DESIGN OF A LETTUCE PRODUCTION SYSTEM

USING NUTRIENT FILM TECHNIQUE

by

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ABSTRACT

Considering the significant amount of lettuce imported in the winter season, year round domestic lettuce production could benefit the Canadian economy and consumer. Nutrient Film Technique (NFT) lends itself well to intensive lettuce production. Lettuce is cropped in various configurations, using NFT throughout Europe and Great Britain. A system maximizing lettuce production, given the constraints and characteristics of protected cropping in Quebec was designed. The economics of the system indicate the break-even cost to be $0.89 per plant. This value can easily be reduced by automation or increased labor productivity.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

In 1982 the total value of lettuce imported to Canada exceeded $83 million, while domestic production was valued at $12.9 million (Statistics Canada 1982, 1983). The Canadian consumer is thus at the mercy of the variations and whims of a foreign industry. The product offered is selected on the basis of its shipping characteristics. Its price, a function of transportation cost, is directly proportional to the cost of fuel oil.

Year round domestic production of lettuce might therefore benefit the Canadian consummer. A higher quality, fresher product would be marketed with the benefits of the industry remaining in the country.

The objective of this study was to design a lettuce production system capable of operating throughout the winter season. The system was based on hydroponic production. The system's economics were also considered.

LITERATURE REVIEW

2.1 Hydroponics

Hydroponics, the growing of plants without soil, has developed as a result of plant nutrition experiments. Scientific records date back to the seventeeth century. Historically, records of soilless culture exist from the time of the Aztecs of Mexico, the hanging gardens of Babylon, and the ancient Chinese and Egyptians. The term hydroponics and its use were popularized in the 1930s by Dr W.F. Gericke. The term hydroponics is derived from two Greek words "hydro" meaning water and "ponos" meaning work.

There are various techniques to deliver the nutrient solution to the growing plants. For this project the nutrient film technique (NFT) was considered.

2.1.1 Nutrient Film Technique

NFT cropping was pionneered by Dr Allen Cooper at the Glasshouse Crops Research Institute in England, in the early 1960s. By the early 1970s NFT was being commercially adopted.

The basic principle of NFT is the recirculation of a shallow stream of nutrient solution over the bare roots of growing plants to provide adequate water, nutrients and aeration. The term film in the name stresses the requirement for a shallow flow.Cooper (1979) list the key requirements to achieve an NFT situation as:

a) the gradient causing the flow of the nutrient solution must be uniform with no localised depressions,

b) the inlet flow rate must not be too great, to keep the depth of flow at an acceptable level,

c) the width of the channel in which the roots are confined must be large enough to avoid damming up of the solution by the root mat,

d) the base of the channel must be flat.

NFT cropping presents several advantages over conventional crop production. Uniformity of nutrient supply is insured, while nutrient concentration can be modified to suit requirements of various growth stages. The root environment can be precisely controlled. Watering is no longer a concern. Rapid turn around between sucessive crops can be achieved.High planting densities are possible. Finally the technique lends itself well to automation.

The disavantages of NFT are the high capital cost of the initial installation, the expertise required by the operator, and the possibilty of disease transmission.

2.2 System Components

The various components of a cropping system based on NFT are considered here. Their limitations, characteristics and configurations described in the literature are reviewed. These considerations will then be used in the design process.

The components of an NFT system and its inputs are shown in Figure 1. The key component of the system is the nutrient solution. A means of conveying the solution to the plants is then required, as well as a plant support mechanism. Furthermoree the environment and solution must be maintained to optimize growth.

2.2.1 Nutrient Solution

The nutrient solution forms the root environment which is regulated for maximum production. The pH, conductivity, temperature and oxygen content must be maintained at optimum levels.

Graves (1983) list the optimum solution pH for salad crops at 6 with tolerance limits to pH 5 and 7. Cooper (1979) states that the pH should be maintained between 6 and 6.5 at all times. Nitric acid, phosphoric acid and potassium hydroxide are generally used to regulate pH.

The nutrient solution is made up by dissolving fertilizer salts in water to supply the essential nutritive elements to the crop. By monitoring the electrical conductivity of the solution an estimate of the total salt concentration is obtained. This is not very practical when the concentration of a specific element must be determined. One technique developed to use conductivity monitoring is to add nutrients to the solution in the same ratio as they are removed by the crop. Thus by maintaining a constant

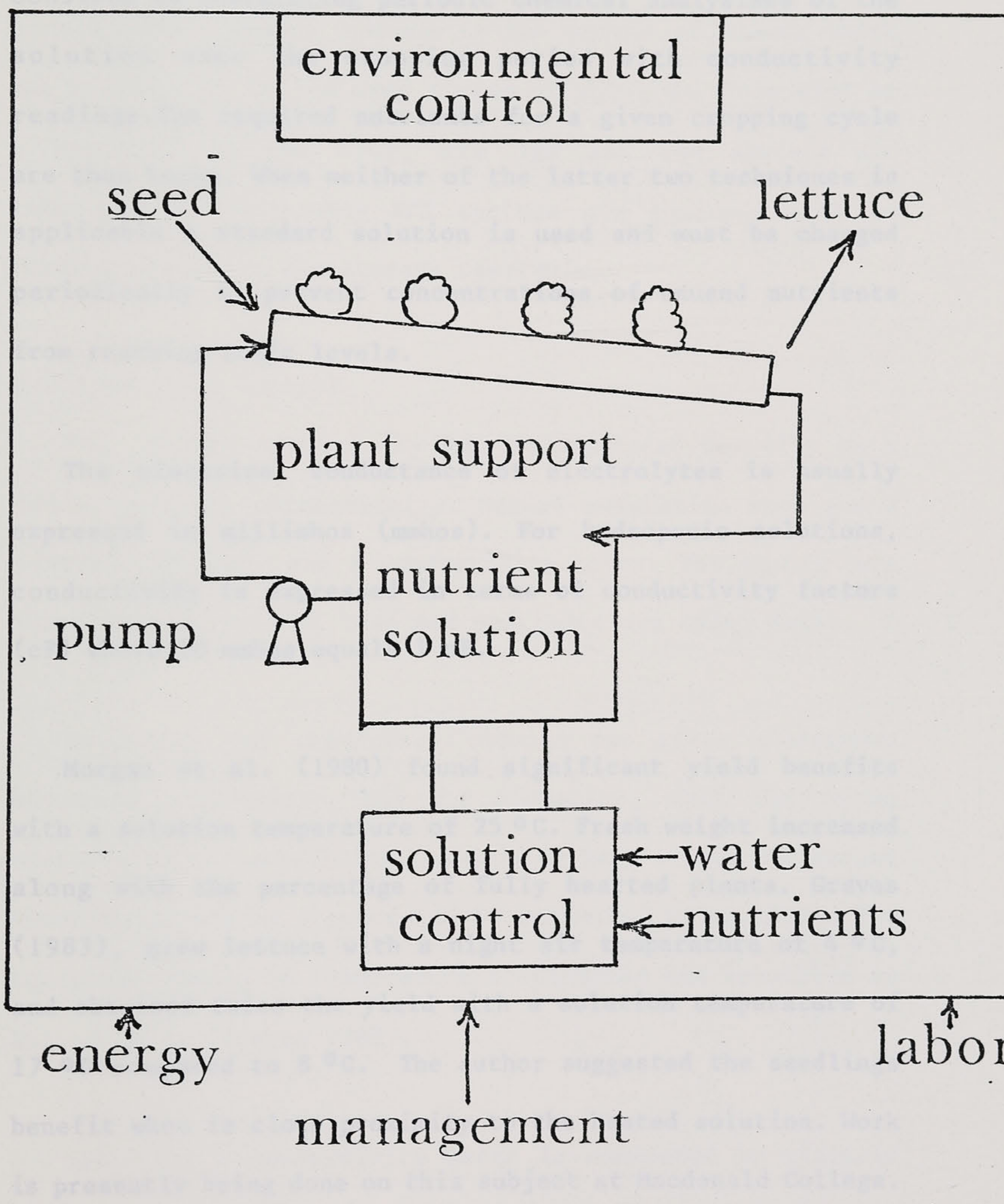

Figure 1: NFT Cropping System

conductivity a proper nutrient balance is obtained. Varley and Burrage (1981) have developed such a solution for lettuce. A second technique using conductivity monitoring consists of correlating periodic chemical analysises of the solution over the cropping period with conductivity readings.The required nutrients for a given cropping cycle are thus known. When neither of the latter two techniques is applicable a standard solution is used and must be changed periodically to prevent concentrations of unused nutrients from reaching toxic levels.

The electrical conductance of electrolytes is usually expressed in millimhos (mmhos). For hydroponic solutions, conductivity is expressed in terms of conductivity factors (cF) where 10 mmhos equals 1 cF.

Morgan et al. (1980) found significant yield benefits with a solution temperature of 25 °C. Fresh weight increased along with the percentage of fully hearted plants. Graves (1983), grew lettuce with a night air temperature of 4 °C, and obtained twice the yield with a solution temperature of 17 °C compared to 8 °C. The author suggested the seedlings benefit when in close proximity to the heated solution. Work is presently being done on this subject at Macdonald College.

Submerged roots may not have sufficient oxygen, which is relatively insoluble in water. However the roots in an NFT system are not totally submerged, and the shallow flowing solution permits oxygen diffusion through it. Thus a good part of the crop oxygen requirement can be met. Jackson (1980) states that when the solution is aerated while passing through the system it can act as a source of oxygen for the plants. What remains unknown is the number of plants which can be subjected to the same stream of solution. This will be a function of the crop, its age and the ambient air temperature. Generally NFT systems are equipped with an aerator placed in the storage reservoir.

2.2.2 Solution Control

The pH and conductivity may be regulated manually on a daily basis or automatically. Manual regulation requires a portable pH meter and a conductivity meter. The appropriate quantities of acid or base and nutrients are added daily.

Automatic pH regulators require two glass electrodes situated separately, one for operation, connected to an electric valve controlling the acid or base input. The second electrode serves as a guard and is connected to an alarm. The equipment should be temperature compensated and sensitive to 0.2 pH units (Graves 1983).

Similarly a conductivity meter is connected to electric valves controlling the addition of two nutrient stock solutions. One solution contains calcium nitrate alone while the other is made up of the balance of nutrients. This prevents the precipitation of the sparingly soluble calcium salts. The meter should be accurate to 50 mmhos for a range of 0-5000 mmhos (Graves 1983).

2.2.3 Support and Configuration

Cooper (1979) described the characteristics of a universal NFT channel. The channel is illustrated in Figure 2. The base is 23 cm wide, the edges are angled at 30 such that the height of the channel is less than 7 cm. This channel is designed to be used on any surface or support and is covered with reflective foil to prevent excessive heating of the solution in areas with intense sunlight. Spensely et al. (1978) suggest small root systems may require only a 75 mm gully width.

Cooper (1979) recommends a minimum slope of 1 in 100 and puts no limit on the maximum. Graves (1983) reports that slopes between 1 in 50 and 1 in 75 are adequate for most purposes, while the maximum gully length beyond which nutrients become limiting is 20 m. This can be compensated for by introducing nutrient solution at different points along the gully.

Morgan and Tan (1983) developed an archway configuration for lettuce production at densities of 40 plants/m^2. Plastic pipe supporting the plants are arranged in horizontal tiers on an arch framework. The structure is 280 cm wide at the base and 230 cm high. This system is designed for a 3.2 m span quonset geenhouse in a north-south

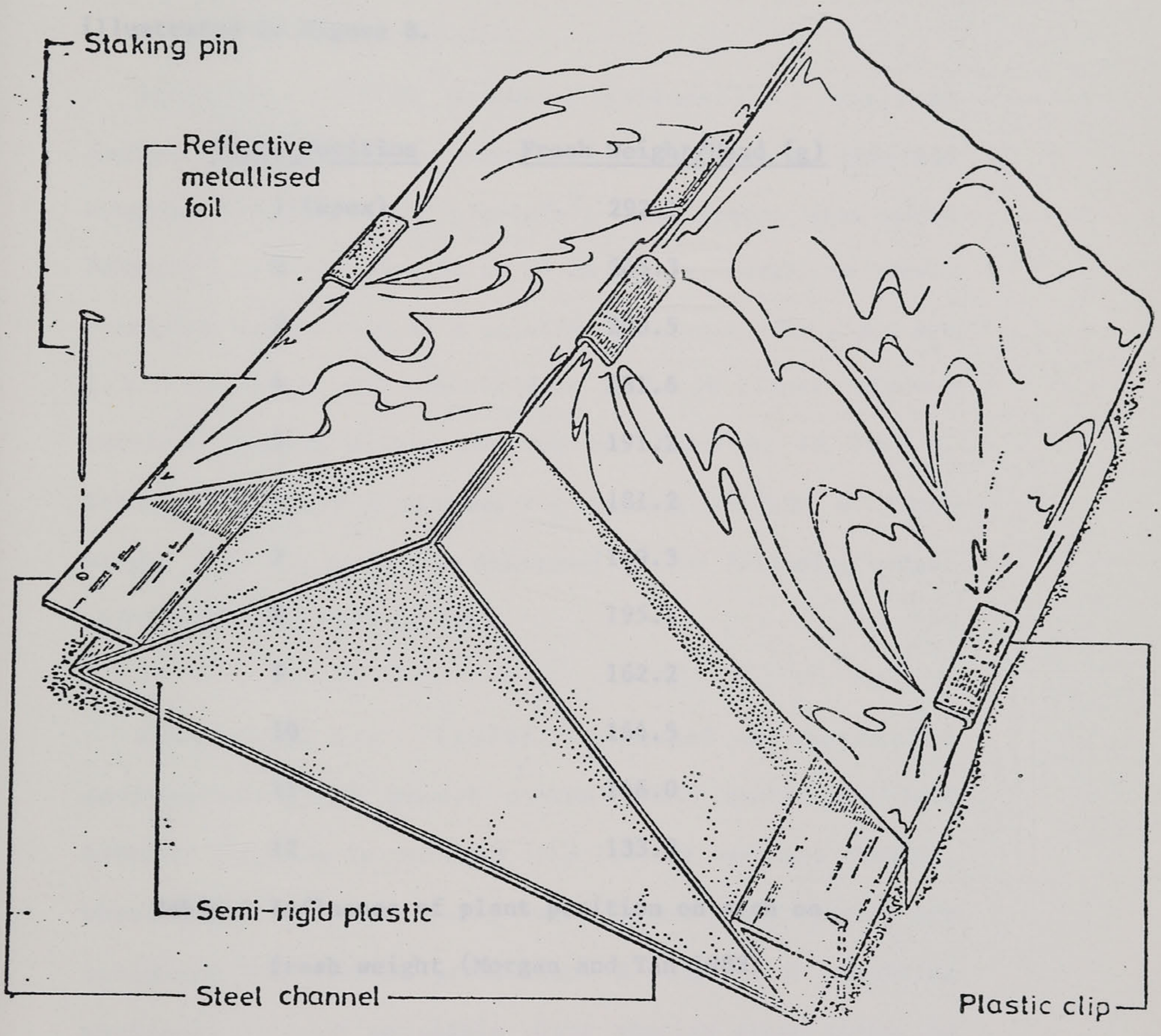

Figure 2: Universal NFT Channel (Cooper 1979)

orientation. The pipes are 30 mm in diameter with 20 mm diameter holes drilled every 20 cm. Fresh weight per head decreased from the apex to the base, as illustrated in Table 1.A similar configuration is used in this study and illustrated in Figure 8.

Plant Position	Fresh Weight/Head (g)
1 (apex)	292.1
2	245.3
3	200.5
4	181.6
5	191.2
6	181.2
7	169.3
8	195.1
9	162.2
10	164.5
11	146.0
12	133.0

Table 1 Influence of plant position on arch on fresh weight (Morgan and Tan 1983)

Len Dingeman, a commercial grower in England produces lettuce in concrete gullies 10 cm wide and 2.5 cm deep, running the length of 45 m sloping bays. The concrete is painted with epoxy resin to isolate it from the nutrient solution. The 4 hectare, greenhouse covered, operation produces 8 million lettuce plants per year (Graves 1983).

Varley and Burrage (1981) produced lettuce between expanded polystyrene sheets. A bottom sheet is covered with polyethylene to carry the solution. The top sheet supports the plants. A cropping density of 24 plants/m^2 was used.

Schippers (1978) produced lettuce in a vertical configuration. The author conservatively estimated a possible cropping density of 36 plants/m^2. This system uses white Polyvinyl chloride pipe 50 to 75 mm square, suspended over a receiving bassin used as a solution reservoir. The pipes are 1.5 m in length and contain from 20 to 28 plants. Minimum required spacing within the row was found to be 0.61 m. Schippers suggest a minimum row spacing of 0.91 m. Fresh weight from top to bottom decreased in the following order: 157-154-147-133 -125 g/plant.

Prince et al. (1976) developed a controlled environment plant growth system (CEPG) system for leaf lettuce. The crop is produced in a totally enclosed chamber, where ligthing, temperature, humidity and plant spacing are optimized for maximum production. A slip joint advancing mechanism is used to obtain plant spacing proportional to plant growth. Five separate beams were slip joint connected, with properly spaced pins that engaged each end of the plant support racks. A gear type rack and pinion located on each side of the shelf drove the spacing mechanism. The spacing beams extend to advance the plant support rack. After spacing the extended beams are lowered by the height drive

(Prince, R. P. and Bartok, J. W. 1978). The system is reproduced in Figure 3. Yields of 117 kg/m^2 year were obtained while yields of 342/m^2 year were anticipated. The production cost are summarized in Table 2 along with the cost of more traditional systems.

System	Price($/kg)
Field grown California head lettuce delivered to eastern markets (USA)	0.44-0.51
Greenhouse grown leaf lettuce	0.55-0.62
CEPG leaf lettuce	0.55-0.84
Hybrid unit (CEPG-Greenhouse) leaf lettuce	0.35-0.44

Table 2 Production costs of leaf lettuce (Prince et al. 1976)

2.2.4 Solution Conveyance

To provide the appropriate circulation of nutrient solution through the crop, a pumping system and solution reservoir are required. The system must be fail-safe and non-phytoxic.

Circulation failure could be disastrous with an NFT crop. The root mat can retain some water after failure. The time interval before the crop is damaged, will depend on the crop and the environmental conditions. Cooper (1979) thus recommends the installation of an alarm system, with the sensor in the return or flow pipes with a stand-by pump to be used in an emergency and a third pump in reserve for repair periods. The system may also be connected to a separate

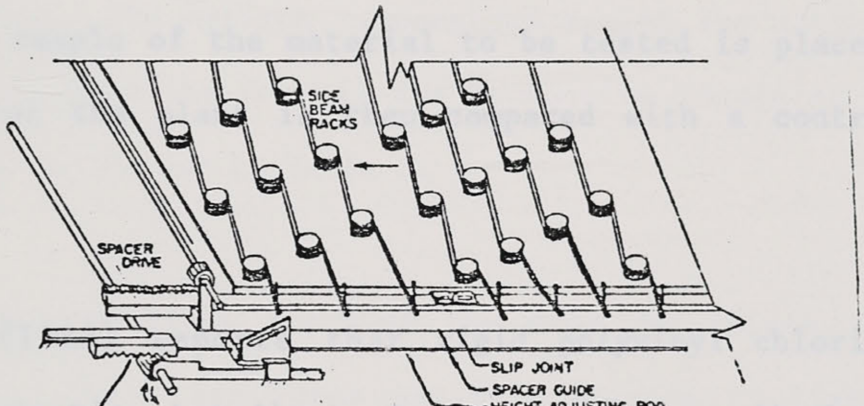

Figure 3: Automated Spacing Mechanism
(Prince, R.P., Bartok, J.W. Jr. 1978)

water supply by means of a float valve.

The materials used in an NFT system must be non-phytotoxic. Phytotoxicity can range from very severe when the plants are killed, to mild when the growth rate is merely reduced. Cooper (1979) suggests a simple test for phytotoxicity; a seedling is grown in a hydroponic solution in which a sample of the material to be tested is placed. The growth of the plant is then compared with a control plant.

Graves (1983) reports that rigid polyvinyl chloride (PVC), acrylnolite butadiene styrene (ABS), or alkathene plastics are satisfactory materials. Cooper (1979) and Graves (1983) indicate that plasticizers used to produce flexible PVC are phytotoxic. Metals releasing trace elements in the presence of the corrosive nutrient solution may cause toxic concentrations to be built up. Examples are copper and galvanised piping the latter to be avoided for the zinc it can release. Graves (1983) recommends that all pipework valves and fittings be made of plastic. Pumps generally used in NFT systems are stainless steel or plastic bodied. Epoxy resins sealing concrete must be allowed to dry thoroughly.

Commercial NFT installations, commonly use concrete catchment tanks sealed with an epoxy resin. Fiberglass is also acceptable. The tank capacity represents 10 to 15 percent of the total volume of solution in the system, the remainder being in the gullies (Graves 1983).

2.2.5 Environmental Control

Year round production of lettuce in a temperate climate requires a means of providing a controlled environment. This section deals with the control of the atmospheric environment. This includes temperature, light, humidity, and carbon dioxide. The optimum temperature regime for lettuce production given by the Conseil des Production Vegetales du Quebec (CPVQ) is listed in Table 3.

The amount of light reaching the crop determines its growth rate. There are three possible sources of light. Natural sunlight, as provided with a greenhouse, artificial lighting, as used in a CEPG system and a combination of the two sources where artificial lighting supplements natural sunlight in a greenhouse. The results of Prince et al. (1976) listed in Table 2 suggest a hybrid system is most economical. This system however, uses artificial lighting only for seedling establishment while the greenhouse holds the growing crop.

Vegetative Level	Temperature(°C) day	night	Ventilation Beyond(°C)
up to gound coverage	12-15	10	16
from coverage to hearting	12-15	6	16
from hearting to harvest	10-12	3	12

Table 3 Temperature regime for lettuce (CPVQ 1983)

When selecting an artificial light source its spectral characteristics and the crop requirements must be taken into consideration. Generally photosynthesis response peaks in the red and blue regions of the spectrum (Aldrich 1983). Prince et al. (1976) found it more efficient to study the response of lettuce to the light source itself rather than match the source's spectrum to the spectral requirements. This resulted in the selection of the Agro-Lite fluorescent lamp developed by Westinghouse over high intensity discharge lamps. Stewart (1980) lists the lighting requirements of lettuce as 12000 lux while Wittwer and Honna (1979) report that good growth can be obtained with as low as 5000 lux.

The control of the moisture content of the air is critical. Condensation on the interior of the greenhouse structure can cause water droplets to fall on the crop and promote disease. This condition is also uncomfortable for labor. Aldrich (1983) list a secondary effect of high relative humidity. Fungal pathogenic organisms which do not germinate at a relative humidity lower than 95%. Prince et al. operated their CEPG system at 80% relative humidity. The

CPVQ recommendation for germinating lettuce is 80% to 90% relative humidity.

Through the process of photosynthesis, carbon dioxide, which enters the plant through the stomata in the leaves, is converted into carbohydrates, an energy and material source for cellular growth. The typical atmospheric concentration of carbon dioxide is about 350 ppm. Productivity can be raised by increasing the carbon dioxide concentration of the atmosphere. Wittwer (1970) reports lettuce producing greater yields with accelerated maturity due to carbon dioxide enrichment of the atmosphere. Stewart (personal communication) recommends concentrations of 700 ppm for winter conditions and 1200 ppm for summer conditions.

Carbon dioxide can be obtained in various forms and sources: liquified under pressure in bottles, as dry ice, from the combustion of sulfur free gaseous and liquid fuels (Bailey et al. 1970). Concentration may be monitored by photochemical sensors, electrochemical sensors or infrared radiation absorption. Photochemical monitoring is the cheapest and simplest method of measuring carbon dioxide concentration. A gas sample is pumped through an indicator solution which can be monitored photoelectrically. Electrochemical measurement involves pumping the sample through deioniozed water such that the change in conductivity is proportional to the concentration of carbon dioxide in the air. Infrared absorption works on the principle that the carbon dioxide molecule absorbs energy in the infra-red region of the spectrum. A standard zero column of gas is compared with the sample by passing identical infra-red beams through them.(Bailey et al. 1970)

Therefore an environmental control system for lettuce production must supply heat, remove heat, and maintain optimum concentrations of moisture and carbon dioxide in the atmosphere.

DESIGN

3.1 Design Objective

The lettuce production system will be optimized given the constraints of the inputs characteristics. Referring to Figure 1 the major input variable will be energy for heating. Labor must also be considered carefully. The remaining inputs, such as seed, nutrients,water and seedling support are a relatively fixed function of the crop output. Therefore optimizing lettuce production in this case implies maximizing production with respect to energy and labor.

3.1.1 Design Characteristics

The system should have the following characteristics:

* relatively low capital cost,
* easily expandable,
* easily retrofited for automation.

3.2 Environmental Control Design

The configuration of the NFT system must be adapted to the greenhouse. Thus the environmental control system is considered first.

3.2.1 Geenhouse Selection

Greenhouse structures vary in shape and material. Possible shapes found in Quebec are the A frame, quonset, gothic and the Brace design. These are illustrated in Figure 4.

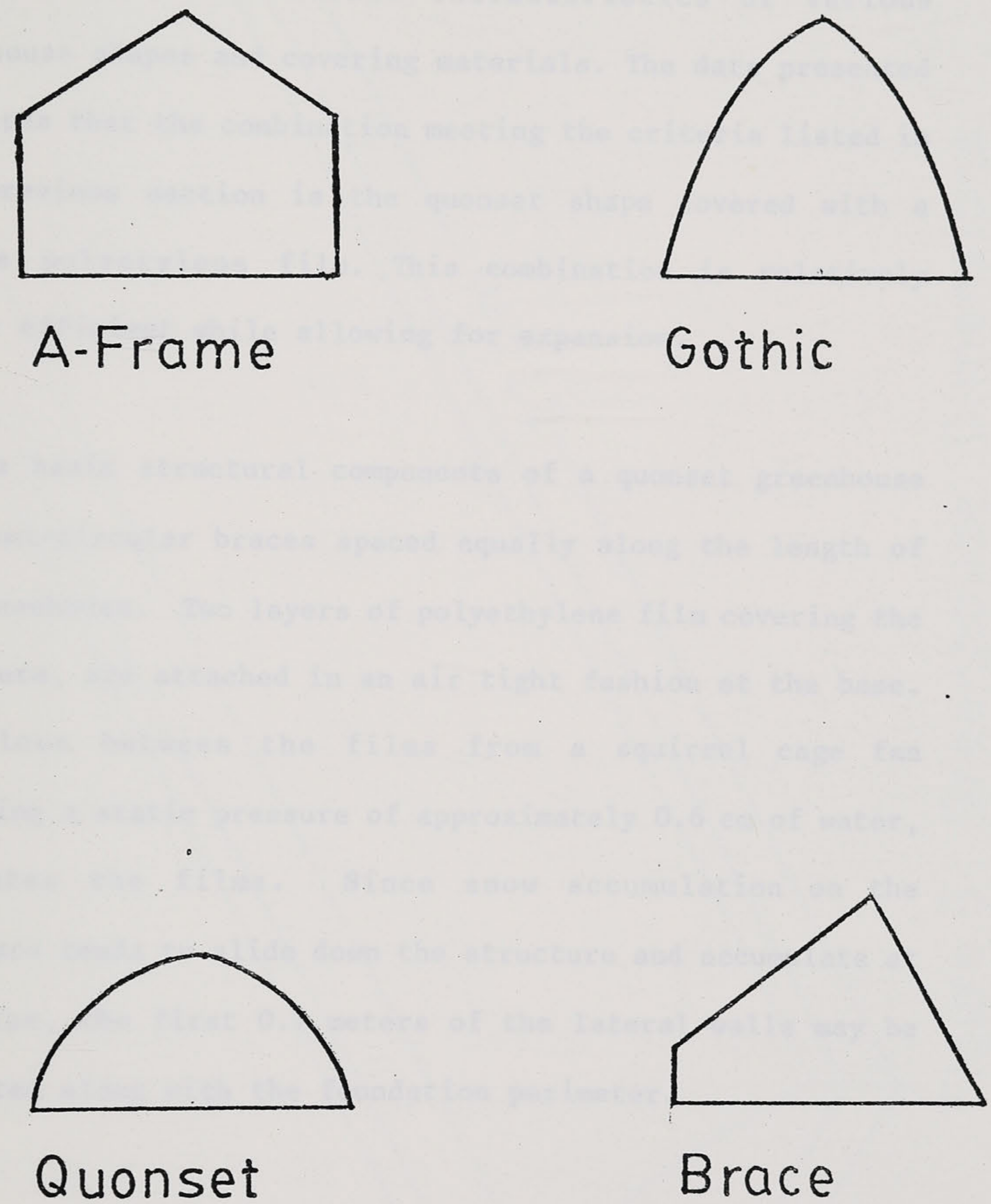

Figure 4: Greenhouse Shapes

The materials used to cover the structures are generally glass, fiberglass, or polyethylene film. The structure or frame may be made of wood or metal. Tables 4 and 5 summarize the different characteristics of various greenhouse shapes and covering materials. The data presented indicates that the combination meeting the criteria listed in the previous section is the quonset shape covered with a double polyetylene film. This combination is relatively energy efficient while allowing for expansion.

The basic structural components of a quonset greenhouse are semi-circular braces spaced equally along the length of the greenhouse. Two layers of polyethylene film covering the structure, are attached in an air tight fashion at the base. Air blown between the films from a squirrel cage fan supplying a static pressure of approximately 0.6 cm of water, separates the films. Since snow accumulation on the structure tends to slide down the structure and accumulate at the base, the first 0.7 meters of the lateral walls may be insulated along with the foundation perimeter.

Quonset greenhouses are presently commercially available. They are designed for Canadian climate wind and snow loads. For the purpose of this study a "Superlight" greenhouse marketed by Ball Superior was considered. Its shape and dimensions are given in Figure 5.

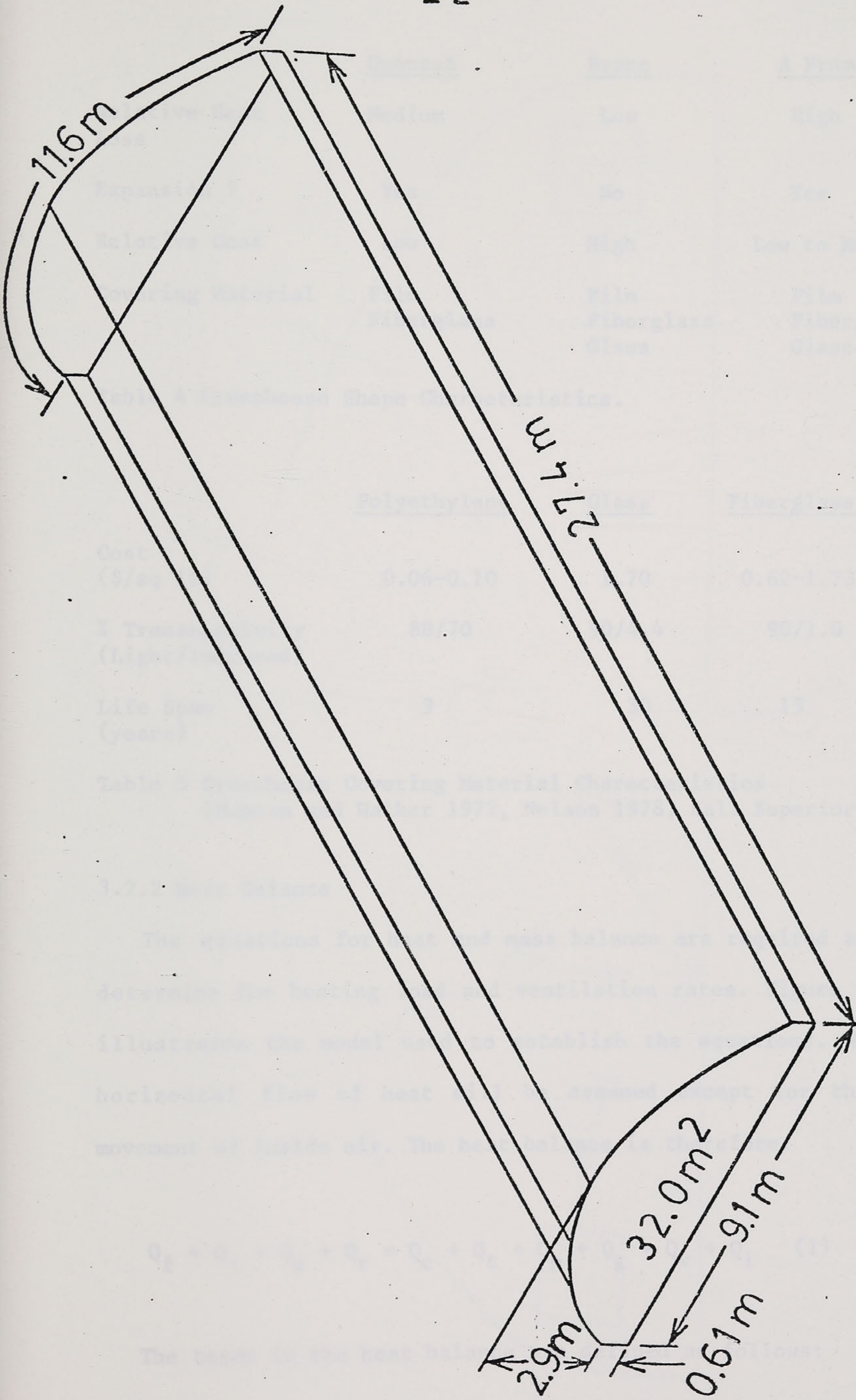

Figure 5 : Greenhouse Dimensions

	Quonset	Brace	A Frame
Relative Heat Loss	Medium	Low	High
Expansion ?	Yes	No	Yes
Relative Cost	Low	High	Low to Medium
Covering Material	Film Fiberglass	Film Fiberglass Glass	Film Fiberglass Glass

Table 4 Greenhouse Shape Characteristics.

	Polyethylene	Glass	Fiberglass
Cost ($/sq ft)	0.06-0.10	1.70	0.62-1.23
% Transmissivity (Light/Infrared)	88/70	90/4.4	90/1.0
Life Span (years)	3	30	15

Table 5 Greenhouse Covering Material Characteristics
(Duncan and Walker 1972, Nelson 1978, Ball Superior 1984)

3.2.2 Heat Balance

The equations for heat and mass balance are required to determine the heating load and ventilation rates. Figure 6 illustrates the model used to establish the equations. No horizontal flow of heat will be assumed except for the movement of inside air. The heat balance is therefore:

$$Q_f + Q_i + Q_e + Q_r = Q_c + Q_t + Q_p + Q_g + Q_v + Q_l \quad (1)$$

The terms in the heat balance are defined as follows:

Q_i = Solar heat gain (W) given by:

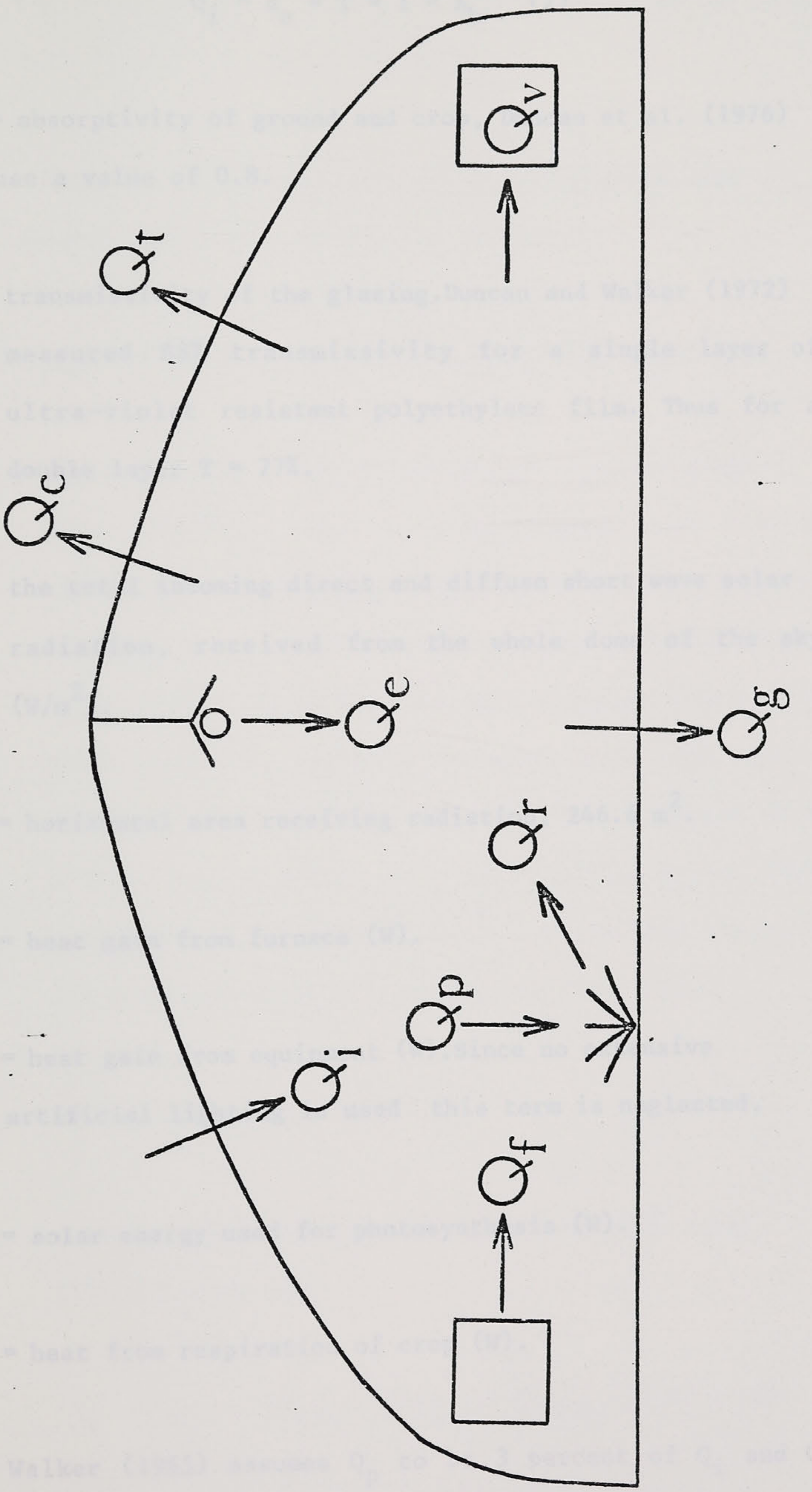

Figure 6: Heat Balance Model

$$Q_i = a_s * T * I * A_h \quad (2)$$

a_s = absorptivity of ground and crop, Duncan et al. (1976) use a value of 0.8.

T = transmissivity of the glazing.Duncan and Walker (1972) measured 88% transmissivity for a single layer of ultra-violet resistant polyethylene film. Thus for a double layer T = 77%.

I = the total incoming direct and diffuse short wave solar radiation, received from the whole dome of the sky (W/m^2).

A_h = horizontal area receiving radiation, 246.6 m^2.

Q_f = heat gain from furnace (W).

Q_e = heat gain from equipment (W).Since no extensive artificial lighting is used this term is neglected.

Q_p = solar energy used for photosynthesis (W).

Q_r = heat from respiration of crop (W).

Walker (1965) assumes Q_p to be 3 percent of Q_i and Q_r to be a fraction of Q_p.Thus these two terms are neglected.

Q_t = thermal radiative losses through the glazing (W). This term is generally included in Q_c.

Q_c = heat lost by conduction through the glazing and through walls and foundation, given by:

$$Q_c = (U_f * A_f + U_w * A_w + U_d * A_d)(T_i - T_o) \quad (3)$$

U_f = overall conductivity of the double layer of plastic film ($W/m^2 °C$). This term is measured such that the conductive and radiative losses are included together. Simpkins et al. (1975) found an overall conductivity of 5.18 $W/m^2 °C$ for an inflated double polyethylene layer. This value is reported to agree with work done by Roberts (1969) who obtained 4.55 $W/m^2 °C$. Duncan et al. (1976) use a value of 3.97 $W/m^2 °C$. Walker (1983) proposes a value of 4.00 $W/m^2 °C$. Given this range, the intermediate value will be used in this study.

A_f = film surface area, 317.8 m^2.

U_w = overall conductivity of the insulated wall areas ($W/m^2 °C$). Given by:

$$U_w = 1/F_o + 1/R_{ext} + 1/R_{ins} + 1/R_{int} + 1/F_i \quad (4)$$

Using data from The Midwest Plan Service Structures and Environment Handbook (1983), U_w may be calculated.

F_o = exterior convective surface resistance, 0.030 $m^2{}^{\circ}C/W$.

R_{ext} = wood siding resistance, 0.143 $m^2{}^{\circ}C/W$.

R_{ins} = insulation resistance, 1.761 $m^2{}^{\circ}C/W$.

R_{int} = plywood resistance, 0.109 $m^2{}^{\circ}C/W$.

F_i = interior convective surface resistance, 0.109 $m^2{}^{\circ}C/W$.

Substituting the above values into (4) U_w becomes 0.017 $W/m^2{}^{\circ}C$.

A_w = insulated wall area, 96.2 m^2.

U_d = overall conductivity of the door, given in the same handbook, as 2.271 $W/m^2{}^{\circ}C$.

A_d = door area, 4.0 m^2.

From these figures it is obvious that with large values of A_f and a relatively large value of U_f, the heat loss terms through the walls, doors and other openings are not significant and may be neglected. The conductive heat loss becomes:

$$Q_c = U_f * A_f * (T_i - T_o) \quad (5)$$

T_i = interior atmospheric temperature (°C).

T_o = outside atmospheric temperature (°C).

Q_v = heat lost by ventilation.Given by:

$$Q_v = Q_s + Q_l \quad (6)$$

Q_s = sensible heat loss (W).Given by:

$$Q_s = m_a * C_p * (T_i - T_o) \quad (7)$$

m_a= mass flow of air, ventilation and infiltration (kg/s).

C_p = specific heat of air, 1011 kJ/kg dry air °C.

Q_l = latent heat loss (W).Given by:

$$Q_l = E * F * Q_i \quad (8)$$

E = ratio of evapotranspiration to solar radiation. Walker (1983) suggests using values of 0.5 to 1, and recommends 0.5 when structural obstructions exist.

F = proportion of greenhouse space in plant production. This term varies from 0.5, for incomplete crop canopies to 1.0 for complete coverage (Walker 1983).

Q_g = heat lost to the ground (W).

Walker (1965) relates the heat loss to the ground to the perimeter and foundation wall. For 0.30 m of perimeter the equivalent heat loss is through 0.09 m^2 of wall area. Thus this loss is small with respect to the loss through the glazing and may be neglected. The heat balance is reduced to:

$$Q_f + Q_s = Q_l + Q_v + Q_c \quad (9)$$

3.2.2 Mass Balance

Taking the moisture generated by evapotranspiration as (kg/s):

$$m_w = Q_l \,/\, L \quad (10)$$

L = latent heat of evaporation of water. Using the operating temperature, from Table 3, at 15 °C, L = 2620 kJ/kg

The mininimum mass flow (kg/s) and volumetric flow rates (m^3/s) of air are thus respectively:

$$m_a = m_w \,/\, (W_i - W_a) \quad (11)$$

$$v_a = m_a / V_a \quad (12)$$

W_i = humidity ratio of the air leaving the greenhouse.Using the operating conditions listed in section 2.2.5, the relative humidity of the air leaving can be assumed at 90%. Therefore W = 0.00096 kg moisture/kg dry air.

W_a = humidity ratio of air entering the greenhouse, this value depends on atmospheric conditions.

V_a = specific volume of air leaving the greenhouse, 0.83 m^3/kg

The infiltration rate should be taken into account at this point. Walker (1983) suggests an air exchange rate of 0.5 exchanges per hour for double layer plastic film greenhouses. However the ventilation load is generally very large with respect of this term and it is neglected.

For summer operation the ventilation requirement is determined by establishing the temperature rise as a function of air exchange rate.

Let the amount of carbon dioxide to be added to the atmosphere be m_c (g/s). Assuming the atmospheric concentration must be maintained at 1000 ppm and is originally at 350 ppm:

$$m_c = 0.75 * m_a + C \quad (13)$$

C = crop consumption of carbon dioxide. Blom and Ingratta indicate this value varies from 0.033 to 0.066 g carbon dioxide per 100 m^2 per second.

Carbon dioxide enrichment is feasible only whith no or little ventilation (Parent 1983). The mass flow of air in this case is taken as the infiltration rate, 0.5 exchanges per hour or 0.15 kg/s.

Assuming natural gas is used to generate carbon dioxide then the volumetric flow (m^3/s) of gas will be, given 1 m^3 of natural gas produces 1600 g of carbon dioxide (Langhans 1983):

$$v_g = m_c / 1600 \quad (14)$$

Substituting the appropriate values in equations (13) and (14) the volumetric flow of natural gas required is 0.00017 m^3 /s. Note that this gas is consummed during periods where there is no ventilation. Since the maximum heat load was determined with ventilation this new energy input does not affect the heat load, or total heat required.

3.2.3 Heat Load

The design temperature for Montreal, given in the ASHRAE Handbook (1977), is -27 ^{o}C, determined from climatic data for the month of January. Maximum solar radiation recorded for the same month is 0. 96 mJ/m^2hour (Environment Canada 1982). Maximum evapotranspiration is assumed (E=1). Substituting equations (2), (5), (7), (8), (10) and (11) into equation (9) and rearranging:

$$Q_f = \frac{(U_f * A_f) + E * F * a_s * A_h * C_p * (T_i - T_o)}{L * (W_i - W_o)} \quad (15)$$

Substituting the appropriate values into equation (15) the heating load is found to be 126 831 W or 432 872 BTU/hour.

3.2.4 Ventilation Load

Since high summer temperatures prevent year round operation the design conditions are based on the climatic data for the month of June, assuming production stops from mid-June to mid-August. The maximum radiation input for June is 2.32 mJ/m^2hour (Environment Canada 1982). With no heating supplied the heat balance becomes:

$$Q_i = Q_1 + Q_s + Q_c \quad (16)$$

In this case consider:

$$Q_s = (N/60) * V_g * C_p * (T_i - T_o) \quad (17)$$

N = number of air exchanges per minute.

V_g = volume of greenhouse, 937.6 m^3.

Substituting equations (2), (5), (8), and (16) into (17) and rearranging:

$$(T_i - T_o) = \frac{(1 - E * F) * a_s * T * I * A_h}{(N/60) * V_g * C_p + U_f * A_f} \quad (18)$$

In this case E is assumed 0.5, due to the high radiation level. Plotting the temperature rise $(T_i - T_o)$ as a function of the exchange rate in Figure 7, indicates the optimum ventilation rate is around one exchange per minute. This is the recommended value in the ASAE Yearbook (1982). One exchange per minute of the volume of air in the greenhouse equals 14.6 m^3/s.

3.2.5 Equipment Selection

To assure an even distribution of heat and adequate recirculation of interior air two unit heaters and a "Fresh Air System" (perforated plastic tubing) are recommended be used. The heaters total capacity must be equal or greater than the heating load, 126 831 W. Duncan (1983) recommends a 0.76 m diameter plastic tube with a 0.76 m diameter fan for adequate recirculation in a 9 m wide greenhouse. The ASAE Yearbook (1982) recommends recirculating 25 to 33 percent of the volume of air in the greenhouse per minute to maintain a uniform temperature distribution. This works out to 3.7 m^3/s. The minimum required ventilation is, using equation (12) with winter design conditions, 3.2 m^3/s.

The staging of the ventilation system can be determined knowing the maximum and minimum ventilation requirements. Table 6 lists the stages recommended by Duncan (1983) and the

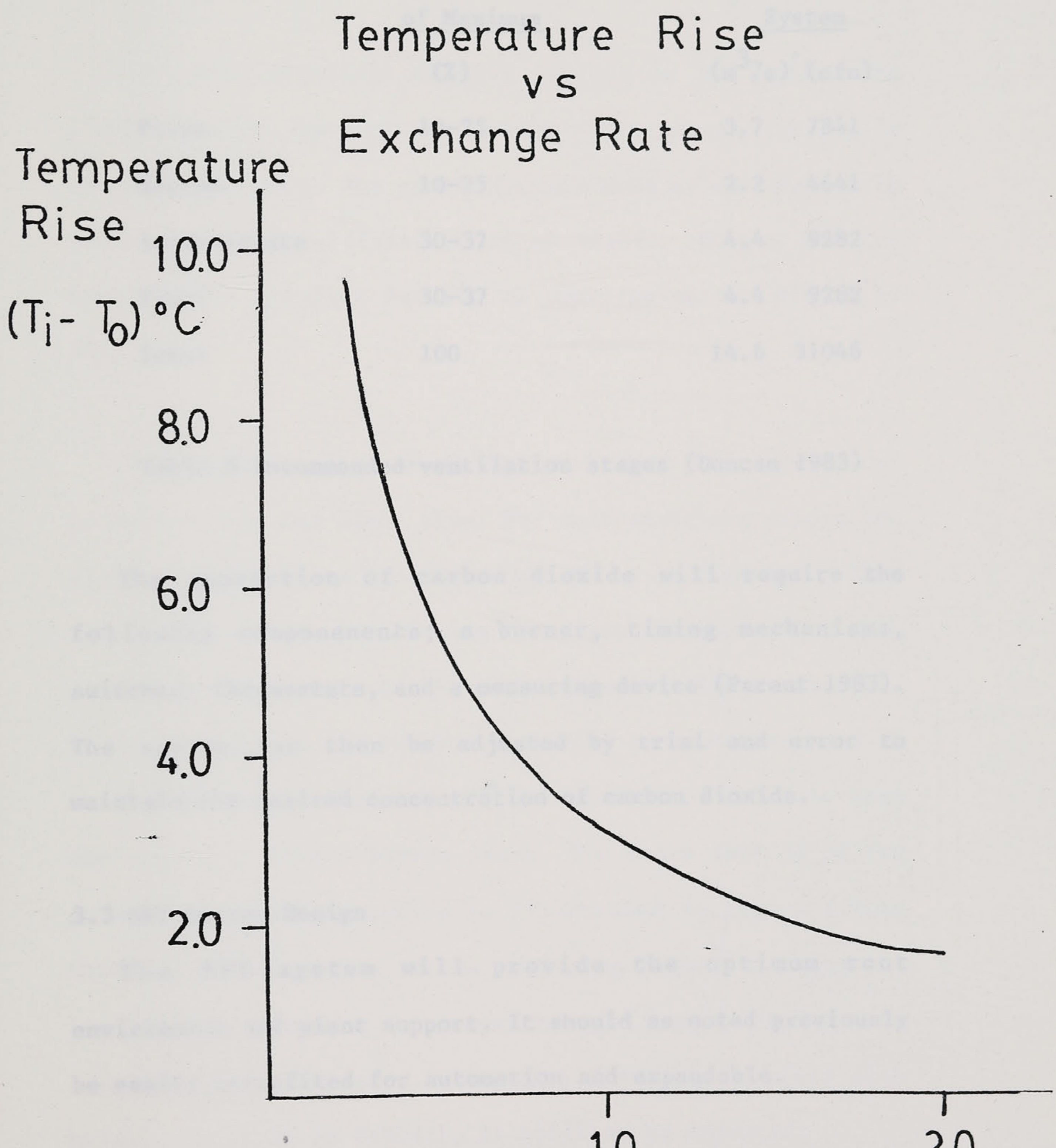
Temperature Rise
vs
Exchange Rate
Temperature
Rise
(Ti - To) °C
10.0
8.0
6.0
4.0
2.0
1.0
2.0
Exchanges
Minute

Figure 7

corresponding stages for this system.

Stage	Recommended Fraction of Maximum (%)	Increment for System (m^3/s)	(cfm)
First	10-25	3.7	7841
Second	10-25	2.2	4641
Intermediate	30-37	4.4	9282
Final	30-37	4.4	9282
Total	100	14.6	31046

Table 6 Recommended ventilation stages (Duncan 1983)

The generation of carbon dioxide will require the following componenents; a burner, timing mechanisms, switches, thermostats, and a measuring device (Parent 1983). The system can then be adjusted by trial and error to maintain the desired concentration of carbon dioxide.

3.3 NFT System Design

The NFT system will provide the optimum root environment and plant support. It should as noted previously be easily retrofited for automation and expandable.

3.3.1 NFT Configuration Selection

To maximize production, a high density configuration must be used. The number of plants per unit volume of greenhouse is considered rather than per unit covered area.

The most suitable configuration, described in the litterature review, for a quonset greenhouse is the arch concept developed by Morgan and Tan (1983).

The basic principle of this concept is to incline the plane on which the crop is growing. The plants overlap in space in this case. The arch structure must be oriented North South for an even distribution of light. Morgan and Tan doubled the cropping density by overlapping the plants by 50%.

The trough spacing along the arch must be proportional to the overlapp and plant size. For this study the plants are assumed to be 15 cm in height and 20 cm in diameter. Thus for a 50% overlap, considering the plant dimensions the arch should form an angle of 56 with respect to the horizontal. To allow access to the arches they will be separated by 0.75 m. The height of the arch will be limited to 2.2 m to keep the uppermost trough within reach. The cross section of the greenhouse with the arches is illustrated in Figure 8.Note that the lower reaches of the arch stop before reaching the ground. This prevents the lowest troughs from suffering from too low light intensity. However a decrease in yield with height, as shown in Table 1, is still to be expected.

3.3.2 Slope and Channel Selection

This section is devoted to the performance of the plant support mechanism. A rectangular channel 60 mm wide and at

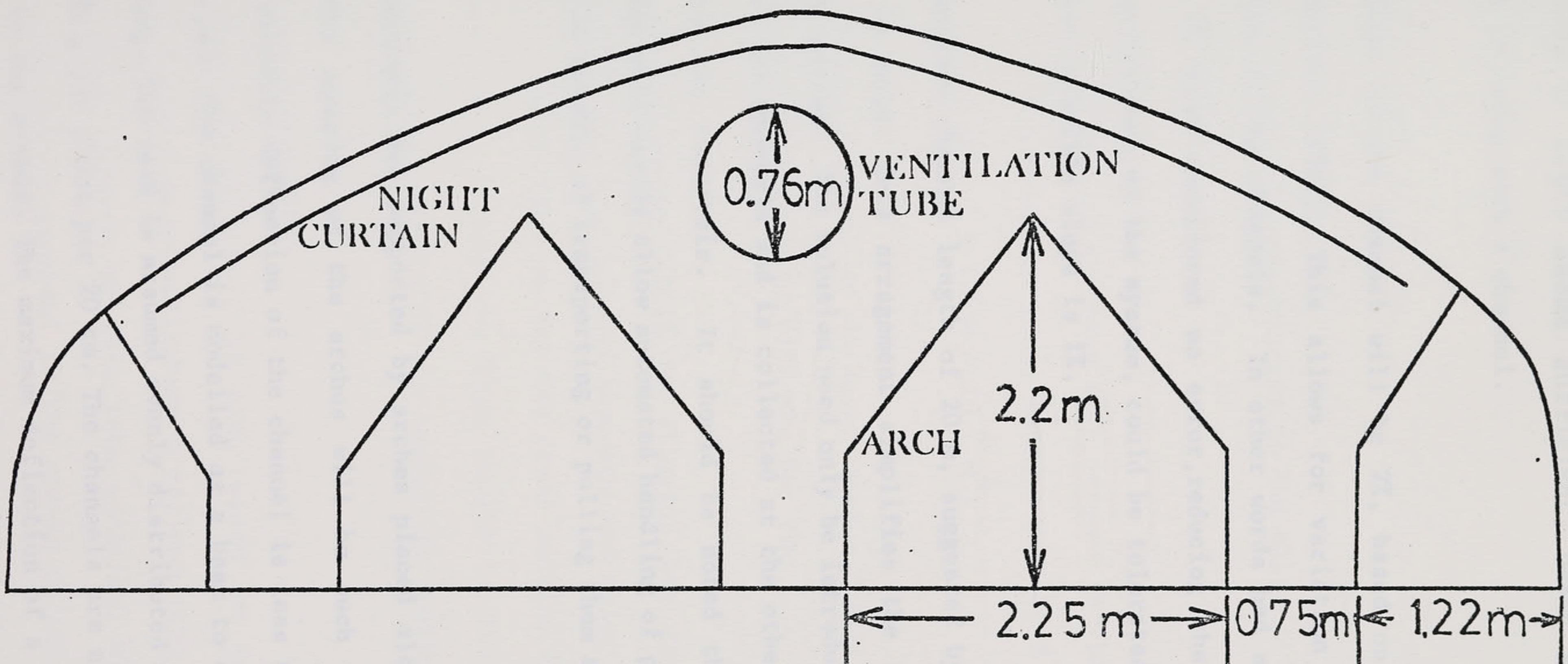

Figure 8 : Greenhouse Cross Section

least 30 mm in depth seems sufficient, based personal experience in using such a channel.

The slope of the channel will be 2%, based on Graves recommendations (1983). This allows for variation in the installation of the channels. In other words had a design slope of 1% been considered no error,reducing the slope, during installation of the system, could be tolerated, since the smallest possible slope is 1%.

The maximum channel length of 20 m, suggested by Graves (1983), is used. This arragement simplifies the solution conveyance system. The solution need only be introduced into one end of the channels and is collected at the other end to return to the reservoir. It should be noted that this arrangement will easily allow automated handling of plants by a mechanism capable of transporting or pulling them along the troughs.

The channels are supported by arches placed along their length.The spacing of the arches will be such that the maximum possible deflection of the channel is less than 0.1% of the span. The channel is modelled as a beam to determine the spacing. The load is assumed evenly distributed and equal to the 250 g per plant per 20 cm. The channels are assumed to be fixed to the arches. The maximum deflection of a beam with fixed ends is given by:

$$d = \frac{W * L^4}{384 * E * I} \quad (19)$$

W = load on channel, 12.25 N/m.

L = length of beam, this corresponds to the distance between channel supports (m).

I = moment of inertia of the beam with respect to itsneutral axis. For a rectangular cross section 3 cm by 6 cm with sides 2 mm thick, $I = 1.634 * 10^{-8}\ m^4$.

E = modulus of elasticity of the beam. Cordon (1979) list values between 2069 MPa to 4137 MPa for PVC.

Setting d equal to 0.001L or allowing the channel to deflect 0.1% of the span between supports and using a median value for E the design span for the cross section described above is 0.86 m. Thus the span should be incresed by modifying the cross section of the channel to decrease I.

3.3.3 Solution Conveyance

The flow of solution, should, based on personnal experience using 6 cm channels,have a maximum rate of 0.5 L per minute per channel. At this rate seedlings with small root systems will be immersed in the stream of solution. As the root systems develop and retard the flow, the rate need not be as high and may be reduced to 0.25 L per channel per minute. The total number of channels in the system illustrated in Figure 8 is 56. Thus the maximum flow rate required will be 28 L per minute. The friction losses in the main pipe and the feeder tubes are calculated using:

$$h_f = \frac{10.675 * Q^n * L}{C^n * D^m} \quad (20)$$

h_f = friction loss in m water.

Q = discharge in m^3/s.

D = diameter of pipe (m).

L = length of pipe (m).

C = 130 for very smooth pipes

n = 1.852

m = 4.8704

The head loss for the feeder tube entrance and fittings is given by:

$$h_f = \frac{K * V^2}{2 * g} \quad (21)$$

K = 1.0 for feeder tube entrance.

K = 0.9 for elbows

V = velocity of flow (m/s).

g = 9.8 m/s^2

The feeder tubes are assumed to be 5 mm in diameter. The main pipe is assumed to be 25 mm in diameter. Table 7 summarizes the components making up the total head loss.

Assuming 1 litre of solution per plant, 56 channels 20 m long and a plant spacing of 20 cm, 5600 litres of solution are required. The channels can contain up to 80% of the solution in the system. The reservoir need not hold the total amount of solution, however in the event of circulation failure, a considerable amount of solution would be lost if the reservoir only held 20% of the total. Also, if present research using intermittent flow for lettuce proves advantageous then a reservoir larger than the 20% minimum will be required. Therefore the design capacity of the reservoir will be taken as 5600 litres. The reservoir will be made of concrete.

Component	Head Loss (m)
Elevation	2.5
Suction	2.5
Main pipe	1.22
Feeder tubes	4.59
Entrance (feeder tubes)	3.99
Elbows	0.11
Total	16.43

Table 7 Head loss components

The power requirement is determined using the following equation:

$$P = \frac{g * o * Q * h}{E_p} \quad (22)$$

o = density of water 1000, kg/m^3

Q = discharge, 0.000467 m^3/s

h = total head loss, 16.43 m.

E_p = pump efficiency, assuming 0.7 in this case.

The solution will return to the reservoir by gravity through a collector pipe and may flow into the basin in such a way as to maximize aeration.

SYSTEM OPERATION

4.1 Cropping Schedule

The system will be operational from mid-August to mid-June, because the high temperatures in July are beyond the tolerable range of lettuce growth. The cropping schedule is illustrated in Figure 9.

The seedlings will be established on benches, in root cubes, from zero to three weeks before being installed in the system. They should be watered with nutrient solution from their second to third week, such that the root cubes remain moist. Excess nutrient solution can be drained back to the reservoir. Thus 6 crops will be harvested. Four days are allowed between cropping cycles for harvesting and transplanting.

The nutrient solution will be monitored daily and nutrients added manually. The solution should be replaced at the end of each harvest (every 6 weeks) to prevent unused nutrient salts from accumulating to toxic levels. Figure 10 illustrates the layout of the greenhouse interior.

4.2 Capital Cost

Table 8 list the main components of the system and their costs. The greenhouse ventilation and heating equipment cost are taken from the 1984 Ball Superior catologue. The troughing is assumed to cost $3.00 per m. Concrete for the

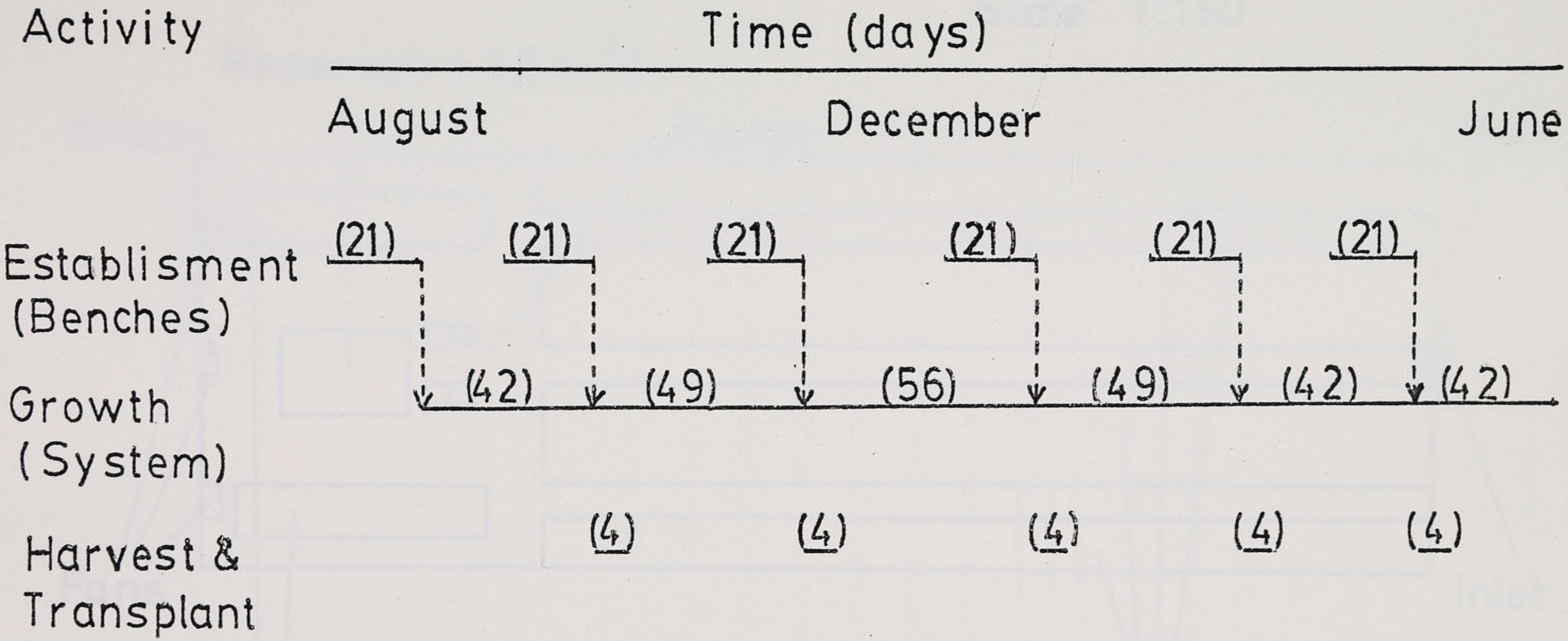

Figure 9: Cropping Schedule

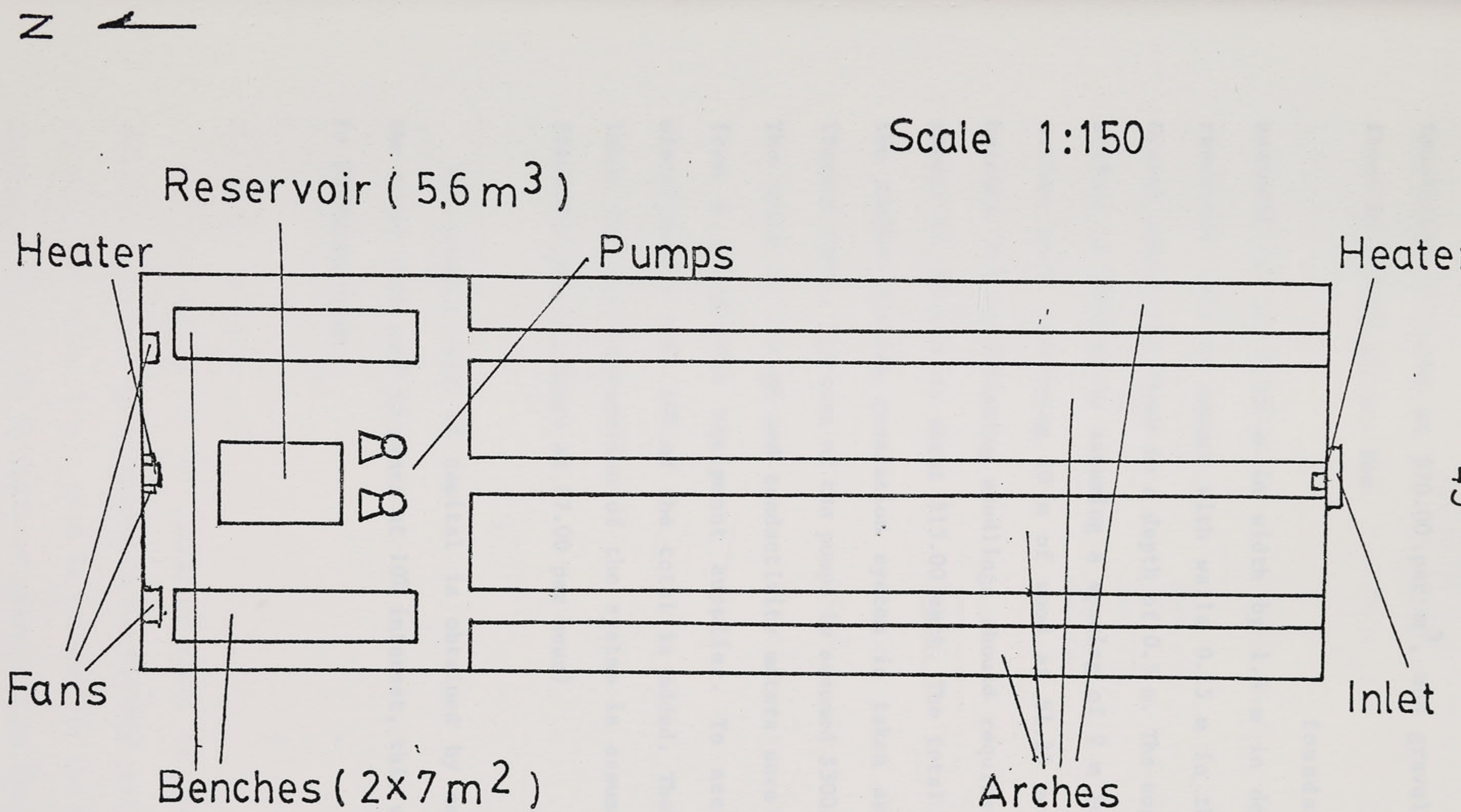

Figure 10: Greenhouse Layout

foundation is taken at $70.00 per m^3, and gravel for the floor at $15.00 per m . The

foundation is assumed to be 0.15 m in width by 1.5 m in depth. The reservoir will be square with walls 0.15 m in thickness. Gravel covers the floor to a depth of 0.5 m. The cost of the arches is derived by assuming a spacing of 2 m for wooden arches each containing 10 m of wood at $1.25 per m. The benches for establishing seedlings should require about 6 sheets of plywood at about $15.00 each. The total cost for the carbon dioxide generation system is taken as $600.00 (Parent 1983). The cost of the pumps is assumed $300.00 each. The price of the pH and conductivity meters were obtained from a scientific equipment supplier. To account for miscellaneous cost 10% of the total is added. The cost of labor for the construction of the system is assumed to be $2100.00 (300 man hours at $7.00 per hour)

The yearly cost of capital is obtained by amortizing the total cost over 15 years at 10% interest, this works out to $3354 per year.

Component	Model	Size	Cost ($)
Greenhouse	Superlight	30x96 feet	5260
Inflation kit			100
Heaters (2)	Modine	225000 Btu/hr	1820
Fresh Air System	C-30-B	7500 cfm	750
Fans (2)	EB-361	2200 cfm	1448
Air Intake	556	4x4 feet	184
Motor Pack for Air Intake			103
Night Curtain		250 m^2	2500
Troughing		1120 m	3360
Concrete		20 m^3	1400
Gravel		123 m^3	1850
Wood		300 m	375
Pump (2)		6 gpm	600
pH Meter	Acumet 600		750
Conductivity Meter	YSI		605
Miscellaneous			2131
Labor			2100
Total			25511

Table 8 Capital costs

4.3 Operating Costs

The calculation of the operating costs is based on a year of operation. The breakdown of the various cost is given in Table 11. The plastic film is included in the operating cost because it must be replaced every two to three years. Assuming Monsanto 603, 6 ml film is used, and replaced every three years, the average cost per year will be $334.

4.3.1 Energy Costs

The energy required to heat the greenhouse is determined using equation 15 and the mean monthly temperature and relative humidity given by Delisle-Rousseau (1983), and the mean daily global solar radiation given by Environment Canada (1982). The conversion efficiency, energy content and cost of natural gas are 80%, 37259 kJ/m^3 and $\$0.22/m^3$ respectively (Delisle-Rousseau 1983). The night curtain is assumed in use 12 hours per day such for half the operating time I=0 and Uf is reduced by 1.5 $W/m^2\,^oC$ to 3.05 $W/m^2\,^oC$ (ASAE Handbook 1982). The energy required per day is thus:

$$Q = (U_f + U_n) * A_f * (T_i - T_o) * 43200 + \ldots$$

$$\ldots \frac{E * F * a_s * T * A_h * C_p * (T_i - T_o)}{L * (W_i - W_o)} \quad (23)$$

All the terms are described in section 3.2.3 except for

U_n = overall heat transfer coefficient for glazing with night curtain in place, 3.05 $W/m_2\,^oC$.

I = mean daily global solar radiation ($mJ/m^2 day$).

E will be taken as 0.75 in this case and F as 1. The monthly cost of gas will be:

$$C = \frac{n * Q * c}{e * q} \quad (24)$$

n = days per month, 365/12

c = cost of natural gas $0.22/m^3$

e = conversion efficiency of heater 0.80

q = energy content of natural gas, 37529 kJ/m^3

The data used and the resulting monthly cost are given in Table 9.

The cost for electricity is determined assuming an efficiency of 0.7 for all the electric motors. The operating time of all the ventilation fans is assumed to be 30% of the time. The inflation fan and circulation pump operarte 100% of the time. The cost of electricity is $0.0395/kWhr. Table 10 summarizes the breakdown of electrical costs.

Month	Temperature (Mean ^{o}C)	Humidity Ratio(*)	I (MJ/m^2 day)	Cost ($)
June	19	0.0086	20.25	-
Mai	13	0.0062	19.07	158
April	6	0.0036	15.87	446
March	-2	0.0024	12.51	690
February	-9	0.0010	8.81	805
January	-9	0.0010	5.3	708
December	-6	0.0018	3.92	596
November	3	0.0038	4.61	375
October	9	0.0048	8.04	240
September	15	0.0078	13.45	-
August	19	0.0096	17.23	-
Total				4018

Table 9 Energy cost data

(*) Taken at mean temperature and mean relative humidity.

Motor(size)	Operating Time (days)	Cost ($)
Ventilation (1.88 hp total)	100.3	185
Inflation (1/6 hp)	301	51
Pump (1/6 hp)	301	51
Total		286

Table 10 Electrical cost calculation

4.3.2 Labor Cost

One full time technician will be required. Part-time labor for each harvest and transplanting is assumed to be 8 man days per crop. Taking the technician's salary at $18000 per year and the cost of part-time labor as $50 per man-day, the total cost of labor is $24000 per year. The technician is considered to be present year round. Maintenance and repairs can thus be done in the summer.

4.3.3 Crop Inputs

The cost of seed, root cubes and fertilizer is considered here. The Ostinata variety of lettuce is used. This variety has been developped for hydroponic production and is available commercially. Based on prices in the Stokes seed catalogue and assuming 85% germination and pelleted seed, annual seed cost will be $160. Oasis root cubes, for seedlng support, marketed by Ball Superior will cost $827.

To determine the amount of fertilizer required the requirements per plant must be known. Schippers (1980) found that lettuce consummed 0.49 g of Nitrogen, 0.18 g of Phosphorus and 0.67 g of Potassium from transplanting to harvest. Allowing for nutrients consummed during establishment, variation with Schippers growing conditions and cultivar used, these values are increased by 30% to determine the total cost. Thus, using Peters Professional Water Soluble Fertilizer (5-11-26) with Calcium Nitrate ($Ca(NO_3)_2$) in the recommended proportion (16:1), each plant will require 8.08 g of (5-11-26) and 0.51 g of Calcium Nitrate. The annual requirement(6x5600 plants) is thus 353.9 kg of (5-11-26) and 22.3 kg of Calcium Nitrate. The nutrients lost when the solution is changed (6 times) total 32.2 kg of (5-11-26) and 2.0 kg of Calcium Nitrate. These products retail at $21.75 per 15 kg of (5-11-26) and $30.46 per 10 kg of Calcium Nitrate. Total fertilizer cost are thus $558 for (5-11-26) and $74 for Calcium Nitrate.

Item	Cost($)
Capital	3354
Labor	20400
Natural Gas	4018
Electricity	286
Seed	160
Root Cubes	827
Fertilizer	632
Plastic film	334
Total	30011

Table 11 Operating costs

DISCUSSION

The system produces lettuce at a rate of 1.363 million plants per hectare per year. This is inferior to the production of Len Dingemans operation in England (Graves 1983) who gets 2 million plants per hectare per year. Assuming 0.250 kg per plant, productivity can be expressed as 34.1 kg/m^2year. Prince et al. (1976) obtained 117 kg /m^2year at a cost of $0.55 to $0.84 per kg. The break-even cost for this sytem is, taking the operation cost over annual production, $0.89 per plant or $3.56 per kg. The cropping density for the plants in the arch is 40 plants/m^2 , identical to Morgan and Tan's (1983) density and superior to Schippers (1978) configuration. However if the whole greenhouse is taken into account, the density is 22 plants /m^2 .

By comparison with other systems the productivity of this system seems low. However, when considering production on a ten month basis and allowing for differences in climate this sytem's productivity compares with Len Dingemans operation. Furthermore, productivity could easily be increased by automation which could increase overall cropping density. Also present research on NFT cropping using intermittent flow and solution heating indicate further gains in productivity. The development of new cultivars is another means of increasing productivity.

Economically, the system is not competitive. The system may be viable if the product can be marketed at a premium price given it superior charcteristis, such as cleanliness, freshness and absence of applied herbicides. This alternative merits research considerations.

The system's economic performance can most likely be improved by making better use of labor. Harvesting could be staggered to reduce peak labor demands. Economies of scale would incur from a larger system where managerial resources are more effectively applied. Also the labor requirements used in this analysis are most likely overestimated in that one technician could probably handle more than one production unit this size.

The parameters calculated and the productivity predicted can only be verified by the actual operation of such a system.Most assumptions pertaining to the physical and biological performance of the system are based on empirical data or physical laws. Thus the accuracy of the predictions on the system's performance is probably acceptable. The economic assumptions however are not as precise and were made with the worst case situation in mind.

CONCLUSION

The production of lettuce throughout the winter season is possible with the above system.However the economic viability of the system is doubtful given the relatively high breakeven point of $0.89 per plant.

The configuration of the system is designed to maximize production with respect to energy requirements and labor. Improvements in productivity are still possible with technological advances, such as automated crop handling and various crop management innovations.

An important conclusion which can be drawn from this study is that the economic viability rest more on the efficiency of labor use than the energy consumption. The latter term is of a major influence on the systems efficiency nevertheless.

Hence a feasible lettuce production system has been designed. Lettuce production is maximized with respect to energy input. However the viability of the system remains open to doubt without empirical data on the performance and cost of labor of this system.

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