NASA CR-166,331

NASA CONTRACTOR REPORT 166331

An Approach to the Mathematical Modelling of a Controlled Ecological Life Support System

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CONTRACT NAS2-10133
August 1981

CELSS

NASA

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An Approach to the Mathematical Modelling of a Controlled Ecological Life Support System

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Prepared for
Ames Research Center
under NASA Contract NAS2-10133

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CELSS

N82-23984#

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ABSTRACT

This report presents an approach to the design of a computer based mathematical model of a controlled ecological life-support system suitable for use in extraterrestrial habitats. The model is based upon elemental mass-balance and contains representations of the metabolic activities of biological components. The model can be used as a tool in evaluating relevant areas of pertinent biological research, as an aid in determining preliminary designs for closed regenerative life-support systems and as a method for predicting the behavior of such systems.

INTRODUCTION

To fully exploit the potential of space, NASA will need to develop the capacity to carry out long duration manned missions. Such missions may include:

- Orbiting space platforms
- Space energy systems
- Lunar bases and planetary bases
- Exploration of the asteroids.

Long mission lengths or difficulty of resupply will dictate that large volumes of consumable supplies be taken along. As the mass of such consumables becomes larger and larger, a point will be reached where regenerative methods will be economically competitive with the carrying or resupply of expendable supplies.

The need for research on regenerative methods was recognized in the 1978 report of the Life Sciences Advisory Committee (1) and the National Academy of Science (2). The development of a regenerative, closed life-support system for extraterrestrial applications will require a long lead time and will be dependent upon a fundamental research in a great variety of disciplines.

The essential functions of such a life-support system would include mechanisms for the maintenance of a habitable atmosphere, provision of food, potable water, and mechanisms of waste processing sufficient to permit minimal storage and resupply, all integrated and managed so as to persist for long periods of time. This system (CELSS) can be envisioned as a rigorously controlled life-support system, dependant upon regenerative processes carried out by fully integrated biological and physicochemical components. As the actual construction of such functional systems would be quite costly and as the time constants of such a system would be quite long, it is of interest to use computer modelling as a useful approach to the study of the behavior and design of conceptualized, closed, regenerative life-support systems.

A unique aspect of the modelling of closed, regenerative, human based life-support systems is the fact that such systems, with the possible exception of the Earth, do not exist. Thus the approach to modelling a CELSS differs from the usual approach which attempts to construct a model whose behavior imitates the behavior of an extant system. Of necessity, any mathematical model of a CELSS must be more speculative and general than accurate, and validation of the model must await the construction of an experimental CELSS.

Within this constraint, a reasonable modelling approach would be to base the model upon the apparant structure and function of studied ecosystems and to incorporate modifications dictated by the requirements of the CELSS. For example, in enclosing a natural ecosystem or reducing its size or species diversity such natural regulatory mechanisms as large buffers are excluded. Therefore such perturbed systems can only be maintained by replacing excluded natural control mechanisms by exogenous management and manipulation. Since the mechanisms of natural, endogenous ecosystem control and regulation are unknown, the nature of the exogeneous management and manipulation required are not clear.

Because a focus of the CELSS program is mass closure with the object of reducing the requirements for mass resupply, it is reasonable to construct models of CELSS behavior which depict the flow of elemental mass in the system. Extensive study of various natural ecosystems suggests that they demonstrate certain common features. The photosynthetic properties of plants allow them to use the energy in sunlight to synthesize complex polymers: carbohydrates, lipids, proteins and nucleic acids, from inorganic minerals and gases. As these nutrients become less available the growth of the plants will be curtailed. If the plants continue to act as sinks for these inorganic nutrients the environment will become depleted. Animals and microorganisms feed upon the plants to obtain energy and materials for growth and in so doing re-mineralize the organic polymers to provide nutrients for continued plant growth. These processes: photosynthesis, predation and decomposition, determine the flow and storage of elemental mass in a natural ecosystem. Analagous processes must form the functional basis of any synthetic, persistant, autonomous, human life-support system. A reasonable modelling approach would be based upon the these processes as described by equations of mass transfer and transformation and guided by the laws of mass conservation.

An input/output mass balance model following these concepts and describing the flow of the elements carbon, oxygen, and nitrogen in a rudimentary, conceptual, regenerative life-support system has been constructed at the Ames Research Center. This model envisions the CELSS to consist of a number of functional compartments between which elemental mass flows and in which elemental mass is stored. The choice of compartments represents a compromise between generality, with concommitant unrealistic simplicity, and detailed specificity with associated unwieldy complexity.

The model envisions that each day a fraction of the plant biomass is harvested and divided into an edible and inedible stream. The inedible stream is processed by a waste processor into inorganic nutrients while the edible fraction is stored as food. Upon dietary demand food, calculated as protein, fats, and carbohdrate, is transferred to the humans. Provision is made to transfer excess food from storage to waste processing as the system requires. The humans metabolize the food to waste materials: carbon dioxide, urea and undigested fecal material. The solid wastes are transferred to a waste processor for decomposition and the resulting inorganic compounds are fed to the plants to provide for growth.

The model can be used to provide insight into inherent CELSS features and characteristics, e.g., the relation of buffer capacity and response time to system stability, the identification of system and process control points, the effect of alternate control strategies upon system behavior and the effect of environmental perturbation upon plant physiology and development.

Diet

An important driver in designing a CELSS mathematical model is the human diet. This in turn will be determined by human nutritional requirements. In the model described herein it is assumed that an adequate human diet will initially be supplied by biologically produced food, specifically grains and vegetables. For example, a 70 Kg person can be sustained by a daily diet of 120 g of protein, 50 g of fat and 400 g of carbohydrate. There are a number of plant combinations that can satisfy these requirements. A daily diet of 360 g of wheat, 200 g of soybean, and 300 g of corn (dry weight) will supply 120 g of protein, 394 g of carbohydrate, 46 g of fat, and 2540 Kcal. In addition, adequate vitamins and minerals will be supplied by this diet with the exception of vitamin B12, and the possible exception of calcium and iron.

Crop Area

With these quantities as daily crop outputs, it is possible to roughly calculate the area required to support these yields. For example, a record yield for wheat has been reported as 14 tons/hectare (3). This is equivalent to 1.27×10^7 g/hectare. The amount of wheat required to maintain a 70 kg person on the above diet for a year is equal to 6.57×10^5 (all units in grams of grain, wet weight). Approximately 0.05 hectares, or 500 M^2 is required to produce the amount of wheat required to maintain one person for one year.

The above calculation is based upon a single yearly crop. In a controlled environment three crops/year should be available. This would reduce the required area to 170 M^2; while 4 crops/year (90 days from seed to harvest) would reduce the area to 125 M^2. Similarly an area of 0.04 hectares, or 400 M^2 could supply one 70 Kg person's requirements for soybeans at one crop/year, 133 M^2 at three crops/year, and 100 M^2 at four crops/year. Also, 0.02 hectares, or 200 M^2, could supply one persons requirements for corn at one crop/year, 87 M^2 at three crops/year and 50 M^2 at four corps/year. Thus a total area of between 275 M^2 and 1100 M^2 in continuous production could supply all the dietary requirements of a 70 Kg person. Further reductions in area would result from optimization of environmental parameters, e.g., carbon dioxide concentration, nutrient concentration, temperature, etc.

Stoichiometry of Soybeans

As soybean is the crop which forms the basis of the food production compartment modelled here, it is useful to go into some detail as to the stoichiometry used in the model. The nutrient composition of dry soybeans is 33.5% carbohydrate, 34.04% protein, 18.0% fat and 14.5% bound water (7). The elemental composition of 100 grams of dry soybeans with regard to C, O, H, and N is therefore:

	Grams				
	C	O	H	N	
Carbohydrate	14.89	16.54	2.07	-	
Fat	13.91	1.95	2.13	-	
Protein	18.19	2.53	2.42	5.37	
Water	-	12.90	1.61	-	
TOTAL	46.99	38.92	8.23	5.37	= 99.51

The difference between the theoretical weight (100 grams) and the calculated weight (99.51) is due to sulfur (0.25 g) and phosphorus (0.25 g).

There is data available in the literature on the elemental composition of whole soybean plants (6). Thus one can calculate the elemental composition of whole soy plants, food, and waste.

	Grams				
	C	O	H	N	TOTAL DRY WEIGHT
Whole Plant	97.87	96.40	16.67	8.22	219.16
Food	47.00	38.90	8.23	5.37	99.50
Waste	50.87	57.50	8.48	2.85	119.66

Elemental Composition of Humans

The following table gives the average composition of a human (8).

COMPONENT	% by WEIGHT
Water	60
Carbohydrate	1.5
Fat	18.5
Protein	15.0
Mineral Elements	5.0

For a 70 Kg person the mass of each component would be:

COMPONENT	Kg
Water	42.0
Carbohydrate	1.05
Fat	12.95
Protein	10.5
Mineral Elements	3.5

Using as a basis the elemental composition of starch, triolein, and casein, the elemental composition of a 70 Kg person is:

	Kg			
COMPONENT	C	O	N	H
Water	-	41.7778	-	4.667
Carbohydrate	.4666	.5185	-	.0648
Fat	10.013	1.4038	-	1.5334
Protein	5.6175	2.3247	1.659	.7484
TOTAL	16.0971	41.5803	1.659	7.0132

MODEL DEVELOPMENT

A model of an ecosystem can be considered as a representation of a system of living and nonliving components occupying a defined space through which energy, mass, and information flows. Since an ecosystem in space will, ideally, be closed to the introduction of mass, a mass-balance technique appears best suited to describe it (4,5). At a gross level, such a model can be represented as in Fig. 1.

The photosynthetic properties of autotrophs, such as plants, allow them to use the radiant energy of sunlight to synthesize complex polymers: carbohydrates, lipids, proteins, and nucleic acids, from CO_2, NO_3, PO_4, and other minerals. As these nutrients become less available the growth rate of the autotrophs will be curtailed. If the autotrophs continue to act as a sink for such minerals, the environment would eventually be depleted. Heterotrophs, such as animals which are incapable of using solar energy directly, feed upon the carbon compounds formed by plants. They are able to oxidize the compounds and thereby extract and trap energy. They are also able to use the compounds either directly or by re-arranging them for their own growth. The oxidation reactions of heterotrophs, including the decomposers, ultimately release CO_2 and the other minerals required by autotrophs.

This cycle of mineral fixation and release is an aspect of an ecosystem that can be simulated using models because the rates of flow of each mineral constituent in and out of the living organisms can be mathematically described. For example, Fig. 2 is a more general description of the reservoirs and flows depicted in Fig. 1, but also includes a more sophisticated view of the controls that can be exerted on the flows. This approach to the construction of mathematical models of ecosystems follows the technique of Quinlan (1975) and Quinlan and Paynter (1975).

Figure 2 depicts the transport of an element, X, between three storage compartments, inorganic nutrient storage (X_1), an autotrophic storage (X_2), and heterotrophic storage (X_3). The autotrophs take up and incorporate the inorganic nutrient into their biomass at a characteristic rate (TX_{12}), which is then ingested by the heterotrophs (TX_{23}) and remineralized back into inorganic nutrients (TX_{31}). In this simple closed loop, the laws of mass conservation dictate that the rate of change of mass in each compartment is a function of the rate of flow of mass into the compartment minus the rate of flow of mass out of the compartment, or:

$$dX_1/dt = TX_{31} - TX_{12}$$

$$dX_2/dt = TX_{12} - TX_{23}$$

$$dX_3/dt = TX_{23} - TX_{31}.$$

The rate of predatory matter flow, (TX_{23}) will fall to zero if either the predator (X_3) or prey (X_2) population goes to zero, and becomes saturated in X_2 as X_2 increases to some level. Finally, the rate of mineralization can be described by:

$$TX_{31} = k * X_{31} * X_3$$

The sum of the rates of change of mass in each compartment must equal zero:

$$\sum dX_m/dt = 0$$

and since mass is neither gained nor lost, it is a constant:

$$X_1 + X_2 + X_3 = M = \text{constant}.$$

The rates of elemental mass flow between the compartments are a function of the state of the compartments. This is indicated in Fig. 2 by the rate modulation signal flow. Thus, for this closed cycle, the following functional dependencies can be written:

$$TX_{12} = k * X_{12} * (X_1/a_1 + X_1) * X_2$$

which describes the observation that the nutrient uptake matter flows go to zero if either the nutrient pool (X_1) or the autotroph population (X_2) goes to zero and saturates in X, as X increases to some value.

Similarly,

$$TX_{23} = k * X_{23} * (X_2/a_2 + X_2) * X_3$$

Since the rate of predatory matter flow, (TX_{23}), will fall to zero if either the predator (X_3) or prey (X_{23}) population goes to zero, and becomes aturated in X_{23} as X_{23} increases to some level. The rate of mineralization can be described by:

$$TX_{31} = k * X_{31} * X_3$$

since the rate of mineralization (TX_{31}) will fall to zero when the heterotroph population (X_3) goes to zero, and is independent of the size of the nutrient pool (X_1) and does not saturate as X_3 increases.

The parameters kX_{12}, kX_{23}, and kX_{31} (rate constants), and a_1, a_2, a_3 (saturation constants) are determined by a number of variables, for example, variations in temperature, pressure, biological species, spatial distribution of elements, and light intensity.

These equations define the behavior in time of a simple closed element cycle model. The major elements in an ecosystem (C, H, N, O, S, P) are all modeled separately, however, and a realistic representation of the flow of elements in any ecosystem must allow for functional couplings such that all the individual element cycles are integrated into a single dynamic system. This can be done by cross-coupling individual element cycles by signal flow linkages. These linkages transmit information from one cycle to another such that the behavior of the latter is modulated by the behavior of the former. For example, Fig. 3 depicts the manner in which the flow of one element (e.g., carbon) might modulate the flow of another (e.g., phosphorus) and vice versa in our simple three-compartment closed ecosystem.

This model depicts the functional coupling of the C and P element cycles through intercycle rate modulations directed at nutrient uptake flows. Thus the state of autotrophic storage of carbon (C_2) regulates the nutrient flow of phosphorus into the autotrophic compartment (P_2) by means of the cross-coupling parameter KPC12, and the state of the autotrophic storage of phosphorus (P_2) regulates the flow of inorganic carbon into the autotroph compartment (C_3) through the cross-coupling parameter KPC12. Thus the rate of change of carbon storage in the autotroph compartment would modulate the rate of phosphorus uptake into the same compartment and vice versa. This is but one example of how elemental cycles can be linked so that perturbations in the behavior of one cycle can be transmitted to other cycles and thereby modulate their behavior.

Real ecosystems are of course vastly more complex than the simple three-compartment, two-element cycle model depicted in Fig. 3. Nevertheless, this simple model does represent a number of features of many closed ecosystems that might be designed for extraterrestrial situations, and as such represents a strategy of modelling that will shed light on the behavior of such systems.

MODEL OF CARBON FLOW

The initial steps involved in modelling the flow of elemental carbon in a CELSS involves disaggregating the conceptualized system into a number of compartments in which carbon is stored or transformed and calculating the mass balance of carbon as it flows between the compartments when the CELSS is functioning at a steady state. The system envisioned consists of six compartments: plant, food, humans, waste, atmosphere and carbon dioxide storage. Plant biomass is harvested and divided into an edible and a non-edible stream. The latter is stored in the food compartment or, if in excess, transferred to the waste compartment. The food is transferred to the humans while the agricultural wastes are processed to carbon dioxide. The humans metabolize the food producing stored fat and waste materials: undigested food, urea, and carbon dioxide. The solid wastes are transferred to the waste compartment where they are processed to carbon dioxide. It should be emphasized that other compartments which are involved in the flow of carbon in the system, e.g., water and oxygen, are ignored as they are not storage nodes for elemental carbon. The atmospheric level of carbon dioxide is adjusted by transferring appropriate quantities of the gas to and from a storage compartment. Finally, more plant biomass is synthesized from atmospheric carbon dioxide.

Tables 1 through 5 depict the stoichiometry of carbon as it flows through the plant compartment.

Table 1 indicates the total net weight relationships between the edible and nonedible portions of the harvested material of those crops that compose a reasonable diet, as discussed in the previous section; wheat, soybeans, and corn.

Table 2 indicates the carbon mass balance for these crops as reported in the literature (6). Table 3 presents the mass balance for carbon for these crops as calculated from their reported average nutrient content (i.e., % protein, % carbohydrate, and % fat) and the carbon content of each nutrient. There is good agreement for soybeans but some disagreement for wheat and corn. For the purposes of this model the data in Table 3 were used.

Table 4 presents the major nutrient content of the dry foodstuff and Table 5 shows the carbon content of the nutrients in each foodstuff.

Tables 6, 7, and 8 depict the stoichiometry of elemental carbon entering the human compartment as food and exiting as waste materials. For ease of calculation all food is considered to be composed of specific amounts of protein (casein), carbohydrate (starch), fat (triolein), and bound water. Tables 6, 7, and 8 present the stoichiometry of the metabolism of casein, starch, and triolein respectively. These data can be used to calculate the steadystate flow of elemental carbon in a simple, closed regenerative life-support system. The rate of change of the flow of carbon through each compartment can be described by a differential equation in the form of

dCARBON/dt = flow of carbon in - flow of carbon out.

The instantaneous level of carbon in each compartment can then be determined by integration of the appropriate differential equation.

Plant Compartment

Only one food crop, soybean, has considered in the model presented herein. The inclusion of other plants in the model for the purpose of completeness can be easily done retrospectively. The plant compartment is treated as if the crop is continuously growing and producing food at a constant rate. This would correspond to planting a small amount of seed and harvesting each day. A constant growth rate over a 115 day growing cycle is assumed. The carbon content in the crop is designated by the variable PLANT.

Each day (PLANT)(.0087) grams of crop carbon is harvested and a similar amount of carbon from atmospheric carbon dioxide is taken up and fixed into crop biomass. The carbon harvested is split into two streams: waste materials and food. The former comprises 51% of the harvested carbon while the latter comprises 49%. Thus the amount of carbon diverted to the waste processes equals (PLANT)(.0087)(.51) or (PLANT)(.0044), and the amount of carbon in the harvested food is (PLANT)(.0087)(.49), or (PLANT)(.0043). The growth rate of the crops is sensitive to many parameters such as atmospheric carbon dioxide levels, humidity, available nutrient levels, water supply, light quality and quantity, and temperature. For illustrative purposes the latter was chosen to be included in the model. Any combination of other parameters can be included in the same fashion. These data are included in the model in such a way as to permit the simulation language in which the model is expressed, ACSL, to modulate the plant growth rate by a factor between zero and one as calculated from the data supplied. Thus all the flows of carbon into and out of the plant compartment can be modulated by "looking up" the appropriate value for the modulating factor when a value for temperature or another parameter is specified. In the following equations the term (TEMPF) indicates the temperature function.

The state equation for the growth of the plant compartment is:

$$dPLANT/dt = (PLANT) * (.0087) * (TEMPF) - (PLANT) * (.0043) * (TEMPF) + (PLANT) * (.0044) * (TEMPF).$$

Food Compartment

The flow of carbon into the food compartment is derived from the plant compartment and is equal to (PLANT)(.0043)(TEMPF), while the flow out goes either to the human compartment, or if excess food, can be directed to the waste processor. The food transferred to the humans is designated by the variable CEAT and is a function of the calories required as defined by the program user (CALR). If however, the amount of food required by CALR is greater than is in the food compartment, the latter is transferred, thus:

$$CEAT = AMIN1(CALR * 0.1, FOOD)$$

where 0.1 converts the CALR to the grams of carbon required to yield that number of calories. Any excess food above a specified setpoint can be transferred to the waste processer. This is expressed by:

$$AMAX1(FOOD - setpoint, 0.)$$

Thus,

$$dFOOD/dT = (PLANT) * (.0043) * (TEMPF) - (CEAT + AMAX1(FOOD - setpoint, 0.))$$

Human Compartment

Food is transferred to the humans at a daily rate determined by their caloric requirements as specified by the program user. The metabolic fate of the carbon ingested, as well as of the stored carbon (human fat deposits), is determined by the relationship between the calories eaten and the calories utilized. When the calories ingested are equal to the calories used, all digested carbon will appear as metabolic wastes. When the calories eaten are greater than the calories utilized, a fraction of the digested carbon will be stored as fat. When the calories eaten are less than the calories used, digested carbon will appear as wastes together with a fraction of the stored carbon. Thus,

(CEAT) = The quantity of carbon eaten

(CEAT) * (.0684) = Undigested carbon

(CEAT) * (.9316) = Digested carbon.

$(1. - \text{AMAX1}(CAL_{in} - CAL_{out})/CAL_{in}, 0.) =$
fraction of digested carbon which is respired as a function of the ratio of calories utilized and calories eaten, and

$$\text{dHUMAN/dt} = (\text{CEAT}) - ((\text{CEAT}) * (.0684)) + \text{AMAX1}(CAL_{out} - CAL_{in}, 0.) * (0.0828) * (\text{CEAT}) * (0.9316) * (1. - \text{AMAX1}(CAL_{in} - CAL_{out})/CAL_{in}, 0).$$

Waste Processing Compartment

The inputs of carbon into the waste processor are: human wastes (fecal material and urine), inedible plant waste, and excess food. It is assumed that the waste is completely oxidized by the processor to carbon dioxide. The human wastes are equivalent to (CEAT) * (0.0684), plant waste to (PLANT) * (0.0044), and excess food to AMAX1(FOOD - setpoint, 0.). The output of carbon is equal to the contents of the waste processor multiplied by a rate constant, (WASTE) * (Rate Constant). Thus the state equation for the waste processing compartment is:

$$\text{dWASTE/dt} = ((\text{CEAT}) * (.0684)) + ((\text{PLANT}) * (0.0044) * (\text{TEMPF})) + \text{AMAX1}(\text{FOOD} - \text{setpoint}, 0.) - ((\text{WASTE}) * (\text{K4})).$$

Atmospheric Carbon Dioxide Compartment

The goal of the control of atmospheric carbon dioxide is to maintain its concentration at a specified point, either by removing or adding a specific amount of gas when it is appropriate. Thus, in addition to the metabolic and physicochemical sources and sinks for carbon dioxide, it is necessary to have a controllable reservoir of carbon dioxide which will function as a buffer.

The inputs of carbon to the atmosphere are: from the humans,

$$AMAX_1(CAL_{out} - CAL_{in}, 0.) * (0.0828) + (CEAT) * (0.9316) * (1. - AMAX1(CAL_{in} - CAL_{out})/CAL_{in}, 0.)$$

from the waste processor,

$$(WASTE) * (K4),$$

and from storage,

$$(K8) * AMAX1(STORE, 0.) * AMAX1(0., setpoint - CO_2).$$

The derivation for the storage term is given below.

The outputs of the atmospheric carbon dioxide compartment go to the plant compartment and to the storage compartment. The former is equal to

$$(PLANT) * (0.0087) * (TEMPF),$$

and the latter is given by:

$$AMAX1(CO_2 - setpoint, 0) * (K9).$$

Thus, the rate of change of elemental carbon in the atmosphere is:

$$dCO_2/dT = AMAX1(CAL_{out} - CAL_{in}, 0.) * (0.0828) + ((CEAT) * (0.9316) * (1. - AMAX1(CAL_{in} - CAL_{out})/CAL_{in}, 0.)) + ((WASTE) * (K4)) + ((K8) * (AMAX1(STORE, 0.)) * (AMAX1(0., setpoint - CO_2)) - ((PLANT) * (0.0087) * (TEMPF)) + ((K9) * AMAX1(CO_2 - setpoint, 0.)).$$

Carbon Dioxide Storage Compartment

The atmospheric carbon dioxide concentration must remain at a level consistant with maintenance of health for both humans and plants. In the model this concentration is predetermined by the user as a setpoint. Any carbon dioxide in excess of this amount is transferred to a storage compartment. The amount transferred is calculated by the expression:

$$AMAX1(CO_2 - setpoint, 0.) * (rate\ constant).$$

If the concentration of atmospheric carbon dioxide falls below the setpoint level, then carbon dioxide is transferred from storage to maintain the atmospheric levels. This flow should fall to zero when the storage compartment is empty. This can be calculated by:

$$AMAX1(STORE, 0.) * (AMAX_1(0., setpoint - CO_2) * (rate\ constant)).$$

The state equation for the carbon dioxide storage compartment is:

$$dSTORE/dT = (AMAX1(CO_2 - setpoint, 0.) * (rate\ constant) - AMAX1(STORE, 0.) * (AMAX1(0., setpoint - CO_2) * (rate\ constant).$$

All of the above state equations, together with appropriate values for initial conditions and rate constants as implemented for the ACSL simulation language, is shown in Program 1.

Lines 1 through 5 allocate values for constants and initial values for state variables. Lines 6 through 8 give the function TEMPF which relates the effect of temperature to a photosynthesis modulation factor. Lines 9 and 10 defines CEAT and CALIN. Lines 11 through 21 define the quantities transferred between the various state variables, while lines 22 through 27 give the differential equations for each state variable. Lines 28 through 34 are the integration commands for each state variable. CHANGE is a dummy variable which is equal to the sum of all the rates of carbon change in the system and ideally should be equal to zero in a mass balanced system. CSUM is the sum of the carbon mass in each state variable at any time and ideally should be a constant in a mass closed system. Line 36 instructs the program when to stop calculating. Model Result 1 is the output of the model when run at steady state.

MODEL OF OXYGEN FLOW

The following section describes the construction of a mathematical model written in ACSL which describes the flow of elemental oxygen in a closed, multicompartment, regenerative, lifesupport system. The dynamics of transformation of oxygen-containing molecules in a CELSS is a good deal more complex than that of either carbon or nitrogen and the modelling approach has been modified to reflect this complexity (Fig. 4).

The general approach consists of disaggregating the system into a number of submodels, each describing the flow of oxygen in the system as a function of the metabolism or chemical transformation of a specific oxygen-containing nutrient or chemical entity. These submodels are then combined to form an overall system model. The submodels developed are:

1. Carbohydrate
2. Protein
3. Fat
4. Bound Water
5. Inedible Plant Wastes
6. Excess Food.

Each of these submodels consists of a number of compartments in which elemental oxygen is stored and between which it flows.

The compartments and their associated symbols are:

COMPARTMENT	SYMBOL
Plant	A
Food	B
Human	C
Waste	D
Oxygen	E
Carbon Dioxide	F
Water	G
Harvest	K
Inedible (Straw)	L
Nitrate	H
Oxygen Reservoir	M
Sulfate	I
Phosphate	J

Carbohydrate Submodel

To model the flow of oxygen associated with the synthesis and metabolism of carbohydrate, it is necessary to determine the stoichiometry of oxygen flow in the closed system and to express these flows in mass-balance state equations. It is envisioned that the plant compartment will produce a daily amount of plant biomass consisting of carbohydrate, fat, protein, and bound water in a specific combination. The volatile water and fibre have been excluded from these calculations for simplicity. This biomass will be traferred to the food compartment. The synthesis of this amount of biomass will be associated with the photosynthetic production of a certain amount of gaseous oxygen. The food will be transferred to the humans, together with a characteristic quantity of gaseous oxygen for respiration. Waste products leaving the humans include undigested nutrient, uric acid, carbon dioxide, and water. The solid wastes and urine are transferred to the waste processors together with a stoichiometric quantity of gaseous oxygen for complete oxidation. The products of oxidation; carbon dioxide, water, and nitrate, are transferred to their respective compartments and from there are transferred to the plants to resynthesize food nutrients.

In the model program each flow is designated by a three-letter code indicating the compartment which is the source (first letter), the sink (second letter) and the letter C to indicate that the flow is part of the carbohydrate cycle. The compartments and their associated symbols were listed on page 18.

Thus, ABC is the flow of oxygen containing molecules between compartments A(PLANT) and B(FOOD) due to carbohydrate metabolism (i.e., starch molecules).

The state equations for the calculation of oxygen flow as a consequence of the metabolism of carbohydrate for each compartment are:

dPLANT/dT = (GAC + FAC) - (ABC + AEC)

dFOOD/dT = ABC - BCC

dHUMAN/dT = (BCC + ECC) - (CDC + CFC + CGC)

$dWASTE/dT = (CDC + EDC) - (DFC + DGC)$

$dOXYGEN/dT = AEC - (ECC + EDC)$

$dCO_2/dT = (DFC + CFC) - FAC$

$dWATER/dT = (CFC + DFC) - GAC$

where:

GAC = the flow of water into the plants for photosynthesis

FAC = the flow of carbon dioxide into the plants for photosynthesis

ABC = the amount of food carbohydrate harvested daily

AEC = the production of photosynthetic oxygen associated with ABC

BCC = the amount of carbohydrate eaten

ECC = the amount of oxygen required to metabolize BCC

CDC = the amount of undigested carbohydrate in wastes

EDC = the flow of oxygen into the waste processor required to oxidize CDC

CFC = the flow of respiratory carbon dioxide from humans to the atmosphere

CGC = the flow of metabolic water from humans to the water compartment

DFC = the flow of carbon dioxide from the waste processor to the carbon dioxide compartment

DGC = the flow of water from the waste processor to the water compartment.

Several of these flows are a function of the temperature of the plant compartment (AEC, FAC, GAC, AEF) while others are a function of the calories eaten and calories expended (CFC, CGC, ECC). Program 2 gives a listing of the carbohydrate submodel of the elemental oxygen cycle as written in ACSL. Model Result 2 gives the output of the submodel run at a steady state.

Fat Submodel

The state equations describing the flow of oxygen in a CELSS as a function of fat metabolism are:

dPLANT/dT = (GAF + FAF) - (ABF + AEF)

dFOOD/dT = ABF - BCF

dHUMAN/dT = (BCF + ECF + ECRF) - (CDF + CFF + CGF + CFRF + CGRF)

dWASTE/dT = (CDF + EDF) - (DFF + DGF)

dOXYGEN/dT = (AEF) - (ECF + EDF + ECRF)

dCO_2/dT = (DFF + CFF + CFRF) - FAF

dWATER/dT = (CGF + DFF + CGRF) - GAF

where:

ABF = transfer of fat from the plant compartment to the food compartment.

AEF = the flow of oxygen produced as a consequence of the synthesis of ABF from the plant compartment to the oxygen compartment

BCF = flow of fat from the food to the human compartment

CDF = flow of undigested fat from humans to the waste processor

CFF = transfer of carbon dioxide produced by the metabolism of exogenous dietary fat from the humans to the carbon dioxide compartment

CFRF = flow of carbon dioxide derived from the metabolism of endogenous stored fats from the human compartment to the carbon dioxide compartment

CGF = flow of water derived from the metabolism of exogenous, dietary fat between the human and water compartment

CGRF = the transfer of water produced by the metabolism of endogenous fats from the human to the water compartment

DFF = the transfer of carbon dioxide produced by the waste processor to the carbon dioxide compartment

DGF = the transfer of water produced by the waste processor to the water compartment

ECF = the transfer of oxygen from the atmosphere to the humans for the oxidation of exogenous, dietary fat

ECRF = the transfer of oxygen from the atmosphere to the humans for the oxidation of endogenous reserve fat

EDF = the transfer of oxygen from the atmosphere to the waste processor for the oxidation of waste fats.

Program 3 gives a listing of the fat submodel. Model Result 3 gives the output of the model run at a steady state.

Protein Submodel

The modelling of the flow of oxygen in a CELSS as a function of the metabolism of protein is similar to that of fats and carbohydrates. The major difference is the need for three additional compartments: nitrate, sulfate, and phosphate, reflecting the presence of elemental nitrogen, sulphur and phosphorus in protein.

The state equations for the flow of protein-related oxygen in a CELSS are:

dPLANT/dT = (FAP + GAP + HAP + IAP + JAP) - (ABP + AEP)

dFOOD/dT = ABP - BCP

dHUMAN/dT = (BCP + ECP) - (CDP + CFP + CGP + CIP + CJP)

$dWASTE/dT = (CDP + EDP) - (DFP + DGP + DHP)$

$dOXYGEN/dT = AEP - (ECP + EDP)$

$dCO_2/dT = (CFP + DFP) - FAP$

$dWATER/dT = (CGP + DGP) - GAP$

$dNITRATE/dT = DHP - HAP$

$dSULFATE/dT = (CIP + DIP) - IAP$

$dPHOSPHATE/dT = (CIP + DJP) - JAP$

where:

ABP = flow of protein from the plants to the food compartment

AEP = flow of photosynthetically produced oxygen associated with the synthesis of protein from the plants to the oxygen compartment

BCP = flow of protein from the food compartment to the humans

CDP = flow of human wastes associated with the ingestion and metabolism of protein from the humans to the waste processor

CFP= flow of carbon dioxide produced by the metabolism of ingested protein from the humans to the atmospheric carbon dioxide compartment

CGP = flow from the humans to the water compartment of the water produced by the metabolism of ingested protein

CIP = flow of waste urinary sulfate from the humans to the sulfate compartment

CJP = flow of waste urinary phosphate from the humans to the phosphate compartment

DFP = flow of carbon dioxide produced by the waste processor to the carbon dioxide compartment

DGP = flow of water produced by the waste processor to the water compartment

DHP = flow of nitrate produced by the waste processor to the nitrate compartment

DIP = flow of sulfate produced by the waste processor to the sulfate compartment

DJP = flow of phosphate produced by the waste processor to the phosphate compartment

ECP = transfer of oxygen from the atmosphere to the human compartment for protein related respiration

EDP = transfer of oxygen from the atmosphere to the waste processor for oxidation of protein related wastes

FAP = flow of carbon dioxide to the plant compartment for protein biosynthesis

GAP = flow of water to the plant compartment for protein biosynthesis

NAP = flow of nitrate to the plant compartment for protein biosynthesis

IAP = flow of sulfate to the plant compartment for protein biosynthesis

JAP = flow of phosphate to the plant compartment for protein biosynthesis.

Program 4 gives a listing of the protein submodel of the oxygen elemental cycle written in ACSL and Model Result 4 gives the output of the submodel run at a steady-state.

Inedible Plant Wastes Submodel

The plant harvest is processed in the model in two streams: edible food and inedible plant wastes. A new compartment, HARVEST, is utilized which has as its input plant biomass, and as its outputs flows to the food compartment and to the inedible plant wastes storage compartment (STRAW).

The state equations for the plant wastes submodel are:

$$dPLANT/dT = (FAS + GAS + HAS) - (AKS + AES)$$

$$dHARVEST/dT = AK - (KLS + KB)$$

$$dOXYGEN/dT = AES - EDS$$

$$dCO_2/dT = DFS - FAS$$

$$dWATER/dT = DGS - GAS$$

$$dNITRATE/dT = DHS - HAS$$

$$dWASTE/dT = (EDS + LDS) - (DFS + DGS + DHS)$$

$$dSTRAW/dT = KLS - LDS$$

where:

FAS = flow of carbon dioxide into the crop for the synthesis of inedible plant biomass

GAS = flow of water into the plant for the synthesis of inedible plant biomass

HAS = flow of nitrate into the plant for the synthesis of inedible plant biomass

AKS = flow of inedible plant biomass into the harvest compartment

AES = synthesis of oxygen by the plants due to the photosynthetic production of inedible plant biomass

AK = total plant biomass (edible and inedible) harvested

KLS = flow of inedible plant biomass from the harvest compartment to the storage compartment

KB = flow of edible plant biomass from the harvest compartment to the food compartment

EDS = flow of oxygen from the atmosphere to the waste processor for the oxidation of inedible plant wastes

LDS = flow of inedible plant wastes from its storage compartment to the waste processor

DHS = flow of nitrate produced by the waste processor by the oxidation of plant wastes to the nitrate compartment

DFS = flow of carbon dioxide produced by the waste processor by the oxidation of plant wastes to the carbon dioxide compartment

DGS = flow of water produced by the waste processor by the oxidation of plant wastes to the water compartment.

Program 5 is a listing of inedible plant waste, as written in ACSL, and Model Result 5 gives the output of the submodel run at a steady state.

Excess Food Submodel

Provision is made in the model for the transfer of food from the food storage compartment to the waste processor whenever the amount of stored food exceeds a user-specified setpoint. Thus a gross mismatch in the rate of food production and utilization will not result in an ever-increasing fraction of the elemental mass being transferred and held in stored food. Alternatively one could bring the rates into congruence by reducing the rate of food production but this would effect other state variables such as oxygen production.

It is envisioned that periodically the amount of food in the stored food compartment is compared to a user-specified setpoint. If the former is greater than the latter, the excess food is transferred to the waste processor together with that amount of oxygen required for its complete oxidation. The oxidation products: water, carbon dioxide, and nitrate, are transferred to their respective storage compartments.

The state equations for this submodel are:

$$dPLANT/dT = (GAX + FAX + HAX) - (AEX + BDX)$$

$$dFOOD/dT = BDX$$

$$dWASTE/dT = (BDX + EDX) - (DGX + DFX + DHX)$$

$$dOXYGEN/dT = AEX - EDX$$

$$dCO_2/dT = DFX - FAX$$

$$dWATER/dT = DGX - GAX$$

$$dNITRATE/dT = DHX - HAX$$

where:

GAX = flow of water from its compartment to the plants for the synthesis of excess food

FAX = flow of carbon dioxide from its compartment to the plants for the synthesis of excess food

HAX = flow of nitrate from its compartment to the plants for the synthesis of excess food

AEX = transfer of oxygen from the plants to the atmosphere as a consequence of the photosynthetic production of excess food

BDX = flow of excess food from the food compartment to the waste processor

EDX = flow of oxygen from the atmosphere to the waste processor for the oxidation of excess food

DEX = flow of carbon dioxide from the waste processor to the atmosphere

DFX = flow of water from the waste processor to its compartment

DHG = flow of nitrate from the waste processor to its compartment.

Program 6 is a listing of the excess food submodel and Model Result 6 is the output of the submodel run at a steady state.

Bound Water Submodel

The harvested and stored food is treated in the model as dry, i.e., all volatile water driven off. However, there is still water associated with the soybean. This nonvolatile water is referred to as bound water and it comprises some 14.5% of the weight of the soybean. Unlike the nutrients modelled above, bound water undergoes only phase changes. It is not chemically transformed, i.e., the molecule of water does not undergo any making or breaking of chemical bonds. For completeness, a bound water submodel has been prepared.

The state equations are:

dPLANT/dT = GAW - ABW

dFOOD/dT = ABW - BCW

dHUMAN/dT = BCW - CGW

dWATER/dT = CGW - GAW

where:

GAW = the transfer of water to the plant for incorporation into soybeans as bound water

ABW = transfer of food-associated bound water from the plants to the food compartment

BCN = transfer of bound water from the food compartment to the humans

CGW = transfer of bound water from the humans to the water compartment.

Oxygen Buffer Submodel

In a CELSS it is necessary to provide a mechanism by which the atmospheric levels of oxygen can be controlled at a desired level. Thus excess oxygen should be removed and placed in storage while the reverse mechanism will raise the oxygen concentration when required. This can be modelled simply as a reversable flow between two compartments: the atmosphere and an oxygen compartment. The direction of flow should be a function of the difference between the actual atmospheric oxygen concentration and the desired concentration (setpoint). The state equations for this submodel are:

$$dSTORAGE/dT = EM - ME$$

where:

EM = the flow of oxygen from the atmosphere to the oxygen storage compartment

ME = flow of oxygen from the storage compartment to the atmosphere

Linking the Submodels

To depict the behavior of the elemental oxygen cycle it is necessary to mathematically link the several submodels described above to run as a single unit. This has been done by a single differential equation which represents the total flow of oxygen through each compartment of the model. This equation is generated by arithmetically adding the several individual submodel streams. Thus the total flow of oxygen through the plant compartment is equal to the flow due to the synthesis of dietary carbohydrate, protein, fat, bound water, inedible wastes, and excess food:

$$dPLANT/dT = (dPLANT_{carb}/dT) + (dPLANT_{prot}/dT) + (dPLANT_{fat}/dT) + (dPLANT_{water}/dT) + (dPLANT_{wastes}/dT) + (dPLANT_{excess}/dT)$$

All of the terms on the right side of the equation are calculated by the state equations for the plant compartment in the respective submodels. In this manner the state equations for all the compartments in the oxygen model can be constructed.

Program 7 gives a listing of the elemental oxygen cycle in a CELSS, as described above, and Model Result 7 gives the output of the model as run in the steady state.

MODEL OF NITROGEN FLOW

Nitrogen is a key element in human metabolism. It is a component of amino acids used in the synthesis of proteins. Of particular concern in the design and function of a closed, regenerative life-support system is the phenomenon of denitrification; the chemical transformation of nitrogen from a solid form (e.g., nitrate) to a gaseous form (e.g., nitrogen gas). If this change of physical form is not reversed, all of the mass of nitrogen will be converted to a form which will not be available for biosynthesis. There are several mechanisms by which denitrification can occur, both microbiological and physicochemical. Thus modelling the flow of nitrogen with special attention to denitrification and nitrogen fixation is of particular importance.

For the purposes of modelling it is envisioned that a CELSS consists of 9 compartments through which elemental nitrogen will flow: plant, harvest, inedible wastes, food, humans, human wastes, nitrous oxide, nitrate and diatomic nitrogen. It is envisioned that each day a fraction of the plant biomass is harvested and a similar amount synthesized from inorganic nutrients and carbon dioxide. The harvested material contains elemental nitrogen primarily incorporated in proteins. The harvested biomass is divided into two streams: edible and inedible. The edible material is stored as food while the inedible material is processed by a waste processor into various nitrogen-containing compounds, the amounts and variety of which is a function of the type of process used. The food is transferred to the humans where it is metabolized and excreted as fecal wastes and uric acid. These wastes are then processed into inorganic nitrogen compounds including nitrate. The nitrate is taken up by the plants. 100 g dry weight of soybean plant biomass contains 8.22 g of elemental nitrogen. Of this amount 2.85 g is in the inedible biomass while 5.37 g is in the edible fraction. Humans (in nitrogen balance) metabolize protein such that 90% of the nitrogen will appear in the urine as uric acid while 10% of the protein nitrogen will appear in the feces. Thus, of 5.37 g of nitrogen ingested, 4.83 g will appear as uric acid while .537 will appear in the feces. This excreted nitrogen will be processed by waste treatment into a variety of end products; nitrate, nitrous oxide, nitrogen gas. The precise end product is a function of the treatment used. Ultimately, all nitrogen must be converted into a form usable by plants to maintain mass balance.

In the model program each flow is designated by a three-letter code indicating the compartment which is its source, the compartment which is its sink and the letter N which indicates that the flow is part of the nitrogen cycle. Thus, DON indicates the flow of nitrogen between compartments D (waste processor) and O (nitrate). Two exceptions to this standard nomenclature are CDFN and CDUN; the former indicating the flow between compartments C and D due to fecal wastes and the latter uric acid.

The state equations for the calculation of nitrogen flow in a CELSS are:

$$dPLANT/dT = OAN - AKN$$

$$dFOOD/dT = KBN - (BCN + BDN)$$

$$dMAN/dT = BCN - (CDFN + CDUN)$$

$$dWASTE/dT = (BDN + LDN + CDUN + CDFN) - (DPN + DON + DNN)$$

$$dHARV/dT = AKN - (KBN + KLN)$$

$$dSTRAW/dT = KLN - LDN$$

$$dNO_3/dT = (DON + PON + NON) - OAN$$

$$dN_2O/dT = DPN - PON$$

$$dN_2/dT = DNN - NON$$

AKN is that amount of plant biomass harvested each day from a crop in steady state growth. It is equal to the plant biomass multiplied by the daily growth rate. Thus, AKN = (NPLANT)(K1).

KLN is that amount of the harvested biomass which is inedible, or (NPLANT) * (K1) * (.3467). KBN is that amount of the harvested biomass which is edible, or (NPLANT) * (K1) * (.6533).

BCN is the food transferred from the food compartment to the humans. The amount of food eaten each day is determined by the caloric requirements (CALR), or, if there is less food than is required, by the amount of food available. Thus, BDN is the excess stored food which is transferred to the waste processor. The expression in the program compares the amount of harvested food plus the amount of stored food to the setpoint. If the former is less than the latter, there is no excess. If the former is greater than the latter, there is excess food and that amount is transferred to the waste processor.

LDN is that fraction of the harvested food which is inedible and which is stored as inedible plant wastes. For soybean 34.67% of the elemental nitrogen is in this fraction.

CDUN is the fraction of dietary nitrogen which is excreted by the human compartment in the form of uric acid.

CDFN is the fraction of dietary nitrogen which is excreted by the human compartment in the form of fecal nitrogen.

DON is the fraction of all the nitrogen which enters the waste processor and is converted to nitrates.

DNN is the fraction of all the nitrogen which enters the waste processor and is converted to nitrous oxide.

DPN is the fraction of all the nitrogen which enters the waste processor and is converted to diatomic nitrogen.

NON is the fraction of nitrous oxide which is oxidized to nitrate.

PON is the fraction of diatomic nitrogen which is converted to nitrate.

DAN is the flow of nitrate from the nitrate compartment to the plant compartment.

Program 8 is a listing of the ACSL version of the nitrate cycle in a CELSS, and Model Result 8 is the output of the model run at steady state conditions.

Finally, all of the described elemental models: carbon, nitrogen, and oxygen, have been integrated into a single model, CELSSMOD, which represents elemental cycling in a CELSS. Program 9 is a listing of CELSSMOD.

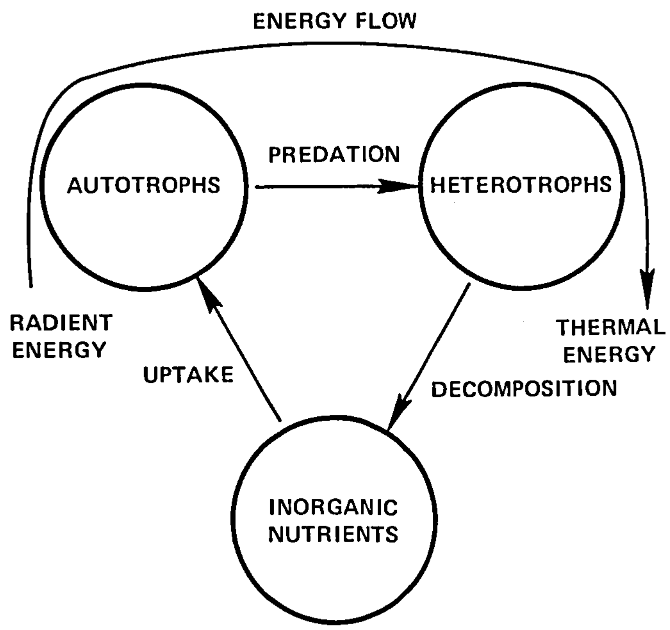

Figure 1. Flow of mass and energy in a conceptualized ecosystem.

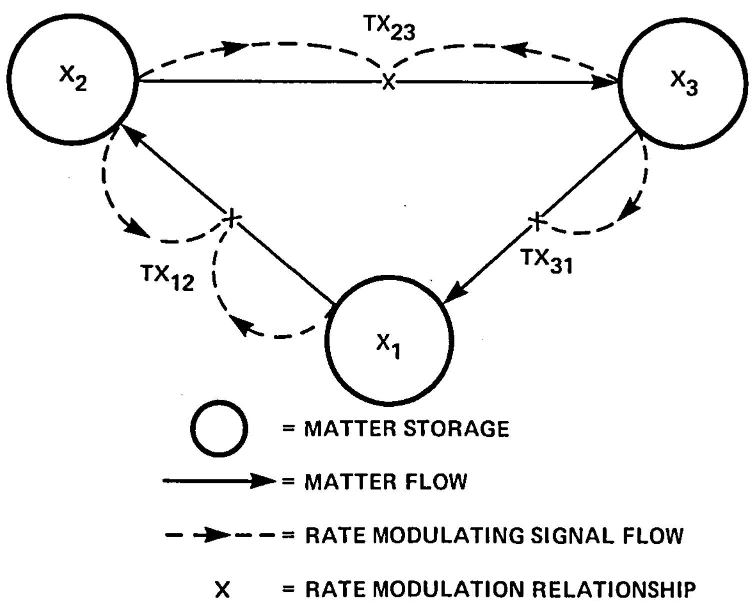

Figure 2. The flow of mass in a small closed ecosystem. The solid lines represent the flow of mass between producing and receiving compartments (circles); the discontinuos lines represent regulating effects imposed by the compartments upon the flow of mass.

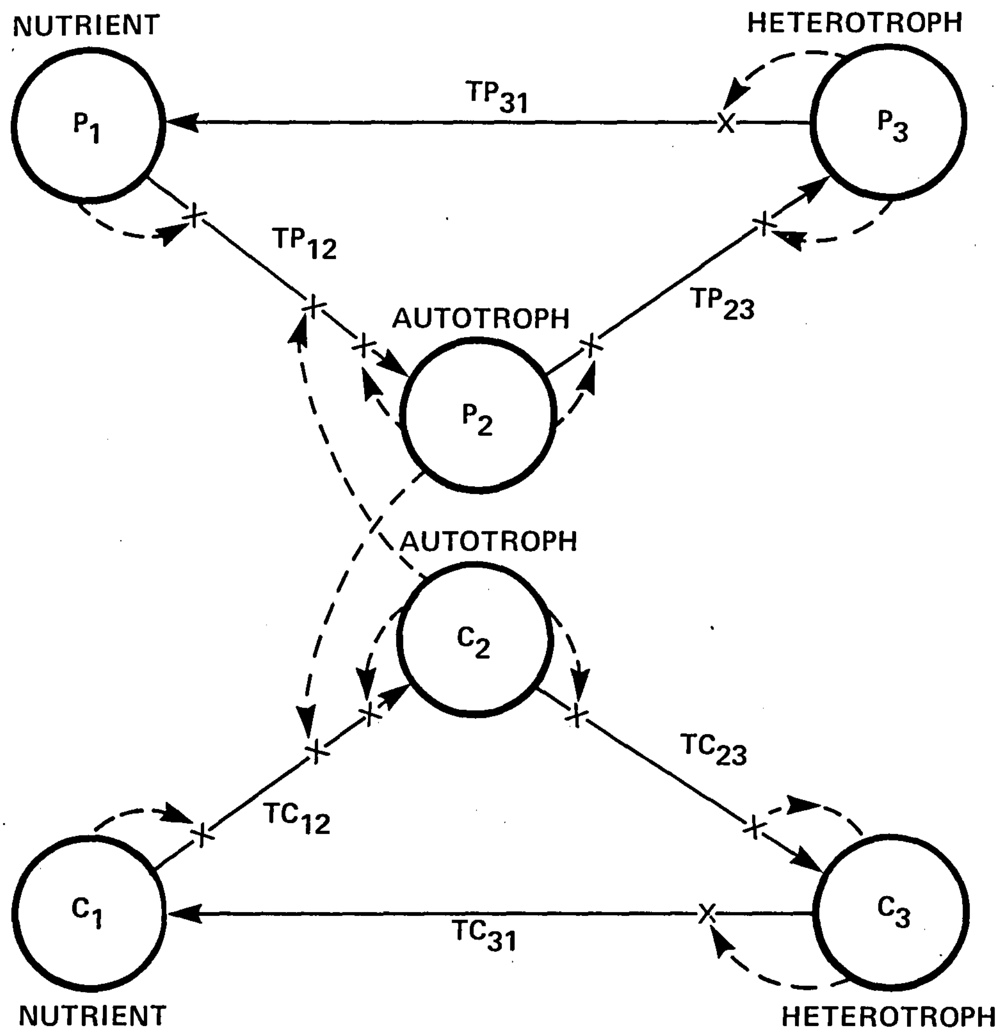

Fig. 3. A representation of the relations between the flows of two different elements, phosphorous and carbon in a closed system. The coupling of the flows, for example in molecules containing both elements, can be represented by modulation effects.

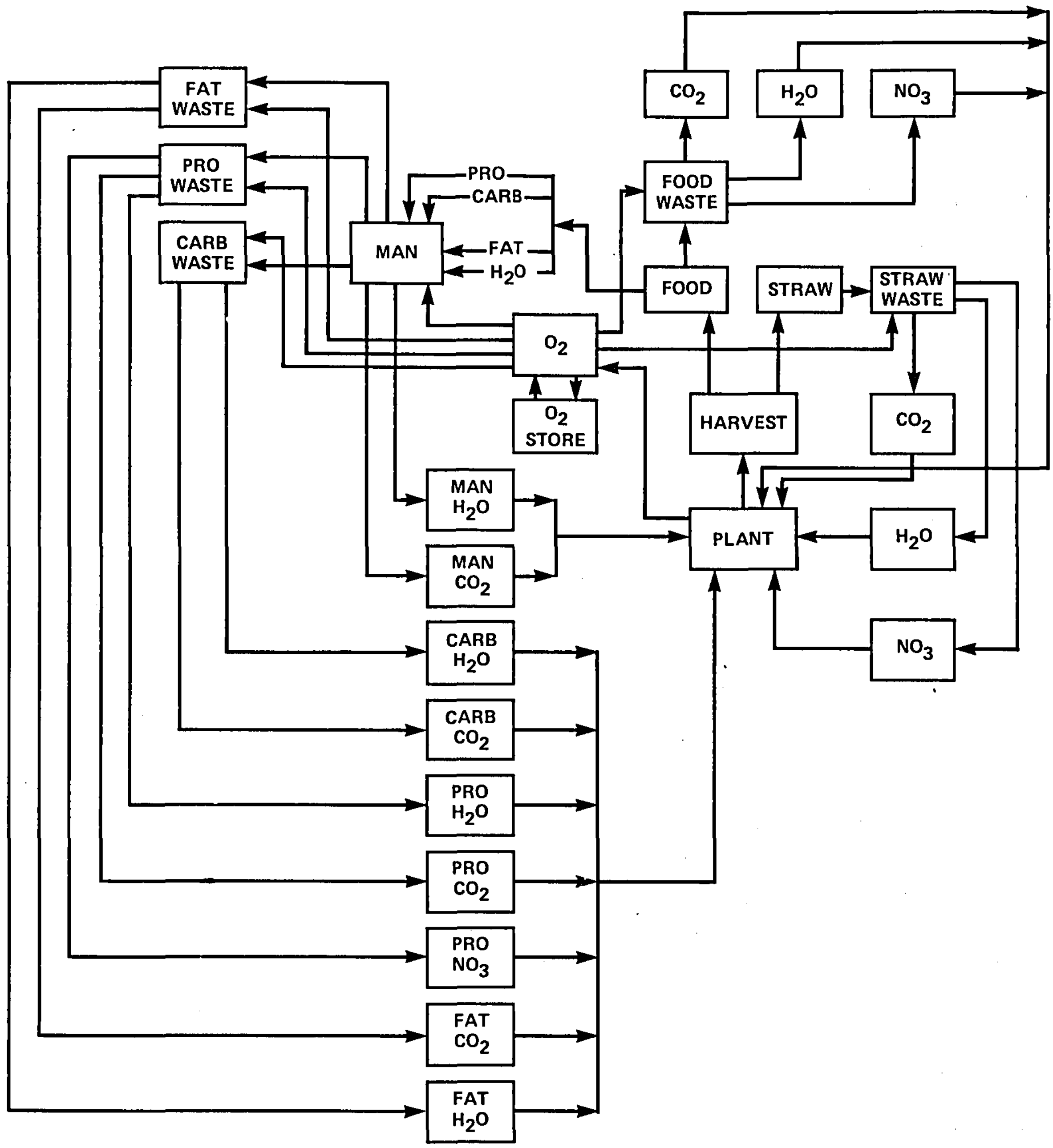

Figure 4. The flow of elemental oxygen in a closed ecological life-support system.

TABLE 1

Wet Weight of Edible and Non-Edible Portions of Crop

Crop	Total Weight, grams: Harvest	Food	Roughage	Hay
Soybean	4620	2103	1634	883
Wheat	3018	1006	-	2012
Corn	1034	220	814	-

TABLE 2

Carbon Mass Balance in Growth of Plants

Crop	Carbon In, grams	Carbon Out, grams: Harvest	Food	Roughage	Hay	Food/ Harvest
Soybean	425	425	211	139	75	.49
Wheat	254	254	85	-	169	.33
Corn	86	86	18	68	-	.21

TABLE 5

Grams of Carbon in Nutrient per 100 grams Foodstuff (Dry Weight)

Crop	Protein	Carbohydrate	Fat	Total
Soybean	18.19	14.89	13.92	47.0
Wheat	6.96	32.00	1.56	40.5
Corn	6.15	33.42	2.55	42.12

TABLE 6

Carbon Mass Balance for Metabolism of Protein

Constituent	Amount, grams	Carbon, grams
Dietary Casein	100.0	53.50
Protein in Feces (2%)	10.0	5.35
Urea Formed	30.48	6.10
CO_2 Formed	154.09	42.05

TABLE 3

Mass Balance for 100 grams of Food (Dry Weight)

Crop	Carbon In, grams	Carbon Out, grams		
		Food	Waste	Food/ Carbon In
Soybean	94.69	47.01	47.68	.49
Wheat	94.26	40.50	53.76	.43
Corn	113.36	42.12	71.24	.37

TABLE 4

Grams of Nutrient per 100 grams Foodstuff (Dry Weight)

Crop	Protein	Carbohydrate	Fat	Bound Water
Soybean	34.0	33.5	18.0	14.5
Wheat	13.0	72.0	2.0	13.0
Corn	11.5	75.2	3.3	10.0

TABLE 7

Carbon Mass Balance for Metabolism of Starch

Constituent	Amount, grams	Carbon, grams
Dietary Starch	100.00	44.44
Carbohydrate in Feces (2%)	2.0	0.89
CO_2 Formed	116.03	43.55

TABLE 8

Carbon Mass Balance for Metabolism of Fat

Constituent	Amount, grams	Carbon, grams
Dietary Triolein	100.00	77.32
Fat in Feces (5%)	5.00	3.87
CO_2 Formed	269.15	73.45

Program 1

```
CONSTANT K1=0.9316,K2=0.0828,K3=0.0684,...
K4=1.0,K5=0.0087,K6=0.0043,K7=0.0044,K8=1.0,...
K9=1.0,ITEND=360.,CALR=3000.,CALO=3000.
CONSTANT CMANI=12600.,CCO2I=1.0E4,CWASTI=542.,CFOODI=1000.,...
TEMP=25.0,CCHANI=0.,CPLANI=1.1E5,CSTORI=1000.
CINTERVAL CINT=60.0
TABLE TEMPF,1,13 ...
/-10.,0.,5.,9.,13.,17.,21.,25.,29.,33.,37.,41.,45.,...
0.,0.,.14,.36,.58,.88,.98,1.,1.,.96,.72,.34,0./
CEAT=AMIN1(CALR*0.1,CFOOD)
CALI=CEAT*10.
A=CEAT
B=CEAT*K3
C=AMAX1(CALO-CALI,0.)*K2
D=CEAT*K1*(1.-AMAX1((CALI-CALO)/CALI,0.))
E=CWASTE*K4
F=AMAX1(CFOOD-1000.,0.)
G=K9*AMAX1(CCO2-CCO2I,0.)
H=K8*AMAX1(CSTORE,0.)*AMAX1(0.,CCO2I-CCO2)
I=CPLANT*K5*TEMPF(TEMP)
J=CPLANT*K6*TEMPF(TEMP)
K=CPLANT*K7*TEMPF(TEMP)
DOTCM=A-(B+C+D)
DOTCWS=(B+F+K)-(E)
DOTCCO=(E+C+D+H)-(G+I)
DOTCPL=(I)-(J+K)
DOTCS=G-H
DOTCFO=(J)-(A+F)
CMAN=INTEG(DOTCM,CMANI)
CCO2=INTEG(DOTCCO,CCO2I)
CFOOD=INTEG(DOTCFO,CFOODI)
CPLANT=INTEG(DOTCPL,CPLANI)
CWASTE=INTEG(DOTCWS,CWASTI)
CSTORE=INTEG(DOTCS,CSTORI)
CCHANG=INTEG(DOTCM+DOTCFO+DOTCCO+DOTCPL+DOTCWS+DOTCS,CCHANI)
CSUM=CMAN+CCO2+CFOOD+CPLANT+CWASTE+CSTORE
TERMT(T.GE.ITEND)
END
```

Program 2

```
CONSTANT CALR=3000.,CAL00=3000.,K5=.0087,K22=.2215,K23=.1011,K10=1.0
CONSTANT K11=1.0,OPLANI=1.E5,OFOODI=1.E3,OMANI=1.E4,OWASTI=1.E2,...
002I=1.E5,OCO2I=1.E4,OH20I=1.E3,ONO3I=1.E3,OHARVI=0.0,OSTRAI=1.E3
CONSTANT OCHANI=0.,OBUFFI=1.E5,TEMP=25.0
CONSTANT ITEND=360.
CINTERVAL CINT=60.0
MAXTERVAL MAXT=1.0
MINTERVAL MINT=0.1
NSTEPS NSTP=60
ALGORITHM IALG=3
TABLE TEMPF,1,13 ...
/-10.,0.,5.,9.,13.,17.,21.,25.,29.,33.,37.,41.,45.,...
0.,0.,.14,.36,.58,.88,.98,1.,1.,.96,.72,.34,0./
INITIAL
RGEAT=CALR*(100./452.35)
END
DYNAMIC
DERIVATIVE
AA=(1.-AMAX1((CALII-CALOO)/CALII,0.))
BB=AMAX1(CALOO-CALII,0.)
GEAT=AMIN1(RGEAT,OFOOD/.3884)
CEAT=GEAT*.4700
OEAT=GEAT*.3884
CALI=4.5235*(CEAT/.4700)
CALII=4.5235*(OEAT/.3884)
GPRO=GEAT*.34
GCARB=GEAT*.335
GFAT=GEAT*.18
GH2O=GEAT*.145
ABC=GCARB*.4938
AEC=TEMPF(TEMP)*(GCARB*1.1569)+(GCARB*.02*1.1805)
BCC=GCARB*.4938
CDC=GCARB*.0099
CFC=(GCARB*1.1603*AA)
CGC=GCARB*.4805*AA
DFC=GCARB*.02*1.1805
DGC=GCARB*.02*.4903
ECC=GCARB*1.1569*AA
EDC=GCARB*.02*1.1805
```

```
FAC=TEMPF(TEMP)*(GCARB*1.1603)+(GCARB*.02*1.1805)
GAC=TEMPF(TEMP)*(GCARB*.4805)+(GCARB*.02*.4903)
DOTAC=(GAC+FAC)-(ABC+AEC)
DOTBC=(ABC)-(BCC)
DOTCC=(BCC+ECC)-(CDC+CFC+CGC)
DOTDC=(CDC+EDC)-(DFC+DGC)
DOTEC=(AEC)-(ECC+EDC)
DOTFC=(DFC+CFC)-(FAC)
DOTGC=(CGC+DGC)-(GAC)
OPLANT=INTEG(DOTAC,OPLANI)
OFOOD=INTEG(DOTBC,OFOODI)
OMAN=INTEG(DOTCC,OMANI)
OWASTE=INTEG(DOTDC,OWASTI)
OO2=INTEG(DOTEC,OO2I)
OCO2=INTEG(DOTFC,OCO2I)
OH2O=INTEG(DOTGC,OH2OI)
OHARV=INTEG(DOTKC,OHARVI)
OSTRAW=INTEG(DOTLC,OSTRAI)
ONO3=INTEG(DOTHC,ONO3I)
OBUFFR=INTEG(DOTMC,OBUFFI)
OSUM=OPLANT+OFOOD+OMAN+OWASTE+OO2+OCO2+OH2O+OBUFFR
END
TERMT(T.GE.ITEND)
END
END
```

<u>Program 3</u>

```
CONSTANT CALR=3000.,CALOO=3000.,K5=.0087,K22=.2215,K23=.1011,K10=1.0
CONSTANT K11=1.0,OPLANI=1.E5,OFOODI=1.E3,OMANI=1.E4,OWASTI=1.E2,...
OO2I=1.E5,OCO2I=1.E4,OH2OI=1.E3,ONO3I=1.E3,OHARVI=0.0,OSTRAI=1.E3
CONSTANT OCHANI=0.,OBUFFI=1.E5,TEMP=25.0
CONSTANT ITEND=360.
CINTERVAL CINT=60.0
MAXTERVAL MAXT=1.0
MINTERVAL MINT=0.1
NSTEPS NSTP=60
ALGORITHM IALG=3
TABLE TEMPF,1,13 ...
/-10.,0.,5.,9.,13.,17.,21.,25.,29.,33.,37.,41.,45.,...
0.,0.,.14,.36,.58,.88,.98,1.,1.,.96,.72,.34,0./
INITIAL
RGEAT=CALR*(100./452.35)
END
DYNAMIC
DERIVATIVE
AA=(1.-AMAX1((CALII-CALOO)/CALII,0.))
BB=AMAX1(CALOO-CALII,0.)
GEAT=AMIN1(RGEAT,OFOOD/.3884)
CEAT=GEAT*.4700
OEAT=GEAT*.3884
CALI=4.5235*(CEAT/.4700)
CALII=4.5235*(OEAT/.3884)
GPRO=GEAT*.34
GCARB=GEAT*.335
GFAT=GEAT*.18
GH2O=GEAT*.145
ABF=GFAT*.1084
AEF=TEMPF(TEMP)*(GFAT*2.7472)+(GFAT*.05*2.8918)
BCF=GFAT*.1084
CDF=GFAT*.0054
CFF=(GFAT*1.957*AA)
CFRF=K22*BB
CGF=GFAT*.8932
CGRF=K23*BB
DFF=GFAT*2.06*.05
DGF=GFAT*.9402*.05
```

```
ECF=GFAT*2.7472*AA
ECRF=BB*.1075*2.8917
EDF=GFAT*2.8918*.05
FAF=TEMPF(TEMP)*(GFAT*2.06*.05)+(GFAT*1.957)
GAF=TEMPF(TEMP)*(GFAT*.8932)+(GFAT*.9402*.05)
DOTAF=(GAF+FAF)-(ABF+AEF)
DOTBF=(ABF)-(BCF)
DOTCF=(BCF+ECF+ECRF)-(CDF+CFF+CGF+CFRF+CGRF)
DOTDF=(CDF+EDF)-(DFF+DGF)
DOTEF=(AEF)-(ECF+EDF+ECRF)
DOTFF=(DFF+CFF+CFRF)-(FAF)
DOTGF=(CGF+DGF+CGRF)-(GAF)
OPLANT=INTEG(DOTAF,OPLANI)
OFOOD=INTEG(DOTBF,OFOODI)
OMAN=INTEG(DOTCF,OMANI)
OWASTE=INTEG(DOTDF,OWASTI)
OO2=INTEG(DOTEF,OO2I)
OCO2=INTEG(DOTFF,OCO2I)
OH2O=INTEG(DOTGF,OH2OI)
OSUM=OPLANT+OFOOD+OMAN+OWASTE+OO2+OCO2+OH2O
END
TERMT(T.GE.ITEND)
END
END
```

Program 4

```
CONSTANT CALR=3000.,CALOO=3000.,K5=.0087,K22=.2215,K23=.1011,K10=1.0
CONSTANT K11=1.0,OPLANI=1.E5,OFOODI=1.E3,OMANI=1.E4,OWASTI=1.E2,...
OO2I=1.E5,OCO2I=1.E4,OH2OI=1.E3,ONO3I=1.E3,OHARVI=0.0,OSTRAI=1.E3
CONSTANT OCHANI=0.,OBUFFI=1.E5,TEMP=25.0
CONSTANT ITEND=360.
CINTERVAL CINT=60.0
MAXTERVAL MAXT=1.0
MINTERVAL MINT=0.1
NSTEPS NSTP=60
ALGORITHM IALG=3
TABLE TEMPF,1,13 ...
/-10.,0.,5.,9.,13.,17.,21.,25.,29.,33.,37.,41.,45.,...
0.,0.,.14,.36,.58,.88,.98,1.,1.,.96,.72,.34,0./
INITIAL
RGEAT=CALR*(100./452.35)
END
DYNAMIC
DERIVATIVE
AA=(1.-AMAX1((CALII-CALOO)/CALII,0.))
BB=AMAX1(CALOO-CALII,0.)
GEAT=AMIN1(RGEAT,OFOOD/.3884)
CEAT=GEAT*.4700
OEAT=GEAT*.3884
CALI=4.5235*(CEAT/.4700)
CALII=4.5235*(OEAT/.3884)
GPRO=GEAT*.34
GCARB=GEAT*.335
GFAT=GEAT*.18
GH2O=GEAT*.145
ABP=GPRO*.2214
AEP=TEMPF(TEMP)*(GPRO*1.3771)+(GPRO*.1*2.3472)+(GPRO*.7315)
BCP=GPRO*.2214
CDP=(GPRO*.2214*.1)+(GPRO*.0813)
CFP=GPRO*1.1204*AA
CGP=GPRO*.3485*AA
CIP=GPRO*.013
CJP=GPRO*.0133
DFP=(GPRO*.1*1.457)+(GPRO*.1626)
DGP=(GPRO*.1*.5704)+(GPRO*.1626)
```

```
DHP=(GPRO*.4877)+(GPRO*.0542)
DIP=GPRO*.013*.1
DJP=GPRO*.0133*.1
ECP=GPRO*1.3771*AA
EDP=(GPRO*.1*2.3472)+(GPRO*.7315)
FAP=TEMPF(TEMP)*(GPRO*1.1204)+(GPRO*.1*1.457)+(GPRO*.1626)
GAP=TEMPF(TEMP)*(GPRO*.3485)+(GPRO*.1*.5704)+(GPRO*.1626)
HAP=TEMPF(TEMP)*(GPRO*.4877)+(GPRO*.0542)
IAP=TEMPF(TEMP)*(GPRO*.013*.1)+(GPRO*.013)
JAP=TEMPF(TEMP)*(GPRO*.0133)+(GPRO*.0133*.1)
DOTAP=(FAP+GAP+HAP+IAP+JAP)-(ABP+AEP)
DOTBP=(ABP)-(BCP)
DOTCP=(BCP+ECP)-(CDP+CFP+CGP+CIP+CJP)
DOTDP=(CDP+EDP)-(DFP+DGP+DHP)
DOTEP=(AEP)-(ECP+EDP)
DOTFP=(CFP+DFP)-(FAP)
DOTGP=(CGP+DGP)-(GAP)
DOTHP=(DHP)-(HAP)
DOTIP=(CIP+DIP)-IAP
DOTJP=(CJP+DJP)-JAP
OPLANT=INTEG(DOTAP,OPLANI)
OFOOD=INTEG(DOTBP,OFOODI)
OMAN=INTEG(DOTCP,OMANI)
OWASTE=INTEG(DOTDP,OWASTI)
OO2=INTEG(DOTEP,OO2I)
OCO2=INTEG(DOTFP,OCO2I)
OH2O=INTEG(DOTGP,OH2OI)
ONO3=INTEG(DOTHP,ONO3I)
OSUM=OPLANT+OFOOD+OMAN+OWASTE+OO2+OCO2+OH2O+ONO3
END
TERMT(T.GE.ITEND)
END
END
```

Program 5

```
CONSTANT CALR=3000.,CALOO=3000.,K5=.0087,K22=.2215,K23=.1011,K10=1.0
CONSTANT K11=1.0,OPLANI=1.E5,OFOODI=1.E3,OMANI=1.E4,OWASTI=1.E2,...
OO2I=1.E5,OCO2I=1.E4,OH2OI=1.E3,ONO3I=1.E3,OHARVI=0.0,OSTRAI=1.E3
CONSTANT OCHANI=0.,OBUFFI=1.E5,TEMP=25.0
CONSTANT ITEND=360.
CINTERVAL CINT=60.0
MAXTERVAL MAXT=1.0
MINTERVAL MINT=0.1
NSTEPS NSTP=60
ALGORITHM IALG=3
TABLE TEMPF,1,13 ...
/-10.,0.,5.,9.,13.,17.,21.,25.,29.,33.,37.,41.,45.,...
0.,0.,.14,.36,.58,.88,.98,1.,1.,.96,.72,.34,0./
INITIAL
RGEAT=CALR*(100./452.35)
END
DYNAMIC
DERIVATIVE
AES=OPLANT*K5*.6011*5.5891*TEMPF(TEMP)
AK=OPLANT*K5*TEMPF(TEMP)
AKS=OPLANT*K5*.6011*TEMPF(TEMP)
KB=OPLANT*K5*TEMPF(TEMP)*.3989
EDS=OPLANT*K5*TEMPF(TEMP)*.6011*5.5891
FAS=OPLANT*K5*.6011*4.8025*TEMPF(TEMP)
GAS=OPLANT*K5*.6011*1.4378*TEMPF(TEMP)
HAS=OPLANT*K5*.6011*.3489*TEMPF(TEMP)
KLS=OPLANT*K5*TEMPF(TEMP)*.6011
LDS=OPLANT*K5*TEMPF(TEMP)*.6011
DHS=OPLANT*K5*TEMPF(TEMP)*.6011*.3489
DGS=OPLANT*K5*TEMPF(TEMP)*.6011*1.4378
DFS=OPLANT*K5*TEMPF(TEMP)*.6011*4.8025
DOTAS=(FAS+GAS+HAS)-(AKS+AES)
DOTES=(AES)-(EDS)
DOTFS=(DFS)-(FAS)
DOTGS=(DGS)-(GAS)
DOTHS=(DHS)-(HAS)
DOTDS=(EDS+LDS)-(DFS+DGS+DHS)
DOTLS=(KLS)-(LDS)
DOTK=AKS-KLS
```

```
OPLANT=INTEG(DOTAS,OPLANI)
OWASTE=INTEG(DOTDS,OWASTI)
OO2=INTEG(DOTES,OO2I)
OCO2=INTEG(DOTFS,OCO2I)
OH2O=INTEG(DOTGS,OH2OI)
OSTRAW=INTEG(DOTLS,OSTRAI)
ONO3=INTEG(DOTHS,ONO3I)
OSUM=OPLANT+OWASTE+OO2+OCO2+OH2O+ONO3
END
TERMT(T.GE.ITEND)
END
END
```

<u>Program 6</u>

```
CONSTANT CALR=3000.,CALOO=3000.,K5=.0087,K22=.2215,K23=.1011,K10=1.0
CONSTANT K11=1.0,OPLANI=1.E5,OFOODI=1.E3,OMANI=1.E4,OWASTI=1.E2,...
OO2I=1.E5,OCO2I=1.E4,OH2OI=1.E3,ONO3I=1.E3,OHARVI=0.0,OSTRAI=1.E3
CONSTANT OCHANI=0.,OBUFFI=1.E5,TEMP=25.0
CONSTANT ITEND=360.
CINTERVAL CINT=60.0
MAXTERVAL MAXT=1.0
MINTERVAL MINT=0.1
NSTEPS NSTP=60
ALGORITHM IALG=3
TABLE TEMPF,1,13 ...
/-10.,0.,5.,9.,13.,17.,21.,25.,29.,33.,37.,41.,45.,...
0.,0.,.14,.36,.58,.88,.98,1.,1.,.96,.72,.34,0./
INITIAL
RGEAT=CALR*(100./452.35)
END
DYNAMIC
DERIVATIVE
AA=(1.-AMAX1((CALII-CALOO)/CALII,0.))
BB=AMAX1(CALOO-CALII,0.)
GEAT=AMIN1(RGEAT,OFOOD/.3884)
CEAT=GEAT*.4700
OEAT=GEAT*.3884
CALI=4.5235*(CEAT/.4700)
CALII=4.5235*(OEAT/.3884)
GPRO=GEAT*.34
GCARB=GEAT*.335
GFAT=GEAT*.18
GH2O=GEAT*.145
DOTBIN=KB-O.
BDX=OHARV*.3989*AMAX1(0.,SIGN(1.,OFOOD-1.E3))+1.*...
AMAX1(0.,OFOOD-1.E3)
AEX=BDX*4.3758
DGX=BDX*1.6812
DFX=BDX*3.2213
DHX=BDX*.4733
EDX=BDX*4.3758
GAX=BDX*1.6812*TEMPF(TEMP)
FAX=BDX*3.2213*TEMPF(TEMP)
```

```
HAX=BDX*.473*TEMPF(TEMP)
KB=OPLANT*K5*TEMPF(TEMP)*.3989
AK=OPLANT*K5*TEMPF(TEMP)
KLS=OPLANT*K5*TEMPF(TEMP)*.6011
DOTAX=(GAX+FAX+HAX)-(AEX+BDX)
DOTBX=0.-BDX
DOTDX=(BDX+EDX)-(DGX+DFX+DHX)
DOTEX=AEX-EDX
DOTFX=DFX-FAX
DOTGX=DGX-GAX
DOTHX=DHX-HAX
DOTKX=AK-(KLS+KB)
OPLANT=INTEG(DOTAX,OPLANI)
OFOOD=INTEG(DOTBX,OFOODI)
OWASTE=INTEG(DOTDX,OWASTI)
OO2=INTEG(DOTEX,OO2I)
OCO2=INTEG(DOTFX,OCO2I)
OH2O=INTEG(DOTGX,OH2OI)
ONO3=INTEG(DOTHX,ONO3I)
OHARV=INTEG(DOTKX,OHARVI)
OSUM=OPLANT+OFOOD+OMAN+OWASTE+OO2+OCO2+OH2O+ONO3+OHARV
END
TERMT(T.GE.ITEND)
END
END
```

Program 7

```
CONSTANT CALR=3000.,CALOO=3000.,K5=.0087,K22=.2215,K23=.1011,K10=1.0
CONSTANT K11=1.0,OPLANI=1.E5,OFOODI=1.E3,OMANI=1.E4,OWASTI=1.E2,...
OO2I=1.E5,OCO2I=1.E4,OH2OI=1.E3,ONO3I=1.E3,OHARVI=0.0,OSTRAI=1.E3
CONSTANT OCHANI=0.,OBUFFI=1.E5,TEMP=25.0
CONSTANT ITEND=360.
CINTERVAL CINT=60.0
MAXTERVAL MAXT=1.0
MINTERVAL MINT=0.1
NSTEPS NSTP=60
ALGORITHM IALG=3
TABLE TEMPF,1,13 ...
/-10.,0.,5.,9.,13.,17.,21.,25.,29.,33.,37.,41.,45.,...
0.,0.,.14,.36,.58,.88,.98,1.,1.,.96,.72,.34,0./
INITIAL
RGEAT=CALR*(100./452.35)
END
DYNAMIC
DERIVATIVE
AA=(1.-AMAX1((CALII-CALOO)/CALII,0.))
BB=AMAX1(CALOO-CALII,0.)
GEAT=AMIN1(RGEAT,OFOOD/.3884)
CEAT=GEAT*.4700
OEAT=GEAT*.3884
CALI=4.5235*(CEAT/.4700)
CALII=4.5235*(OEAT/.3884)
GPRO=GEAT*.34
GCARB=GEAT*.335
GFAT=GEAT*.18
GH2O=GEAT*.145
ABC=GCARB*.4938
AEC=TEMPF(TEMP)*(GCARB*1.1569)+(GCARB*.02*1.1805)
BCC=GCARB*.4938
CDC=GCARB*.0099
CFC=(GCARB*1.1603*AA)
CGC=GCARB*.4805*AA
DFC=GCARB*.02*1.1805
DGC=GCARB*.02*.4903
ECC=GCARB*1.1569*AA
EDC=GCARB*.02*1.1805
```

```
FAC=TEMPF(TEMP)*(GCARB*1.1603)+(GCARB*.02*1.1805)
GAC=TEMPF(TEMP)*(GCARB*.4805)+(GCARB*.02*.4903)
DOTAC=(GAC+FAC)-(ABC+AEC)
DOTBC=(ABC)-(BCC)
DOTCC=(BCC+ECC)-(CDC+CFC+CGC)
DOTDC=(CDC+EDC)-(DFC+DGC)
DOTEC=(AEC)-(ECC+EDC)
DOTFC=(DFC+CFC)-(FAC)
DOTGC=(CGC+DGC)-(GAC)
ABF=GFAT*.1084
AEF=TEMPF(TEMP)*(GFAT*2.7472)+(GFAT*.05*2.8918)
BCF=GFAT*.1084
CDF=GFAT*.0054
CFF=(GFAT*1.957*AA)
CFRF=K22*BB
CGF=GFAT*.8932
CGRF=K23*BB
DFF=GFAT*2.06*.05
DGF=GFAT*.9402*.05
ECF=GFAT*2.7472*AA
ECRF=BB*.1075*2.8917
EDF=GFAT*2.8918*.05
FAF=TEMPF(TEMP)*(GFAT*2.06*.05)+(GFAT*1.957)
GAF=TEMPF(TEMP)*(GFAT*.8932)+(GFAT*.9402*.05)
DOTAF=(GAF+FAF)-(ABF+AEF)
DOTBF=(ABF)-(BCF)
DOTCF=(BCF+ECF+ECRF)-(CDF+CFF+CGF+CFRF+CGRF)
DOTDF=(CDF+EDF)-(DFF+DGF)
DOTEF=(AEF)-(ECF+EDF+ECRF)
DOTFF=(DFF+CFF+CFRF)-(FAF)
DOTGF=(CGF+DGF+CGRF)-(GAF)
ABP=GPRO*.2214
AEP=TEMPF(TEMP)*(GPRO*1.3771)+(GPRO*.1*2.3472)+(GPRO*.7315)
BCP=GPRO*.2214
CDP=(GPRO*.2214*.1)+(GPRO*.0813)
CFP=GPRO*1.1204*AA
CGP=GPRO*.3485*AA
CIP=GPRO*.013
CJP=GPRO*.0133
```

```
DFP=(GPRO*.1*1.457)+(GPRO*.1626)
DGP=(GPRO*.1*.5704)+(GPRO*.1626)
DHP=(GPRO*.4877)+(GPRO*.0542)
DIP=GPRO*.013*.1
DJP=GPRO*.0133*.1
ECP=GPRO*1.3771*AA
EDP=(GPRO*.1*2.3472)+(GPRO*.7315)
FAP=TEMPF(TEMP)*(GPRO*1.1204)+(GPRO*.1*1.457)+(GPRO*.1626)
GAP=TEMPF(TEMP)*(GPRO*.3485)+(GPRO*.1*.5704)+(GPRO*.1626)
HAP=TEMPF(TEMP)*(GPRO*.4877)+(GPRO*.0542)
IAP=TEMPF(TEMP)*(GPRO*.013*.1)+(GPRO*.013)
JAP=TEMPF(TEMP)*(GPRO*.0133)+(GPRO*.0133*.1)
DOTAP=(FAP+GAP+HAP+IAP+JAP)-(ABP+AEP)
DOTBP=(ABP)-(BCP)
DOTCP=(BCP+ECP)-(CDP+CFP+CGP+CIP+CJP)
DOTDP=(CDP+EDP)-(DFP+DGP+DHP)
DOTEP=(AEP)-(ECP+EDP)
DOTFP=(CFP+DFP)-(FAP)
DOTGP=(CGP+DGP)-(GAP)
DOTHP=(DHP)-(HAP)
DOTIP=(CIP+DIP)-IAP
DOTJP=(CJP+DJP)-JAP
ABW=GH20*.889
BCW=GH20*.889
CGW=GH20*.889
GAW=GH20*.889
DOTAW=GAW-ABW
DOTBW=ABW-BCW
DOTCW=BCW-CGW
DOTGW=CGW-GAW
AES=OPLANT*K5*.6011*5.5891*TEMPF(TEMP)
AK=OPLANT*K5*TEMPF(TEMP)
AKS=OPLANT*K5*.6011*TEMPF(TEMP)
KB=OPLANT*K5*TEMPF(TEMP)*.3989
EDS=OPLANT*K5*TEMPF(TEMP)*.6011*5.5891
FAS=OPLANT*K5*.6011*4.8025*TEMPF(TEMP)
GAS=OPLANT*K5*.6011*1.4378*TEMPF(TEMP)
HAS=OPLANT*K5*.6011*.3489*TEMPF(TEMP)
KLS=OPLANT*K5*TEMPF(TEMP)*.6011
```

```
LDS=OPLANT*K5*TEMPF(TEMP)*.6011
DHS=OPLANT*K5*TEMPF(TEMP)*.6011*.3489
DGS=OPLANT*K5*TEMPF(TEMP)*.6011*1.4378
DFS=OPLANT*K5*TEMPF(TEMP)*.6011*4.8025
DOTAS=(FAS+GAS+HAS)-(AKS+AES)
DOTES=(AES)-(EDS)
DOTFS=(DFS)-(FAS)
DOTGS=(DGS)-(GAS)
DOTHS=(DHS)-(HAS)
DOTDS=(EDS+LDS)-(DFS+DGS+DHS)
DOTLS=(KLS)-(LDS)
DOTK=(AK)-(KLS+KB)
EM=K10*AMAX1(OO2-OO2I,0.)
ME=K11*AMAX1(OBUFFR,0.)*AMAX1(0.,OO2I-OO2)
DOTM=EM-ME
DOTBIN=KB-0.
BDX=OHARV*.3989*AMAX1(0.,SIGN(1.,OFOOD-1.E3))+1.*...
AMAX1(0.,OFOOD-1.E3)
AEX=BDX*4.3758
DGX=BDX*1.6812
DFX=BDX*3.2213
DHX=BDX*.4733
EDX=BDX*4.3758
GAX=BDX*1.6812*TEMPF(TEMP)
FAX=BDX*3.2213*TEMPF(TEMP)
HAX=BDX*.473*TEMPF(TEMP)
DOTAX=(GAX+FAX+HAX)-(AEX+BDX)
DOTBX=0.-BDX
DOTDX=(BDX+EDX)-(DGX+DFX+DHX)
DOTEX=AEX-EDX
DOTFX=DFX-FAX
DOTGX=DGX-GAX
DOTHX=DHX-HAX
DOTA=DOTAC+DOTAF+DOTAP+DOTAS+DOTAW+DOTAX
DOTB=DOTBC+DOTBF+DOTBP+DOTBW+DOTBX+DOTBIN
DOTBB=KB-(BDX+BCC+BCF+BCP+BCW)
DOTC=DOTCC+DOTCF+DOTCP+DOTCW
DOTD=DOTDC+DOTDF+DOTDP+DOTDS+DOTDX
DOTE=DOTEC+DOTEF+DOTEP+DOTEX+DOTES+ME-EM
```

```
DOTF=DOTFC+DOTFF+DOTFP+DOTFS+DOTFX
DOTG=DOTGC+DOTGF+DOTGP+DOTGW+DOTGS+DOTGX
DOTH=DOTHP+DOTHX+DOTHS
DOTL=DOTLS
OPLANT=INTEG(DOTA,OPLANI)
OFOOD=INTEG(DOTBB,OFOODI)
OMAN=INTEG(DOTC,OMANI)
OWASTE=INTEG(DOTD,OWASTI)
OO2=INTEG(DOTE,OO2I)
OCO2=INTEG(DOTF,OCO2I)
OH2O=INTEG(DOTG,OH2OI)
OHARV=INTEG(DOTK,OHARVI)
OSTRAW=INTEG(DOTL,OSTRAI)
ONO3=INTEG(DOTH,ONO3I)
OBUFFR=INTEG(DOTM,OBUFFI)
OCHANG=INTEG(DOTA+DOTB+DOTC+DOTD+DOTE+DOTF+DOTG+DOTH+DOTM,OCHANI)
OSUM=OPLANT+OFOOD+OMAN+OWASTE+OO2+OCO2+OH2O+OBUFFR
END
TERMT(T.GE.ITEND)
END
END
```

Program 8

```
CONSTANT CALR=3000.,K5=.0087,K111=1.0,K222=0.0,K333=0.0,...
NPLANI=1.E5,NFOODI=1.E3,NMANI=1.E4,NWASTI=1.E2,NSTRAI=1.E3,...
NHARVI=1.E3,NNO3I=1.E2,NN2OI=1.E2,NN2I=1.E2,NCHANI=0.0,ITEND=360.0
CINTERVAL CINT=60.0
MAXTERVAL MAXT=1.0
MINTERVAL MINT=0.1
NSTEPS NSTEP=60
ALGORITHM IALG=3
INITIAL
RGEAT=CALR*100.0/452.35
END
DYNAMIC
DERIVATIVE
NEAT=GEAT*.0537
GPRO=GEAT*.34
GEAT=AMIN1(RGEAT,NFOOD*18.62)
AKN=NPLANT*K5
KLN=NPLANT*K5*.3467
KBN=NPLANT*K5*.6533
BCN=GPRO*.1580
BDN=NHARV*.6533*AMAX1(0.,SIGN(1.,NFOOD-1.E3))+...
1.*AMAX1(0.,NFOOD-1.E3)
LDN=NPLANT*K5*.3467
CDUN=GPRO*.1580*.9
CDFN=GPRO*.1580*.1
DON=(BDN+CDFN+CDUN+LDN)*K111
DNN=(BDN+CDFN+CDUN+LDN)*K222
DPN=(BDN+CDFN+CDUN+LDN)*K333
PON=DPN
NON=DNN
OAN=PON+DON+NON
DOTAN=OAN-AKN
DOTKN=AKN-(KBN+KLN)
DOTLN=KLN-LDN
DOTBN=KBN-(BCN+BDN)
DOTCN=BCN-(CDFN+CDUN)
DOTDN=(BDN+LDN+CDUN+CDFN)-(DPN+DON+DNN)
DOTPN=DPN-PON
DOTON=(DON+PON+NON)-OAN
```

```
DOTNN=DNN-NON
NPLANT=INTEG(DOTAN,NPLANI)
NFOOD=INTEG(DOTBN,NFOODI)
NMAN=INTEG(DOTCN,NMANI)
NWASTE=INTEG(DOTDN,NWASTI)
NHARV=INTEG(DOTKN,NHARVI)
NSTRAW=INTEG(DOTLN,NSTRAI)
NNO3=INTEG(DOTON,NNO3I)
NN2O=INTEG(DOTPN,NN2OI)
NN2=INTEG(DOTNN,NN2I)
NCHANG=INTEG(DOTAN+DOTKN+DOTLN+DOTBN+DOTCN+DOTDN+...
DOTPN+DOTON+DOTNN,NCHANI)
NSUM=NPLANT+NFOOD+NMAN+NWASTE+NHARV+NSTRAW+...
NNO3+NN2O+NN2
END
TERMT(T.GE.ITEND)
END
END
```

Program 9

```
CONSTANT CALR=3000.,CALOO=3000.,K5=.0087,K22=.2215,K23=.1011
CONSTANT OPLANI=1.E5,OFOODI=1.E3,OMANI=1.E4,OWASTI=1.E2,...
OO2I=1.E5,OCO2I=1.E4,OH2OI=1.E3,ONO3I=1.E3,OHARVI=0.0,OSTRAI=1.E3
CONSTANT OCHANI=0.,OBUFFI=1.E5
CONSTANT ITEND=360.
CINTERVAL CINT=60.0
MAXTERVAL MAXT=1.0
MINTERVAL MINT=0.1
NSTEPS NSTP=60
ALGORITHM IALG=3
TABLE TEMPF,1,13 ...
/-10.,0.,5.,9.,13.,17.,21.,25.,29.,33.,37.,41.,45.,...
0.,0.,.14,.36,.58,.88,.98,1.,1.,.96,.72,.34,0./
INITIAL
RGEAT=CALR*(100./452.35)
END
DYNAMIC
DERIVATIVE
AA=(1.-AMAX1((CALII-CALOO)/CALII,0.))
BB=AMAX1(CALOO-CALII,0.)
GEAT=AMIN1(RGEAT,OFOOD/.3884)
CEAT=GEAT*.4700
OEAT=GEAT*.3884
CALI=4.5235*(CEAT/.4700)
CALII=4.5235*(OEAT/.3884)
GPRO=GEAT*.34
GCARB=GEAT*.335
GFAT=GEAT*.18
GH2O=GEAT*.145
ABC=GCARB*.4938
AEC=TEMPF(TEMP)*(GCARB*1.1569)+(GCARB*.02*1.1805)
BCC=GCARB*.4938
CDC=GCARB*.0099
CFC=(GCARB*1.1603*AA)
CGC=GCARB*.4805*AA
DFC=GCARB*.02*1.1805
DGC=GCARB*.02*.4903
ECC=GCARB*1.1569*AA
EDC=GCARB*.02*1.1805
```

```
FAC=TEMPF(TEMP)*(GCARB*1.1603)+(GCARB*.02*1.1805)
GAC=TEMPF(TEMP)*(GCARB*.4805)+(GCARB*.02*.4903)
DOTAC=(GAC+FAC)-(ABC+AEC)
DOTBC=(ABC)-(BCC)
DOTCC=(BCC+ECC)-(CDC+CFC+CGC)
DOTDC=(CDC+EDC)-(DFC+DGC)
DOTEC=(AEC)-(ECC+EDC)
DOTFC=(DFC+CFC)-(FAC)
DOTGC=(CGC+DGC)-(GAC)
ABF=GFAT*.1084
AEF=TEMPF(TEMP)*(GFAT*2.7472)+(GFAT*.05*2.8918)
BCF=GFAT*.1084
CDF=GFAT*.0054
CFF=(GFAT*1.957*AA)
CFRF=K22*BB
CGF=GFAT*.8932
CGRF=K23*BB
DFF=GFAT*2.06*.05
DGF=GFAT*.9402*.05
ECF=GFAT*2.7472*AA
ECRF=BB*.1075*2.8917
EDF=GFAT*2.8918*.05
FAF=TEMPF(TEMP)*(GFAT*2.06*.05)+(GFAT*1.957)
GAF=TEMPF(TEMP)*(GFAT*.8932)+(GFAT*.9402*.05)
DOTAF=(GAF+FAF)-(ABF+AEF)
DOTBF=(ABF)-(BCF)
DOTCF=(BCF+ECF+ECRF)-(CDF+CFF+CGF+CFRF+CGRF)
DOTDF=(CDF+EDF)-(DFF+DGF)
DOTEF=(AEF)-(ECF+EDF+ECRF)
DOTFF=(DFF+CFF+CFRF)-(FAF)
DOTGF=(CGF+DGF+CGRF)-(GAF)
ABP=GPRO*.2214
AEP=TEMPF(TEMP)*(GPRO*1.3771)+(GPRO*.1*2.3472)+(GPRO*.7315)
BCP=GPRO*.2214
CDP=(GPRO*.2214*.1)+(GPRO*.0813)
CFP=GPRO*1.1204*AA
CGP=GPRO*.3485*AA
CIP=GPRO*.013
CJP=GPRO*.0133
```

```
DFP=(GPRO*.1*1.457)+(GPRO*.1626)
DGP=(GPRO*.1*.5704)+(GPRO*.1626)
DHP=(GPRO*.4877)+(GPRO*.0542)
DIP=GPRO*.013*.1
DJP=GPRO*.0133*.1
ECP=GPRO*1.3771*AA
EDP=(GPRO*.1*2.3472)+(GPRO*.7315)
FAP=TEMPF(TEMP)*(GPRO*1.1204)+(GPRO*.1*1.457)+(GPRO*.1626)
GAP=TEMPF(TEMP)*(GPRO*.3485)+(GPRO*.1*.5704)+(GPRO*.1626)
HAP=TEMPF(TEMP)*(GPRO*.4877)+(GPRO*.0542)
IAP=TEMPF(TEMP)*(GPRO*.013*.1)+(GPRO*.013)
JAP=TEMPF(TEMP)*(GPRO*.0133)+(GPRO*.0133*.1)
DOTAP=(FAP+GAP+HAP+IAP+JAP)-(ABP+AEP)
DOTBP=(ABP)-(BCP)
DOTCP=(BCP+ECP)-(CDP+CFP+CGP+CIP+CJP)
DOTDP=(CDP+EDP)-(DFP+DGP+DHP)
DOTEP=(AEP)-(ECP+EDP)
DOTFP=(CFP+DFP)-(FAP)
DOTGP=(CGP+DGP)-(GAP)
DOTHP=(DHP)-(HAP)
DOTIP=(CIP+DIP)-IAP
DOTJP=(CJP+DJP)-JAP
ABW=GH2O*.889
BCW=GH2O*.889
CGW=GH2O*.889
GAW=GH2O*.889
DOTAW=GAW-ABW
DOTBW=ABW-BCW
DOTCW=BCW-CGW
DOTGW=CGW-GAW
AES=OPLANT*K5*.6011*5.5891*TEMPF(TEMP)
AK=OPLANT*K5*TEMPF(TEMP)
AKS=OPLANT*K5*.6011*TEMPF(TEMP)
KB=OPLANT*K5*TEMPF(TEMP)*.3989
EDS=OPLANT*K5*TEMPF(TEMP)*.6011*5.5891
FAS=OPLANT*K5*.6011*4.8025*TEMPF(TEMP)
GAS=OPLANT*K5*.6011*1.4378*TEMPF(TEMP)
HAS=OPLANT*K5*.6011*.3489*TEMPF(TEMP)
KLS=OPLANT*K5*TEMPF(TEMP)*.6011
```

```
LDS=OPLANT*K5*TEMPF(TEMP)*.6011
DHS=OPLANT*K5*TEMPF(TEMP)*.6011*.3489
DGS=OPLANT*K5*TEMPF(TEMP)*.6011*1.4378
DFS=OPLANT*K5*TEMPF(TEMP)*.6011*4.8025
DOTAS=(FAS+GAS+HAS)-(AKS+AES)
DOTES=(AES)-(EDS)
DOTFS=(DFS)-(FAS)
DOTGS=(DGS)-(GAS)
DOTHS=(DHS)-(HAS)
DOTDS=(EDS+LDS)-(DFS+DGS+DHS)
DOTLS=(KLS)-(LDS)
DOTK=(AK)-(KLS+KB)
EM=K10*AMAX1(OO2-OO2I,0.)
ME=K11*AMAX1(OBUFFR,0.)*AMAX1(0.,OO2I-OO2)
DOTM=EM-ME
DOTBIN=KB-0.
BDX=OHARV*.3989*AMAX1(0.,SIGN(1.,OFOOD-1.E3))+1.*...
AMAX1(0.,OFOOD-1.E3)
AEX=BDX*4.3758
DGX=BDX*1.6812
DFX=BDX*3.2213
DHX=BDX*.4733
EDX=BDX*4.3758
GAX=BDX*1.6812*TEMPF(TEMP)
FAX=BDX*3.2213*TEMPF(TEMP)
HAX=BDX*.473*TEMPF(TEMP)
DOTAX=(GAX+FAX+HAX)-(AEX+BDX)
DOTBX=0.-BDX
DOTDX=(BDX+EDX)-(DGX+DFX+DHX)
DOTEX=AEX-EDX
DOTFX=DFX-FAX
DOTGX=DGX-GAX
DOTHX=DHX-HAX
DOTA=DOTAC+DOTAF+DOTAP+DOTAS+DOTAW+DOTAX
DOTB=DOTBC+DOTBF+DOTBP+DOTBW+DOTBX+DOTBIN
DOTBB=KB-(BDX+BCC+BCF+BCP+BCW)
DOTC=DOTCC+DOTCF+DOTCP+DOTCW
DOTD=DOTDC+DOTDF+DOTDP+DOTDS+DOTDX
DOTE=DOTEC+DOTEF+DOTEP+DOTEX+DOTES+ME-EM
```

```
DOTF=DOTFC+DOTFF+DOTFP+DOTFS+DOTFX
DOTG=DOTGC+DOTGF+DOTGP+DOTGW+DOTGS+DOTGX
DOTH=DOTHP+DOTHX+DOTHS
DOTL=DOTLS
OPLANT=INTEG(DOTA,OPLANI)
OFOOD=INTEG(DOTBB,OFOODI)
OMAN=INTEG(DOTC,OMANI)
OWASTE=INTEG(DOTD,OWASTI)
OO2=INTEG(DOTE,OO2I)
OCO2=INTEG(DOTF,OCO2I)
OH2O=INTEG(DOTG,OH2OI)
OHARV=INTEG(DOTK,OHARVI)
OSTRAW=INTEG(DOTL,OSTRAI)
ONO3=INTEG(DOTH,ONO3I)
OBUFFR=INTEG(DOTM,OBUFFI)
OCHANG=INTEG(DOTA+DOTB+DOTC+DOTD+DOTE+DOTF+DOTG+DOTH+DOTM,OCHANI)
OSUM=OPLANT+OFOOD+OMAN+OWASTE+OO2+OCO2+OH2O+OBUFFR
CONSTANT K1=0.9316,K2=0.0828,K3=0.0684,...
K4=1.0,K5=0.0087,K6=0.0043,K7=0.0044,K8=1.0,...
K9=1.0,K10=1.0,K11=1.0,CALR=3000.,CALO=3000.
CONSTANT CMANI=12600.,CCO2I=1.0E4,CWASTI=542.,CFOODI=1000.,...
TEMP=25.0,CCHANI=0.,CPLANI=1.1E5,CSTORI=1000.
A=CEAT
B=CEAT*K3
C=AMAX1(CALO-CALI,0.)*K2
D=CEAT*K1*(1.-AMAX1((CALI-CALO)/CALI,0.))
E=CWASTE*K4
F=AMAX1(CFOOD-1000.,0.)
G=K9*AMAX1(CCO2-CCO2I,0.)
H=K8*AMAX1(CSTORE,0.)*AMAX1(0.,CCO2I-CCO2)
I=CPLANT*K5*TEMPF(TEMP)
J=CPLANT*K6*TEMPF(TEMP)
K=CPLANT*K7*TEMPF(TEMP)
DOTCM=A-(B+C+D)
DOTCWS=(B+F+K)-(E)
DOTCCO=(E+C+D+H)-(G+I)
DOTCPL=(I)-(J+K)
DOTCS=G-H
DOTCFO=(J)-(A+F)
```

```
CMAN=INTEG(DOTCM,CMANI)
CCO2=INTEG(DOTCCO,CCO2I)
CFOOD=INTEG(DOTCFO,CFOODI)
CPLANT=INTEG(DOTCPL,CPLANI)
CWASTE=INTEG(DOTCWS,CWASTI)
CSTORE=INTEG(DOTCS,CSTORI)
CCHANG=INTEG(DOTCM+DOTCFO+DOTCCO+DOTCPL+DOTCWS+DOTCS,CCHANI)
CSUM=CMAN+CCO2+CFOOD+CPLANT+CWASTE+CSTORE
CONSTANT K111=1.0,K222=0.0,K333=0.0,...
NPLANI=1.E5,NFOODI=1.E3,NMANI=1.E4,NWASTI=1.E2,NSTRAI=1.E3,...
NHARVI=1.E3,NNO3I=1.E2,NN2OI=1.E2,NN2I=1.E2,NCHANI=0.0,ITEND=360.0
NEAT=GEAT*.0537
AKN=NPLANT*K5
KLN=NPLANT*K5*.3467
KBN=NPLANT*K5*.6533
BCN=GPRO*.1580
BDN=NHARV*.6533*AMAX1(0.,SIGN(1.,NFOOD-1.E3))+...
1.*AMAX1(0.,NFOOD-1.E3)
LDN=NPLANT*K5*.3467
CDUN=GPRO*.1580*.9
CDFN=GPRO*.1580*.1
DON=(BDN+CDFN+CDUN+LDN)*K111
DNN=(BDN+CDFN+CDUN+LDN)*K222
DPN=(BDN+CDFN+CDUN+LDN)*K333
PON=DPN
NON=DNN
OAN=PON+DON+NON
DOTAN=OAN-AKN
DOTKN=AKN-(KBN+KLN)
DOTLN=KLN-LDN
DOTBN=KBN-(BCN+BDN)
DOTCN=BCN-(CDFN+CDUN)
DOTDN=(BDN+LDN+CDUN+CDFN)-(DPN+DON+DNN)
DOTPN=DPN-PON
DOTON=(DON+PON+NON)-OAN
DOTNN=DNN-NON
NPLANT=INTEG(DOTAN,NPLANI)
NFOOD=INTEG(DOTBN,NFOODI)
NMAN=INTEG(DOTCN,NMANI)
```

```
NWASTE=INTEG(DOTDN,NWASTI)
NHARV=INTEG(DOTKN,NHARVI)
NSTRAW=INTEG(DOTLN,NSTRAI)
NNO3=INTEG(DOTON,NNO3I)
NN2O=INTEG(DOTPN,NN2OI)
NN2=INTEG(DOTNN,NN2I)
NCHANG=INTEG(DOTAN+DOTKN+DOTLN+DOTBN+DOTCN+DOTDN+...
DOTPN+DOTON+DOTNN,NCHANI)
NSUM=NPLANT+NFOOD+NMAN+NWASTE+NHARV+NSTRAW+...
NNO3+NN2O+NN2
END
TERMT(T.GE.ITEND)
END
```

Model Result 1

T	CMAN	CPLANT	CFOOD	CWASTE
0.	12599.999	110000.00	1000.0000	542.00000
59.999656	12599.999	110000.00	1172.9995	677.51922
119.99874	12599.999	110000.00	1172.9995	677.51922
179.99874	12599.999	110000.00	1172.9995	677.51922
239.99874	12599.999	110000.00	1172.9995	677.51922
299.99874	12599.999	110000.00	1172.9995	677.51922
359.99875	12599.999	110000.00	1172.9995	677.51922

T	CCO2	CSTORE	CSUM
0.	10000.000	1000.0000	135142.00
59.999656	10000.000	691.47796	135142.00
119.99874	10000.000	691.47796	135142.00
179.99874	10000.000	691.47796	135142.00
239.99874	10000.000	691.47796	135142.00
299.99874	10000.000	691.47796	135142.00
359.99875	10000.000	691.47796	135142.00

Model Result 2

T	OMAN	OPLANT	OFOOD	OWASTE
0.	10000.000	100000.00	1000.0000	100.00000
60.000000	10000.000	99998.598	1000.0000	101.25290
120.00000	10000.000	99997.186	1000.0000	102.50580
179.99999	10000.000	99995.784	1000.0000	103.75869
240.00000	10000.000	99994.373	1000.0000	105.01159
300.00000	10000.000	99992.961	1000.0000	106.26449
359.99999	10000.000	99991.559	1000.0000	107.51739

T	002	OC02	OH20
0.	100000.00	10000.000	1000.0000
60.000000	100000.00	10000.000	1000.0000
120.00000	100000.00	10000.000	1000.0000
179.99999	100000.00	10000.000	1000.0000
240.00000	100000.00	10000.000	1000.0000
300.00000	100000.00	10000.000	1000.0000
359.99999	100000.00	10000.000	1000.0000

Model Result 3

T	OMAN	OFOOD	OPLANT	OWASTE
0.	10000.000	1000.0000	100000.00	100.00000
60.000000	10000.000	1000.0000	100000.00	99.856719
120.00000	10000.000	1000.0000	100000.00	99.713439
179.99999	10000.000	1000.0000	100000.00	99.570159
240.00000	10000.000	1000.0000	100000.00	99.426879
300.00000	10000.000	1000.0000	100000.00	99.283599
359.99999	10000.000	1000.0000	100000.00	99.140319

T	OO2	OCO2	OSUM
0.	100000.00	10000.000	222100.01
60.000000	100000.00	10000.000	222099.85
120.00000	100000.00	10000.000	222099.73
179.99999	100000.00	10000.000	222099.56
240.00000	100000.00	10000.000	222099.44
300.00000	100000.00	10000.000	222099.25
359.99999	100000.00	10000.000	222099.16

Model Result 4

T	OMAN	OFOOD	OPLANT	OWASTE
0.	10000.000	1000.0000	100000.00	100.00000
60.000000	9998.1250	1000.0000	100039.83	97.564697
120.00000	9996.2501	1000.0000	100079.69	95.129394
179.99999	9994.3752	1000.0000	100119.53	92.694091
240.00000	9992.5003	1000.0000	100159.38	90.258789
300.00000	9990.6253	1000.0000	100199.22	87.823486
359.99999	9988.7495	1000.0000	100239.06	85.388183

T	002	0C02	0H20	0N03
0.	100000.00	10000.000	1000.0000	1000.0000
60.000000	100000.00	10000.000	1000.0000	1000.0000
120.00000	100000.00	10000.000	1000.0000	1000.0000
179.99999	100000.00	10000.000	1000.0000	1000.0000
240.00000	100000.00	10000.000	1000.0000	1000.0000
300.00000	100000.00	10000.000	1000.0000	1000.0000
359.99999	100000.00	10000.000	1000.0000	1000.0000

T	OSUM
0.	223100.01
60.000000	223135.51
120.00000	223171.06
179.99999	223206.59
240.00000	223242.13
300.00000	223277.68
359.99999	223313.18

Model Result 5

T	OPLANT	OSTRAW	OWASTE	OO2
0.	100000.00	1000.0000	100.00000	100000.00
60.000000	100003.27	1000.0000	96.861572	100000.00
120.00000	100006.55	1000.0000	93.724365	100000.00
179.99999	100009.84	1000.0000	90.586423	100000.00
240.00000	100013.12	1000.0000	87.450199	100000.00
300.00000	100016.40	1000.0000	84.313230	100000.00
359.99999	100019.69	1000.0000	81.177005	100000.00

T	OCO2	OH2O	ONO3	OSUM
0.	10000.000	1000.0000	1000.0000	212100.00
60.000000	10000.000	1000.0000	1000.0000	212100.14
120.00000	10000.000	1000.0000	1000.0000	212100.29
179.99999	10000.000	1000.0000	1000.0000	212100.43
240.00000	10000.000	1000.0000	1000.0000	212100.57
300.00000	10000.000	1000.0000	1000.0000	212100.74
359.99999	10000.000	1000.0000	1000.0000	212100.86

Model Result 6

T	OPLANT	OHARV	OFOOD	OWASTE
0.	100000.00	0.	1000.0000	100.00000
60.000000	100000.00	-0.0036621	1000.0014	100.00000
120.00000	100000.00	-0.0073242	1000.0028	100.00000
179.99999	100000.00	-0.0109863	1000.0044	100.00000
240.00000	100000.00	-0.0146484	1000.0058	100.00000
300.00000	100000.00	-0.0183105	1000.0072	100.00000
359.99999	100000.00	-0.0219727	1000.0087	100.00000

T	OO2	OCO2	OH2O	ONO3
0.	100000.00	10000.000	1000.0000	1000.0000
60.000000	100000.00	10000.000	1000.0000	1000.0000
120.00000	100000.00	10000.000	1000.0000	1000.0000
179.99999	100000.00	10000.000	1000.0000	1000.0000
240.00000	100000.00	10000.000	1000.0000	1000.0000
300.00000	100000.00	10000.000	1000.0000	1000.0000
359.99999	100000.00	10000.000	1000.0000	1000.0000

T	OSUM
0.	213100.00
60.000000	213100.00
120.00000	213100.00
179.99999	213100.00
240.00000	213100.00
300.00000	213100.00
359.99999	213100.00

Model Result 7

T	OMAN	OFOOD	OWASTE	OO2
0.	10000.000	1000.0000	100.00000	100000.00
60.000000	9998.1250	1089.1187	95.538539	100000.00
120.00000	9996.2501	1089.2595	91.075620	100000.00
179.99999	9994.3752	1089.4004	86.610965	100000.00
240.00000	9992.5003	1089.5414	82.146272	100000.00
300.00000	9990.6253	1089.6822	77.680482	100000.00
359.99999	9988.7495	1089.8231	73.212890	100000.00

T	OCO2	OH2O	OHARV	OSTRAW
0.	10000.000	1000.0000	0.	1000.0000
60.000000	10000.000	1000.0000	-0.0026245	1000.0000
120.00000	10000.000	1000.0000	-0.0050049	1000.0000
179.99999	10000.000	1000.0000	-0.0074463	1000.0000
240.00000	10000.000	1000.0000	-0.0099487	1000.0000
300.00000	10000.000	1000.0000	-0.0123901	1000.0000
359.99999	10000.000	1000.0000	-0.0148315	1000.0000

T	ONO3	OPLANT	OBUFFR	OCHANG
0.	1000.0000	100000.00	100000.00	0.
60.000000	1001.5767	100040.32	100000.00	15608.477
120.00000	1003.1822	100080.64	100000.00	31127.972
179.99999	1004.7899	100120.94	100000.00	46647.567
240.00000	1006.4011	100161.26	100000.00	62167.177
300.00000	1008.0140	100201.58	100000.00	77686.600
359.99999	1009.6293	100241.89	100000.00	93205.976

T	OSUM
0.	322099.99
60.000000	322223.13
120.00000	322257.28
179.99999	322291.32
240.00000	322325.46
300.00000	322359.58
359.99999	322393.72

Model Result 8

T	NMAN	NFOOD	NPLANT	NWASTE
0.	10000.000	1000.0000	100000.00	100.00000
60.000000	10000.000	1410.5524	99589.433	99.999084
120.00000	10000.000	1410.5524	99589.433	99.998168
179.99999	10000.000	1410.5524	99589.433	99.997253
240.00000	10000.000	1410.5524	99589.433	99.996337
300.00000	10000.000	1410.5524	99589.433	99.995422
359.99999	10000.000	1410.5524	99589.433	99.994506

T	NHARV	NSTRAW	NNO3	NN2O
0.	1000.0000	1000.0000	100.00000	100.00000
60.000000	999.99990	1000.0000	100.00000	100.00000
120.00000	999.99990	1000.0000	100.00000	100.00000
179.99999	999.99990	1000.0000	100.00000	100.00000
240.00000	999.99990	1000.0000	100.00000	100.00000
300.00000	999.99990	1000.0000	100.00000	100.00000
359.99999	999.99990	1000.0000	100.00000	100.00000

T	NN2	NCHANG	NSUM
0.	100.00000	0.	113400.00
60.000000	100.00000	-7.935E-04	113399.98
120.00000	100.00000	-0.0017090	113399.98
179.99999	100.00000	-0.0026245	113399.98
240.00000	100.00000	-0.0035400	113399.98
300.00000	100.00000	-0.0044556	113399.98
359.99999	100.00000	-0.0053711	113399.98

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1. Report No. NASA CR- 166331	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle An Approach to the Mathematical Modelling of a Controlled Ecological Life Support System		5. Report Date August 1981
		6. Performing Organization Code
7. Author(s) Maurice Melvin Averner		8. Performing Organization Report No.
9. Performing Organization Name and Address Complex Systems Research Center University of New Hampshire Durham, NH 03824		10. Work Unit No. T5425
		11. Contract or Grant No. NAS2-10133
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 24056		13. Type of Report and Period Covered Contractor Report
		14. Sponsoring Agency Code 199-60-62

15. Supplementary Notes

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16. Abstract

This report presents an approach to the design of a computer based mathematical model of a closed ecological life-support system suitable for use in extraterrestrial habitats. The model is based on elemental mass-balance and contains representations of the metabolic activities of biological components. The model can be use as a tool in evaluating relevant areas of pertinent biological research, as an aid in determining preliminary designs for closed regenerative life support systems and as a method for predicting the behavior of such systems.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
CELSS Life Support Systems Model Mass-Balance	Unclassified - Unlimited STAR Catergory 54

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
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