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An Approach to the Preliminary Evaluation
of Closed Ecological Life Support System (CELSS)
Scenarios and Control Strategies

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TABLE OF CONTENTS

Chapter	Page
1. Introduction	1
2. Closed Ecosystems	2
3. Model Development	4
4. A Generalized Sensitivity Analysis Procedure	5
5. Simulations	9
6. Discussion	14
References	15
Tables	17
Figures	20
Nomenclature	38
Bibliography of CELSS Reports	42

1. INTRODUCTION

Life support systems for manned space missions use a combination of replenishment and recycle. As mission durations increase and crew sizes enlarge, either partial or total recycle options become more attractive (Modell 1977).

Potential life support systems that provide the essentials of air, water, and food through waste recycling have been referred to as CELSS (Closed Ecological Life Support Systems) and PCELSS (Partially Closed Ecological LSS) (Meissner, Modell 1979).

For each possible partial or total recycle scenario a break-even point exists at which it becomes more economical to send into space all the equipment and materials needed to close the recycle loops than to stock all the needed provisions for use on a once through basis (Modell, Spurlock 1979). Presently the knowledge needed to identify the optimum recycle PCELSS or CELSS option for a given type of mission does not exist.

A scenario analysis method has been proposed for the initial step of comparing scenario options and identifying promising alternatives (Modell, Spurlock 1979). The method consists of five steps:

- 1) Specify the diet.
- 2) Select the food-producing processes.
- 3) Determine waste-processing requirements and methods.
- 4) Characterize equipment and facility requirements.
- 5) Test control strategies and determine the ability of the scenario to ensure man's survival.

This paper presents the results of applying the scenario analysis method on a simplified CELSS scenario. Emphasis is on the fifth step of the method. Control strategies and survivability are evaluated with a new approach to the analysis of environmental systems developed by Hornberger and Spear (1980). The approach combines probabilistic Monte-Carlo simulation techniques with the notion of descriptors of system behavior to evaluate system performance. The ability of the simplified scenario to ensure man's survival is investigated with this approach. The approach can also be used as a generalized sensitivity analysis procedure to isolate the critical uncertainties in the system and derive information of use in focusing the next phase of research.

The results presented can not be viewed as a prediction of the survivability of any future CELSS. The scenario model developed is simplified to such an extent that it does not have that kind of predictive value. Much of the information needed to develop even first preliminary predictive models has not yet been collected.

Instead, the model has been developed and the scenario analysis approach applied to it to serve as an example of how the approach may be utilized on more realistic predictive models to evaluate the attractiveness of alternative partial or total recycle systems. One goal of this paper is to create an awareness of the Monte-Carlo System Descriptor evaluation process among those responsible for supplying information to the system modelers.

2. CLOSED ECOSYSTEMS

A closed ecosystem can be considered as a collection of living and non-living components combined in such a way that they are closed to mass exchange across the total system boundary. Within the boundary, however, mass may

collect in a flow among the components as determined by the dynamics of the ecosystem.

To survive indefinitely, the mass flows must form closed cycles. The simplest ecosystem cycle is a three step process (Quinlan 1975, Quinlan, Paynter 1976) illustrated in Figure 1. First, plants (autotrophs) use radiant energy to synthesize complex organics from carbon dioxide and other nutrients. Next, the plants are eaten by food consumers (heterotrophs). Ultimately the consumer's oxidized waste products return to the inorganic nutrient pool to complete the cycle.

A simple CELSS that includes closed mass flow cycles is shown conceptually in Figure 2. In this envisioned space colony humans are the heterotrophs. The autotrophs are the plants required to provide the food supply. The human's metabolism oxidizes to carbon dioxide and water a portion of the food. The remainder appears as partially oxidized products in the human's waste products. If the recycler fully oxidizes the partially oxidized wastes and any nonedible portion of the plants, the inorganic nutrients needed for plant photosynthesis are reproduced. The net effect of human metabolism plus waste oxidation is the reverse of the net plant photosynthesis and the gross material balance cycle is closed (Modell, Spurlock 1979).

Note that the CELSS shown in Figure 2 contains two basic types of elements -- flow elements and storage elements. The flow elements are considered to be "transducers" that transduce a stream of inputs to a steady stream of outputs. With the exception of the growing food, a negligible fraction of the system mass is contained in the flow elements. Most mass is held in the various storages.

3. MODEL DEVELOPMENT

A state equation model based on the conceptual CELSS of Figure 2 has been developed to demonstrate scenario and control strategy evaluation by means of Monte-Carlo simulation with descriptors of system survival. The five step scenario analysis method guided the model development.

The inputs required to support a person in space are shown in Table 1. A simple diet scenario based on wheat can be specified to meet the dry food requirement. Given this harvest requirement, the carbon dioxide, water, and nutrient inputs and the oxygen output must be determined for the food producing processes.

The human requirements for oxygen, food, and water have already been given, but the corresponding outputs of carbon dioxide and water vapor must be calculated. Finally, the waste inputs and characteristics of the waste recycler must be specified. For details of these calculations see Stahr (1979).

The recycler is based on an incineration oxidizer proposed by Meissner and Modell (1979). The recycler outputs are chosen to close the material balance cycles. This situation corresponds to the ideal case in which all waste inputs can be successfully recycled and the CELSS system could survive indefinitely as long as each system component performs at its steady state operation point without perturbation.

The next step of the scenario analysis method is the equipment and facility specifications. This step along with the survival analysis is essential for the break even cost point determination, however, specific details are not considered here because they are not needed to illustrate the evaluation process.

The analysis just completed determines a simplified equilibrium flow CELSS model. The steady state mass flow values derived in Stahr (1979) are

shown in Figure 3. The state equations, each of which expresses mass continuity for the particular storage involved, are listed in Figure 4.

A constant growth rate over the plant's 196 day growing cycle is assumed. The average biomass holdup (GROW) is half the harvest biomass. So, each day $\frac{2 \text{GROW}}{196}$ of the growing food is harvested.

To achieve interesting dynamic behavior model development must proceed beyond just equilibrium flow considerations. Some examples of the type of behavior that should be present in the model include:

- 1) The plant growth rate should be affected by environmental conditions.
- 2) Required human inputs should be dependent on the level of human activity.
- 3) Control laws for the recycler and purifier and other flows such as the nutrient flow to the growing crop must be formulated. Flows needing such laws are indicated with a flow valve indicator in Figure 3.
- 4) Flows from a storage should go to zero as the volume of material held in storage approaches zero.

All these examples and others are included in the model. For instance, the plant growth rate is affected by four variables -- the levels of applied nutrient and water, the atmosphere carbon dioxide partial pressure, and the relative humidity. Some simulations include a fifth variable, a random parameter that models a growth rate limit due to some unknown cause.

A detailed term by term derivation of the model equations is given in Stahr (1979).

4. A GENERALIZED SENSITIVITY ANALYSIS PROCEDURE

The analysis approach developed by Spear and Hornberger is now presented in summary form. (See Hornberger and Spear 1980, Spear 1970a, 1970b for a more

detailed exposition).

4.1 The Monte-Carlo System Descriptor Analysis Approach

Consider processes that can be modeled by a set of first order differential equations of the form (other models may be handled similarly):

$$\frac{d\mathbf{x}(t)}{dt} = \dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x}(t), \mathbf{\epsilon}, \mathbf{u}(t))$$

where: $\mathbf{x}(t)$ = state vector $\mathbf{\epsilon}$ = uncertain parameters

$\mathbf{u}(t)$ = inputs, forcing function, time variable functions,
assumed deterministic here for simplicity.

Different equations correspond to different CELSS scenarios or different control strategies within a scenario. Each element of the parameter vector $\mathbf{\epsilon}$ is considered to be a random variable with a distribution corresponding to the uncertainties in the flows to be expected to or from a CELSS component, or to the uncertainty in the required volume of each storage. The parameter distributions define an ensemble of models for the scenario.

For each randomly chosen parameter set $\mathbf{\epsilon}^*$ there corresponds a unique state trajectory $\mathbf{x}(t)$ and observation vector $\mathbf{y}^*(t)$. A behavior descriptor for the system is defined in terms of $\mathbf{y}(t)$. For CELSS this descriptor could be survival or nonsurvival of the human occupants for the mission duration. More complex multi-possibility behavior categories could be defined.

Multiple computer simulations are performed for random choices of $\mathbf{\epsilon}$ from the predefined distributions. Each simulation either results in a behavior, B, or not a behavior, \bar{B} . For each element, ϵ_k , of the parameter vector $\mathbf{\epsilon}$ the multiple runs result in a set of values ϵ_k associated with B and a set associated with \bar{B} . The subset of parameters that account most strongly for

the occurrence of B or \bar{B} must be identified. A large fraction of the parameters are often unimportant to the critical behavior.

A sensitivity ranking can be based on a measure of the separation of the cumulative distribution functions $F(\epsilon_k|B)$ and $F(\epsilon_k|\bar{B})$ using the Kolmogorov-Smirnov two sample test statistic:

$$d_{m,n} = \sup_x |S_n(x) - S_m(x)|$$

where for n behaviors and m nonbehaviors:

S_n = sample distribution corresponding to $F(\epsilon_k|B)$.

S_m = sample distribution corresponding to $F(\epsilon_k|\bar{B})$.

Large values of $d_{m,n}$ indicate that the parameter distributions have separated and the occurrence of B or \bar{B} is sensitive to the parameter value. In cases where induced covariance is small the converse is true for small values of $d_{m,n}$.

A parameter might be strongly coupled with other parameters to affect the behavior. Therefore the induced covariance structure must be included in a full sensitivity ranking. (See Hornberger and Spear 1980.)

Upper and lower limit probability bounds for a sample distribution may be obtained through use of the statistic

$$D_n = \sup_x |S_n(x) - F(x)|$$

where $S_n(x)$ = the sample cumulative distribution.

$F(x)$ = the true distribution (assumed to be continuous).

Kolmogorov determined the distribution of D_n . A confidence band about $S_n(x)$ that includes $F(x)$ with a given probability can be set up.

$$P \{D_n = \sup_x |S_n(x) - F(x)| > d_\alpha\} = \alpha$$

Given n and α , d may be found in any elementary book on statistics or in Spear (1970b). Finally, confidence regions for the true distribution may be found from:

$$P \{S_n(x) - d_{\alpha} \leq F(x) \leq S_n(x) + d_{\alpha} \text{ for all } x\} = 1 - \alpha.$$

4.2 Model Survival Criteria

In the model simulations, the behavior, B , is defined as nonsurvival of the human occupants. The CELSS must be designed to maximize the probability of the survival of the occupants, \bar{B} . Failure to survive is evaluated with three criteria:

- 1) Oxygen. If the human lung alveolar oxygen partial pressure ever drops below 35mm Hg the humans perish due to lack of oxygen (Billings 1972).
- 2) Food. If the humans do not receive their ideal food supply a food deficit starts accumulating. Failure occurs if they receive the equivalent of no food for a fifty day period.

$$\text{Food} \begin{cases} \text{Survive if: } \int_0^{T_{\max}} \frac{1}{50} \left(1 - \frac{FM}{FMII}\right) dt < 1 \\ \text{Fail if: } \int_0^{T_{\max}} \frac{1}{50} \left(1 - \frac{FM}{FMII}\right) dt \geq 1 \end{cases}$$

If a food deficit exists and plenty of food is presently available, FM will increase above $FMII$ to start decreasing the deficit.

- 3) Drinking water. Similarly, failure occurs if the humans receive the equivalent of no water for a five day period.

$$\text{Water} \left\{ \begin{array}{l} \text{Survive if: } \int_0^{T_{\max}} \frac{1}{5} \left(1 - \frac{\text{HMD}}{\text{HDSS}} \right) dt < 1 \\ \text{Fail if: } \int_0^{T_{\max}} \frac{1}{5} \left(1 - \frac{\text{HMD}}{\text{HDSS}} \right) dt \geq 1 \end{array} \right.$$

Failure occurs if any of the three criteria indicates failure.

5. SIMULATIONS

5.1 Control Laws

Two control strategies are contrasted in the simulations. These strategies will be called proportional control and supervisory control.

The proportional control regulates the flows from storage based solely on the amount of matter contained in the storage. The rate laws for three of the flows are illustrated in Figure 5. The laws for the other rates, for example the waste recycler operation rate (RRTE), are all directly proportional to the storage involved (WSTR in this case).

$$\text{RRTE} = \frac{2}{\text{WSTG}} \cdot \text{WSTR} \cdot \text{RRAO}$$

The proportional gains, WSTG in this instance, are all set so that the steady state recycler rate is reached when the storage contains 25 days worth of material. RRTE is more complicated than the other rates because it contains a modulating factor, RRAO, included to model incomplete combustion at low atmospheric oxygen concentrations.

The supervisory control monitors the food and oxygen level and takes corrective action if either level starts becoming low. Two steps are taken to raise the level

- 1) More crops are planted which produce more oxygen.
- 2) The recycler operation rate is decreased which decreases the recycler's oxygen consumption.

When the food storage becomes low the planting rate is increased.

Notice that if the system does become unbalanced, pressure can be applied only at certain points such as those above, to attempt a correction. However, such attempts could conceivably unbalance some other part of the system and lead to different failures.

5.2 Flow Uncertainty Results

The first simulations were conducted with three random parameters relating to flow uncertainties. They are:

- 1) UH1. Reflects uncertainty in the fraction of the harvest that is edible food.
- 2) ULOA. Uncertainty in the human level of activity which affects all the human inputs and outputs.
- 3) UBOP. A growth rate limit due to some unknown or unmodeled cause (i.e., not nutrient, water, carbon dioxide or humidity levels).

Each parameter was given an independent, rectangular probability density function distribution with upper and lower limits 25% away from the steady state values of 1. Since only upper and lower limits are known, the rectangular distribution will provide the least biased specification of the parameters.

For both control schemes 100 simulation runs of 500 day length were conducted with different storage volume initial conditions. The results of these runs are presented in Table 2. Looking at the results for the Supervisory control with 100 day storage it is seen that no failures occurred. Thus, the

estimate of the probability of success (survival) is unity. Since 100 simulations were performed we can say that

$$0.96 < \text{probability of survival} \leq 1$$

with 95% confidence. (See Clopper and Pearson, 1934.) 250 days supplies are required to make the same statement with the proportional control.

Figure 6 shows state variable plots for one of the 200 day supply proportional control failures. The humans perished at 410 days from insufficient oxygen. This failure like all the others presented in this paper is a consequence of the system's dynamics and can not be predicted on the basis of an algebraic analysis of flows.

5.3 Recycler Shutdown

The response of the model to the unexpected event of a twenty day recycler shutdown was studied next. For these simulations the factors UH1, ULOA, and UBOP were all set to their steady state value of 1 so that the system could operate at steady state in the presence of no disturbances. Storages were set to 25 days supplies.

We might expect system survival since storages exceed shutdown time. This expectation, however, is not necessarily correct as can be seen from the proportional control results of Figure 7 and the supervisory control results of Figure 8.

With the proportional control, the twenty day shutdown causes a failure more than 800 days after the event. The system is never able to re-reach steady state. The additional flexibility of the supervisory control allows the system to recover without failure.

The importance of selecting "good" control strategies is illustrated by

the improved supervisory control performance in this and the earlier simulations.

5.4 Storage Size Sensitivity Analysis

In the previous flow uncertainty simulations we found that 100 days worth of supplies were needed to ensure survival. However, some of these storages may have been unimportant to survival and been sized much larger than actually necessary. The sensitivity of individual storage sizes to the recycler shutdown event is now studied. The more effective supervisory control is used in the study.

The storage initial conditions were given rectangular probability density functions with the limits indicated in Figure 9. Two hundred fifty simulations of 500 day missions were performed which resulted in 103 survivals and 147 failures. The cumulative distributions for each storage are shown in Figure 10. Table 3 contains the Kolmogorov-Smirnov statistics, $d_{m,n}$ for each storage.

The statistic for two storages, NSTR (nutrient storage) and WSTR (waste storage), indicate at above the 99% level of significance that the simulative distributions fail the null hypothesis of identical distributions. All other storages fall below the 99% level. These results indicate, at least in terms of a univariate analysis, that the NSTR and WSTR storage sizes are the most important determinants of the behavior.

Note that the distributions for FSTR show that for the initial condition ranges used, there are regions such that the survival probability is high for cases with small initial food storage. Also, there are regions such that the survival probability is low for cases with large initial food storage. However, univariate analysis is misleading due to the multiple modes of failure. An analysis of the covariance structure should uncover significant couplings among the initial condition parameters, if they exist.

It may also seem odd that the WSTR initial condition should affect the survival probability significantly. However, the supervisory control gains part of its flexibility from being able to decide how fast to recycle the wastes in storage. This flexibility is lost if only small amounts of waste are present.

The univariate analysis indicates that the NSTR and WSTR storages are adversely affecting the CELSS survival as presently sized. The next step in the storage size design process is to increase these storages and repeat the multiple simulations.

NSTR was increased from its previous range of values to a constant value of 200 days supply. The large figure was chosen because the NSTR separation was so large and the additional nutrient weight is negligible compared to the total weight of the CELSS storages. WSTR was increased to the upper limit of its previous range. The full initial condition set for this second set of multiple runs may be found in Figure 11.

In a set of 250 simulations absolutely no failures occurred with these new initial conditions. The estimated probability of survival is unity. Thus, with 95% confidence we can say that

$$0.98 < \text{probability of survival} \leq 1$$

for the modified initial conditions when subjected to this particular unexpected event. (See Clopper and Pearson, 1934.) With this level of confidence we can now conclude that the storage initial conditions as presently sized provide a high probability of survival for the recycler shutdown event.

We might wish to examine a design alternative that does not involve increasing the waste storage size. If we want to change any of the initial condition probability densities, the entire analysis process must be repeated. A multiple run could be done in which all WSTR initial conditions were set

equal to zero. New sets of cumulative distributions would be determined that might now indicate different sensitivities caused by the changed system structure.

Similarly a different unexpected event could require different storage sizing to ensure survival. The total range of possible events, rather than a single event, must be defined and considered in a complete CELSS scenario evaluation.

6. DISCUSSION

An approach to the problem of comparing alternative CELSS or PCELSS scenarios and control strategies within a scenario has been illustrated in this paper. We see that once probability distributions have been assigned to all uncertain parameters of the system, this method performs a generalized sensitivity analysis. This enables us to determine the critical parameters or regions within the range of the parameters leading to a high probability of survival.

If the model does not include provision in some form for a possible critical failure mode of the real system, there is nothing in the sensitivity analysis method that will uncover the sensitivity. For instance, microelements may build up in the plants or humans or microorganisms might be present that could lead to other possible failures.

The existence of failure modes that are a consequence of the system's dynamic interactions and not predictable from static analysis, complicates the modeling task in CELSS systems because it is more difficult to determine the elements of the system that can be neglected in simulation studies. The generalized sensitivity analysis presented here should help in that effort as well as find use in control strategy evaluation.

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INPUT	Gram Person ⁻¹ Day ⁻¹
Food (Dry)	600
Oxygen	900
Drinking Water	1800
Sanitary Water	2300
Domestic Water	16800

TABLE 1: Inputs required to support a person in space.
Adapted from Modell (1977)

NUMBER OF STEADY STATE DAYS STORAGE FOR ALL STORAGES	NUMBER OF FAILURES IN 100 RUNS (500 day mission length)	
	PROPORTIONAL CONTROL	SUPERVISORY CONTROL
50	39	22
100	21	0
150	13	0
200	6	-
250	0	-

TABLE 2: Flow uncertainty results.

STORAGE	$d_{m,n}$
GROW	.1345
FSTR	.1763
NSTR	.6561
AOST	.1576
HSTR	.1019
CSTR	.1567
WSTR	.2510
SDST	.0965

Acceptance limit for the Kolmogorov-Smirnov two sample test (Lindgren 1976)

$$\alpha = .01 \quad 1.63 \sqrt{\frac{n+m}{n \cdot m}} = 1.63 \sqrt{\frac{103+147}{103 \cdot 147}} = .2095$$

TABLE 3: Kolmogorov-Smirnov two sample test statistic for each storage. 103 survivals. 147 failures.

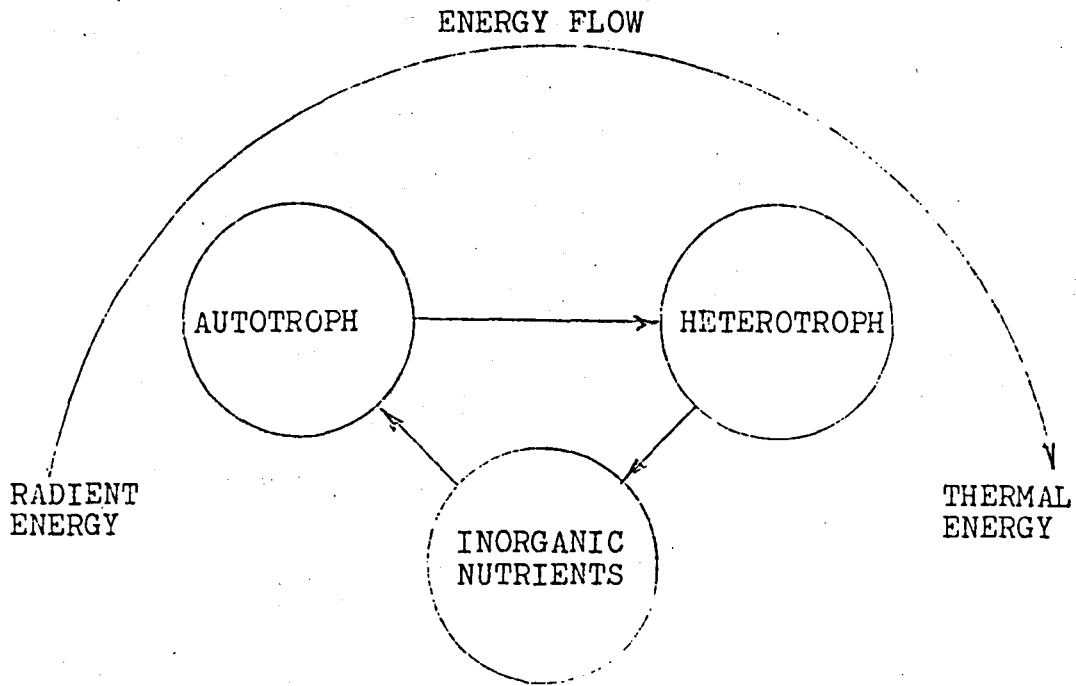
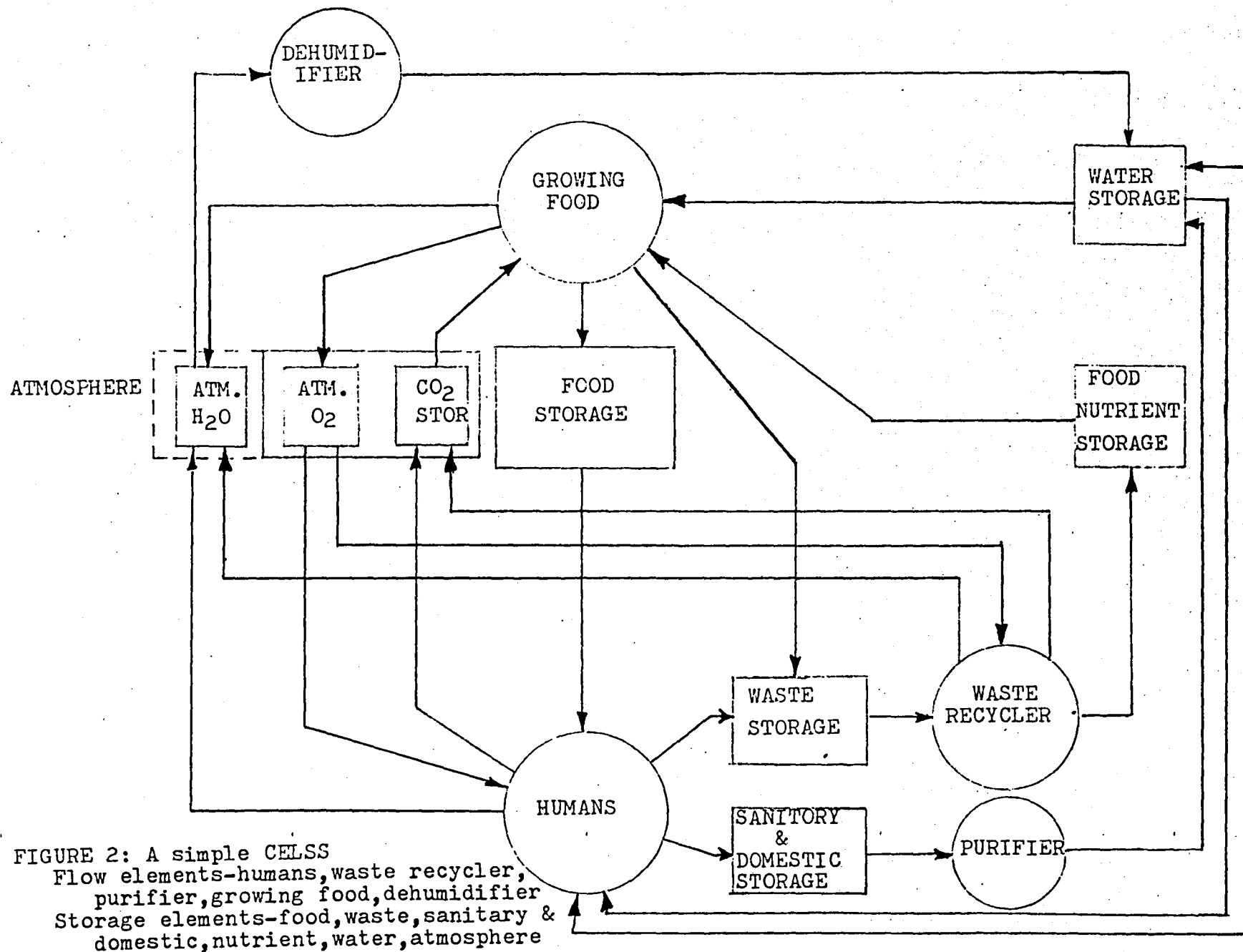


FIGURE 1: Simple ecosystem cycle



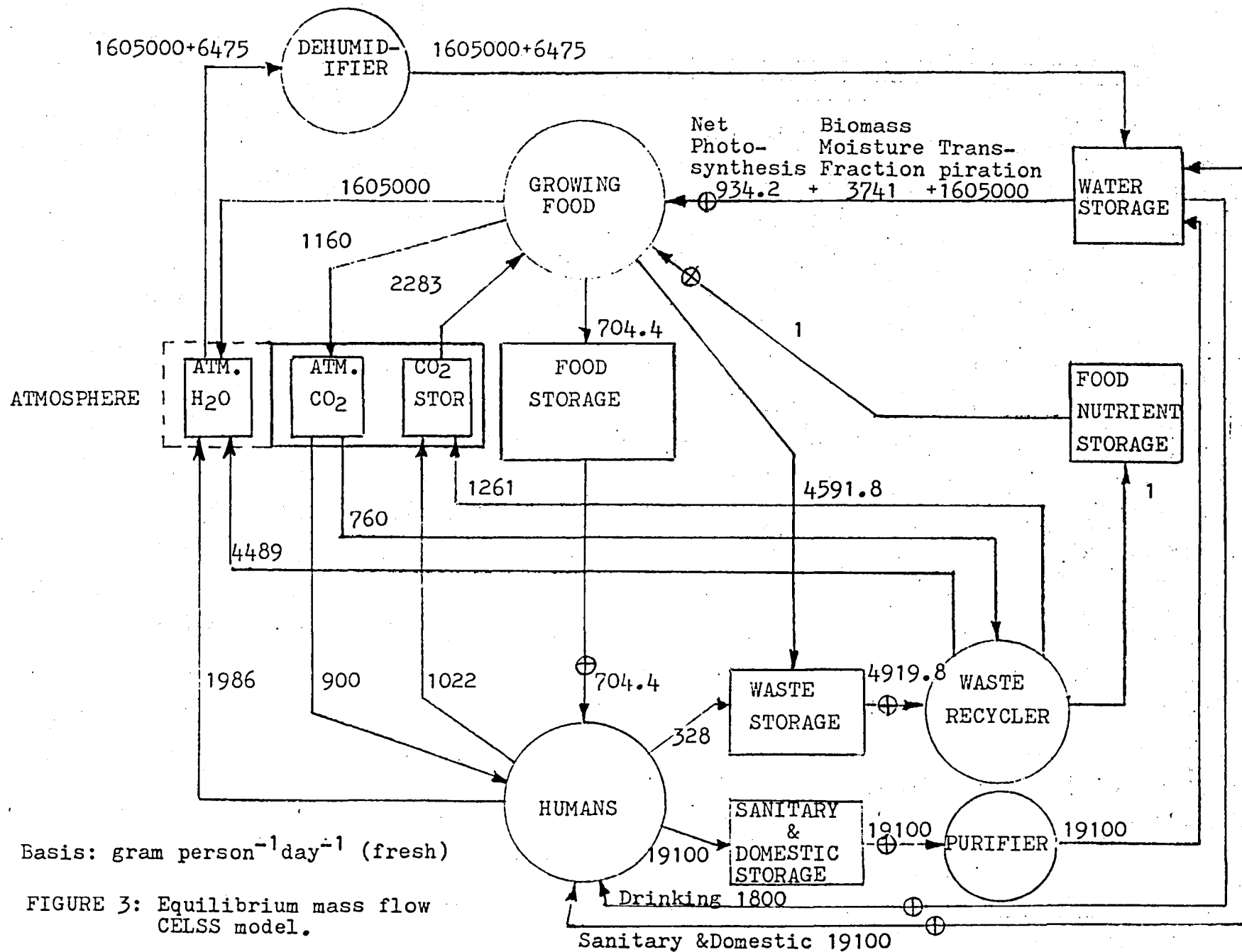


FIGURE 3: Equilibrium mass flow
CELSS model.

$$\frac{d}{dt} \text{GROW} = \text{BO} - \frac{\text{GROW}}{98}$$

$$\frac{d}{dt} \text{FSTR} = .133 \cdot \text{UH1} \cdot \frac{\text{GROW}}{98} - \text{FM}$$

$$\frac{d}{dt} \text{WSTR} = .867 \cdot \text{UH2} \cdot \frac{\text{GROW}}{98} + \text{WM} - \text{WRSS} \cdot \text{RRTE}$$

$$\frac{d}{dt} \text{NSTR} = \text{NRSS} \cdot \text{RRTE} - \text{NF}$$

$$\frac{d}{dt} \text{SDST} = \text{SDM} - \text{SDPS} \cdot \text{PRTE}$$

$$\frac{d}{dt} \text{AOST} = \text{OF} - \text{OM} - \text{OWSS} \cdot \text{RRTE}$$

$$\frac{d}{dt} \text{HSTR} = \text{HPSS} \cdot \text{PRTE} + \text{AHF} + \text{AHM} + \text{AHWS} \cdot \text{RRTE} - \text{HM} - \text{HF}$$

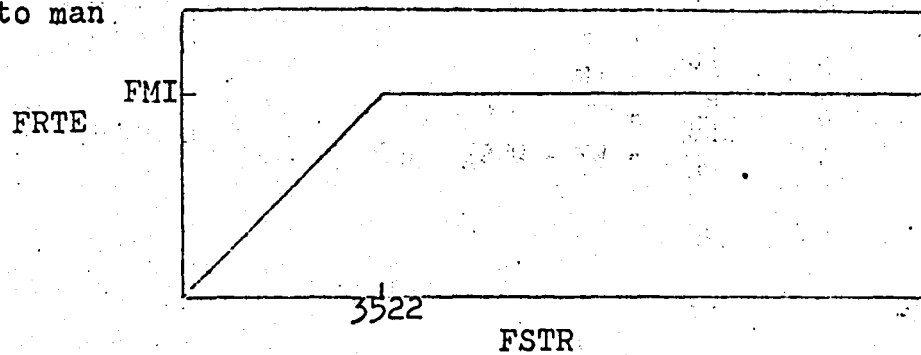
$$\frac{d}{dt} \text{CSTR} = \text{CM} + \text{CWSS} \cdot \text{RRTE} - \text{CF}$$

STATE EQUATION NOMENCLATURE

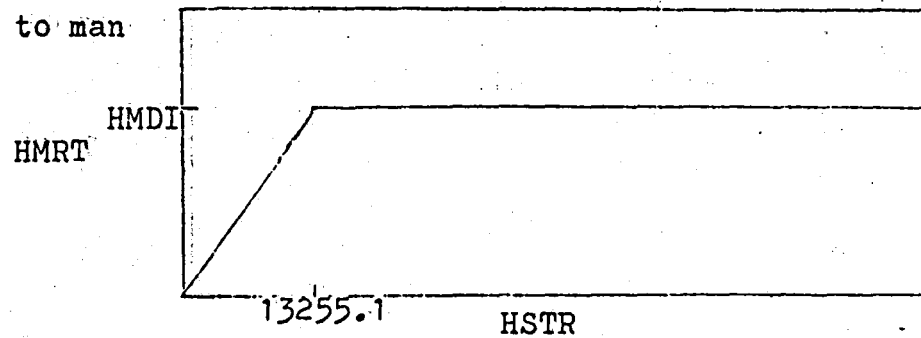
AHF	Plant atmospheric water output
AHM	Human water output to atmosphere
AHWS	Steady state waste recycler water output
AOST	Atmospheric oxygen storage
BO	Plant net growth rate
CM	Human carbon dioxide output flow
CSTR	Carbon dioxide storage
CWSS	Steady state waste recycler carbon dioxide output
FM	Actual flow of food to man
FSTR	Food storage
GROW	Growing food crop
HF	Actual plant water flow
HM	Water flow to humans
HPSS	Steady state purifier output
HSTR	Water storage
NF	Actual nutrient flow to crop
NRSS	Steady state recycler nutrient production rate
NSTR	Nutrient storage
OF	Oxygen output rate of plants
OM	Actual oxygen flow to humans
OWSS	Steady state waste recycler output
PRTE	Purifier control rate
RRTE	Recycler operation rate
SDM	Sanitary and domestic water flow to humans
SDPS	Steady state purification rate
SDST	Sanitary and domestic storage
UH1	Edible crop fraction uncertainty
UH2	Inedible crop fraction uncertainty
WM	Actual human waste production
WRSS	Steady state waste recycler input
WSTR	Waste storage

FIGURE 4: Model state equations and nomenclature

a) Food to man



b) Water to man



c) Water to plants

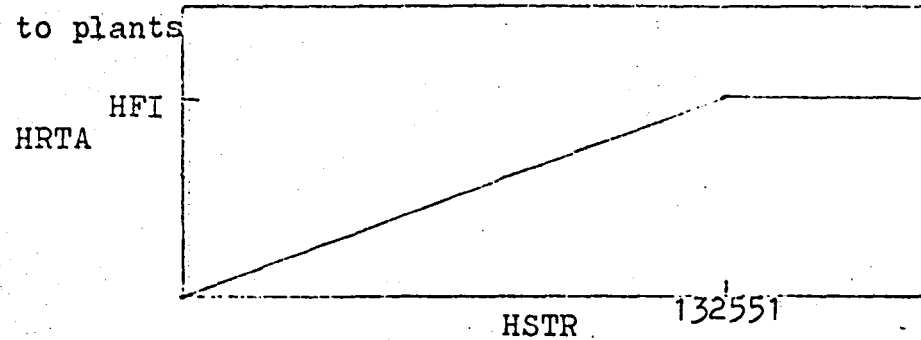


FIGURE 5: Flow laws

- a) Ideal flow until FSTR contains 5 days supply of food.
- b) Ideal flow until HSTR contains 7.4 days supply of drinking water for the humans (.5 days total water requirement).
- c) Ideal flow until HSTR contains 23.6 days supply of water for the growing crop (5 days total water requirement).

PROPORTIONAL CONTROL

Initial Conditions
(200 days supplies)

GROW=519027.6
FSTR=140880
NSTR=200
AOST=332000
HSTR=5302040
CSTR=548000
WSTR=0
SDST=0

Comments: • UH1=1.094
 • ULOA=1.224
 • UBOP=.7616
 • Failure at 410 days due to lack of oxygen.

FIGURE 6A: 200 day supply, uncertain flow, proportional control, failure.

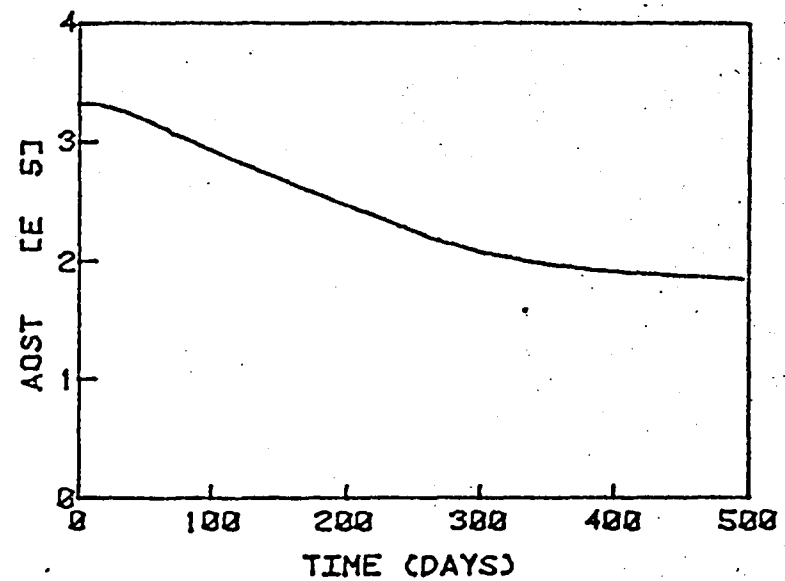
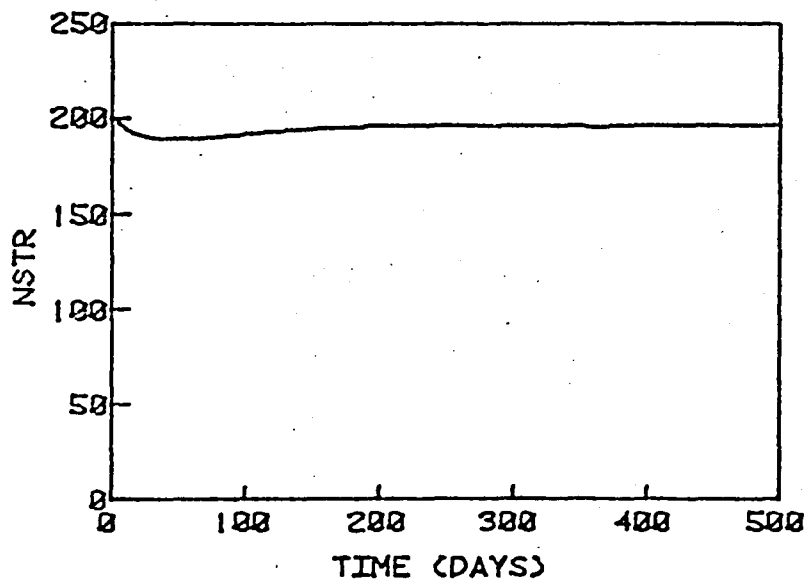
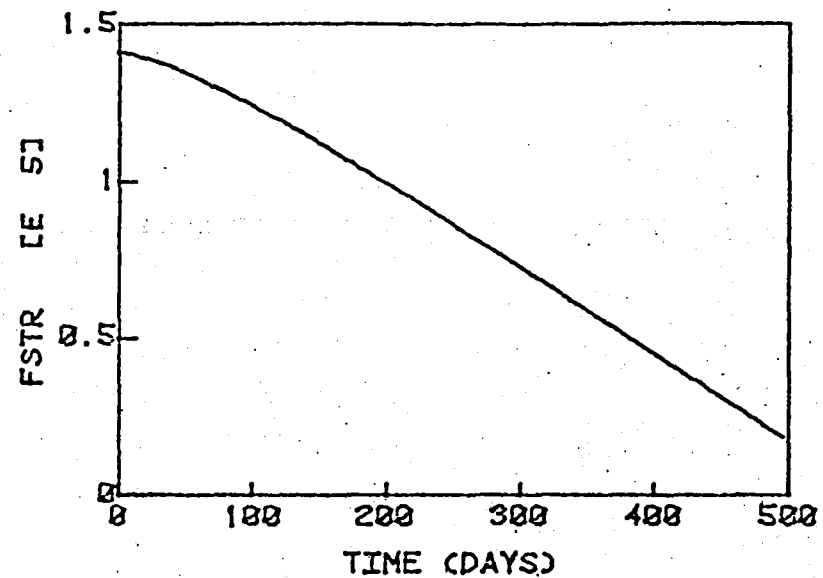
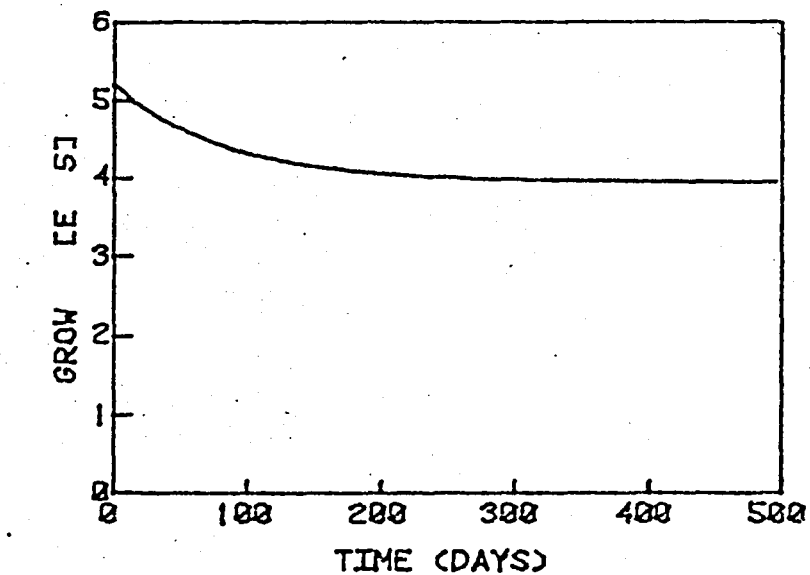


FIGURE 6B: 200 day supply, uncertain flow, proportional control, failure.

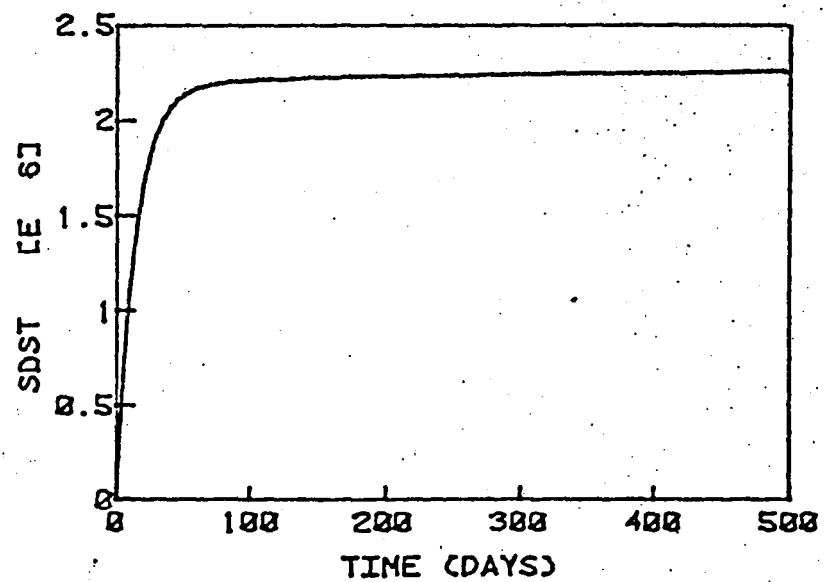
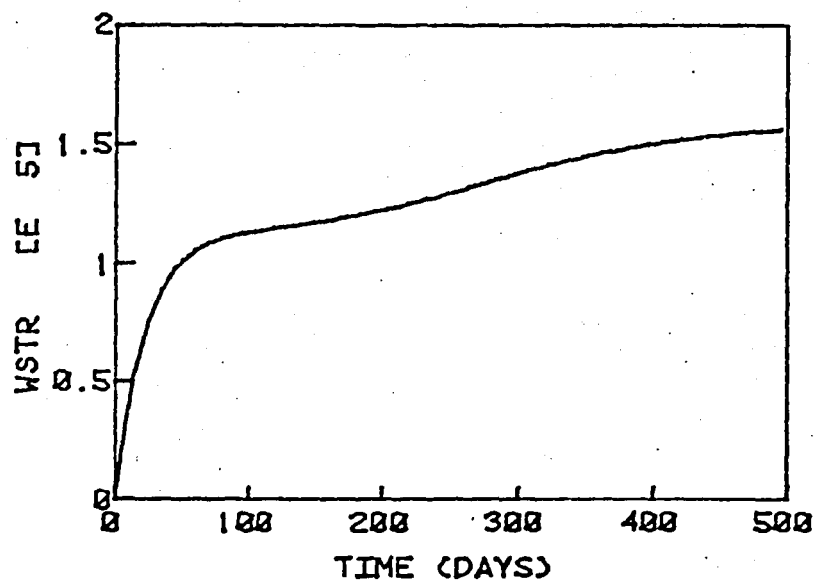
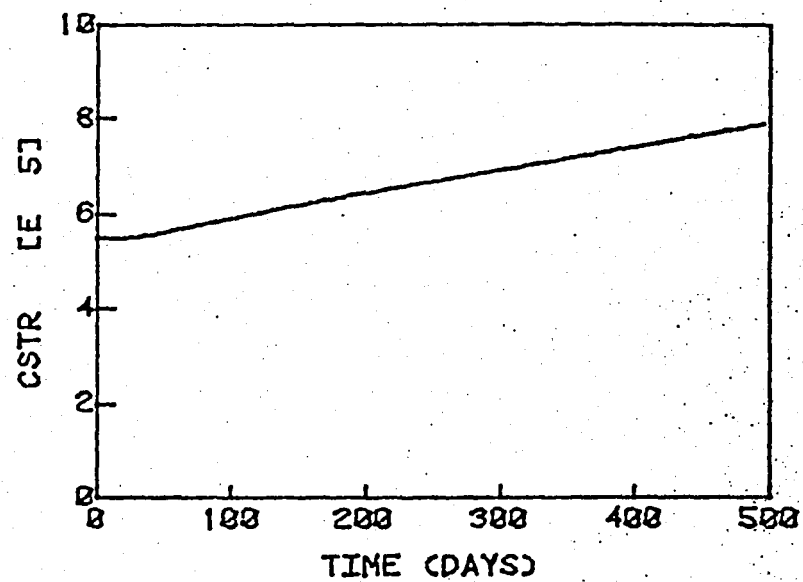
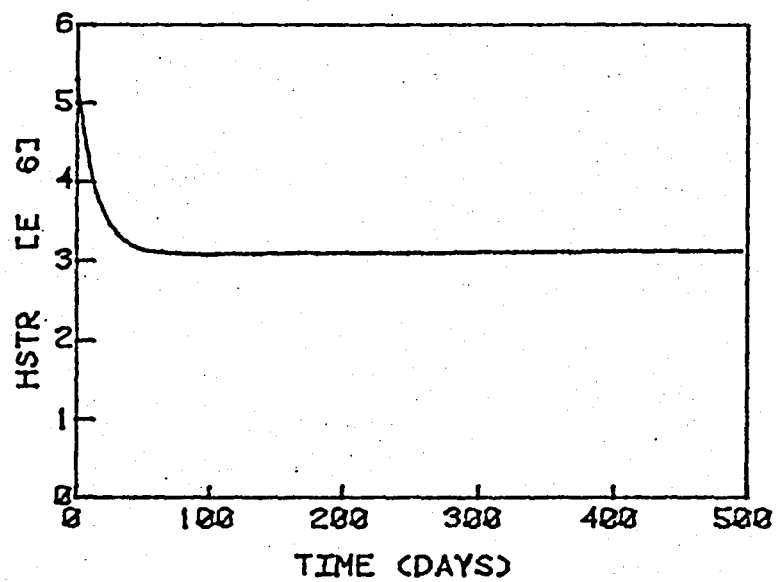


FIGURE 6C: 200 day supply, uncertain flow, proportional control, failure.

PROPORTIONAL CONTROL

Initial Conditions
(25 days supplies)

GROW=519027.6
FSTR=17610
NSTR=25
AOST=41500
HSTR=662755
CSTR=68500
WSTR=122995
SDST=477500

Comments: •Recycler shutoff for 20 days starting at day 10.
•UH1,ULOA & UBOP all set equal to 1.
•Failure at 880 days due to lack of food.

FIGURE 7A: Recycler shutdown, proportional control, failure.

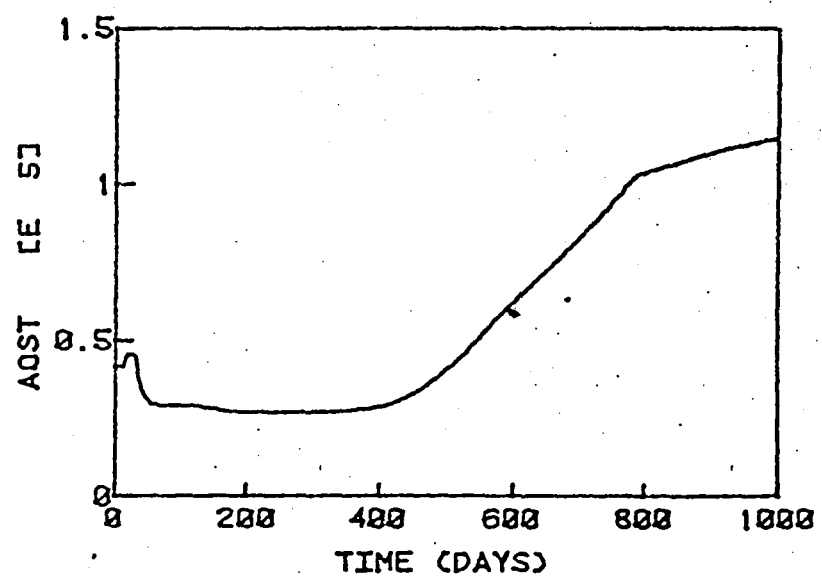
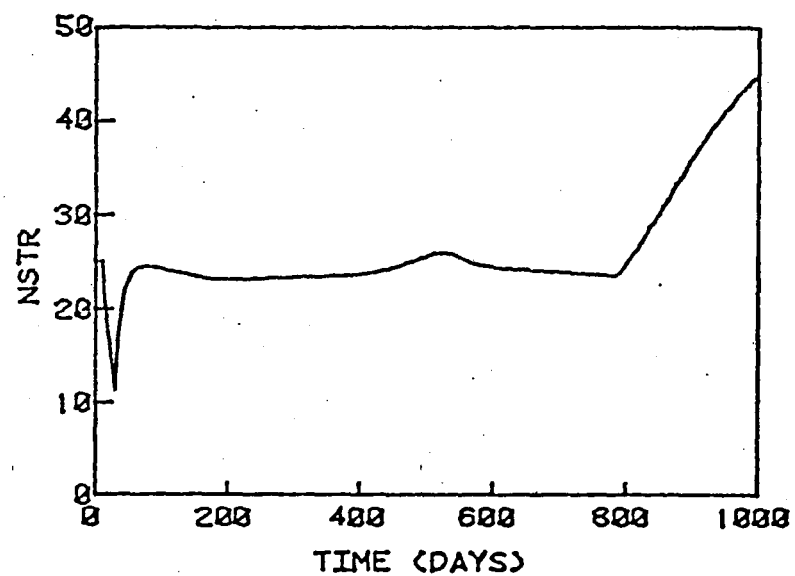
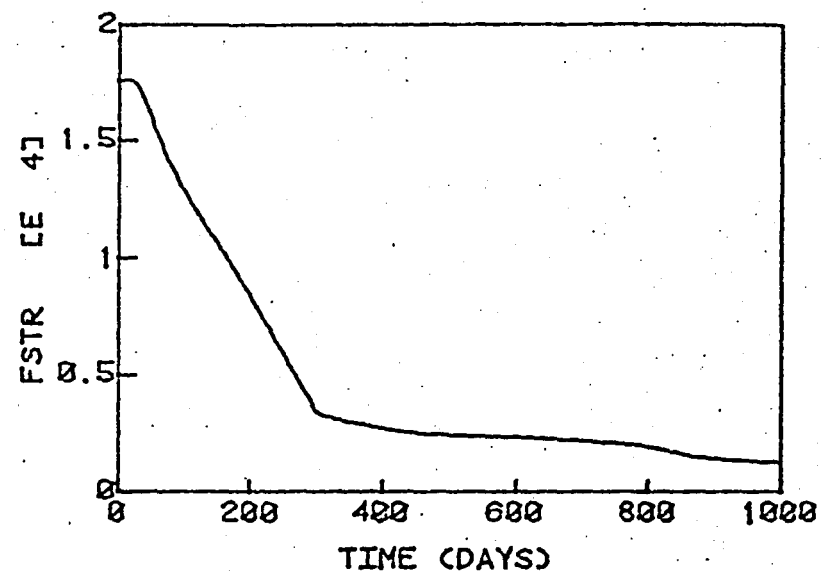
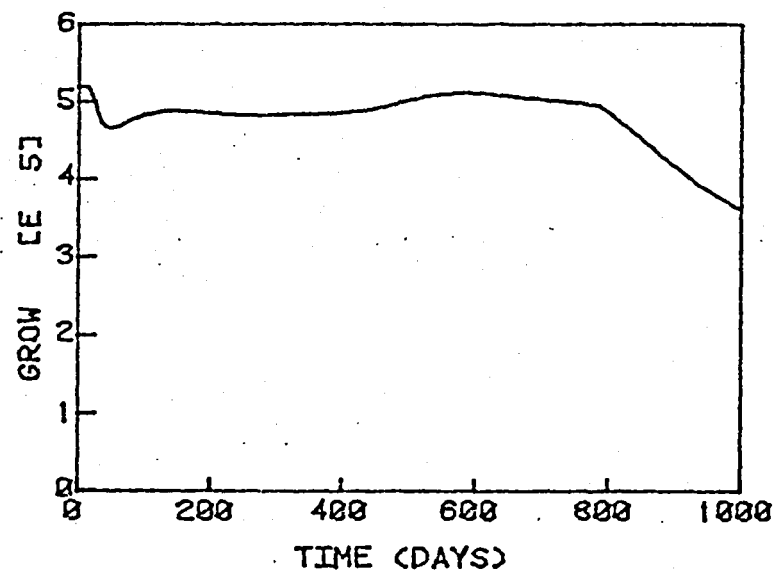


FIGURE 7B: Recycler shutdown, proportional control, failure.

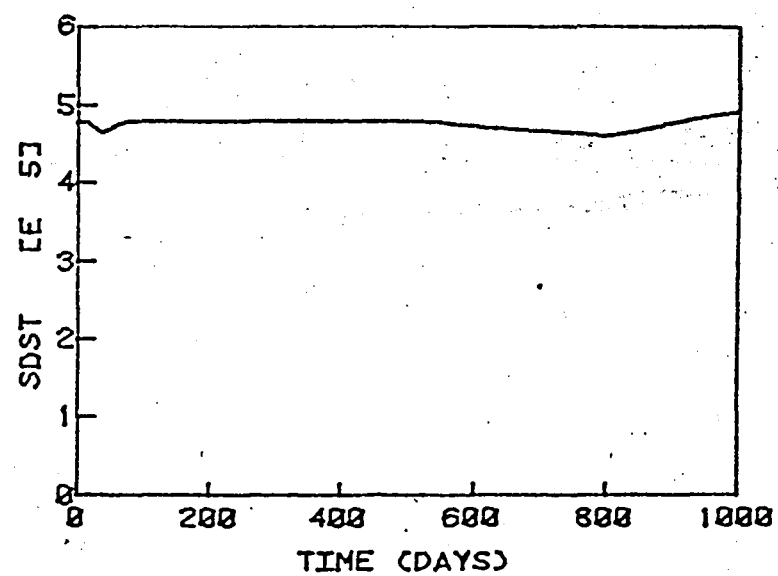
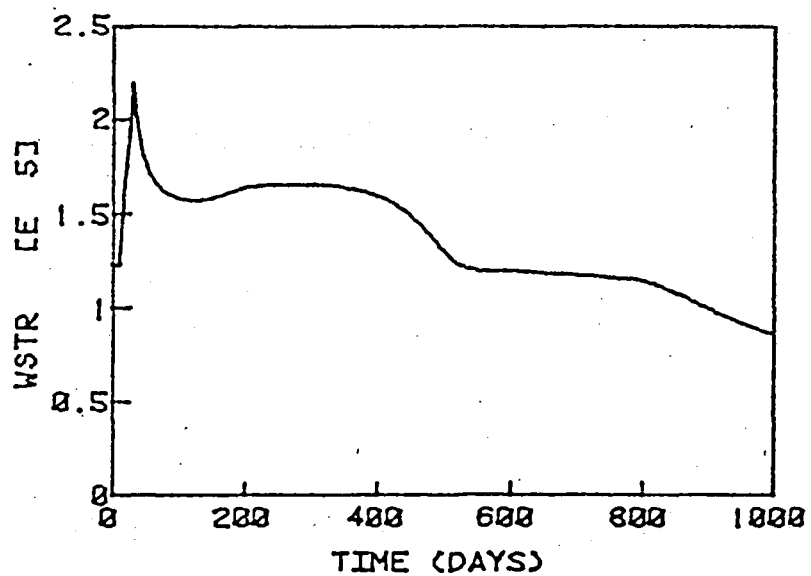
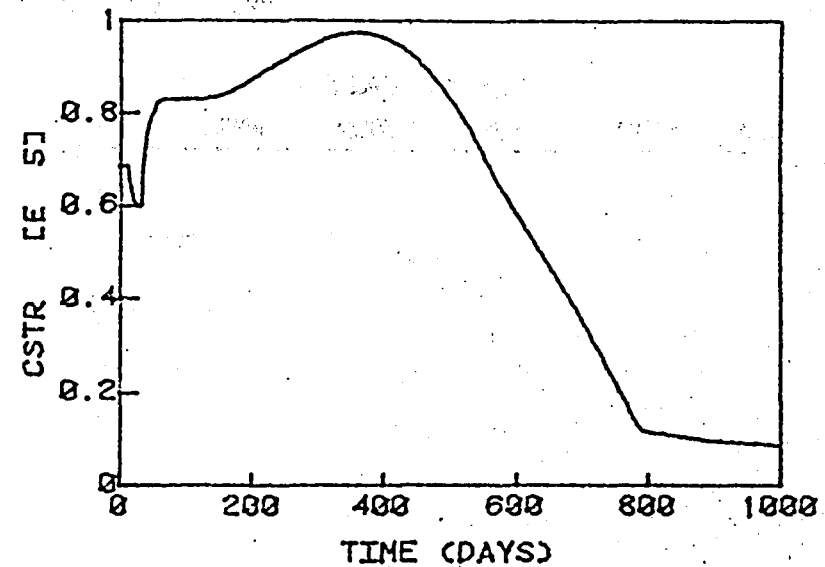
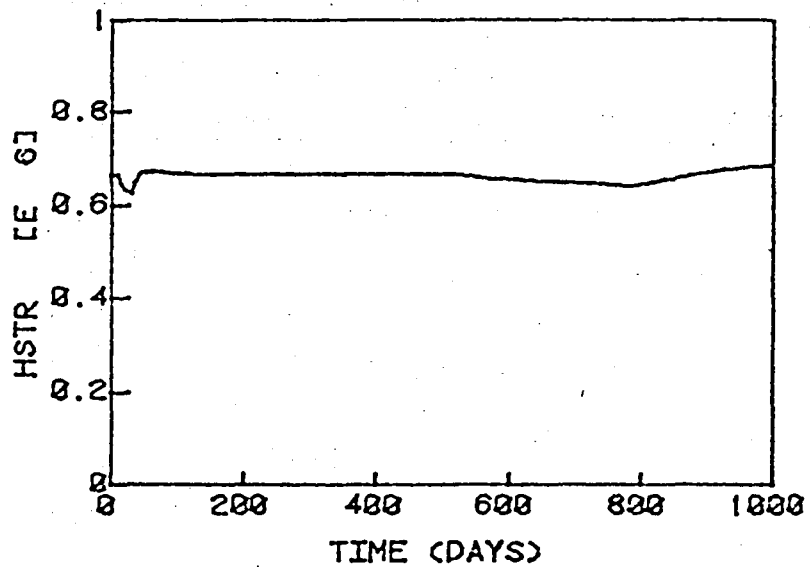


FIGURE 7C: Recycler shutdown, proportional control, failure.

SUPERVISORY CONTROL

Initial Conditions
(25 days supplies)

GROW=519027.6
FSTR=17610
NSTR=25
AOST=41500
HSTR=662755
CSTR=68500
WSTR=122995
SDST=477500

Comments: •Recycler shutoff for 20 days starting at day 10.
•UH1,ULOA,&UBOP all set equal to 1.
•Failure at 880 days due to lack of food.

FIGURE 8A: Recycler shutdown, supervisory control, survival. Compare with figure 7.

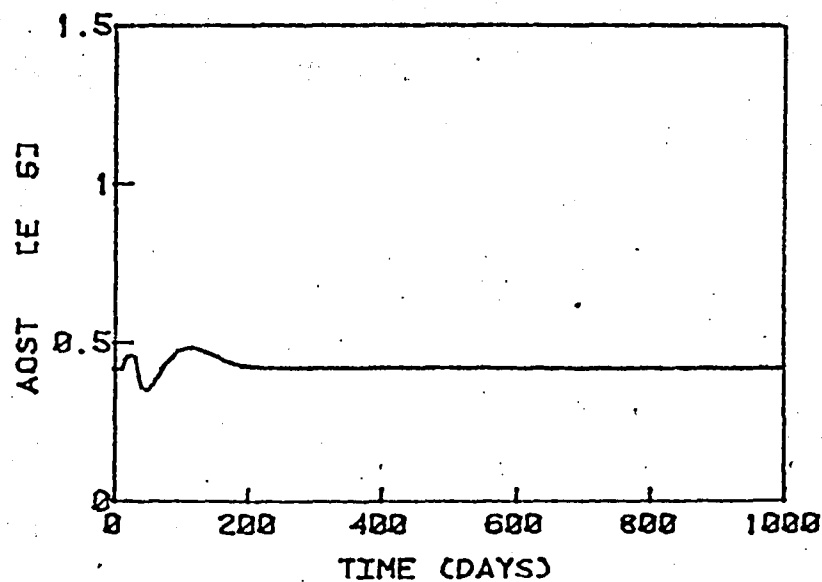
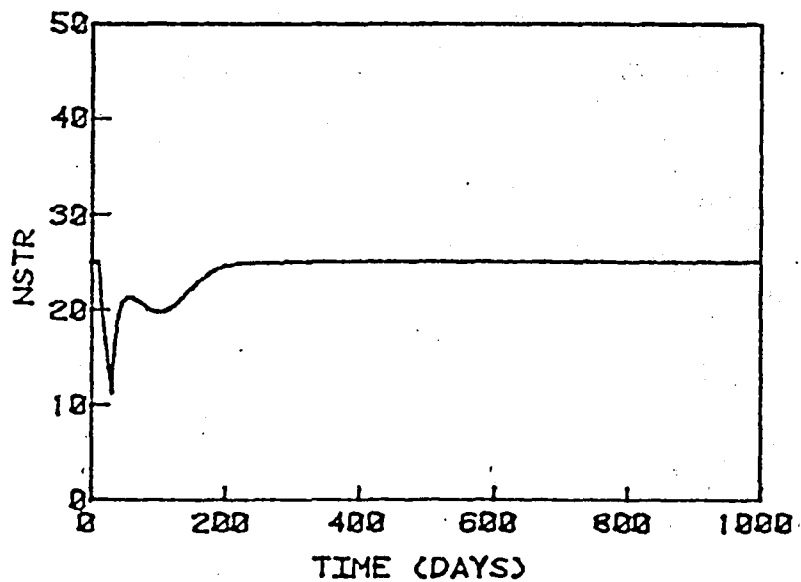
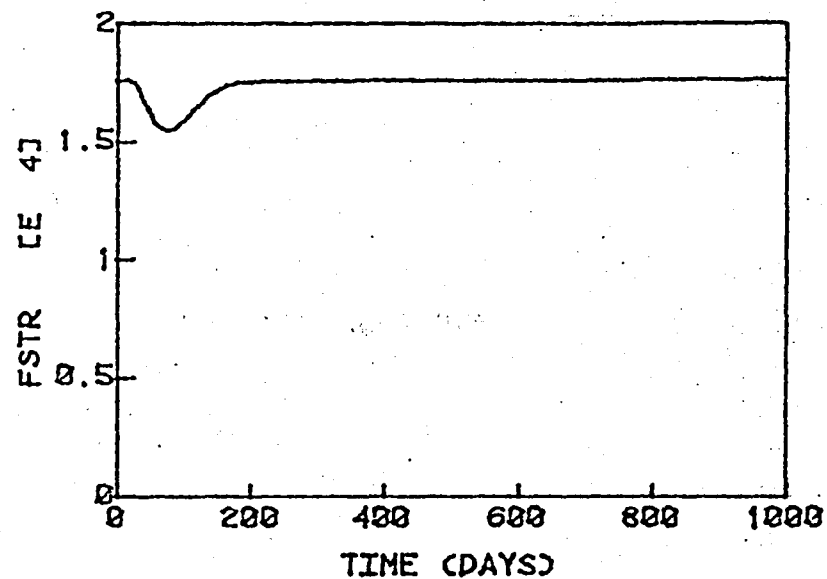
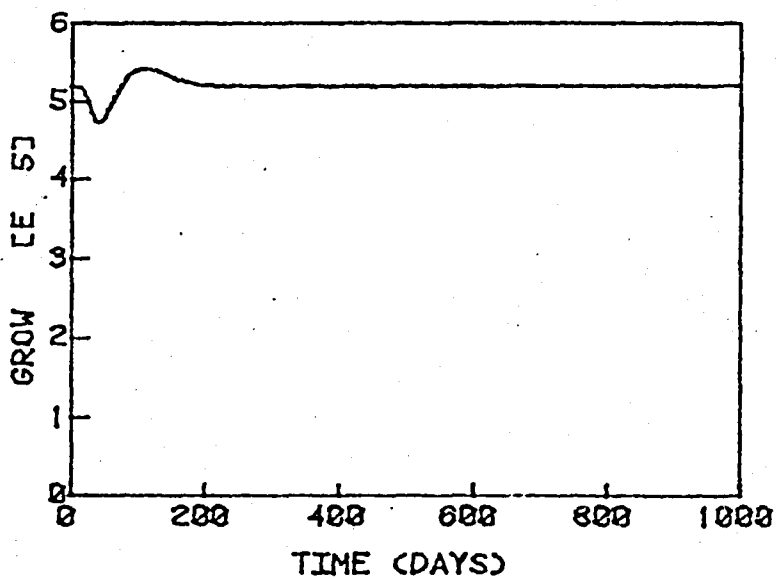


FIGURE 8B: Recycler shutdown, supervisory control, survival..Compare with figure 7.

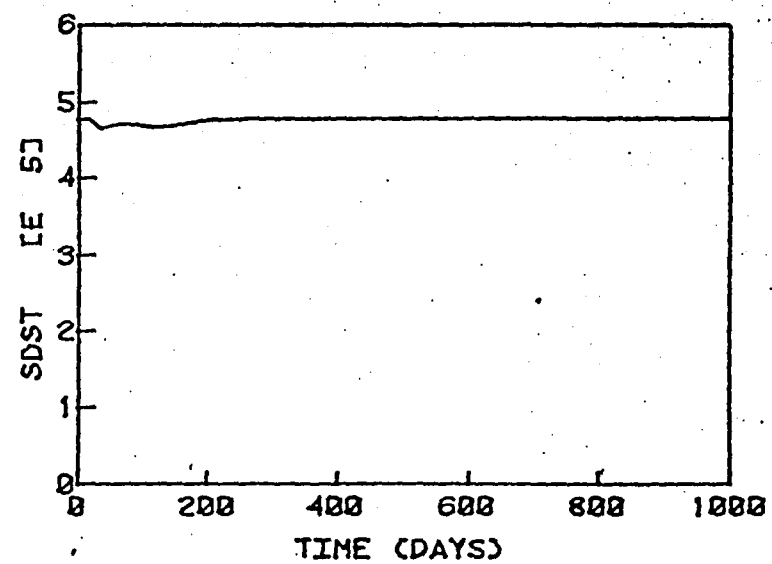
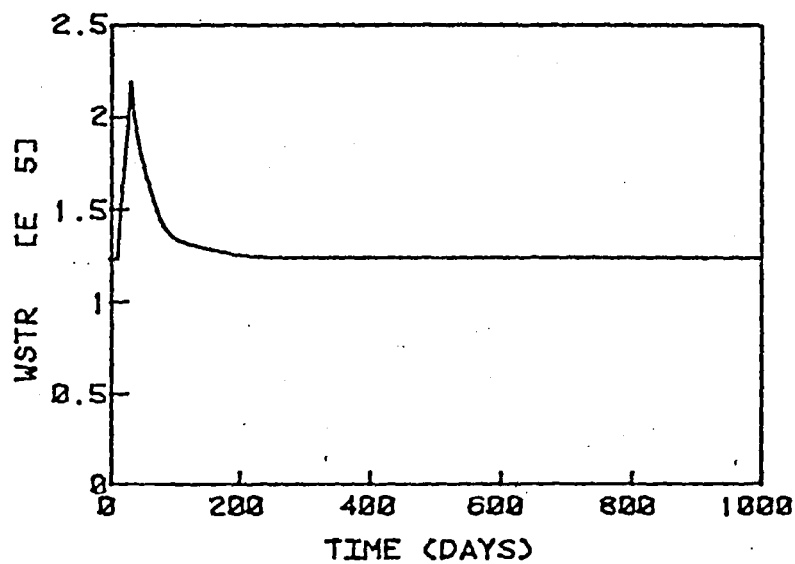
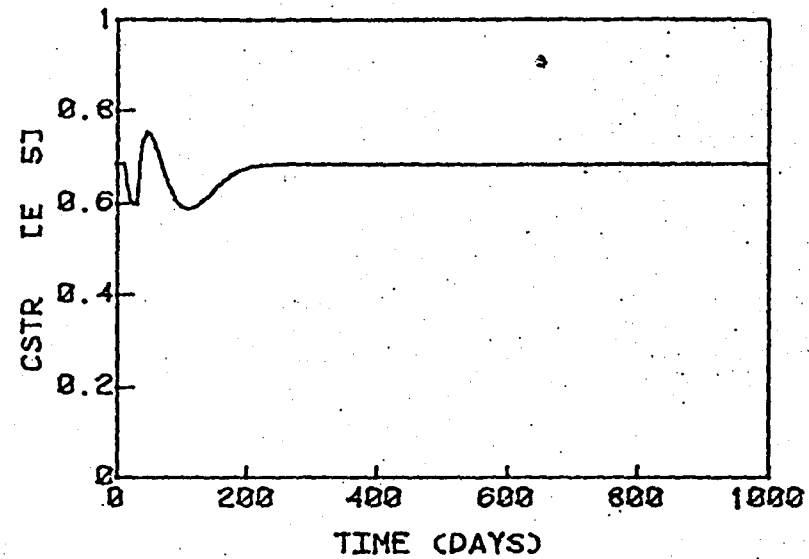
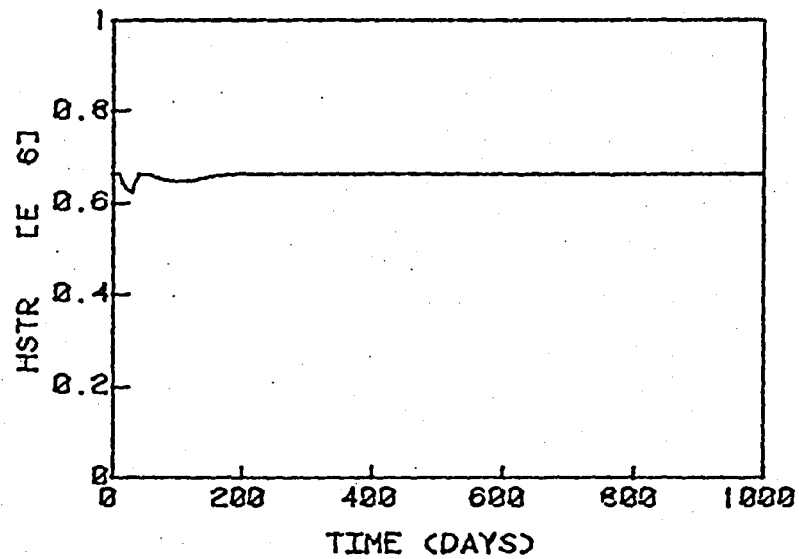


FIGURE 8C: Recycler shutdown, supervisory control, survival. Compare with figure 7.

SUPERVISORY CONTROL

INITIAL CONDITION	LOWER LIMIT	UPPER LIMIT
GROW	.8.519027.6	1.2.519027.6
FSTR	.4.17610	1.2.17610
NSTR	.4.25	1.2.25
AOST	1.41500	1.2.41500
HSTR	.4.662755	1.2.662755
CSTR	.4.68500	1.2.68500
WSTR	0	122995
SDST	0	477500

- Comments:
- I.C.'s selected from rectangular probability density functions.
 - UH1, ULOA & UBOP all set equal to 1
 - The atmospheric volume is dependent on the AOST I.C.

FIGURE 9: Storage size sensitivity analysis initial conditions.

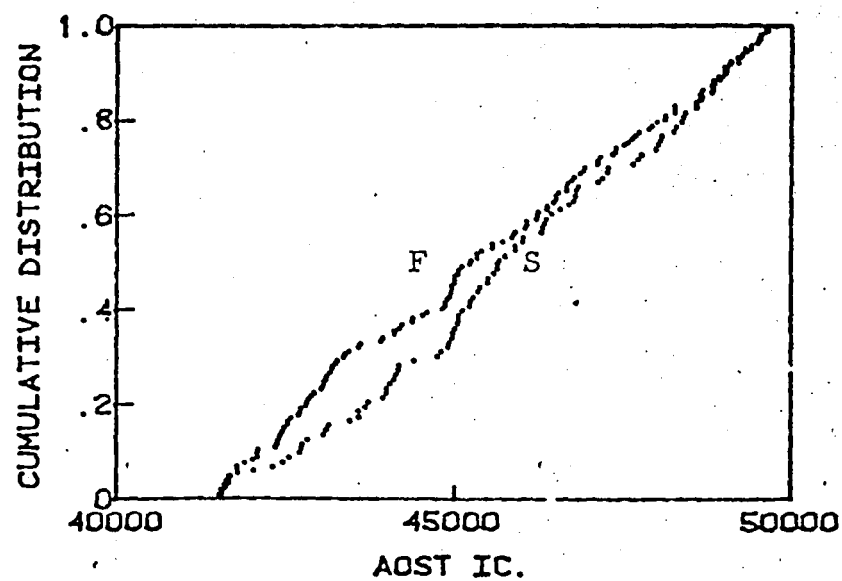
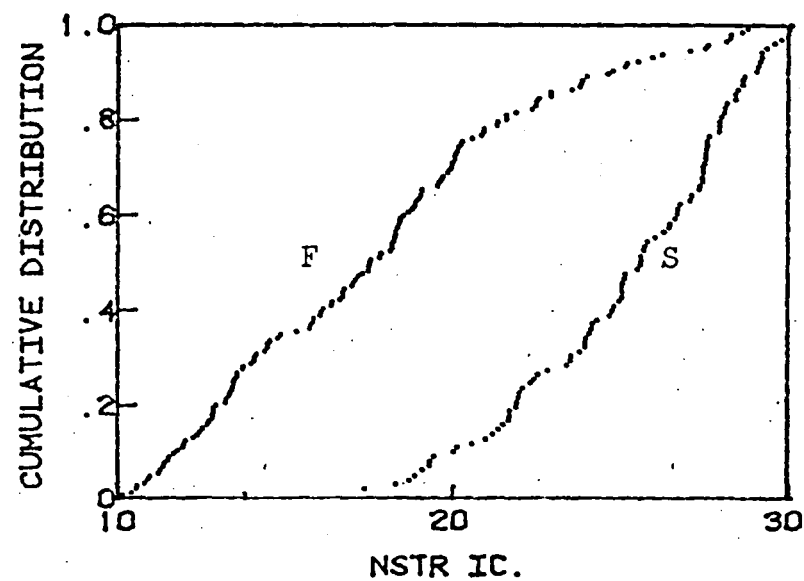
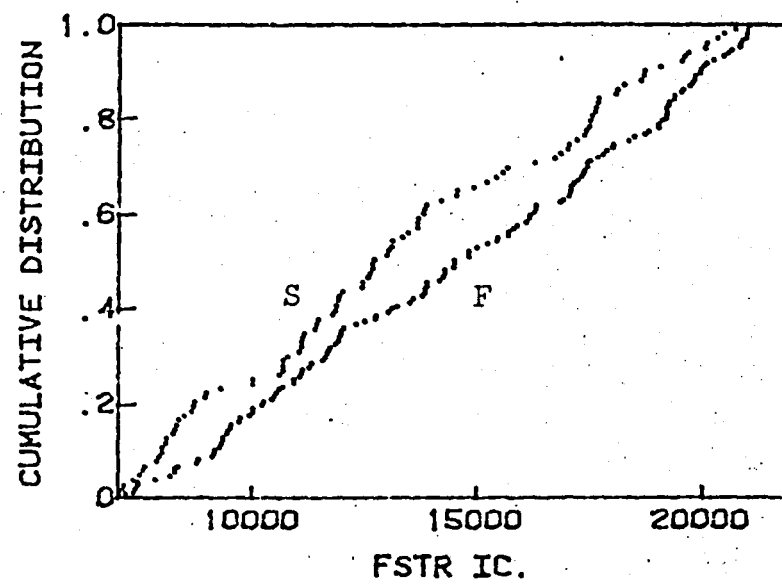
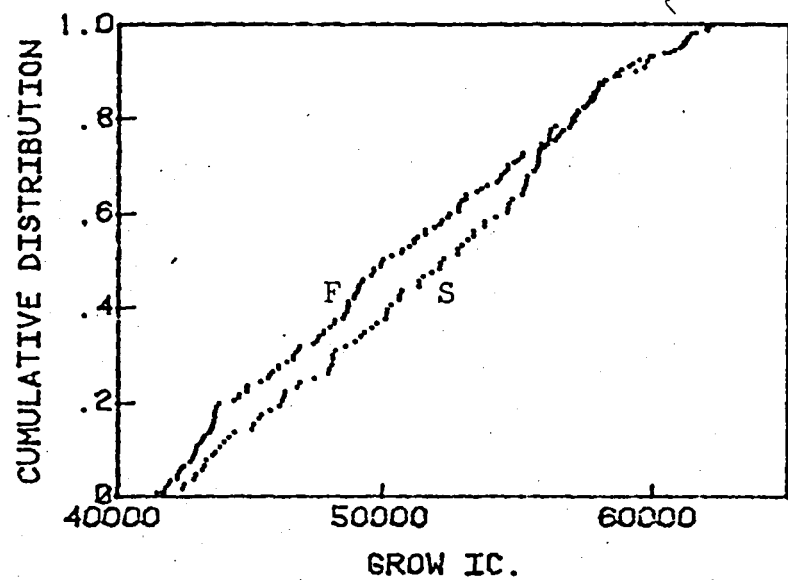


FIGURE 10A: Cumulative distributions.

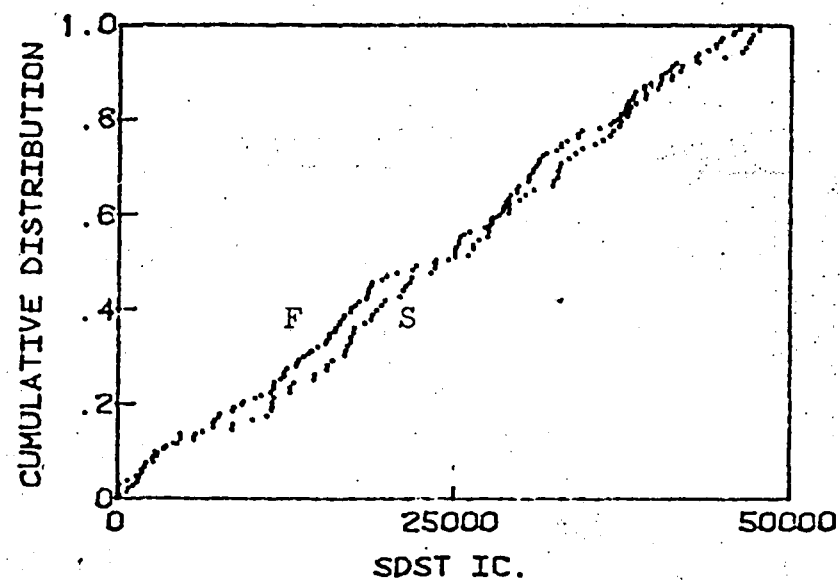
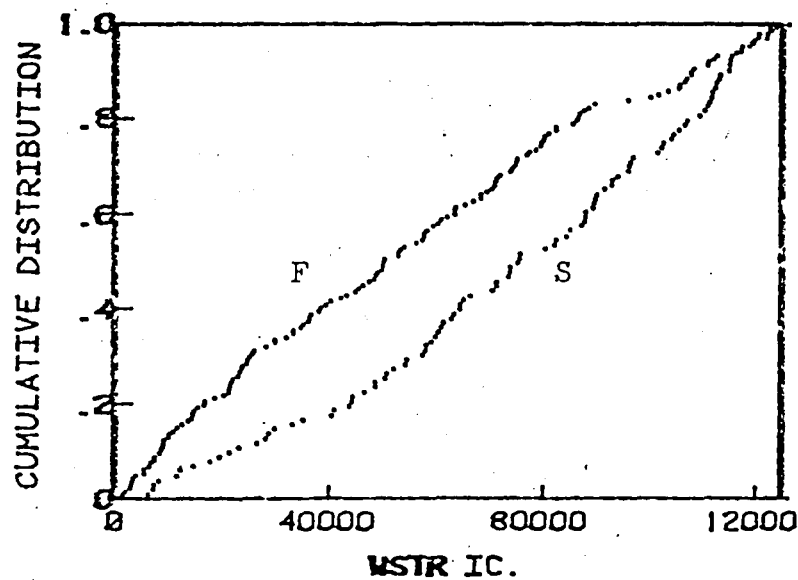
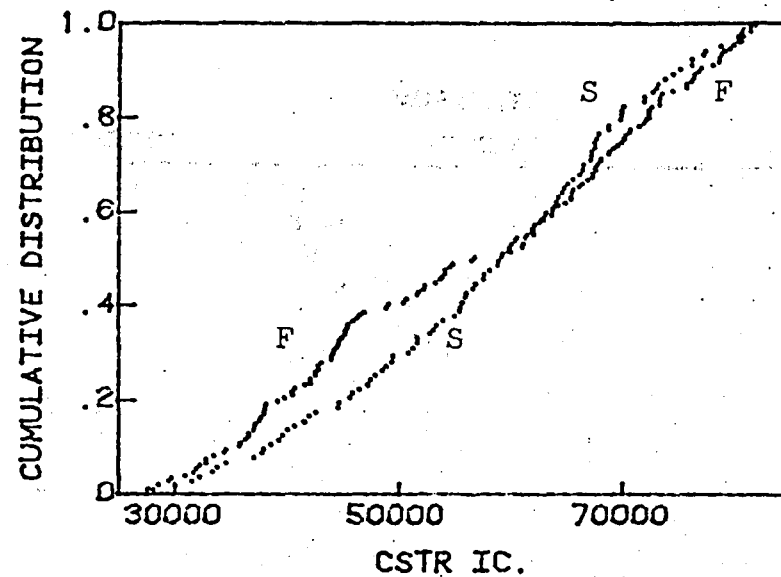
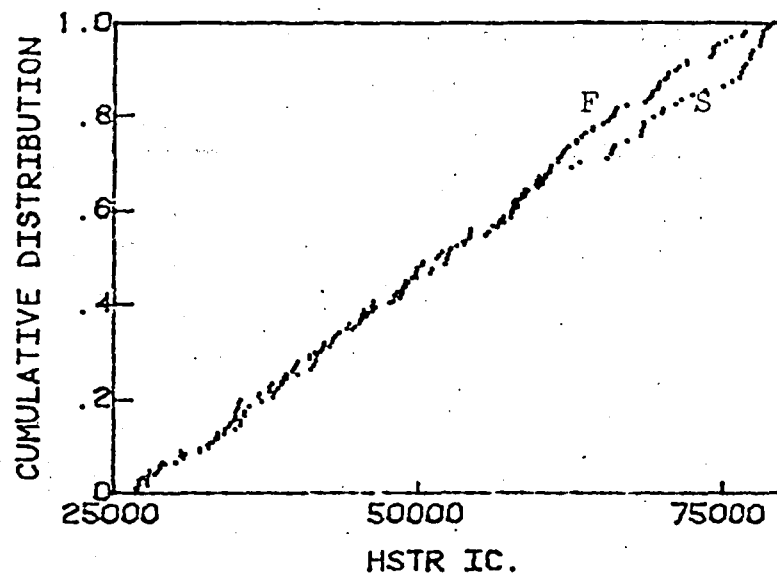


FIGURE 10B: Cumulative distributions.

SUPERVISORY CONTROL

INITIAL CONDITION	LOWER LIMIT	UPPER LIMIT
GROW	.8•519027.6	1.2•519027.6
FSTR	.4•17610	1.2•17610
NSTR	200	200
AOST	1•41500	1.2•41500
HSTR	.4•662755	1.2•662755
CSTR	.4•68500	1.2•68500
WSTR	122995	122995
SDST	0	477500

- Comments:
- I.C.'s selected from rectangular probability density functions. NSTR & WSTR increased from figure 9 values.
 - UH1, ULOA & UBOP all set equal to 1
 - The atmospheric volume is dependent on the AOST I.C.

FIGURE 11: Increased NSTR & WSTR storage size sensitivity analysis initial conditions.

Nomenclature

AHF	Plant atmospheric water output
AHFS	Steady state plant respiration fraction
AHGS	Steady state plant lost moisture fraction
AHM	Human water output to atmosphere
AHMO	Human water output to atmosphere due to oxidation
AHMT	Human water output to atmosphere (sweating, breathing)
AHST	Water vapor mass per unit volume of atmosphere
AHWS	Steady state waste recycler water output
ANST	Nitrogen mass per unit volume of atmosphere
AOST	Oxygen storage in total atmosphere
BAC	Atmospheric carbon dioxide growth rate modulating factor
BAH	Humidity growth rate modulating factor
BH	Available water to ideal water fraction
BN	Available nutrient to ideal nutrient fraction
BO	Plant net growth rate
BOP	Plant total growth rate
BOPS	Steady state total plant growth rate
BOR	Plant respiration rate
BORS	Steady state plant respiration rate
BOSS	Steady state plant net growth rate
CF	Plant carbon dioxide input flow
CFPS	Total plant photosynthesis carbon dioxide flow
CFRS	Plant respiration carbon dioxide flow
CM	Human carbon dioxide output flow
CMSS	Steady state human carbon dioxide output flow
CO2V	Atmospheric carbon dioxide level modulating factor
CSTR	Carbon dioxide storage
CWSS	Steady state waste recycler carbon dioxide output
FDEF	Food deficit
FM	Actual flow of food to humans
FMDf	Food deficit flow modulating factor
FMI	Ideal flow of food to humans (including food deficit)
FMII	Ideal flow of food to humans (not including food deficit)
FMSS	Steady state flow of food to humans
FRTE	Controlled flow level of food to humans
FSTR	Food storage
FSVL	Food survival criteria
GROS	Steady state growing food crop
GROW	Growing food crop
HDEF	Human water deficit
HDSS	Steady state human drinking water flow
HF	Actual plant water flow
HFGS	Steady state plant photosynthesis water flow
HFI	Ideal water flow to plants
HFMS	Steady state plant moisture fraction water flow
HM	Water flow to humans
HMD	Actual human drinking water flow
HMDf	Water deficit modulating factor

HMDI	Ideal human drinking water flow
HMRT	Controlled water rate to humans
HPSS	Steady state purifier output
HRTA	Available water flow to crop
HSDS	Steady state sanitary and domestic water flow
HSTG	Sanitary and domestic control gain
HSTR	Water storage
HSVL	Water survival criteria
LOA	Steady state human level of activity
LOAA	Actual level of activity
LOAC	Carbon dioxide level LOA modulating factor
LOAF	Food deficit LOA modulating factor
LOAI	"Ideal" level of activity
MFB	Supervisory control food level modulating factor
MOB	Supervisory control oxygen level modulating factor
MOF	Supervisory control oxygen level modulating factor
N	Total moles in the atmosphere
NF	Actual nutrient flow to crop
NFA	Available nutrient flow to crop
NFI	Ideal nutrient flow to crop
NFSS	Steady state nutrient flow to crop
NRSS	Steady state recycler nutrient production rate
NRTE	Controlled nutrient flow level
NSTG	Nutrient control gain
NSTR	Nutrient storage
OF	Oxygen output rate of plants
OFPS	Steady state total photosynthesis oxygen production rate
OFRS	Steady state plant respiration oxygen consumption
OM	Actual oxygen flow to humans
OMI	Ideal oxygen flow to humans
OMSS	Steady state oxygen flow to humans
ORTE	Oxygen flow to humans modulating factor
OSVL	Oxygen survival criteria
OWSS	Steady state waste recycler output
P	Atmospheric pressure
PCO2	Carbon dioxide atmosphere fraction
PH2O	Water vapor atmosphere fraction
PN2	Nitrogen atmosphere fraction
PO2	Oxygen atmosphere fraction
PO2L	Lung alveolar oxygen partial pressure
PRTE	Purifier control rate
RH	Relative humidity
RRAO	Oxygen level recycler rate modulating factor
RRTE	Recycler operation rate
SDM	Sanitary and domestic water flow to humans
SDPS	Steady state purification rate
SDRT	Sanitary and domestic water flow control rate
SDSG	Sanitary and domestic control gain
SDST	Sanitary and domestic waste storage
SEED	Planting rate
SVL	Total survival criteria
UBOP	Growth rate uncertainty

UH1	Edible crop fraction uncertainty
UH2	Inedible crop fraction uncertainty
ULOA	Random growth rate limiting factor
VATM	Atmosphere volume
WM	Actual human waste production
WMSS	Steady state human waste production
WRSS	Steady state waste recycler input
WSTG	Waste recycler control gain
WSTR	Waste storage

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16. Abstract An approach to the problem of evaluating Closed Ecological Life Support System (CELSS) scenarios and different strategies within a scenario is presented. The approach combines probabilistic Monte-Carlo simulation techniques with the notion of descriptors of system behavior to determine system performance. A simple CELSS model is developed along with two alternative control strategies. The approach is applied to this model to demonstrate the scope and limitations of the method. The simulations show that dynamic behavior and selection of control laws can be crucial to CELSS survival.					
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