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A METHOD OF VARIABLE SPACING FOR CONTROLLED PLANT GROWTH SYSTEMS IN SPACEFLIGHT AND TERRESTRIAL AGRICULTURE APPLICATIONS

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CELSS

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CELSS

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SUMMARY

A higher plant growth system for Controlled Ecological Life Support System (CELSS) applications is described. The system permits independent movement of individual plants during growth. Enclosed within variable geometry growth chambers, the system allocates only the volume required by the growing plants. This variable spacing system maintains isolation between root and shoot environments, providing individual control for optimum growth. The advantages of the system for hydroponic and aeroponic growth chambers are discussed. Two applications are presented: (1) the growth of soybeans in a Space Station common module, and (2) in a terrestrial city greenhouse.

INTRODUCTION

Manned space missions of extended duration, such as the exploration of Mars and the asteroid belt, will require materially closed life support systems (Gustan and Vinopal, 1982). With increased mission duration and/or distance from Earth, the practicality of food and oxygen resupply decreases. The alternative, a regenerative ecologically based life support system, appears necessary for future space missions. On a low Earth orbit (LEO) space station, a Controlled Ecological Life Support System (CELSS) could provide an economical alternative to conventional life support systems.

A typical CELSS design consists of four principle subsystems: human crew, plants, waste processing system, and food processing system. Lower plants, such as algae, cannot be easily processed to provide human nourishment. For this, as well as for psychological reasons, the inclusion of higher plants such as legumes, grains, and vegetables in a CELSS is desirable (Tibbits and Alford, 1982).

Growing higher plants in space presents several unique problems, however. For example, current space structure technology and limited funds place severe restrictions on the volume that can be made available for plant growth. This constraint requires minimizing the size of any CELSS component. On Earth, a small seedling can be allowed to occupy the volume it will require as a mature plant. In space, economics will dictate squeezing the maximum number of plants into a given volume. Variable plant spacing would achieve this goal by using a plant "assembly line". Seedlings occupy only the volume required for initial size and are gradually moved through a variable geometry chamber to accommodate growth. A possible scheme for a growth chamber would involve a pyramidal configuration with seedlings at the apex and mature plants at the base. Space savings would be realized by either nesting separate growth chambers, or by shaping a single growth chamber to fill the given volume.

Critical to volume savings envisioned is achieving maximum control over plant environment. With increasing knowledge of plant physiology, larger yields will be possible over shorter growth cycles. Atmospheric content (CO_2 concentrations), atmospheric pressure, temperature, and air velocity will be carefully monitored and controlled in separate root and shoot chambers. Stem parallel air flow is desirable in the shoot chamber to reduce temperature and diffusion gradients. Visible radiation should also be of optimum spectral distribution and intensity.

Control of the root environment is also crucial to maximum plant production. A major concern is the culture medium because the traditional method of growing crops in soil is unsuitable for space applications. Soil is an excellent medium for pathogens, loses its structure over time, and is depleted of nutrients in a few years (Resh, 1978). Soil culture also exacts major weight penalties for space applications.

Alternatives include water cultures and other soil-less substrates such as vermiculite, perlite, pumice and synthetic foams.

Two methodologies suitable for variable plant growth spacing, hydroponics and aeroponics, require a separating membrane that is impermeable to air, light, and nutrient solution. This membrane must maintain differences in the root and shoot atmospheres, insure that light does not damage the roots nor foster the growth of photosynthetic algae in the nutrient solution, and prevent the corrosive nutrient solution from reaching electronic monitoring equipment in the shoot area. This technical memorandum describes a system that is volume efficient, yet maintains separation between root and shoot compartments. The system would be equally useful for space or terrestrial locations where protected environment is required or total volume are limited.

TECHNICAL SECTION: DESIGN CRITERIA

Conditions critical to limited-volume plant growth, depicted schematically in Fig. 1, include: (1) variable spacing, (2) a soil-less culture medium not susceptible to deterioration or pathogen growth, and (3) separate environments for the root and shoot areas.

A comprehensive list of the criteria used in the design process to maintain these conditions follows:

1) Variable plant separation in one or two dimensions during growth must be possible while maintaining a high quality seal between root and shoot environments, even during plant movement.

2) Flexibility in plant movement is required in case of plant growth variations or death.

3) The stem environment must be nonconstrictive to allow for growth and must not permit violation of the root/shoot separation.

4) Present technology, simplicity, and adaptability in the design are desired. In addition, ease of construction, reliability, and amenability to automation are necessary. These criteria allow for a variety of plant movement track configurations and readily-constructed functional tests.

5) All materials must be biocompatible and flight approved. They should not adversely affect the plants or other system components. Finally, the materials should be rupture-immune, sterile, lightweight and inexpensive.

ZIPPERSEAL SYSTEM

A number of existing and newly conceived concepts have been reported (Resh, 1978, and Oleson et al, 1985) and were evaluated with respect to the criteria listed above. None of these examined concepts were found capable of satisfying all the criteria. The zipperseal system described herein has the potential to satisfy all the listed design criteria. Our system consists of two principle parts: the zipperseal membrane and plant holding zipper.

To achieve atmospheric separation a recloseable seal, similar to those used in food storage bags, will be used to divide the root and shoot zones. It will be oriented along the line of travel followed by a plant as it grows from seedling to maturity. As seen in the cross section in Fig. 2, the critical sealing component consists of a protruding circular nob which, when sealed, is gripped by a "C" shaped protrusion. The mated components join the two sides of the membrane and can be either closed or opened by the plant holding-zipper described below. To present the zipper with a large guide area and to improve the seal quality a configuration of the zipperseal that uses two adjacent sealing ridges was chosen for the present design.

The plant holding zipper supports the plant using an internal polyfoam material. The rigid outer zipper opens the zipperseal ridges in front of the moved plant-containing plug and then closes the ridges behind it, maintaining the seal between the root and shoot zones. The polyurethane plug, centered in the zipper, supports the plant, maintains the seal between zipper and stem, and expands to allow for stem growth. As illustrated in Fig. 3, the wedge of the zipper's lower half both separates the zipperseal ridges and and guides them around the stem. The areas surrounding the wedge provide a sealing surface by sandwiching the membrane between the zipper halves, thus maintaining a functional seal during zipperseal ridge separation. Figure 4 shows a cross-sectional view of the zipper through the widest part of the plug-containing wedge.

ADVANTAGES OF ZIPPERSEAL SYSTEM

The inherent advantages of the zipperseal system are modularity, simplicity, and adaptability. The modular nature of the zipper allows for independent and flexible spacing of plants. Plants can be tightly packed despite variations in growth, saving both space and light energy which would otherwise be wasted. A number of options are available for moving the zipper - a simple robot could perform the required movement. Simplicity is inherent in the design since only the zipper moves relative to the membrane. The large sealing surface ensures that atmospheric isolation will be maintained during separation of the zipperseal ridges. Teflon TM (Dupont), flame retardent thermoplastic poly (ether) urethane, or a similar flight approved material will be used for the membrane to assure good support and low friction. Such materials are light, tough and relatively inexpensive. Also, these materials are readily sterilized.

A variety of plants could be grown. Large plants such as soybeans or potatoes would be grown individually in a plug. Alternatively, several plants of a grain such as wheat could be planted in a single plug. With appropriate treatment of the polyurethene no plant tissue damage occurs (Wheeler et al, 1985).

The overall system has tremendous versatility. Since the flexible membrane and zipperseal can be formed around a curve or any number of tortuous paths, many track configurations are possible. The modularity of the system allows for a range of development, from an experimental plant growth unit with just a few plants to a production unit with hundreds of plants. Since the design is based on a current technology, reclosable storage bag seals, experimentation is feasible and inexpensive. Neither the seal nor the zipper movement is dependent on gravity or the absence of gravity. Thus ground based experimental units, space based experimental units, and eventually functional CELSS production systems are all feasible applications.

APPLICATIONS OF SYSTEM

To examine the potential advantages of the zipperseal system as a part of the higher plant subsystem of a spaceborne CELSS, a conceptual design has been developed for a LEO space station common module. Soybeans were chosen for this application due to their high nutritional value, growth geometry and convenience for variable spacing growth chambers. The following factors were considered in the selection of a track configuration: best fit in a cylindrical volume, ease of control over plant inputs, simplicity, and adaptability to ground based testing. The radial wedge concept, shown in a common module cross-sectional view in Fig. 5, was chosen for suitability to a cylindrical volume. The radial wedge consists of a linear track enclosed by a chamber displaying width and height increases along the length. To maximize atmospheric control and reduce the spread of disease, each track would be enclosed in an independent chamber. Ground testing of the concepts developed for the radial wedge can be easily accomplished using independent chambers.

The approximate chamber dimensions required for the soybean plant were calculated from the recommended field planting density. These dimensions were then modified slightly such that twelve chambers would fit into the 4.2 meter inside diameter of the common module (Oleson et al, 1985). The resulting chamber characteristics are shown in Fig. 6.

Five plant maintainence functions require either robotic or manual access to the plant growth chambers: (1) planting (placing the seedling into the chamber), (2) moving the plants as required by growth, (3) sampling plant tissues for nutrient concentrations, (4) removing dead or diseased plants from the chamber to prevent contamination and eliminate the waste of space, and (5) harvesting (removing the mature plant from the chamber). The configuration shown in Fig. 5 is for robotic access. However, it can, by removing chambers or allowing space between disks, allow for human access as might be required for experimental flight testing.

Since the functions described above are required infrequently, a single multi-functional robot could perform those duties for several of the disks formed by a set of twelve plant growth chambers. A system of interconnecting rails would allow this robot complete access to all chambers. A set of outward opening doors on both ends of the chambers would open into the plane of a disk just before the arrival of the robot. Only a brief loss of root/shoot and chamber/module atmospheric isolation would be expected and negative pressure could assure containment. Thus, the robot could carry a zipper with a new seedling into a chamber and slide it onto the membrane, remove mature plants to a food processing facility, and replace dead plants with viable ones.

Plants require different nutrient solutions at different stages for optimum growth (Resh, 1978). This need can be met using a transverse Nutrient Flow Technique (NFT). The amplified role played by surface tension of liquids in microgravity makes the NFT method feasible. Figure 7 illustrates a growth chamber using this method.

The initial results from this conceptual design study indicate that the zipperseal system is feasible in a CELSS plant subsystem application. Initial calculations of space savings over traditional methods that do not move the plant during growth indicate that at least three times as many soybean plants can be grown in the same volume. The additional factors of increased environmental control, reduced energy consumption, and minimized labor requirements further merit the development of a zipperseal system.

TERRESTRIAL USES OF THE ZIPPERSEAL SYSTEM

Many advantages of the zipperseal system, and a wedge shaped growth area in particular, also apply to greenhouse production of crops. Space savings gained by this system could facilitate the city growth of fruits and vegetables in existing buildings. Plant production could occur in remote areas, or areas with poor soil and/or poor climate as well. Both root/shoot separation and transverse NFT give a high degree of control over plant inputs. The net result would be increased yields over shorter growth periods. A variable pitch lead screw for plant movement, shown in Fig. 8, with human labor used for other functions would supply all necessary plant needs. A configuration for a terrestrial greenhouse is shown in Fig. 9.

The use of the zipperseal system can potentially increase yields, and reduce crop cycle time, in any application where greenhouse production is feasible. As in space, expensive artificial lighting is not wasted on empty surfaces. Smaller buildings would be required for the same amount of crop. Less heat, maintenance and associated costs would follow. Clearly the potential applications of the zipperseal system exist on Earth as well as in space.

CONCLUSION

A system has been designed for controlled plant growth. It has good potential for use both in space and on Earth because volume, energy, and labor required in crop production are minimized. A conceptual design of a CELSS plant subsystem using this system has been devised. A working model can be fabricated very easily, and work is underway to construct and test this system for quality of seal and ease of movement, and to test the reaction of plants to root movement along a surface and through a transverse NFT.

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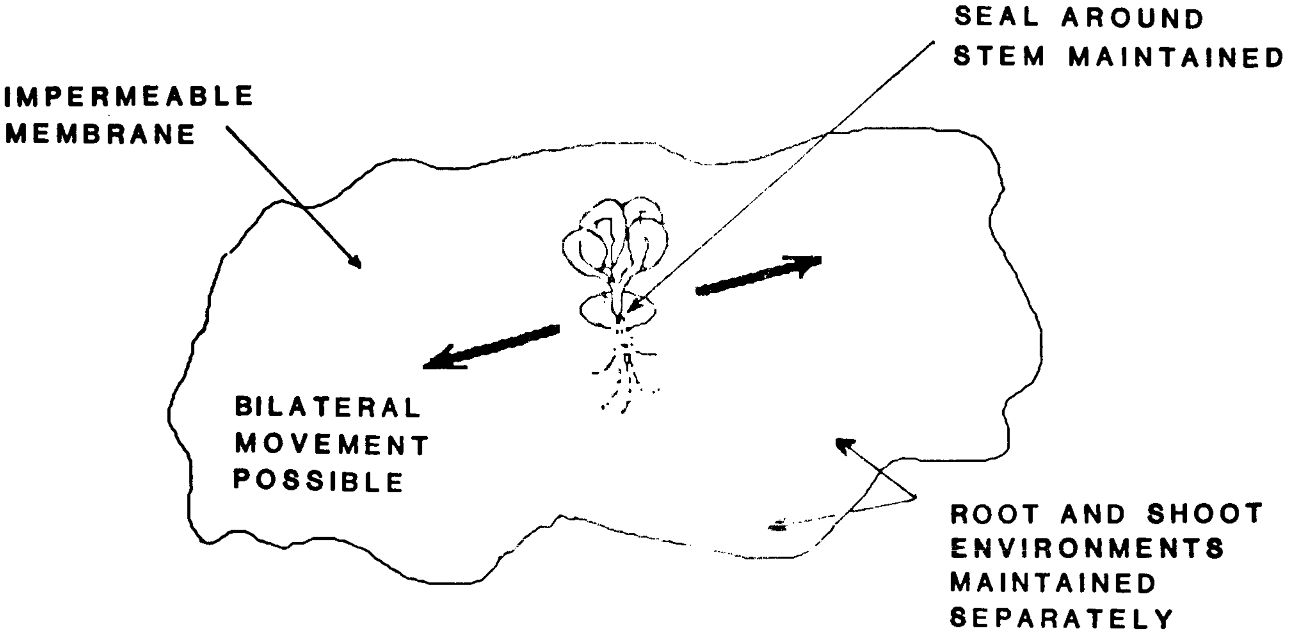
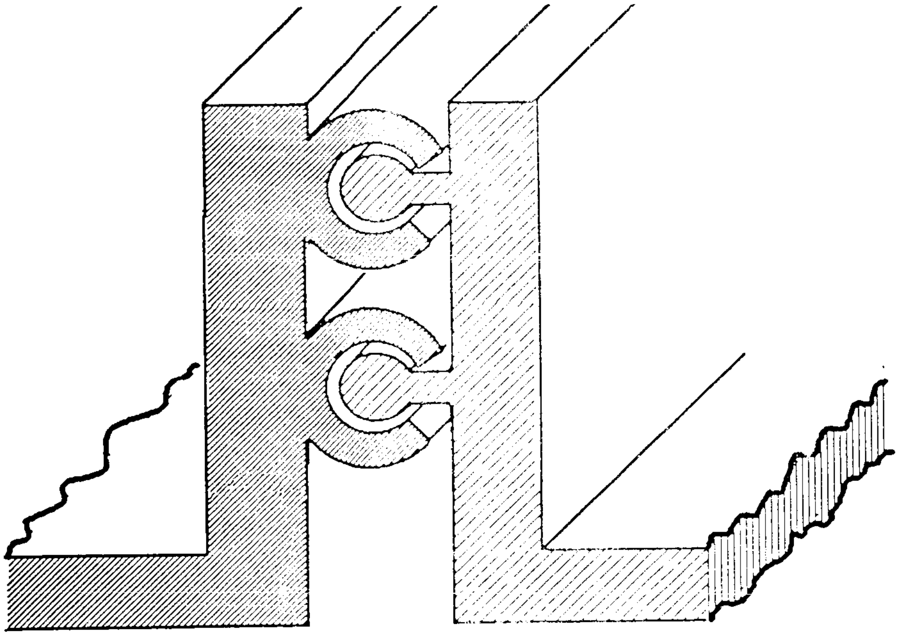
CONDITIONS FOR PLANT GROWTH IN SPACE

FIGURE 1



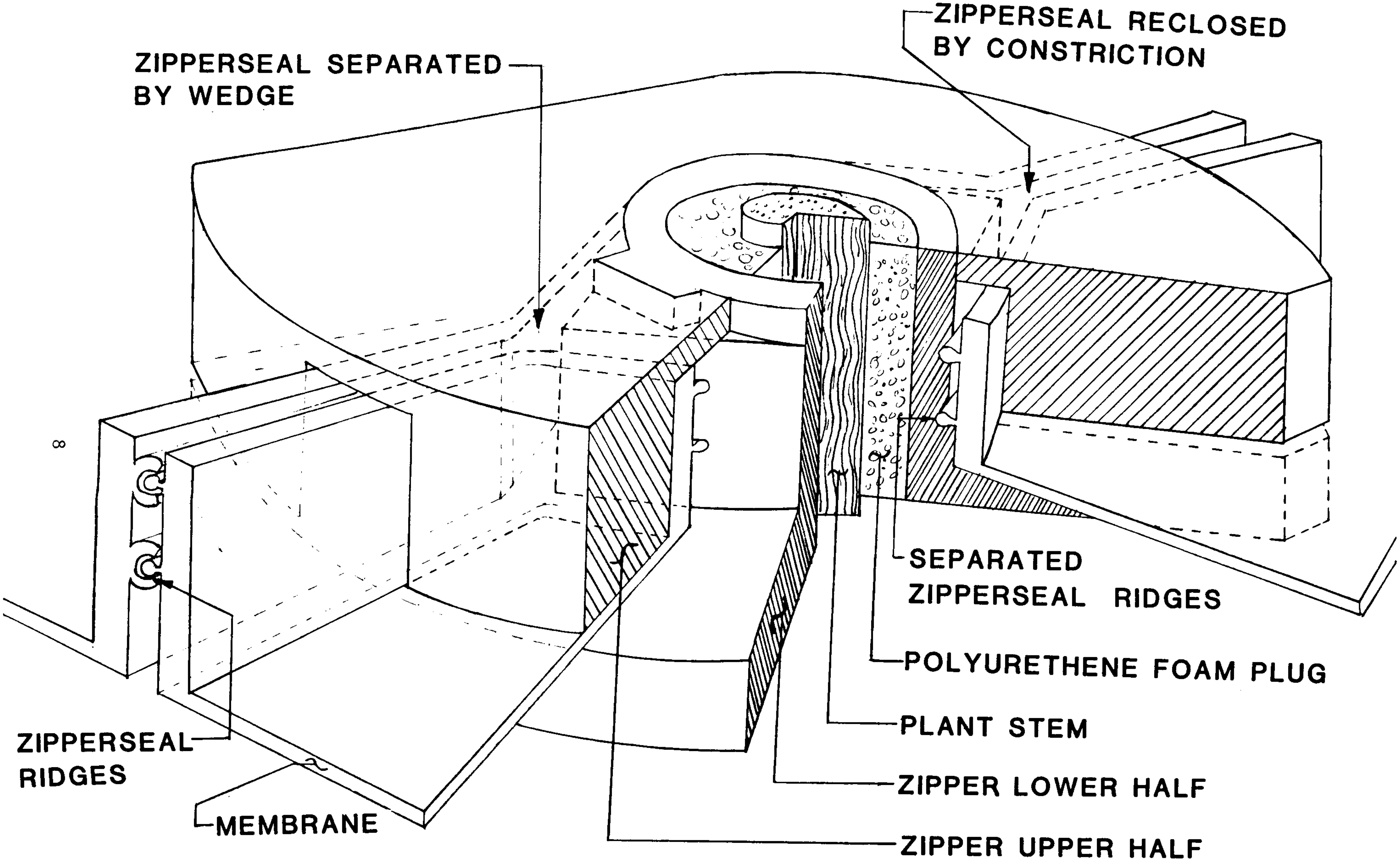


ZIPPERSEAL MEMBRANE

FIGURE 2

PLANT RETAINING ZIPPER

FIGURE 3



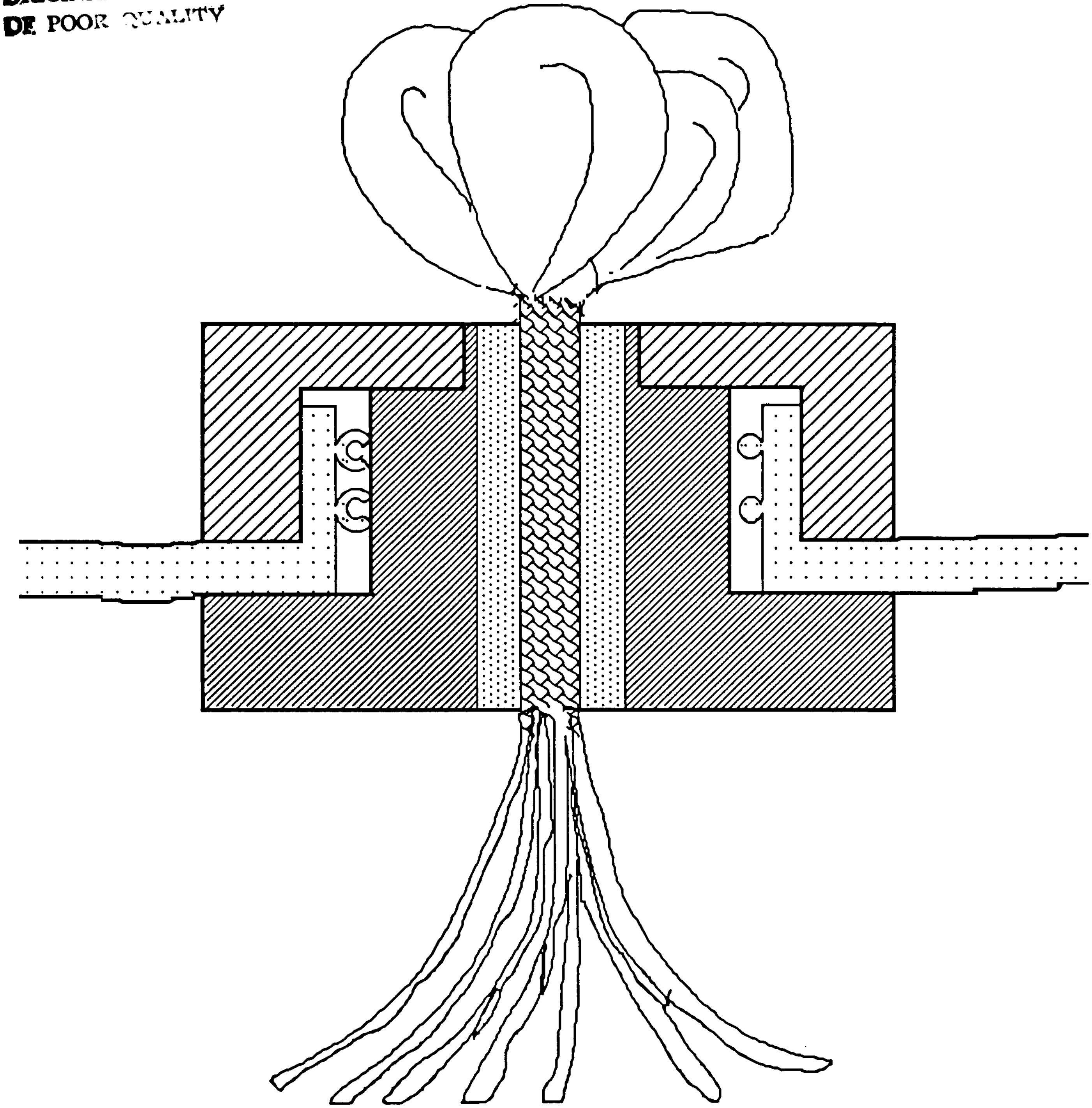
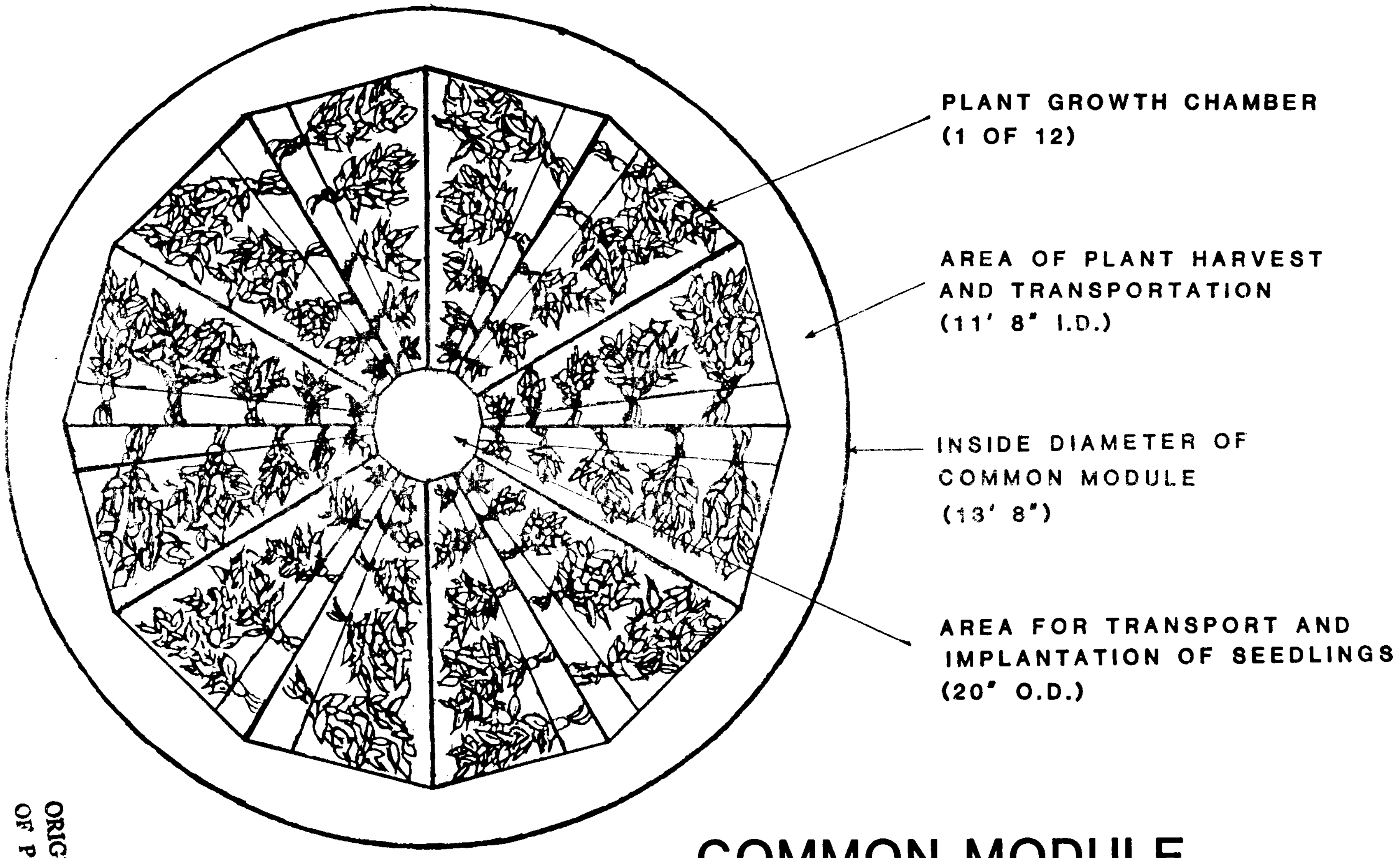


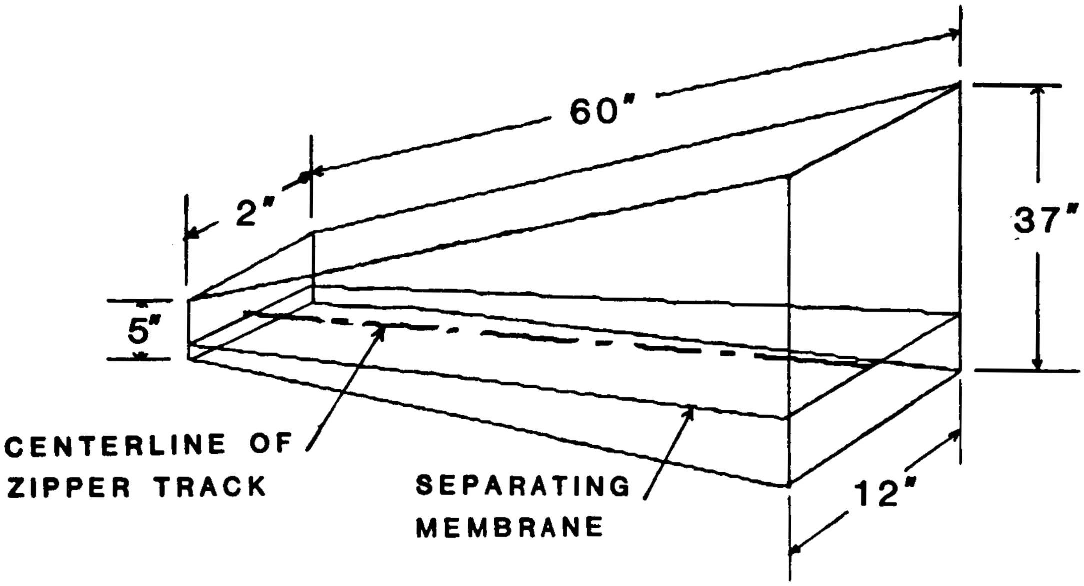
FIGURE 4

PLANT RETAINING ZIPPER

CROSS SECTION

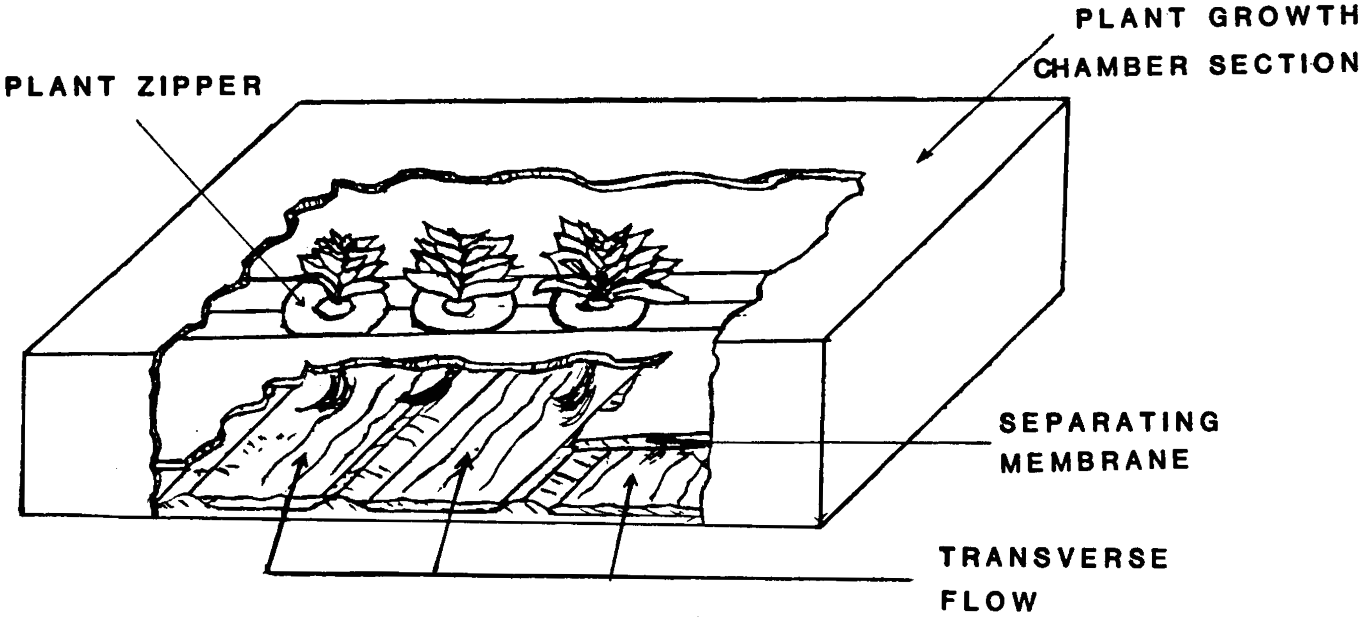


COMMON MODULE
CROSS SECTION
FIGURE 5



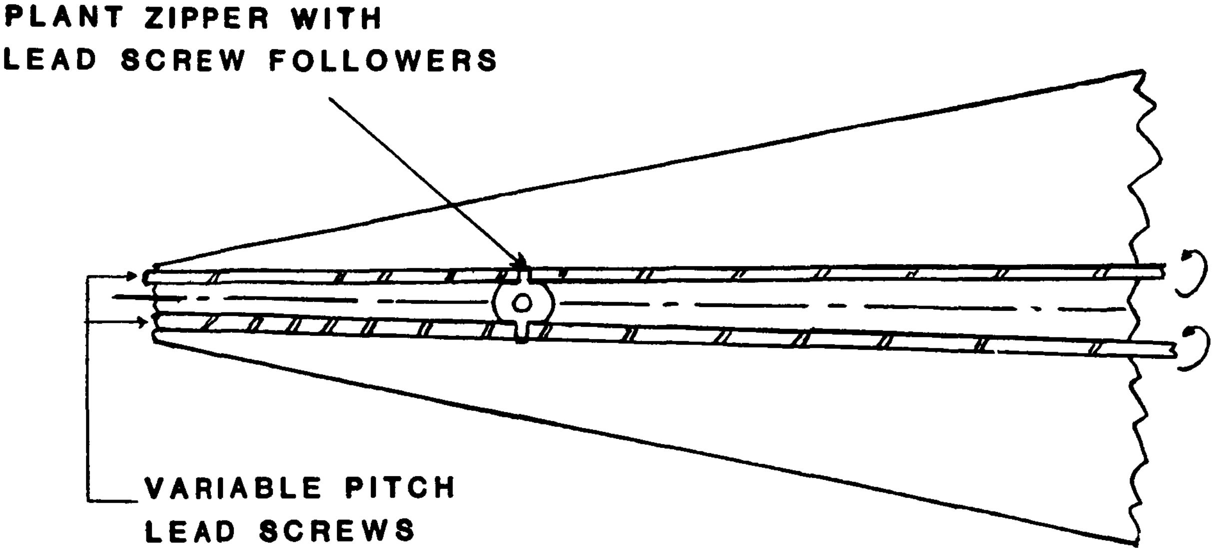
SOYBEAN PLANT GROWTH CHAMBER

FIGURE 6

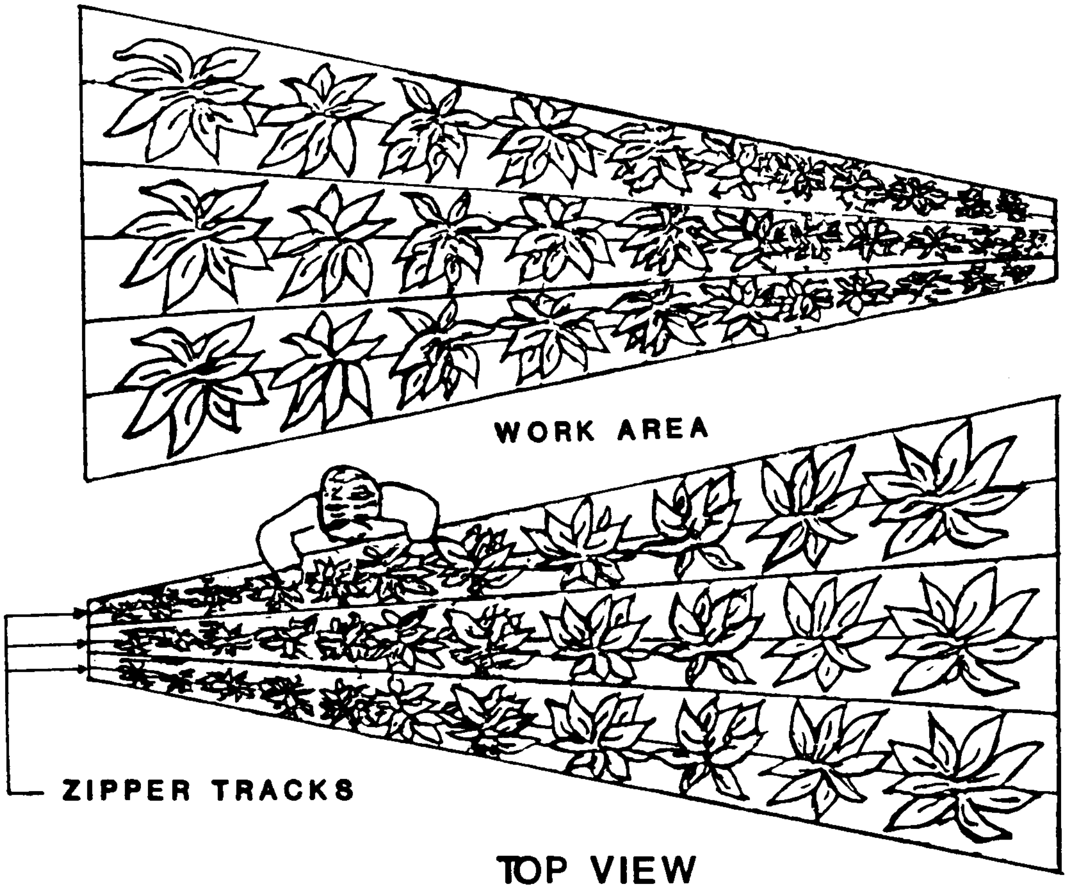


TRANSVERSE FLOW NUTRIENT FILM TECHNIQUE

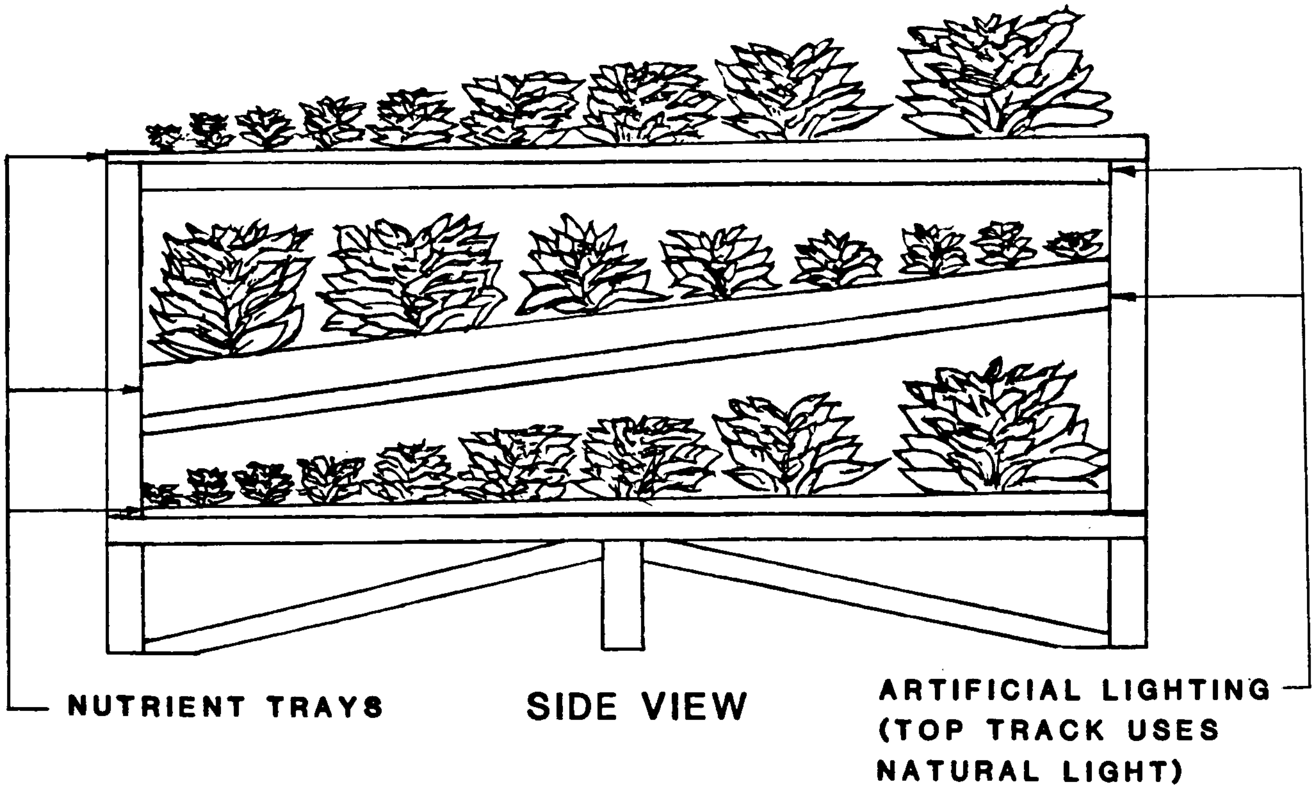
FIGURE 7



LEAD SCREW METHOD FOR
TERRESTRIAL GREENHOUSE
FIGURE 8



TOP VIEW



SIDE VIEW

TERRESTRIAL GREENHOUSE

FIGURE 9

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