CELSS Scenario Analysis: Breakeven Calculations

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April 1980

NASA
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Prepared for
Ames Research Center
under Purchase Order (P.O.) A70035 B

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N82-23982#
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INTRODUCTION

PURPOSE

This report summarizes the results of effort aimed toward the development of a rudimentary model that illustrates the relative mass requirements of food production components in a controlled ecology life support system (CELSS) based on regenerative concepts. The report is intended as a working paper which can provide a basis for further model development and analysis.

The model and analytic results can be useful for developing an understanding of the mass requirements for food production in a CELSS and how these requirements compare with food resupply requirements. Such an understanding aids in making knowledgeable decisions about research investment options in regenerative life support. More importantly, the documentation of the model and results reveals gaps in knowledge and thereby provides guidance for improving the model and the analysis procedures.

BACKGROUND

The need for life support options based on regenerative methods becomes increasingly important from a logistics standpoint for long duration missions. This need has been recognized and discussed in several workshops and reports (1,2,3,4,5).

Other studies, reports, and papers have proposed using scenario analyses to help evaluate research progress and to help program managers assess technology options for regenerative systems (6,7,8,9,10,11,12). The scenario analysis approach, although utilized in these prior studies, has heretofore not been documented in the detail necessary for comparative studies by other researchers. This report provides documentation of the initial model and illustrates its use and its sensitivity to changes in assumptions and parameter values. In addition to documenting the overall scenario model, this report also updates the diet assumed for the 1977 summer study (e.g., see 9).
MODEL SCOPE AND STRUCTURE

SCOPE

Assumptions

The model is a simple deterministic formulation that equates the mass required for food supply under two different scenarios: A) complete resupply of diet materials (baseline scenario) and B) part of the diet supplied by food grown in the space habitat by regenerative methods (alternative scenario). The model thus uses time as the dependent variable, permitting the calculation of a "breakeven time," which may be considered as the mission duration for which the total mass required for supplying dietary requirements under the baseline scenario equals the mass required under the alternative scenario.

Several simplifying general assumptions are implicit in the resulting formulation:

1. Mass requirements for the baseline food supply scenario are linear with time.

2. Total mass requirement for each scenario may be represented by a simple summation of component masses. Each component represents a particular necessary function and may further be subdivided into expressions representing subcomponents or macrocategories of design factors.

3. Several functional requirements which may be substantially different in the two scenarios are included from the model: energy collection, power generation, energy storage, and waste energy rejection; human and food supply waste processing requirements; and food and waste storage requirements.

4. Food production by conventional biological growth (plant photosynthesis) is a viable candidate food production process. (See also reference 13.)

Focus and Limitations

The above assumptions indicate the model's focus on the food production function itself and not on components and functions which may
be heavily dependent on the choice of food supply. The model, at this stage of development, therefore is useful primarily for comparing conventional food supply alternatives which are judged not to have a substantial difference in requirements for (or impacts on) energy and waste processing functions. The results of model calculations also can indicate orders of magnitudes of mass requirements on an absolute scale, providing a starting point for assessing alternative food supply scenarios and for determining the relative mass of food supply components.

MODEL STRUCTURE

Baseline Scenario (Resupply)

The baseline scenario is characterized by full resupply of necessary diet materials. The diet requirements are often given on a person-day or person-year basis. By letting $M_R$ by the resupply mass required for food (g/person-year), the food resupply mass for a population of $N_p$ for a period of $T$ years is given by

$$ (M_R)(N_p)(T). \quad (1) $$

To this mass should be added the mass required for air revitalization. Engineering considerations (14) suggest that this mass can be modeled by an expression representing a fixed mass and plus a mass which is linearly dependent on the number of persons:

$$ M_o + (M_{ov})(N_p). \quad (2) $$

The mass required for the resupply is thus given by the sum of (1) plus (2).

Alternative Scenario

The alternative scenario is characterized by recycling of nutrients, utilizing plants for growing food. The mass required for growing and processing the food may be represented by the sum of five mass components: the food-producing biomass ($M_B$), the mass of the harvesting equipment ($M_H$), the food production system mass (system components for plant growth, excluding the plant biomass itself, $M_{PS}$), the mass of the food processing equipment ($M_{PP}$), and the mass of the water of transpiration ($M_{WT}$) required in the plant growth environment (including the atmospheric/vapor phase and the nutrient reservoir but excluding the water contained in the plant biomass). Each mass would be given in grams (or kilograms) unless
other dimensions are specified. The total mass for the alternative scenario is given by

$$M_B + M_H + M_{PS} + M_{FP} + M_{WT}.$$  \hspace{1cm} (3)

Calculations for each of the components are given in the following paragraphs.

**Food Producing Biomass.** The total biomass required for the food production function is given by the sum of the biomass required for each of the individual foods in the diet. Letting $M_{Bj}$ be the biomass required to produce the daily dietary requirement of one person for food $j$, the total productive biomass is given by

$$\sum_j(M_{Bj})(N_p).$$  \hspace{1cm} (4)

$M_{Bj}$ is calculated from the dietary requirements which are met by the food produced by the plants. If the daily diet amount of food $j$ is $R_{ej}$, this is equal to the production rate of fresh edible food (g/person-day) and thus the total biomass harvest rate, $B_{oj}$ (g/person-day) is given by

$$B_{oj} = (R_{ej})/(e_{Bj}),$$  \hspace{1cm} (5)

where $e_{Bj}$ is the edible fraction (fresh). Assuming a simplified model of linear biomass growth over time, with $t_H$ as the total growing period (time to harvest), then

$$M_{Bj} = (B_{oj})(t_H/2).$$  \hspace{1cm} (6)

**Harvesting Equipment.** Food harvesting equipment for a CELSS has not been designed, and much of the harvesting functions may be fulfilled manually. Grain products (e.g., wheat) may be an exception, and this model assumes a single grain harvester (plot harvester) with a mass of 800 kg (15). That is, the initial assumption for harvesting equipment requirements is:

$$M_H = 800.$$  \hspace{1cm} (7)

**Food Production System.** The food production system consists of the components necessary to sustain productive plant growth in a controlled environment. These components include lighting, atmospheric control, plant support, and control components. Estimates for these components, based initially on a design for earth-based phytotron facilities, have been placed into three categories: (1) fixed mass components, whose mass is independent of the total growing area required (e.g., control
components), (2) an unscaled mass which is linearly related to the size of the growing area (e.g., lighting components), and (3) a scaled mass which increases with the size of the growing area by a power relationship (e.g., atmospheric control components). The last category uses the empirical engineering rule of 0.6 scaling, in which the mass requirement increases with the 0.6 power of the area. Such a scaling is consistent with components whose capacity would be related to volume rather than area, for example. (Appendix A gives the individual components of a ground-based controlled environment (phytotron-type) system, their mass, and the estimated masses for the three model categories.)

The model calculation for the food production system mass \( M_{PS} \) is therefore

\[
M_{PS} = M_{PSC} + (M_a)(A) + (M_{as})(A_B)^{0.6},
\]

where \( M_{PSC} \) is the total fixed (control component) mass, \( A \) is the growing area (or total illuminated area), \( M_a \) is the factor for the unscaled (linearly related to area) mass, and \( M_{as} \) is the scaled area factor.

The biomass growing area required per person (\( A_B \), in \( m^2 \)/person) is calculated from the dietary requirements for the diet components and the plant productivities. For food \( j \), the required area is given by

\[
A_{Bj} = \frac{(R_{ej})}{[(P_j)(e_{Bj})]},
\]

where \( R_{ej} \) is the dietary requirement (required fresh edible production rate), \( e_{Bj} \) is the edible fraction (fresh) of the total biomass harvested daily, and \( P_j \) is the biomass productivity, or total biomass growth rate (g/m\(^2\)-day).

**Food Processing Equipment.** Food processing equipment mass is estimated from data on current food preparation system technology and assumed engineering developments (16). The mass assumed for this equipment is

\[
M_{FP} = K(N_p)^x,
\]

where the factor \( K \) and the power \( x \) are determined by fitting a curve to the data for populations of 10 and 100 persons, and these parameters are 302.7 and 0.415, respectively, for \( M_{FP} \) in kilograms.

**Water Reservoir Mass.** The final component of mass in the alternative scenario is the water of transpiration, \( M_{WT} \) (kg). This mass includes the atmospheric (vapor phase) moisture in the plant growth chamber and the mass of the nutrient reservoir, but excludes the water in the plant...
biomass. Plants differ in the amount of water they transpire daily, but the amount can be modeled by a linear relationship to the dry biomass of the plant. Consequently, in order to compare different plants and different diets, the model incorporates a parameter which represents the number of days of transpired water assumed to be required in the system for the growing biomass. For plant \( j \), the water of transpiration mass, \( M_{WTj} \) is given by

\[
M_{WTj} = (10)(m_{Bdj})(N_p)(T_r),
\]

where \( m_{Bdj} \) is the dry biomass (kg/person) of plant \( j \), 10 is the empirical factor representing the ratio of water mass transpired (per day) to the plant's dry biomass, \( N_p \) is the population, and \( T_r \) is the design factor representing the number of days of transpiration water required by the system.
EXAMPLE CALCULATIONS

DIET AND PLANT GROWTH ASSUMPTIONS

Diet Basis

The diet requirements assumed for both the baseline and alternative scenarios are based on a "thrifty food plan." This diet is characterized by less consumption of animal tissue and somewhat more grain consumption than actual consumption patterns of food stamp recipients. The diet assumed for the model is the thrifty plan with small variations due to the assumed percentage of waste and to minor diet variations. Table 1 compares the actual food consumption pattern, the thrifty diet, and the diet assumed for the model. Note that the last column in the table also is equivalent to the required production rate of edible fresh food.

Plant Growth Rates

Plant growth data are taken from the literature on crop yield and plant productivity studies. The other model parameters related to ratios of fresh and dry weights, edible and total biomass, etc., are taken from the same literature. Table 2 presents these and the related calculated values for the major food plants in the assumed diet.

STORAGE AND RESUPPLY ASSUMPTIONS

For the baseline scenario, food must be stored or resupplied. The mass of this stored or resupplied food is assumed to be linearly related to the edible dry biomass, with the small residual moisture content and packaging mass being 53% of the dry mass. The daily resupply mass for food j is therefore

\[ M_{Rj} = (1.53)EB_{dj} \]  

where \( EB_{dj} \) is the edible biomass, dry, of food j.

The mass required for air revitalization, a function assumed to be performed adequately by the plants in the alternative scenario, is given by expression 2 for the baseline scenario. From reference 14, the total mass for air revitalization has a small (90.4 kg) fixed component and a larger variable component. The parameters for expression 2 are \( M_o = 90.4 \) and \( M_{ov} = 415.8 \).
Table 1. Food Quantities - Comparison of Consumption Pattern, Thrifty Diet, and Model Assumptions¹
(fresh weight, grams/person-day)

<table>
<thead>
<tr>
<th>Food Consumption Pattern</th>
<th>Thrifty Food Plan</th>
<th>Diet Assumed for Model Calculations (R_ej)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Milk, cheese, ice cream</td>
<td>548.4</td>
<td>404.5</td>
</tr>
<tr>
<td>B. Meat, poultry, fish</td>
<td>209.2</td>
<td>196.5</td>
</tr>
<tr>
<td>C. Eggs</td>
<td>41.1</td>
<td>34.3</td>
</tr>
<tr>
<td>D. Dry beans, peas, nuts</td>
<td>16.2</td>
<td>28.5</td>
</tr>
<tr>
<td>E. Potatoes</td>
<td>84.3</td>
<td>131</td>
</tr>
<tr>
<td>F. Dark green, deep yellow vegetables</td>
<td>24.3</td>
<td>25.3 Leaf Cabbage</td>
</tr>
<tr>
<td>G. Citrus fruit, tomatoes</td>
<td>110.3</td>
<td>116.7</td>
</tr>
<tr>
<td>H. Other vegetables, fruit</td>
<td>230.2</td>
<td>239.3</td>
</tr>
<tr>
<td>I. Grain products</td>
<td></td>
<td>Cereal 57.7 Wheat Equiv. 352</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flour 59.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bread 148.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other Bakery Products 86.3</td>
</tr>
<tr>
<td>J. Fats, oils</td>
<td>38.9</td>
<td>61.6</td>
</tr>
<tr>
<td>K. Sugar, sweets</td>
<td>55.1</td>
<td>55.8</td>
</tr>
<tr>
<td>L. Accessories</td>
<td>Not Given</td>
<td>Not Given</td>
</tr>
</tbody>
</table>

Notes:

¹Adapted from "The Thrifty Food Plan" (17) and "Report to J. Spurlock" (BSSG) from Marcus Karel (18).

²Based on National Survey of Food Stamp and Food Distribution Program Recipients, November, 1973 (Average 4-person Household); from "The Thrifty Food Plan" (17).

³Based on 20-54 year-old male nutritional requirements; amounts for some groups allow for approximately 5% discard and waste (e.g., egg shells).

⁴Tomatoes replace oranges on equal mass basis.

⁵Melons replace apples and bananas on 2.48 g per gram basis.
### Table 2. Plant Productivity Parameters for Major Foods

<table>
<thead>
<tr>
<th>Food</th>
<th>Column 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( R_e )</td>
<td>( t_H )</td>
<td>( T_{B_d} )</td>
<td>( P )</td>
<td>( E_{B_d} )</td>
<td>( E_{B_f} )</td>
<td>( e_B )</td>
<td>( B_o )</td>
<td>( A_B )</td>
<td>( w_e )</td>
<td></td>
</tr>
<tr>
<td>Dry Beans</td>
<td>16.2</td>
<td>47</td>
<td>43.1</td>
<td>204.3</td>
<td>21.1</td>
<td>24.3</td>
<td>0.119</td>
<td>136.1</td>
<td>0.67</td>
<td>0.132</td>
<td>19</td>
</tr>
<tr>
<td>Peanut Butter</td>
<td>12.3</td>
<td>110</td>
<td>49.5</td>
<td>355.0</td>
<td>8.2</td>
<td>9.4</td>
<td>0.026</td>
<td>473.1</td>
<td>1.33</td>
<td>0.126</td>
<td>20</td>
</tr>
<tr>
<td>Leaf, Head Cabbage</td>
<td>25.9</td>
<td>30</td>
<td>10.4</td>
<td>180.8</td>
<td>9.9</td>
<td>172.1</td>
<td>0.952</td>
<td>27.2</td>
<td>0.15</td>
<td>0.942</td>
<td>21</td>
</tr>
<tr>
<td>Carrots</td>
<td>11.7</td>
<td>80</td>
<td>43.6</td>
<td>315.6</td>
<td>21.3</td>
<td>154.2</td>
<td>0.489</td>
<td>23.9</td>
<td>0.08</td>
<td>0.862</td>
<td>21</td>
</tr>
<tr>
<td>Tomatoes</td>
<td>116.7</td>
<td>215</td>
<td>7.9</td>
<td>113.5</td>
<td>6.2</td>
<td>95.0</td>
<td>0.84</td>
<td>138.9</td>
<td>1.22</td>
<td>0.93</td>
<td>22</td>
</tr>
<tr>
<td>Potatoes</td>
<td>131.0</td>
<td>120</td>
<td>20.2</td>
<td>134.6</td>
<td>13.7</td>
<td>97.9</td>
<td>0.727</td>
<td>180.2</td>
<td>1.34</td>
<td>0.86</td>
<td>23</td>
</tr>
<tr>
<td>Green Beans</td>
<td>44.8</td>
<td>60</td>
<td>108.9</td>
<td>920.6</td>
<td>26.3</td>
<td>305.2</td>
<td>0.332</td>
<td>134.9</td>
<td>0.15</td>
<td>0.914</td>
<td>24</td>
</tr>
<tr>
<td>Lettuce</td>
<td>20.1</td>
<td>28</td>
<td>11.6</td>
<td>221.1</td>
<td>8.5</td>
<td>161.3</td>
<td>0.730</td>
<td>27.5</td>
<td>0.12</td>
<td>0.947</td>
<td>25</td>
</tr>
<tr>
<td>Melons</td>
<td>253.0</td>
<td>107</td>
<td>32.9</td>
<td>396.5</td>
<td>19.9</td>
<td>298.9</td>
<td>0.754</td>
<td>335.5</td>
<td>0.85</td>
<td>0.933</td>
<td>26</td>
</tr>
<tr>
<td>Peas</td>
<td>9.7</td>
<td>50</td>
<td>15.6</td>
<td>99.9</td>
<td>0.6</td>
<td>3.7</td>
<td>0.037</td>
<td>262.2</td>
<td>2.62</td>
<td>0.838</td>
<td>27</td>
</tr>
<tr>
<td>Wheat</td>
<td>352.2</td>
<td>196</td>
<td>148.4</td>
<td>505.3</td>
<td>58.5</td>
<td>67.2</td>
<td>0.133</td>
<td>2648.1</td>
<td>5.24</td>
<td>0.129</td>
<td>24</td>
</tr>
<tr>
<td>Totals</td>
<td>993.6</td>
<td>486.1</td>
<td>4387.6</td>
<td>13.77</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* \( R_e \) = daily requirement (g-person\(^{-1}\)·day\(^{-1}\); fresh); \( t_H \) = time to harvest (days); \( T_{B_d} \) = total biomass, dry; 
  \( P \) = productivity; \( E_{B_d} \) = edible biomass, dry; \( E_{B_f} \) = edible biomass, fresh (all g-m\(^{-2}\)·day\(^{-1}\)); \( e_B \) = edible fraction, fresh; \( B_o \) = biomass harvest rate (g-person\(^{-1}\)·day\(^{-1}\)); \( A_B \) = growing area required (m-person\(^{-1}\)); 
  \( w_e \) = fraction moisture, edible.
BREAKEVEN CALCULATION PROCEDURE AND RESULTS

The calculation of times (years) for which the baseline and alternative scenario mass requirements are equal initially was performed using two programs for a programmable hand calculator (HP-67). These programs, described in Appendixes C and D, permit rapid evaluation of detailed scenarios and the evaluation of the model's sensitivity to changes in single parameter values. Appendix B summarizes the nomenclature conventions for both programs.

The first program (Appendix C) calculates the plant productivity, growing area requirements, and the other calculated plant parameters from the fresh and dry total and edible biomass productivity factors, the dietary requirements, and the growing period (time to harvest) for individual cultivars.

The second program uses the results of the first and design parameters (population and assumed parameter values for the growing environment and food processing component masses) to calculate the mission duration for which the mass requirements of the two scenarios are equal. This program is a preliminary, incomplete version of the model outlined in the text above. Specifically, the program in Appendix D does not include expression (2), the mass assumed to be required for air revitalization components in the baseline scenario. Therefore, the program is particularly useful for calculating breakeven times for individual food items/cultivars (scenario comparisons in which air revitalization is required both for the baseline case and an alternative that involves limited on-board food production).

Table 3 presents the results of calculations for the major plant-produced foods. Note that wheat has the earliest breakeven time, followed by beans (dry and green), melons, and potatoes, with peas having the longest breakeven time.

For the alternative scenario in which virtually all plant-derived food is grown, with the biomass providing both food production and air revitalization functions, the breakeven time is 12.4 years, as shown in Table 4. This table also shows the results of modifying the initial values of the parameters to generate additional alternative scenarios for comparison with the resupply case.
Table 3. Breakeven Analysis Results – Comparison of Resupply and Regenerative Scenarios

Assumptions: Resupply mass = 1.53 x dry mass of food required.
Initial alternative scenario parameter values:
\[ N_p = 10 \quad M_f = 0 \quad M_{TSC} = 15.88 \quad M_a = 83.2 \]

<table>
<thead>
<tr>
<th>Food</th>
<th>(Baseline) Resupply Mass</th>
<th>Biomass Holdup Mass</th>
<th>Growing Env. Equip. Mass</th>
<th>MWT (kg)</th>
<th>TBE (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kg-person-yr(^{-1}))</td>
<td>(kg-person(^{-1}))</td>
<td>(kg)</td>
<td>(kg)</td>
<td>(yrs)</td>
</tr>
<tr>
<td>A. Dry Beans</td>
<td>7.87</td>
<td>3.22</td>
<td>955.3</td>
<td>69.9</td>
<td>13.1</td>
</tr>
<tr>
<td>B. Peanut Butter</td>
<td>6.00</td>
<td>25.6</td>
<td>1677</td>
<td>355.5</td>
<td>34.3</td>
</tr>
<tr>
<td>C. Cabbage</td>
<td>0.84</td>
<td>4.07</td>
<td>361.8</td>
<td>2.4</td>
<td>43.4</td>
</tr>
<tr>
<td>D. Carrots</td>
<td>1.00</td>
<td>1.01</td>
<td>189.2</td>
<td>13.9</td>
<td>22.7</td>
</tr>
<tr>
<td>E. Tomatoes</td>
<td>4.56</td>
<td>14.9</td>
<td>1578</td>
<td>109</td>
<td>37.3</td>
</tr>
<tr>
<td>F. Potatoes</td>
<td>10.24</td>
<td>10.8</td>
<td>1710</td>
<td>162.3</td>
<td>18.4</td>
</tr>
<tr>
<td>G. Green Beans</td>
<td>2.15</td>
<td>4.14</td>
<td>296.3</td>
<td>46.6</td>
<td>16.1</td>
</tr>
<tr>
<td>H. Lettuce</td>
<td>0.60</td>
<td>0.402</td>
<td>266.8</td>
<td>2.1</td>
<td>44.9</td>
</tr>
<tr>
<td>I. Melons (for Apples)</td>
<td>4.00</td>
<td>7.64</td>
<td>578.5</td>
<td>63.4</td>
<td>16.2</td>
</tr>
<tr>
<td>(for Bananas)</td>
<td>2.33</td>
<td>4.46</td>
<td>381.0</td>
<td>37.0</td>
<td>18.3</td>
</tr>
<tr>
<td>(for Fresh Fruit)</td>
<td>3.13</td>
<td>5.94</td>
<td>475.1</td>
<td>49.3</td>
<td>16.9</td>
</tr>
<tr>
<td>J. Peas</td>
<td>0.88</td>
<td>6.54</td>
<td>3061</td>
<td>102.1</td>
<td>360</td>
</tr>
<tr>
<td>K. Grain (Wheat)</td>
<td>171.3</td>
<td>259.5</td>
<td>5688</td>
<td>7629</td>
<td>7.9</td>
</tr>
</tbody>
</table>
Table 4. Breakeven Analysis, All Plants Combined

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Breakeven Time (T_{BE}, Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Initial values, above</td>
<td>12.4</td>
</tr>
<tr>
<td>B. As A, with M_o = M_{ov} = 0</td>
<td>12.4</td>
</tr>
<tr>
<td>C. As A, with peas resupplied</td>
<td>9</td>
</tr>
<tr>
<td>D. As C, with T_r = 1.1</td>
<td>8.5</td>
</tr>
<tr>
<td>E. As C, with peanut butter resupplied</td>
<td>9.7</td>
</tr>
<tr>
<td>F. As C, with NP = 100</td>
<td>8.5</td>
</tr>
<tr>
<td>G. As E, with N_p = 100</td>
<td>7.7</td>
</tr>
</tbody>
</table>

Initial Values

\[
M_{TR} = 214.8 \text{ (kg person}^{-1} \text{ yr}^{-1}) \quad M_{PSC} = 15.9 \text{ (kg)}
\]
\[
N_p = 10 \text{ (persons)} \quad M_a = 83.2 \text{ (kg m}^2\text{)}
\]
\[
T_r = 1 \quad M_{as} = 122 \text{ (kg m}^2\text{)}
\]
\[
N = 10 \quad M_{fp} = 787^* \quad A_B = 13.8 \text{ (m}^2\text{-person}^{-1})
\]
\[
M_B = 344.6 \text{ (kg person}^{-1})
\]
\[
M_{Bd} = 86.4 \text{ (kg person}^{-1})
\]
\[
M_H = 800 \text{ (kg)}
\]

Other values given in Table 2.

*Corresponding to \( K = 302.7 \) and \( \chi = 0.415 \) in equation (10).
DISCUSSION

ISSUES FOR FURTHER STUDY

The results of applying the model thus far indicate several issues which should be considered further. These issues are outlined in the following paragraphs.

Plant Productivity Measures

The area of the growth chamber has a relatively large impact on the overall CELSS mass requirements. Consequently, plant productivity, as measured by the yield of edible (and digestible) biomass per unit area, is an important consideration.

Another contributor to total mass of the regenerative system is the standing biomass, or "biomass holdup." Plants which have low biomass holdup for a given edible production are thus desirable. (Note that time to harvest, or maturity period, is not directly, or solely, an adequate measure of productivity.)

Functional Components

The results indicate that the components associated with the growth chamber (scaled and unscaled components) are significant contributors to the total mass. Reductions in the mass required for these components (e.g., lighting) should be possible.

CONCLUSIONS

The model, although limited in scope, provides a useful starting point for analyzing alternative diet and plant growth scenarios. Further refinement is underway to improve the model's utility and to facilitate its application by other researchers.
NOTES AND REFERENCES


13. "Biological Issues in Regenerative Life Support Research" (tentative title), Berrien Moore and Robert M. Mason (Eds.); Report on two workshops held in the Fall of 1979 at the New England Center, University of New Hampshire; to be available May, 1980.


15. Personal communication with David Raper, July, 1979. Estimate is based on substitution of lightweight materials for structural components of a commercially available plot harvester having a mass of approximately 1500 kg.

16. "Weight and Power Requirements of Grain Milling, Baking, and Feeding Systems for Space Habitats of 10 and 100 People, for a Limited PCELSS, Using Certain Simplifying Assumptions;" Unpublished report to J. Spurlock (Bioenvironmental Systems Study Group) from Marcus Karel, June, 1979. Adapting present systems and assuming some engineering development, the total milling, kitchen, and baking system masses are: 10 persons - 900 kg, and 100 persons - 2500 kg.


# Appendix A

## CONTROLLED ENVIRONMENT WEIGHT ESTIMATES

<table>
<thead>
<tr>
<th>System Component</th>
<th>Estimated Weights (lbs)</th>
<th>Initial</th>
<th>Optimistic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Net</td>
<td>(Net)</td>
</tr>
<tr>
<td></td>
<td>Fixed</td>
<td>Per .98m²</td>
<td>Per .98m²</td>
</tr>
<tr>
<td>1. Panels</td>
<td>612</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2. Fan Coil Assembly</td>
<td>150</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3. Refrigeration Cond. Unit</td>
<td>185</td>
<td>-</td>
<td>(Include w/heat rejection)</td>
</tr>
<tr>
<td>4. Lighting</td>
<td>150</td>
<td>-</td>
<td>150*</td>
</tr>
<tr>
<td>5. Control Console</td>
<td>76</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>6A. Humidification</td>
<td>33</td>
<td>-</td>
<td>33</td>
</tr>
<tr>
<td>b. Dehumidification</td>
<td>205</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7A. Exhaust &amp; Make up Air Blower</td>
<td>76</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B. CO₂ Analyzer</td>
<td>-</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>8. Plant Support Structure</td>
<td>150</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>9. Misc. Components</td>
<td>160</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>(Wireways-50; Insulation-10; Piping-50; Vibration Links-5; Wires-30; Valves, etc.-15)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (lb)</td>
<td>1797</td>
<td>35</td>
<td>180</td>
</tr>
<tr>
<td>(kg)</td>
<td>812.12</td>
<td>15.88</td>
<td>81.65</td>
</tr>
<tr>
<td>(kg/m²)</td>
<td>827.6</td>
<td>NA</td>
<td>83.21</td>
</tr>
</tbody>
</table>

1. David Raper, personal communication (estimates from Environmental Specialties, Raleigh, North Carolina).

2. Estimates by Mike Modell, Jack Spurlock, Dave Raper, and Bob Mason (79/06/26).

*Reduction should be possible.
Appendix B

NOMENCLATURE AND CONVENTIONS

Conventions

Subscript $j$ refers to type of crop in cultivar.
Total biomass defined as edible and inedible.
Underbar: per person basis.

<table>
<thead>
<tr>
<th>Parameter or Variable</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growing area ($m^2\cdot person^{-1}$)</td>
<td>$A_{ Bj}$</td>
</tr>
<tr>
<td>Total biomass harvest rate ($g\cdot person^{-1}\cdot day^{-1}$)</td>
<td>$B_{ oj}$</td>
</tr>
<tr>
<td>Edible fraction, fresh</td>
<td>$e_{ Bj}$</td>
</tr>
<tr>
<td>Mass requirement for growing area, unscaled components ($kg\cdot m^{-2}$)</td>
<td>$M_a$</td>
</tr>
<tr>
<td>Mass requirement for growing area, scaled components ($kg\cdot m^{-2}$)</td>
<td>$M_{ as}$</td>
</tr>
<tr>
<td>Dry biomass holdup ($g\cdot person^{-1}$)</td>
<td>$M_{ Bdj}$</td>
</tr>
<tr>
<td>Food processing equipment mass for 10 persons (kg)</td>
<td>$M_{ fp}$</td>
</tr>
<tr>
<td>Mass of food harvesting equipment (kg)</td>
<td>$M_H$</td>
</tr>
<tr>
<td>Total growing area equipment mass (kg)</td>
<td>$M_{ PS}$</td>
</tr>
<tr>
<td>Mass of control equipment for food production module (kg)</td>
<td>$M_{ PSC}$</td>
</tr>
<tr>
<td>Additional mass required for alternative scenario above that required for baseline scenario</td>
<td>$M_{ TP}$</td>
</tr>
<tr>
<td>Mass required for resupply/storage of food $j$ ($kg\cdot person^{-1}\cdot yr^{-1}$)</td>
<td>$M_{ TRj}$</td>
</tr>
<tr>
<td>Mass of (transpiration) water required for adequate humidity and nutrient reservoir</td>
<td>$M_{ wt}$</td>
</tr>
</tbody>
</table>
Parameter or Variable (cont.)

<table>
<thead>
<tr>
<th>Parameter or Variable</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>( N_p )</td>
</tr>
<tr>
<td>Total growth rate of fresh biomass ( (g \ m^{-2} \text{-day}^{-1}) )</td>
<td>( P_j )</td>
</tr>
<tr>
<td>Production rate of fresh edible food ( (g \text{ person}^{-1} \text{-day}^{-1}) )</td>
<td>( R_{ej} )</td>
</tr>
<tr>
<td>(Set equal to daily requirement)</td>
<td></td>
</tr>
<tr>
<td>Harvest waste, fresh ( (g \text{ person}^{-1} \text{-day}^{-1}) )</td>
<td>( R_{wj} )</td>
</tr>
<tr>
<td>Breakeven time (yrs); mission duration for which mass requirements of baseline and alternative scenarios are equal</td>
<td>( T_{BE} )</td>
</tr>
<tr>
<td>Total time to harvest (days)</td>
<td>( t_{Hj} )</td>
</tr>
<tr>
<td>Number of days of transpiration supply assumed</td>
<td>( T_r )</td>
</tr>
<tr>
<td>Fraction of water in total biomass</td>
<td>( w_{Bj} )</td>
</tr>
<tr>
<td>Fraction of water in edible portion</td>
<td>( w_{ej} )</td>
</tr>
<tr>
<td>Fraction of water in inedible portion</td>
<td>( w_{wj} )</td>
</tr>
<tr>
<td>Harvest waste water ( (g \text{ person}^{-1} \text{-day}^{-1}) )</td>
<td>( w_{wj} )</td>
</tr>
</tbody>
</table>
Appendix C

HP-67 PROGRAM FOR CULTIVAR CALCULATIONS

Storage

0 \( \mathbf{R}_{\mathbf{ej}} \)  
1 \( \mathbf{w}_{\mathbf{ej}} \)  
2 \( \mathbf{w}_{\mathbf{wj}} \)  
3 \( \mathbf{e}_{\mathbf{Bj}} \)  
4 \( \mathbf{t}_{\mathbf{Hj}} \)  
5 \( \mathbf{P}_j = TB_{fj} \)  
6 \( \mathbf{B}_{\mathbf{oj}} \)  
7 \( (TB_{dj}) \)  
8 \( (EB_{dj}) \)  
9 \( (EB_{fj}) \)  

Program Instructions

1. Key in \( TB_{dj} \), press \[ \text{ENT} \]
2. " " TB_{fj} " "
3. " " EB_{dj} " "
4. " " EB_{fj} " " \[ \text{A} \]
5. " " t_{Hj} " " \[ \text{ENT} \]
6. " " \( \mathbf{R}_{\mathbf{ej}} \) " " \[ \text{B} \]
7. Read out: 1) \( \mathbf{R}_{\mathbf{ej}} \)  
8) \( \mathbf{w}_{\mathbf{ej}} \)
9) \( \mathbf{w}_{\mathbf{wj}} \)
10) \( \mathbf{e}_{\mathbf{Bj}} \)
11) \( \mathbf{t}_{\mathbf{Hj}} \)
12) \( \mathbf{P}_j \)
13) \( \mathbf{w}_{\mathbf{wj}} \)
AGRICULTURAL DATA INPUT CONVERSIONS

Input Data Arrays

\[ \text{TB}_{dj} : \text{Total biomass, dry (g m}^{-2}\text{ day}^{-1}) \]
\[ \text{TB}_{fj} : \text{Total biomass, fresh (g m}^{-2}\text{ day}^{-1}) \]
\[ \text{EB}_{dj} : \text{Edible biomass, dry (g m}^{-2}\text{ day}^{-1}) \]
\[ \text{EB}_{fj} : \text{Edible biomass, fresh (g m}^{-2}\text{ day}^{-1}) \]

Derived Variable Arrays

\[ w_{ej} : \text{Fraction of water in edible portion} \]
\[ w_{wj} : \text{Fraction of water in inedible portion} \]
\[ e_{Bj} : \text{Edible fraction, fresh} \]
\[ P_{j} : \text{Total growth rate of fresh biomass (g m}^{-2}\text{ day}^{-1}) \]

Sequence of Calculations

\[ w_{ej} = \frac{\text{EB}_{fj} - \text{EB}_{dj}}{\text{EB}_{fj}} = 1 - \frac{\text{EB}_{dj}}{\text{EB}_{fj}} \]
\[ w_{wj} = \frac{(\text{TB}_{fj} - \text{EB}_{fj}) - (\text{TB}_{dj} - \text{EB}_{dj})}{(\text{TB}_{fj} - \text{EB}_{fj})} = 1 - \frac{\text{TB}_{dj} - \text{EB}_{dj}}{\text{TB}_{fj} - \text{EB}_{fj}} \]
\[ e_{Bj} = \frac{\text{EB}_{fj}}{\text{TB}_{fj}} \]
\[ P_{j} = \text{TB}_{fj} \]
ALGORITHM FOR AGRICULTURAL PRODUCTION

Design Variables

\[ N_p \] : Population

\[ R_{ej} \] : Production rate of fresh edible food (g person\(^{-1}\) day\(^{-1}\))

Data Arrays

\[ w_{ej} \] : Fraction of water in edible portion

\[ w_{wj} \] : Fraction of water in inedible portion

\[ e_{Bj} \] : Edible fraction, fresh

\[ t_{Hj} \] : Total time to harvest (days)

\[ P_{j} \] : Total growth rate of fresh biomass (g m\(^{-2}\) day\(^{-1}\))

Derived Variables

\[ w_{Bj} \] : Fraction of water in total biomass

\[ A_{Bj} \] : Growing area (m\(^2\) person\(^{-1}\))

\[ B_{oj} \] : Total biomass harvest rate (g person\(^{-1}\) day\(^{-1}\))

\[ M_{Bj} \] : Total biomass holdup (g person\(^{-1}\))

\[ R_{wj} \] : Harvest waste, fresh (g person\(^{-1}\) day\(^{-1}\))

\[ W_{wj} \] : Harvest waste water (g person\(^{-1}\) day\(^{-1}\))

Sequence of Calculations

1. \[ w_{Bj} = w_{ej} e_{Bj} + w_{wj} (1-e_{Bj}) \]
2. \[ A_{Bj} = \frac{R_{ej}}{P_{j} e_{Bj}} \]
3. \[ B_{oj} = \frac{R_{ej}}{e_{Bj}} \]
4. \[ M_{Bj} = B_{oj} t_{Hj}/2 \]
5. \[ R_{wj} = B_{oj} (1-e_{Bj}) \]
6. \[ W_{wj} = R_{wj} w_{wj} \]
<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>STO 9</td>
<td>29.</td>
</tr>
<tr>
<td>3.</td>
<td>÷</td>
<td>30.</td>
</tr>
<tr>
<td>4.</td>
<td>STO 8</td>
<td>31.</td>
</tr>
<tr>
<td>5.</td>
<td>÷</td>
<td>32.</td>
</tr>
<tr>
<td>6.</td>
<td>STO 5</td>
<td>33.</td>
</tr>
<tr>
<td>7.</td>
<td>÷</td>
<td>34.</td>
</tr>
<tr>
<td>8.</td>
<td>STO 7</td>
<td>35.</td>
</tr>
<tr>
<td>9.</td>
<td>1</td>
<td>36.</td>
</tr>
<tr>
<td>10.</td>
<td>RCL 8</td>
<td>37.</td>
</tr>
<tr>
<td>11.</td>
<td>RCL 9</td>
<td>38.</td>
</tr>
<tr>
<td>12.</td>
<td>÷</td>
<td>39.</td>
</tr>
<tr>
<td>13.</td>
<td>-</td>
<td>40.</td>
</tr>
<tr>
<td>14.</td>
<td>STO 1</td>
<td>41.</td>
</tr>
<tr>
<td>15.</td>
<td>RCL 7</td>
<td>42.</td>
</tr>
<tr>
<td>16.</td>
<td>RCL 8</td>
<td>43.</td>
</tr>
<tr>
<td>17.</td>
<td>-</td>
<td>44.</td>
</tr>
<tr>
<td>18.</td>
<td>RCL 5</td>
<td>45.</td>
</tr>
<tr>
<td>19.</td>
<td>RCL 9</td>
<td>46.</td>
</tr>
<tr>
<td>20.</td>
<td>-</td>
<td>47.</td>
</tr>
<tr>
<td>21.</td>
<td>÷</td>
<td>48.</td>
</tr>
<tr>
<td>22.</td>
<td>CHS</td>
<td>49.</td>
</tr>
<tr>
<td>23.</td>
<td>1</td>
<td>50.</td>
</tr>
<tr>
<td>24.</td>
<td>÷</td>
<td>51.</td>
</tr>
<tr>
<td>25.</td>
<td>STO 2</td>
<td>52.</td>
</tr>
<tr>
<td>26.</td>
<td>RCL 9</td>
<td>53.</td>
</tr>
<tr>
<td>27.</td>
<td>RCL 5</td>
<td>54.</td>
</tr>
</tbody>
</table>

**CULTIVAR CALCULATIONS PROGRAM LISTING**
Appendix D

HP-67 PROGRAM FOR BREAKEVEN CALCULATION

Storage

<table>
<thead>
<tr>
<th>Register</th>
<th>Parameter</th>
<th>Register</th>
<th>Parameter</th>
<th>Register</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>N_p</td>
<td>6</td>
<td>M_PSC</td>
<td>2</td>
<td>A_B</td>
</tr>
<tr>
<td>9</td>
<td>M_fp</td>
<td>5</td>
<td>M_h</td>
<td>1</td>
<td>M_as</td>
</tr>
<tr>
<td>8</td>
<td>T_r</td>
<td>4</td>
<td>M_Bd</td>
<td>0</td>
<td>M_a</td>
</tr>
<tr>
<td>7</td>
<td>M_TR</td>
<td>3</td>
<td>M_B</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Operating Instructions

1. Key in N_p Press (ENT)
2. " " M_TR " " (kg)
3. " " T_r " "
4. " " M_fp " " A
5. " " M_B \cdot 10^{-3} " (ENT) (M_B \cdot 10^{-3}) = \text{kg-person}^{-1}
6. " " M_Bd \cdot 10^{-3} " " (M_Bd \cdot 10^{-3}) = \text{kg-person}^{-1}
7. " " M_h " "
8. " " M_PSC " " B
9. " " M_a " " (ENT)
10. " " M_as " "
11. " " A_B " " C
12. Read out: T_{BE} Breakeven time (years)

M_{tp} Total PCELSS mass requirement (above resupply component mass)
M_{wt} Water mass - transpiration reservoir
M_{ps} Total growing environment equipment mass

Notes

To run again changing only a few parameter values:

key in new value, press STO X , where X is from above table. Repeat for each changed value

Press CTO 1 0 2 5 R/S
CELSS BREAK EVEN ANALYSIS PROGRAM LISTING

1. *LBL A 29. ENT 57. 1
2. STO 9 30. RCL 0 58. 5
3. + 31. X 59. y^X
4. STO 8 32. X + Y 60. RCL 9
5. + 33. . 61. X
6. STO 7 34. 6 62. STO C
7. + 35. y^X 63. RCL 3
8. STO I 36. RCL 1 63a. RCL I
9. R/S 37. X 63b. x
10. *LBL B 38. + 64. +
11. STO 6 39. RCL 6 65. RCL 5
12. + 40. + 66. +
13. STO 5 41. STO A 67. RCL A
14. + 42. RCL 1 68. +
15. STO 4 43. RCL 8 69. RCL B
16. + 44. X 70. +
17. STO 3 45. RCL 4 71. STO D (M_{TP})
18. R/S 46. X 72. RCL 7
19. *LBL C 47. 1 73. RCL I
20. STO 2 48. 0 74. X
21. + 49. X 75. ;
22. STO 1 50. STO B 76. - X - (T_{BE})
23. + 51. RCL I 77. RCL D'
24. STO 0 52. 1 78. - X - (M_{TP})
25. RCL 1 53. 0 79. RCL B
26. RCL 2 54. ; 80. - X - (M_{wt})
27. X 55. . 81. RCL A
28. ENT 56. 4 82. - X - (M_{PS})
29. RTN
Calculations

1. \( M_{\text{PSS}} = M_{\text{as}} (A \cdot B \cdot N_p)^6 \)
2. \( M_{\text{PSU}} = M_{\text{a-B-} N_p} \)
3. \( M_{\text{PS}} = M_{\text{PSS}} + M_{\text{PSU}} + M_{\text{PSC}} \) (STO A)
4. \( M_{\text{wt}} = 10 \cdot \frac{M_{\text{Bd}}}{N_p} \cdot T_r \) (STO B)
5. \( M_{\text{fp}} = M_{\text{fp}} \cdot \frac{N_p}{1.415} \) (STO C)
6. \( M_B = N_p \cdot M_B \)
7. \( M_{\text{TP}} = M_B + M_H + M_{\text{FP}} + M_{\text{PS}} + M_{\text{wt}} \) (STO D)
8. \( T_{\text{BE}} = M_{\text{TP}} \div (M_{\text{TR}} \cdot N_p) \)
APPENDIX E

FORTRAN Program for Breakeven Calculation

Purpose: This program is based on the PRELIMINARY SCENARIO ANALYSIS MODEL by Robert M. Mason.

Author: Martha Sadler, New View, Sept 1980

Environment:
DEC VAX-11/780 VAX/VMS VAX-11 FORTRAN IV-PLUS

Non-Standard Code:
VAX-11 FORTRAN IV-PLUS extensions of ANS FORTRAN 1966:
- Data types: CHARACTER, LOGICAL*1,
- Block IF logical structure: IF THEN, ELSE, ELSE IF, ENDIF statements
- END= and ERR= in READ or WRITE statements
- OPEN, CLOSE, DEFINE FILE file control specifications

Commons Used:
<name>    <description>
REAL1     Real variables
CHAR2     Character variables
INT3      Integer variables
LOG4      Logical variables

Subroutines Called:
<name>    <description>
BLOCK DATA COMMON DATA
PRODUC     This subroutine performs cultivar calculations.
BREAK      This subroutine performs breakeven calculations.
DESCRT     Gives description of variables when '?' input.
MPREIN     Modified version of FREEIN.FOR written by Walton
MDECDE     Modified version of DECODE.FOR written by Walton

Limitations
Exit Points
Constraints and Cautions
<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>DESCRIPTION</th>
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</thead>
<tbody>
<tr>
<td>TR</td>
<td>NUMBER OF DAYS OF TRANSPIRATION</td>
</tr>
<tr>
<td>MCONST</td>
<td>RATIO OF PLANT WHICH IS DRY WEIGHT</td>
</tr>
<tr>
<td>TBDJ</td>
<td>TOTAL DRY BIOMASS (G PER SQ M PER DAY)</td>
</tr>
<tr>
<td>TBD</td>
<td>TOTAL DRY BIOMASS (G PER SQ M PER DAY)</td>
</tr>
<tr>
<td>TBFJ</td>
<td>TOTAL FRESH BIOMASS (G PER SQ M PER DAY)</td>
</tr>
<tr>
<td>TBD</td>
<td>TOTAL DRY BIOMASS (G PER SQ M PER DAY)</td>
</tr>
<tr>
<td>EBDJ</td>
<td>DRY BIOMASS (G PER SQ M PER DAY)</td>
</tr>
<tr>
<td>EBD</td>
<td>DRY BIOMASS (G PER SQ M PER DAY)</td>
</tr>
<tr>
<td>EBFJ</td>
<td>FRESH BIOMASS (G PER SQ M PER DAY)</td>
</tr>
<tr>
<td>EBF</td>
<td>FRESH BIOMASS (G PER SQ M PER DAY)</td>
</tr>
<tr>
<td>WEJ</td>
<td>FRACTION OF WATER IN EDIBLE PORTION</td>
</tr>
<tr>
<td>MBD</td>
<td>DRY BIOMASS HOLDUP (G PER PERSON)</td>
</tr>
<tr>
<td>MSCP</td>
<td>MASS OF CONTROL EQUIPMENT FOR FOOD PRODUCTION MODULE (KG)</td>
</tr>
<tr>
<td>MA</td>
<td>MASS REQUIREMENT FOR GROWING AREA, UNSCALED COMPONENTS (KG PER SQ M)</td>
</tr>
<tr>
<td>MAS</td>
<td>MASS REQUIREMENT FOR GROWING AREA, SCALED COMPONENTS (KG PER SQ M)</td>
</tr>
<tr>
<td>MFP</td>
<td>FOOD PROCESSING EQUIPMENT MASS FOR 10 PERSONS (KG)</td>
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<td>MHB</td>
<td>MASS OF FOOD HARVESTING EQUIPMENT (KG)</td>
</tr>
<tr>
<td>WWJ</td>
<td>FRACTION OF WATER IN INEDIBLE PORTION</td>
</tr>
<tr>
<td>EBJ</td>
<td>EDIBLE FRACTION FRESH</td>
</tr>
<tr>
<td>PJ</td>
<td>TOTAL GROWTH RATE OF FRESH BIOMASS (G PER SQ M PER DAY)</td>
</tr>
<tr>
<td>WBJ</td>
<td>FRACTION OF WATER IN TOTAL BIOMASS</td>
</tr>
<tr>
<td>ABJ</td>
<td>GROWING AREA (SQ M PER PERSON)</td>
</tr>
<tr>
<td>REJ</td>
<td>PRODUCTION RATE OF FRESH EDIBLE FOOD (G PER PERSON PER DAY)</td>
</tr>
<tr>
<td>BOJ</td>
<td>TOTAL BIOMASS HARVEST RATE (G PER PERSON PER DAY)</td>
</tr>
<tr>
<td>THJ</td>
<td>TOTAL TIME TO HARVEST (DAYS)</td>
</tr>
<tr>
<td>TH</td>
<td>TOTAL TIME TO HARVEST (DAYS)</td>
</tr>
<tr>
<td>RWJ</td>
<td>HARVEST WASTE, FRESH (G PER PERSON PER DAY)</td>
</tr>
<tr>
<td>MBJ</td>
<td>TOTAL BIOMASS HOLDUP (G PER PERSON)</td>
</tr>
<tr>
<td>MB</td>
<td>TOTAL BIOMASS HOLDUP (G PER PERSON)</td>
</tr>
<tr>
<td>TOTMBJ</td>
<td>BIOMASS HOLDUP FOR TOTAL POPULATION</td>
</tr>
<tr>
<td>TOTMFP</td>
<td>FOOD PROCESSING EQUIPMENT MASS FOR TOTAL POPULATION (KG)</td>
</tr>
<tr>
<td>MTRJ</td>
<td>MASS REQUIRED FOR RESUPPLY/STORAGE OF FOOD J (KG PER PERSON PER YR)</td>
</tr>
<tr>
<td>MTP</td>
<td>ADDITIONAL MASS REQUIRED FOR ALTERNATIVE SCENARIO ABOVE</td>
</tr>
<tr>
<td>MWT</td>
<td>THAT REQUIRED FOR BASELINE SCENARIO</td>
</tr>
<tr>
<td>MPS</td>
<td>MASS OF WATER REQUIRED FOR ADEQUATE HUMIDITY AND NUTRIENT RESERVOIR</td>
</tr>
<tr>
<td>NP</td>
<td>POPULATION</td>
</tr>
<tr>
<td>TBE</td>
<td>BREAKEVEN TIME (YEARS)</td>
</tr>
</tbody>
</table>
FORTRAN PROGRAM

C SEE 'PRELIMINARY SCENARIO ANALYSIS MODEL', CELSS WORKING PAPER, C WP754-1 BY ROBERT MASON, APRIL, 1980

REAL DEFVAL(6,11), NUMBER, AMOUNT, GENVAR(6,2), USRVAL(6,11), TR,
X MCONST, TBDJ, TBFJ, EBDJ, EBFJ, WEJ, MBD, MPSC, MA, MAS, MFP, MH,
X WWJ, EBJ, PJ, WBJ, ABJ, REJ, BOJ, THJ, RWJ, MBJ, TOTMBJ, TOTMFP,
X MTRJ, MTP, MWT, MPS, NP, TBE, ALLMBD, ALLMTR, ALLMBJ, ALLABJ
CHARACTER*13 FDNAME(11), WHICH
CHARACTER*80 LINE
CHARACTER*6 VRNAME(6), GENAME(6), THIS
LOGICAL*1 FINISH, COMBND, POPULN
INTEGER OMEGA, VAL, FOOD, TERMOT, TERMIN, ANSR, LAST, DEFAUT, USER, SAVE
COMMON/REAL1/DEFVAL, NUMBER, AMOUNT, GENVAR, USRVAL, TR, MCONST,
* TBDJ, TBFJ, EBDJ, EBFJ, WEJ, MBD, MPSC, MA, MAS, MFP, MH, WWJ, EBJ, PJ, WBJ,
* ABJ, REJ, BOJ, THJ, RWJ, MBJ, TOTMBJ, TOTMFP, MTRJ, MTP, MWT, MPS, NP, TBE
COMMON/CHAR2/FDNAME, WHICH, LINE, VRNAME, GENAME, THIS
COMMON/LOG4/FINISH, COMBND, POPULN
COMMON/INT3/OMEGA, VAL, FOOD, TERMOT, TERMIN, ANSR, LAST, DEFAUT, USER

C
LAST = 6
SAVE = 12
OMEGA = 11
USER = 2
DEFAUT = 1
TERMOT = 6
TERMIN = 5
FINISH = .FALSE.
COMBND = .FALSE.
POPULN = .FALSE.

C
WRITE (TERMOT, 5)

5 FORMAT (' THIS PROGRAM IS BASED X ON THE PRELIMINARY SCENARIO',/,
X' ANALYSIS MODEL BY ROBERT M. MASON',//,
X' TO OBTAIN A DESCRIPTION OF A VARIABLE, TYPE IN--?VARIABLE',//,
X' NAME--WHEN INPUT IS ASKED FOR')
OPEN (UNIT=10, NAME='MASON.DAT', TYPE='OLD')

WRITE (TERMOT, 10)

10 FORMAT (' ', 'DO YOU WISH TO RUN A COMBINATION OF FOODS FOR',//,
* ' BREAKEVEN ANALYSIS, 1=YES, 0=NO')

C
READ (TERMIN, 15) LINE

15 FORMAT (A80)

C
IF (LINE(1:1).EQ.'?') THEN
   CALL DESCRT (LINE, 9)
ELSE
   MODE = 1
   CALL MFREIN (LINE, MODE, ANSR, NVAR, 9)
END IF

C
IF (ANSR.EQ.1) THEN
RUN COMBINATION

COMBND = .TRUE.
OPEN (UNIT=12,NAME='COMB.DAT',TYPE='NEW')
END IF

CALL PRODUC

C IF A COMBINATION IS RUN, BREAK EVEN CALCULATIONS ARE MANDATORY
IF (COMBND) THEN
  ANSR = 1
  GO TO 167
END IF

WRITE (TERMOT,160)
FORMAT ('DO YOU WISH BREAK EVEN CALCULATIONS, 1=YES, 2=NO')
READ (TERMIN,165) LINE

IF (LINE(1:1).EQ.'?') THEN
  CALL DESCRT (LINE,159)
ELSE
  MODE = 1
  CALL MFREIN (LINE,MODE,ANSR,NVAR,159)
END IF

IF (ANSR.EQ.1) THEN
  WRITE (TERMOT,168)
  FORMAT ('BREAK EVEN CALCULATIONS')
  IF (.NOT.POPULN) THEN
    WRITE (TERMOT,170)
    FORMAT ('ENTER POPULATION')
    READ (TERMIN,172) LINE
    FORMAT (A80)
    IF (LINE(1:1).EQ.'?') THEN
      CALL DESCRT (LINE,169)
    ELSE
      MODE = 0
      CALL MFREIN (LINE,MODE,NP,NVAR,169)
    END IF
  END IF
END IF

CALL BREAK
WRITE (SAVE,200) FDNAME(FOOD),MTRJ,MBJ,MBD,ABJ
FORMAT (A11,F6.2,F7.3,F7.3,F6.2)
END IF

IF (.NOT.COMBND) THEN

WRITE (TERMOT,600)
FORMAT ('DO YOU WISH TO RUN THE PROGRAM AGAIN, 1=YES, 0=NO')
READ (TERMIN,602) LINE
FORMAT (A80)
IF (LINE(1:1).EQ.'?') THEN
  CALL DESCRT (LINE,599)
ELSE
MODE = 1
CALL MFREIN (LINE,MODE,ANSR,NVAR,599)
END IF

C
IF (ANSR.EQ.1) THEN
   GO TO 20
END IF
ELSE
   POPULN = .TRUE.
END IF
WRITE (TERMOT,610)
FORMAT ("ANOTHER FOOD?, 1=YES, 0=NO")
READ (TERMOT,615) LINE
C
IF (LINE(1:1).EQ.?') THEN
   CALL DESCRT (LINE,605)
ELSE
   MODE = 1
   CALL MFREIN (LINE,MODE,ANSR,NVAR,605)
END IF
C
IF (ANSR.EQ.0) THEN
   FINISH = .TRUE.
ENDFILE SAVE
CLOSE (UNIT=12)
OPEN (UNIT=12,NAME='COMB.DAT',TYPE='OLD')
ALLMBD = 0
ALLMTR = 0
ALLMBJ = 0
ALLABJ = 0
READ (SAVE,700,END=710) MTRJ,MBJ,MBD,ABJ
700 FORMAT (11X,F6.2,F7.3,F7.3,F6.2)
ALLMTR = ALLMTR + MTRJ
ALLMBJ = ALLMBJ + MBJ
ALLMBD = ALLMBD + MBD
ALLABJ = ALLABJ + ABJ
GO TO 690
C
FDNAME(FOOD) = 'DIET'
MBD = ALLMBD
MTRJ = ALLMTR
MBJ = ALLMBJ
ABJ = ALLABJ
C
WRITE (TERMOT,720)
720 FORMAT ('BREAKEVEN CALCULATIONS FOR DIET')
CALL BREAK
C
ELSE
   GO TO 20
END IF
END IF
CLOSE (UNIT=10)
CLOSE (UNIT=12)
STOP
END
BLOCK DATA
REAL DEFVAL(6,11),NUMBER,AMOUNT,GENVAR(6,2),USRVAL(6,11),TR,
X MCONST,TBDJ,TBFJ,EBDJ,EBFJ,WEJ,MBD,MPSC,MA,MAS,MFP,MH,
XWWJ,EBJ,PJ,WBJ,ABJ,REJ,BOJ,THJ,RWJ,MBJ,TOTMBJ,TOTMFP,
X MTRJ,MTP,MWT,MPS,NP,TBE
CHARACTER*13 FDNAME(11),WHICH
CHARACTER*80 LINE
CHARACTER*6 VRNAME(6),GENAME(6),THIS
LOGICAL*1 FINISH,COMBND,POPULN
INTEGER OMEGA,VAL,FOOD,TERMOT,TERMIN,ANSR,LAST,DEFAULT,USER
COMMON/REAL1/DEFVAL,NUMBER,AMOUNT,GENVAR,USRVAL,TR,
X MCONST,TBDJ,TBFJ,EBDJ,EBFJ,WEJ,MBD,MPSC,MA,MAS,MFP,MH,
XWWJ,EBJ,PJ,WBJ,ABJ,REJ,BOJ,THJ,RWJ,MBJ,TOTMBJ,TOTMFP,
X MTRJ,MTP,MWT,MPS,NP,TBE
COMMON/CHAR2/FDNAME,WHICH,LINE,VRNAME,GENAME,THIS
COMMON/LOG4/FINISH,COMBND,POPULN
COMMON/INT3/OMEGA,VAL,FOOD,TERMOT,TERMIN,ANSR,LAST,DEFAULT,USER
DATA FDNAME/'DRY BEANS','PEANUT BUTTER','CABBAGE','CARROTS',
X'TOMATOES',' POTATOES',' GREEN BEANS',
X'LETTUCE','MELONS','PEAS','WHEAT',
X'MA','MAS'/
DATA VRNAME/'TH','TBD','TBF','EBD',
X 'EBF','MCONST'/
DATA DEFVAL/47.0,43.1,204.3,21.1,24.3,.217,
X110.0,49.5,355.0,8.2,9.4,.6,3.7,.156,96.0,148.4,505.3,58.5,67.2,294/END

SUBROUTINE PRODUC
THIS SUBROUTINE PERFORMS CULTIVAR CALCULATIONS

REAL DEFVAL(6,11),NUMBER,AMOUNT,GENVAR(6,2),USRVAL(6,11),TR,
X MCONST,TBDJ,TBFJ,EBDJ,EBFJ,WEJ,MBD,MPSC,MA,MAS,MFP,MH,
XWWJ,EBJ,PJ,WBJ,ABJ,REJ,BOJ,THJ,RWJ,MBJ,TOTMBJ,TOTMFP,
X MTRJ,MTP,MWT,MPS,NP,TBE
CHARACTER*13 FDNAME(11),WHICH
CHARACTER*80 LINE
CHARACTER*6 VRNAME(6),GENAME(6),THIS
LOGICAL*1 FINISH,COMBND,POPULN
INTEGER OMEGA,VAL,FOOD,TERMOT,TERMIN,ANSR,LAST,DEFAULT,USER
COMMON/REAL1/DEFVAL,NUMBER,AMOUNT,GENVAR,USRVAL,TR,
X MCONST,TBDJ,TBFJ,EBDJ,EBFJ,WEJ,MBD,MPSC,MA,MAS,MFP,MH,
XWWJ,EBJ,PJ,WBJ,ABJ,REJ,BOJ,THJ,RWJ,MBJ,TOTMBJ,TOTMFP,
X MTRJ,MTP,MWT,MPS,NP,TBE
COMMON/CHAR2/FDNAME,WHICH,LINE,VRNAME,GENAME,THIS
COMMON/LOG4/FINISH,COMBND,POPULN
COMMON/INT3/OMEGA,VAL,FOOD,TERMOT,TERMIN,ANSR,LAST,DEFAULT,USER
9 WRITE(TERMOT,10)
10 FORMAT(' ', 'WOULD YOU LIKE A LIST OF FOODS STORED IN THE LIBRARY,
X1=YES,0=NO')
READ(TERMOT,20)LINE
IF (LINE(1:1).EQ.'?') THEN CALL DESCRT (LINE,9)
ELSE
  MODE = 1
  NVAR = 1
  CALL MFREIN (LINE,MODE,ANSR,NVAR,9)
END IF

IF (ANSR.EQ.1) THEN
  WRITE (TERMOT,30) (FDNAME(I),I=1,OMEGA)
  FORMAT(' ',A13)
ENDIF

WRITE (TERMOT,50)
FORMAT (' ',/,' ENTER A SINGLE FOOD NAME')
READ (TERMIN,55) LINE

IF (LINE(1:1).EQ.'?') THEN
  CALL DESCRT (LINE,49)
ELSE
  WHICH = LINE(1:13)
END IF

DO 57 I=1,OMEGA
  IF (WHICH.EQ.FDNAME(I)) THEN
    FOOD=I
    GO TO 35
  ENDIF
57 CONTINUE

WRITE (TERMOT,60)
FORMAT (' ','FOOD NOT IN LIBRARY',/)
GO TO 9

WRITE (TERMOT,40) WHICH
FORMAT (' ',/,'WOULD YOU LIKE A LIST OF THE VARIABLES AND THEIR XDEFAULT VALUES FOR',/,' ',A13,' IN THE LIBRARY,ENTER 1 FOR YES, X0 FOR NO')
READ (TERMIN,45) LINE

IF ? THEN GETS DESCRIPTION OF VARIABLE
IF (LINE(1:1).EQ.'?') THEN
  CALL DESCRT (LINE,35)
ELSE
  MODE = 1
  NVAR = 1
C RETURNS ANSR
  CALL MFREIN (LINE,MODE,ANSR,NVAR,35)
END IF

IF (ANSR.EQ.1) THEN

DO 74 I=1,LAST
WRITE (TERMOT,71)VRNAME(I),DEFVAL(I,FOOD)
    FORMAT (' ',A6,4X,F5.1)
    CONTINUE
C
ENDIF
C
DO 75 VAL = 1,LAST
    USRVAL(VAL,FOOD) = DEFVAL(VAL,FOOD)
    CONTINUE
C
WRITE (TERMOT,80)
FORMAT (' ',W9,'WOULD YOU LIKE TO CHANGE A DEFAULT VALUE,1=YES,0 X=NO')
READ (TERMIN,85) LINE
FORMAT (A80)
C
IF (LINE(1:1).EQ.'?') THEN
    CALL DESCRT (LINE,77)
ELSE
    MODE = 1
    NVAR = 1
    CALL MPREIN (LINE,MODE,ANSR,NVAR,77)
END IF
C
IF (ANSR.EQ.1) THEN
    WRITE (TERMOT,90)
FORMAT (' ','WHICH VARIABLE?')
READ (TERMIN,95) LINE
FORMAT (A80)
C
IF (LINE(1:1).EQ.'?') THEN
    CALL DESCRT (LINE,98)
ELSE
    THIS = LINE(1:6)
END IF
C
WRITE (TERMOT,100)
FORMAT (' ','ENTER VALUE')
READ (TERMIN,101) LINE
FORMAT (A80)
C
IF (LINE(1:1).EQ.'?') THEN
    CALL DESCRT (LINE,98)
ELSE
    MODE = 0
    CALL MPREIN (LINE,MODE,NUMBER,NVAR,98)
END IF
C
DO 110 I=1,OMEGA
    IF (THIS.EQ.VRNAME(I)) THEN
        USRVAL(I,FOOD)=NUMBER
        GO TO 77
    ENDIF
C
110 CONTINUE
C
C ERROR ROUTINE
WRITE (TERMOT,115)
115 FORMAT (' ', 'VARIABLE NOT IN FILE')
GO TO 35
ENDIF

C VARIABLES SET TO DEFAULT OR USER DEFINED VALUES
THJ=USRVAL(1,FOOD)
TBDJ=USRVAL(2,FOOD)
TBFJ=USRVAL(3,FOOD)
EBDJ=USRVAL(4,FOOD).
EBFJ=USRVAL(5,FOOD)
MCONST = USRVAL(6,FOOD)

C WRITE (TERMOT,139),FDNAME(FOOD)
139 WRITE (TERMOT,140),FDNAME(FOOD)
140 FORMAT (' ', 'TO RUN PROGRAM ENTER DAILY REQUIREMENT OF ' ,A13, '/
X' IN GRAMS')
READ (TERMIN,141) LINE
141 FORMAT (A80)
C
IF (LINE(1:1).EQ.'?') THEN
   CALL DESCRT(LINE,139)
ELSE
   MODE = 0
   CALL MFREIN(LINE,MODE,AMOUNT,NVAR,139)
ENDIF

C EQUATIONS FOR CALCULATIONS
REJ = AMOUNT
WEJ = 1 - EBDJ / EBFJ
WWJ = 1 - ((TBDJ - EBDJ) / (TBFJ - EBFJ))
EBJ = EBFJ / TBFJ
PJ = TBFJ
WBJ = WEJ * EBJ + WWJ * (1-EBJ)
ABJ = REJ / (PJ * EBJ)
BOJ = REJ / EBJ
MBJ = (BOJ * THJ / 2) / 1000.
RWJ = BOJ * (1-EBJ)
HARWWJ = RWJ * WWJ

C WRITE (TERMOT,145)
145 FORMAT (' ', 'FOOD',10X,'REJ',5X,'TH',
X 4X,'TBDJ',3X,'TBFJ',3X,'EBDJ',
X3X,'EBFJ',3X,'EBJ',3X,'BOJ',5X,'ABJ',3X,'WEJ')
WRITE(TERMOT,150) FDNAME(FOOD),REJ,THJ,TBDJ,
X TBFJ,EBDJ,EBFJ,BOJ
X,ABJ,WEJ
150 FORMAT (' ',A13,F5.1,2X,F5.0,2X,4(F5.1,2X),F4.3,1X,F7.1,
X1X,F6.2,1X,F4.3)
C
RETURN
END

C
C
C SUBROUTINE BREAK
C THIS SUBROUTINE PERFORMS BREAKEVEN CALCULATIONS
REAL DEFVAL(6,11), NUMBER, AMOUNT, GENVAR(6,2), USRVAL(6,11), TR,
X MCONST, TBDJ, TBFJ, EBDJ, EBFJ, WEJ, MBD, MPSC, MA, MAS, MFP, MH,
X WWJ, EBJ, PJ, WBJ, ABJ, REJ, BOJ, THJ, RWJ, MBJ, TOTMBJ, TOTMFP,
X MTRJ, MTP, MWT, MPS, NP, TBE
CHARACTER*13 FDNAME(11), WHICH
CHARACTER*80 LINE
CHARACTER*6 VRNAME(6), GENAME(6), THIS
LOGICAL*1 FINISH, COMBND, POPULN
INTEGER OMEGA, VAL, FOOD, TERMOT, TERMIN, ANSR, LAST, DEFM
COMMON/REAL1/DEFVAL, NUMBER, AMOUNT, GENVAR, USRVAL, TR, MCONST,
* TBDJ, TBFJ, EBDJ, EBFJ, WEJ, MBD, MPSC, MA, MAS, MFP, MH, WWJ, EBJ, PJ, WBJ,
* ABJ, REJ, BOJ, THJ, RWJ, MBJ, TOTMBJ, TOTMFP, MTRJ, MTP, MWT, MPS, NP, TBE
COMMON/CHAR2/FDNAMB, WHICH, LINE, VRNAME, GENAME, THIS
COMMON/LOG4/FINISH, COMBND, POPULN
COMMON/INT3/OMEGA, VAL, FOOD, TERMOT, TERMIN, ANSR, LAST, DEFM, USER

WRITE (TERMOT, 180)
FORMAT(' ', 'DO YOU WISH A LIST OF VARIABLES AND DEFAULT VALUES,
X0=NO, 1=YES')
READ (TERMOT, 185) LINE
FORMAT(A80)

IF (LINE(1:1) .EQ. '?') THEN
  CALL DESCRT (LINE, 179)
ELSE
  MODE = 1
  CALL MFREIN (LINE, MODE, ANSR, NVAR, 179)
END IF

IF (ANSR .EQ. 1) THEN
  DO 210 I = 1, LAST
    WRITE (TERMOT, 195) GENAME(I), GENVAR(I, DEFM)
  END
  WRITE (TERMOT, 250)
  CONTINUE
ENDIF

C SETS DEFAULT VALUES TO USER VALUES
DO 220 I = 1, LAST
  GENVAR(I, USER) = GENVAR(I, DEFM)
END

WRITE (TERMOT, 230)
FORMAT(' ', 'DO YOU WISH TO CHANGE THE VALUE OF A VARIABLE,
X1=YES, 0=NO')
READ (TERMOT, 240) LINE
FORMAT (A80)

IF (LINE(1:1) .EQ. '?') THEN
  CALL DESCRT (LINE, 225)
ELSE
  MODE = 1
  CALL MFREIN (LINE, MODE, ANSR, NVAR, 225)
END IF

IF (ANSR .EQ. 1) THEN
  WRITE (TERMOT, 250)

36
FORMAT (' ' 'WHICH VARIABLE')
READ (TERMIN,260) LINE

IF (LINE(1:1).EQ.'?') THEN
   CALL DESCRT (LINE,249)
ELSE
   THIS = LINE(1:6)
END IF

WRITE (TERMOT,270)
FORMAT(' ' 'ENTER VALUE')
READ (TERMIN,272) LINE

IF (LINE(1:1).EQ.'?') THEN
   CALL DESCRT (LINE,269)
ELSE
   MODE = 0
   CALL MFREIN (LINE,MODE,NUMBER,NVAR,269)
END IF

DO 280 I=1,LAST
   IF (THIS.EQ.GENAME(I)) THEN
      GENVAR(I,USER)=NUMBER
      GO TO 225
   ENDIF
280  CONTINUE

WRITE (TERMOT,285)
FORMAT (' ' 'VARIABLE NOT IN FILE')
GO TO 179

SETS VARIABLES EQUAL TO USER VALUES
TR = GENVAR(1,USER)
MFP = GENVAR(2,USER)
MH = GENVAR(3,USER)
MPSC = GENVAR(4,USER)
MA = GENVAR(5,USER)
MAS = GENVAR(6,USER)

IF THE PLANT COMBINATION IS NOT COMPLETED (.NOT.FINISH) THEN
   MBD = MBJ * MCONST
   MTRJ = (EBDJ * 365.25 * 1.53 * ABJ) / 1000.
END IF

EQUATIONS FOR BREAK EVEN CALCULATIONS
MPS = (MPSC) + (MAS * (ABJ * NP) ** .6) + (MA * ABJ * NP)
MWT = 10. * MBD * NP * TR
TOTMFP = MFP * (NP / 10.) ** .415
TOTMB = NP * MBJ
MTP = TOTMB + MH + TOTMFP + MPS + MWT
TBE = MTP / (MTRJ * NP)

WRITE (TERMOT,290)
SUBROUTINE DESCRT(LINE,*)
C THIS SUBROUTINE RETURNS THE DESCRIPTION OF ANY VARIABLE WHEN A '?'
C VARIABLE NAME IS ENTERED

CHARACTER*80 LINE
CHARACTER*90 RECORD
CHARACTER*6 VARBLE
CHARACTER*83 SCRIPT
INTEGER FILE,TERMOT

FILE = 10
TERMOT = 6

C READS THE FILE THAT CONTAINS DESCRIPTIONS
5 READ (FILE,10,END=25) VARBLE,SCRIPT
10 FORMAT (A6,1X,A83)

C COMPARSES WITH FILE TO FIND DESCRIPTION
   IF (LINE(2:7).EQ.VARBLE) THEN
      WRITE (TERMOT,15) VARBLE,SCRIPT
15 FORMAT (' ',A6,3X,A83)
   GO TO 40
   C

C READS ANOTHER
ELSE
   GO TO 5
   C

C ERROR ROUTINE
25 WRITE (TERMOT,30)
30 FORMAT (' ',DESCRIPTION OF VARIABLE NOT FOUND')

C SETS POINTER AT BEGINNING OF FILE
40 REWIND FILE
RETURN
END
**Abstract**

This report considers a model of the relative mass requirements of food production components in a controlled ecological life support system (CELSS) based on regenerative concepts. Included are a discussion of model scope, structure, and example calculations. The report is intended to serve as a working paper which can provide a basis for further model development and analysis. Computer programs for cultivar and breakeven calculations are included.