DYNAMIC CONSIDERATIONS FOR CONTROL

OF CLOSED LIFE SUPPORT SYSTEMS

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ABSTRACT

Reliability of closed life support systems will depend on their ability to continue supplying the crew's needs in the face of perturbations and equipment failures. These dynamic considerations interact with the basic static (equilibrium) design through the sizing of storages, the specification of excess capacities in processors, and the choice of system initial state (total mass in the system). This paper uses a very simple system flow model to examine the possibilities for system failures even when there is sufficient storage to buffer the immediate effects of the perturbation. Two control schemes are shown which have different dynamic consequences in response to component failures.

INTRODUCTION

The usefulness of a Closed Environmental Life Support System (CELSS) depends critically on its mass and volume. The larger and heavier the system, the more costly it will be to move to its operating orbit. At a certain point it becomes more feasible to resupply or stock enough resources for the entire mission (Gustan and Vinopal, 1982). Therefore, the sizes of the CELSS' internal mass and storage tanks are critical to determining the role regenerative schemes will play in such missions.

Initial design studies for closed life-support systems concentrate on the equilibrium requirements for supporting the crew (Modell and Spurlock, 1979). These studies give some indication of mass and volume requirements by specifying the flows that will be necessary through various processors, and thus give some indication of the minimum unit size. However, the life support system must be capable of maintaining vital functions during temporary failures of some of its components. Extra storage must be provided, processors must have the capability of operating above (or below)

their equilibrium flows, and total amounts of flowing masses in the system must be specified. This part of the design can only be done by considering the system's dynamic behavior as none of these parameters enter into the static equilibrium calculation.

An important consequence of finite size storage in a closed system is that if the storage is full, the flow that would be going into it will have to go somewhere else. It is our assumption in this work that such overflows will always have deleterious effects. The only way to guarantee that there will be no overflows is to make all storages large enough to contain all of the system's mass.

Through the use of a simplified, abstract model of a CELSS, we will show that the system's dynamics depend on the storage tank sizes and the internal mass of the system. There are many nonintuitive consequences that result from changing the size of various internal components. Further, the choice of control scheme is shown to have a dramatic effect on the dynamic behavior of the system after a component failure. Though there are no firm conclusions to be drawn from these experiments, the peculiar interaction of delays, mass location within the system, and the relative storage tank sizes should be noted. A true CELSS will have many more flow paths and internal loops and will probably have much more complex dynamic behavior than is shown in this simplified model.

THE CELSS MODEL

A CELSS is usually viewed as having mass closure but an external supply of energy. It is possible to model such a system using conservation of mass equations that describe the storage tank behavior. Flows between tanks can be treated as controllable variables. Averner (1981) used this approach where the mass balance was per-

formed on the elemental masses (H, O, N, etc.) in the system. Stahr, et al. (1982) developed a model where bulk masses (water, CO2, edible food, etc.) are followed through the system. We will use the latter approach in this paper, because it lends itself to examinations of storage tank size and system mass interaction.

To examine the dynamic interaction of internal system mass and storage tank sizes, the model of a CELSS shown in Figure 1 is used. This abstract model is a simplification of the true complexity of the system. It does, however, contain some essential components of a CELSS: i.e. constant mass, finite storage tank sizes, and limited processor capacities. We will be showing some of the dynamic interplay between these components.

To understand the model better, we examine its behavior at steady state. The crew consumes food at a rate of one unit/day (steady state) from food storage. With the food plants growing to maturity in 60 days, the 6 plant chambers produce a harvest every 10 days. This harvest must have an edible mass of 10 units for the system to stay at steady state. The harvest has both an edible and inedible component, which each comprise 50% of the harvest under normal conditions.

The inedible part of the harvest is placed in waste storage. As food is consumed, the crew's waste also goes into this tank. The waste is reoxidized in the waste processor and the resulting nutrients, water, etc., are placed in the plant chambers. To insure adequate growth for the steady state, this processor flow must be 2 units/day.

The food storage and waste storage have capacities. If a capacity is exceeded, the tank's output flow is increased. The waste processor also has a capacity. If the waste flow to the processor exceeds its capacity, some of the flow is bypassed. Clearly overflow conditions can occur given finite storage tanks and a component failure.

The flows in this model are mixtures of solids, gases and liquids. Thus, the "nutrient" flow refers to nutrients, water, CO2, and other material needed for plant growth. The "harvest" contains excess water, O2, edible and inedible plant matter, and other byproducts of plant growth. The proper mixing of the elements in the nutrient and harvest flows is assumed. Therefore, the plant growth depends only on the rate of the input stream.

Plants are grown in 6 chambers. Each chamber's plants are at a different stage of growth so there can be harvests at 10-day intervals. As a simplification, an independent supply of seeds is assumed for this model. The steady state plant growth is shown in Figure 2 (top). This curve follows the general behavior of plant growth (Salisbury and Ross, 1979). The plant mass reaches 10% of the harvest mass in the first 20 days from a nutrient flow of 0.1 units/day. The plant grows faster in the second 20 days reaching 45% of its total mass. During these 40 days no edible mass has grown. In the last 20 days, 90.9% of the growth is in edible mass. This results in a harvest that is 50% edible.

If the nutrient flow into the plant chamber is not at the steady state value two effects are seen (Incropera, 1975). First, the slopes, representing the total plant mass in Figure 2 (top), change as this is a representation of conservation of mass. Second, if this occurs during the last 20 days of the growth cycle (when the edible mass is grown), the percent of the nutrient flow that becomes edible mass is affected as shown in Figure 2 (center). The nutrient flow into the 6 chambers is always divided so as to do the least damage to the growing plants.

If the waste processor's capacity is exceeded, the bypass flow goes into the plant chambers (see Figure 1), according to this model. This waste overflow accumulates as "inert matter" in the plant chambers and does not contribute to the plants' growth. If there is inert matter in the plant chamber during the last 20 days (when the edible part of the plant is growing), its growth is inhibited (see Figure 2 bottom). The inert matter is removed from the plant chamber during harvest, and is sent to the waste storage with the inedible part of the harvest.

Figure 3 shows the system operating at steady state. Both the food and waste storage tanks have an extra supply that can maintain their respective outputs for 10 days. The harvest occurs at 10-day intervals. Each harvest (both edible and inedible) causes a vertical jump in the storage curves, and continuous output flows cause the smooth downward slopes.

A 10-DAY PROCESSOR FAILURE

Dynamic interaction of system mass and storage sizes can be seen when we consider the case where the waste processor fails for 10 days, stopping the supply of water and nutrients to the plants. During this failure, from the fifth to the fifteenth day, the output of the waste storage is set to zero to avoid a bypass of the processor. From a static design viewpoint the steady state contains enough food and waste in their respective storages to ride out the 10-day processor failure. In this section we will examine the system's dynamic behavior during transients using a few combinations of system mass, storage size, and processor control.

The simplest action to take after the failure is to maintain the storage output flows at their steady state values. Figure 4 shows that the system returns to an equilibrium in 60 days. This is not the original steady state, however. The original food buffer of 10 units is gone and the waste buffer has increased from 20 units to 30. This transfer of mass leaves the system in a configuration that would be disastrous if another processor failure occurred.

In addition to moving away from the original steady state, two other dynamic effects occur that could not be predicted from a static design. First, although the waste storage had an adequate supply for the failure, for a period of 10 days the plants did not receive any nutrients or water. Considering that the plants did not die over this 10-day period, the reduced yield of the plants causes a 2-day period with no food in the food storage (i.e., no food to eat) on the 38th day, 13 days after the failure. Second, the waste storage needs a capacity of 50 units to absorb the transient without causing an overflow (see Figure 4, bottom).

CONTROL OF PLANTING

To enable the system to return to its original steady state (10-day food and waste storage buffer), a means is needed to increase the edible yield. There are many ways to accomplish this. We consider first the case where each plant chamber is only 50% occupied by seeds, and therefore plants, when the system is operating at steady state. If the food storage is not at its desired level when a crop is harvested, the number of seeds planted at this time is adjusted to compensate. The system keeps track of the number of seeds in each chamber. Also, the flow of nutrients, water, etc., to each tank is scaled to the number of seeds so that the edible yield of each individual plant is 90.9% of its maximum. We assume that there is perfect knowledge of the plant behavior so this yield can be achieved reliably. If the waste storage is empty or overflowing this goal will not necessarily be achieved.

The seed planting control is shown in Figure 5 where the planting correction is proportional to the error between the actual and desired food storage levels. Hence, this control is called a proportional or P control.

Using the P control with a gain of 0.2 generates the results seen in Figure 6. The initial transient is the same as when no control action was taken (see Figure 4). However, at the 70th day extra seeds are planted because of the low food storage level. Subsequent adjustments in the number of seeds planted return the system to the original steady state by approxi-

mately day 250. The 2 days without food about the 38th day are not avoided.

The system behavior can be drastically altered by changing the control gain. Figure 7 shows the consequences of raising the gain to 1. The initial transient is unchanged. At the 70th day extra seeds are planted and this correction continues for a few planting periods. As these plants grow they require a high flow of nutrients, reducing the level of the waste storage. When this crop is harvested, the food storage level climbs, resulting in fewer seeds planted. When, in turn, they are harvested, there is not enough food for a few harvests in a row. This pattern repeats about every 200 days without ever diminishing. This is all due to a processor failure for 10 days and a control gain set at 1.

THE EFFECT OF STORAGE SIZE

We repeat the last example, but now introduce a waste storage tank size of 50 units (Figure 8). This is large enough to absorb the initial transient. However, at day 190, the waste storage is full and the output flow must be increased to avoid an overflow. During this time the plants are exposed to nutrient flows above their steady state. The waste processor has a capacity of 5 units/day and this value is exceeded for a short time causing a bypass of the processor. These two effects, excess flow of nutrients, water, etc., and the bypass of unprocessed waste, reduce the edible yield of the growing plants. Harvests then contain little or no edible food for a period of 65 days. This oscillation continues without dissipating. In this example the food storage level never exceeds 38 units (see Figure 8, center), and hence, we can consider that the food storage has any capacity above this level. For convenience we will use 40 for this capacity.

In the next example (Figure 9) the food storage capacity is reduced to 20 and the waste storage capacity is increased to 70. Hence, the total capacity of the system storage is unchanged from the previous example. Now the system returns to its original steady state by the 160th day. This result is due to the smaller food storage capacity stabilizing the system. It redistributes the system mass back to its steady state value. While the systems in Figures 8 and 9 have the same total capacity, their different dynamic behavior results from the placement of the excess capacity. Hence, small storages are not always detrimental to the system behavior. The location of the small storage can be more critical than its size.

CONTROL OF GROWTH

We now consider an alternative scheme for controlling the edible harvest, and hence, the food storage level. In each chamber are planted a constant number of seeds producing the maximum number of plants the chamber will hold. At steady state (Figure 3) the flow from the waste storage is only enough to achieve half the total edible yield. In other words, the plant chambers are full but the plants are only growing at 50% of their maximum rate. The control structure remains the same as shown in Figure 5, but now the "nutrient" flow to plants is adjusted instead of seed numbers. We call this a "growth control" scheme to distinguish it from the "seed planting control" described previously. The equilibrium level of the waste storage is increased because this new control policy requires 3 units/day of waste output. This new level is in accordance with the static design for a 10-day processor failure.

Figure 10 shows the system behavior caused by a waste processor failure from the fifth day to the fifteenth day. The proportional gain of the growth control is set to 1 and the system recovers to the original steady state in 200 days. There are a few short periods with no food during the transient. Once again, recovery depends on the storage tanks having enough excess capacity to absorb the transients.

In comparing Figure 10 with Figure 7 it can be seen that the growth control with a gain of 1 is more useful than the seed planting control with a gain of 1. First, notice that the two proportional gains are not equivalent. The growth control always gives larger harvests under the same constant disturbance. Although larger gains were shown to give erratic behavior using the seed planting control, the growth control, with its higher effective gain, gives improved system stability.

This apparent contradiction is resolved when the dynamics of the control and system interaction are examined. The seed planting control can only affect a part of the system that will not show up in the food storage for 60 days. On the other hand, the growth control affects all 6 plant chambers, so its results are seen in 10 days. The controller can then make further adjustments to the plants as they are growing. Delays, such as those between the control measurement and action, have a critical effect on the system behavior.

In Figure 11 the effect of waste storage capacity is shown. The waste storage capacity is set to 50 units and the growth control still has a gain of 1. Although the capacity is only exceeded for 6 days at day 20, the system has no food for more than 100 days. And although the system recovers to the steady state by day 380 (one year after the disturbance), such transient behavior is not likely to be survivable.

As a final example of dynamic interaction within the system, the waste storage capacity is raised to 70 units and the food storage buffer is reduced by 10 units. Now the system has less mass in it than in the previous 2 examples. Here the system is not able to return to a steady state but there are no long periods without food (see Figure 12). The reduction of mass in the system did not result in obvious disaster.

DISCUSSION

Simplified, abstract models of CELSS show complex dynamic behavior. The system must have excess capacity to absorb transients caused by component failure. Also, the amount and location of this excess capacity can critically affect the system performance. Excess internal mass is used during transients and the level and location of these buffers has been found to have a nonintuitive relation to the survivability of the system.

Following a component failure the system needs to return mass back to its original configuration. This can only be accomplished by altering the flows from the steady state values through a control policy. The dynamic interaction of the control with the system can introduce unusual results.

In this paper we have assumed that the effects of input flows on the plants are understood. In this way the controller can reliably improve the edible yield when this is required by the control algorithm. In practice this may not be achievable without sophisticated monitoring of each plant as it is growing (i.e., state estimation). Also, the consequences of each plant behaving individually within the chamber has not been examined.

Finally, with this model we have only considered a single "loop". A more realistic CELSS contains one loop with the atmospheric gases, another with the food and solids, and another with the water and liquids. The dynamic interaction of these loops may introduce system behavior that is more peculiar than the examples shown in this paper.

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Stahr, J., D.Auslander, R.Spear, G.Young. (1982). An Approach to the Preliminary Evaluation of Closed Ecological Life Support System (CELSS) Scenarios and Control Strategies. NASA CR-166368. NASA Ames Research Center, Moffett Field, California.

Figure 2: Plant Growth

Figure 1: A CELSS Model
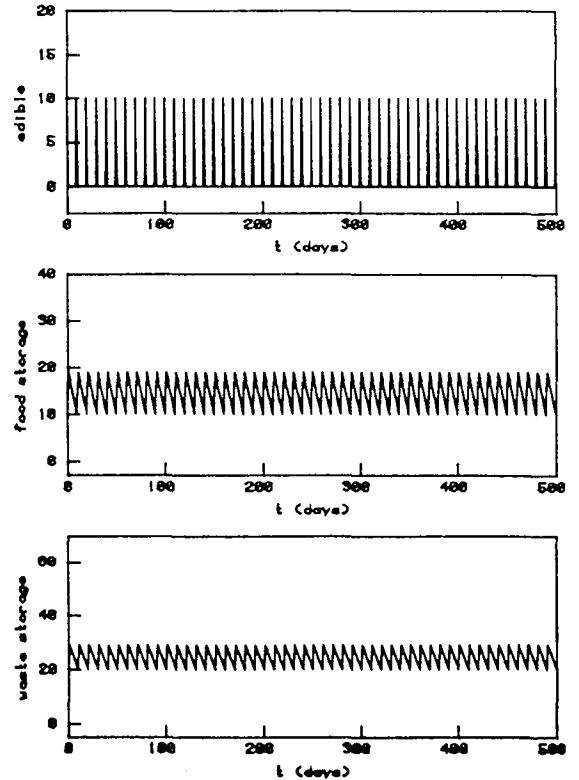
Figure 3: Steady State
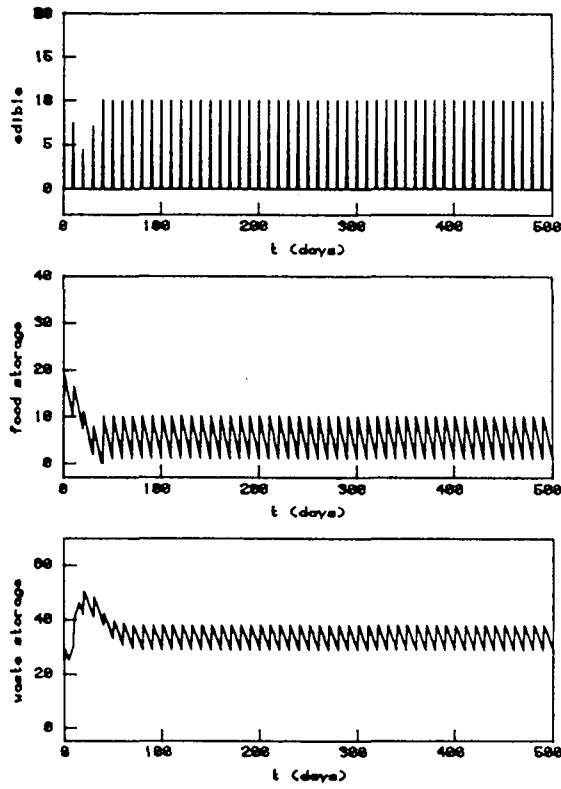
Figure 4: Failure Response – Steady State Flows
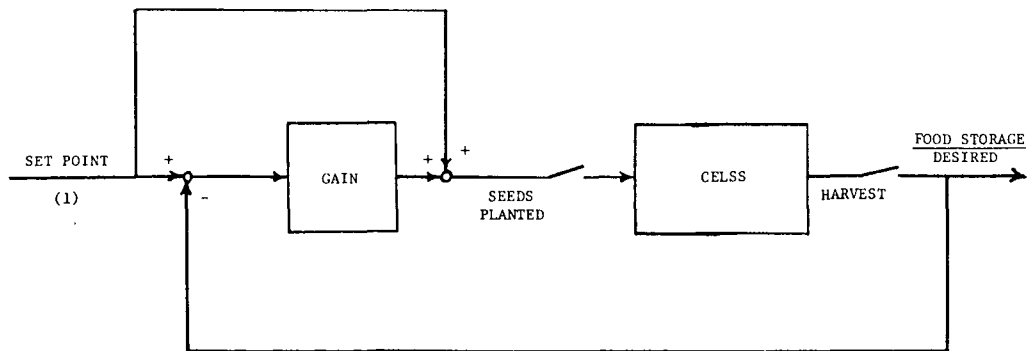
Figure 5: CELSS With Seed Planting Control
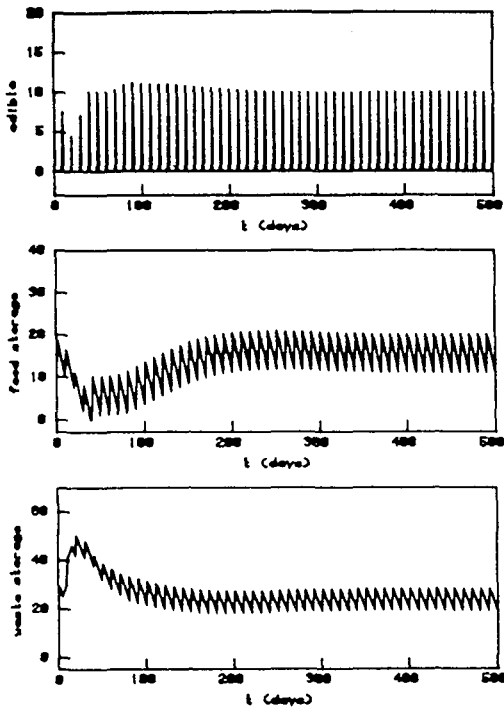
Figure 6: Planting Control – Gain = 0.2
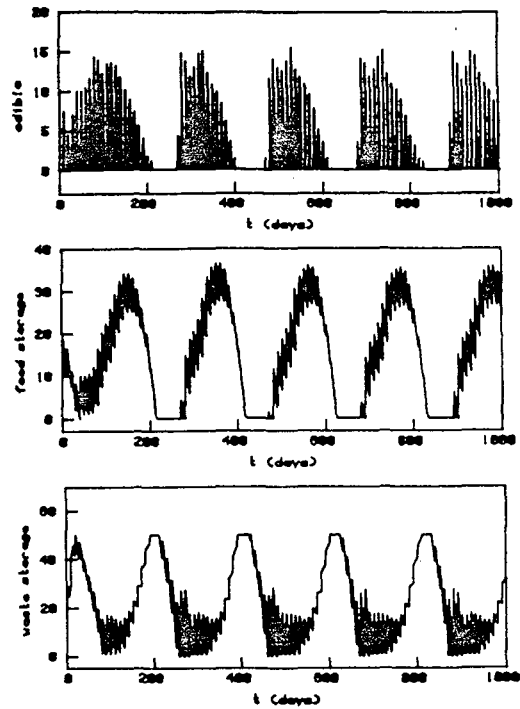
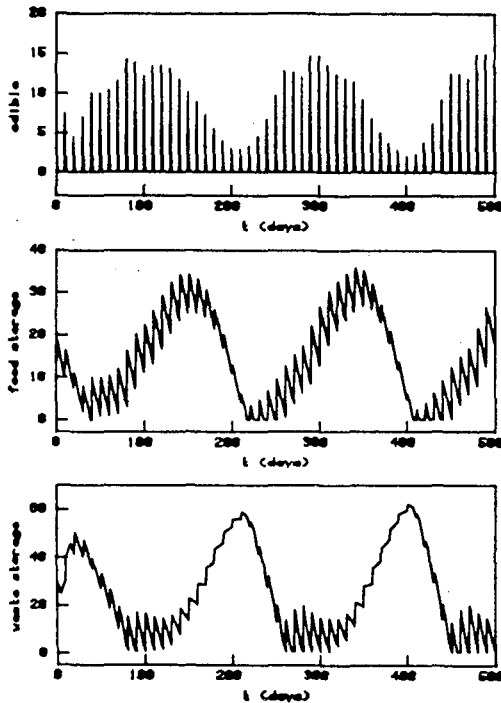Figure 8: Waste Storage Capacity = 50
Planting Control – Gain = 1

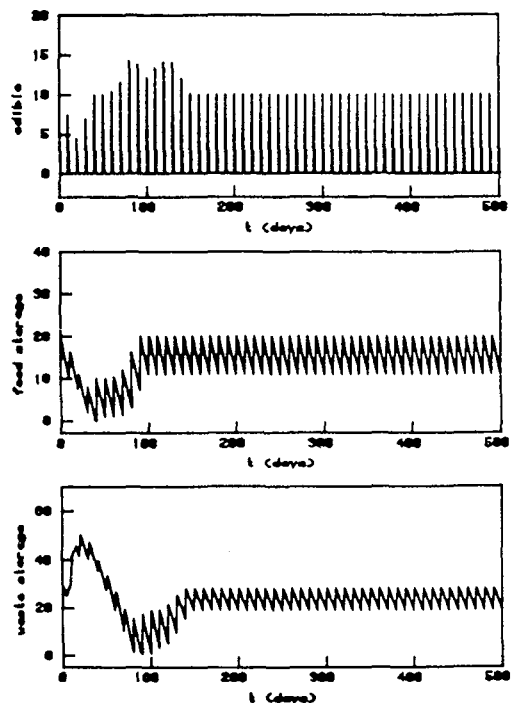Figure 7: Planting Control – Gain = 1

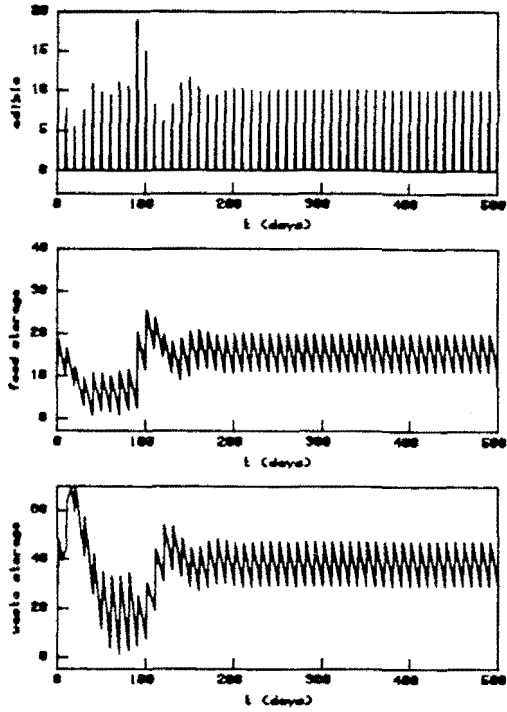Figure 9: Food Storage Capacity = 20
Planting Control – Gain = 1

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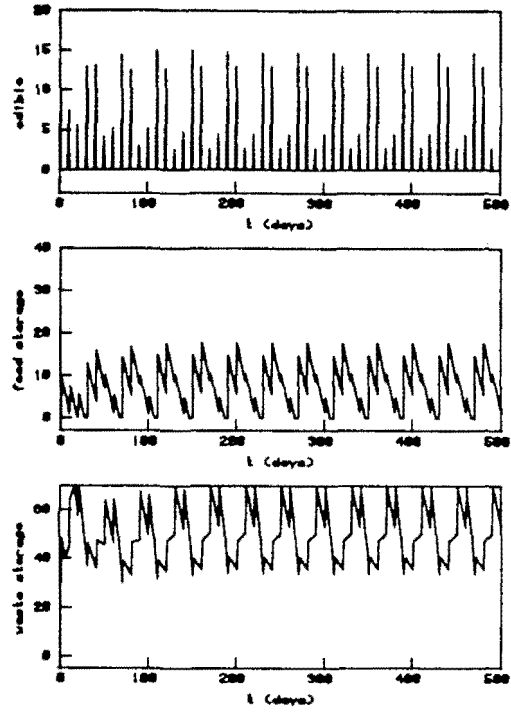Figure 10: Growth Control - Gain = 1

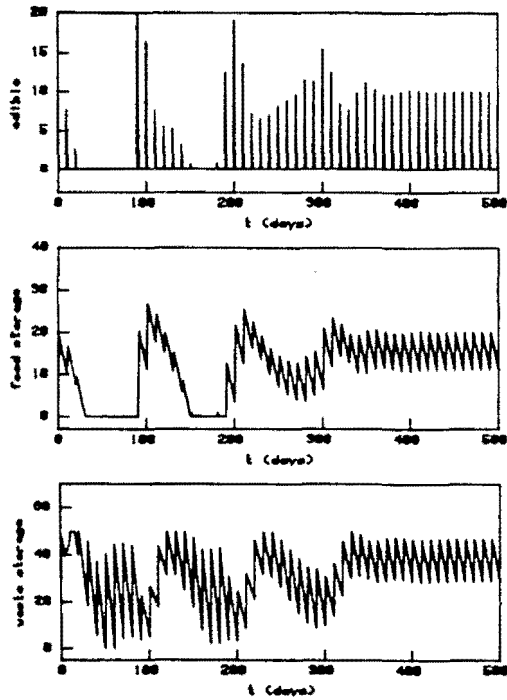Figure 12: Food Buffer = 0
Growth Control - Gain = 1

Figure 11: Waste Storage Capacity = 50
Growth Control - Gain = 1

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