EGM 4001

ENGINEERING SCIENCES DESIGN

Design and Implementation of Components for a Bioregenerative
System for Growing Higher Order Plants in Space

Prepared for

National Aeronautics and Space Administration
Kennedy Space Center, Florida

Universities Space Research Association

April 1989

Prepared by

EGM 4001 Engineering Design
Department of Aerospace Engineering, Mechanics
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EXECUTIVE SUMMARY

This report summarizes the design efforts of the EGM 4001 class during the Spring 1989 semester. The primary goal was to address specific needs in the design of an integrated system to grow higher plants in space. These needs were identified the previous semester after extended research was done on such a system. With these needs defined, the emphasis of this semester was placed on the design and fabrication of devices to meet these needs. Specific attention was placed on a hand-held harvester, a nutrient concentration sensor, an air-water separator and a closed-loop biological system simulation.

INTRODUCTION

In order to ensure man's exploration of space on long-term missions, a reliable, self-supporting life support system capable of operation in micro-gravity conditions is necessary. The EGM 4001 Design class of the University of Florida in conjunction with the National Aeronautics and Space Administration (NASA) and Universities Space Research Association (USRA) is working on a prototype closed-loop life support system designed to grow higher plants in space. The generic Closed-loop Life Support System (CLLSS) concept addressed in the following report is loosely based on the Closed Ecological Life Support System (CELSS) designed by NASA. While the research being performed by NASA at Kennedy Space Center (KSC) revolves around a prototype plant growth unit, the focus of the Design class centers on the needs of a successful, real-time CLLSS.

OVERVIEW OF CELSS

The CELSS program is a long-term research and development effort that addresses the future needs of NASA for recycling and regenerating materials needed for human sustenance during extended space missions. Ideally, this closed system will provide basic life support requirements such as food, potable water and breathable atmosphere for space crews on long-term space missions or during extraterrestrial habitation. Using a "bioregenerative system" where the products of the producer are the nutrients of the

consumer and vice versa. CELSS will include three major units: a food production system to grow high order plants under controlled conditions; a food processing system to derive maximum edible content from all plant parts; and a waste management system to recover and recycle all solid, liquid and gaseous components necessary to life support.

To ensure the success of a completely independent bioregenerative system, precise sensing and control strategies regarding different facets of standard operation are warranted. The aim of the Spring Design class was to surmount some of the potential obstacles introduced in the development of these strategies. The following reports are representative of the sensing and control issues confronted by the Design class.

AIR/WATER SEPARATOR

The Design of a Dehumidifier for Use in
a Micro-Gravity Environment

Prepared by

Bryce Brakman
Lillie Dioso
David Parker

SUMMARY

A vital concern in a CLLSS is the maintenance of the humidity level within specific ranges. The humidity level plays a critical role in the plant's ability to maintain efficient respiration and transpiration rates. In addition, if the humidity level becomes too high, condensation may occur and lead to subsequent equipment damage. The focus of the following report is on the design and fabrication of an air/water separator (dehumidifier).

The purpose of this investigation is to design and build a dehumidifier that will operate in a micro-gravity environment. The initial design is used as a basis for modifications with the intent of identifying the possible problems that may occur as a result of micro-gravity. The objective of this group is to design, build, and test different dehumidifiers with the goal of developing a successful prototype.

ACKNOWLEDGEMENTS

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INTRODUCTION

The concept of a CLLSS is based on growing higher plants in space. Present research concerning the separation of water and air in a CLLSS dictates the necessity to develop a dehumidifier capable of operation in micro-gravity. This environment introduces limitations on the traditional equipment due to the absence of gravity. Therefore, new equipment must be developed to maintain conditions desirable for optimal plant growth. Humidity is a major concern in maintaining an environment ideal for plant growth.

The initial design is based on the concept of removing water from air. Modern day condensers are used to separate water or water vapor from the atmospheric air; however, these condensers are gravity dependent. This report implements a dehumidifier capable of operation in micro-gravity environment. The design concept entails connecting a large stainless steel pipe to a smaller polyvinyl-chloride (PVC) pipe. The steel pipe is cooled via an ice bath during which humid air is blown through the pipe using a blower. The water condenses due to the steel pipe cooled to below the dew point temperature. As the water condenses, the moving air transports the water particles along the steel pipe. Eventually, a dead zone area, a region where air velocity approaches zero, is encountered and the water is removed by suction through a pump.

DESIGN REQUIREMENTS

The design specifications of the dehumidifier are as follows:

1. The system must be able to separate a sufficient amount of water from air to obtain the specified humidity level.

2. Materials should be easily obtainable, reasonably inexpensive, durable, and easily replaced.

3. The system must be able to operate under the worst case scenario (i.e. against gravity).

4. The system must be able to withstand the high wind velocity generated by the blower.

5. The main pipe must be cooled below the dew point temperature of water in order for condensation to occur.

6. The system must be sealed to prevent infiltration of outside air or water.

7. The system must have temperature and pressure indicators with simple access and easy visibility.

8. The system must have emergency water ports at the base of the system in the event that all the water must be removed to prevent damage to the system.

SYSTEM DESCRIPTION

The resulting dehumidifier is a modification of first and second generation prototypes. The dehumidifier consists of a five foot long and four inch diameter steel pipe surrounded by a six inch diameter PVC pipe. The PVC pipe holds ice to cool the steel pipe. Air is run through the steel pipe by a blower at a volumetric rate of 300 cfm maximum capacity. An annulus is created by a third pipe made of tin, five feet long and three inches in diameter. By centering the tin pipe inside the steel pipe, the air velocity is increased near the surface of the pipe. Ice is placed inside the annulus to increase the cold surface area by approximately 33%. Two water collecting collars, short cylinders with water troughs cut to catch the water, are located inside the metal pipes. One of the collars is attached to the inside of the steel pipe, while the other is attached to the outside of the annular pipe. The annular pipe has a series of eight inch long and 0.5 inch wide vertical slits cut at the top of the pipe to allow the air to exit the system. Both collecting collars are offset beneath the vertical slits. The outer collar is placed lower than the inner collar for optimal stream line flow. The condensate, driven into the collars by the air velocity, is drawn out by a series of eight thin tubes and exits out the top into an accordion-like plastic pipe. This pipe directs the air into a humidity chamber, made of PVC pipe and polyethylene sheeting. From here,

1.3

the air is drawn back into the bottom of the system by the vacuum end of the blower.

METHOD OF OPERATION

The dehumidifier operates by cooling air below its dewpoint temperature. The cooling is accomplished with an ice bath and causes the water vapor to condense on the cold surfaces of the outer steel pipe and the inner annular pipe. A high air flow rate is provided by the blower to move the condensate to the collector collars. At these collector collars, the air flows in such a way as to create a dead zone of near zero velocity. The condensate slows down at this point and is drawn from the system by a pump.

EXPERIMENTS

FIRST GENERATION

<u>MATERIALS</u>

To meet the design specifications, the following materials were used:

Stainless steel pipe (4" diameter)	Acrylic
PVC pipe (6" diameter)	Humidifier
PVC pipe (1" diameter)	Ice water
Aluminum plates (4.5" diameter)	Water reservoir
1 HP electric blower	Pressure gauges

1.4

Suction tubes	Pipe surface
Silicone	Wet bulb
	thermometer
Assorted Hardware	Water spickets
Support Brackets	

BUILDING PROCEDURE

The system (Fig. 1) is designed to stand in an upright position requiring the humid air to move against gravity (the worst case scenario). The stainless steel pipe is central to the test apparatus. The bottom end of the steel pipe is connected to the blower. The upper end is connected to an aluminum plate attached by brackets to the outside diameter of the steel pipe. Connected to the aluminum plate is an acrylic plate which in turn is attached to the smaller tube. The acrylic plate and smaller tube are both easily removable. An aluminum plate is connected approximately 1.5 ft. from the end of the steel pipe. This plate provides support for the PVC pipe used to create the ice bath. The entire piping system is supported by four brackets. Pressure gauges and both dry and wet bulb thermometers are set up to measure the pressure and temperature of the system before and after the condensation process.
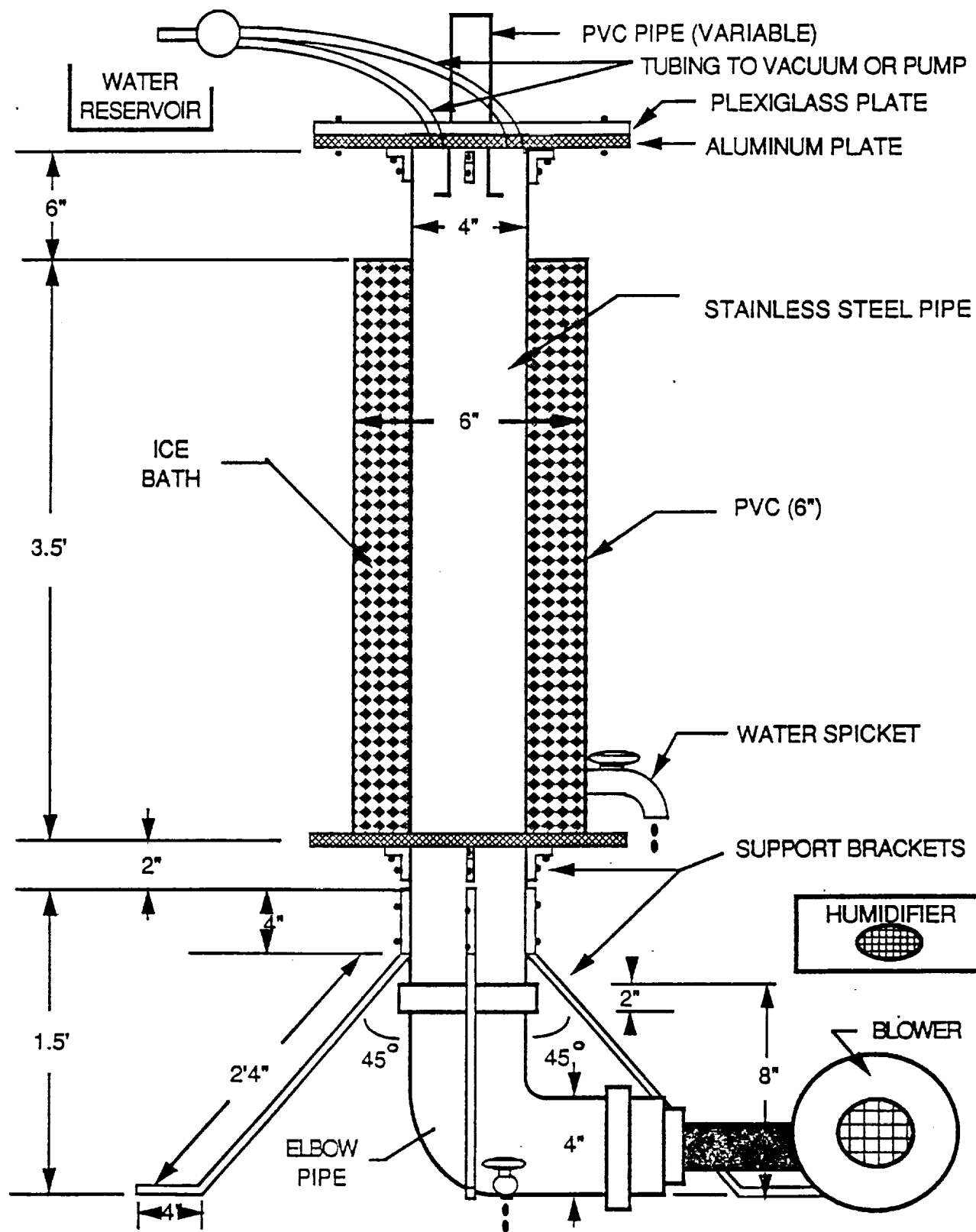
Figure 1. First Generation Air/Water Separator Design

TESTING PROCEDURE

Air from the humidity chamber is taken in by the vacuum of the blower. If the worst possible scenario of 80% humid air is chosen, a successful system should result in 60% humidity after the condensation process. As the humid air is moved along the cooled pipe, water begins to condense and is driven along the sides of the pipe. Eventually, the water becomes trapped in the dead zone area. It is then removed by a suction pump or the vacuum inlet of the blower. By creating a slightly negative pressure in the water exit tubes, a sharper boundary layer results. This draws the water into the dead zone area where it is removed.

PROBLEMS ENCOUNTERED

There were several problems associated with the first generation prototype of the dehumidifier. One of the major problems involved with this prototype was creating enough force to propel the water droplets upward against adhesive forces and the force of gravity. Another problem in the initial prototype was inadequate sealing and insulation of the humidity chamber. This allowed outside air and temperature to infiltrate the system and reduced the necessary control over the system. These problems were analyzed and remedied in the second generation prototype of the dehumidifier.

SECOND GENERATION

MODIFICATIONS

The next step was modifying the initial prototype through several improvements (Fig. 2). One improvement was the addition of a permanent annulus to the system. The annulus was created by placing a metal pipe of smaller radius within the original outer metal pipe and cutting slits at the top. These slits allow air to flow through the system, but the water is retained by the collecting collars. The annulus accomplishes two tasks: it increases the cold surface area in contact with the flowing air and also increases the velocity of the air inside the pipe. The increased velocity is now able to force the water droplets taken from the system upward inside the pipe. Other modifications included the addition of insulation around the humidity chamber as well as more effective sealing procedures. The sealing was improved to prevent any air leakage into the system from the outside. The chamber was insulated to prevent outside temperature effects to influence the inner system.

WATER RESERVOIR

TUBING TO VACUUM OR PUMP

PLEXIGLASS PLATE

6"

STAINLESS STEEL PIPE (4")

ICE BATH

PVC (6")

3.5'

WATER SPICKET

SUPPORT BRACKETS

2"

4"

2

1.5

BLOWER

8"

4"
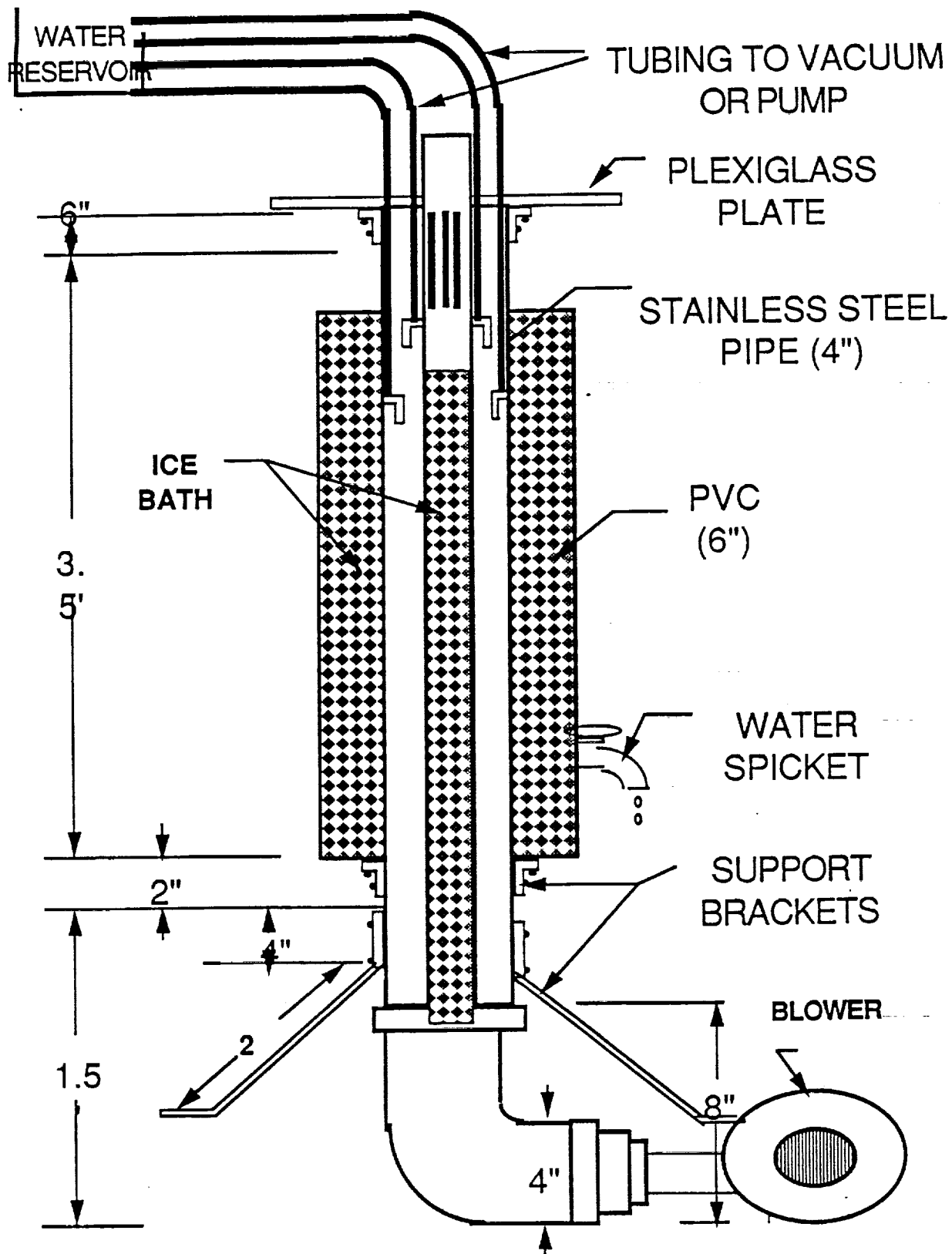
Figure 2.   Second Generation Air/Water Separator

1.9

TESTING PROCEDURE

After creating an annulus in the steel pipe, water droplets were sprayed into the system. The annulus caused an increase in the air velocity, forcing the water droplets to move rapidly to the top of the steel pipe. Air exiting from the top of the humidity chamber was fed into the blower. The blower, in turn, recirculated the air back into the bottom of the humidity chamber. After running the system for five minutes, the temperature of the humidity chamber was significantly less than in the first generation, but still not ideal.

PROBLEMS ENCOUNTERED

A large problem encountered in this prototype is the cooling rate of the air. Currently the cooling rate is too slow and the heat flux into the humidity chamber is too large to drop the temperature of the air sufficiently. The temperature must drop from 80 degrees fahrenheit to 55 degrees fahrenheit, the dew point temperature of the air, in order to effect condensation. One method to solve this problem is to better insulate the humidity chamber.

RESULTS

The results obtained from the final prototype established that the principles of the system were correct. To provide for faster

1.10

results, a fine spray of water was directly introduced into the system. The water was sprayed directly into the steel pipe until the air was completely saturated. This introduction caused a considerable amount of water droplets to cling to the surfaces of both the annulus and the pipe. To support the design, the water droplets must be forced up, against gravity, into the collection collars. The blower was turned on and after only a few minutes, water droplets began to come through the extraction tubes at a rate of about one every five to ten seconds. The system continued extracting water until the humidity level became too low. The appearance of water droplets in the extraction tubes demonstrated that the principles of the system were valid.

CONCLUSION

The current design of the dehumidifier demonstrates a great potential for removing water from air efficiently. In order for this system to be useful in a micro-gravity environment, future testing and modifications are required. It has been demonstrated that the principle of using air flow to move condensed water droplets through a pipe and out of a collection system is a viable method of dehumidification in a micro-gravity environment.

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Dewitt, David P., _Fundamentals of Heat and Mass Transfer_.

APPENDIX

The following is an analysis of the heat transfer of the dehumdifier:

Given constants

pi = 3.1415927

r1 = radius of the annulus = 1.5 in

r2 = radius of the steel pipe = 2.0 in

A = area of air in system = pi * $(r2^2 - r1^2)$

V = mean velocity

Q = volumetric flow rate = A * V = 300 ft^3/min

dT = temperature change to get condensate

Initial conditions

A = 5.49779 in^2

Temperature of incoming air = 80.33 F = 300 K

Relative humidity = 80%

Dewpoint temperature = 73 F from psychrometric charts

Heat transfer analysis

dT = (80.33 - 73) F = 7.33 F

Assuming T(average) for full run = (80.33 + 73)/2 = 76.665 F

V = Q/A = (300 ft^3/5.49779 in^2 min) * 144 in^2/ft^2 =

= 7857.703 ft/min = 89.29 mph

Hydraulic diameter for the annulus is:

1.14

$Dh = Do - Di = 4 \text{ in} - 3 \text{ in} = 1 \text{ in}$

Reynolds number is:

$Re = \text{rho} * V * Dh/\text{mu} = 65059$

$\text{mu} = \text{kinematic viscosity} = 184.6 \times 10^{-7} \text{ Ns/m}^2 \text{ at T(average)}$

$\text{rho} = P/RT = 1.17654 \text{ kg/m}^3 \text{ at 300 k}$

$\text{rho} = 1.18459 \text{ kg/m}^3 \text{ at T(average)} = 297.96 \text{ K}$

Flow is fully turbulent for Re >= 4000 and therefore Re is turbulent (also assuming flow is fully developed through out the annulus).

$Nu = .023 * Re^{.8} * P^n = 146.960$

$n = .3$ for cooling

P = Prandtl number and is the ratio of the momentum and thermal
  diffusivities

  $= .707$ at T(average) = 300 K

Using these numbers there can be calculated the average heat flux per given area in the system.

$q = \text{heat flux} = Nu * k/Dh \quad [T(\text{average}) - T(\text{water})]$

$\quad = 3775.861 \text{ W/m}^2$

k = ratio of specific heats

The expression for q is derived from Newton's Law of Cooling
  $[q = h(Ts - Tm)]$
  $[h = Nu * k/D]$

h = convection of coefficient

Therefore, heat flow = q * At

At = total area of the surface in contact with the air in the

1.15

annulus = 9.162978 ft^2

heat flow = Qd = q * At = 3213.96 W

    From psychrometric charts:

Enthalpy for 80 F and 80% relative humidity

    h1 = 38.5 Btu/lbm

    Initial mass in a container measuring

Mass of air in tank + Mass of air in connecting tubing + Mass of

    air in annulus = 24.4854 ft^3

mass = PV/RT = .815634 kg = 1.79847 lbm

    Therefore, at the dewpoint temperature

h2 = 35 Btu/lbm at 73 F and 100% relative humidity

dh = h1 - h2 = 3.5 Btu/lbm

Qt = 6640.86 J

    And so,

Qt/Qd = t = 2.066 sec

    If we assume Q = 100 ft^3/min due to losses in the system then:

V = 43.65 ft/s = 29.76 mph

Re = 21648.43

Nu = 61.02

q = 1567.54832 W/m^2

Qd = 1334.274 W

Qt = 6640.86 J

t = Qt/Qd = 6640.86/1334.274 = 4.977 sec
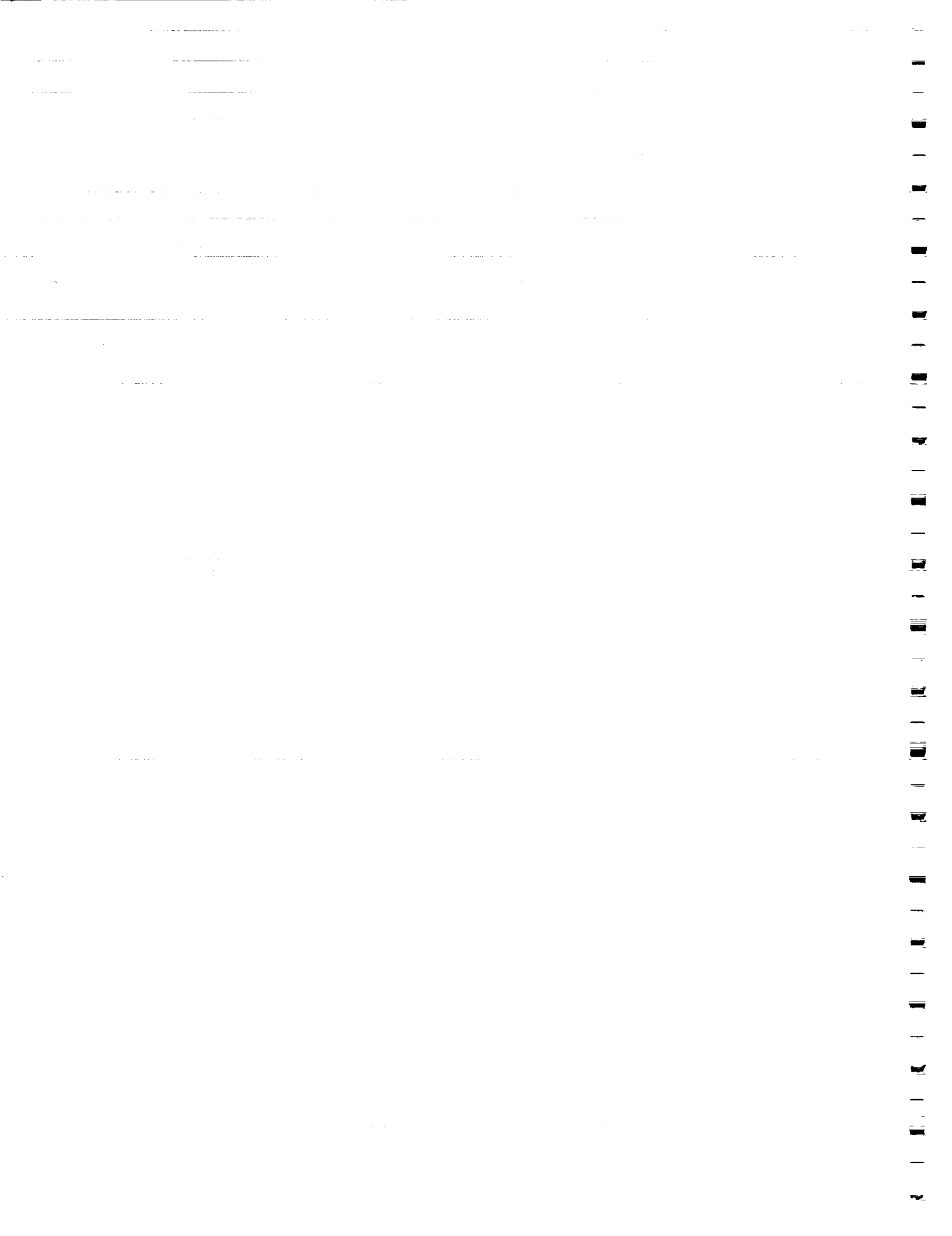
MICRO-GRAVITY WHEAT HARVESTER

Hand-held, Automated Harvester
Capable of Removing and Containing Wheat Heads
in a Micro-gravity Environment

Prepared by

Leslie Segal
Caleb Merriman
Ivan Howard

SUMMARY

In order to facilitate the processing of crops generated in the CLLSS, a mechanism for harvesting the crops must be designed. This unit should capable of removing the processible component of the plant either manually or when attached to a robotic arm. Because of the impact of nourishment on the well-being of the crew, crop processing must be reliable and efficient.

The following paper summarizes the design efforts of a three-man team to produce a hand-held wheat harvester. The harvester is capable of removing the heads off mature dwarf wheat plants and holding them for further processing. After stating the criteria required of the design, methods of wheat head removal, transport and containment are discussed.

ACKNOWLEDGEMENTS

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INTRODUCTION

In order to successfully sustain a CLLSS, methods for fulfilling the nutritional requirements of crew members must be feasible. The prototype CLLSS simulated by the Spring 1989 Design Class satisfies these nutritional requirements by growing, processing and consuming crops grown in the PGU.

The particular area under consideration is the harvesting of wheat. The wheat heads must be removed from the stalk to be further processed into an edible form. This leads to the need for a mechanical harvester capable performing such a function.

DESIGN REQUIREMENTS

Research toward the design of a practical wheat harvester was divided into two areas. The first part of the research was design criteria, or what is required of the harvester. Once these criteria were established, possible methods of removing the wheat head were considered.

The requirements of a working harvester model are as follows:

1. The unit must be hand-held (disregarding weight).

2. It must be capable of removing wheat heads from live, rooted plant.

3. The heads should remain intact.

4. No particles should be introduced into the PGU.

5. The heads should be contained for further processing and study purposes.

These criteria were used to assess possible methods of cutting, transporting and containing the heads.

2.2

SYSTEM DESCRIPTION

The harvesting unit consists of a driving motor, a vacuum unit and a rotating drum/blade unit. Motion of the harvester across the plant tray can be accomplished either by human power or by a robot arm. A handle on the top of the unit allows for this interchangeable feature.

The forward portion of the harvester consists of a rotating drum (Appendix A, Fig. 1). As the drum rotates, nylon rings grab the wheat stalks. The nylon rings, normally held apart by compression springs and riding on two outer axles, are forced together to pinch the wheat (Appendix A, Fig. 2). This pinching is activated by two collars opening and closing at precise locations during rotation of the drum (Appendix A, Fig. 3 and Fig. 4). The collars are 0.25 inch thick aluminum strips which ride on a center axle made of copper. A wire placed between each collar, on either side of the center axle, controls the motion of the collars. Attached to each wire is a steel roller which rides along a variable diameter steel function plate (Appendix A, Fig.5). This function plate is located midpoint on the center axle. Both the function plate and the axle remain stationary while the drum rotates. The steel rollers are located such that they contact the plate at all times during rotation.

A stationary metal blade is located by each set of nylon rings. These blades serve to shear the wheat stalks as the stalks

are dragged across them.

Located 180 degrees from the front of the drum is an opening to the vacuum bag. The bag and vacuum source are located in the upper rear portion of the harvesting unit, below the handle. An acrylic channel leading to the opening of the vacuum bag aids in directing the wheat into the bag.

The driving motor is located below the handle and vacuum bag. It consists of a modified power drill with variable rotation speed. Electronic feedback maintains a constant rotation of the chuck regardless of the load being applied. The chuck is replaced with an alloy sprocket enabling it to drive a light chain. The power control to the drill doubles as the power control to the harvester unit.

The drum is connected to a sprocket which is, in turn, connected to the motor sprocket by a chain. As the motor sprocket turns it forces rotation of the connected sprocket and drum. The drum's sprocket and chain combination is separated from the nylon rings by a circular sheet of acrylic. The entire unit is contained in an acrylic box with an upper handle, a side handle/power controller and a hood to direct any loose wheat.

METHOD OF OPERATION

To remove the wheat heads, a gentle method had to be employed to avoid damaging them. This is accomplished by a slow-moving rotating drum with compressed washers to grasp the stalks. Stalks are grasped at every 180 degree rotation of the drum. Nylon washers, mounted on the drum and held apart by springs, are compressed in a pinching action. Once the stalks are grasped by the compressed washers, the drum rotates. The rotation of the drum causes the stalks to be stretched across a blade. This blade serves to cut the stalks. The cut stalk\head piece continues around the drum 180 degrees until it is located in front of the vacuum source. The washers release the pieces which are then sucked into the vacuum inlet and containment bag. The vacuum draws the heads into a removable vacuum bag that stores them for further processing.

The operation of the compressible washers is effected by the compression of plates on either sides of the washers. These plates, or yokes, are connected by two wires with a small rotatable pulley. As the drum rotates, this pulley rides along the function plate attached to the stationary central axle. When a pressure is applied to the pulley and wire, the wire tries to fold, pulling the plates together and compressing the washers. The function plate causes the wire to fold and the washers to compress at the correct locations. The amount the wire is folded is a function of the

diameter of the function plate. The plate compresses the washers onto the stalks and maintains the compressed position throughout rotation. The stalks are released by the vacuum, 180 degrees away.

RESULTS

Passive wheat head removal is a viable method of micro-gravity harvesting. By gently pinching, cutting and transporting the wheat heads all of the original design criteria were met. Possible modifications to the design include the method of severing the stalks and the choice of materials. The single blade cutting scheme relies on the pressure of the stalk against the blade to achieve a cut. Because this could lead to possible uprooting of the wheat plant, a less violent technique must be explored. Another important consideration is the friction of rubbing parts which causes premature wear and excessive noise. A selection of more compatible materials would reduce this friction and increase the life of the harvester.

CONCLUSIONS

Equiped with feasible methods to generate and maintain a food source in a CLLSS, a successful self-sufficient environment is possible. This hand-held, automated wheat harvester aids in the preparation of the wheat crop into a foodstuff without relying on a skilled operator. The method employed is designed to be manually operated or automated. The use of a robot arm would increase the efficiency of the harvesting process, liberating crew members from such tasks.
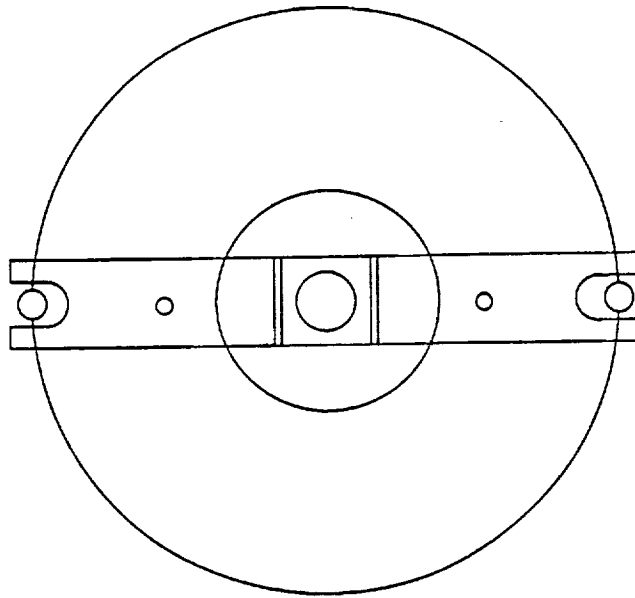
Figure 1.   Cross-Section View of Rotating Drum without Nylon
             Rings.
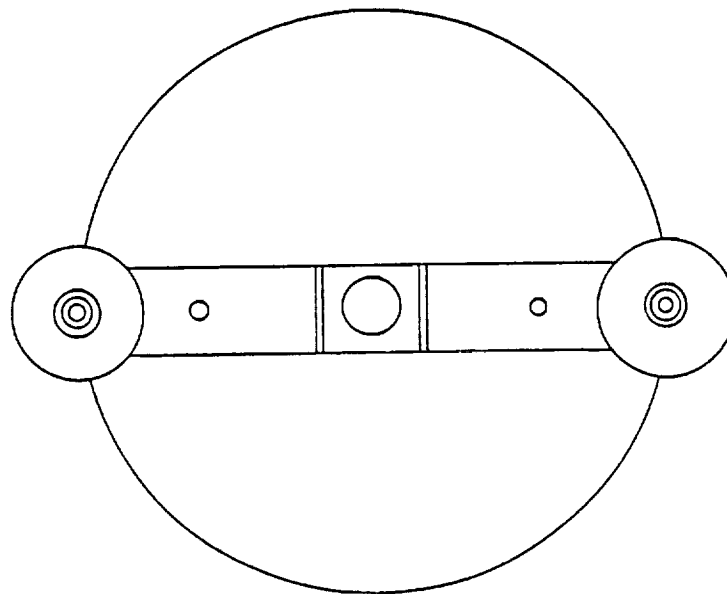
Figure 2.   Cross-Section View of Rotating Drum with Nylon Rings.

2.8
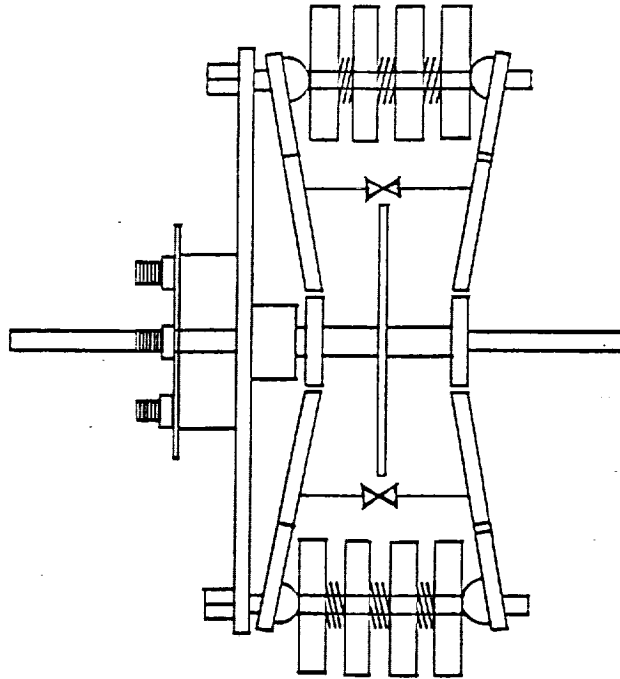
Figure 3.   Rotating Drum in Open Position.
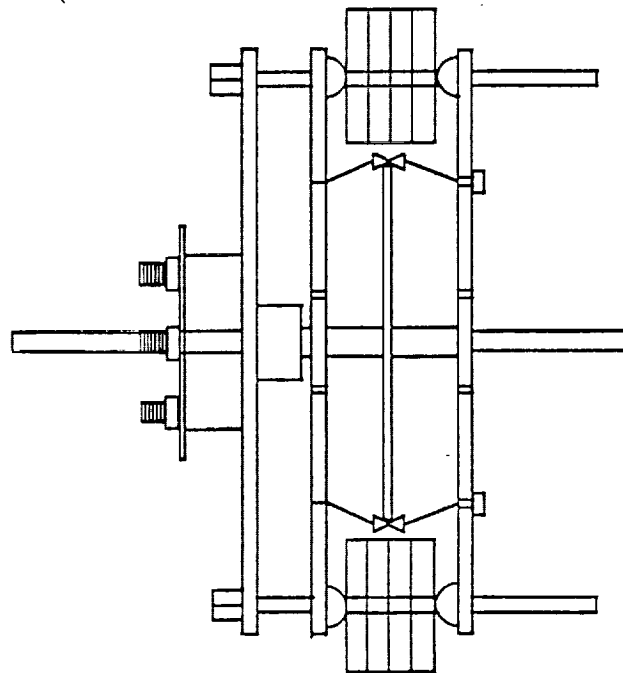
Figure 4.   Rotating Drum in Closed Position.

2.9
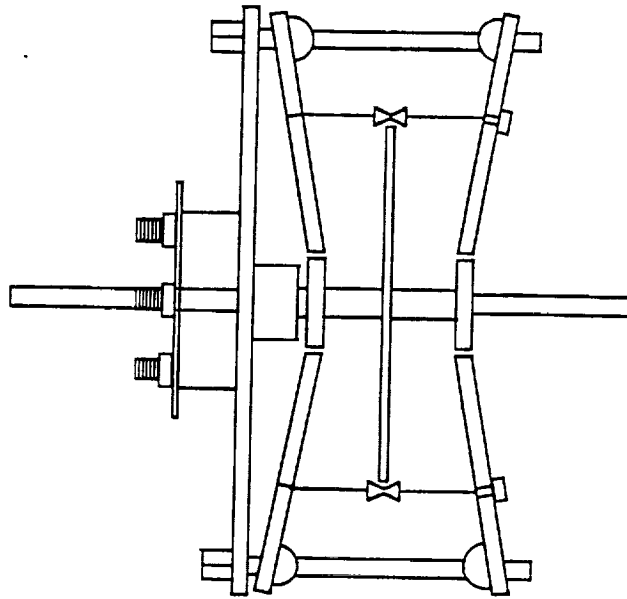
Figure 5. Rotating Drum in Open Posiion without Nylon Rings.

ION CONCENTRATION SENSOR

A Method For Testing the Concentration of Ions
in Solution Using Selective Absorption

Prepared by

Hai Vu
Ken Anderson
Stephenie Riley
Drew Amery

SUMMARY

In order to ensure the effectiveness of a self-contained life support system, optimal plant health is a major factor. To maintain this level of plant health, the nutrient solution delivered to the plants must be carefully and continually monitored. Plants function most efficiently when their required nutrients are received in specific relative concentrations. However, present methods do not allow for precise, real-time measurement of ion concentrations.

To meet these needs, design efforts were focused on building a sensing device that could measure the ion concentrations in solution and yield precise, real time results. The sensor actually measures thermal changes in the solution during exposure to an ion-specific wavelength of light. These thermal changes are a function of the solution concentration. Experiments were performed on control groups of distilled water with and without incident light. Test groups included different salt solutions in varying concentrations. Results were in support of the concept and design.

ACKNOWLEDGEMENTS

The design team of the Spring 1989 Engineering Sciences
Design class would like to thank the following people for their
help in making this project a success:

Dr. Rick Yost, professor in the Chemistry Department at the
University of Florida.

Dr. Robert Hirko; professor in the Aerospace Engineering,
Mechanics and Engineering Sciences Department at the
University of Florida.

Ara Manukian and Jim Bledsoe; students in Aerospace
Engineering, Mechanics and Engineering Sciences Department
at the University of Florida.

Jeff Bohren, teaching assistant in the Engineering Design
class at the University of Florida.

Dr. Gale Nevill, professor in the Engineering Sciences
Department at the University of Florida.

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INTRODUCTION

In a system such as CLLSS, where the products of the producer are the nutrients of the consumer, the containment of all nutrients in the system is of the utmost importance. In the prototype CLLSS simulated by the Spring 1989 Design class, plants are the primary food source of the crew. Therefore, the status of plant health is a major interest. The particular concern in this area is how to evaluate and monitor plant health. One of the most important parameters controlling plant health is the concentration of the macro- and micro-nutrients in the nutrient solution.

PROBLEM DEFINITION

Presently, the concentration of these ions and minerals is measured indirectly by monitoring pH and electrical conductivity levels. Although relative amounts of ions can be determined, the exact quantity of each ion is unknown. Other methods do exist to determine ion concentrations, but these are unreliable for long term use, too time consuming and/or completely destructive to the sample being tested. For example, ion selective electrodes that measure the concentration of specific ions are available, but their uses are limited. In addition to requiring an individual electrode for each ion being tested, the electrodes are cumbersome and tend to become clogged. Over a long period of time the electrodes tend to drift from precise calibration.

An ideal ion concentration sensor would require little space,

be non-destructive to the sample being tested, fast, accurate, and produce real time results.

PROJECT DESCRIPTION

Various methods were considered to meet these needs: spectral methods, magnetic resonance, and wavelength-specific absorption. After evaluating and comparing the options, the wavelength-specific absorption method was chosen. This decision was based on the variety of potential designs for sensors and their probability for success.

The design concept that the ion concentration sensor was modeled on was based upon thermal changes that could be induced in the solution. The idea is based partly on Beer's Law which states that electromagnetic absorption depends only on the number of absorbing molecules through which the radiation passes. Since energy is absorbed at ion-specific wavelengths and then released in form of heat, temperature change in the solution should correspond to the concentration of the specific ion.

DESIGN REQUIREMENTS

To design an effective and useful sensor, certain criteria must be met:

1. The sensor must use a method that is non-destructive to the sample. The sample must be able to be returned to the stock solution.

2. The sensor must be compact and easily adaptable to various nutrient delivery systems.

3. The sensor must be accurate and reliable over long periods of time.

4. The sensor must produce real time results.

5. The sensor should be totally automated, not requiring continual monitoring by crew members.

These criteria were developed with aspirations of producing a sensor that would offer benefits not found in present sensing technology.

SYSTEM DESCRIPTION

THEORY AND CONCEPTS

The premise the ion concentration sensor is based on is the specific wavelengths of light that the ions will absorb at. If light of a characteristic wavelength is incident upon a solution containing its corresponding ion, these ions will absorb this light energy and eventually release it as thermal energy to its surroundings. According to Beer's Law, the higher the ion concentration is in the solution, the more energy it will be able to absorb. This light energy the ions absorb will be released as thermal energy. Therefore, the temperature change in the solution can be correlated to the concentration of ions in the solution.

Initial research provided peak absorption wavelengths of various ions (Table 1).

3.4

Table 1. Characteristic Ion Absorption Peaks

ELEMENT	ABSORPTION
Nitrogen	No Data as NO_3
Phosphorous	No Data as PO_4
Sodium	No Data as Ion
Potassium	No Data as Ion
Calcium	393.3 nm
Magnesium	279.5 nm
Sulfur	No Data as SO_4
Chlorine	479.4 nm
Iron	238.2 nm
Boron	345.1 nm
Manganese	257.6 nm
Zinc	202.5 nm
Copper	213.5 nm
Molybdenum	281.6 nm

The convenience and availability of visible light sources facilitated the choice of an ion in the visible spectrum. This limited the selection of possible ions, for use in testing, to calcium and chloride. The accessibility and machinability of acrylic Plexi-glass made it an ideal material for the construction of the test chamber. The absorption peak of calcium corresponds very closely to that of the acrylic (375nm), therefore, chloride became the ideal choice. Although only one ion is being sense, justification of this decision is based on the expectation that if results supported a successful system for the detection of chloride ions, the system could easily be adapted to sense for other ions in solution. By limiting testing to one ion variables in the system design are reduced hopefully allowing errors or necessary changes in the physical system to be more apparent.

OVERALL DESIGN

Conceptually, the design for CLLSS would divert a small portion of the nutrient solution to test chambers just before and after the plant growth unit. By determining the ion concentrations as the solution enters and exits the plant trays, not only exact concentrations of nutrients are known, but also the amounts taken up by the plants. This can aid in monitoring plant health.

CHAMBER DESIGN

The test chamber is the section of the system that contains the actual solution sample (Fig. 1). The chamber is constructed of acrylic. It consists of a sub-chamber which the test sample is diverted to, a light filter, and a parabolic mirror. Also contained within this sub-chamber is a thermistor (a highly sensitive temperature transducer, Appendix B). This thermistor is connected to a computer via an A/D converter.

The light filter is attached to the front of the test chamber. This filter allows only light of 480 nm +.3.5 nm to pass into the chamber. Therefore, the light entering the chamber is specific to the absorbing wavelength of the chloride ion. To maximize the amount of light incident on the sample, a parabolic mirror is attached to the back of the test chamber.

Initially, the test chamber was placed between two air chambers (Fig. 2). These chambers served to insulate the sample in the test chamber from any fluctuations in the surrounding environment. Because of the sensitivity of the thermistor, the conditions of the surroundings should remain as stable as possible. Subsequent testings, however, revealed that the air chambers were not sufficient source of insulation.

To alleviate this problem, the entire test chamber is suspended in an chamber made of insulating foam board. This chamber has three inch thick walls and allows about two inches of dead air space around the test chamber (Fig. 3).

TEST SAMPLE   THERMISTOR

FILTER (480nm)   MIRROR
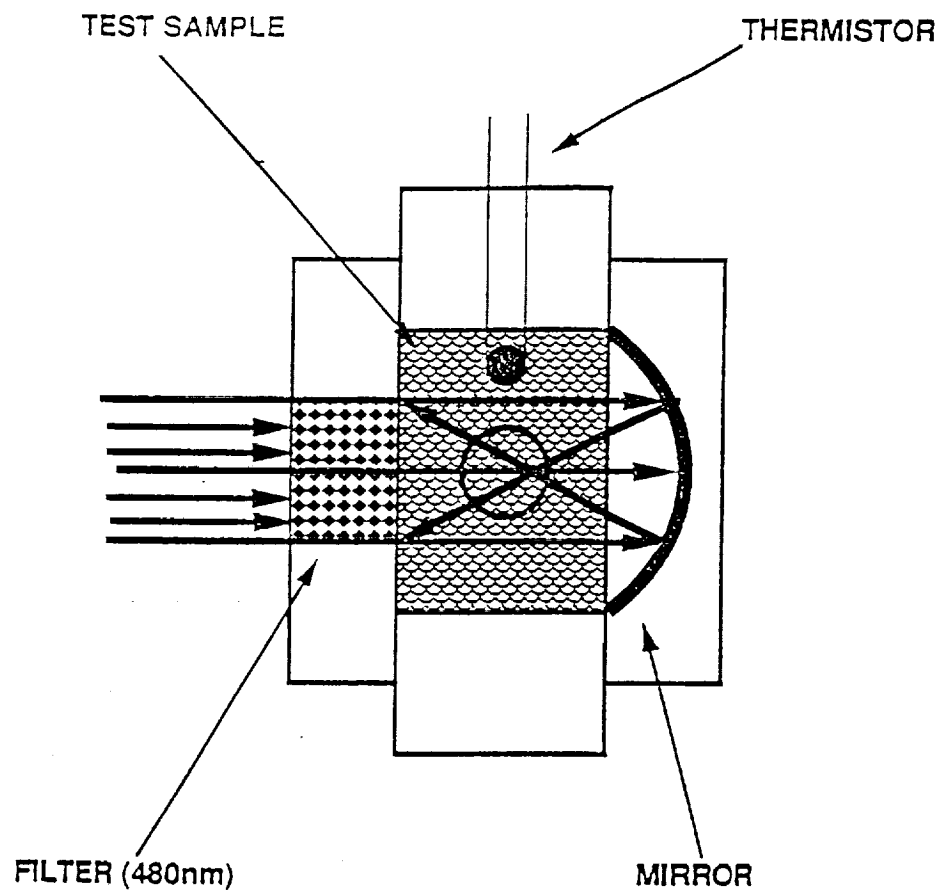
Figure 1.   Present Test Chamber

AIR CHAMBERS

TEST CHAMBER

THERMISTOR

FILTER

PARABOLIC MIRROR
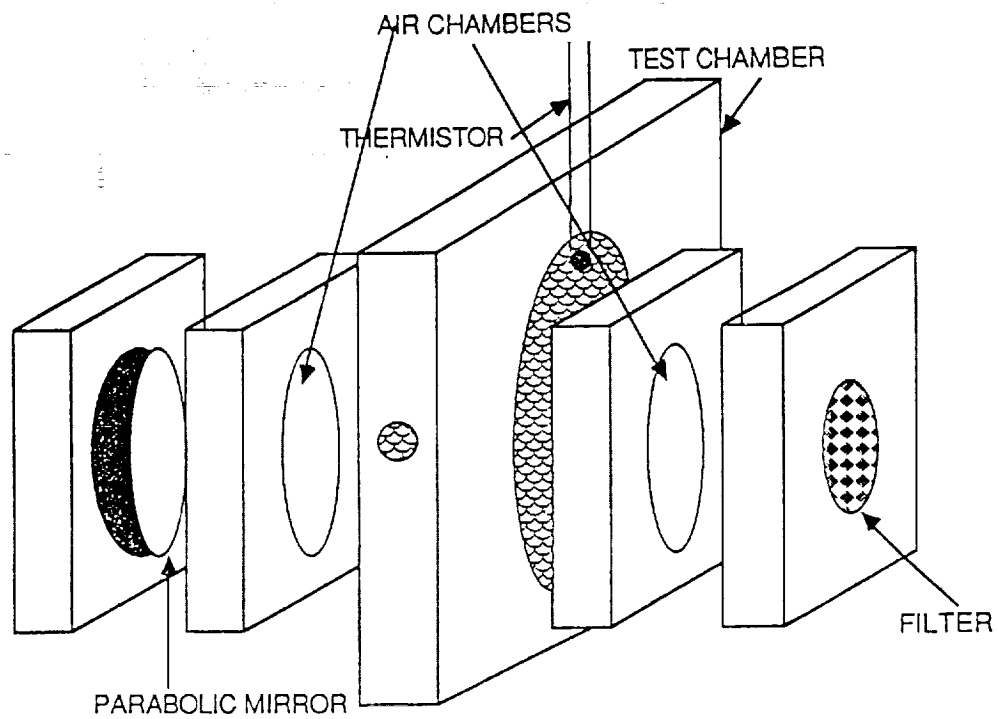
Figure 2.   Original Test Chamber

3.8

OUTFLOW

INSULATING
BOX

INFLOW
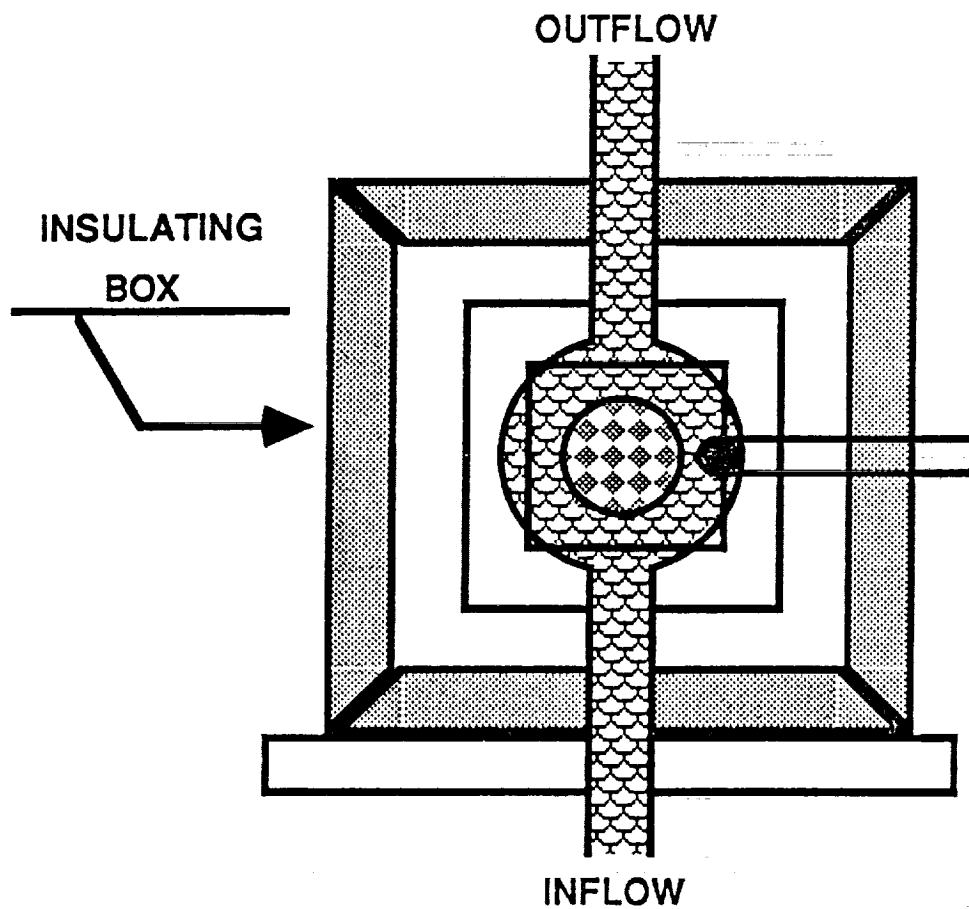
Figure 3. Test Chamber Contained In The Insulating Box

SYSTEM DESIGN

The sensor is composed of a light source, a series of lenses, an insulating chamber, a test chamber, and a computer interfaced to the system to monitor changes. The system is set up such that the light originating from the light source first passes through a piece of heat glass. The heat glass filters out the infrared light. By doing this, the possibility of a temperature change due to heating from the light source is essentially eliminated. The light proceeds through two lenses which condense and focus the light on the filter located on the outside layer of the test chamber. The computer is interfaced to the system through the thermistor.

METHOD OF OPERATION

The experiments were conducted in a consistent manner to minimize variation in results. Before each experiment was performed, the computer was allowed to warm up for approximately thirty minutes. This was to permit heating in the wires, connecting the thermistor to the computer, to equilibrate. The test solution was allowed to flow through the chamber for a short period of time before the valves were closed and the chamber was sealed off. After the valves were closed, the test sample was kept static for ten minutes. Readings were taken every five seconds for ten minutes. The data were recorded and graphed.

3.10

EXPERIMENTS

Six sets of experiments were performed. Three of the experiments serve as control, while the other three test various concentrations of chloride ions. Listed below are the experiments and the order in which they were performed:

1. Heat gain test of distilled water at room temperature. This experiment was performed before any modifications were made.

2. Heat gain test of distilled water at room temerature after modifications.

3. Heat gain test of distilled water at room temperature with light incident on the sample.

4. Heat gain test of 25g of salt in 375g of water at room temperature with light incident on the sample.

5. Heat gain test of 50g of salt in 375g of water at room temperature with light incident on the sample.

6. Heat gain test of 100g of salt in 375g of water at room temperature with light incident on the sample.

RESULTS

Original tests were run with the initial chamber design that included only the air chambers as insulating devices. With this configuration, the tests run with distilled water and no incident light were displaying significant noise (Appendix A, Fig. 4). These first trials prompted the idea of suspending the test chamber within the insulating box. The goal was to contain the environment of the test chamber to the best possible extent.

The modification proved to be very effective. The next sets of control tests run demonstrated anticipated results. The control tests were run with test samples of distilled water with and without incident light (Appendix A, Fig. 5 and Fig. 6). For both these sets of control experiments results were the same. There was no appreciable heating of the distilled water with or without incident light.

The next set of results displayed the effects of the incident light on different salt solutions (Appendix A, Fig. 7). Consistent with expectations, there were definite temperature changes in the solutions containing the chloride ion. In addition to these promising results, the change in temperature increased with the concentration of the solution.

3.12

The 25g NaCl in 375g water experiment showed a thirty ohm change in resistance while the 50/375g and the 100/375g yielded changes of 90 ohm and 120 ohm, respectively. These results demonstrate that higher concentrations of salt in solution do correspond to higher temperature change.

CONCLUSIONS

Although the research and design was limited to the chloride ion, experimentation substantiated the specific-wavelength absorption theory. With more resources, this idea could be a feasible method of determining ion concentration. Application to a variety of ion solutions would require minor modifications such as light sources and filters.

For future study, controlled experiments should be conducted to ascertain the mathematical relationship between the solution concentrations and temperature changes. Ultimately, the system should would be fully automated and integrated into the nutrient delivery system.

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APPENDICES

APPENDIX A

RESISTANCE
(ohms x 10^3)
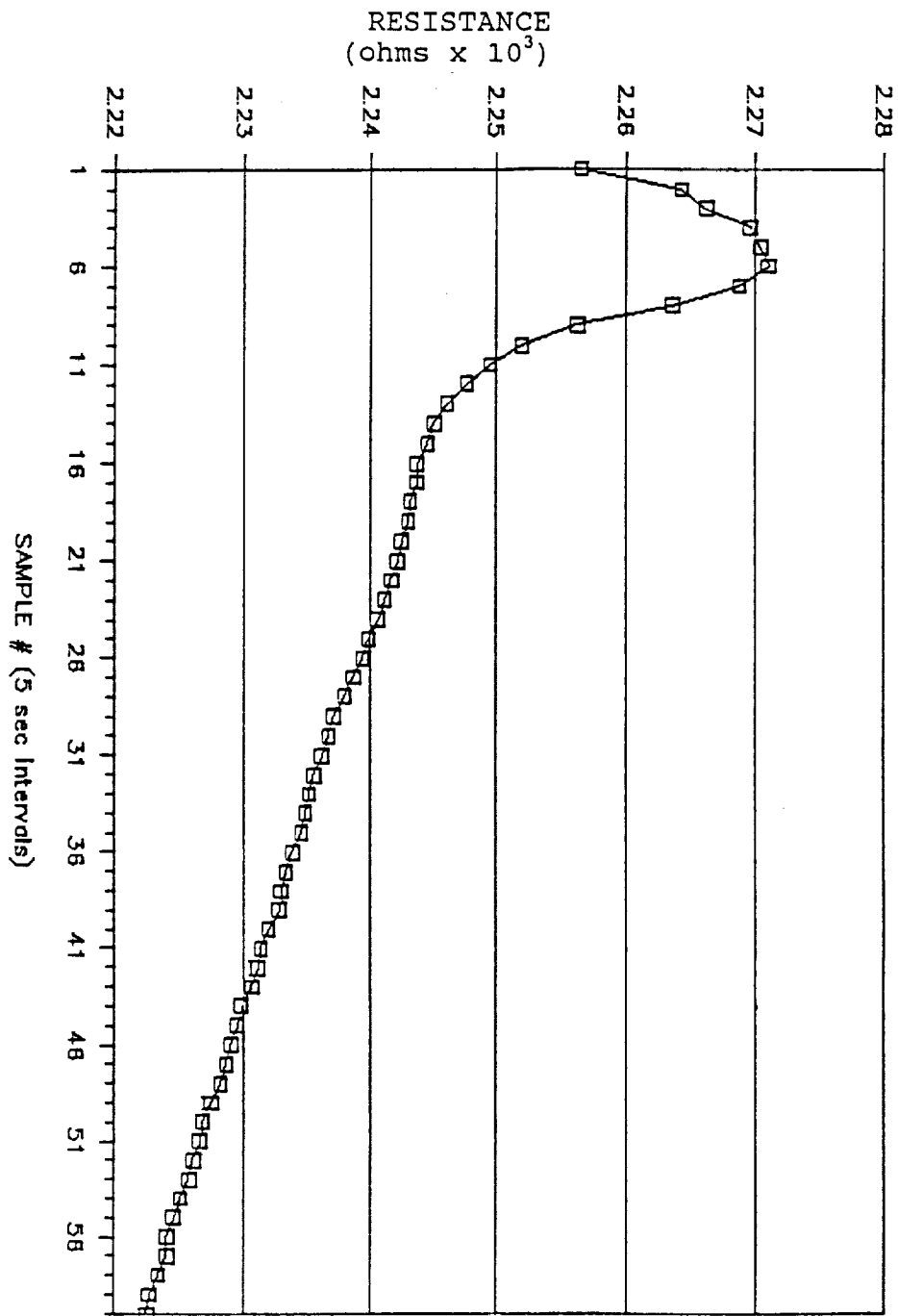
Figure 4. Distilled Water With No Incident Light
(Original Design)

3.16
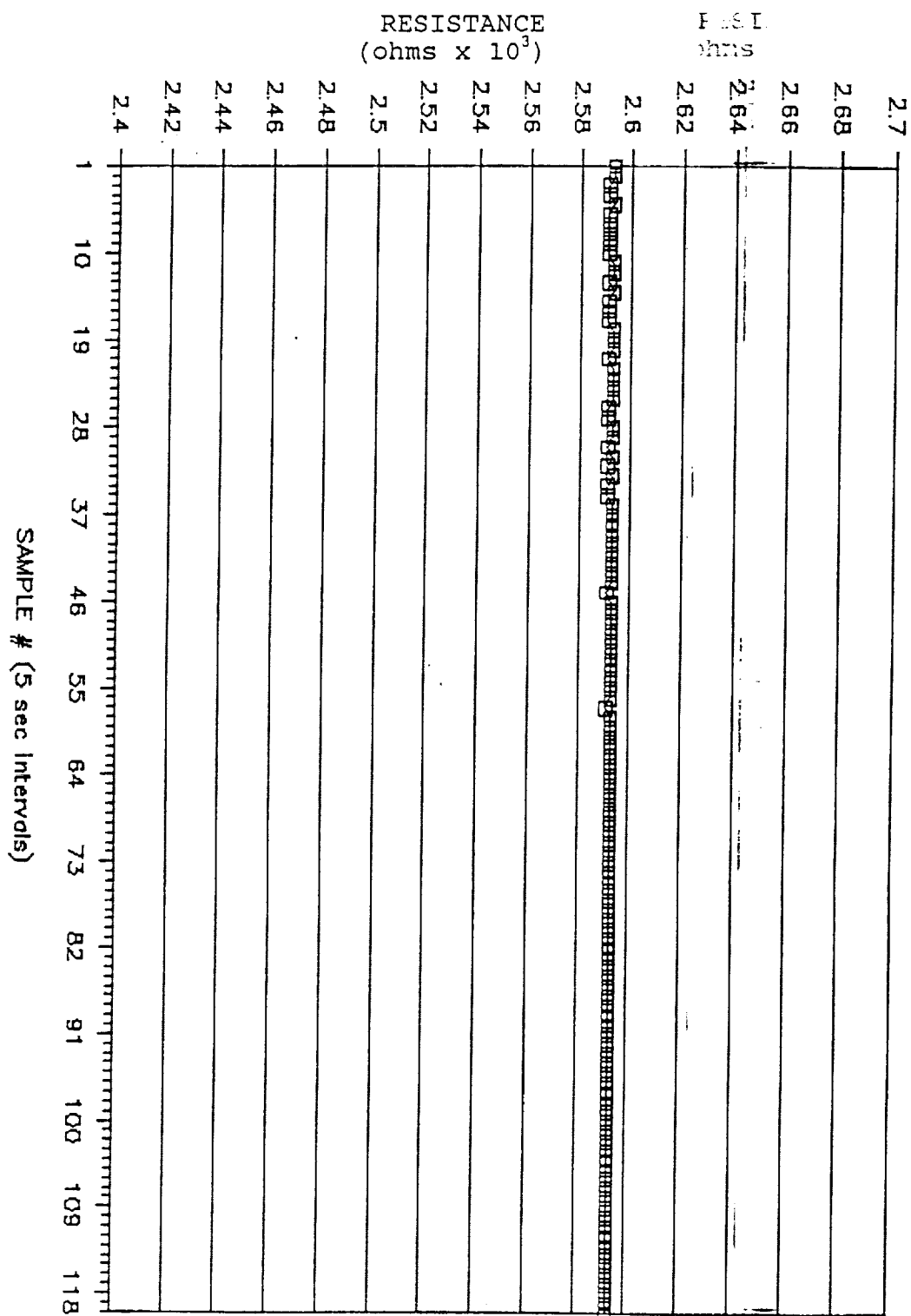
Figure 5. Distilled Water With No Incident Light

3.17

RESISTANCE
(ohms x 10^3)

2.4 2.42 2.44 2.46 2.48 2.5 2.52 2.54 2.56 2.58 2.6 2.62 2.64 2.66 2.68 2.7

1 16 31 46 61 76 91 106 121 136 151 166 181 196 211 226 241 256 271 286

TIME (SEC)
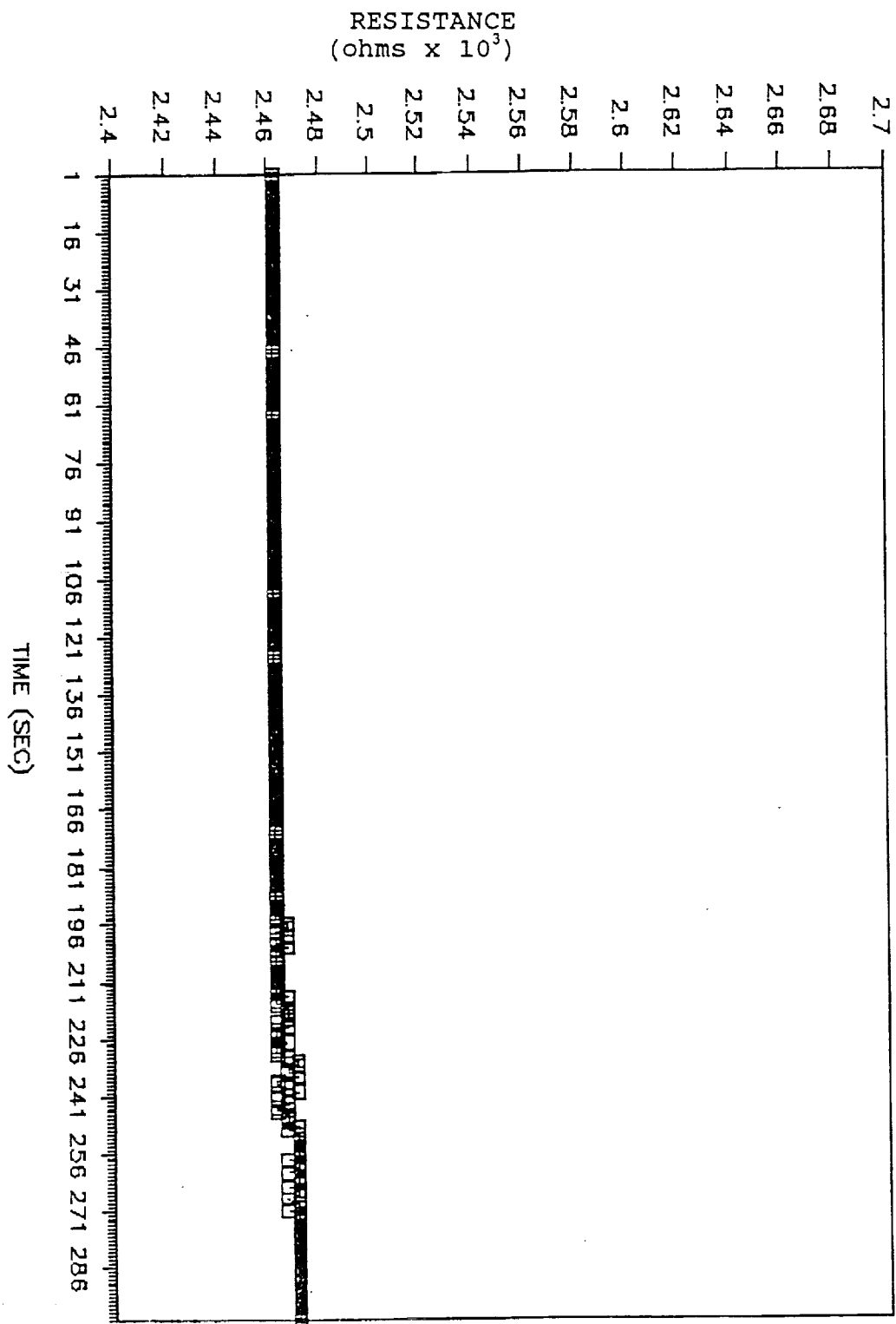
Figure 6.   Distilled Water With Incident Light

3.18
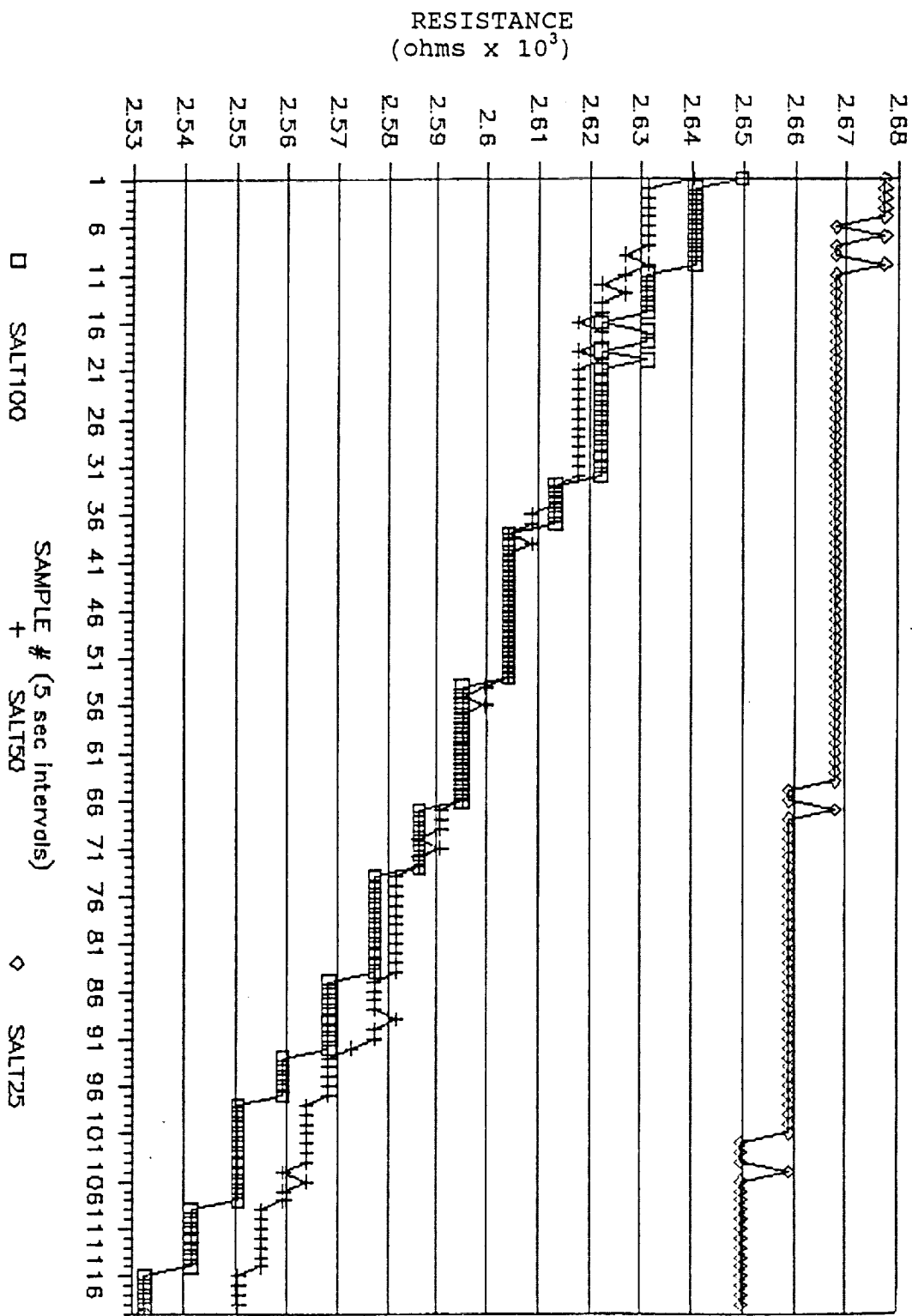
Figure 7.   Salt of Varying Concentrations
With Incident Light

APPENDIX B

THERMISTORS

The word "thermistor" is a contraction of the two words "thermal resistor". A thermistor is a ceramic semiconductor which exhibits a large change in resistance due to a small change its body temperature. They are typically composed of metal oxides such as nickel, copper, iron, or titanium oxide.

A thermistor was chosen as the temperaure sensing device because of its advantages:

1. Fast response

2. Small size

3. High resistance (eliminates lead resistance problems)

4. Rugged

5. Comparatively low cost

The main disadvantage of the thermistor is its nonlinear resistance characteristics (shown below). However, its characteristics are linear over a short range of temperatures, making thermistors an ideal temperature sensing device.
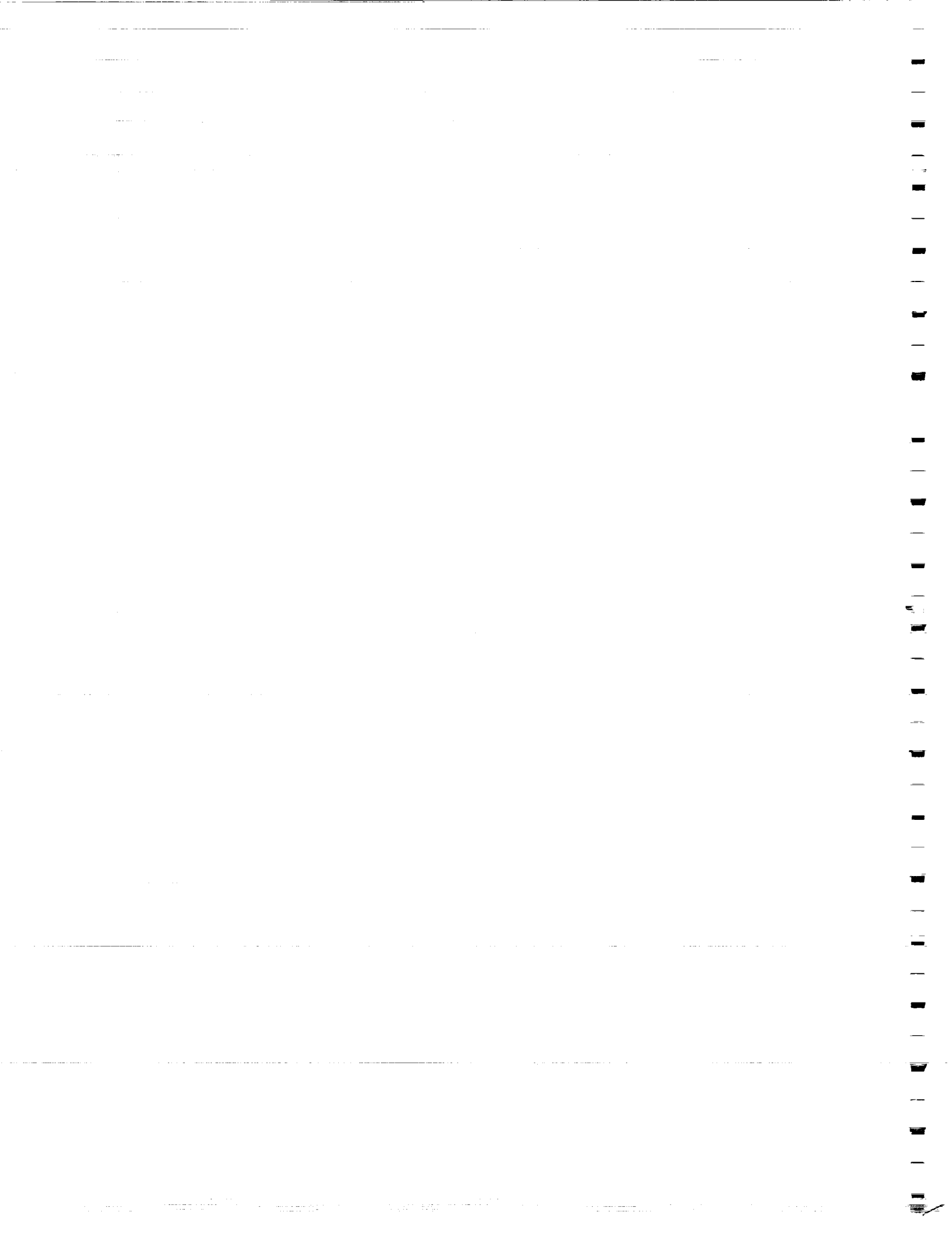
MODELING, SIMULATION, AND CONTROL

The Modeling, Simulation, and Control of a
Plant Growth Unit for a Closed-Loop
Life Support System

Prepared by

Cinnamon Buckels
Jim Larson
Paul Brachhold
Carole Rhoads

SUMMARY

The success of growing higher plants in space is dependent on much design work. The design process can be made more efficient if the behavior of the system is investigated. Using a model and subsequent computer simulation, some behaviors may be quantified prior to the physical construction of the system. Insights gained through the use of a computer simulation could aid in the design process.

The focus of the Spring 1989 Design class was on the optimization of control and sensing needs. Control and plant growth have an interdependent relationship. Control affects plant growth while plant growth, in turn, defines future control parameters. The following report discusses the specific model and simulation created by the Design class.

The final simulation developed by the Design class accomplished many purposes. The uncontrolled plant chamber simulation gives some results of the system's behavior, which may be used to prioritize sensing and control needs. Secondly, the simulation can be used as a testbed for simple control schemes. Future improvements on the simulation should include increasing the complexity of the model and controller by replacing many of the assumed constants in the system with functions.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

INTRODUCTION

The future of long term manned space missions is dependant on many factors. Due to a limited amount of space for resource storage, the future extended missions must be equipped with recycling capabilities. One of the most important of these capabilities is the growing and harvesting of food and the recycling of waste. In order to better understand and predict some of the problems that will be encountered while designing such a system, a simple simulation of a closed loop plant growth system with control was developed. The closed loop system was modeled using system dynamics and simulated using DYNAMO simulation language. The simulation consisted of three sections. A plant/chamber loop was developed to simply model some of the basic physiological cycles of the plant; such as photosynthesis, respiration, and transpiration. An energy loop was developed to keep track of simple energy flow in the system. Lastly, a controller was implemented to maintain balance in the system.

The plant and energy loops modeled do not represent all of the complicated processes which would actually take place in a closed loop system. Their purpose, however, is to roughly predict some of the major trends of the system. This rough model serves as an abstract test environment for proposed sensing and control systems. Therefore, the simulation provides a preliminary test bed for various controllers of the modeled system.

The purpose of the simulation project was to establish a

generic model of a closed loop plant growth chamber, to create a simulation of the simple system using the DYNAMO language, and to vary the initial conditions and the control in the simulation to evaluate the effects on the system. In order to better understand the control needs of a plant growth system, the simulation was used to assess some of the sensing needs of the system.

DESIGN REQUIREMENTS

To develop a model and simulation of a plant growth chamber several design criteria were established. First the system was divided into three sections: a plant loop, an energy loop and a control loop. Then constraints were placed on each of these sections of the model. Once a reasonable model was established and a simulation was developed, the output criteria were manipulated to provide useful and understandable results.

PLANT/CHAMBER REQUIREMENTS

In order to obtain a working model of a plant growth chamber within the time frame of the semester, several simplifying assumptions had to be made. The model's purpose was to represent generic processes that take place in a plant growth chamber. The processes represented were photosynthesis, transpiration, and respiration.

The simplifying assumptions were made in the plant physiology equations. The photosynthesis equation was modeled to be, exclusively, a function of varying carbon dioxide levels and the light in the chamber. Similarly, transpiration was limited to being a function of photosynthesis, temperature, and humidity. Finally, respiration was modeled only in terms of photosynthesis and maintenance respiration (see appendix A for plant physiology equations).

4.3

ENERGY REQUIREMENT

The requirements for a simplified energy model for a CLLSS system are numerous. Energy flows between the various parts of the model should be easy to follow and recordable. Also, these energy flows should be related to the mass flows from the rest of the system. The temperature of the growth chamber should be an integral part of the total model and should be monitored and controlled. Heat should be easily added or removed from the growth chamber as well as the atmosphere processor. Finally, the total energy flow into the system should be monitored to ensure that the total energy requirement is reasonable and practical.

CONTROL REQUIREMENTS

Many internal parameters of the CLLSS simulation have a tendency to grow unbounded, exceeding acceptable ranges. This tendency demonstrates the need for systematic control of the model. A control system should limit the parameters of the model while providing them with a degree of stability. Stabilizing the individual parameters contributes to the stability of the overall system. The design of such a controller was completed in stages, beginning with an elementary control system and increasing in complexity. At this stage, a controller which limits the parameters, but does not achieve the necessary degree of stability, has been designed.

4.4

SYSTEM DESCRIPTION

SYSTEM DYNAMICS NOTATION

Both the plant/chamber and the energy models were developed using system dynamics modeling notation (Fig. 1).

MASS FLOW

INFORMATION FLOW

LEVEL OR STATE VARIABLE

SYSTEM RATE

CONTROL RATE

AUXILARY
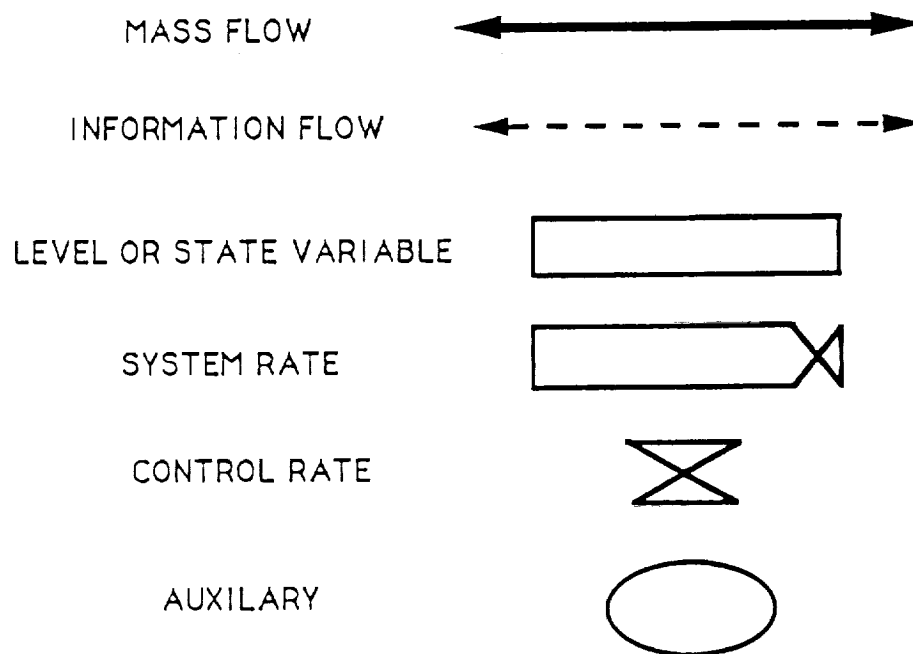
Figure 1. System Dynamics Modeling Notation

The system consists of state variables or levels. These levels, such as oxygen or humidity, are changed by rates. There are two types of rates in the system. Plant physiological rates, such as transpiration and photosynthesis, cannot be directly controlled. However, they are controlled indirectly by rates associated with

4.5

control equipment, such as humidity. The solid lines represent material flow in the system. An example of this is water moving from the plant into the atmosphere through transpiration. Information flows are represented by the dashed lines. For example, because photosynthesis is directly dependent on the carbon dioxide in the chamber, there is an information flow from the CO_2 level to the photosynthetic rate.

PLANT CHAMBER SYSTEM

The model developed is based on short time intervals. That is, the focus of the model is on instantaneous changes. Instantaneous changes occur in the composition of the atmosphere and in the temperature. In contrast, plant growth would be an example of a long-term change. Because the model is short term, it is not considered closed. Closing the model could be achieved using the current mass model and adding the effects of harvesting, waste regeneration, and human interactions.

The mass model (Fig. 2) is based on five state variables (levels) and three storage levels. The model focuses on immediate plant growth and its effect on the atmosphere. There are three primary plant physiological interactions or natural rates which affect the model. They are:

1. Photosynthesis - plants converting CO_2 and light into plant mass and O_2
2. Respiration   - plants consuming mass for energy and producing CO_2
3. Transpiration - plants evaporating water to the atmosphere
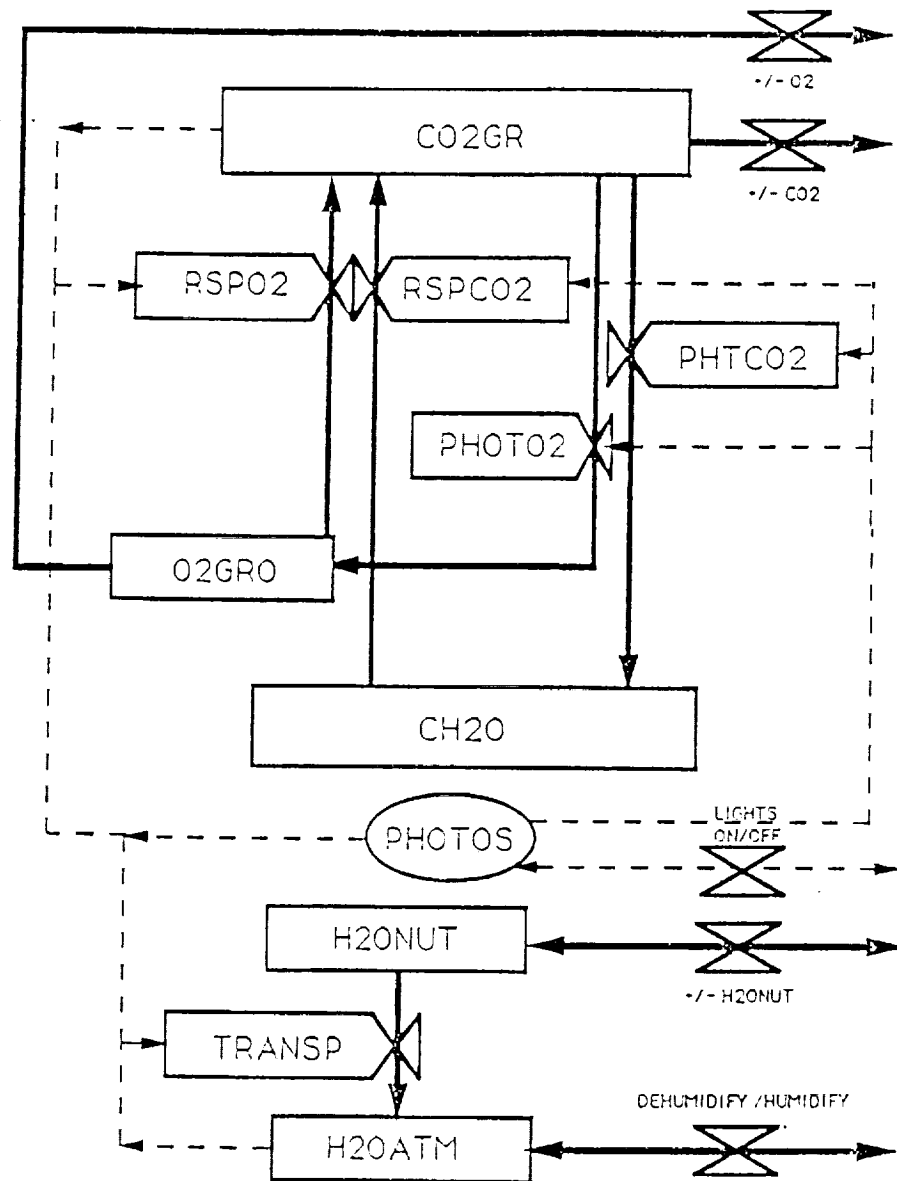
Figure 2. Plant Chamber Mass Model
(a glossary of terms is
offered in Appendix A)

Plant physiology can only be approximated, however this approximation is adequate when assessing control problems. Storage levels are also present in the model in order to simulate realistic conditions and to determine control action.

ENERGY SYSTEM

One method of examining the characteristics of a model is through the analysis of the energy flows of the model's simulation. If huge amounts of energy are required for the model to function, then it is in the designer's best interest to modify the system for better energy performance. On the other hand, if the model produces more energy than is put into the system, an error exists within the model.

The current energy model consists of three energy levels: the energy level of the growth chamber; the energy level of the atmosphere system; and the level of energy supplied to the system.

The energy of the growth chamber is affected by several factors in the model. The lights add energy to the system which is expressed as a percentage of the total incident light. The heat loss from the chamber is expressed as a percentage of the total energy in the chamber. Additionally, the atmosphere and nutrient solution flows in and out of the chamber will add and remove energy, respectively.

The energy level of the atmosphere is affected by four rates. Changes in the energy level of the growth chamber will affect the

energy level of the atmosphere. Additionally, a heater and cooler to control the atmospheric temperature will affect its energy level.

An energy source is included in the model to supply energy to the system. The energy source level supplies energy to the lighting system and the atmospheric heater and cooler. By monitoring the energy flow into the system a better understanding of the system behavior may be gained.

ENERGY AND MASS LOOP INTERACTIONS

In this model, as in a real system, energy and mass flows are closely related. With each mass flow there is an associated energy flow. The flows of oxygen, carbon dioxide, and the nutrient solution are being considered and related to the energy flow in the simplified model. The mass flow per unit time multiplied by its specific heat will yield the energy flow per unit time.

Energy flows and energy balances are important in the accurate modeling of any dynamic system. By analyzing energy levels in different parts of the model, the performance of the model can be evaluated and optimized. The energy flows and balances can also indicate deficiencies or strong points of the model and in turn, the actual system. Overall, energy flows and balances are a necessary part of any simulation.

CONTROL SYSTEM

Control is effected through the manipulation of the rates which add to or subtract from levels of the model. Only levels which can be directly controlled by mechanical means in a real-life situation are chosen for direct control in the simulation. The levels which are selected for direct control are the plant chamber gas levels, the light level, the humidity level, and the air temperature of the chamber. All the major equations within the simulation are functions of these quantities. Their direct control leads to the indirect control of the entire model.

A rule of thumb in control theory is to design the simplest controller that will elicit the desired system response. The initial system response criteria involved restriction of various levels within the growth chamber to specific ranges of acceptable values. This criteria allowed for the design of a basic controller which subtracts or adds a constant value to the level when it exceeds its bounded range. Once this controller was designed, the desired system response was updated to include not only maintenance within a range, but also some measure of stability. This stability required the design of a proportional controller. The first step in designing a proportional controller was to design a controller which utilizes negative feedback to maintain appropriate levels.

METHOD OF OPERATION

The simulation is designed to run at minute time intervals. Because of the versatility of the simulation language used, several of the system parameters may be changed before each execution. These parameters include system constants and initial values of state variables. Therefore, initial system conditions may be varied to compare the effects of different starting levels on the operation of the chamber. In addition, the simulation length and time step intervals are variable parameters. For example, the simulation can be run for a total of 120 time steps (each time step is a minute in the coded model). The state of the system is evaluated at each of these time steps and may be plotted or tabulated. The choice of run length and saved step interval is dependent on the desired output.

PLANT/CHAMBER OPERATIONS

SIMULATION WITHOUT CONTROL

The first version of the simulation is used to observe the trends of an uncontrolled system. The behavior of an uncontrolled plant growth chamber can provide valuable information regarding the sensing and control needs of the model. An uncontrolled version of the simulation also provides a basis for comparison.

The uncontrolled simulation known as NONCON runs at several different time steps and lengths. Without control, the system

4.11

changes rapidly in the first few hours but reaches an equilibrium in approximately two hours. The system equilibrates because the plant physiological rates saturate or deplete critical state variables. Good examples of the uncontrolled system behavior are the transpiration rate and water level in the atmosphere (Appendix C, Fig 5).

Transpiration is the only factor affecting the humidity, while at the same time it is dependent on the humidity. Once the air becomes saturated with water the plants can no longer transpire. Therefore, the transpiration rate becomes zero and the humidity equilibrates. Similarly, the photosynthetic rate approaches zero when the carbon dioxide level is depleted.

SIMULATION WITH CONTROL

Another version of the simulation is designed to run with a controller. Instead of the system stabilizing to a nonproductive equilibrium stage, the system remains relatively stable. To affect the plant rates, the controller changes the state variable which, in turn, influences the physiological rates. By maintaining the optimum range for each critical state variable the plant growth equations (photosynthesis, respiration, and transpiration) remain finite rates. A good example of system control is the photosynthetic rate and carbon dioxide level in the system (Appendix C, Fig 6).

Photosynthesis is directly proportional to the level of carbon dioxide in the system. As the plants take in CO_2, the controller

adds CO_2 to the atmosphere and the level of CO_2 in the chamber stays within a specified range. This, in turn, keeps the photosynthetic rate within a productive range.

ENERGY LOOP OPERATIONS

The operation of the energy loop is based on several levels and rates (Fig. 3). An imaginary source of energy is created to represent the energy source of the entire system, such as a generator. This level steadily decreases with time, showing a continuous draw of power from the source.

Another level models the energy present in the plant growth chamber (PGU), and is given an arbitrary initial value. The lights in the PGU and a heater increase this energy level, while a cooler and heat leakage from the PGU decrease the energy level. A temperature variable is calculated from the energy level in the PGU. If the temperature is too high, a cooler is switched on by the controller. If the temperature of the growth chamber is too low, a heater is turned on.

An atmosphere processing system is described to contain the heating and cooling devices for the atmosphere in the PGU. The atmosphere processor level is monitored to establish its effect on the energy level of the entire system. Consequently, energy added, in the form of heat, to the energy level of the PGU would result in a decrease in the energy level of the atmosphere processor. Cooling of the PGU would result in the reverse effects on the energy levels. The controller turns on or off the heater or cooler

4.13

depending on the temperature of the PGU. This allows the DYNAMO
user to specify a desired temperature range for the PGU.
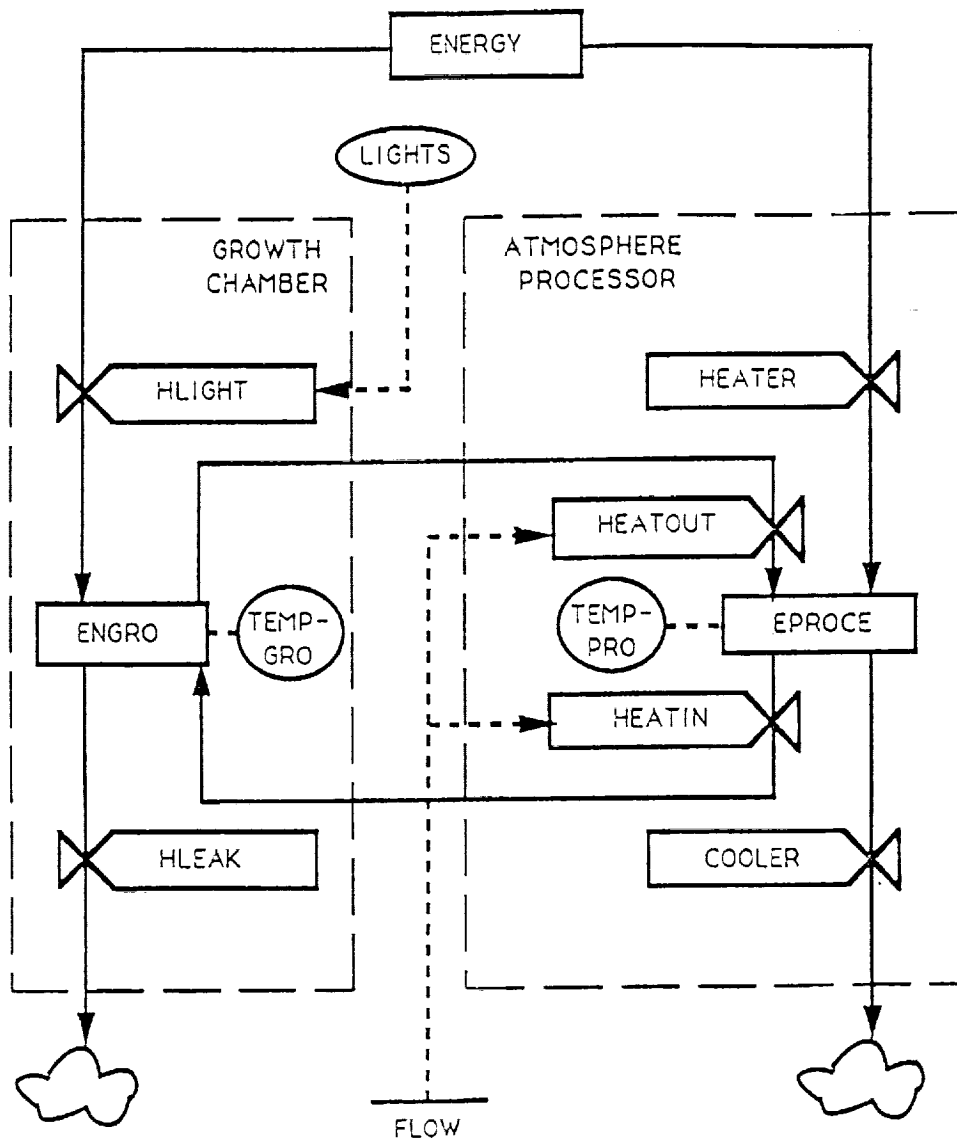
Figure 3. Plant Chamber Energy Model.

CONTROL LOOP OPERATIONS

The process of designing a controller for the CLLSS simulation was rather intuitive. Again, the initial system response criteria involved the maintenance of various levels within specified ranges. The most logical way of effecting this type of control was to design a series of controllers. Each controller would add to or subtract from a specific level when that level exceeded its acceptable range.

This controller was designed in the simulation language DYNAMO, thus confining the design to the limits of the syntax of the language. In DYNAMO, a "clip" statement proved to be very useful in the design of the additive-subtractive controller. The clip statement appears as follows:

$$RATE=CLIP(W, X, Y, Z).$$

This is interpreted as: When Y is greater than or equal to Z, let RATE equal W or else RATE equals X. Clipping at the lower bound of a range may be achieved by negating Y and Z or by setting W equal to zero. The variable RATE represents a rate into or out of the level Y. RATE was designed to represent a rate of operation of a piece of control equipment such as an air processor or a pump. Similarly, the clip equation also serves as a simulation of a sensor. It "senses" the present value of level Y when the computer checks to see if Y is greater than or equal to Z.

The additive-subtractive control is achieved by setting W equal to a constant and X equal to zero. Thus when Y is greater than or equal to Z, the clip equation "turns on" and RATE is equal

4.15

to the constant W. This rate is used in evaluating the new value
of the level Y. This use of the clip equation simulates the
operation of a constant speed motor such as a water pump.

If it is assumed that variable speed equipment will be used,
then a conditional negative feedback loop may be employed (Fig.
4). This loop also uses the clip equation, but with a subtle
difference. Instead of letting W equal a constant, W is assigned
the value of a percentage of the output level. (Example: $W=k*Y$,
where $0<=k<=1$).

TRANSP $\quad$ + $\quad$ H2OATM $\quad$ $\dfrac{1}{S}$ $\quad$ H2OATM

K
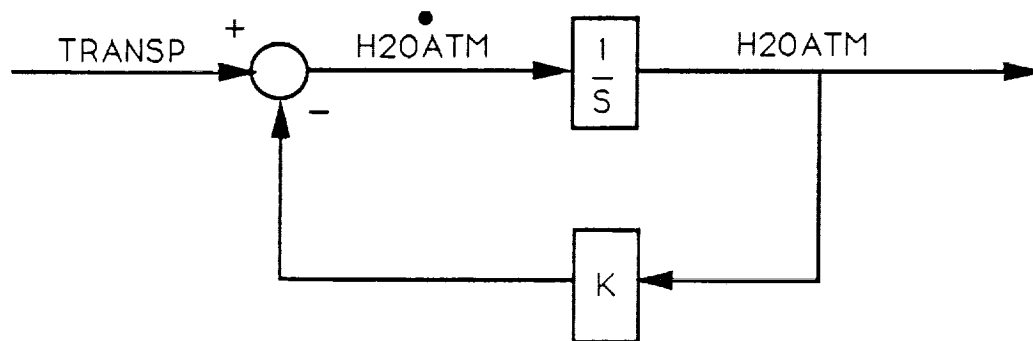
Figure 4. Negative Feedback Example.

4.16

In this example, a humidity equation from the model is used to demonstrate feedback. The equation appears in the form:

H2OATM.K=H2OATM.J+DT*(TRANSP.JK+CHUMID.JK-CDEHUM.JK).

In this equation, H2OATM is the level (Y) and CHUMID.JK and CDEHUM.JK represent the feedback ($\pm kY$). CHUMID.JK is equal to -k*H2OATM and CDEHUM.JK is equal to k*H2OATM. Thus, as the humidity changes, the rate of humidification or dehumidification is adjusted accordingly.

This control, however, does not yet increase the stability of the system. The simulation still remains in constant oscillation within the appropriate boundaries. The choice of the feedback constant k will increase or decrease the number of oscillations in a given period of time, but will not cause the system to stabilize about a designated value. In order to stabilize the system, a form of PID (Proportional-Integral-Derivative) controller must be implemented. This controller is the subject of present research.

4.17

EXPERIMENTS

CONTROL PARAMETER VARIATION

Once the plant model reached an advanced stage, experimentation with control parameters was possible. First, an appropriate range was chosen to be ± 0.01 times the initial value of the level. This meant that the controller would start operation when the level moved out of this designated range. Next, the simulation was run with various values of the feedback constant. These values ranged from 0.1, which appeared to be too small, to 0.4 which appeared to cause radical changes.

In addition, the simulation was run with a provision for turning the system lighting on and off, imitating a standard day. The results of the simulation with lights on were compared to those with the lights off. This comparison also provided an extra check on the model equations, since many parameters of the simulation should decrease markedly when the lights are turned off.

4.18

RESULTS

OVERALL SYSTEM BEHAVIOR

MASS MODEL

As the feedback constants were varied, the response of the mass model was visually evaluated. Regardless of the feedback constants the system would continually oscillate. An attempt was made to find a constant which would generate the fewest oscillations per unit time. The constant also needed to cause the values of the level to fluctuate somewhat uniformly about the set point (initial level value).

After much trial and error, the approximate "best" value for the feedback constant, k, appeared to be 0.3. This constant provided the least volatile system response of all the values tested. If too small a constant was chosen, the level would merely oscillate slightly about the high or low end of its range. Conversely, if too large a constant was chosen, one process would overcompensate to the extent of initiating the reverse process. As an example, the controller would dehumidify the air so much that it would need to be rehumidified to maintain the humidity within the designated range.

In addition, it was determined that the plant model was operating correctly due to the tendency of the system to almost "shut down" during the lights-off period.

ENERGY MODEL

The energy input level to the entire energy system increases linearly with time, indicating relatively smooth system behavior. The temperature of the growth chamber, using a simplified control system, remains between 16°C and 28°C. This is close to the setpoint temperature of 23°C.

Currently, the energy leakage from the growth chamber was set at 2% of the total growth chamber energy. Based on the system response this assumption appeared to be reasonable. The energy and temperature of the atmosphere processing system is not as stable as those of the growth chamber. The temperature fluctuates over a wider temperature range, indicating that more work and research is needed in this area. Some of the fluctuation may be due to mass flows in other parts of the system since the energy level of the atmosphere processor is dependent on them. Considering the limitations of the energy model, the response of the mass model to the energy model is acceptable.

SENSING AND CONTROL NEEDS

By varying the control parameters of the simulation, it was possible to determine which state variables were the most sensitive to parameter changes. The variables which were least sensitive were only slightly affected by variations of the feedback constant.

CRITICAL SENSING/CONTROL NEEDS

The most critical variable to sense and control proved to be humidity because it varies in magnitude more quickly than any other variable. Humidity needs to be sensed continuously and controlled frequently, if not constantly.

NONCRITICAL SENSING/CONTROL NEEDS

Of less critical importance is the level of CO_2 in the chamber. This level causes variations in the transpiration rate of the plants and requires periodic sensing and control. The O_2 level tends to vary even less than that of the CO_2 level. With a range of 9400 ± 94 moles, O_2 does not require control over periods of time less than a day. Similarly, the nutrient solution level changes very slowly requiring less frequent sensing and control.

CONCLUSIONS

PROJECT SUMMARY

The simulation of a closed plant growth chamber that has been developed serves many purposes. By comparing the results of the uncontrolled and controlled simulations, the sensing and control needs of a plant growth system may be evaluated and prioritized.

FURTHER RESEARCH

PLANT PHYSIOLOGY

In order to model the physiology of the plants in the chamber many simplifying assumptions had to be made. The most important aspects of each physiological rate are kept as variables, while other less significant factors are kept constant. In order to improve the accuracy of the results of the simulation, fewer assumptions concerning the constants in the plant physiology equations should be made.

ENERGY SPECIFICS

The energy loop in the simulation may be improved by better defining the mass contained in the system, because the total energy in the system is dependent on the specific heats of the equipment in the chamber. In addition some of the defined constants in the simulation should be redefined as variables. Heat leakage, heat due to lighting, and chamber heating and cooling rates are

currently defined as constant rates. To improve the results of the simulation, each of these rates should be dependent upon the chamber environment rather than be considered as constants.

ADVANCED CONTROL TECHNIQUES

Further research will be initiated in the areas of advanced control system design and the application of PID control to the present simulation. The compatibility of this type of control with the restrictions of the DYNAMO language will be evaluated.

4.23

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APPENDICES

APPENDIX A

<u>PHOTOSYNTHESIS</u>

PHOTOS = ((D*LFMAX)/K)*ln[(((1-M)LFMAX + QE*K*PPFD)/((1-M)*LFMAX
         + QE*K*PPFD*EXP(-K*LAI)))]/1440

```
        =   gCH2O/m**2 minute
D       =   converts micromoles (CO2/m**2 sec) to (gCH2O/m**2 day)
K       =   light extinction coefficient
LAI     =   leaf area index (leaf area/floor area)
LFMAX   =   maximum leaf photosynthesis (micromoles/m**2 sec)
        =   TAU*CO2 concentration
M       =   light extinction coefficient
PHOTOS  =   photosynthesis (gCH2O/m**2 day)
PPFD    =   photon flux density (micromoles/m**2 day)
QE      =   leaf quantum efficiency (micromoles CO2 fixed/micromoles
            photon)
TAU     =   (micromoles CO2/m**2 sec vpm CO2)
```


<u>RESPIRATION</u>

```
RESPIR  =   (1-E)*PHOTOS - MRESP
        =   gCH2O/(m**2 minute)
MRESP   =   Q10^(.1*(TEMPGR-2.0))*(R*WPLT))/1440
Q10     =   temperature sensitivity (dimensionless)
R       =   respiration requirements
WPLT    =   plant weight grams/m**2
TEMPGR  =   temperature in growth chamber (degrees celsius)
```

<u>TRANSPIRATION</u>

```
TRANSP  =   (PHOTOS - RESPIR)/WUE
        =   gH2O/m**2 minute
WUE     =   1.6*C*(PA)/DELP
        =   water use efficiency(mass accumul./H2O transpired)
PA      =   partial pressure CO2 (atms)
DELP    =   saturation vapor pressure minus vapor pressure
            at leaf temperature (atms)
```

The Following Pages Contain the Documented Code

For Both the Uncontrolled and the

Controlled Simulations.

```
*              SIMULATION OF PLANT AND ENERGY WITHOUT CONTROL
*
*MASS FLOW********************************************************************
*-----------------------------CHAMBER CONSTANTS------------------------------
C   AREAGR=1000            m**2              area of growth chamber
N   VOLGR=AREAGR*1.5       m**3              volume of growth chamber
N   ATMGR=VOLGR*MATMM3     moles             moles of atmosphere
P   MATMM3=44.6            moles/m**3        moles of atmosphere per m**3
P   PATM=1.0               atm               atmospheric pressure
A   A1.K=PA.K*0
A   A2.K=PA.K*0
A   A3.K=PA.K*0
*----------------------------------------------------------------------------
*                    WATER LOOP
*----------------------------------------------------------------------------

L   H2ONUT.K=H2ONUT.J+DT*(-TRANSP.JK)
N   H2ONUT=IH2ONT          grams             grams water in nutrient system,
N   IH2ONT=AREAGR*GWM2     grams             nutrient resevoir and atmosphere
C   GWM2=5000              g/m**2            grams of nutrient solution/m**2

*--------------TRANSPIRATION--------------------
R   TRANSP.KL=MAX((CH2O.KL/WUE.K),0)
*                          g H2O/min         transpiration
A   WUE.K=1.6*C*(PA.K)/(DELP.K)
*                          unitless          water use efficiency
C   C=.5
A   PA.K=(CO2GR.K/ATMGR)*PATM   atm          partial pressure of CO2
*                                            at leaf temperature
*------------H2O IN ATMOSPHERE-----------------
L   H2OATM.K=H2OATM.J+DT*(TRANSP.JK)
*                          grams             H2O in atmosphere
N   H2OATM=IH2OAT          grams             initial H2O in atmosphere
N   IH2OAT=VOLGR*MH2OM3    grams
C   MH2OM3=18.02           grams/m**3
*
*---------------------- HUMIDITY AUXILARY ------------------------------------
A   TR.K=(1.8*TEMGRO.K+32)+459.7
*                          deg R             temperature conversion
A   PS.K=(.0886)*EXP(19.85*(491.7/TR.K)**.125*(1-491.7/TR.K))
*                          unitless          saturation pressure
A   PHI.K=MAX(MIN(W.K*P/(PS.K*(W.K+.622)),1),0)
*                          lb/in**2          saturation ratio
A   PV.K=PHI.K*PS.K        lb/in**2
A   PERSAT.K=PHI.K*100     %                 percent saturation
C   P=14.696               lbs/in**2         pressure
A   DELP.K=MAX(((PS.K-PV.K)/14.696),.000001)
*                          atm               vapor pressure deficit
A   W.K=(H2OATM.K)/(VOLGR*MATMM3*29)
*                          g H2O vapor/g atmosphere
*
*----------------------------------------------------------------------------
*      ATMOSPHERE
*----------------------------------------------------------------------------
*
*-----------------------PHOTOSYNTHESIS---------------------------------------
*
A   PHOTOS.K=MAX(((((D*LFMAX.K))*LOGN(((1-M)*LFMAX.K+QE*K*PPFD.K)/((1-M)*^
    LFMAX.K+QE*K*EXP(LAI*(-K)))))*AREAGR/1440),0)
*              gCH20/min                     photosynthesis
*                                            1440 converts days to minutes
```

```
*                    umol/m**2-sec                    maximum leaf photosynthesis
C   TAU=.0693        umol/m**2 sec vpm CO2
C   D=2.593                                           conversion micromolesCO2/m**2 sec
*                                                     to gCO2/m**2 day
C   K=.58                                             light extinction coefficient
C   QE=.056                                           leaf quantum efficiency
C   M=.1                                              light extinction coefficient
C   LAI=4.5          leaf area/floor area             leaf area index
A   PPFD.K=1350*LIGHTS.KL
*                    umol/m**2-s                      photosynthetic flux density
R   LIGHTS.KL=PULSE(1,400,0,700)                      lights on/off
*
*--------PLANT MASS ACCUMULATION---------
*
R   CH2O.KL=PHOTOS.K-RESPIR.K        g CH2O/min  rate of accumulation
L   PMASS.K=PMASS.J+DT*(CH2O.JK)     g CH2O      total plant mass accumulated
N   PMASS=IPMASS
N   IPMASS=0.0
*
*--------------RESPIRATION--------------
*
A   RESPIR.K=((1-E)*PHOTOS.K+MRESP.K)
A   MRESP.K=((Q10**(.1*(TEMGRO.K-2.0))*(R*WPLT))/1440)*AREAGR
C   R=.01                                             respiration requirements
C   WPLT=500                 g/m**3                   volumetric plant mass
C   E=.9                                              grams tissue/g CH2O
C   Q10=1.4                  unitless                 temperature sensitivity
*
*-------CARBON DIOXIDE IN CHAMBER--------
*
R   PHTCO2.KL=(PHOTOS.K/D)*.08640                     mol/min CO2
R   RSPCO2.KL=(RESPIR.K/D)*.08640                     mol/min CO2
L   CO2GR.K=(CO2GR.J+DT*(RSPCO2.JK-PHTCO2.JK))
N   CO2GR=ICO2GR             mol                      initial CO2 in atmosphere
N   ICO2GR=VOLGR*MCO2M3
A   CO2GRO.K=CO2GR.K*44.0    grams                    CO2 in growth chamber
C   MCO2M3=.04               mol/m**3                 moles CO2/m**3
*
*---------OXYGEN IN CHAMBER-------------
*
R   PHTO2.KL=(PHOTOS.K/D)*.08640                      moles O2/min into chamber
R   RSPO2.KL=(RESPIR.K/D)*.08640                      moles O2/min used
L   O2GR.K=O2GR.J+DT*(PHTO2.JK-RSPO2.JK)
N   O2GR=IO2GR              moles                     initial O2 in atmosphere
N   IO2GR=VOLGR*MO2M3
A   O2GRO.K=O2GR.K*32.0     grams                     O2 in atmosphere
C   MO2M3=9.4               moles                     moles O2/m**3
*
*------------------------------------------------------------------------

SAVE TRANSP,H2OATM,H2ONUT,PHOTOS,RESPIR,CH2O,CO2GR,O2GR,LIGHTS
SPEC DT=1/LENGTH=1000/SAVEPER=10/SAVPER=10
SAVE ENERGY,ENGRO,TEMGRO,HLIGHT,HLEAK
*      ,EPROCE,TEMPRO,HEATER,RAHEAT,^
*      COOLER,RACOOL,HEAOUT,RCOOL,HEATIN


*------------------------------------------------------------------------
* Energy Flow *****************************************************************

L   ENERGY.K=ENERGY.J+DT*(-HLIGHT.JK)
N   ENERGY=IENERG
```

4.28

```
L    ENGRO.K=ENGRO.J+DT*(HLIGHT.JK-HLEAK.JK)
N    ENGRO=IENGRO
N    IENGRO=(2000*1000*25)              initial PGU energy in J (KG*GM*TEMGRO.K)

NOTE Growth Chamber Energy
A    TEMGRO.K=(ENGRO.K)/SPHEAT.K
A    SPHEAT.K=((ATMGR*30*1.005)+(H2OATM.K*18.02*1.0)^
     +(MPLANT*1.0)+(MOTHER*1.5))       PGU temperature from specific heats of the
*                                       atmosphere, water vapor, plants, and "other"
N    MPLANT=AREAGR*3                     plant mass in kg from growth area
C    MOTHER=1000                         other mass in kg


R    HLIGHT.KL=EFFIC*INTES*LIGHTS.KL*AREAGR HEAT IN(EFFICIENCY*INTENSITY*ON/OFF)
C    EFFIC=.4                            %heat generation from lights
C    INTES=9000                          intensity of lights in J/m**2

R    HLEAK.KL=LOSS*ENGRO.K               heat loss out of PGU
C    LOSS=.02                            10% loss through walls of chamber

*------------------------------------------------------------------------
```

C-2   4.29

```
*       SIMULATION OF PLANT AND ENERGY LOOPS WITH CONTROL
*
*MASS FLOW*****************************************************************
*--------------------------------CHAMBER CONSTANTS---------------------------------
C   AREAGR=1000              m**2              area of growth chamber
N   VOLGR=AREAGR*1.5         m**3              volume of growth chamber
N   ATMGR=VOLGR*MATMM3       moles             moles of atmosphere
P   MATMM3=44.6              moles/m**3        moles of atmosphere per m**3
P   PATM=1.0                 atm               atmospheric pressure


*--------------------------------------------------------------------------------
*                        WATER LOOP
*--------------------------------------------------------------------------------


L   H2ONUT.K=H2ONUT.J+DT*(CH2OIN.JK-TRANSP.JK)
N   H2ONUT=IH2ONT            grams             grams water in nutrient system,
N   IH2ONT=AREAGR*GWM2       grams             nutrient resevoir and atmosphere
C   GWM2=5000                g/m**2            grams of nutrient solution/m**2
A   A1.K=PA.K*0
A   A2.K=PA.K*0
A   A3.K=PA.K*0
*-----------TRANSPIRATION-------------------
R   TRANSP.KL=MAX((CH2O.KL/WUE.K),0)
*                            g H2O/min         transpiration
A   WUE.K=1.6*C*(PA.K)/(DELP.K)
*                            unitless          water use efficiency
C   C=.5
A   PA.K=(CO2GR.K/ATMGR)*PATM   atm            partial pressure of CO2
*                                              at leaf temperature
*-----------H2O IN ATMOSPHERE---------------
L   H2OATM.K=H2OATM.J+DT*(TRANSP.JK+CHUMID.JK-CDEHUM.JK)
*                            grams             H2O in atmosphere
N   H2OATM=IH2OAT            grams             initial H2O in atmosphere
N   IH2OAT=VOLGR*MH2OM3      grams
C   MH2OM3=18.02             grams/m**3
*
*---------------------- HUMIDITY AUXILARY --------------------------------
A   TR.K=(1.8*TEMGRO.K+32)+459.7
*                            deg R             temperature conversion
A   PS.K=(.0886)*EXP(19.85*(491.7/TR.K)**.125*(1-491.7/TR.K))
*                            unitless          saturation pressure
A   PHI.K=MAX(MIN(W.K*P/(PS.K*(W.K+.622)),1),0)
*                            lb/in**2          saturation ratio
A   PV.K=PHI.K*PS.K          lb/in**2
A   PERSAT.K=PHI.K*100       %                 percent saturation
C   P=14.696                 lbs/in**2         pressure
A   DELP.K=MAX(((PS.K-PV.K)/14.696),.000001)
*                            atm               vapor pressure deficit
A   W.K=(H2OATM.K)/(VOLGR*MATMM3*29)
*                            g H2O vapor/g atmosphere
*
*========================= WATER CONTROL ================================
*
R   CDEHUM.KL=CLIP(RTOH2O.K,0,H2OATM.K,HUMHGH)   rate H2O out air >HUMHGH
R   CH2OUT.KL=CLIP(RTNUTO.K,0,H2ONUT.K,H2OHGH)   subtract soln. if >H2OHGH
R   CHUMID.KL=CLIP(RTIH2O.K,0,-H2OATM.K,-HUMLOW) rate H2O in air if <HUMLOW
R   CH2OIN.KL=CLIP(RTNUTI.K,0,-H2ONUT.K,-H2OLOW) add'l soln. if <H2OLOW
N   HUMHGH=IH2OAT+(.01*IH2OAT)   grams
N   HUMLOW=IH2OAT-(.01*IH2OAT)   grams
N   H2OHGH=IH2ONT+(.01*IH2ONT)   grams
N   H2OLOW=IH2ONT-(.01*IH2ONT)   grams
```

```
A    RTIH2O.K=KATM*(H2OATM.K)        g/min
A    RTNUTO.K=KNUT*(H2ONUT.K)        g/min
A    RTNUTI.K=KNUT*(H2ONUT.K)        g/min
C    KATM=.0175                     unitless    feedback constant for H2OATM level
C    KNUT=.0175                     unitless    feedback constant for H2ONUT level
L    H2OSTO.K=H2OSTO.J+DT*(CDEHUM.JK-CH2OIN.JK+CH2OUT.JK-CHUMID.JK)
*                                   grams       water storage (control) level
N    H2OSTO=IH2OST
N    IH2OST=18020000                grams       (1000 liters)
*
*-----------------------------------------------------------------------
*    ATMOSPHERE
*-----------------------------------------------------------------------
*
*-----------------------PHOTOSYNTHESIS-----------------------------------
*
A    PHOTOS.K=MAX(((((D*LFMAX.K))*LOGN(((1-M)*LFMAX.K+QE*K*PPFD.K)/((1-M)*^
     LFMAX.K+QE*K*EXP(LAI*(-K)))))*AREAGR/1440),0)
*               gCH2O/min                       photosynthesis
*                                               1440 converts days to minutes
A    LFMAX.K=TAU*(CO2GR.K/(44.6*VOLGR))*100000
*               umol/m**2-sec                   maximum leaf photosynthesis
C    TAU=.0693       umol/m**2 sec vpm CO2
C    D=2.593                                     conversion micromolesCO2/m**2 sec
*                                                to gCO2/m**2 day
C    K=.58                                       light extinction coefficient
C    QE=.056                                     leaf quantum efficiency
C    M=.1                                        light extinction coefficient
C    LAI=4.5         leaf area/floor area        leaf area index
A    PPFD.K=1350*LIGHTS.KL
*               umol/m**2-s                      photosynthetic flux density
R    LIGHTS.KL=PULSE(1,400,0,700)               lights on/off
*
*-------PLANT MASS ACCUMULATION---------
*
R    CH2O.KL=PHOTOS.K-RESPIR.K        g CH2O/min  rate of accumulation
L    PMASS.K=PMASS.J+DT*(CH2O.JK)     g CH2O      total plant mass accumulated
N    PMASS=IPMASS
N    IPMASS=0.0
*
*---------------RESPIRATION--------------
*
A    RESPIR.K=((1-E)*PHOTOS.K+MRESP.K)
A    MRESP.K=((Q10**(.1*(TEMGRO.K-2.0)))*(R*WPLT))/1440)*AREAGR
C    R=.01                                       respiration requirements
C    WPLT=500                g/m**3              volumetric plant mass
C    E=.9                                        grams tissue/g CH2O
C    Q10=1.4                 unitless            temperature sensitivity
*
*-------CARBON DIOXIDE IN CHAMBER--------
*
R    PHTCO2.KL=(PHOTOS.K/D)*.08640              mol/min CO2
R    RSPCO2.KL=(RESPIR.K/D)*.08640              mol/min CO2
L    CO2GR.K=(CO2GR.J+DT*(RSPCO2.JK-PHTCO2.JK+CINCO2.JK-COTCO2.JK))
N    CO2GR=ICO2GR            mol                 initial CO2 in atmosphere
N    ICO2GR=VOLGR*MCO2M3
A    CO2GRO.K=CO2GR.K*44.0   grams               CO2 in growth chamber
C    MCO2M3=.04              mol/m**3            moles CO2/m**3
*
*----------OXYGEN IN CHAMBER-------------
*
```

4.31

```
R   RSPO2.KL=(RESPIR.K/D)*.08640              moles O2/min used
L   O2GR.K=O2GR.J+DT*(PHTO2.JK-RSPO2.JK+CINO2.JK-COUTO2.JK)
N   O2GR=IO2GR              moles              initial O2 in atmosphere
N   IO2GR=VOLGR*MO2M3
A   O2GRO.K=O2GR.K*32.0     grams              O2 in atmosphere
C   MO2M3=9.4               moles              moles O2/m**3
*
*==========================ATMOSPHERE CONTROL================================
*
*------CARBON DIOXIDE---------
R   COTCO2.KL=CLIP(CRATEO.K,0,CO2GR.K,CO2HGH)   CO2 out of chamber if >CO2HGH
R   CINCO2.KL=CLIP(CRATEI.K,0,-CO2GR.K,-CO2LOW) CO2 into chamber if <CO2LOW
L   CO2STO.K=CO2STO.J+DT*(COTCO2.JK-CINCO2.JK)  storage (control) level
N   CO2STO=ICO2ST
C   ICO2ST=100000          moles              initial CO2 in storage
N   CO2HGH=ICO2GR+(.01*ICO2GR)
N   CO2LOW=ICO2GR-(.01*ICO2GR)
A   CRATEO.K=KCO2*CO2GR.K       mol/min        rate CO2 out of chamber
A   CRATEI.K=KCO2*CO2GR.K       mol/min        rate CO2 into chamber
C   KCO2=.0175                             feedback constant for CO2GR level
*
*------OXYGEN---------------
R   COUTO2.KL=CLIP(ORATEO.K,0,O2GR.K,O2HIGH)   O2 out of chamber if >O2HIGH
R   CINO2.KL=CLIP(ORATEI.K,0,-O2GR.K,-O2LOW)   O2 into chamber if <O2LOW
L   O2STO.K=O2STO.J+DT*(COUTO2.JK-CINO2.JK)
N   O2STO=IO2STO
C   IO2STO=1000              moles
N   O2HIGH=IO2GR+(.01*IO2GR)
N   O2LOW=IO2GR-(.01*IO2GR)
A   ORATEO.K=KO2*O2GR.K     moles/min      RATE O2 OUT CHAMBER IF >O2HIGH moles
A   ORATEI.K=KO2*O2GR.K     moles/min      RATE O2 INTO CHAMBER IF <O2LOW moles
C   KO2=.0175               feedback constant for O2GR level


*------------------------------------------------------------------------

SAVE TRANSP,H2OATM,CDEHUM,CHUMID,H2ONUT,CH2OIN,CH2OUT,PHOTOS,^
     RESPIR,CH2O,CO2STO,CO2GR,CINCO2,COTCO2,O2STO,O2GR,CINO2,^
     COUTO2,H2OSTO,LIGHTS,A1,A2,A3
SPEC DT=1/LENGTH=1000/SAVEPER=10/SAVPER=10
SAVE ENERGY,ENGRO,TEMGRO,HLIGHT,HLEAK,EPROCE,TEMPRO,HEATER,RAHEAT,^
     COOLER,RACOOL,HEAOUT,RCOOL,HEATIN


*------------------------------------------------------------------------
* Energy Flow *******************************************************

L   ENERGY.K=ENERGY.J+DT*(-HLIGHT.JK-HEATER.JK)
N   ENERGY=IENERG
N   IENERG=0

L   ENGRO.K=ENGRO.J+DT*(HLIGHT.JK+HEATIN.JK-HEAOUT.JK-HLEAK.JK)
N   ENGRO=IENGRO
C   IENGRO=50e6   (2000*1000*25)        initial PGU energy in J (KG*GM*TEMGRO.K)

NOTE Growth Chamber Energy
A   TEMGRO.K=(ENGRO.K)/SPHEAT.K
A   SPHEAT.K=((ATMGR*30*1.005)+(H2OATM.K*18.02*1.0)^
    +(MPLANT*1.0)+(MOTHER*1.5))       PGU temperature from specific heats of the
*                                     atmosphere, water vapor, plants, and "other"
N   MPLANT=AREAGR*3                   plant mass in kg from growth area
C   MOTHER=1000                       other mass in kg
```

4.32

```
R   HLIGHT.KL=EFFIC*INTES*LIGHTS.KL*AREAGR HEAT IN(EFFICIENCY*INTENSITY*ON/OFF)
C   EFFIC=.4                                %heat generation from lights
C   INTES=9000                              intensity of lights in J/m**2

R   HLEAK.KL=LOSS*ENGRO.K           heat loss out of PGU
C   LOSS=.02                        10% loss through walls of chamber

L   EPROCE.K=EPROCE.J+DT*(HEAOUT.JK+HEATER.JK-COOLER.JK-HEATIN.JK)
N   EPROCE=IEPROC
C   IEPROC=2.5e6     (100*1000*25)   initial processor energy in J
*                                    (mass*grams/kg*TEMGRO.K)

A   TEMPRO.K=(EPROCE.K)/(1000*1000*1.4)   (mass*grams/kg/specific heat)

R   HEATER.KL=CLIP(0,RAHEAT.K,TEMPRO.K,22)
A   RAHEAT.K=(JHM3*VOLGR)           heat addition/ m**3 minute (processor)
C   JHM3=5000                       joules added/ m**3 minute
*
R   COOLER.KL=CLIP(RACOOL.K,0,TEMPRO.K,24)
A   RACOOL.K=(JCM3*VOLGR)           heat removal/ m**3 minute (processor)
C   JCM3=5000                       joules subtracted/ m**3 minute
*
R   HEAOUT.KL=CLIP(RCOOL.K,0,TEMGRO.K,25)
A   RCOOL.K=(JHOM3*VOLGR)           heat removal/ m**3 minute (chamber)
C   JHOM3=7000

R   HEATIN.KL=CLIP(0,RHEAT.K,TEMGRO.K,22)
A   RHEAT.K=(JHIM3*VOLGR)           heat addition/ m**3 minute (chamber)
C   JHIM3=7000

*-------------------------------------------------------------------------
```

APPENDIX C

Figure 5. Uncontrolled (top) and controlled examples (bottom)
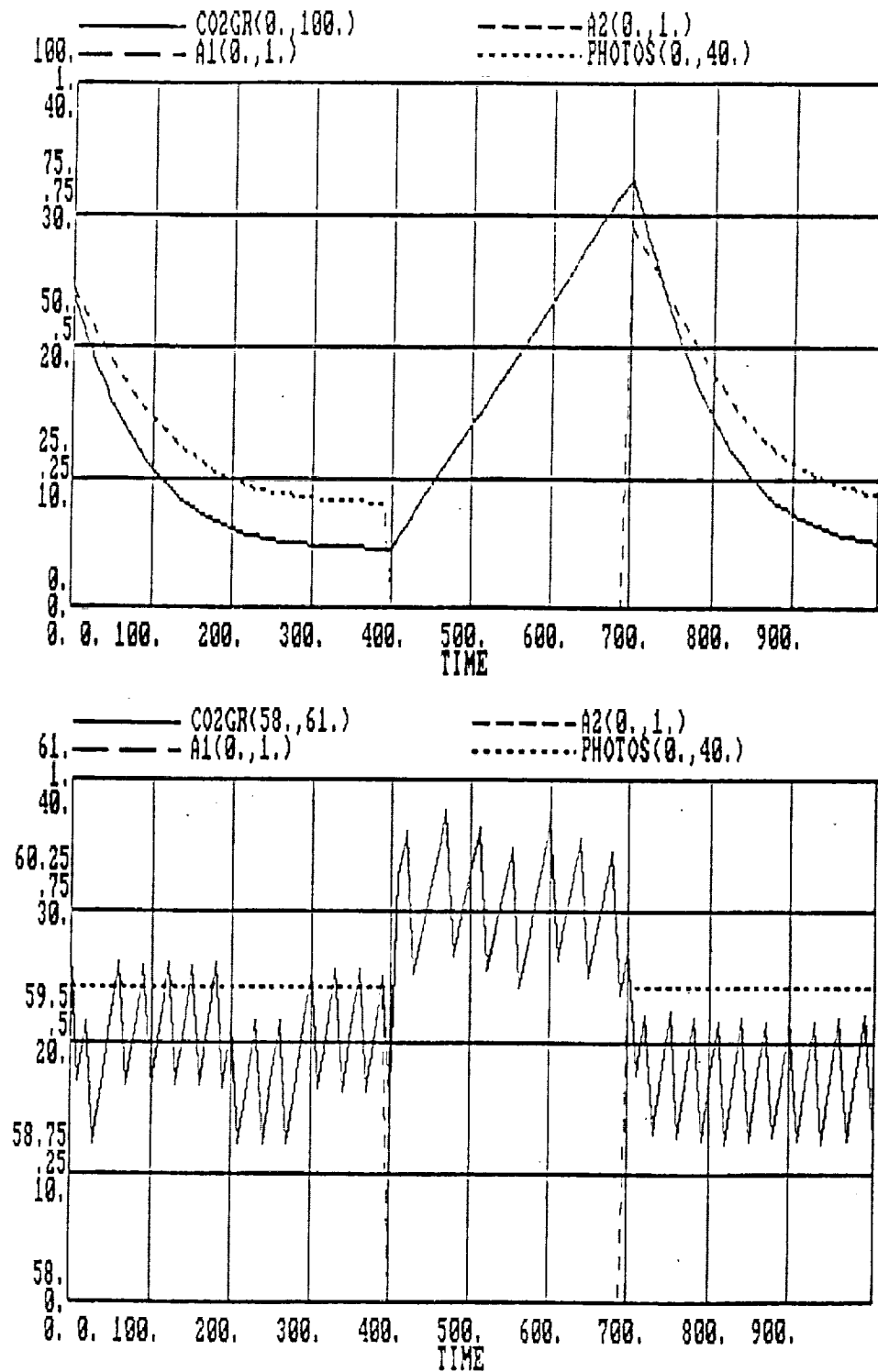examples of system behavior

Figure 6.   Uncontrolled (top) and controlled examples (bottom)
examples of system behavior

CONCLUSION

This paper encompasses the research and design accomlishments of the Spring 1989 Design class at the University of Florida. These projects establish a good foundation in addressing the needs encountered in a CLLSS. Although none of the designs are final prototypes, the theories behind them provide avenues for actual, future designs to be used in a prototype CLLSS.