generated by the program. The program, which is called the Model Building Utility (MBU), therefore accomodates change and allows for the continual updating and improvement of the basic CELSS nutritional model, as new data become available and new concepts are implemented.

Another important feature of the MBU is its menu-developing capability. The items currently included in the data sheets are single foods. Some of them are edible as such, but most can be combined with other products on the list to create composite products and, eventually, menus. The program that has been developed allows for projections of phytomass requirements for any diet under consideration, providing it is composed of the basic products included in the data sheets. If a food product is not included, it may be added.

This program therefore has the capability of analyzing both products already developed and new composite products that may be introduced, and of then projecting the phytomass requirement for these composite products. This appears to be a potentially useful method for dealing with the dynamic nature of CELSS nutritional questions.

The MBU program was written in Turbo Pascal (Borland) for the Apple MacIntosh personal computer. It was developed by Arthur Figueiredo of the Department of Operations Research, the George Washington University, Washington, D.C. through a project sponsored and supervised by the author. The program has the capability of accessing basic product data stored in spreadsheet programs; from these data, linear mathematical models are generated according to user needs and specifications.

A brief description of the MBU software follows.

MODEL BUILDING UTILITY

FILE MENU:

New - Reset all program pointers.
Save - Save currently defined model to a file.
Read - Read previously saved model from file.
Transfer - Transfer to another Macintosh application.
Quit - Return to Macintosh finder.

EDIT MENU:

Products - Modify objective function coefficients, define usage of product (in/out of model).
Nutrients - Modify right hand side values, define >, <, = or data constraints.
Import spreadsheet data - Specify save spreadsheet from which to collect model data.

BUILD MENU:

Create LINDO Model - Specify name of LINDO model to be created.
Percentage Constraints - Specify percentage constraints for data variables.
Manufacture Products - Allows users to put several basic products together into a composite product.

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Appendix A

Nutritional Models for CELSS

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I. INTRODUCTION

Long term habitation of space by humans requires a reliable and efficient means of insuring adequate supplies of food, air, and water. Transporting such supplies between earth and the space environment will be costly and time consuming, and on very long flights, it may be impossible. To address these concerns, the Controlled Ecological Life Support System (CELSS) Program of the National Aeronautics and Space Administration (NASA) is researching and initiating development of a system capable of producing and regenerating food, air, and water in the closed environment of a spacecraft. Activities to date have concentrated on establishing the feasibility of a CELSS by studying various aspects of the system such as food requirements, food production and food processing, waste management, and regeneration techniques.

This paper is an analysis of nutritional food requirements. Studies were carried out to determine optimal CELSS diets, based on nutritional content of various foods and minimum food production requirements of the various diets. In doing so, optimal food sources are examined. The assumptions and procedures that were used to determine the diets are outlined in Section 2 of the report followed by a summary of the results (Section III-IV) and a description of suggested future studies (Section VI).

II. PROCEDURES AND ASSUMPTIONS

For the purpose of this report, an optimal CELSS diet is defined as a diet that satisfies a set of caloric, protein, fat, and carbohydrate constraints, while allowing for the production of a minimum food biomass possible within these constraints.

Optimal diets were obtained by linear optimization. Two types of diets were studied: diets consisting solely of plants, and plant diets with chicken and eggs added. The types of food included in the plant-only diets were soybeans, wheat, potatoes, and peanuts. Chicken and eggs were then introduced into the problem as protein supplements. Chicken was selected due to its high feed efficiency, though other animals can be substituted or added to the problem in the same manner. The diets are based on daily consumption per person. Nutritional constraints were determined by recommended dietary allowances (RDA's) (1), which are listed in Table 1. The nutritional value of each food type was determined by the nutritional composition of foods and their biomass yields, as shown in Table 2. Biomass yields for plants reflect the maximum crop yields that have been achieved to date by researchers in the laboratory. The meat yield of chicken was estimated by assuming maximum usage and consumption of chicken parts (e.g., bones used for chicken stock). The egg yields was taken from The United States Department of Agriculture's Composition of Foods Handbook No. 8 (2).

III. PLANT-ONLY DIET

The initial plant models sought to minimize total plant biomass, while satisfying the general caloric, protein, fat, and carbohydrate requirements listed in Table 1. Separate calculations were made to determine the levels of more specific nutrient requirements. For protein, specific requirements are essential amino acids (EAA's) at the levels listed in Table1. The requirement for fat is linoleic acid at 3% of total calories; no specific requirement has been established for carbohydrate.

The calculations made indicate deficiences in linoleic acid and the EAA methionine. Consequently, the model was modified to determine minimum plant biomass, based on calories > 2800, linoleic acid > 3%, and methionine > 2.2 g, which are the respective RDA's. Results of this problem are shown in Table III. The values derived are 2800 calories, 14% protein, 7% fat, and 79% carbohydrate. In this model, linoleic acid and methionine met their RDA's. Other EAA's are 100% to 300% of their RDA's. A human diet can safely consist of up to 300% of the RDA's of EEA's. In the plant model, the RDA exceeds 300% for two EEA's: lysine (350% of its RDA) and threonine (325% of its RDA). Further studies should be done to determine th effects of marginal excesses of these EAA's.

The diet described above relies on large amounts of soybeans to satisfy the linoleic acid and methionine requirements. This use of soybeans causes protein to remain at about the same level, 7%, but fat is lower than its RDA, and carbohydrate is much higher than recommended. Although fat intake as high as 42% of total calories is permissible, the only established fat requirement is for linoleic acid, which is satisfied by this diet. As there have not been any substantive claims to the contrary, it will be accepted as valid that there is not a toxic level for carbohydrate in healthy individuals providing all other nutrient requiremnts are satisfied.

IV. PLANT, CHICKEN, AND EGG-DIET

Chicken, meat, and eggs were then added to the plant model as protein supplements, with the objective still remaining to minimalize total food biomass, based on caloric, linoleic acid, and methionine RDA's. In addition, the plant, chicken, and egg-model requires that total food biomass be no more than 20% chicken and egg biomass. This constraint prevents developing a diet with chicken products as the primary food source, which is undesirable since the purpose of this problem is to study animal products as supplements to the plant diet.

A detailed analysis of chicken feed requirements for five different plant, chicken, and egg combinations was performed (Table 4). These combinations differ in terms of the amount of chicken and eggs allowed in each diet. In the first combination, chicken and eggs are forced into the diet. Chicken was specified to be 37 g per day, which means at least one broiler will be available for consumption at a given time. Eggs were specified at one-half egg per day, which is equivalent to 22.5 g per day, assuming one large egg weighs 50 g. In the second diet combination, chicken and eggs are again forced into the diet. There exist only lower bounds on the amount of both chicken and eggs. At least 37 g of chicken and one-half egg are allowed. In the third combination, chicken and eggs are not forced into the diet. In the fourth combination, chicken and eggs are forced into the diet, but there exist restrictions of exactly 37 g of chicken and one-half egg per day. In the fifth combination, only eggs are produced to provide one-half egg per day. There is no breeding of chickens, but the egg-laying chicken is consumed at the end of its egg production cycle. In addition to the data in Table 2, chicken type, body weight, life span, egg production rate, and feed consumption are necessary. This information is shown in Table 5.

Optimal diets for the five diet combinations are shown in Tables 6a through 6e. Specific nutritional requirements of the chickens were not incorporated into the model; a separate analysis of overall chicken feed requirements and numbers of chickens required for each diet is shown in Table 7. The number of total chickens required for each diet is the sum of: (a) broilers for human consumption, (b) hens producing eggs for human consumption (c) hens producing broilers, (d) hens producing egg-laying chickens, and (d) roosters. The total chicken feed requirement is the sum of feed consumed daily by each type of chicken. Since all diets satisfy human nutritional requirements, the values of the five diets were assessed based on the food biomass for human consumption to chicken feed biomass ratios. These biomass ratios are more desirable than those yielded by previously constructed models since they imply low penalties for chicken products in the diet. Asymptotic values of the ratios were found by determining chicken and feed biomass requirements as crew sizes approched infinity. Ratios were approximately 1, 1, 1.5, 3, and 7 for diets one through five, respectively. In terms of the number of chickens required, total food and chicken feed biomass, and nutritional composition of diets most closely approximating that of the RDA's, diets five and four are the most attractive.

Protein, fat, carbohydrate, and linoleic acid content were the same for the five diets. As can be expected, protein and fat content is higher for diets with large amounts of meat. Although food biomass increases as the quantity of chicken and eggs in the diet decreases, total food and chicken feed biomass decreases as the amount of chicken and eggs decrease.

Although the amount of protein varies only slightly between the five diets, there are fewer cases of excessive EAA's in diets four and five than in diets one and two. Diets one and two have more than 300% of the RDA's of isoleucine, leucine, lysine, threonine, and valine, with amounts ranging from approximately 320% to 520% of their RDA's. Diet three exceeds the leucine, lysine, and threonine requirements by containing 340% to 490% of their RDA, while diets five and six contain 325% to 380% of the RDA's of lysine and threonine. These results are due to the fact that the first three diets have much larger amounts of chicken and eggs, which have high concentrations of EEA's, than diets five and six, which have very limited amounts of chicken and eggs. The excess of lysine and threonine is characteristic of the all-plant and primarily plant diets. There are no significant nutritional benefits to the large amount of chicken and eggs in the diet. Diets with 37 g of chicken and/or 22.5 g egg per day per person provide nutrients in approximately the same proportions as diets with large amounts of chicken and eggs with much smaller total food and chicken feed biomass requirements and there are fewer cases of excessive EAA's.

V. DISCUSSION OF RESULTS

As a result of the analyses described above, the three diets listed below are the most favorable in terms of total biomass and nutritional characteristics of diets studied to date.

1) Plant-only diet

2) Plant; 22.5 g eggs per person per day; 3.67 g chicken per person per day (obtained by eating egg-laying chicken)

3) Plants; 22.5 g eggs per person per day; 37 g chicken per person per day

Minimum food biomass requirements of the plant-only diet are 925 g per person per day. Total biomass, including food and chicken feed, increases to 1380 g per person per day when one-half egg and consumption of the egg laying chicken are allowed. Biomass reaches 1590 g per day when one half egg and 37 g chicken per day are allowed. The yields of the diets , based only on food biomass, are 74%, 77%, and 84% for plant, plant and egg, and plant, egg, and chicken diets, respectively. The yields based on food and feed biomass, assuming 90% consumption of feed biomass by chickens, is approximately 81% and 84% for egg and egg-with-chicken diets, respectively. Therefore, it is plausible that animal products can be incorporated into a CELSS diet with a 45% to 70% increase in total human and animal food biomass relative to a purely plant diet, resulting in increased yield and variety in the diet.

VI. FUTURE STUDIES

These studies only begin to address the types of questions that need to be answered as environmental support systems for spacecraft are designed and tested. Future feasibility studies of CELSS will need to examine additional nutritional requirements (e.g., minerals and vitamins), conversion of nonedible biomass to edible products, and system parameters (power, volume, and area) implied by feasible CELSS diets. These studies will naturally result in additional food sources and diet options, options that will be based on more detailed feasibility studies. The nutritional requirements of the diets will also need to incorporate such factors as the body's ability to store certain nutrients for extended periods of time, since such nutrients can possibly be specified at levels lower than their RDA's. And crop failure will have to be taken into consideration: types and quantities of foods that should be stored in such an emergency must be decided. A determination of the possible variety and appeal of foods vis-a-vis nutritional and system constraints must also be made at some point.

Most importantly, these studies should be carried out in conjunction with development and testing of food processing, and waste management requirements for CELSS, since these efforts are necessarily interdependent.

VII. LITERATURE CITED

1. The National Research Council, Recommended Dietary Allowances, Ninth Edition, 1980.

2. United States Department of Agriculture, Composition of Foods, Handbook No. 8, June 1979.

3. The National Research Council, Nutrient Requirements of Poultry, Eighth Edition, 1984.

Recommended Daily Allowances*

Item	RDA
Caloric	2800 clories
Protein	12% of total calories
Histidine	2.0 g
Isoleucine	1.4-1.68 g
Leucine	2.2-2.24 g
Lysine	1.6-1.68 g
Methionine	2.2 g
Phenylalanine	2.2 g
Threonine	1.0-1.12 g
Trytophan	0.42-0.5 g
Valine	1.6-1.99 g
Fat	42% of total calories
Linoleic Acid	3% of total calories
Carbohydrate	46% of total calories

*Reference 1

Table 1. Reccomended Daily Allowances (RDA) for caloric, protein, fat, and carbohydrate intake. Values are for a 70 kg male.

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*Composition of Foods

Item Per 100 g Biomass	Soy Beans (Green-Raw)	Wheat (Hard Red Spring)	Potatoes (Raw Flesh)	Peanuts (Dry Kernels)	Chicken (Raw Flesh&Skin)	Eggs (Raw-Wheel)
**yield (g)	50	40	80	20	85	88
calories (kcal)	498	498	413	395	675	624
Protein (g)	39.846	16.092	9.839	27.499	54.69	47.74
Histidine	1	0.25	0.25	1	1.647	1.152
Isoleucine	1.8	0.5	0.375	1	2.706	2.985
Leucine	2.8	1	0.625	2	4	4.192
Lysine	2.4	0.5	0.625	1	4.471	3.225
***Methionine	0.8	0.5	0.25	1	2.118	2.614
Phenylalnine	1.8	0.75	0.375	1.5	2.118	2.698
Threonine	1.6	0.5	0.375	1	2.235	2.344
Trytophan	0.4	0.25	0.125	0.5	0.588	0.763
Valine	1.8	0.75	0.5	1	2.706	3.437
Fat (g)	20.923	2.529	0.475	52.683	44.28	43.85
Linoleic Acid	11.597	1.149	0.204	16.641	9.5	5.702
Carbohydrates	34	79.425	85.456	17.333	0	4.72

*Reference 2. Dry Weight of Foods
**Research Data
***Methionine Composed of Methionine and Cystine

Table 3

Item	Soybeans	Wheat	Potatoes	Peanuts	Total
Amount In Diet					
Biomass (g)	176.5	0	747	0	923.5
Yield (g)	88.25	0	597.6	0	685.85
Protein	144.73	0	239.04	0	13.71% of calories
Calories					
Fat	171.21	0	29.88	0	7.18% of calories
Calories					
Carbohydrates	123.55	0	2091.6	0	79.11% of calories
Calories	439.49		2360.52		
Histidine (g)	0.945	0	1.49	0	2.435
Isoleucine	1.548	0	2.24	0	3.788
Leucine	2.47	0	3.74	0	6.21
Lysine	2.12	0	3.74	0	5.86
Methionine	0.71	0	1.49	0	2.2
Phenylalnine	1.59	0	2.24	0	3.83
Threonine	1.41	0	2.24	0	3.65
Trytophan	0.35	0	0.75	0	1.1
Valine	1.59	0	2.94	0	4.58
Linoleic Acid	95.31	0	14.94	0	3.94% of calories
Calories					

Table 4
PLANT, CHICKEN, AND EGG COMBINATIONS

Problem

Minimize: Total Plant, Chicken, and Egg Biomass
Such That: Total Calories > 2800
Linoleic Acid > 3% of Total Calories
Methionine (including cystine) > 2.2 g

Additional Constraints (daily)

Combination1: Eggs = 22.5g (1/2 egg per day)
Chicken > 37 g (at least one broiler available for consumption)
Combination 2: Eggs > 22.5 g
Chicken > 37 g
Combination 3: Chicken and eggs not forced Into diet: no lower bounds on chicken products
Combination 4: Eggs = 22.5 g
Chicken = 37 g
Combination 5: Eggs = 22.5 g
Egg-laying chicken consumed when egg laying cycle completed. Results in 3.67 g meat.

Table 5

	Broilers	Egglayers	Hens	Roosters
Average Weight	2000 g	1620 g	1140 g	1495 g
Average Feed Consumption	110 g	110 g	144 g	188 g
per day				
Egg Production Rate (average)	-	50%	57%	-
over Life Span				
Life Span	40 weeks	70 weeks	40 weeks	40 weeks
*Reference 3				

Table 6a, Combination 1

Item	Soybeans	Wheat	Potatoes	Peanuts	Chicken	Eggs	Total
Amount in Diet							
Biomass (g)	0	0	620.09	0	132.52	22.5	775.11 g
Yield (g)	0	0	496.07	0	112.64	19.8	
Protein	0	0		0			
Calories	0	0	198.43	0	253.11	38.97	17.52%
Fat	0	0		0			
Calories	0	0	24.8	0	463.82	80.75	20.33%
Carbohydrates	0	0		0			
Calories	0	0	1736.25	0	0	3.85	62.15%
Histidine (g)	0	0	1.24	0	1.86	0.23	3.33 g
Isoleucine	0	0	1.86	0	3.05	0.59	5.5 g
Leucine	0	0	3.1	0	4.5	0.83	8.43 g
Lysine	0	0	3.1	0	5	0.63	8.73 g
Methionine	0	0	1.24	0	2.39	0.52	4.15 g
Phenylalanine	0	0	1.86	0	2.39	0.24	3.49 g
Threonine	0	0	1.86	0	2.52	0.47	4.75 g
Tryptophan	0	0	0.62	0	0.66	0.16	1.48 g
Valine	0	0	2.48	0	3.05	0.68	6.21 g
Linoleic Acid	0	0		0			
Calories	0	0	12.4	0	99.39	122.28	4.37%

Table 6b, Combination 2

Item	Soybeans	Wheat	Potatoes	Peanuts	Chicken	Eggs	Total
Amount in Diet							
Biomass	0	0	618.36	0	37	117.59	772.95
Yield (g)	0	0	494.69	0	31.45	103.48	629.68
Protein	0	0		0			
Calories	0	0	197.88	0	70.67	203.67	16.87
Fat	0	0		0			
Calories	0	0	24.73	0	129.5	422.03	20.58
Carbohydrates	0	0		0			
Calories	0	0	173.41	0	0	0	62.66
Histidine	0	0	1.24	0	0.52	11.18	2.94 g
Isoleucine	0	0	1.86	0	0.85	3.06	5.77 g
Leucine	0	0	3.09	0	1.26	4.35	8.7 g
Lysine	0	0	3.09	0	1.41	3.29	7.79 g
Methionine	0	0	11.24	0	0.67	2.7	4.61 g
Phenylalanine	0	0	1.86	0	0.67	2.82	5.33 g
Threonine	0	0	0.186	0	0.7	2.47	5.03 g
Trytophan	0	0	0.62	0	0.19	0.82	1.63 g
Valine	0	0	2.47	0	0.85	3.53	6.85 g
Linoleic Acid	0	0		0			
Calories	0	0		0	27.75	54.8	3.39%

Table 6c, Combination 3

Item	Soybeans	Wheat	Potatoes	Peanuts	Chicken	Eggs	Total
Amount in Diet							
Biomass (g)	112.441	0	779.236	0	10.654	0	902.331 g
Yield (g)	56.22	0	623.39	0	9.06	0	68.67 g
Protein		0		0		0	
Calories	92.2	0	249.36	0	20.35	0	12.93%
Fat		0		0		0	
Calories	109.07	0	31.17	0	37.29	0	6.34%
Carbohydrates		0		0		0	
Calories	78.71	0	2181.86	0	0	0	80.73%
Histidine	0.56	0	1.56	0	0.15	0	2.27 g
Isoleucine	1.01	0	2.34	0	0.25	0	3.60 g
Leucine	1.57	0	3.9	0	0.36	0	5.83 g
Lysine	1.35	0	3.9	0	0.4	0	5.65 g
Methionine	0.45	0	1.56	0	0.19	0	2.20 g
Phenylalanine	1.01	0	2.34	0	0.19	0	3.54 g
Threonine	0.9	0	2.34	0	0.2	0	3.44 g
Trytophan	0.22	0	0.78	0	0.05	0	1.05 g
Valine	1.01	0	3.12	0	0.25	0	4.38 g
Linoleic Acid		0		0		0	
Calories	60.72	0	15.58	0	7.79	0	3.01%

Table 6d, Combination 4

Item	Soybeans	Wheat	Potatoes	Peanuts	Chicken	Eggs	Total
Amount in Diet							
Biomass (g)	53.392	0	735.275	0	37	22.5	848.167 g
Yield (g)	26.696	0	588.22	0	31.45	19.8	666.167 g
Protein		0		0			
Calories	43.78	0	235.258	0	70.67	38.97	13.88%
Fat		0		0			
Calories	51.79	0	29.411	0	129.5	80.75	10.41%
Carbohydrates		0		0			
Calories	37.374	0	2058.77	0	0	3.85	75.00%
Histidine (g)	0.286	0	1.47	0	0.52	0.23	2.506 g
Isoleucine	0.468	0	2.21	0	0.85	0.59	4.118 g
Leucine	0.75	0	3.68	0	1.26	0.83	6.53 g
Lysine	0.64	0	3.68	0	1.41	0.63	6.36 g
Methionine	0.21	0	1.47	0	0.67	0.52	2.87 g
Phenylalanine	0.468	0	2.21	0	0.67	0.24	3.588 g
Threonine	0.43	0	2.21	0	0.7	0.47	3.81 g
Tryptophan	0.11	0	0.74	0	0.19	0.16	1.20 g
Valine	0.468	0	2.94	0	0.85	0.68	4.938 g
Linoleic Acid		0		0			
Calories	28.832	0	14.706	0	27.75	10.44	3%

Table 6e, Combination 5

Item	Soybeans	Wheat	Potatoes	Peanuts	Chicken	Eggs	Total
Amount in Diet							
Biomass (g)	103.262	0	759.324	0	3.67	22.5	888.75g
Yield (g)	51.53	0	607.459	0	3.12	19.8	682.01g
Protein							
Calories	84.67	0	242.98	0	7.01	38.97	13.34%
Fat Calories	100.164	0	30.373	0	12.85	80.75	8100%
Carbohydrates							
Calories	72.283	0	2126.107	0	0	0	78.65%
Histidine (g)	0.533	0	1.52	0	0.05	0.23	2.35g
Isoleucine	0.906	0	2.28	0	0.08	0.59	3.86g
Leucine	1.45	0	3.8	0	0.12	0.83	6.20g
Lysine	1024	0	3.8	0	0.14	0.63	5.81g
Methionine	0.41	0	1.52	0	0.07	0.52	2.52g
Phenylalanine	0.43	0	2.28	0	0.07	0.24	3.52g
Threonine	0.83	0	2.28	0	0.07	0.47	3.65g
Tryptophan	0.21	0	0.76	0	0.02	0.16	1.15g
Valine	0.93	0	3.04	0	0.08	0.68	4.73g
Linoleic Acid							
Calories	55.761	0	15.186	0	2.75	3.85	3.00%

Table 7, Chicken Feed Analysis*

Item	Combination 1	Combination 2	Combination 3	Combination4	Combination
Grams Chicken Biomass	132.522	37	127.715	37	
Number of Broilers Satisfy Chicken Biomass	4.24	1.18	4.09	1.18	
Number of Hens to Produce Broilers	1	1	1	1	
Grams Eggs Biomass	22.5	117.59	0	22.5	22.
Number of Hens to Produce Egg Laying Chickens	1	1	0	1	
Number of Roosters (3 hens per rooster)	1	1	0	1	
Total Number of Chickens	8.14	8.88	5.09	5.08	2.
Feed Yield Required to Support Total Chickens (90% yield assumed)	1041	1123	782	662	44
Feed Biomass Required	1157	1248	869	736	49
Human Feed:Chicken Feed Biomass (ratio)	0.69	0.64	0.92	1.09	1.6

*Combinations defined in Table 4. Data based on results in Table 6 and characteristics in Table 5

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Appendix B

BYPRODUCT CONVERSION

LINEAR MODELING

DERIVATION OF HARVEST/PRODUCTION INDICES FOR RAW PRODUCT, EDIBLE PRODUCT, AND PRODUCT/BYPRODUCT MODELS

BYPRODUCT CONVERSION
LINEAR MODELING; DERIVATION OF HARVEST/PRODUCTION INDICES FOR RAW PRODUCT, EDIBLE PRODUCT, AND PRODUCT/BYPRODUCT MODELS

In linear programming the central equation is called the objective function. The objective function is in effect the statement of purpose of the model. In the group of models developed for this report the objective function is a minimization statement which requires that the phytomass be minimized while the constraints are met. It is essential to have a coefficient for each variable represented in the objective function. The coefficients used represent cost to the system; they are equivalent to cost in an economic model. In these models they represents the cost in waste phytomass that occurs when a unit of edible raw or processed product is produced. The harvest index, which is used in the raw product models as the objective function coefficient, is the ratio of edible to nonedible mass for a crop plant. The production indices are derived from the harvest indices and the production yield, which is the amount of finished product derived per unit of raw product. For example, for soybeans: the harvest index is .5, which means that the edible portion of the plant is 50% of the total; the other 50% is lignin-hemicellulose-cellulose (LHC), which is not digestible by humans unless first treated to break down the chemical bonds yielding glucose.

Digestion of the glucose polymers composing the cellulosic portion of the LHC is considered here only in terms of possible effects on total phytomass production requirements. The most optimistic yields reported to date (90%, by the Purdue Method) are used in these models. (For further information, see References 1-3) The soybeans example was used so that the relative value of utilizing the cellulosic fraction of the LHC would be demonstrated. To better understand the actual method of derivation, soymilk can be taken as an example: soybeans are 50% LHC and of this amount 39.2% is cellulose. It is assumed that 90% of the cellulose will be converted into glucose sugar.

For 100 g of soybeans:
39.2% of 50 g = 19.6 g of cellulose
90% of 19.6 g = 17.64 g converted cellulose

17.64 g (glucose) + 50 g (edible fraction of soybean) = 67.64 g of usable product
1/.6764 = 1.47 which is the harvest index of soybeans when the cellulosic fraction is included.
The production yield was determined as 5.32 and 5.32/1.47 = 3.62 and 1/3.62 = .276: the objective function coefficient value used in the models 4-7. This procedure is repeated for each of the products, except soy and wheat sprouts which do not have LHC fractions.

The additional kilocalories yielded for each crop by the converted cellulose are also determined. For example, with soymilk there are 17.64 g of glucose from cellulose which when multiplied by 4, which is the combustion factor for carbohydrate, yields 70.56 kcal, which, when added to 35.9, the original kilocalorie value for soymilk, yields 106.5 total kilocalories. This type of calculation is also repeated for each product used in the Product/Byproduct models.

Carbohydrate yield in kilocalories is the same as energy yield and it can be added to the original carbohydrate yield to obtain total carbohydrate yield. In soymilk, 70.56 is the kcal yield of carbohydrate. This value added to 8.8 kcal, the original yield, results in a total of 79.36 kcal.. The total carbohydrate yield for soymilk.
*Note: All values are per 100 gram samples.

Harvest Indices

x1 spinach .70 (1/.7=1.42)	x7 rice .45 (1/.45=2.2)
x2 lettuce .85 (1/.85=1.17)	x8 soybeans .50 (1/.5=2)
x3 tomatoes .45 (1/.45=2.2)	x9 wheat meal .4 (1/.4=2.5)
x4 sweetpotatoes .83 (1/.83=1.2)	x10 potatoes .80 (1/.80=1.25)
x5 onions .75 (1/.75=1.33)	x11 sunflower .33 (1/.33=3)
x6 greenbeans .60 (1/.6=1.6)	x12 peanuts .2 (1/.2=5)

Product Models: Derivation of Production Index

		product yield	: gram of raw product	production yield
x1	soymilk	5.3	:1g	.375
x2	tofu	4.00g	:1g	.5
x3	tempeh	1.75	:1g	1.14
x4	soy sprouts	1.00g	:1g	1.00
x5	roast soy beans	.500g	:1g	2.00

x6 baked potato	.800g	:1g	1.25
x7 boiled potato	.800g	:1g	1.25
x8 baked sweet potato	.830g	:1g	1.20
x9 boiled sweet potato	.830g	:1g	1.20
x10 boiled onions	.750g	:1g	1.33
x11 boiled greenbeans	.600g	:1g	1.60
x12 sun flower	.330g	:1g	3.00
x13 cooked rice	1.90g	:1g	1.15
x14 wheat meal	.400g	:1g	2.50
x15 boiled spinach	.700g	:1g	1.42
x16 lettuce	.850g	:1g	1.17
x17 tomatoes	.450g	:1g	2.20
x18 wheat sprouts	1g	:1g	1.00

Objective function values:
CELSS Model (no byproducts)
.375x1+.5x2+1.14x3+x4+2x5+1.25x6+1.25x7+1.2x8+1.2x9+1.33x10+1.6x11+3x12+1.15x13+2.5x14+1.42x15+1.17x16+2.2x17+x18

INCLUSION OF BYPRODUCTS

The inclusion of cellulosic byproducts in a CELSS would require the conversion of cellulose to glucose by the Purdue Method or some other comparable method of saccharification. Percentages of cellulose used for x10, 11, 12, 13, 15, 16, and 17 are averages taken from reference #2.

Cellulosic Composition of Select Crops

Wheat = ~46.8% cellulose from a total LHC fraction of 60%
Soybeans = ~39.2% cellulose from a total LHC of 50%
Potatoes = ~52% cellulose from a total LHC of 20%

Sweet potatoes = ~54% cellulose from a total LHC of 17%

x1 soymilk=cellulose=39.2% of 50% LHC fraction x 90% (saccharification rate)
=19.6 x 90%=17.64 + 50 (yield) = 67.64 + 1/.6764 = 1.47 and production yield = 5.32 and /1.47 = 3.62 =1/3.62=.276

x2 tofu (same as x1 except production yield is different) 4.00/1.47=2.72=1/2.72=.367

x3 tempeh (same as x1 and x2) production yield = 1.75 and 1.75/1.47 = 1.19=1/1.19=.84

x5 roasted soybeans=cellulose=39.2% of 50 g x 90% = 17.64+ 50 = 67.64 and 1/.676 = 1.47

x6 and x7 potatoes = cellulose = 52% LHC fraction of 20% x 90% saccharification rate
= 9.36% + 80 (harvest yield) = 89.36 = 1/.8936 = 1.11

x8 and x9 sweet potatoes = cellulose = 54% LHC fraction 17% x 90% saccharification rate = 8.26 + 83 (harvest yield) = 91.26 and 1/.9126 = 1.09

x10 boiled onions = cellulose = 34.3% of 25 g x 90% = 7.71 +75 = 82.71 and 1/.8271=1.20

x11 cooked greenbeans = cellulose =34.3% of 40 g x90% = 12.34 + 60 = 72.34
and 1/.7234=1.38

x12 sunflower 34.3% of 67 g x 90%=16.9 + 45 =61.9 and 1/.619 = 1.61 and 190/1.61 =1.18

X13 cooked rice 34.3% of 55g x90% =16.9 +45 =61.9 and 1/.619 = 1.61 and 190/1.61=1.18 and 1/1.18=.847

x14 wheat meal = cellulose 46.8% of total LHC fraction of 60% = 28.08 x 90% = 25.27 + 40 = 65.27 and 1/.6527 = 1.53

x15 boiled spinach 34.3% of 30 g x 90%=9.26 + 70=79.26 and 1/.7926 = 1.26

x16 lettuce 34.3% of 15 g x 90%=4.63 + 85 = 89.63 and 1?.8963 = 1.11

x17 tomatoes 34.3% of 55 g x 90% = 16.97 + 45 = 61.93 and 1?.6193 = 1.61

Objective Function Coefficient Values for CELSS Byproduct Models:

.276x1+.367x2+.84x3+x4+1.47x5+1.11x6+1.11x7+1.09x8+1.09x9+1.20x10+1.38x11+1.61x12+.847x13+1.53x14+1.26x15+1.11x16+1.61x17+x18

Additional Kilocalorie Yield:

x1 = 17.64 (grams of converted cellulose) x 4 (combustion factor for carbohydrate) = 70.56 + 35.9 (kcal in original sample) = 106.5
x2 = 70.56 + 78.69.16 = 142.56
x3 = 70.56 + 216.6 = 287.16
x6 = 9.36 x 4 = 37.44 + 110.9 = 148.34
x7 = 37.44 + 87.7 = 125.14
x8 = 8.26 x 4 = 33.04 + 104.9 = 138
x9 = 33.04 + 106.7 = 139.8
x10 = 30.84 + 30.6 = 61.44
x11 = 49.36 + 41.9 = 91.26
x12 = 82.72 + 612 = 694.72
x13 = 67.76 + 106.7 = 174.46
x14 = 25.27 x 4 = 101 + 353.3 = 454.3
x15 = 37.04 + 29.22 = 66.26
x16 = 18.52 + 14 = 32.52
x17 = 22.6 + 67.88 = 90.48

Additional Carbohydrate Yield:

x1 = 8.8 + 70.56 = 79.36
x2 = 9.6 + 70.56 = 80.16
x3 = 69.8 + 70.56 = 140.36
x5 = 130.8 + 70.56 = 201.3
x6 = 37.44 + 100.8 = 138.24
x7 = 37.44 + 80 = 117.44

x8 = 33.04 + 97.2 = 130.24
x9 = 33.04 + 97.2 = 130.24
x10 = 30.84 = 25.2 = 56.04
x11 = 49.36 = 31.6 = 80.96
x12 = 82.72 + 75 = 157.72
x13 = 67.76 + 93.6 = 161.36
x14 = 101 + 280 = 381
x15 = 37.04 + 15 = 52.04
x16 = 18.52 + 8.36 = 26.88
x17 = 67.88 + 17.2 = 85.08

References

1) Wilke, C.R. (ed) "Cellulose as a Chemical Energy Resource," Biotechnology and Bioengineering Symposium 5: 29, 1975.

2) Tsao, G.T. et al. "Fermentation Substrates from Cellulosic Materials: Production of Fermentable Sugars from Cellulosic Materials," Annual Reports on Fermentation Processes 2: 1-21, 1978.

3) "Fermentable Sugars from Cellulosic Residues" Process Biochemistry 21-25, 1979.

4) There are many sources for information on harvest and production indices. Some of those used for the data utilized in this report are:

A) Agricultural Statistics, United States Department of Agriculture, 1936-present.

B) Field Crop Research 9(2) 1984.

C) "Biological Yield and Harvest Indices" Oryza 18(1), 1981

D) "Growth Analysis for Biological Yield, Harvest Index and Fruit Yield" The Madras Agricultural Journal 9, 1981.

E) Cooked rice yields are available from any cookbook.

F) Shurtleff, W. and Aoyagi, A. Tofu and Soymilk Production: Food for Mankind Lafayette, CA: The Soyfoods Center, 1979, 329 pps.

G) Shurtleff, W. and Aoyagi, A. The Book of Tempeh New York: Harper and Row, 1979, 173 pps.

Appendix C

CELSS Linear Models

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SCALING FROM TABLES TO MODELS

It was necessary to scale some of the nutrient values used in the models. The necessity for this arises because the LINDO program is generally unable to solve models containing values that span a range greater than six degrees of magnitude. Many of the nutrient values were as small as .000n and others were as great as n0,000. As a result of this situation, initial runs of the models resulted in nonfeasible solutions, a problem that was easily resolved by scaling. This makes it necessary to do some mathematical adjusting when interpreting the solution values. The adjustments that have been used are:

Fiber x 10
Essential Fatty Acids x 10
Vitamin E x 10
Riboflavin x 100
Niacin x 10
Pantothenic acid x 100
Pyridoxine x 100
Thiamin x 100
Iron x 10
Copper x 10
Manganese x 10
Molybdenum x 100
Zinc x 10

Raw Product Model Diets

```
 MIN     1.42 X1 + 1.17 X2 + 2.2 X3 + 1.2 X4 + 1.33 X5 + 1.6 X6 + 2.2 X7
      + 2 X8 + 2.5 X9 + 1.25 X10 + 3 X11 + X12 + X13
 SUBJECT TO
       LEU)   223 X1 + 70 X2 + 33 X3 + 120 X4 + 41 X5 + 112 X6 + 728
X7 + 926 X8
       + 670 X9 + 105 X10 + 1659 X11 + 664 X12 >=   1200
    ISOLEU)   147 X1 + 75 X2 + 21 X3 + 82 X4 + 42 X5 + 66 X6 + 371 X7
+ 570 X8
       + 434 X9 + 92 X10 + 1139 X11 + 394 X12 >=   840
      VITA)   6715 X1 + 330 X2 + 1133 X3 + 20063 X4 + 668 X6 + 180
X8 + 274 X9
       + 113 X10 + 987 X11 + 552 X12 <=   50000
      THRE)   122 X1 + 53 X2 + 22 X3 + 52 X4 + 28 X5 + 79 X6 + 293 X7 +
516  X8
       + 288 X9 + 83 X10 + 928 X11 + 458 X12 >=   560
     TRYPT)   39 X1 + 8 X2 + 7 X3 + 20 X4 + 17 X5 + 19 X6 + 91 X7 + 157
X8
       + 123 X9 + 22 X10 + 348 X11 + 181 X12 >=   250
       VAL)   161 X1 + 62 X2 + 23 X3 + 108 X4 + 27 X5 + 90 X6 + 512 X7
+ 576 X8
       + 468 X9 + 113 X10 + 1351 X11 + 442 X12 >=   980
       TYR)   237 X1 + 78 X2 + 38 X3 + 167 X4 + 59 X5 + 109 X6 + 712
X7
       + 1050 X8 + 867 X9 + 58 X10 + 1835 X11 + 576 X12 >=   1120
      KCAL)   CALS >=   3400
       EFA)   10 X1 + 3.5 X2 + 10 X3 + 10 X4 + 3.7 X5 + 10 X6 + 40 X7 +
444  X8
       + 200 X9 + 4198 X11 + 37 X12 + 5 X13 >=   0
     FIBER)   9 X1 + 5.3 X2 + 5 X3 + 9 X4 + 4.4 X5 + 11 X6 + 31 X7 + 20.5
X8
       + 18 X9 + 5 X10 + 41.6 X11 + 23 X12 + 22 X13 >=   0
    NIACIN)   7 X1 + 1.87 X2 + 6 X3 + 7 X4 + 6.7 X5 + 7.5 X6 + 15 X7 +
16.5  X8
       + 44 X9 + 15 X10 + 45 X11 + 11 X12 + 9 X13 >=   0
     PYRID)   20 X1 + 4 X2 + 5 X3 + 26 X4 + 15.7 X5 + 7.4 X6 + 17 X7 +
39  X9
       + 39 X10 + 80 X11 + 18 X12 >=   0
        FE)   27 X1 + 5 X2 + 5 X3 + 6 X4 + 3.7 X5 + 10.4 X6 + 10 X7 + 35.5
X8
       + 43 X9 + 6 X10 + 67.7 X11 + 21 X12 >=   0
        CU)   1.3 X1 + 1.7 X4 + 2 X7 + 9.3 X9 + 3.1 X10 + 17.5 X11 + 4.2
X12
```

>= 0
MN) 9 X1 + 1.5 X2 + 1.2 X3 + 3.7 X4 + 1.3 X5 + 2.1 X6 + 15 X7 +
34 X9
+ 6.3 X10 + 20.2 X11 + 7 X12 + 0.8 X13 >= 0
MB) 2.6 X1 + 1.5 X7 + 3.6 X8 + 3.6 X9 + 3 X10 >= 0
ZN) 5.3 X1 + 2.2 X2 + 1.1 X3 + 2.8 X4 + 1.8 X5 + 2.4 X6 + 13 X7
+ 34 X9 + 5.8 X10 + 50.6 X11 + 11.7 X12 >= 0
VITAK) 3.5 X1 + 80 X3 + 2.2 X6 >= 0
FOLACIN) 194 X1 + 56 X2 + 9.4 X3 + 13.8 X4 + 19.9 X5 + 36.5 X6 +
29 X7
+ 52 X9 + 25 X10 + 237 X11 + 171.8 X12 >= 0
NA) 79 X1 + 9 X2 + 8 X3 + 13 X4 + 2 X5 + 6 X6 + 8 X7 + 3 X9 + 3
X10
+ 3 X11 + 14 X12 >= 0
K) 558 X1 + 158 X2 + 207 X3 + 204 X4 + 155 X5 + 209 X6 + 85
X7
+ 435 X9 + 407 X10 + 689 X11 + 484 X12 >= 0
I) 12 X1 + 3 X3 + 2.2 X4 + 3 X6 + 1.8 X7 + 4.1 X9 + 4 X10 >= 0
MG) 79 X1 + 9 X2 + 11 X3 + 10 X4 + 10 X5 + 25 X6 + 28 X7 + 113
X9
+ 20 X10 + 354 X11 >= 0
SE) 1.7 X1 + X3 + 6.1 X4 + 6 X6 + 20.3 X7 + 62.7 X9 + X10 + X13
>= 0
CA) 99 X1 + 19 X2 + 7 X3 + 22 X4 + 25 X5 + 37 X6 + 32 X7 + 197
X8
+ 37 X9 + 7 X10 + 116 X11 + 67 X12 + 22 X13 >= 0
VITAC) 28 X1 + 3.9 X2 + 18 X3 + 23 X4 + 8.4 X5 + 16.3 X6 + 29 X8
+ 9 X10
+ 13 X12 >= 0
PROTEIN) 11.6 X1 + 4 X2 + 3.66 X3 + 6.8 X4 + 4.8 X5 + 7.2 X6 + 33.6
X7
+ 51.8 X8 + 50.8 X9 + 8.4 X10 + 77.2 X11 + 52.4 X12 + 28 X13 - 0.1
CALS
>= 0
CHO) 168.39999 X1 + 8.36 X2 + 17.2 X3 + 97.2 X4 + 29.2 X5 +
28.4 X6
+ 310.79999 X7 + 44.2 X8 + 280 X9 + 68.4 X10 + 96.4 X11 + 44.8
X12
+ 154 X13 - 0.7 CALS >= 0
CALS) 28.7 X1 + 14 X2 + 27 X3 + 106.7 X4 + 36.7 X5 + 36.5 X6
+ 354.29999 X7 + 157.2 X8 + 353.29999 X9 + 77.7 X10 +
621.59998 X11
+ 157.5 X12 + 188.3 X13 - CALS = 0

MET) 88 X1 + 28 X2 + 20 X3 + 54 X4 + 31 X5 + 40 X6 + 323 X7 +
275 X8
+ 373 X9 + 46 X10 + 945 X11 + 130 X12 >= 0
P) 49 X1 + 20 X2 + 23 X3 + 28 X4 + 29 X5 + 38 X6 + 127 X7 +
198 X8
+ 386 X9 + 53 X10 + 705 X11 + 164 X12 + 150 X13 >= 0
THIAMIN) 8 X1 + 4.6 X2 + 6 X3 + 7 X4 + 6 X5 + 8.4 X6 + 13 X7 +
43.5 X8
+ 66 X9 + 10 X10 + 11 X11 + 34 X12 + X13 >= 0
RIBO) 19 X1 + 3 X2 + 5 X3 + 15 X4 + X5 + 10.5 X6 + 4 X7 + 17.5 X8
+ 12 X9 + 4 X10 + 25 X11 + 12 X12 + 21 X13 >= 0
PANAC) 7 X1 + 4.6 X2 + 25 X3 + 56 X4 + 13.2 X5 + 9.4 X6 + 55 X7 +
110 X9
+ 20 X10 + 70 X11 + 93 X12 >= 0
BIOTIN) 6.9 X1 + 1.5 X3 + 4.3 X4 + 3 X7 + 9 X9 + 34 X12 >= 0
F) X1 + 2.4 X3 + 19 X7 + 5.3 X9 + 4.5 X10 >= 0
FATS) 2.7 X1 + 1.71 X2 + 6.3 X3 + 2.7 X4 + 2.7 X5 + 0.9 X6 + 9.9
X7
+ 61.2 X8 + 22.5 X9 + 0.9 X10 + 448 X11 + 60.3 X12 + 6.3 X13 - 0.2
CALS
>= 0
VITE) 18 X1 + 4 X2 + 3.4 X3 + 45 X4 + 3.1 X5 + 0.2 X6 + 3.5 X7 +
8.9 X9
+ 0.1 X10 + 320 X11 + 0.3 X12 >= 0
LYS) 174 X1 + 75 X2 + 33 X3 + 81 X4 + 56 X5 + 88 X6 + 319 X7 +
775 X8
+ 274 X9 + 113 X10 + 937 X11 + 552 X12 >= 840
41) X7 >= 0.5
42) X4 >= 0.5
END

OBJECTIVE FUNCTION VALUE

1) 19.2680900

VARIABLE	VALUE	REDUCED COST
X1	.895342	.000000
X2	.000000	1.112904
X3	.000000	2.057625
X4	.500000	.000000
X5	.000000	1.130902
X6	.000000	1.421175
X7	.500000	.000000
X8	.000000	1.467855
X9	.000000	.619543
X10	.000000	.808342
X11	1.325130	.000000
X12	.000000	.470147
X13	12.321310	.000000
CALS	3400.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
LEU)	1622.052200	.000000
ISOLEU)	1027.439000	.000000
VITA)	32648.373000	.000000
THRE)	951.452600	.000000
TRYPT)	301.563700	.000000
VAL)	1264.401000	.000000
TYR)	1963.310000	.000000
KCAL)	.000000	-.005563
EFA)	5658.457000	.000000
FIBER)	354.252310	.000000
NIACIN)	187.790030	.000000
PYRID)	145.417300	.000000
FE)	121.885600	.000000
CU)	26.203723	.000000
MN)	54.032760	.000000
MB)	3.077889	.000000
ZN)	79.696900	.000000
VITAK)	3.133698	.000000
FOLACIN)	509.152220	.000000
NA)	85.207420	.000000

K)	1557.116000	.000000
I)	12.744110	.000000
MG)	558.828120	.000000
SE)	27.043392	.000000
CA)	540.422800	.000000
VITAC)	36.569580	.000000
PROTEIN)	137.882700	.000000
CHO)	.000000	-.008655
CALS)	.000000	.002023
MET)	1519.538000	.000000
P)	2903.785100	.000000
THIAMIN)	44.060480	.000000
RIBO)	318.387300	.000000
PANAC)	154.526500	.000000
BIOTIN)	9.827861	.000000
F)	10.395341	.000000
FATS)	.000000	-.007641
39)	.000000	-.151284
40)	.000000	-.554006

NO. ITERATIONS= 1

OBJECTIVE FUNCTION VALUE

1) 19.5031600

VARIABLE	VALUE	REDUCED COST
X1	1.000870	.000000
X2	.000000	1.112904
X3	.000000	2.057625
X4	.500000	.000000
X5	.000000	1.130902
X6	.000000	1.421175
X7	.500000	.000000
X8	.000000	1.467855
X9	.000000	.619543
X10	.000000	.808342
X11	1.260293	.000000
X12	.500000	.000000
X13	12.101050	.000000
CALS	3400.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
LEU)	1870.019200	.000000
ISOLEU)	1166.101000	.000000
VITA)	31727.750000	.000000
THRE)	1133.158000	.000000
TRYPT)	373.615720	.000000
VAL)	1414.795200	.000000
TYR)	2157.343000	.000000
KCAL)	.000000	-.005563
EFA)	5404.722100	.000000
FIBER)	359.159020	.000000
NIACIN)	189.128700	.000000
PYRID)	151.340800	.000000
FE)	130.845300	.000000
CU)	27.306251	.000000
MN)	56.996574	.000000
MB)	3.352262	.000000
ZN)	82.825410	.000000
VITAK)	3.503045	.000000
FOLACIN)	600.158100	.000000
NA)	100.349600	.000000

K)	1813.327000	.000000
I)	14.010440	.000000
MG)	544.212300	.000000
SE)	27.002530	.000000
CA)	572.003110	.000000
VITAC)	46.024360	.000000
PROTEIN)	154.134000	.000000
CHO)	.000000	-.008655
CALS)	.000000	.002023
MET)	1532.553000	.000000
P)	2912.206000	.000000
THIAMIN)	60.971230	.000000
RIBO)	320.145810	.000000
PANAC)	197.226600	.000000
BIOTIN)	27.556003	.000000
F)	10.500870	.000000
FATS)	.000000	-.007641
39)	.000000	-.151284
40)	.000000	-.554006
41)	.000000	-.470147

NO. ITERATIONS= 1

OBJECTIVE FUNCTION VALUE

1) 19.8129310

VARIABLE	VALUE	REDUCED COST
X1	.996250	.000000
X2	.000000	1.112904
X3	.000000	2.057625
X4	.500000	.000000
X5	.000000	1.130902
X6	.000000	1.421175
X7	.500000	.000000
X8	.000000	1.467855
X9	.500000	.000000
X10	.000000	.808342
X11	1.247812	.000000
X12	.500000	.000000
X13	11.204820	.000000
CALS	3400.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
LEU)	2183.284000	.000000
ISOLEU)	1368.207000	.000000
VITA)	31634.090000	.000000
THRE)	1265.012000	.000000
TRYPT)	430.592310	.000000
VAL)	1631.190300	.000000
TYR)	2566.846100	.000000
KCAL)	.000000	-.005563
EFA)	5447.801200	.000000
FIBER)	347.881300	.000000
NIACIN)	202.468700	.000000
PYRID)	169.750000	.000000
FE)	151.375620	.000000
CU)	31.731834	.000000
MN)	72.985910	.000000
MB)	5.140250	.000000
ZN)	99.169410	.000000
VITAK)	3.486876	.000000
FOLACIN)	622.304000	.000000
NA)	101.447200	.000000

K)	2019.650100	.000000
I)	16.005002	.000000
MG)	595.929200	.000000
SE)	57.448444	.000000
CA)	568.881000	.000000
VITAC)	45.895004	.000000
PROTEIN)	153.422540	.000000
CHO)	.000000	-.008655
CALS)	.000000	.002023
MET)	1706.852200	.000000
P)	2961.747000	.000000
THIAMIN)	92.900760	.000000
RIBO)	306.925300	.000000
PANAC)	251.320600	.000000
BIOTIN)	32.024124	.000000
F)	13.146250	.000000
FATS)	.000000	-.007641
VITE)	446.082330	.000000
LYS)	1115.547300	.000000
41)	.000000	-.151284
42)	.000000	-.554006
43)	.000000	-.470147
44)	.000000	-.619543

NO. ITERATIONS= 1

Edible Product Model Diets

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MIN 0.375 X1 + 0.5 X2 + 1.14 X3 + X4 + 2 X5 + 1.25 X6 + 1.25 X7
+ 1.2 X8 + 1.2 X9 + 1.33 X10 + 1.6 X11 + 3 X12 + 1.15 X13 + 2.5
X14
+ 1.42 X15 + 1.17 X16 + 2.2 X17 + X18
SUBJECT TO
PROTEIN) 13.6 X1 + 31.2 X2 + 77.7 X3 + 52.4 X4 + 158.3 X5 + 9.2 X6
+ 6.8 X7
+ 6.8 X8 + 6.8 X9 + 3.6 X10 + 7.6 X11 + 91.12 X12 + 10.4 X13 +
50.8 X14
+ 11.88 X15 + 4.04 X16 + 3.5 X17 + 28 X18 - 0.1 CALS >= 0
SCAA) 113 X1 + 214 X2 + 584 X3 + 130 X4 + 1172 X5 + 65 X6 +
49 X7
+ 56 X8 + 54 X9 + 23 X10 + 41 X11 + 945 X12 + 91 X13 + 373 X14
+ 90 X15
+ 28 X16 + 20 X17 >= 700
ARAA) 327 X1 + 23 X2 + 1733 X3 + 576 X4 + 3550 X5 + 187 X6 +
140 X7
+ 174 X8 + 169 X9 + 45 X10 + 113 X11 + 1835 X12 + 166 X13 +
867 X14
+ 247 X15 + 78 X16 + 38 X17 >= 1120
VAL) 175 X1 + 359 X2 + 979 X3 + 442 X4 + 1970 X5 + 130 X6 +
96 X7
+ 112 X8 + 108 X9 + 21 X10 + 93 X11 + 1351 X12 + 107 X13 + 468
X14
+ 168 X15 + 62 X16 + 23 X17 >= 980
THREO) 136 X1 + 232 X2 + 77 X3 + 458 X4 + 1710 X5 + 840 X6 +
62 X7
+ 86 X8 + 82 X9 + 22 X10 + 82 X11 + 928 X12 + 58 X13 + 288 X14
+ 127 X15
+ 53 X16 + 22 X17 >= 560
LYS) 207 X1 + 454 X2 + 1125 X3 + 552 X4 + 2630 X5 + 140 X6 +
104 X7
+ 85 X8 + 81 X9 + 43 X10 + 91 X11 + 937 X12 + 54 X13 + 274 X14
+ 182 X15
+ 75 X16 + 33 X17 >= 840
LEU) 295 X1 + 61 X2 + 1063 X3 + 664 X4 + 3220 X5 + 138 X6 +
103 X7
+ 126 X8 + 121 X9 + 32 X10 + 116 X11 + 1659 X12 + 131 X13 + 67
X14
+ 231 X15 + 70 X16 + 33 X17 >= 1120
ISOLEU) 181 X1 + 355 X2 + 1000 X3 + 394 X4 + 1920 X5 + 93 X6 +
7 X7

+ 86 X8 + 82 X9 + 32 X10 + 69 X11 + 1139 X12 + 76 X13 + 434
X14
+ 152 X15 + 75 X16 + 21 X17 >= 840
BIOTIN) 2.1 X1 + 53 X3 + 4.3 X9 + X13 + 9 X14 + 1.5 X17 >= 0
B12) 3.9 X3 >= 0
FOLACIN) 10 X1 + 52 X3 + 171.8 X4 + 204.59999 X5 + 11 X6 + 8.9
X7 + 22.6 X8
+ 11 X9 + 12.7 X10 + 33 X11 + 6 X13 + 52 X14 + 145.8 X15 + 56
X16
+ 9.4 X17 >= 0
VITA) 40 X1 + 69 X3 + 11 X4 + 2 X5 + 21822 X8 + 17054 X9 +
666 X11
+ 50 X12 + 8190 X15 + 330 X16 + 1133 X17 <= 50000
VITC) 15 X4 + 4.6 X5 + 13 X6 + 7 X7 + 25 X8 + 17 X9 + 6 X10 + 10
X11
+ 9.8 X15 + 3.9 X16 + 18 X17 >= 0
CA) 21 X1 + 128 X2 + 93 X3 + 67 X4 + 270 X5 + 10 X6 + 8 X7 +
28 X8
+ 21 X9 + 27 X10 + 46 X11 + 116 X12 + 10 X13 + 37 X14 + 136
X15 + 19 X16
+ 7 X17 + 22 X18 >= 0
P) 48 X1 + 126 X2 + 206 X3 + 164 X4 + 649 X5 + 57 X6 + 40 X7
+ 55 X8
+ 27 X9 + 23 X10 + 39 X11 + 705 X12 + 28 X13 + 386 X14 + 56
X15 + 20 X16
+ 23 X17 + 159 X18 <= 2000
K) 196 X1 + 42 X2 + 367 X3 + 484 X4 + 1364 X5 + 418 X6 + 328
X7
+ 348 X8 + 184 X9 + 152 X10 + 299 X11 + 689 X12 + 28 X13 + 435
X14
+ 466 X15 + 158 X16 + 207 X17 >= 0
MG) 111 X2 + 70 X3 + 72 X4 + 228 X5 + 27 X6 + 20 X7 + 20 X8 +
10 X9
+ 10 X10 + 25 X11 + 354 X12 + 8 X13 + 113 X14 + 87 X15 + 9 X16
+ 11 X17
>= 0
NA) 7 X2 + 6 X3 + 14 X4 + 2 X5 + 8 X6 + 5 X7 + 10 X8 + 13 X9 + 8
X10
+ 3 X11 + 3 X12 + 373 X13 + 3 X14 + 70 X15 + 9 X16 + 8 X17 >= 0
I) 1.43 X3 + 5.6 X6 + 5.6 X7 + 6.1 X8 + 6.1 X9 + 1.9 X10 + 3 X11
+ 4 X13 + 2.6 X17 >= 0
TRY) 51 X1 + 131 X2 + 282 X3 + 181 X4 + 575 X5 + 360 X6 + 27
X7 + 21 X8

+ 20 X9 + 13 X10 + 20 X11 + 348 X12 + 28 X13 + 123 X14 + 40
X15 + 8 X16
+ 7 X17 >= 210
RIBO) 3 X1 + 3 X2 + 11.1 X3 + 12 X4 + 75 X5 + 3.5 X6 + 2 X7 + 13
X8
+ 14 X9 + X10 + 10 X11 + 450 X12 + X13 + 12 X14 + 23.6 X15 + 3
X16
+ 5 X17 + 21 X18 >= 0
PANAC) 26 X1 + 35.5 X3 + 93 X4 + 47.3 X5 + 56 X6 + 51 X7 + 65
X8 + 53 X9
+ 13 X10 + 7 X11 + 13 X13 + 110 X14 + 14.5 X15 + 4.6 X16 + 25
X17
>= 0
PYRID) 2 X1 + 30 X3 + 18 X4 + 25.5 X5 + 35 X6 + 27 X7 + 24 X8 +
24 X9
+ 18 X10 + 6 X11 + 4 X13 + 39 X14 + 24.2 X15 + 4 X16 + 5 X17 >=
0
THIAMIN) 8 X1 + 6 X2 + 13 X3 + 34 X4 + 42.7 X5 + 11 X6 + 10 X7 +
7 X8
+ 5 X9 + 4 X10 + 7 X11 + 25 X12 + 2 X13 + 66 X14 + 9.5 X15 +-4.6
X16
+ 6 X17 + X18 >= 0
VITE) 7.4 X2 + 40 X8 + 45.6 X9 + 2 X10 + 8.9 X14 + 4 X16 + 3.4
X17
>= 0
VITK) 2.5 X11 + 80 X17 >= 0
FE) 8 X1 + 19 X2 + 26 X3 + 21 X4 + 39.5 X5 + 14 X6 + 3 X7 + 5 X8
+ 6 X9 + 2 X10 + 13 X11 + 67.7 X12 + 2 X13 + 43 X14 + 35.7 X15 +
500 X16
+ 5 X17 >= 0
MN) 14.3 X3 + 7 X4 + 21.8 X5 + 2.3 X6 + 1.4 X7 + 5.6 X8 + 3.4 X9
+ 1.1 X10 + 2.9 X11 + 20.2 X12 + 4.7 X13 + 34 X14 + 9.3 X15 + 1.5
X16
+ 1.2 X17 >= 0
CU) 7.2 X1 + 6.7 X3 + 4.2 X4 + 10.7 X5 + 3 X6 + 1.67 X7 + 2.08 X8
+ 1.61 X9 + X11 + 17 X12 + 9.3 X14 + 1.74 X15 >= 0
MB) 2.6 X6 + 1.9 X7 + 2.1 X11 + 3.9 X13 + 3.6 X14 >= 0
SE) X4 + 9 X6 + 9 X7 + 1.2 X10 + 5.3 X13 + 62.7 X14 + X17 + X18
>= 0
ZN) 3 X1 + 6 X2 + 18 X3 + 11 X4 + 47 X5 + 3.2 X6 + 2.7 X7 + 2.9
X8
+ 1.8 X10 + 3.6 X11 + 50.6 X12 + 4 X13 + 34 X14 + 7.6 X15 + 2.2
X16

```
     + 1.1 X17 >=   0
   FIBER)   X1 + 30 X3 + 23 X4 + 53.8 X5 + 7 X6 + 4 X7 + 8 X8 + 9 X9 +
4 X10
     + 14 X11 + 41.6 X12 + X13 + 18 X14 + 8.8 X15 + 5.3 X16 + 5 X17 +
22 X18
     >=  0
     EFA)   12 X1 + 30 X2 + 59 X3 + 3.8 X4 + 169 X5 + X9 + X10 + X11 +
419 X12
     + 2 X13 + 20 X14 + 1.1 X15 + X17 + 5 X18 >=  0
  NIACIN)   2 X1 + X2 + 46 X3 + 11 X4 + 10 X5 + 16.4 X6 + 13 X7 + 6
X8 + 6 X9
     + X10 + 6 X11 + 45 X12 + 4 X13 + 44 X14 + 4.9 X15 + 1.87 X16 + 6
X17
     + 9 X18 >=  0
   KCAL)   CALS >=   3400
     CHO)   8.8 X1 + 9.6 X2 + 69.8 X3 + 44.8 X4 + 130.88 X5 + 100.8 X6
+ 80 X7
     + 97.2 X8 + 97.2 X9 + 25.2 X10 + 31.6 X11 + 75 X12 + 93.6 X13 +
280 X14
     + 15 X15 + 8.36 X16 + 17.2 X17 + 154 X18 - 0.7 CALS >=   0
     FAT)   13.5 X1 + 37.8 X2 + 69.1 X3 + 60.3 X4 + 194.5 X5 + 0.9 X6 +
0.9 X7
     + 0.9 X8 + 2.7 X9 + 1.8 X10 + 2.7 X11 + 446 X12 + 2.7 X13 + 22.5
X14
     + 2.34 X15 + 1.71 X16 + 1.8 X17 + 6.3 X18 - 0.2 CALS >=   0
    CALS)   35.9 X1 + 78.6 X2 + 216.59999 X3 + 157.5 X4 + 483.5 X5 +
110.9 X6
     + 87.7 X7 + 104.9 X8 + 106.7 X9 + 30.6 X10 + 41.9 X11 + 612 X12
     + 106.7 X13 + 353.29999 X14 + 29.22 X15 + 14 X16 + 22.6 X17 +
188.3 X18
     - CALS =   0
 END
```

OBJECTIVE FUNCTION VALUE

1) 34.6962620

VARIABLE	VALUE	REDUCED COST
X1	.000000	3.782580
X2	.000000	8.490887
X3	.000000	.000000
X4	.000000	12.513940
X5	.000000	38.357210
X6	6.378200	.000000
X7	8.915112	.000000
X8	.000000	.967258
X9	2.927656	.000000
X10	.000000	1.427042
X11	.000000	2.860195
X12	1.435225	.000000
X13	6.748488	.000000
X14	.000000	8.848358
X15	.000000	5.700637
X16	.000000	2.183634
X17	.000000	2.775493
X18	.000000	4.177586
CALS	3400.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
PROTEIN)	.172248	.000000
SCAA)	2279.917000	.000000
ARAA)	5569.500000	.000000
VAL)	3682.281000	.000000
THREO)	7313.794000	.000000
LYS)	2926.484100	.000000
LEU)	4297.785100	.000000
ISOLEU)	2203.253000	.000000
BIOTIN)	19.337410	.000000
B12)	.000000	-4.930859
FOLACIN)	222.199820	.000000
VITA)	.000000	.000074
VITC)	195.092520	.000000
CA)	430.554700	.000000
P)	.000000	.016250

K)	7306.761000	.000000
MG)	941.847800	.000000
NA)	2655.153000	.000000
I)	130.495200	.000000
TRY)	3073.829100	.000000
RIBO)	733.740900	.000000
PANAC)	1054.746000	.000000
PYRID)	561.202700	.000000
THIAMIN)	223.327200	.000000
VITE)	133.501100	.000000
VITK)	.000000	.000000
FE)	244.267800	.000000
MN)	97.814483	.000000
CU)	63.135190	.000000
MB)	59.841133	.000000
SE)	173.406800	.000000
ZN)	144.097400	.000000
FIBER)	173.110600	.000000
EFA)	617.784000	.000000
NIACIN)	329.644000	.000000
KCAL)	.000000	-.020856
CHO)	.000000	-.361314
FAT)	.000000	-.399828
CALS)	.000000	.312030

NO. ITERATIONS= 0

OBJECTIVE FUNCTION VALUE

1) 35.4097820

VARIABLE	VALUE	REDUCED COST
X1	.000000	3.782580
X2	.000000	8.490887
X3	.000000	.000000
X4	.000000	12.513940
X5	.000000	38.357210
X6	5.655707	.000000
X7	9.722499	.000000
X8	.000000	.967258
X9	2.927661	.000000
X10	.500000	.000000
X11	.000000	2.860195
X12	1.433309	.000000
X13	6.703397	.000000
X14	.000000	8.848358
X15	.000000	5.700637
X16	.000000	2.183634
X17	.000000	2.775493
X18	.000000	4.177586
CALS	3400.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
PROTEIN)	.172024	.000000
SCAA)	2278.103000	.000000
ARAA)	5558.928000	.000000
VAL)	3668.953100	.000000
THREO)	6763.564400	.000000
LYS)	2926.573200	.000000
LEU)	4288.156200	.000000
ISOLEU)	2152.104000	.000000
BIOTIN)	19.292340	.000000
B12)	.000000	-4.930859
FOLACIN)	227.517700	.000000
VITA)	.000000	.000074
VITC)	194.351920	.000000
CA)	442.615800	.000000
P)	.000000	.016250

K)	7343.000000	.000000
MG)	942.449210	.000000
NA)	2640.585000	.000000
I)	131.740300	.000000
TRY)	2840.102000	.000000
RIBO)	732.419610	.000000
PANAC)	1061.377100	.000000
PYRID)	566.534700	.000000
THIAMIN)	225.315600	.000000
VITE)	134.501340	.000000
VITK)	.000000	.000000
FE)	237.355200	.000000
MN)	97.582473	.000000
CU)	62.283480	.000000
MB)	59.320840	.000000
SE)	174.531900	.000000
ZN)	144.588020	.000000
FIBER)	173.157940	.000000
EFA)	617.390900	.000000
NIACIN)	328.524530	.000000
KCAL)	.000000	-.020856
CHO)	.000000	-.361314
FAT)	.000000	-.399828
CALS)	.000000	.312030
41)	.000000	-1.427042

NO. ITERATIONS= 38

OBJECTIVE FUNCTION VALUE

1) 36.5016020

VARIABLE	VALUE	REDUCED COST
X1	.000000	3.782580
X2	.000000	8.490887
X3	.000000	.000000
X4	.000000	12.513940
X5	.000000	38.357210
X6	4.076869	.000000
X7	11.895560	.000000
X8	.000000	.967258
X9	2.917992	.000000
X10	.500000	.000000
X11	.000000	2.860195
X12	1.431402	.000000
X13	6.513282	.000000
X14	.000000	8.848358
X15	.000000	5.700637
X16	.500000	.000000
X17	.000000	2.775493
X18	.000000	4.177586
CALS	3400.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
PROTEIN)	.226810	.000000
SCAA)	2276.334000	.000000
ARAA)	5570.221000	.000000
VAL)	3679.355000	.000000
THREO)	5584.981400	.000000
LYS)	2956.198000	.000000
LEU)	4299.863200	.000000
ISOLEU)	2040.570000	.000000
BIOTIN)	19.060650	.000000
B12)	.000000	-4.930859
FOLACIN)	256.243600	.000000
VITA)	.000000	.000074
VITC)	190.824100	.000000
CA)	451.386440	.000000
P)	.000000	.016250

K)	7466.392000	.000000
MG)	945.489130	.000000
NA)	2572.275000	.000000
I)	134.248440	.000000
TRY)	2328.213000	.000000
RIBO)	731.556300	.000000
PANAC)	1083.104200	.000000
PYRID)	570.955320	.000000
THIAMIN)	231.502700	.000000
VITE)	136.060400	.000000
VITK)	.000000	.000000
FE)	471.203300	.000000
MN)	96.778500	.000000
CU)	61.127990	.000000
MB)	58.603210	.000000
SE)	178.872200	.000000
ZN)	145.646100	.000000
FIBER)	173.091840	.000000
EFA)	616.202100	.000000
NIACIN)	330.912040	.000000
KCAL)	.000000	-.020856
CHO)	.000000	-.361314
FAT)	.000000	-.399828
CALS)	.000000	.312030
41)	.000000	.000000
42)	.000000	-1.427042
43)	.000000	-2.183634

NO. ITERATIONS= 1

Product/Byproduct Model Diets

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MIN 0.276 X1 + 0.367 X2 + 0.84 X3 + X4 + 1.47 X5 + 1.11 X6 + 1.11 X7
+ 1.09 X8 + 1.09 X9 + 1.2 X10 + 1.38 X11 + 1.8 X12 + 0.847 X13
+ 1.53 X14 + 1.26 X15 + 1.11 X16 + 1.61 X17 + X18
SUBJECT TO
PROTEIN) 13.6 X1 + 31.2 X2 + 77.7 X3 + 52.4 X4 + 158.3 X5 + 9.2 X6 + 6.8 X7
+ 6.8 X8 + 6.8 X9 + 3.6 X10 + 7.6 X11 + 91.12 X12 + 10.4 X13 + 50.8 X14
+ 11.88 X15 + 4.04 X16 + 3.5 X17 + 28 X18 - 0.1 CALS >= 0
SCAA) 113 X1 + 214 X2 + 584 X3 + 130 X4 + 1172 X5 + 65 X6 + 49 X7
+ 56 X8 + 54 X9 + 23 X10 + 41 X11 + 945 X12 + 91 X13 + 373 X14 + 90 X15
+ 28 X16 + 20 X17 >= 700
ARAA) 327 X1 + 23 X2 + 1733 X3 + 576 X4 + 3550 X5 + 187 X6 + 140 X7
+ 174 X8 + 169 X9 + 45 X10 + 113 X11 + 1835 X12 + 166 X13 + 867 X14
+ 247 X15 + 78 X16 + 38 X17 >= 1120
VAL) 175 X1 + 359 X2 + 979 X3 + 442 X4 + 1970 X5 + 130 X6 + 96 X7
+ 112 X8 + 108 X9 + 21 X10 + 93 X11 + 1351 X12 + 107 X13 + 468 X14
+ 168 X15 + 62 X16 + 23 X17 >= 980
THREO) 136 X1 + 232 X2 + 77 X3 + 458 X4 + 1710 X5 + 840 X6 + 62 X7
+ 86 X8 + 82 X9 + 22 X10 + 82 X11 + 928 X12 + 58 X13 + 288 X14 + 127 X15
+ 53 X16 + 22 X17 >= 560
LYS) 207 X1 + 454 X2 + 1125 X3 + 552 X4 + 2630 X5 + 140 X6 + 104 X7
+ 85 X8 + 81 X9 + 43 X10 + 91 X11 + 937 X12 + 54 X13 + 274 X14 + 182 X15
+ 75 X16 + 33 X17 >= 840
LEU) 295 X1 + 61 X2 + 1063 X3 + 664 X4 + 3220 X5 + 138 X6 + 103 X7
+ 126 X8 + 121 X9 + 32 X10 + 116 X11 + 1659 X12 + 131 X13 + 67 X14
+ 231 X15 + 70 X16 + 33 X17 >= 1120
ISOLEU) 181 X1 + 355 X2 + 1000 X3 + 394 X4 + 1920 X5 + 93 X6 + 7 X7

+ 86 X8 + 82 X9 + 32 X10 + 69 X11 + 1139 X12 + 76 X13 + 434
X14
+ 152 X15 + 75 X16 + 21 X17 >= 840
BIOTIN) 2.1 X1 + 53 X3 + 4.3 X9 + X13 + 9 X14 + 1.5 X17 >= 0
B12) 3.9 X3 >= 0
FOLACIN) 10 X1 + 52 X3 + 171.8 X4 + 204.59999 X5 + 11 X6 + 8.9
X7 + 22.6 X8
+ 11 X9 + 12.7 X10 + 33 X11 + 6 X13 + 52 X14 + 145.8 X15 + 56
X16
+ 9.4 X17 >= 0
VITA) 40 X1 + 69 X3 + 11 X4 + 2 X5 + 21822 X8 + 17054 X9 +
666 X11
+ 50 X12 + 8190 X15 + 330 X16 + 1133 X17 <= 50000
VITC) 15 X4 + 4.6 X5 + 13 X6 + 7 X7 + 25 X8 + 17 X9 + 6 X10 + 10
X11
+ 9.8 X15 + 3.9 X16 + 18 X17 >= 0
CA) 21 X1 + 128 X2 + 93 X3 + 67 X4 + 270 X5 + 10 X6 + 8 X7 +
28 X8
+ 21 X9 + 27 X10 + 46 X11 + 116 X12 + 10 X13 + 37 X14 + 136
X15 + 19 X16
+ 7 X17 + 22 X18 >= 0
P) 48 X1 + 126 X2 + 206 X3 + 164 X4 + 649 X5 + 57 X6 + 40 X7
+ 55 X8
+ 27 X9 + 23 X10 + 39 X11 + 705 X12 + 28 X13 + 386 X14 + 56
X15 + 20 X16
+ 23 X17 + 159 X18 <= 2000
K) 196 X1 + 42 X2 + 367 X3 + 484 X4 + 1364 X5 + 418 X6 + 328
X7
+ 348 X8 + 184 X9 + 152 X10 + 299 X11 + 689 X12 + 28 X13 + 435
X14
+ 466 X15 + 158 X16 + 207 X17 >= 0
MG) 111 X2 + 70 X3 + 72 X4 + 228 X5 + 27 X6 + 20 X7 + 20 X8 +
10 X9
+ 10 X10 + 25 X11 + 354 X12 + 8 X13 + 113 X14 + 87 X15 + 9 X16
+ 11 X17
>= 0
NA) 7 X2 + 6 X3 + 14 X4 + 2 X5 + 8 X6 + 5 X7 + 10 X8 + 13 X9 + 8
X10
+ 3 X11 + 3 X12 + 373 X13 + 3 X14 + 70 X15 + 9 X16 + 8 X17 >= 0
I) 1.43 X3 + 5.6 X6 + 5.6 X7 + 6.1 X8 + 6.1 X9 + 1.9 X10 + 3 X11
+ 4 X13 + 2.6 X17 >= 0
TRY) 51 X1 + 131 X2 + 282 X3 + 181 X4 + 575 X5 + 360 X6 + 27
X7 + 21 X8

+ 20 X9 + 13 X10 + 20 X11 + 348 X12 + 28 X13 + 123 X14 + 40
X15 + 8 X16
+ 7 X17 >= 210
RIBO) 3 X1 + 3 X2 + 11.1 X3 + 12 X4 + 75 X5 + 3.5 X6 + 2 X7 + 13
X8
+ 14 X9 + X10 + 10 X11 + 450 X12 + X13 + 12 X14 + 23.6 X15 + 3
X16
+ 5 X17 + 21 X18 >= 0
PANAC) 26 X1 + 35.5 X3 + 93 X4 + 47.3 X5 + 56 X6 + 51 X7 + 65
X8 + 53 X9
+ 13 X10 + 7 X11 + 13 X13 + 110 X14 + 14.5 X15 + 4.6 X16 + 25
X17
>= 0
PYRID) 2 X1 + 30 X3 + 18 X4 + 25.5 X5 + 35 X6 + 27 X7 + 24 X8 +
24 X9
+ 18 X10 + 6 X11 + 4 X13 + 39 X14 + 24.2 X15 + 4 X16 + 5 X17 >=
0
THIAMIN) 8 X1 + 6 X2 + 13 X3 + 34 X4 + 42.7 X5 + 11 X6 + 10 X7 +
7 X8
+ 5 X9 + 4 X10 + 7 X11 + 25 X12 + 2 X13 + 66 X14 + 9.5 X15 + 4.6
X16
+ 6 X17 + X18 >= 0
VITE) 7.4 X2 + 40 X8 + 45.6 X9 + 2 X10 + 8.9 X14 + 4 X16 + 3.4
X17
>= 0
VITK) 2.5 X11 + 80 X17 >= 0
FE) 8 X1 + 19 X2 + 26 X3 + 21 X4 + 39.5 X5 + 14 X6 + 3 X7 + 5 X8
+ 6 X9 + 2 X10 + 13 X11 + 67.7 X12 + 2 X13 + 43 X14 + 35.7 X15 +
500 X16
+ 5 X17 >= 0
MN) 14.3 X3 + 7 X4 + 21.8 X5 + 2.3 X6 + 1.4 X7 + 5.6 X8 + 3.4 X9
+ 1.1 X10 + 2.9 X11 + 20.2 X12 + 4.7 X13 + 34 X14 + 9.3 X15 + 1.5
X16
+ 1.2 X17 >= 0
CU) 7.2 X1 + 6.7 X3 + 4.2 X4 + 10.7 X5 + 3 X6 + 1.67 X7 + 2.08 X8
+ 1.61 X9 + X11 + 17 X12 + 9.3 X14 + 1.74 X15 >= 0
MB) 2.6 X6 + 1.9 X7 + 2.1 X11 + 3.9 X13 + 3.6 X14 >= 0
SE) X4 + 9 X6 + 9 X7 + 1.2 X10 + 5.3 X13 + 62.7 X14 + X17 + X18
>= 0
ZN) 3 X1 + 6 X2 + 18 X3 + 11 X4 + 47 X5 + 3.2 X6 + 2.7 X7 + 2.9
X8
+ 1.8 X10 + 3.6 X11 + 50.6 X12 + 4 X13 + 34 X14 + 7.6 X15 + 2.2
X16

```
     + 1.1 X17 >=   0
   FIBER)  X2 + 30 X3 + 23 X4 + 53.8 X5 + 7 X6 + 4 X7 + 8 X8 + 9 X9 +
4 X10
     + 14 X11 + 41.6 X12 + X13 + 18 X14 + 8.8 X15 + 5.3 X16 + 5 X17 +
22 X18
     >=  0
     EFA)  12 X1 + 30 X2 + 59 X3 + 3.8 X4 + 169 X5 + X9 + X10 + 2 X11
     + 419 X12 + 2 X13 + 20 X14 + 1.1 X15 + X17 + 5 X18 >=   0
  NIACIN)  2 X1 + X2 + 46 X3 + 11 X4 + 10 X5 + 16.4 X6 + 13 X7 + 6
X8 + 6 X9
     + X10 + 6 X11 + 45 X12 + 4 X13 + 44 X14 + 4.9 X15 + 1.87 X16 + 6
X17
     + 9 X18 >=  0
    KCAL)  CALS >=  3400
     FAT)  13.5 X1 + 37.8 X2 + 69.1 X3 + 60.3 X4 + 194.5 X5 + 0.9 X6 +
0.9 X7
     + 0.9 X8 + 2.7 X9 + 1.8 X10 + 2.7 X11 + 446 X12 + 2.7 X13 + 22.5
X14
     + 2.34 X15 + 1.71 X16 + 1.8 X17 + 6.3 X18 - 0.2 CALS >=   0
    CALS)  106.46 X1 + 142.5 X2 + 287.16 X3 + 157.5 X4 + 554 X5 +
148.34 X6
     + 125.1 X7 + 138 X8 + 139.7 X9 + 61.4 X10 + 91.26 X11 +
694.70001 X12
     + 174.39999 X13 + 454.29999 X14 + 66.2 X15 + 35.5 X16 + 90.48
X17
     + 188.3 X18 - CALS =   0
     CHO)  79.3 X1 + 80.16 X2 + 140.3 X3 + 44.8 X4 + 211.3 X5 + 138.2
X6
     + 117.4 X7 + 130.2 X8 + 130.2 X9 + 56 X10 + 80.9 X11 + 157.7 X12
     + 161.3 X13 + 381 X14 + 52 X15 + 26.8 X16 + 85.08 X17 + 154
X18
     - 0.7 CALS >=  0
      41)  X8 >=  0.5
      42)  X17 >=  0.5
      43)  X14 >=  0.5
 END
```

OBJECTIVE FUNCTION VALUE

1) 12.2620500

VARIABLE	VALUE	REDUCED COST
X1	10.963390	.000000
X2	.085781	.000000
X3	.000000	.000000
X4	.000000	1.643888
X5	.000000	2.246654
X6	.000000	.403909
X7	.000000	.480829
X8	.500000	.000000
X9	.000000	.361057
X10	.000000	.899671
X11	.000000	.976613
X12	1.137271	.000000
X13	7.807065	.000000
X14	.000000	.102320
X15	.000000	1.198251
X16	.000000	1.185891
X17	.000000	.000000
X18	.000000	.637279
CALS	3400.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
PROTEIN)	.000000	-.029829
SCAA)	2370.384000	.000000
ARAA)	5936.865200	.000000
VAL)	3397.197000	.000000
THREO)	2502.119000	.000000
LYS)	2998.070000	.000000
LEU)	5091.890000	.000000
ISOLEU)	3106.514000	.000000
BIOTIN)	30.830180	.000000
B12)	.000000	-.368086
FOLACIN)	167.776300	.000000
VITA)	38593.601000	.000000
VITC)	12.500000	.000000
CA)	465.205130	.000000
P)	415.075400	.000000

K)	3328.604200	.000000
MG)	484.572000	.000000
NA)	2921.047300	.000000
I)	34.278260	.000000
TRY)	985.238030	.000000
RIBO)	559.226310	.000000
PANAC)	419.039940	.000000
PYRID)	65.155040	.000000
THIAMIN)	135.767700	.000000
VITE)	20.634780	.000000
VITK)	.000000	-.013930
FE)	184.444300	.000000
MN)	62.466064	.000000
CU)	99.310000	.000000
MB)	30.447550	.000000
SE)	41.377441	.000000
ZN)	123.629000	.000000
FIBER)	59.203300	.000000
EFA)	626.264600	.000000
NIACIN)	107.418000	.000000
KCAL)	.000000	-.003551
FAT)	.000000	-.062882
CALS)	.000000	.055938
CHO)	.000000	-.062756
41)	.000000	-.379150

NO. ITERATIONS= 1

OBJECTIVE FUNCTION VALUE

1) 12.8192400

VARIABLE	VALUE	REDUCED COST
X1	11.100050	.000000
X2	.094608	.000000
X3	.000000	.000000
X4	.000000	1.643888
X5	.000000	2.246654
X6	.000000	.403909
X7	.000000	.480829
X8	.500000	.000000
X9	.000000	.361057
X10	.000000	.899671
X11	.000000	1.011437
X12	1.132369	.000000
X13	7.476552	.000000
X14	.000000	.102320
X15	.000000	1.198251
X16	.000000	1.185891
X17	.500000	.000000
X18	.000000	.637279
CALS	3400.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
PROTEIN)	.000000	-.029829
SCAA)	2363.006300	.000000
ARAA)	5936.896400	.000000
VAL)	3393.794000	.000000
THREO)	2510.034000	.000000
LYS)	3024.425200	.000000
LEU)	5097.813400	.000000
ISOLEU)	3114.181000	.000000
BIOTIN)	31.536653	.000000
B12)	.000000	-.368086
FOLACIN)	171.859800	.000000
VITA)	38021.880000	.000000
VITC)	21.500000	.000000
CA)	468.831110	.000000
P)	408.613610	.000000

K)	3446.629000	.000000
MG)	486.672420	.000000
NA)	2801.813000	.000000
I)	34.256210	.000000
TRY)	985.903930	.000000
RIBO)	559.626500	.000000
PANAC)	430.796440	.000000
PYRID)	66.606310	.000000
THIAMIN)	139.130400	.000000
VITE)	22.400100	.000000
VITK)	40.000000	.000000
FE)	187.212400	.000000
MN)	61.413640	.000000
CU)	100.210610	.000000
MB)	29.158550	.000000
SE)	40.125720	.000000
ZN)	123.071900	.000000
FIBER)	61.177700	.000000
EFA)	625.954500	.000000
NIACIN)	109.157500	.000000
KCAL)	.000000	-.003551
FAT)	.000000	-.062882
CALS)	.000000	.055938
CHO)	.000000	-.062756
41)	.000000	-.379150
42)	.000000	-1.114380

NO. ITERATIONS= 2

OBJECTIVE FUNCTION VALUE

1) 12.8704000

VARIABLE	VALUE	REDUCED COST
X1	9.293263	.000000
X2	.077738	.000000
X3	.000000	.000000
X4	.000000	1.643888
X5	.000000	2.246654
X6	.000000	.403909
X7	.000000	.480829
X8	.500000	.000000
X9	.000000	.361057
X10	.000000	.899671
X11	.000000	1.011437
X12	1.165180	.000000
X13	7.160098	.000000
X14	.500000	.000000
X15	.000000	1.198251
X16	.000000	1.185891
X17	.500000	.000000
X18	.000000	.637279
CALS	3400.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
PROTEIN)	.000000	-.029829
SCAA)	2343.938400	.000000
ARAA)	5786.866200	.000000
VAL)	3316.017300	.000000
THREO)	2416.492000	.000000
LYS)	2793.417200	.000000
LEU)	4610.261000	.000000
ISOLEU)	3011.485000	.000000
BIOTIN)	31.925951	.000000
B12)	.000000	-.368086
FOLACIN)	177.893210	.000000
VITA)	38092.510000	.000000
VITC)	21.500000	.000000
CA)	447.870800	.000000
P)	290.193840	.000000

K)	3323.036300	.000000
MG)	550.383300	.000000
NA)	2685.256300	.000000
I)	32.990394	.000000
TRY)	955.605400	.000000
RIBO)	574.604000	.000000
PANAC)	434.706110	.000000
PYRID)	81.226921	.000000
THIAMIN)	157.762220	.000000
VITE)	26.725260	.000000
VITK)	40.000000	.000000
FE)	195.526000	.000000
MN)	77.589090	.000000
CU)	92.409553	.000000
MB)	29.724382	.000000
SE)	69.798522	.000000
ZN)	134.944700	.000000
FIBER)	71.209312	.000000
EFA)	626.881830	.000000
NIACIN)	127.737740	.000000
KCAL)	.000000	-.003551
FAT)	.000000	-.062882
CALS)	.000000	.055938
CHO)	.000000	-.062756
41)	.000000	-.379150
42)	.000000	-1.114380
43)	.000000	-.102320

NO. ITERATIONS= 1

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15. Supplementary Notes

16. Abstract

NASA's Controlled Ecological Life Support System (CELSS) Program is involved in developing a bioregenerative life support system that will supply food, air, and water to space crews on long-duration missions. An important part of this effort is is development of the knowledge and technological capability of producing and processing foods to provide optimal diets for space crews. This involves such interrelated factors as determination of the diet, based on knowledge of nutrient needs of humans and adjustments in those needs that may be required as a result of the unique conditions of long-duration spaceflight; determination of the optimal mixture of crops required to provide nutrients at levels that are sufficient but not excessive or toxic; and consideration of the critical issues of spacecraft space and power limitations, which impose a phytomass minimization requirement. This publication examines the complex interactions among these factors, with the goal of supplying a diet that will satisfy human needs while minimizing the total phytomass requirement. The approach taken has been to collect plant nutritional composition and phytomass production data, identify human nutritional needs and estimate the adjustments to the nutrient requirements likely to result from spaceflight, and then to generate mathematical models from these data.

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