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HEAT TRANSFER PROBLEMS IN PLASTIC COVERED TOMATO GREENHOUSES WITH GROUND BEDS IN MANITOBA

by

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Heat Transfer Problems in Plastic Covered Tomato Greenhouses with Ground Beds in Manitoba

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INTRODUCTION

1.1 The Potential Market for Greenhouse Tomatoes in Manitoba

Most people like big, fresh tomatoes for making sandwiches and salads. The major supply of tomatoes for Manitoba is produced in Ontario, the United States or Mexico. Unfortunately, these tomatoes do not have the flavorful quality of vine-ripened tomatoes. The transportation expenses and the damage done in transit add to the final cost to the consumer.

A marketing study found that consumers were willing to pay a higher price of up to twenty cents per pound more for greenhouse tomatoes compared to storage ripened tomatoes (21).* Manitoba greenhouse tomato producers can profitably fill the shortage in the local supply of high quality tomatoes if technical information is available.

1.2 Engineering Aspects of Greenhouse Tomato Production

1.2.1 Basic Structure

The plastic covered greenhouse has some advantages over glass covered greenhouses (53). These advantages are:

(a) Less heat loss (double layer assumed).

(b) Diffusive light transmission resulting in less fruit cracking.

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*Number(s) in parenthesis refer to the number in references.

(c) Lower capital cost of construction.

(d) More airtight for efficient and economical carbon dioxide enrichment.

Various types of structural designs can be used. Glue laminated, wooden arch rafters are modest in cost and offer clear spans for the growing area. Rafter size and spacing should be selected so as to minimize shading. The use of plastic covering materials results in a very lightweight structure. Thus only small footings or grade beams are required for foundations.

Many types of outer coverings are available but maximum transmission of incident radiant energy is important. The inner lining, required for minimizing heat loss and condensation, can be of polyethylene film (see figures 1-1 and 1-2).

1.2.2 Temperature Control

The optimum temperatures for different stages of tomato growth are summarized in table 1 (53).

When the temperature is low the rate of cell division and growth is also low. At relatively high temperatures growth is rapid and sugars do not accumulate but are used in respiration and growth. For accurate control of temperature, a thermostat should be installed where it is screened from direct radiation and forced air movement.

Tomato seedling temperatures range from 60 to 65F. In order to promote the development of large cotyledons (seed leaves) and thick stems, a cold treatment is given. Cold treatment tends to double the number of flowers in the first and often the second clusters, and to

FIGURE 1-1 Exterior View of Experimental Greenhouse at University of Manitoba

FIGURE 1-2 Interior Design of Greenhouse at University of Manitoba

TABLE 1

Night and Day Temperatures for Tomatoes

Growth Stages	Sunlight Conditions	Night (F)	Day (F)
1. Seed Germination	Not critical	65 - 70	65 - 70
2. Cold treatment: 10 days to 2 weeks	Sunny or partly cloudy	52 - 56	55 - 60
2 to 3 weeks	Cloudy or dull	52 - 56	55 - 58
3. After the cold treatment and until plants are transplanted into beds	Sunny or partly cloudy	58 - 62	65 - 75
	Cloudy or dull	58 - 60	60 - 62
4. During flowering and fruiting	Sunny or partly cloudy	60 - 65	65 - 75
	Cloudy or dull	60 - 62	60 - 62

increase the early and total yield. The young tomato plants are exposed to night temperatures from 52 to 56F for ten days to three weeks. Following this cold treatment temperatures during day and night should be raised to 58 to 75F (see table 1 for details).

1.2.3 Humidity Control

The relative humidity inside the greenhouse should be kept below 90 percent to control leaf mold disease which is very destructive to greenhouse tomato plants (44). Humidstats are available to control the opening of ventilators (26,41) for humidity control. Double layer covered greenhouses tend to have less condensation on internal surfaces in cold weather than single layer covered greenhouses (49).

Relative humidity of 55 to 65 percent at 70 to 75F is considered to be optimum (4). Most pathogenic spores will not germinate unless the relative humidity is 96 percent or higher (37). Relative humidity levels in the range of 70 percent or higher are necessary for the continued growth of most pathogens (42).

The upper leaves will be dried by solar radiation and induced air currents, whereas the lower leaves will still remain moist. A fan with a perforated plastic distribution tube will maintain more uniform temperature and humidity, and prevent cold and moist spots (12).

1.2.4 Soil Moisture and Nutrients

If fruiting plants become deficient in moisture or nutrients, top yields of high-quality greenhouse tomatoes cannot be obtained. Warm, soft water is required for irrigation. Automatic irrigation systems can be controlled by solar evaporimeters or tensiometers (41).

The required nutrients are best determined by soil and tissue tests. The accepted method of supplying nutrients is to supply appropriate soluble fertilizers. Required nitrogen, phosphorus, potassium, calcium, magnesium and trace elements in dilute form are applied with the irrigation water.

1.2.5 Light

The energy for photosynthesis is provided by radiant energy. The quantity of energy, the spectral distribution of energy and the relative light and dark periods determine the rate and type of growth.

The portion of the electromagnetic spectrum that is involved in photochemical reactions in plants is from 290 nanometers to 850 nanometers (1 nanometer (nm) = 10^{-9} meters) (17). The energy in the spectrum band, 380 nm to 760 nm, can be detected by the human eye and is defined as light. Natural daylight (sunlight) has the correct spectral balance for proper growth of tomatoes.

Photosynthetic reactions in tomato plants under natural conditions saturate at light levels of approximately 1500 foot-candle (ft-c) (17). Sunlight intensity on a clear June day at noon is approximately 10,000 ft-c.

To avoid pathological conditions, tomato plants need a dark period of at least 7 hours. The natural diurnal cycle provides the needed dark period.

1.2.6 Carbon Dioxide Enrichment

Normally air contains about 0.03 percent or 300 ppm (parts per million, volume basis) of carbon dioxide. The optimal concentration is from 1000 to 1500 ppm (53).

From 10 A.M. to 4 P.M. on bright sunny days is the most beneficial period to increase the concentration of carbon dioxide because of the high rate of photosynthesis.

Perforated plastic air distribution tubes can be used with a fan to distribute and circulate supplementary carbon dioxide. Carbon dioxide can be supplied from solid dry ice, pressurized liquid carbon dioxide or from burning hydrocarbon fuels of low sulphur content.

A simple, cheap and reliable colorimeter for measuring carbon dioxide concentration is available (40).

1.2.7 Disease Control

Good air circulation, fresh air and optimal temperatures in the greenhouse will control fungus diseases. The heating and air circulating system should be designed to avoid cold air pockets and high moisture levels around the base of the plants. Removing leaves to the level of the ripening fruit will improve air circulation (53).

Soil sterilization prior to planting is necessary for control of soil-borne diseases and detrimental microorganisms. Soil in small quantities can be sterilized with heat from electrical heaters. Soil in growing beds is usually sterilized with steam or chemicals.

1.3 Objectives

The scope of this investigation was limited to areas where immediate problems existed. The main problem area was steam sterilization of the ground beds using portable steam generators. The other problem areas were the design of the heating system and the design of the ventilation system. The objectives were:

1. To evaluate steam sterilization of the soil beds and to compare with chemical sterilization.

2. To compare estimated heat losses with that estimated from the measured fuel consumption.

3. To estimate solar heat gains and to evaluate the ventilation system design for removal of excess solar heat.

CHAPTER II

REVIEW OF LITERATURE

2.1 Steam Sterilization

2.1.1 Benefits of Steam Sterilization

The bacterial destroying capacity of steam is a combination of moisture and heat. Dry heat sterilization requires much higher temperatures and longer heating times than moist heat. Bacteria are killed by protein coagulation. Much higher temperatures are needed to coagulate protein when moisture content is low. With dry heat this necessitates the destruction of the bacteria by actual burning (29, 36).

Effective soil sterilization with steam is fundamentally dependent on the type of pathogens or harmful organisms present as well as soil moisture, soil density, soil parent material, and soil structure. These factors affect the treatment temperature and the temperature distribution which determines the sterilization effectiveness.

Steam sterilization is faster, easier, cheaper and more effective than other methods of destroying fungi, bacteria, nematodes, weeds and insects (13). Steam releases a large quantity of heat at the point to be heated and provides the most efficient method for treating a large stationary soil mass (13).

2.1.2 Sterilization Temperatures and Times

Fungi are relatively sensitive to heat. Most pathogenic fungi are destroyed by time-temperature relationships of the order of 140F for 30 minutes. Hot water treatment would control fungi diseases (14).

Most bacteria that cause plant diseases can be killed at 140F for 10 minutes since these bacteria do not form heat resistant spores as do some animal pathogens and some food-spoiling bacteria (14).

Most nematodes will be killed at 130F for 10 to 15 minutes (14). Insects and mites in the egg stage cannot survive at temperatures exceeding 160F. Worms, slugs, centipedes and similar animals will be killed at 140F for 30 minutes using moist heat (14).

Viruses do not persist in soil but they do live in dried infected plant tissue that is left in the soil. These viruses can survive for at least 2 years and some can even survive 200F for 10 minutes (14).

Under ideal sterilizing conditions most of the organisms of concern can be killed by heating the soil to 140F for 30 minutes. Because clods or lumps require a heating time that is proportional to the square of their diameters (34), recommended temperatures are higher than 140F. Soil that is turned should be heated to a final temperature of 180F for 30 minutes and stationary soil masses should be heated to 212F for 30 minutes (14,15).

2.1.3 Sterilization Methods

Soil may be sterilized either by using a stationary soil mass method or a moving soil mass method. The choice of method depends on the efficiency, dependability, cost and chance of reinfection.

If steam is used as the heat source a stationary soil mass method will prove best in most cases. Where the source of heat is dry heat a moving soil mass method will be much more efficient and easier to control (1,15,19).

The Thomas or surface method of steaming is usually limited to 8 inch soil depths but with underground tiles the method can provide efficient steaming for soil beds with depths of 24 inches or greater (15).

2.1.4 Heating of Soil Clods

Heat conduction in soils improves as porosity and pore size decrease, and moisture content increases. Convection increases with large pores, but decreases in wet soil because of reduced pore size and permeability to air. Heat transfer by radiation increases with small pores and wet soil (14). Dry soils ranked in order of thermal conductivity from highest to lowest would be sand, loam, clay and peat (14, 16,30).

Steam moves through the air spaces in the soil mainly by molecular diffusion, micro-convection, and macro-convection. The heating process inside clods is mainly due to diffusion and condensation of steam, but also partly due to thermal conduction. According to Morris and Winspear (34), it has been shown that the time required to raise the temperature at the center of a spherical clod was proportional to the square of the clod diameter. The assumed modes of heat transfer were diffusion and condensation as well as conduction (34).

2.1.5 Condensation of Steam in Soil

Even if steam were at high pressure and high temperature in buried clay tiles, the pressure quickly drops to approximately atmospheric on release from the tiles into the soil mass. The steam temperature will also reduce on contact with the cool soil particles and the cool soil air. Thus, the soil and soil air will be heated by released latent heat as the steam condenses.

The amount of heat released at any radial location is determined by the temperature differential of the steam mixture and the soil and soil air in the advancing condensation zone (14).

The heat transfer and mass transfer between the steam mixture, soil air and the surfaces of the soil particles could be represented by the enthalpy potential difference, the convective coefficient and the specific heat of the steam mixture (43).

2.1.6 Steam Movement from Buried Clay Tile

According to Baker and Roistacher (13) steam expands from buried tile orifices in a pattern of spheroids with elongated tops. They based this conclusion on research of Morris (33) and Bunt (20). They concluded that:

> If the distance of movement above the outlet is 1d, then that below it is approximately $\frac{1}{2}$d and that to the sides is $\frac{1}{2}$d to 5/8d.

This is illustrated in the diagram on the following page.

For fine soil, the heat front forming a boundary between cold and hot soil is about 0.27 inches thick (34).

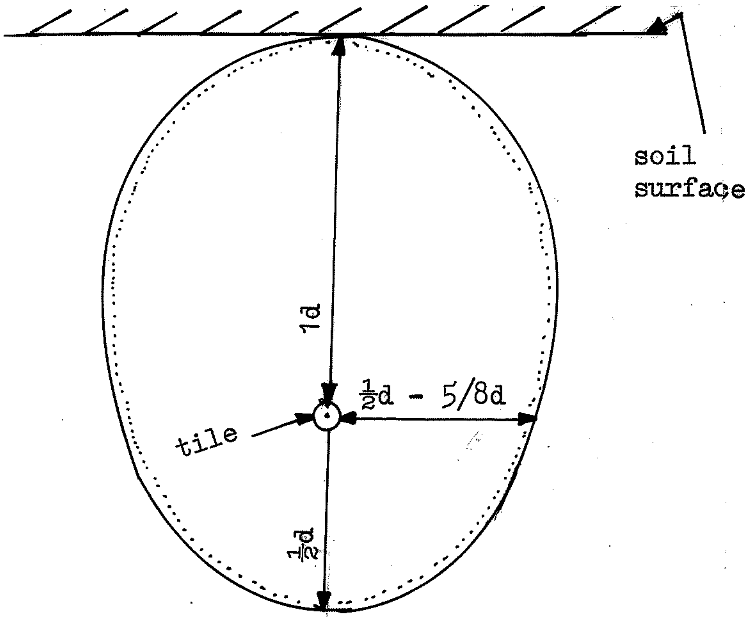


FIGURE 2-1. Cross Section View of Steam Expansion

2.2 Estimating Heat Losses

2.2.1 Heating Methods

Under Manitoba conditions it is important to provide a suitable heating system for successful greenhouse operation. Practical designs are based on the requirements of (41):

(a) Uniform temperature distribution.

(b) Low capital and/or operating costs.

(c) Reduced overhead obstruction and space taken up by heating equipment so that greater sunlight is transmitted to the growing crop and there is more space available for the crop.

(d) Heating ducts or pipes arranged to permit growing of crops in rows or beds.

Heat for greenhouses may be supplied from direct or indirect sources. In direct systems the heat is supplied directly to the heating medium for transfer to the house interior. In indirect systems the heat is supplied to an intermediate medium that transfers it to the house in general. Examples of the two systems are hot air electric systems and steam systems respectively (28).

Recommended electrical tubular heaters are those which are waterproofed and made from aluminum. These are fixed around the walls of the greenhouses with the lowest heater about 4 to 6 inches above the soil level to provide for an efficient air circulation while taking up minimum space. Copper-sheathed electrical cables insulated with mineral wool can also be fitted in a similar position in place of the tubular heaters (24).

Gas-fired or oil-fired air heaters can also be used. The maximum temperature of exit air from these heaters must be no more than 130F (41). Natural gas is the preferred fuel for gas-fired furnaces but manufactured gas or propane gas may also be used. If gas is not available, fuel oil can be used but great care must be taken to insure that exhaust fumes are kept out of the greenhouse. The high levels of carbon dioxide and sulphur dioxide in the exhaust fumes are fatal to plants (53).

There is a trend to the use of steam boilers for greenhouse units larger than three-quarters of an acre (41). Heating pipes are used throughout the greenhouse to distribute either steam or hot water for heating. For high-pressure systems high-level pipes are considered safer than low-level pipes because of the possibility of accidental burns with low-level systems. The high operating temperature (300F) of high-pressure systems requires fewer overhead pipes and therefore gives less shading.

None of the above heating methods provides an absolutely uniform temperature distribution throughout the greenhouse. A perforated plastic tube with a circulating fan installed at the end of the greenhouse will improve the temperature distribution within the house (12).

2.2.2 Determination of Heat Losses

The maintenance of uniform desired temperatures is very important in greenhouses. Heat losses from the greenhouse are due to thermal radiation and convection losses from the covering, conduction through the walls and soil, and condensation on the inner surface and plant transpiration. A reliable heating system must be supplied to the greenhouse since the heat gains from solar radiation, accessory equipment and biological respiration are rather erratic (48).

Takakura et al.(45), have developed a dynamic greenhouse model which considers the difference between leaf temperature and inside air temperature, moisture balance, heat storage in the floor, effects of radiation and convection on the plant leaf temperature, convective heat transmission coefficients of outside surfaces as a function of wind speed, and the solar transmissivity due to wall orientation.

In general a steady state method is used to design greenhouse heating systems (Appendix 1). For steady state conditions the rate of heat input at any point to the system must be exactly equal to the rate of heat loss if there is no net storage or loss of energy in the system. In lightly-constructed plastic-covered greenhouses this assumption is approached (3).

The following equation for calculating heat loss is recommended by the National Greenhouse Manufacturer's Association (25):

$$Q = (A_1 + A_2 \times R) \times \Delta T \times G \times W \times C \tag{2-1}$$

where

Q = heat loss, Btu/hr

A_1 = exposed glass area, ft^2

A_2 = exposed wall area other than glass, ft^2

R = resistance of curtain wall to transmission of heat (in relation to transmission through glass), dimensionless

ΔT = highest temperature to be maintained in greenhouse minus outside design temperature, F

G = coefficient of transmission of glass Btu/hr-ft^2-F

W = wind factor, dimensionless

C = construction factor, dimensionless

Commercial heating installers size greenhouse heating systems using a "rule-of-thumb" based on experience. The "rule-of-thumb" value for Winnipeg conditions is 7 Btu/hr-ft^3. This value is used to calculate the required heat input to the furnaces.

2.3 Estimating Solar Heat Gain

The total shortwave radiation, I, reaching a terrestrial surface is the sum of the direct solar radiation, I_D, the diffuse sky radiation, I_d, and the solar radiation reflected from the surroundings, I_r. If the intensity, normal to the sun's rays, is I_n, and the angle of incidence, between the incoming solar rays and a line perpendicular to the surface, is θ, then a general relationship is (9):

$$I = I_n \times \cos\theta + I_d + I_r \quad \text{Btu/hr - ft}^2 \tag{2-2}$$

For the solar heat gain, within a greenhouse treated as a horizontal surface, the equation can be written (48):

$$Q_i = (\alpha_s \tau_s I) \cdot (A_1) \tag{2-3}$$

where

Q_i = solar heat gain, Btu/hr

α_s = average apparent absorptivity of plants and soil surface, dimensionless

τ_s = average apparent solar transmittance of greenhouse coverings and wood frames, dimensionless

A_1 = the area of ground and foliage, ft^2

The value of I_n at the surface of the earth on a clear day is dependent on the latitude, the time of day, the time of year, the tilt of the surface, and the condition of the atmosphere (27).

Glass types of greenhouse coverings are virtually opaque to the long wave radiation emitted by surfaces at temperatures below about 250F. Short-wave solar radiation can pass through these coverings. The reradiation from the inside surfaces (below 250F) cannot pass back through the covering and this is why a greenhouse is warm inside even when the outside air is cool. This phenomenon is called "the greenhouse effect" (11). Unfortunately, many of the plastic coverings are not completely opaque to thermal radiation at the long wavelengths (48).

CHAPTER III

ANALYTICAL PROCEDURES AND THEIR APPLICATION TO THE EXPERIMENTAL GREENHOUSE

3.1 Soil Sterilization

The steam requirement depends on the steam quality, the moisture content, density, volume and temperature of the soil. Required capacity can be approximately determined from the quantity of soil to be heated:

$$H = \gamma S (T_2 - T_1) \tag{3-1}$$

where

H = heat requirement per unit volume, Btu/ft^3

γ = weight density, lb/ft^3

S = specific heat, Btu/lb-F

T_2 = average soil temperature after steam sterilization, F.

T_1 = average initial soil temperature before sterilization, F

The specific heats of oven-dry soils are 0.19 and 0.20 Btu/lb-F respectively for light and heavy soils (32). The variation of specific heat with moisture content can be found from the following formula (32):

$$S = (S_o + M)/(1 + M) \tag{3-2}$$

where

S_o = specific heat of oven-dry soil, Btu/lb-F

M = moisture content as a fraction of the oven-dry weight.

According to figure 3-1, the heat capacities of three different soils at 25 percent moisture content are 32, 38, 31, Btu/F-ft^3 for peat soil, light soil and heavy soil, respectively (33). The ordinate values from figure 3-1 represent the γS factor of equation 3-1. To determine the total amount of heat required for sterilization, the chart values would be multiplied by the total soil volume (ft^3) and the temperature differential.

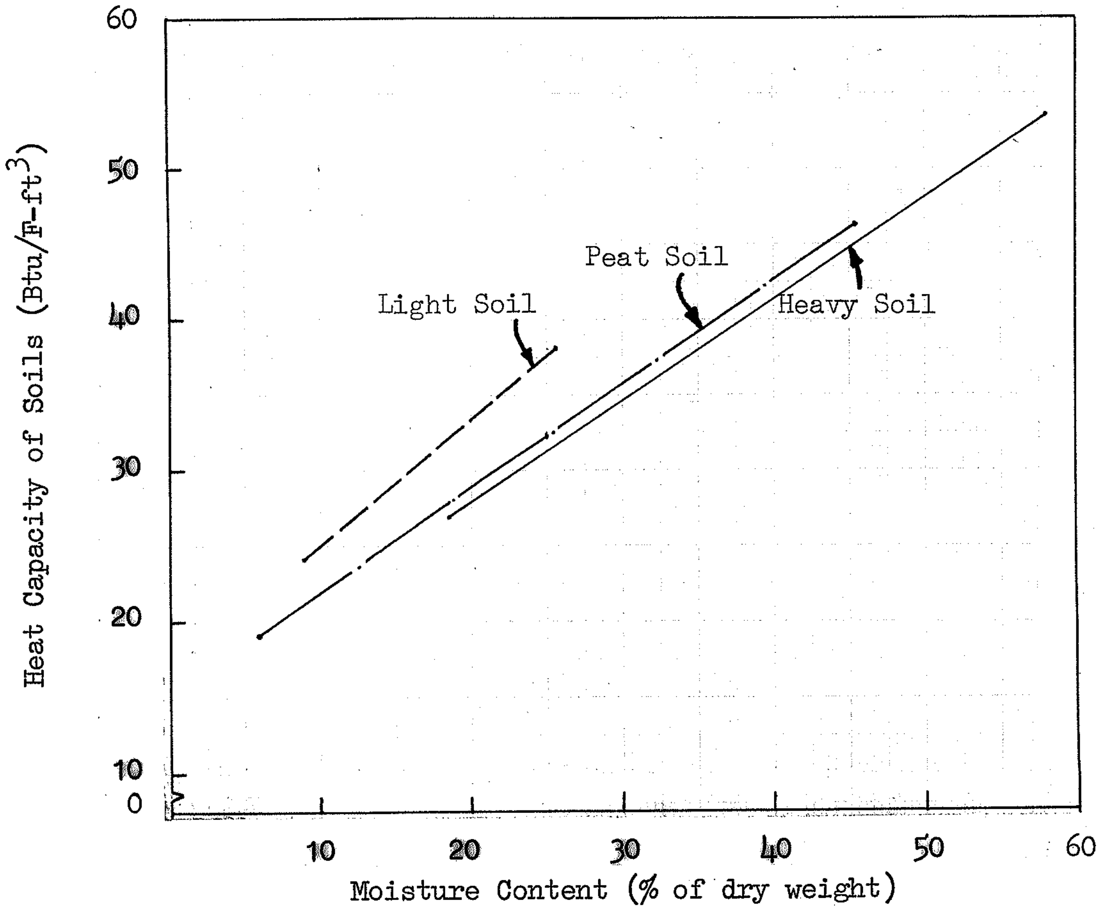


FIGURE 3-1 Heat Capacity versus Moisture Content (33)

The soil profile in the experimental greenhouse is made up of a 1 ft deep layer of peat soil, a 0.5 ft deep layer of coarse sand, and a 0.375 ft deep layer of clay soil. The depth of clay soil that was assumed to be sterilized was calculated on the basis of the expected pattern of sterilization shown in figure 2-1. This pattern is illustrated in figure 3-2. The clay tile lines were 2 ft apart and 42 ft long.

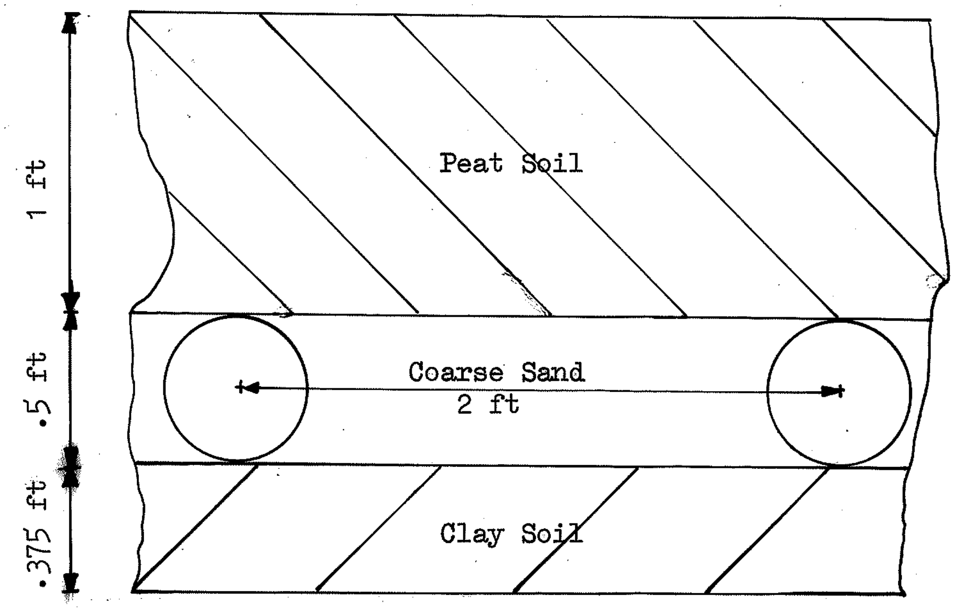


FIGURE 3-2 Soil Profile Subjected to Sterilizing Steam

The volume of each soil component sterilized along each tile can be calculated. Then the required heat per degree can be calculated by multiplying the γS value for each soil component by the respective volume and then summing (neglecting the volume of tile):

$$Q = (1 \times 2 \times 42) \times 32 + (0.5 \times 2 \times 42) \times 38 + (0.375 \times 2 \times 42) \times 31 = 5260 \text{ Btu/F}$$

The initial and final soil temperatures were assumed as 65.6F and 180F, respectively. Therefore the total heat required per tile line was approximately:

$$Q_T = 5260\ (180-65.6) = 601{,}744 \text{ Btu}$$

Assuming 50 percent efficiency, the steam capacity (boiler hp) required to sterilize the volume of soil along each tile in one hour can be calculated as:

$$\text{Boiler hp} = 601{,}744 \frac{\text{Btu}}{\text{hr}} \times \frac{1}{0.5} \times \frac{1 \text{ boiler hp}}{33446 \text{ Btu}} = 36.0 \text{ hp}$$

A ten boiler horsepower steam generator was available. Using this steam generator it will take 3.60 hours for sterilizing the soil mass.

3.2 Heat Loss Calculations

3.2.1 Heat Balance in the Greenhouse

If the only moisture input to the greenhouse is from evapotranspiration, the energy balance at steady state can be written by the following relationship (3,48):

$$Q_f + Q_i + Q_a + Q_r = Q_c + Q_t + Q_p + Q_g + Q_e + Q_s \qquad (3\text{-}3)$$

where

Q_f = heat added by furnace or heater, Btu/hr

Q_i = solar heat gain, Btu/hr

Q_a = heat from the equipment, Btu/hr

Q_r = heat released by crop respiration, Btu/hr

Q_c = heat loss through the greenhouse covering, Btu/hr

Q_t = thermal radiation transmitted through the greenhouse covering to sky, Btu/hr

Q_p = heat utilized by photosynthesis, Btu/hr
Q_g = heat loss to the ground, Btu/hr
Q_e = latent heat loss due to ventilation, Btu/hr
Q_s = sensible heat loss due to ventilation, Btu/hr

For design purposes, the heat balance equation can be simplified. Two critical cases will be considered. The first case considered will be a heat balance for a winter night and the second case will be a heat balance for a summer midday. These two cases will determine required furnace capacity and required ventilation rate, respectively.

3.2.2 Heat Loss Calculations and Furnace Capacity

The heat released by equipment such as air ducts, electric motors and the lighting system is negligible (39). The heat used for photosynthesis is only about 3 percent of solar radiation intensity on a clear day. The heat of respiration of growing plants is about one-eighth to one-tenth of the heat for photosynthesis under strong sunlight (48). Therefore the amount of heat from respiration is negligible and will be neglected.

For case one (winter-night heat-balance) the heat balance equation simplifies to:

$$Q_f = Q_c + Q_t + Q_g \qquad (3\text{-}4)$$

The total heat loss by conduction ($Q_c + Q_g$) through the semi-cylindrical roof, north end wall, south end wall, the foundation wall loss and the interior loss to the ground beds was calculated (Appendix 1). These calculations were based on a wind speed of 15 mph, inside temperature of 70F, outside temperature of -17F, and deep soil temperature of 50F. The result of the above calculation was:

$$Q_c + Q_g = 148{,}700 \text{ Btu/hr} \qquad (3\text{-}5)$$

Infrared radiation heat loss is the difference between the thermal radiation emitted from the greenhouse and the thermal radiation gained from the atmosphere. The net radiation exchange is given by (48):

$$Q_t = \tau A_1 \delta (\varepsilon_s T_s^4 - \varepsilon_a T_a^4) \qquad (3\text{-}6)$$

where

Q_t = infrared radiation loss, Btu/hr

τ = thermal radiation transmittance of covering, dimensionless

δ = Stefan Boltzman constant, 0.1714×10^{-8} Btu/hr-ft^2-R^4

A_1 = ground and foliage area of greenhouse, ft^2

ε_s = emissivity of the radiating surface within the greenhouse, dimensionless

T_s = absolute temperature of the radiating surfaces, R

ε_a = apparent emissivity of the atmosphere, dimensionless

T_a = ambient air temperature, R

The mean effective thermal transmittance will decrease as condensation on the covering increases. For heavy condensation, τ will be 28 to 36 percent of the transmittance without condensation (51). The apparent emissivity of the atmosphere, ε_a, varies with the carbon dioxide and water vapor content in the atmosphere (18,38,48).

For the experimental greenhouse, the following values were used:

$\delta = 0.1714 \times 10^{-8}$ Btu/hr-ft^2-R^4

$A_1 = (32 \times 50.5)(1 + 0.30)$ ft^2 (Leaf area = 0.30 floor area (assumed)) (Ref. 45)

$\tau = 0.708 \times 0.12$ (0.708 for Polyethylene, 0.12 for Fulcon) (Ref. 23 and 50)

$\varepsilon_s = 0.95$ (Ref. 38)

$\varepsilon_a = 0.70$ (Ref. 18)

$T_s = 70 + 460 = 530$ R

$T_a = -17 + 460 = 443$ R

Thus, $Q_t = 14{,}700$ Btu/hr (3-7)

Summing the results of equation (3-7) and equation (3-5) the estimated total heat from the greenhouse was obtained. This heat loss must be supplied from the furnace so that:

$$Q_f = 163{,}000 \text{ Btu/hr} \qquad (3\text{-}8)$$

An average value for natural-gas furnace efficiency can be assumed. Initial efficiencies may be 80 percent, but a more realistic value is 75 percent (46). Using this value introduces a factor of safety. The rated input capacity for the natural gas furnaces would therefore be 217,000 Btu/hr.

3.3 Estimation of Solar Heat Gain and Ventilation Rate

3.3.1 Solar Heat Gain Estimation

For Winnipeg conditions (50 Degrees North Latitude) at solar noon on June 21, on a horizontal surface, under a clear sky, the following values are applicable:

I_n = 274 Btu/hr-ft^2 (Ref. 9)

Cos θ = Sin (solar altitude) = Sin (63.4) = 0.894 (Ref. 10)

I_r = 0 (horizontal surface)

I_d = 0.134 x I_n = 36.7 Btu/hr-ft^2 (Ref. 11)

α_s = 0.85 (Ref. 48)

Fulcon, solar transmittance = 0.95 (Ref. 23)

Polyethylene, solar transmittance = 0.89 (Ref. 23)

Opaque wood frame (percent of floor area) = 7 percent

τ_s = 0.95 x 0.89 = 0.8455

A_1 = (32 (50.5) (1 + 0.3 - 0.07)) = 1987.68 ft^2

Substituting the above values into equation (2-3) results in:

$$Q_i = (\alpha_s \tau_s I) A_1 \qquad (3\text{-}9)$$

$$Q_i = (0.85)(0.8455)(274(0.894) + 36.7)(1987.68)$$

$$= 395{,}000 \text{ Btu/hr.} \qquad (3\text{-}10)$$

3.3.2 Sensible Heat Loss Due to Ventilation

The sensible heat loss can be computed by the following formula:

$$Q_s = M\,C_{pa}\,(t_i - t_o) \qquad (3\text{-}11)$$

where

Q_s = sensible heat flow rate, Btu/hr

M = rate of ventilating air, lb/hr

t_o = outside air, dry bulb temperature, F

t_i = inside air, dry bulb temperature, F

C_{pa} = specific heat of dry air = 0.24 Btu/lb-F

If the ventilation rate is expressed in cubic feet/minute (CFM) and the specific volume of air, Va, is expressed in cubic feet per pound, the rate of ventilating air (M) can be expressed as:

$$M = \frac{CFM\ (60)}{Va} \tag{3-12}$$

3.3.3 Latent Heat Loss Due to Ventilation

In general, the latent heat loss can be expressed by the following equation:

$$Q_e = M\ (HR_o - HR_i) \cdot h_{fg} \tag{3-13}$$

where

Q_e = rate of latent heat flow, Btu/hr

M = rate of ventilating air, lb/hr

HR_o = humidity ratio of outside air

HR_i = humidity ratio of inside air

h_{fg} = latent heat of vaporization or fusion at condensing or dew point temperature, Btu/lb

The influence of evapotranspiration, which is the evaporation of water vapor from the soil and transpiration of water from plant leaf surfaces, can be evaluated by consideration of the latent heat term. When vaporization takes place around 80F, an approximation to equation (3-13) can be used. The approximate latent heat loss can be estimated by (48):

$$Q_e = 5440\ A_g\ E_p \tag{3-14}$$

where

E_p = evaporation rate, in./hr

A_g = ground area within the greenhouse, ft^2

An evapotranspiration rate of 0.0252 in./hr may be assumed for tomato greenhouse culture during clear summer periods (48).

CHAPTER IV

EXPERIMENTAL PROCEDURES

4.1 Steam Sterilization

4.1.1 Preparing Soil for Steaming

The ideal soil for steaming has a suitable moisture content, and is free of lumps. In order to germinate weed seeds and to reduce the resistance to steam of pathogens, the soil should be premoistened 3 days before steam application (19). If the soil is too wet, more steam will be used because the specific heat of water is five times that of dry soil. Soil moist enough for planting is suitable for steaming (13).

Uneven soil compaction will result in uneven heating. If big clods are present, steam may blow out of the soil surface. The soil in the greenhouse was well plowed with a two-wheeled garden tractor and the big clods of soil or peat were pulverized. The soil surface was also raked smooth.

One month after removal of the spring-crop plants, the soil near the surface was dry. The soil was moistened 3 days before steaming.

4.1.2 Steam Equipment and Installation

Since the experimental greenhouse was heated by a gas-fired hot air furnace, a portable 10-boiler-horsepower steam generator (tradename—Saskatoon) was rented from an equipment rental company (Simmons Rental). This boiler was the biggest unit that could be rented in Winnipeg (figure 4-1).

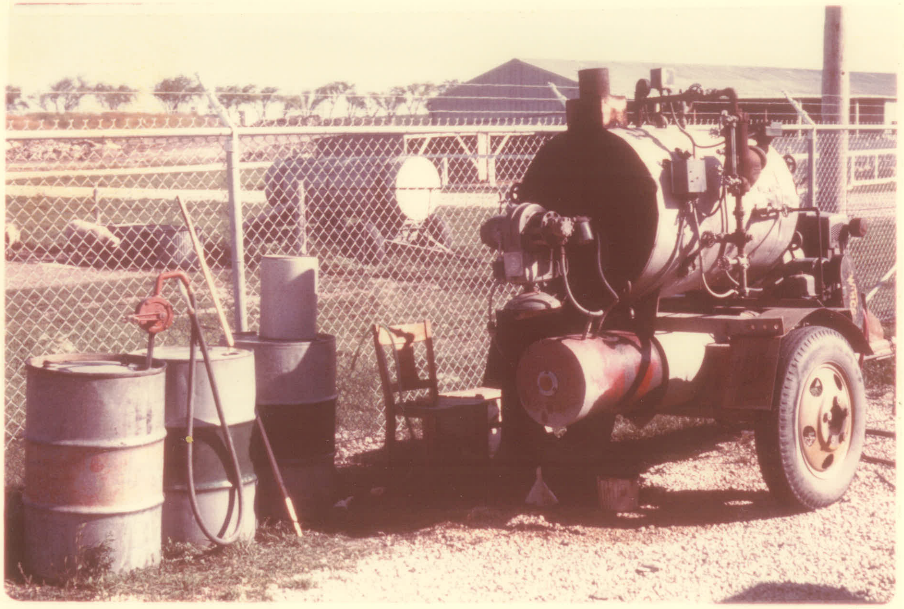


FIGURE 4-1 Saskatoon Boiler

In order to prevent the greenhouse covering from getting dirty with exhaust emissions, the oil-burning boiler was located outside and down-wind from the greenhouse. A 100-ft steam hose, 1 in. inside diameter, fed the steam to the clay tile lines from the boiler.

4.1.3 Treating the Soil During and After Steaming

A plastic covering, 4 ft wide, was placed over each tile line during steaming. The edges were weighted in order to prevent the escape of steam.

Steam was applied for a duration until the surface temperatures were at least 180F for 30 minutes. The covering was removed for cooling the treated soil. After all the beds were sterilized, water was applied for cooling. The cooling water also helps to leach out toxic amounts of ammonium and manganese and other soluble salts that may be released by oversteaming (53).

4.1.4 Assessing Steam Effectiveness

The effectiveness of the steam sterilization was assessed by before and after nematode counts. Most of the nematodes are long, cylindrical wormlike organisms, tapered at both ends. The usual length is from 0.5 to 2 mm (52).

The procedure for nematode counts was as follows. Soil samples were randomly taken from the surface of ground beds before and after steaming. Soil moisture content was determined by the oven drying method. Fifty-gram samples were weighed out on a dry-weight basis, stored at 38F in plastic bags for 1 to 8 weeks, and kept at room temperature for 6 days prior to processing.

Nematode extraction utilized an 8-inch diameter telfon coated pan (47) containing a plastic ring 6.5 inches in diameter and 0.5 inches deep. Across the base of the ring was stretched 29 mesh nylon gauze. The ring was raised on 1/8-inch plastic legs above the pan. Three layers of Kleenex tissue were cut $\frac{1}{4}$ inch larger than the ring diameter and placed on the gauze. The soil was added to the tissue and 90 ml of sterile distilled water, aerated for 2 hours immediately before use, was added to the pan. The pans were stacked in a plastic bag which was sealed and kept at 77F and 75 percent relative humidity in a storage chamber for 7 days.

The water in the pans was swirled, poured off, and stored at 38F. Then the pans were set up again with the same soil and another

50 ml of aerated water per pan for a further 3 days. After this, the dish was washed with 10-ml of sterile water from a wash bottle. The water solutions (about 150 ml) were combined and the nematodes allowed to settle. The top 125 ml of the solution was removed and discarded. The remaining solution (about 25 ml) was poured into a 100 mm by 15 mm plastic dish and swirled to obtain even distribution of the nematodes. Five drops of solution were extracted from each dish. The dead and live nematodes were counted, using a microscope.

Each drop was 0.01 ml fromaa 25 ml sample from a 50-g soil sample. The nematode population can be calculated by the following formula:

$$\mathrm{NPG} = \frac{\mathrm{N}\ (25\ \mathrm{ml})}{0.01\ \mathrm{ml}\ (50\mathrm{g})} = 50\ (\mathrm{N}) \qquad (4\text{-}1)$$

where

N = average nematode count per drop

NPG = nematode count per gram of soil

4.2 Temperature and Humidity Measurement

Two methods were used to measure temperatures. Continuous temperature recordings were obtained in two locations with hygrothermographs (see figure 4-2). The first location was at the middle of the greenhouse at ground level. The second location was 6 ft above ground level on the north partition wall. These hygrothermographs were also used to continuously record relative humidities.

The second method of measuring temperatures was with thermocouples located in many locations in the greenhouse. These measurements

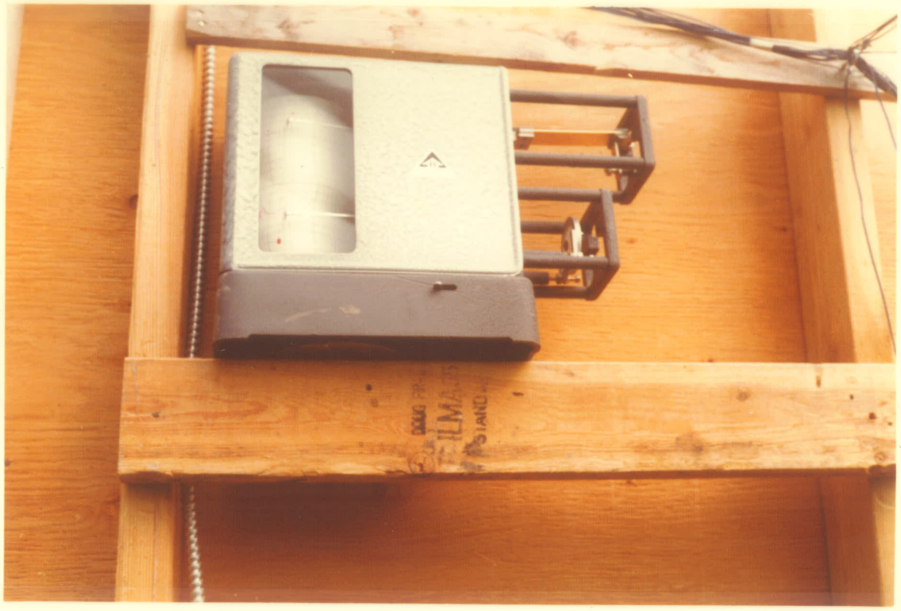


FIGURE 4-2 Hygrothermograph Used to Record Temperature and Relative Humidity

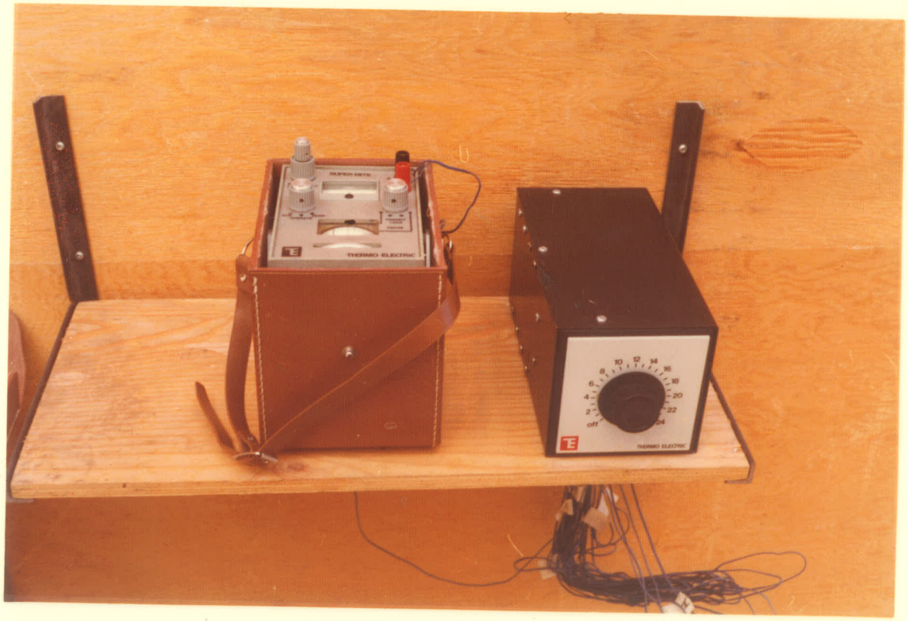


FIGURE 4-3 Temperature Measurement Using the Portable Potentiometer and Thermocouples

were used to obtain an average temperature to be used in the prediction equations. Copper-constantan thermocouples were used with temperature readings taken directly with a portable potentiometer (Supermite, Thermo Electric Co.) (see figure 4-3). The thermocouple junctions were soldered and then dipped in an insulating paint (red Glyptol, G1201, General Electric Co.) to prevent corrosion, especially for the junctions in the soil. Figures 4-4 and 4-5 illustrate the locations of the thermocouples.

1-19	Soil temperatures
12,41	Duct temperatures
20-24	Outside surface temperatures
25-29	Temperature between two plastic films
30-34	Inside surface temperatures
35-36	Temperatures, 6 in. off surface
37-38	Polytube temperatures
39-40	Temperatures, 6 in. off surface
42-43	Outside temperatures, 12.5 ft above the ground
44-45	Outside temperatures, 8 ft above the ground
46-49	Inside temperatures, 6 ft above the ground
50	Temperature on exhaust fan wall
HTG 1	Hygrothermograph 1, 6 ft above the ground
HTG 2	Hygrothermograph 2, at the ground level

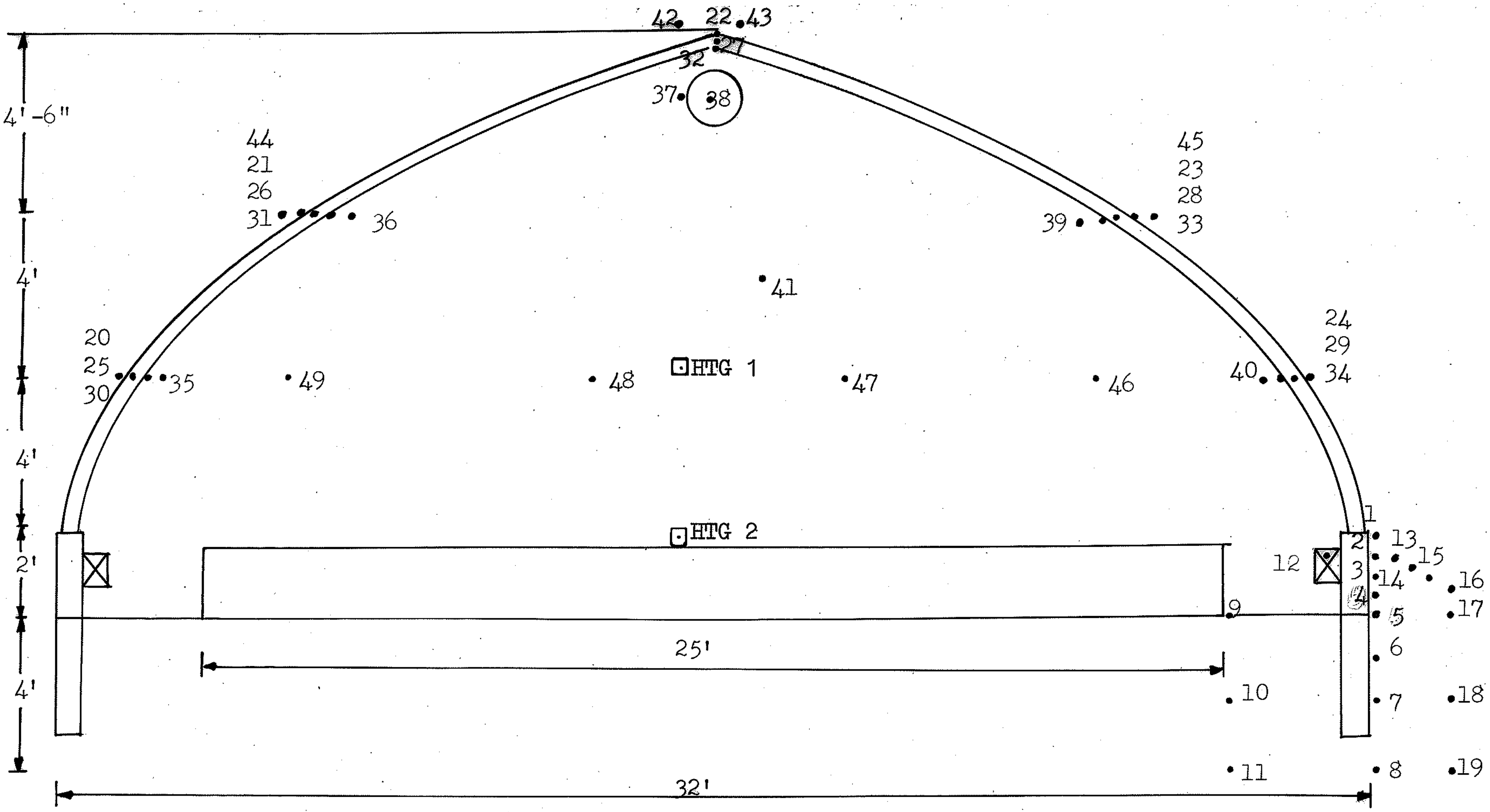
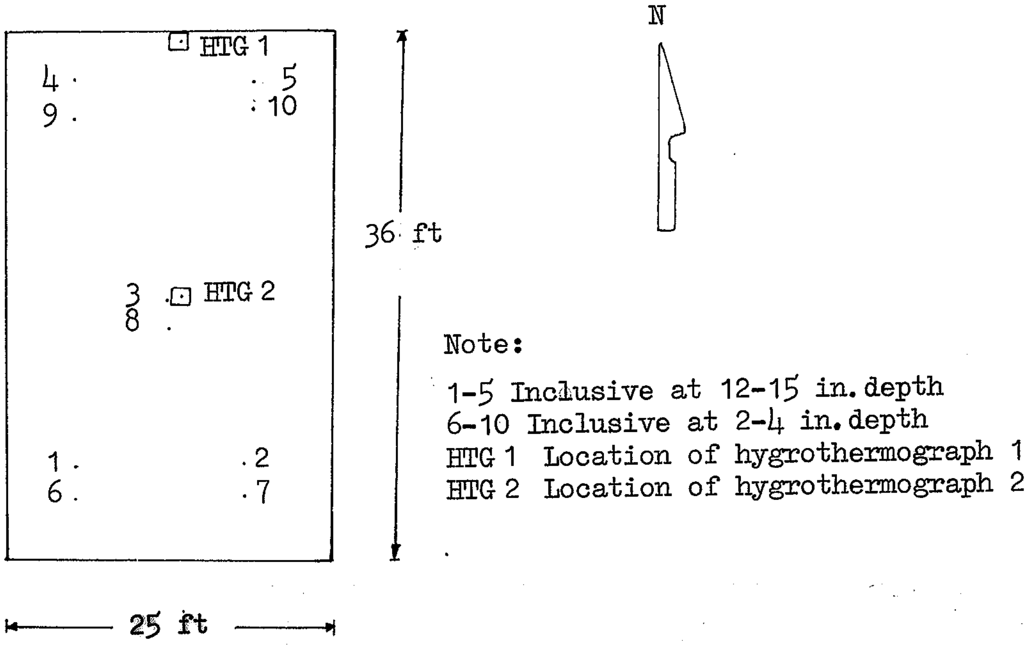


FIGURE 4-4 Location of Temperature Measurements



Note:

1-5 Inclusive at 12-15 in. depth
6-10 Inclusive at 2-4 in. depth
HTG 1 Location of hygrothermograph 1
HTG 2 Location of hygrothermograph 2

FIGURE 4-5 Location of Thermocouples for Measuring Soil Bed Temperatures

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Steam Sterilization

5.1.1 Soil Temperature and Time Required for Steaming

Temperatures were measured at eight locations along the length of the ground bed during steaming. Thermocouples were used to measure the soil temperature approximately 0.5 inches below the surface. The history of average soil temperatures for each bed is plotted in figures A-3 and A-4 (Appendix 4). Table 5-1 includes an estimate of the steaming efficiency based on the rated capacity of the boiler. Steaming efficiency, η, is defined as:

$$\eta = \frac{\text{calculated time}}{\text{actual time}} \times 100\% \qquad (5\text{-}1)$$

Table 5-1 shows all the calculations for determining the steaming efficiency. The values in column 3 and column 4 are respectively the average initial temperatures and the expected temperature 180F except tiles 5 and 6. The differential temperatures between column 3 and column 4 are entered directly in column 5. An example calculation of calculated time in column 6 with the data of tile 1 has been shown in Section 3.1. The actual time in column 7 is obtained by linear interpolation from figures A-3 and A-4 at 180F. Because the calculated time in column 6 is based on efficiency of 50 percent (see Section 3.1), it is divided by 2 before substituting into equation 5-1. The steam

TABLE 5-1

Steaming Time and Estimate of Steaming Efficiency

Tile No.	Steaming Order	Soil Temperature (F)			Steaming Time (hr)		
		Initial	Expected	Differential	Calculated[a]	Actual	Steaming Efficiency (%)[c]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	4	65.6	180	114.4	3.60	5.07	35.5
2	5	97.5	180	82.5	2.59	4.26	30.4
3	6	131.4	180	48.6	1.53	1.33	57.5
4	7	134.8	180	45.2	1.42	3.00	23.7
5[b]	1	65.8	162.6	96.8	3.04	4.00	38.0
6[b]	1	65.8	162.6	96.8	3.04	4.00	38.0
7	15	116.9	180	63.1	1.98	1.83	54.1
8	14	168.1	180	11.9	0.37	0.22	84.1
9	12	93.8	180	86.2	2.71	3.06	44.3
10	13	157.9	180	22.1	0.70	1.38	25.4
11	2	76.8	180	103.2	3.25	3.15	51.6
12	3	114.6	180	65.4	2.06	1.95	52.8
13	8	89.8	180	90.2	2.84	3.55	40.0
14	9	117.5	180	62.5	1.97	2.25	43.8
15	10	143.5	180	36.5	1.15	2.35	24.5
16	11	133.5	180	46.5	1.46	3.45	21.1
SUM		1773.3	2845.2	1071.9	33.71	44.85	664.8
AVERAGE		110.8	177.8	69.9	2.20	2.80	41.6

[a] Calculated time was based on boiler efficiency of 50 percent

[b] Tiles 5 and 6 sterilized at the same time

[c] Calculated as 100 (calculated time/2)/(Actual Time)

efficiency is entered in column 8 after calculating from equation 5-1.

With the exception of beds 5 and 6 all the beds had a final average temperature of over 180F. Beds 5 and 6 were the first beds to be steamed. An attempt was made to steam the two beds at the same time. After 8 hours there was no further increase in the bed temperature and the steaming had to be discontinued to prevent the soils from over-steaming. Subsequently all beds were steamed individually.

The low steaming efficiency achieved in beds 4, 10, 15 and 16 was due mainly to inadequate sealing of the bed surface to prevent steam leakage. This was especially true of bed 16 which was on the outside of the growing area adjacent to the gravel walk. It was impossible to seal the porous gravel walk.

5.1.2 Cost Comparison of Steam and Chemical Sterilization

Soil sterilization by steam was compared to two chemical methods as to cost and time required. The cost comparisons were based on current prevailing costs in Winnipeg.

For the comparisons all equipment was charged on a rental basis and labor was assumed to cost $2.00 per hour. The comparisons were also based on the actual growing area (32 ft by 42 ft; 1344 ft^2) and then converted to a 1000 ft^2 basis. No charge was made for the use of electricity or water.

The 10-boiler-hp steam-generator was rented for 3 days (63.25 hours of actual steaming time) at $40 per day. One hundred and fifty Imperial gallons (Imp Gal) of stove oil were consumed costing $0.20 per Imp Gal. Summing the costs of boiler rent, labor and fuel gave $276.50

for the cost of steaming the growing area or \$206 per 1000 ft^2.

The cost of Vapam sterilization was calculated on the use of two Imperial quarts (IQ) per 100 ft^2 (35). It was assumed that an applicator was rented for 1 day at \$3.00 per day and that the application could be done in 4 hours. With Vapam costing \$4.80 per Imp Gal the total cost for rent, labor and chemical was \$43.30 for the growing area or \$32.20 per 1000 ft^2.

The cost of methyl bromide sterilization was calculated on the use of 4 lb per 100 ft^2 (35). Assuming the same rent and labor costs as for Vapam the cost of methyl bromide sterilization was \$63.70 for the growing area or \$47.40 per 1000 ft^2. Methyl bromide cost \$0.98 per pound.

As noted above the time for steaming was 63.25 hours. The growing beds were ready for planting as soon as they cooled. Vapam sterilization requires additional aeration time before planting can start. A Vapam treatment of 5 to 7 days is usually followed by an aeration time of 2 to 3 weeks (22,35). A methyl bromide treatment of 24 to 48 hours usually has a 1 week aeration time (22,35). The various costs and required times for the three sterilization methods are summarized in table 5-2.

Table 5-2 indicates that steam sterilization using small steam generators is very costly but if the greenhouse operation has a central steam supply then steaming is the least expensive assuming no charge for steam. The rate of application of chemicals and the aeration times must be increased if the soil in the beds is cold and wet. The extra aeration time can be costly if the fall crop is delayed since fall light conditions and temperatures are lower (2). The net result would be lower yield but higher operating cost and therefore less income.

TABLE 5-2

Comparison of Costs and Time for Steam and Chemical Sterilization per 1000 ft^2

Sterilization Method	Cost (dollars) Total	Excluding labor	Excluding labor and Rent	Time (days)
Steam	206	112	22	3
Vapam	32	26	24	21
Methyl bromide	53	41	39	10

The costs listed in table 5-2 can be extrapolated to a standard commercial greenhouse (40 ft by 200 ft) by multiplying the table value by a factor of 6. For example the cost of Vapam sterilization for the larger greenhouse would be approximately 32 x 6 = $192.

5.1.3 Evaluating the Effectiveness of Steam Sterilization

The method of nematode extraction as described in Section 4.1.4 was used. The results of before and after steaming nematode counts are listed in table 5-3. Samples A, B and C were randomly taken from the surface of beds 2, 8 and 14, respectively, before steaming. After steaming, samples D, E and F were taken from the surface of beds 2, 8 and 14, respectively. Five 0.01 ml drops were extracted from each sample.

TABLE 5-3

Steaming Evaluation by Nematode Counts

Sample (Drops)		Number of Nematodes 1	2	3	4	5	Total	Moisture Content of Sample (%)
Before	A	4	2	2	1	2	11	24.4
	B	6	3	3	1	3	16	25.5
	C	2	1	6	3	8	20	26.4
After	D	0	0	0	0	0	0	30.0
	E	3	1	5	4	4	17	27.9
	F	0	0	0	0	0	0	27.2

Averages, Nematodes per drop

Before	3.13
After	1.13

The average nematode counts for before and after were substituted into equation 4-1 in order to calculate the number of nematodes per gram of soil. The results were 157 nematodes per gram of soil for before steaming and 57 nematodes per gram of soil after steaming. The nematode population was significantly decreased by steam sterilization of the soil beds. A simple t-test was used to establish the significance at the 1 percent level. The difference was significant at the 1 percent level (see Appendix 3).

When individual samples were compared it was noticed that sample E showed an increase in nematodes over sample B. This could have been due to recontamination with nematodes during the extraction procedure or large clods may not have been effectively steamed. If the latter were true then the nematodes were not killed and were able to reproduce.

In all samples soil moisture showed an increase. Table 5-3 shows an average increase of soil moisture of approximately 3 percent. Baker and Roistacher (13) found soil moisture content increases of from 2 to 7 percent.

5.2 Temperature and Humidity Measurement

As noted in section 4.2 continuous temperature and humidity measurements were obtained with hygrothermographs at two locations. Figure 5-1 and figure 5-2 show a portion of a typical weekly record of temperature and humidity for the 1971 spring crop. The temperature and humidity fluctuations are a result of furnaces on-off cycle.

The data were reduced by using only the daily maximum temperature and the daily minimum temperature to plot figure 5-3 for the spring crop. The maximum daily temperatures were not controlled by ventilation prior to 5 May, as a result the temperatures were in general too high. On 5 May exhaust fans were installed and operated manually. By 9 June the ventilation system was completed and after that date the exhaust fans and the internal air circulating fan were controlled automatically by thermostats. The daily temperatures were then kept close to the optimum temperature in spite of much higher outside maximum temperatures.

The heating system was capable of maintaining acceptable daily minimum temperatures. The temperatures at the 6 ft and surface levels were more uniform after the internal air circulating fan was started on 9 June 1971.

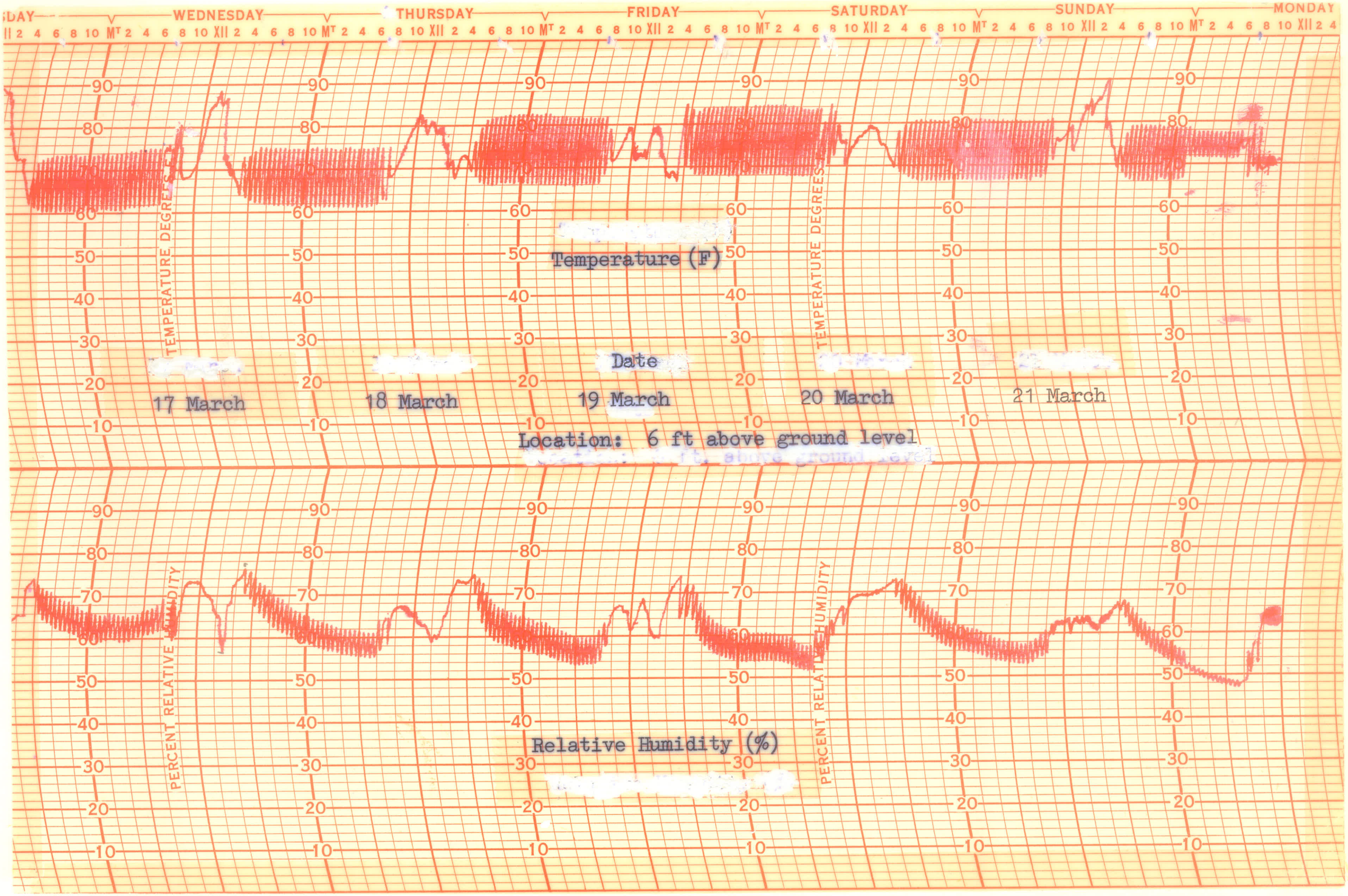


FIGURE 5-1 Portion of Typical Weekly Record of Greenhouse Temperature and Humidity of 1971 (Hygrothermograph Recording at 6 ft above Ground Level)

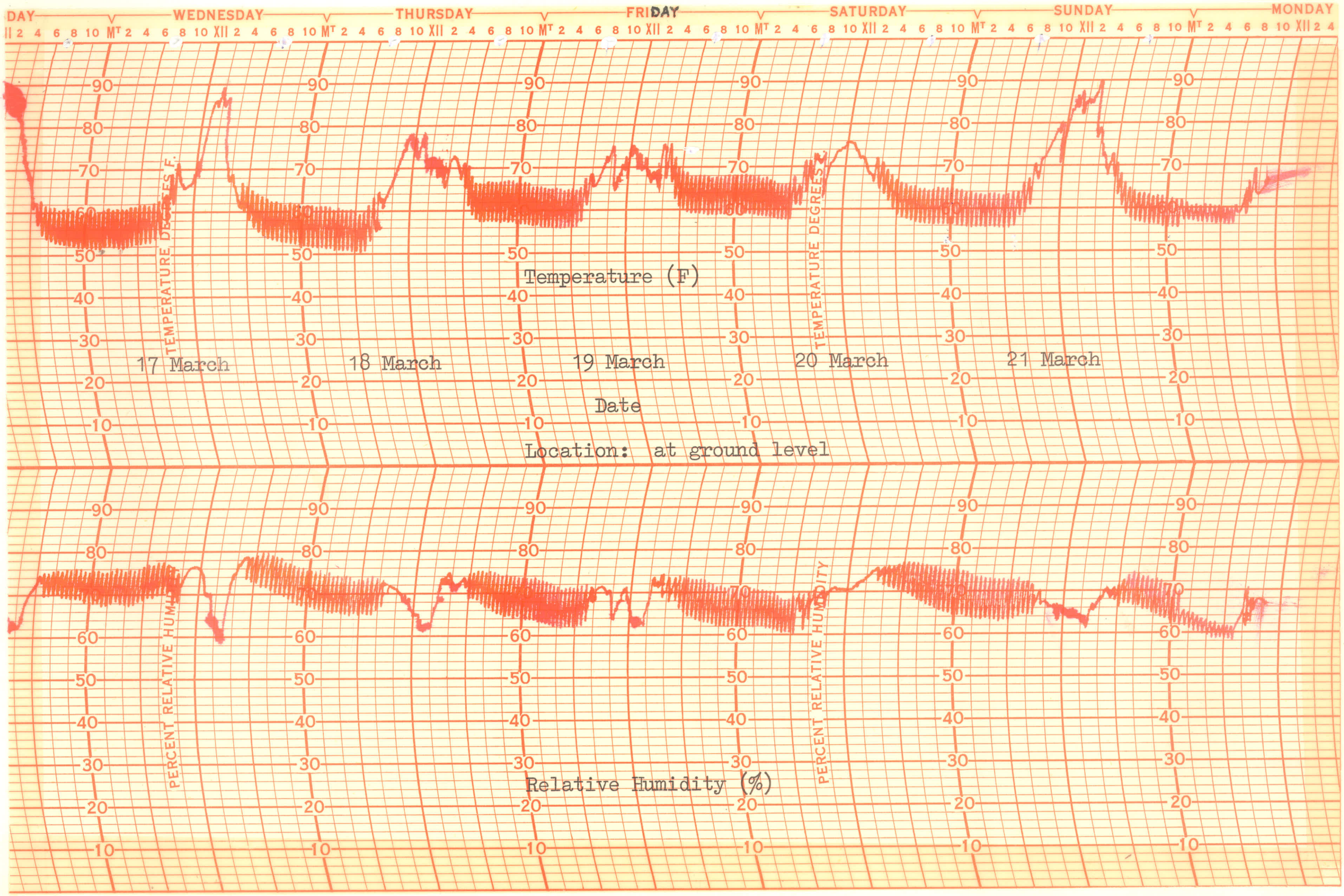


FIGURE 5-2 Portion of Typical Weekly Record of Greenhouse Temperature and Humidity of 1971 (Hygrothermograph Recording at Ground Level)

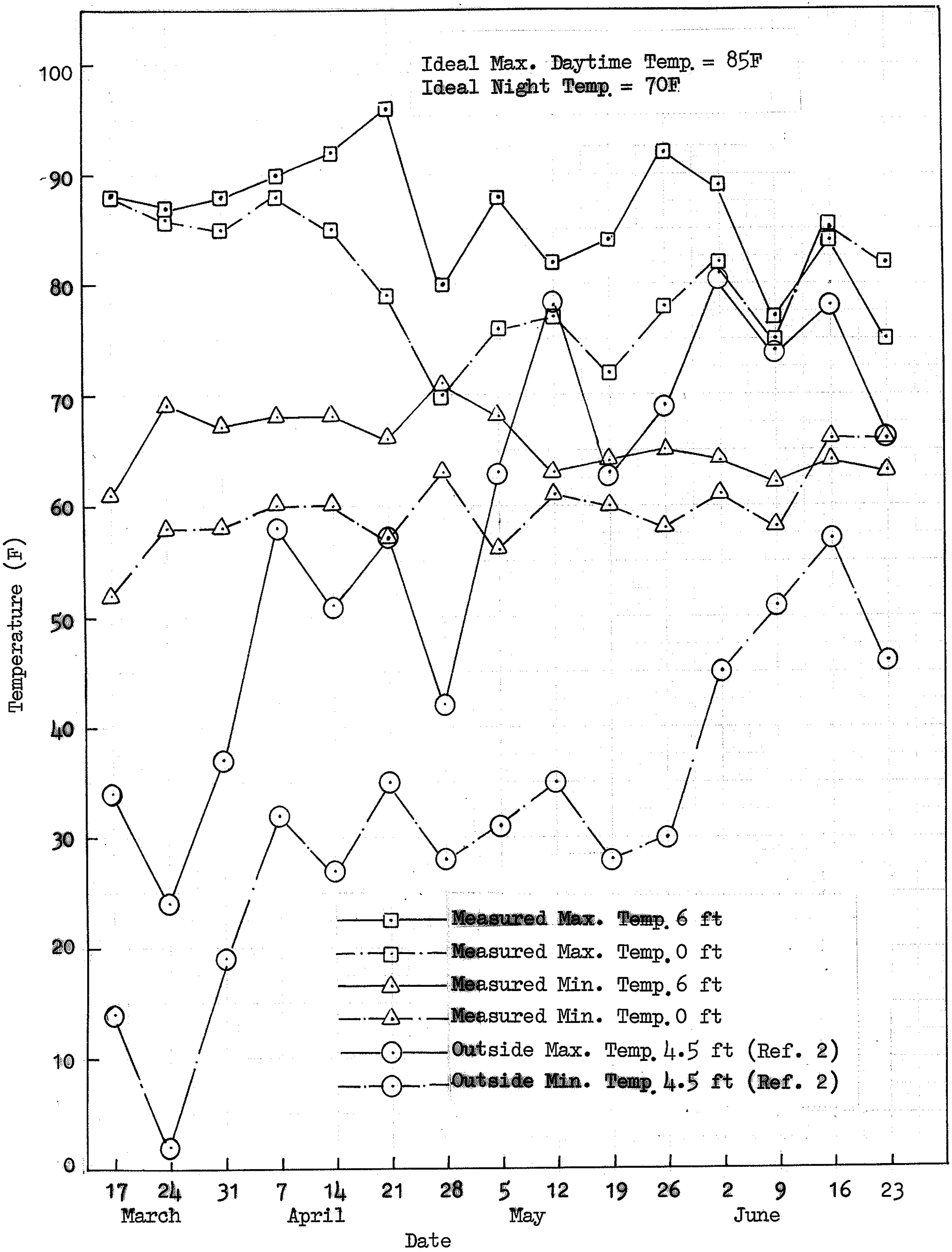


FIGURE 5-3 Comparison Interior and External Air Temperatures of 1971 Spring Crop

Figure 5-4 illustrates the maximum and minimum daily temperatures at two locations for the 1971 fall crop. The ventilation and internal air circulating system was in continuous operation for the duration of the fall crop. The temperature was better controlled than for the spring crop when the system was not installed until late in the season.

The average soil temperatures at two depths are given in figure 5-5. The initial soil temperatures for the spring crop were not recorded but observation of the tomato plants suggested that the soil temperature was too cold. This was certainly possible since the soil mass had been frozen before the furnaces were started. Hot air was applied to the soil through the tile. The plant response was immediate with very rapid growth occurring. Thermocouples were installed in the soil by 28 April. After this date the soil temperatures were satisfactory.

As illustrated in figures 5-1 and 5-2 the relative humidity varied as the heat input from the furnaces varied. The relative humidity data were reduced by the same method as was used for the temperature data. Weekly maximum and minimum relative humidities were taken from the recorded data of the two hygrothermographs. The results for the 1971 spring and fall crops are presented in figures 5-6 and 5-7, respectively.

For the 1971 spring crop there were great variations in the relative humidities at the two locations prior to the installation of the internal air circulating system. After early June when the circu-

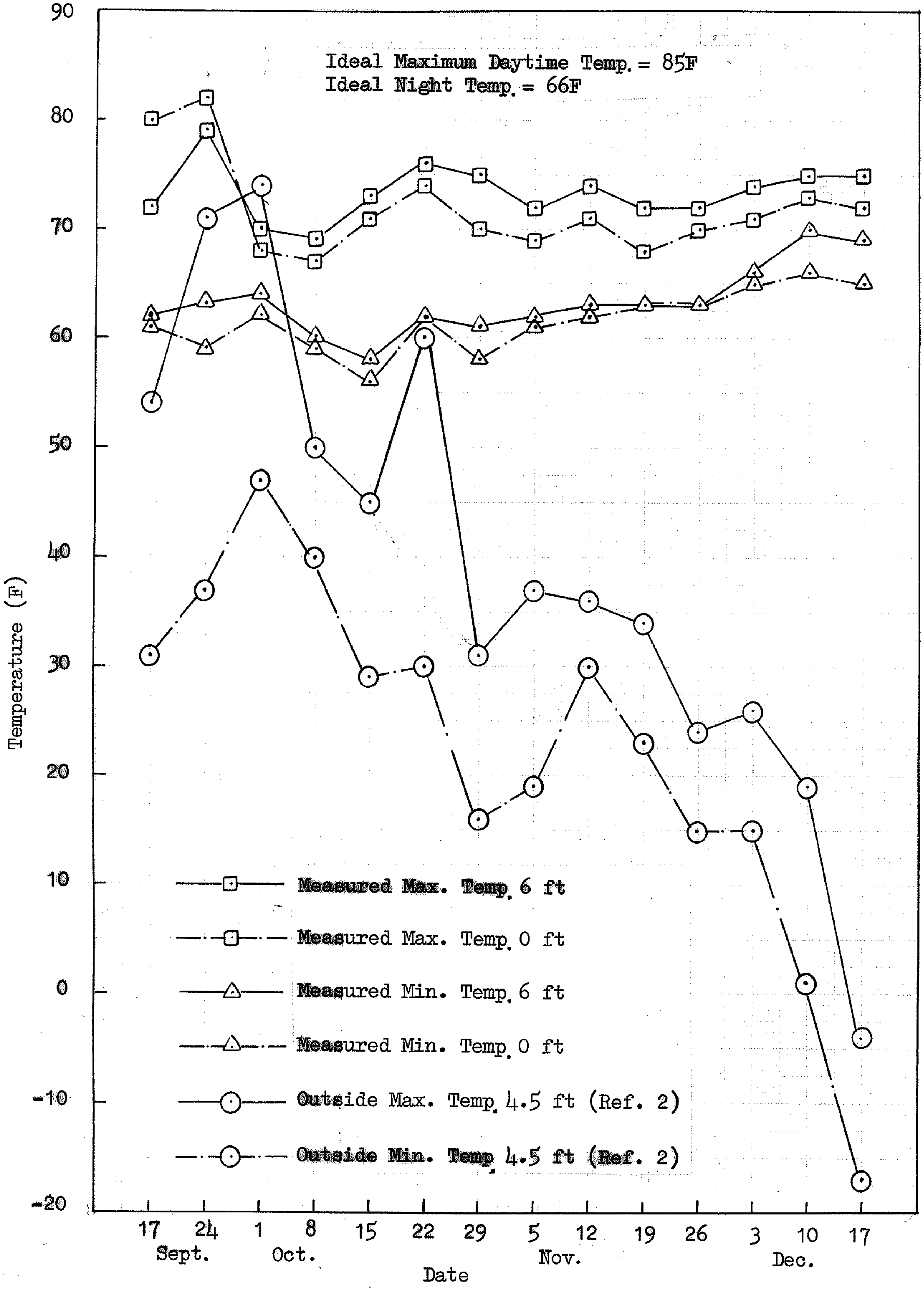
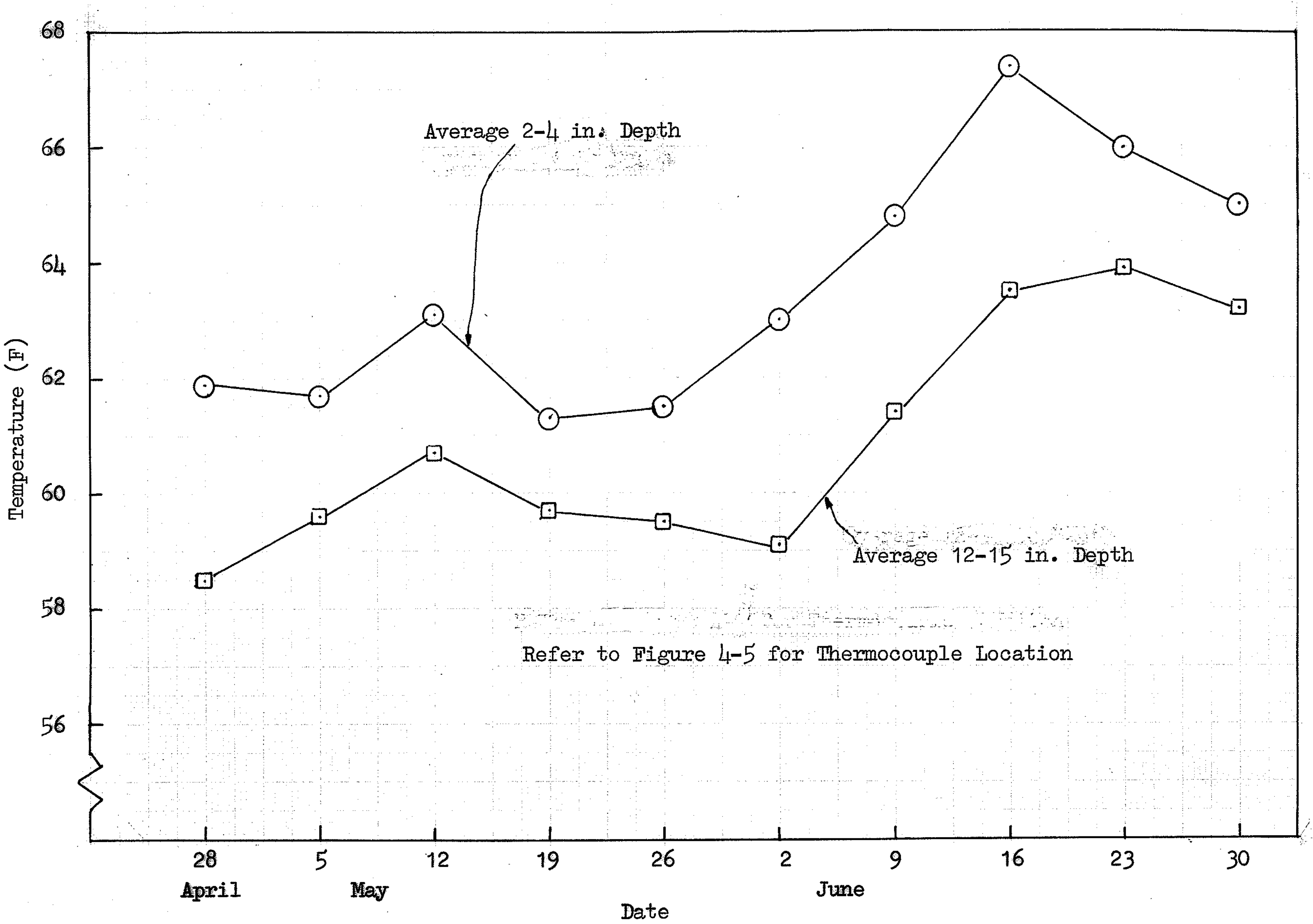


FIGURE 5-4 Comparison of Interior and External Air Temperatures of 1971 Fall Crop



Average 2-4 in. Depth

Average 12-15 in. Depth

Refer to Figure 4-5 for Thermocouple Location

FIGURE 5-5 Average Temperature of 1971 Spring Crop at Two Soil Depths

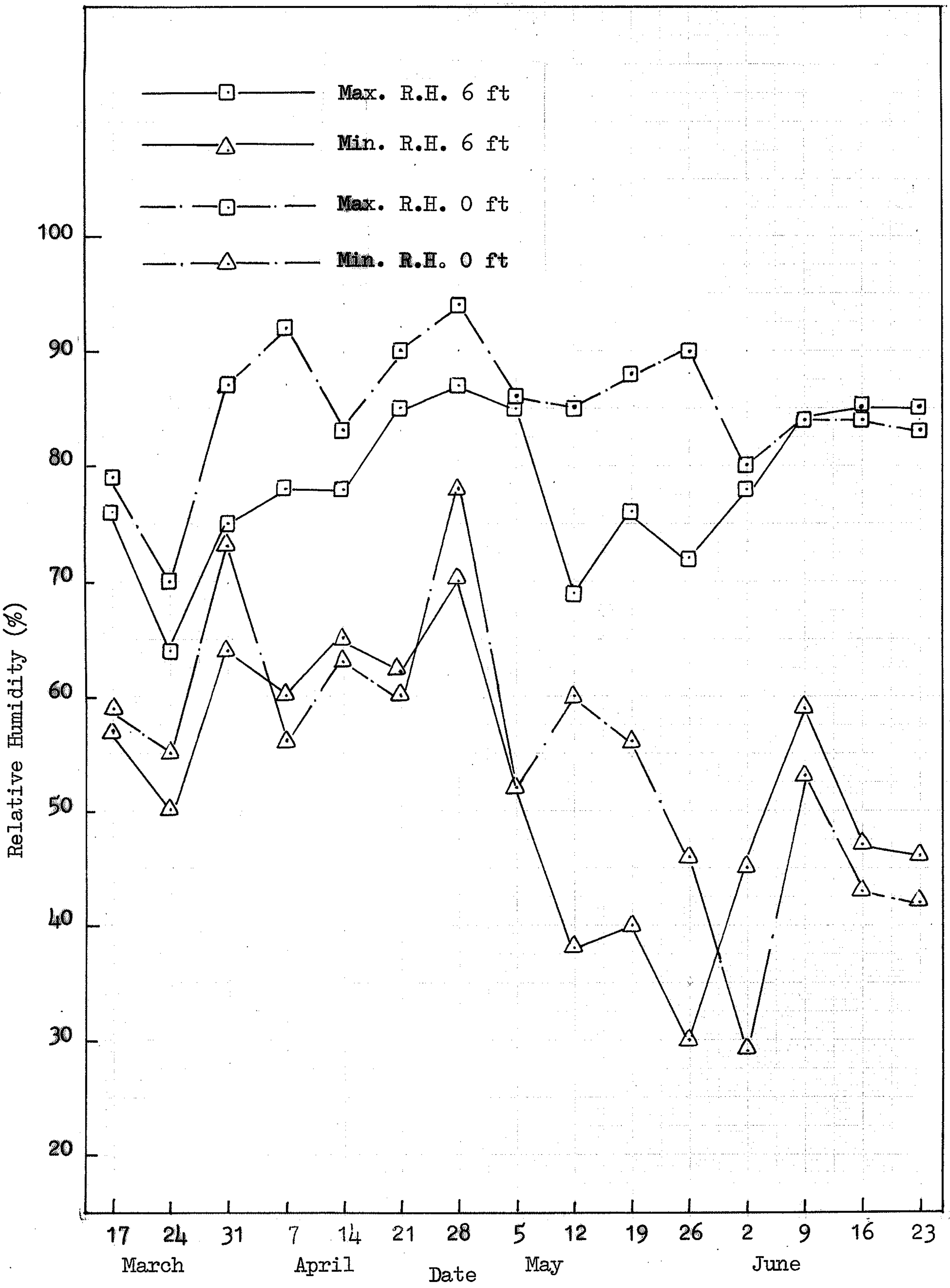


FIGURE 5-6 Greenhouse Relative Humidity for 1971 Spring Crop

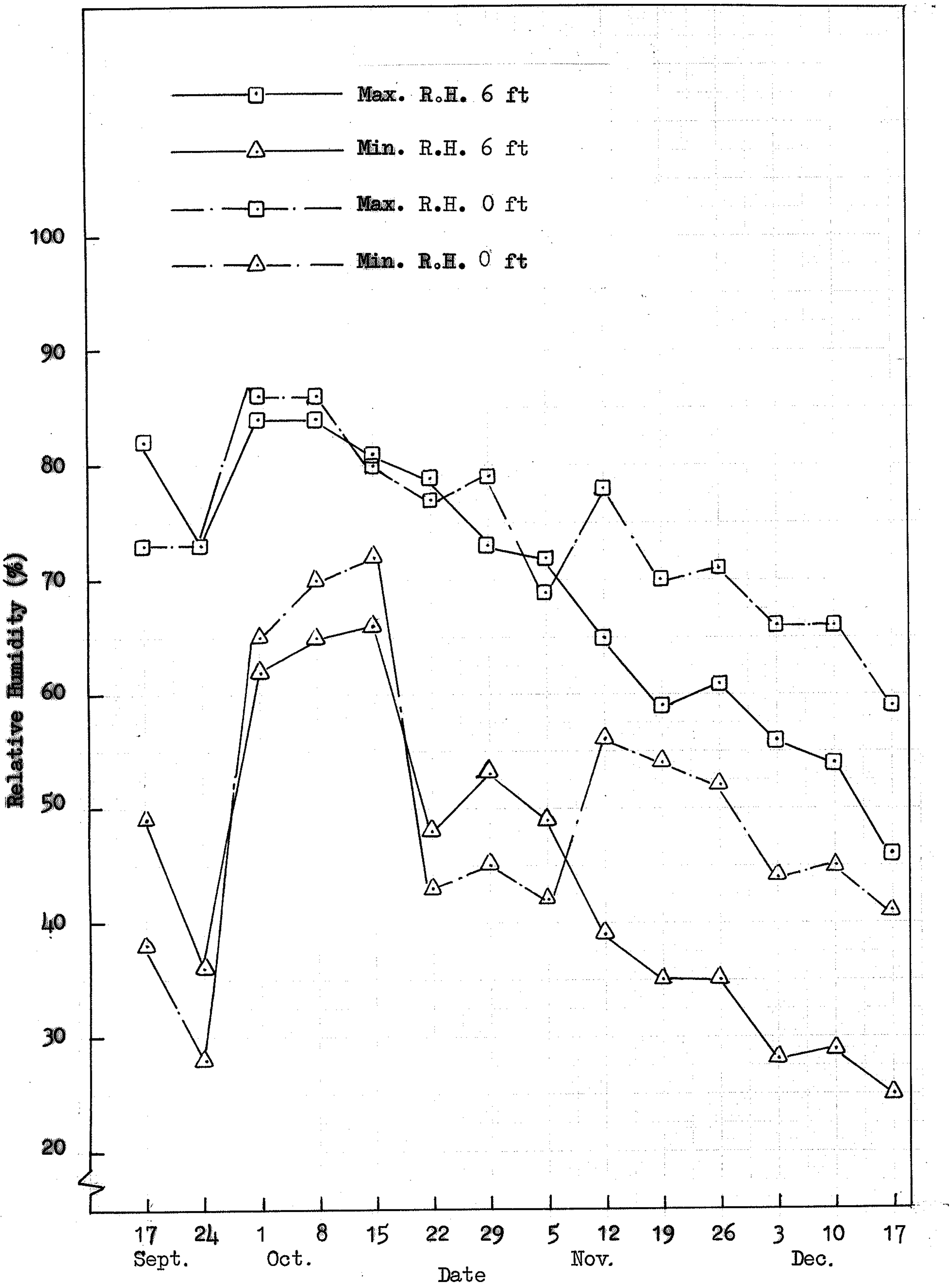


FIGURE 5-7 Greenhouse Relative Humidity for 1971 Fall Crop

lating system was installed the maximum and minimum relative humidities tended to be the same for both the 6 ft and ground levels (figure 5-6). This trend was also evident for the fall crop. More uniform relative humidities parallel the more uniform temperatures noted with the operation of the internal air circulating system, of course. With the onset of cold fall weather there was a gradual decrease in the greenhouse relative humidity whereas in the spring there was an increase with the increasingly hotter summer weather.

The temperature variation in the growing space was only 6F as shown in figure 5-8. There were higher temperatures near the roof and near the heating ducts but within the growing space the nonuniformity of temperature was acceptable. Figure 5-8 also shows the temperature profiles for the roof, soil and side walls.

5.3 Gas Consumption Measurement

Temperature and gas consumption were measured for 12 nights early in the spring during the 1972 spring crop. The data are presented in table 5-4. The heat loss estimated by gas consumption was compared to the theoretical heat loss calculated by heat transfer theory. This comparison was based on an estimate of the efficiency of the furnace. The efficiency of furnaces vary according to many factors such as amount of excess air, cleanliness of heat transfer surfaces etc. The theoretical equation used was derived assuming a constant overall heat transfer coefficient, U (Ref. 39, page 110). The equation was:

$$M_f = \frac{Q_f (t_r - t_a) N}{(t_i - t_o) F_{cu} E_s} \qquad (5\text{-}2)$$

Average Outside Temperature = 7F
Average Inside Temperature = 67F
All Temperatures are Degrees Fahrenheit

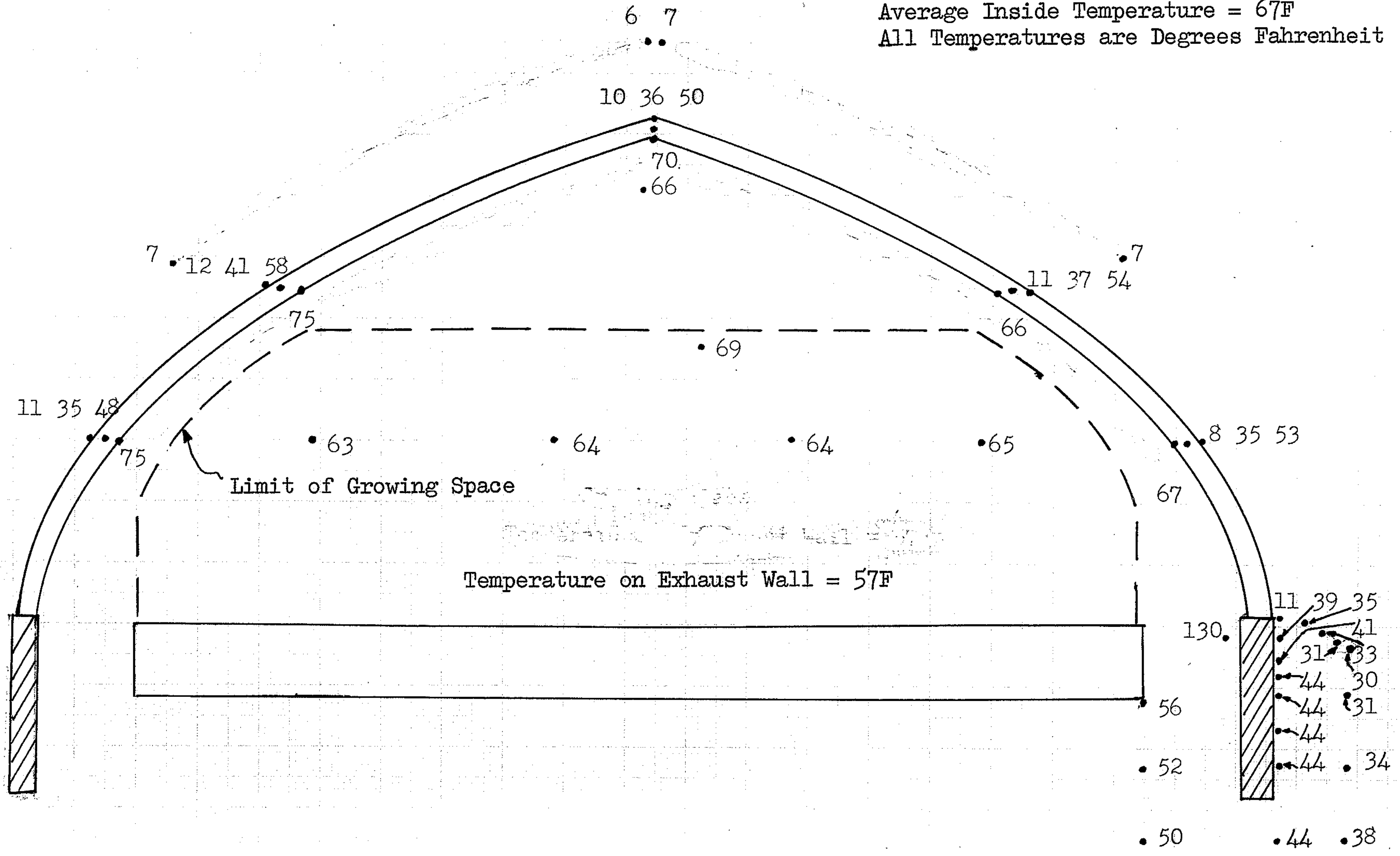


FIGURE 5-8 Temperature Distribution for Greenhouse Cross-Section at 23:20 Hours on 3 April 1972 (Refer to Figure 4-4 for Thermocouple Location)

TABLE 5-4

Gas Consumption Measurement and Comparison (1972 Spring Crop)

Date	Observation Period (hr)	Elapsed Time (hr)	Actual Gas Used (ft^3)	Gas Consumption Rate (ft^3/hr)		Temperature Differential (F)[c]	Wind Speed[d] (mph)	
				Actual	Predicted[b]		Mean	Max
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
27 MARCH	1930-2330	4.00	350	87.5	93.7	37.5	13.5	20
28	1930-2350	4.33	300	69.3	87.7	35.1	4.6	8
29	2007-2345	3.63	400	110.2	108.7	43.5	4.9	8
30	1930-2330	4.00	350	87.5	86.4	34.6	7.7	13
3 APRIL	1700-2320	6.33	800	126.4	142.4	57.0	12.6	19
6	2005-2355	3.83	400	104.4	105.7	42.3	11.0	16
7	1930-2320	3.83	320	83.6	79.4	31.8	13.2	15
8	2005-0025[a]	4.33	400	92.4	85.7	34.3	16.8	20
9	2020-2400	3.67	500	136.2	86.9	34.8	15.5	20
10	2020-0010[a]	3.83	400	104.4	92.4	37.0	7.7	13
11	2010-0015[a]	4.08	300	73.5	78.7	31.5	5.0	10
12	2000-2335	3.58	200	55.9	53.0	21.2	9.0	15

[a] Next day

[b] Predicted by equation 5-2

[c] Difference of average inside and outside temperature

[d] Data from meteorlogical summary, Department of Environment (2)

where

M_f = unit of fuel required per heating period, ft^3 of gas

Q_f = calculated heat losses under design conditions, Btu/hr

t_r = average inside temperature, F

t_a = average outside temperature, F

N = number of hours in the heating period, hr

t_i = inside design temperature, F

t_o = outside design temperature, F

F_{cu} = heat content per unit of fuel, Btu/ft^3

E_s = efficiency of fuel utilization, dimensionless

The heat loss, Q_f, from the greenhouse under design conditions was calculated using equation (3-4).

A sample calculation of the use of equation 5-2 can be found in Appendix 2. A typical temperature distribution for a cross section of the greenhouse is shown in figure 5-8. The predicted gas consumption is compared to the actual gas consumption in figure 5-9. The actual gas consumption data points have been fitted to a line of regression of actual gas consumption on the difference of inside temperature to outside temperature.

The regression equation is:

$$GVC = 1.94 \Delta T + 23.0 \qquad (5\text{-}3)$$

where

GVC = gas consumption, ft^3/hr

ΔT = difference between inside and outside temperature, F

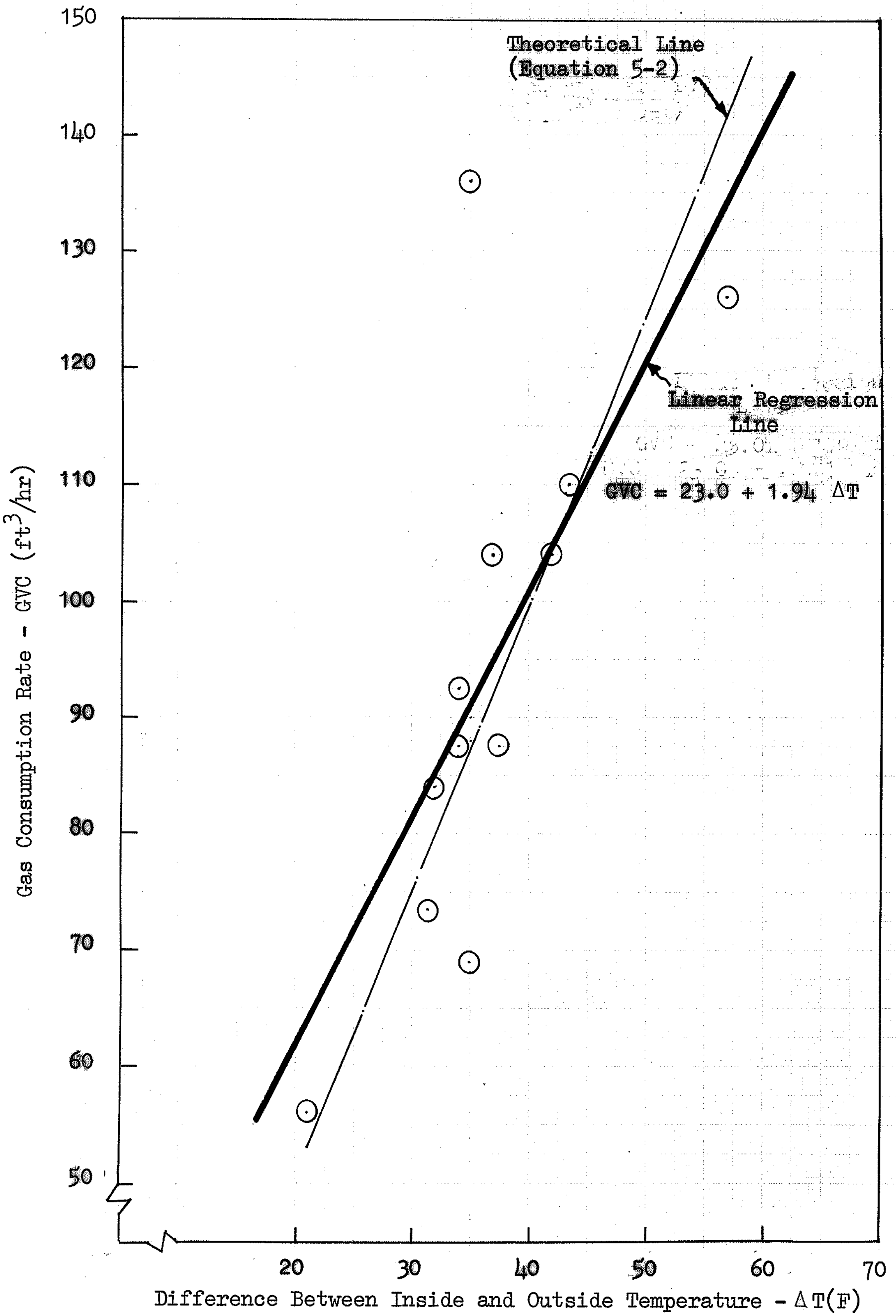


FIGURE 5-9 Comparison of Calculated Gas Consumption to Actual Gas Consumption

The intercept (23.0 ft^3/hr) provides for heat input at a temperature difference of zero. This heat was used for evaporation and transpiration. The theoretical gas consumption curve (equation 5-2) does not account for evapotranspiration and therefore indicates zero gas use for zero temperature differential. At small temperature differences the gas use predicted by theory was less than that used. At large temperature differences the actual gas use was less than that predicted by theory. The error in this case contributes to a higher factor of safety if the theory were used to design the capacity of the furnaces. Wind direction and speed contributed to the observed variation between actual gas use and predicted gas use.

5.4 Heat Requirements for Commercial Greenhouses

Commercial plastic-covered greenhouses are basically similar to the experimental greenhouse except size is increased. The dimensions of a commercial greenhouse are 40 ft by 200 ft. The inside and outside radii for the roof can be approximated as 19.67 ft and 20 ft, respectively. If the commercial greenhouse is of light framing similar to the experimental greenhouse, then the heat transfer coefficients will be the same. Assuming that the coefficients are approximately correct the total heat loss for the commercial greenhouse is

$$Q_f = 800{,}000 \text{ Btu/hr}$$

The above value of heat loss represents the maximum predicted heat loss for design temperatures of -17F outside temperature, and 70F inside temperature. This amount of heat must be supplied by the heating system if there is a sustained period of -17F outside temperature. If different outside design temperatures are considered to apply then figure 5-10 predicts the total heat loss for night time conditions. For example, if it were desired to grow during January and a -25F outside design temperature is assumed then the predicted total heat loss would be 868,000 Btu/hr.

The heat loss values must be modified by consideration of fuel conversion efficiency and a reasonable factor of safety in order to specify the heating system capacity. Figure 5-11 illustrates how these factors can be applied to the above predicted heat loss of 800,000 Btu/hr for a standard 40 ft by 200 ft commercial greenhouse (outside design temperature = -17F). A factor of safety equal to 1.0 would only be used in conditions where supplemental heating equipment was available. If a factor of safety of 1.5 is assumed the indicated installed input capacity for natural gas furnaces would be 1,600,000 Btu/hr (75 percent efficiency) or 1,200,000 Btu/hr for electric heating (100 percent efficiency, 350kw). Implied factors of safety for the "rule-of-thumb" value of 7 Btu/hr-ft^3 appear to be .77 for the experimental greenhouse and 1.1 for the 40 ft by 200 ft greenhouse. The units installed in the experimental greenhouse gave a factor of safety of 1.04 (assuming furnace efficiency of 75 percent).

5.5 Ventilation Requirements for Commercial Greenhouses

The ventilation system should be designed to maintain permissible greenhouse temperatures when there is maximum radiant-energy input. The maximum solar-heat-gain would normally occur at solar noon

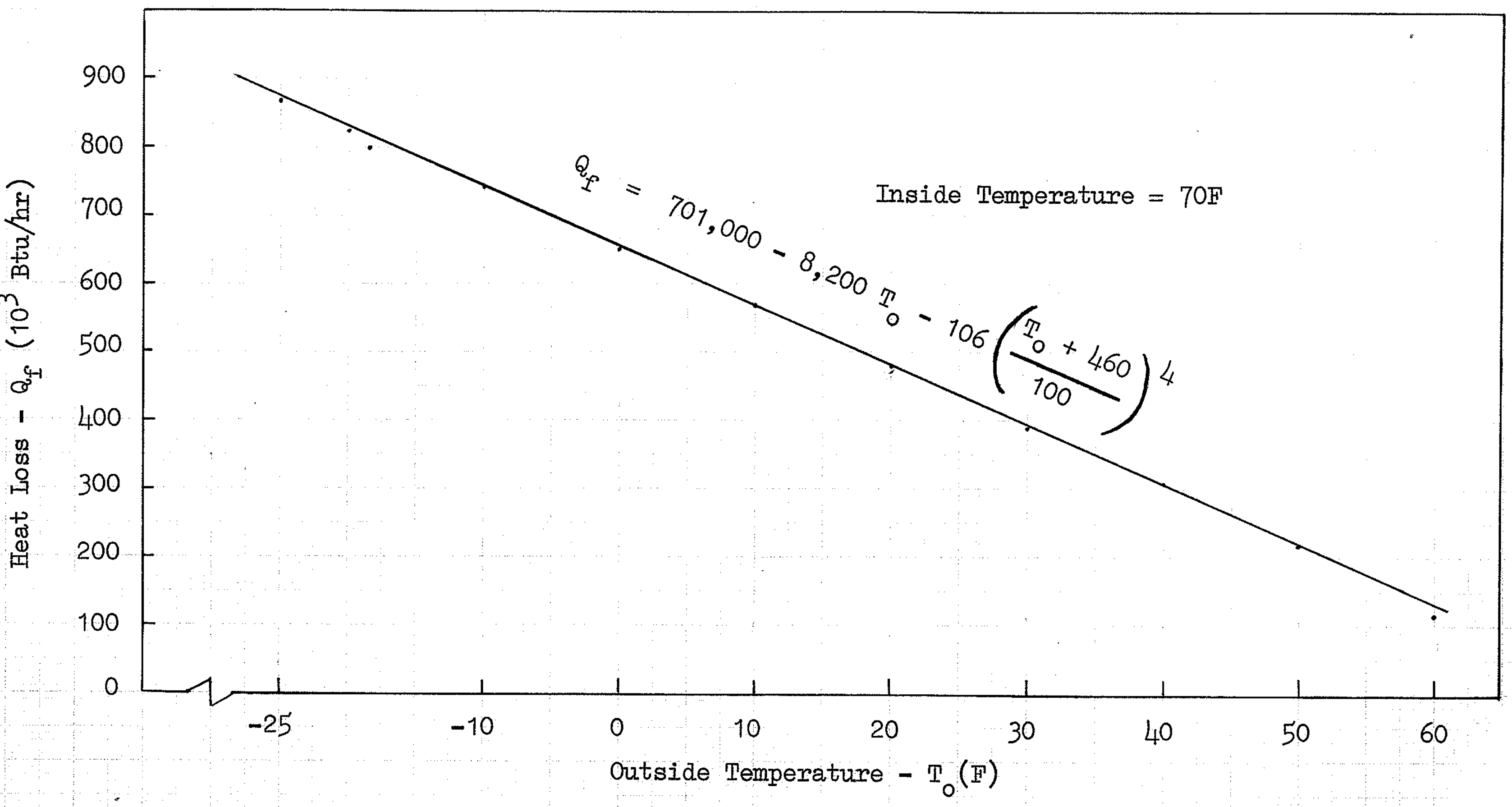


FIGURE 5-10 Predicted Heat Loss from 40 ft x 200 ft Greenhouse at Various Outside Temperatures

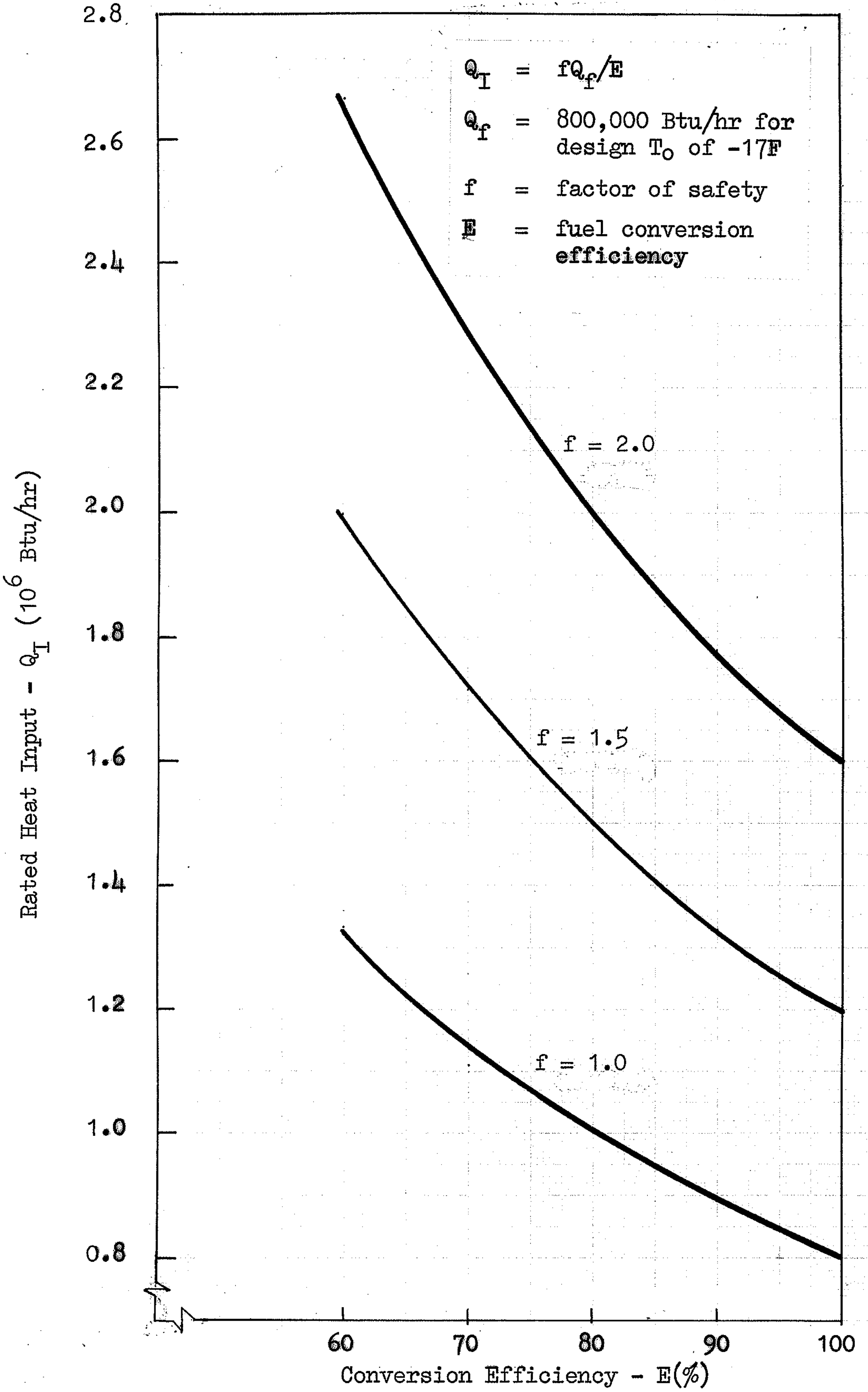


FIGURE 5-11 Heating System Input Capacity for Various Conversion Efficiencies and Factors of Safety

on 21 June. If the outside air temperature at this time is also high it will not be possible to control the inside temperatures at permissible levels. Assuming a commercial greenhouse of similar construction to the experimental greenhouse and using the methods of Section 3.3.1, the required ventilation rate to maintain the inside temperature at no more than 10F higher than the outside temperature would be 81,500 ft^3/min for the 40 ft by 200 ft greenhouse. This ventilation rate is equivalent to 0.65 air changes per minute (ACM).

Figure 5-12 was developed using equations (3-11), (3-12), and (3-14) to illustrate the problem of ventilation when outside temperatures are too high. The curves apply only to the design of the ventilation system at the maximum solar-heat-input period. For the above ventilation rate (0.65 ACM) and if the outside temperature exceeds 60F the greenhouse temperature cannot be held to a desirable 70F. For example, if the outside temperature was 65F and the same ventilation rate was used the inside temperature would be approximately 75F. If the ACM were increased to 1.3 the desired 70F inside temperature could be maintained. At the ventilation capacity of 1.0 ACM recommended by the ASHRAE Guide and Data Book (4) the greenhouse temperature will not be controlled at the desirable 70F whenever the outside temperature exceeds approximately 64F. In practice the permissible greenhouse temperature must be allowed to increase, i.e. at 1.0 ACM the greenhouse inside temperature can be maintained at 90F for an outside temperature of approximately 84F.

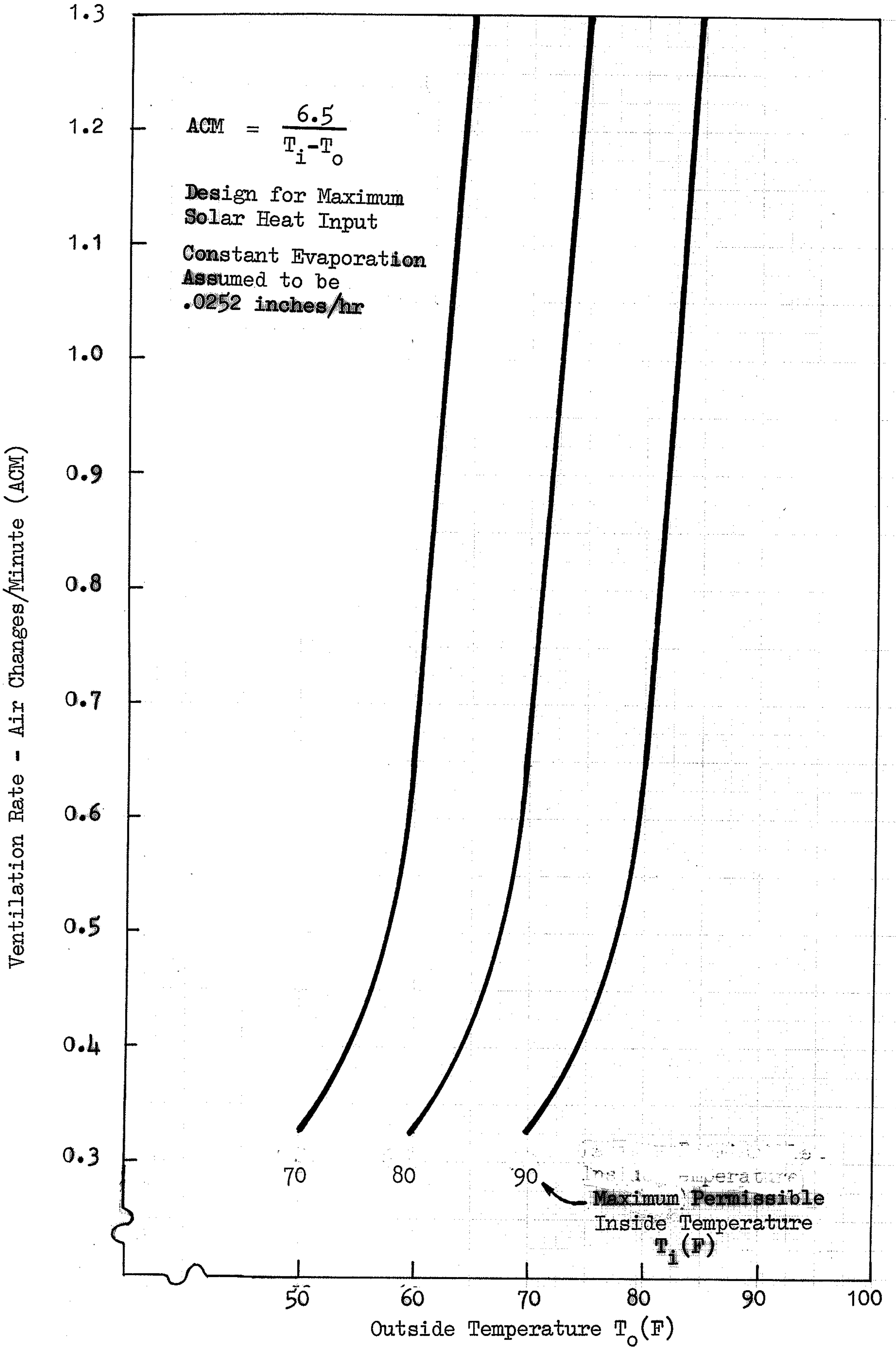


FIGURE 5-12 Ventilation Rates for Permissible Inside Temperatures at Different Outside Temperatures

CHAPTER VI

CONCLUSIONS

Based on the foregoing results and discussion the following conclusions were made:

1. Steam sterilization using small rented steam generators raised the temperature of the ground beds to sterilization temperatures but was more expensive than chemical sterilization. If the greenhouse has a central steam supply and if it is assumed there is no charge for the steam then steaming is less expensive than chemical sterilization.

2. Although the treatment times for the steam sterilization of individual tile lines varied it is concluded that the rule of thumb of "10 ft^2 of bed area per boiler horsepower" applies and results in reasonable treatment times per unit area.

3. Based on rated boiler-horsepower the steaming efficiency using small portable steam generators was approximately 42 percent.

4. To obtain good steaming efficiency, the surface of the beds must be completely sealed to prevent the leakage of steam and the soil in the beds should be well worked to give a homogeneous soil mass.

5. For small areas steam sterilization can be faster than chemical methods since there is no aeration time required and cooling times are very short so that the next crop can be planted sooner.

6. Installed heating capacity based on estimated heat losses was higher than that estimated from the measured fuel consumption but

the excess capacity provides for a necessary safety factor.

7. Ventilation capacity rated at one air change per minute will not maintain greenhouse temperatures cool enough if the outside air temperature exceeds 84F, and even at this outside air temperature the interior temperature will be higher than ideal for tomatoes.

CHAPTER VII

RECOMMENDATIONS FOR FURTHER STUDY

1. Recent developments in air-steam sterilization of soils should be investigated and tested on the ground beds to see if there is any improvement in efficiency or reduction in costs.

2. Although sterilization effectiveness was evaluated by nematode counts there should be a follow-up evaluation based on the performance of the next crop with respect to disease control.

3. The effectiveness of evaporative cooling by a simple water spray on the roof should be studied since temperature control on hot spring and summer days is inadequate.

4. Supplemental light for use in late fall, winter and early spring should be investigated.

5. Methods of reducing heat losses at night should be investigated as to feasibility, ease of use, potential for automation and possible operating cost reduction.

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APPENDICES

APPENDIX 1

Calculation of Greenhouse Heat Loss and Heat Gain

In a design situation it is necessary to estimate the maximum heat loss from the greenhouse in order to specify the heating system capacity. The maximum heat gain must be estimated so that a ventilation system of adequate capacity can be specified. In the following calculations conventional heat transfer relationships have been used (3, 5, 6, 7, 8, 9, 10, 11, 27, 39, 48).

A. Heat loss from the greenhouse roof

To simplify the calculations the greenhouse was modeled as a semicylinder and the relationships for radial heat flow were considered to apply. Figure A-1 illustrates typical sections of the roof.

The heat loss through the roof was estimated from

$$q_1 = U_r A_r (T_i - T_o) \tag{A-1}$$

where

q_1 = heat flow rate from the roof, Btu/hr

U_r = overall heat transfer coefficient for the roof

= .571 Btu/hr-ft^2-F

A_r = outside area of the roof

= 2380 ft^2

T_i = inside design temperature

= 70F

T_o = outside design temperature

= -17F

Substituting the above values into equation (A-1) resulted in

q_1 = 118,000 Btu/hr.

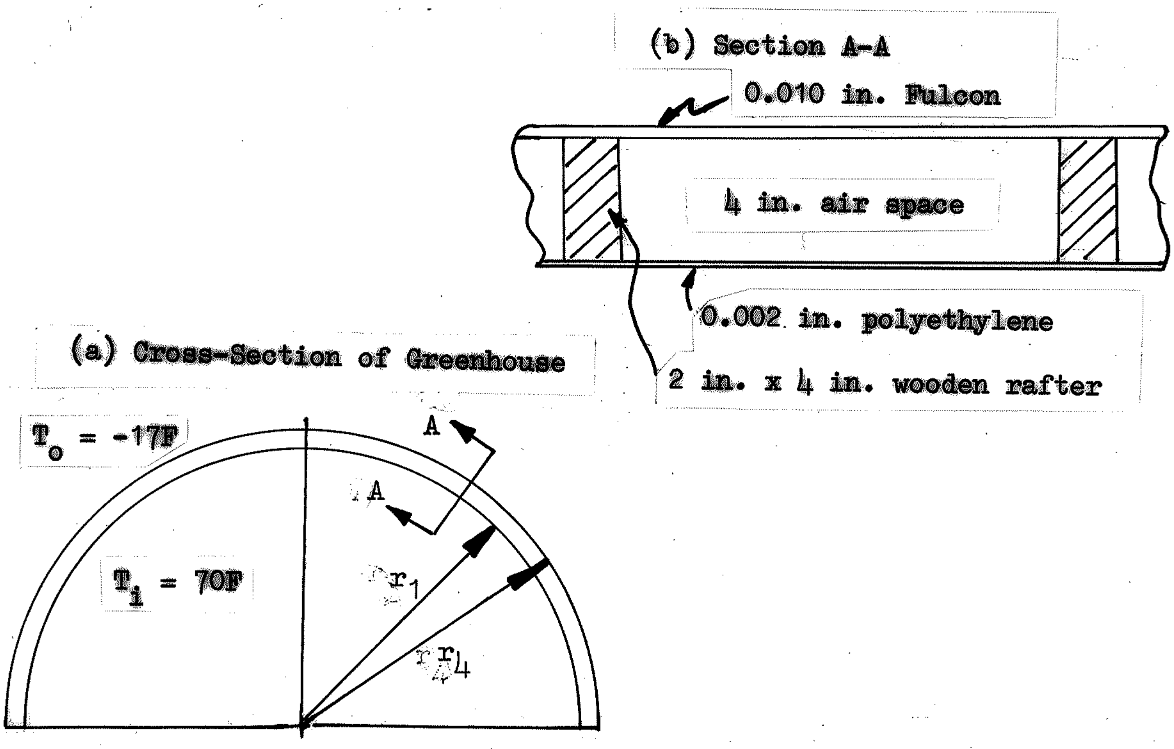

FIGURE A-1 Typical Cross-Sections of the Plastic Covered Greenhouse

The calculation of the overall heat transfer coefficient, U_r, was as follows. The thermal resistances of the polyethylene liner and the Fulcon covering were considered very small and were ignored. The radius to the inside surface of the Fulcon was considered approximately equal to the radius to the outside of the covering. Under these simplifying assumptions the expression for the overall heat transfer coefficient became (Ref. 27, page 38):

$$U_r = \frac{1}{\dfrac{1}{h_o} + \dfrac{r_4/r_1}{h_i} + \dfrac{r_4 \ln (r_4/r_1)}{(1 - \frac{\ell_a}{\ell}) K_W + \frac{\ell_a}{\ell} K_a}} \qquad \text{(A-2)}$$

where

h_o = outside surface conductance

= 6 Btu/hr-ft^2-F (Ref. 5)

h_i = inside surface conductance

= 1.6 Btu/hr-ft^2-F (Ref. 5)

r_4 = outside radius of greenhouse model

= 15 ft

r_1 = inside radius of greenhouse model

= 14.67 ft

ℓ = length of greenhouse

= 50.5 ft

ℓ_a = axial length of air space (rafters excluded)

= 46.1 ft

K_W = thermal conductivity of plywood

= .067 Btu/hr-ft-F (Ref. 7)

K_a = thermal conductivity of air space

= .38 Btu/hr-ft-F (from conductance of 4 in. air space, 1.14 Btu/hr-ft^2-F) (Ref. 6)

The above values substituted into equation (A-2) resulted in U_r = .571 Btu/hr-ft^2-F, the value used in equation (A-1).

If the radius of curvature for the roof is considered to be very large, a horizontal plane could have been assumed for the heat transfer. The heat loss through the rafters was ignored since the rafters made up a small percentage of the total area. With these assumptions

$$U = \frac{1}{1/h_i + 1/C_{as} + 1/h_o} \qquad \text{(A-3)}$$

$$= .599 \text{ Btu/hr-ft}^2\text{-F}$$

where

C_{as} = overall conductance coefficient for the 4 in. air space (Assume effective emissivity = .82, mean temperature = 50F)

= 1.14 Btu/hr-ft^2-F (Ref. 6) and the heat loss becomes

q_1 = 124,000 Btu/hr.

B. Heat loss from north end wall

The construction of the north end wall is shown in the following figure, A-2. The studs and the door have been omitted from the calculation.

The heat loss from the north end wall was calculated from

$$q_2 = U_n A_n (T_i - T_o) \qquad \text{(A-4)}$$

where

q_2 = heat flow across the north end wall, Btu/hr

U_n = overall heat transfer coefficient for the wall

= .111 Btu/hr-ft^2-F (calculated result from equation A-5)

A_n = area of the north end wall

= 353 ft^2

T_i, T_o as shown in sketch.

With the above values the heat loss from the north end wall was calculated as

q_2 = 3400 Btu/hr

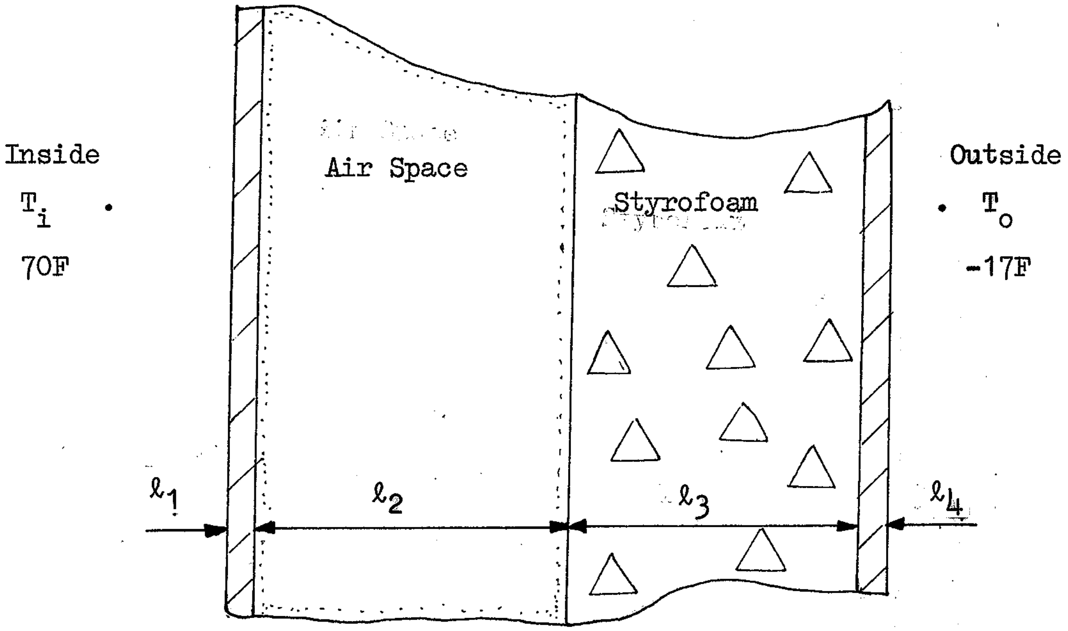

FIGURE A-2 Detail of North End Wall Cross-Section

The overall heat transfer coefficient, U_n, was estimated by the following relationship:

$$U_n = 1/\left(\frac{1}{h_i} + \frac{\ell_1}{k_1} + \frac{1}{C_{as}} + \frac{\ell_3}{k_3} + \frac{\ell_4}{k_4} + \frac{1}{h_o}\right) \qquad \text{(A-5)}$$

where h_i, h_o as before, but h_i = 1.46 Btu/hr-ft^2-F for vertical wall

ℓ_1, ℓ_4 = thickness of plywood sheathing

= 3/8 in. = 0.0313 ft

k_1, k_4 = thermal conductivity of the sheathing

= 0.067 Btu/hr-ft-F

C_{as} = thermal conductance for the vertical 2.5 in. air space

= (effective emissivity) (heat transfer by radiation) + heat transfer by the combined of conduction and convection

= (.82)(.9) + .310 = 1.048 Btu/hr-ft^2-F (Ref. 39, page 67)

ℓ_3 = thickness of Styrofoam insulation

= 1.5 in. = 0.125 ft

k_3 = thermal conductivity of Styrofoam

= 0.02 Btu/hr-ft-F (Ref. 8)

Using the above values for calculating U_n resulted in U_n = .111 Btu/hr-ft^2-F.

C. Heat loss from the south end wall

The south end wall was similar to the roof in cross-section but was located entirely in a vertical plane. Equations (A-1) and (A-3) were used to calculate the heat loss. The overall heat transfer coefficient, U_s, was evaluated using

h_i = 1.46 Btu/hr-ft^2-F (Ref. 5)

h_o = 6.0 Btu/hr-ft^2-F (Ref. 5)

C_{as} = 1.07 Btu/hr-ft^2-F (for vertical plane) (Ref. 6)

The results of the calculations were:

U_s = .559 Btu/hr-ft^2-F

q_3 = 17,200 Btu/hr.

D. Heat loss from the greenhouse edges

Heat lost from the low foundation wall and from the edges of the ground beds is referred to as "edge loss" and was calculated as follows:

$$q_4 = f\ell\,(T_f - T_o) \qquad \text{(A-6)}$$

where

q_4 = heat loss from the low foundation wall and all the floor space within 3 ft of any exposed edge, Btu/hr

f = edge loss factor which varies with the amount of insulation used, .54 Btu/hr-ft-F (extrapolation from Ref. 39, page 72)

ℓ = length of exposed edges, ft

= 165 ft

T_f = inside air temperature at floor level, F

= 70F

T_o = outside air temperature at floor level, F

= -17F

The above values substituted into equation (A-6) resulted in

$$q_4 = 7{,}750 \text{ Btu/hr}$$

E. Heat loss from interior of greenhouse ground bed

The heat loss from the greenhouse ground beds was calculated from the equation

$$q_5 = U_f A_i (T_f - T_g) \qquad \text{(A-7)}$$

where

q_5 = heat loss from the ground beds, Btu/hr

U_f = overall heat transfer coefficient for heat loss to the soil due to convection at the surface as well as conduction in the soil

= 0.10 Btu/hr-ft^2-F (Ref. 48)

A_i = interior floor area (excluding a 3 ft wide strip along the exposed edges of the greenhouse) (Ref. 39, page 73)

= 1,157 ft^2

T_f = inside temperature at ground level

= 70F

T_g = average deep soil temperature

= 50F (by actual measurement, 6 ft deep).

The heat loss calculated with the above values was

$$q_5 = 2{,}300 \text{ Btu/hr}$$

F. Heat loss by radiation

The net radiation heat loss from the greenhouse to the surroundings has been given by equation (3-6). As described previously the result of applying equation (3-6) gave

$$q_6 = 14{,}700 \text{ Btu/hr}$$

Summary of heat losses from the greenhouse

The component heat losses, q_i, were summed to give the total estimated heat loss from the greenhouse. The result was

$$\begin{aligned} Q_f &= q_1 + q_2 + q_3 + q_4 + q_5 + q_6 \\ &= 163{,}000 \text{ Btu/hr} \end{aligned} \tag{A-8}$$

The above estimate assumes no ventilation, a condition found at night when the minimum temperature would be likely to occur. The greenhouse heating system must supply this amount of heat. In practice the heating system capacity would be increased by a reasonable factor of safety.

Solar Heat Gain and Ventilation Rate

The total solar heat gain has been estimated in Section 3.3.1 where the amount is given as

$$Q_i = 395{,}000 \text{ Btu/hr}$$

A portion of the heat gain is lost as latent heat in the evaporation of water in the greenhouse. If the evaporation rate is assumed to be

0.0252 in./hr (48) then the heat loss can be estimated by equation (3-14) as

$$Q_e = 221{,}000 \text{ Btu/hr}$$

The net heat gain will be the difference between the above values and must be removed from the greenhouse by ventilation. The net amount is

$$Q_s = 174{,}000 \text{ Btu/hr}$$

The above sensible heat can be removed by providing a ventilation rate as calculated by equation (3-11) and (3-12). The ventilation rate was based on a 10F temperature difference and was calculated as

$$\text{CFM} = 16{,}400 \text{ ft}^3/\text{min.}$$

The internal volume of the experimental greenhouse was estimated to be 17,850 ft^3 so that the number of air changes per minute was 0.92.

APPENDIX 2

Sample Calculation of Predicted Gas Consumption

For the night of 27 March the inside temperature readings were:

Thermocouple Number	Temperature (F) at 19:30	Temperature (F) at 23:30
35	77.4	60.1
36	74.5	57.4
37	68.8	56.9
38	71.8	59.5
39	68.9	60.8
40	65.5	59.3
41	67.0	67.0
46	61.2	68.6
47	61.2	69.4
48	61.2	73.7
49	61.2	74.0
50	56.8	70.0
	795.5	776.7

$$\text{Grand mean } t_r = \frac{795.5 + 776.7}{24} = 65.5\text{F}$$

The outside temperature readings were:

Thermocouple Number	Temperature (F) at 19:30	Temperature (F) at 23:30
42	35.5	37.3
43	25.2	24.9
44	25.2	24.5
45	25.8	25.5
	111.7	112.2

Grand mean $t_a = \dfrac{111.7 + 112.2}{8} = 28.0\text{F}$

Temperature difference $t_r - t_a = 65.5 - 28.0 = 37.5\text{F}$

From equation (5-2)

$$M_f = \frac{Q_f\ (t_r - t_a)\ N}{(t_i - t_o)\ F_{cu}\ E_s} \qquad (5\text{-}2)$$

where

Q_f = 163,000 (from equation (A-8), Appendix 1)

$t_r - t_a$ = 37.5F (from above calculation)

t_i = -17F (designed inside temperature)

t_o = 70F (designed outside temperature)

N = 1 hr

F_{cu} = 1,000 Btu/ft^3 (for natural gas)

E_s = 75 percent

With the above values, the gas consumption rate was calculated as

$M_f = 93.7\ \text{ft}^3/\text{hr}$

APPENDIX 3

T-test for Significant Difference of Two Means (31)

	X_1 (Nematodes per Drop-Before)	X_2 (Nematodes per Drop-After)	
	4	0	
	2	0	
	2	0	
	1	0	
	2	0	
	6	3	
	3	1	
	3	5	
	1	4	
	3	4	
	2	0	
	1	0	
	6	0	
	3	0	
	8	0	
X	47	17	
X^2	207	67	$\bar{X}_1 - \bar{X}_2 = 2.00$
$\bar{X}$	3.13	1.13	
$(X)^2$	2209	289	

$$S^2 = \frac{X^2 - (X)^2/n}{n-1}$$

$$(n_1-1)\ S_1^{\ 2} = 207 - \frac{2209}{15} = 59.74$$

$$(n_2-2)\ S_2^{\ 2} = 67 - \frac{289}{15} = 47.73$$

$$S_w^{\ 2} = \frac{(n_1-1)\ S_1^{\ 2} + (n_2-2)\ S_2^{\ 2}}{n_1 + n_2 - 2} = \frac{59.74 + 47.74}{15 + 15 - 2} = 3.84$$

$$t_{cal} = \frac{\bar{X}_1 - \bar{X}_2}{S_w(\frac{1}{n_1} + \frac{1}{n_2})^{\frac{1}{2}}} = \frac{2.00}{(3.84)^{\frac{1}{2}}\ (\frac{1}{15} + \frac{1}{15})^{\frac{1}{2}}} = 2.80$$

To test

$H_o : u_1 = u_2$

$H_1 : u_1 > u_2$ (Reject H_o, if $t_{cal} > t_{\alpha}\ (n_1 + n_2 - 2)$)

$t_{.05}\ (28) = 1.701$ (5% significance level, $\alpha = .05$)

$t_{.01}\ (28) = 2.467$ (1% significance level, $\alpha = .01$)

Since $2.80 > 2.467$ we reject H_o and conclude the mean Nematode Count before steaming is higher than that after steaming at 1% of significance level.

APPENDIX 4

Average Soil Temperatures Versus Steaming Time for Estimating Column 7 of Table 5-1

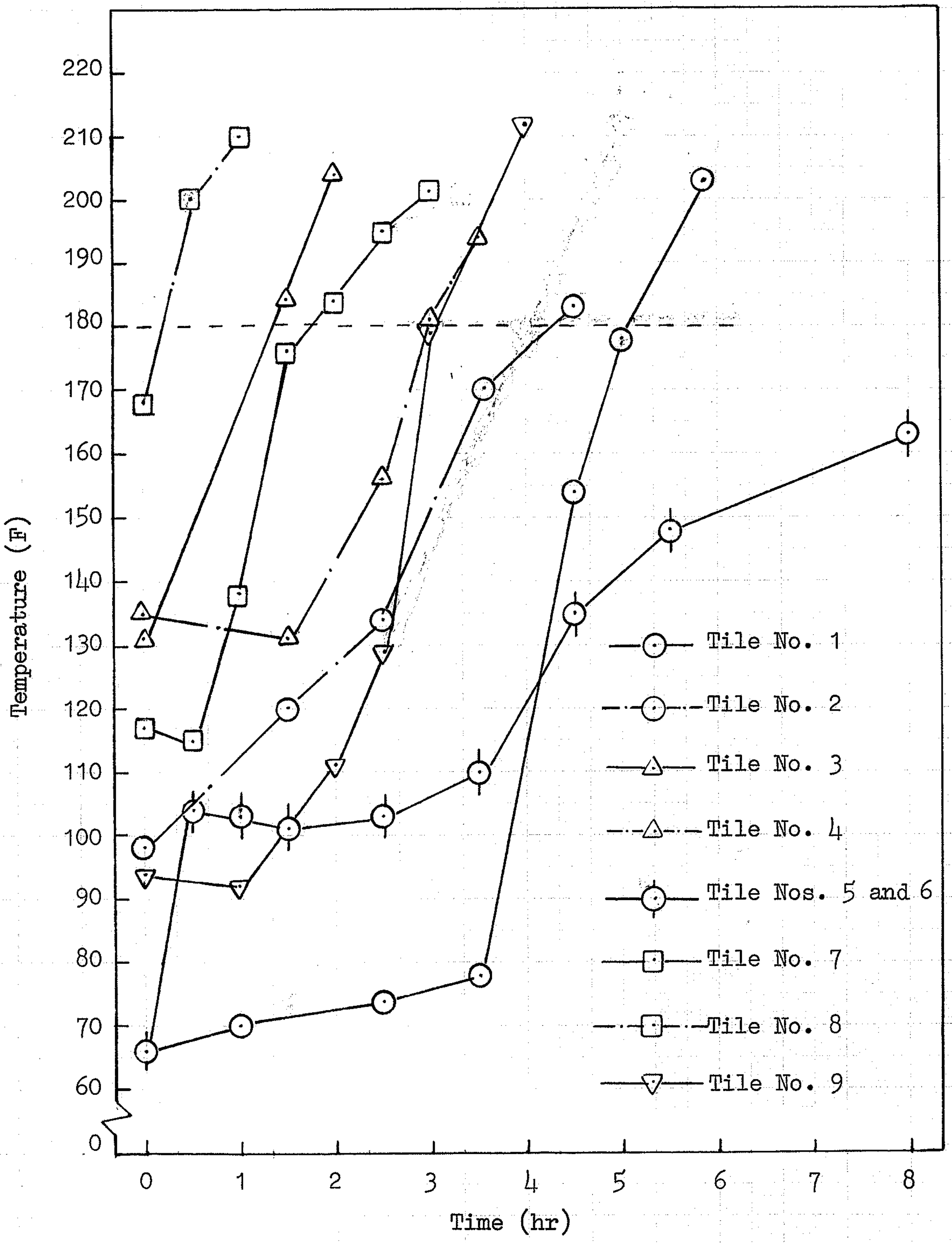

FIGURE A-3 Average Soil Temperatures Versus Steaming Time for Estimating Column 7 of Table 5-1 (Tile Nos. 1, 2, 3, 4, 5, 6, 7, 8, and 9)

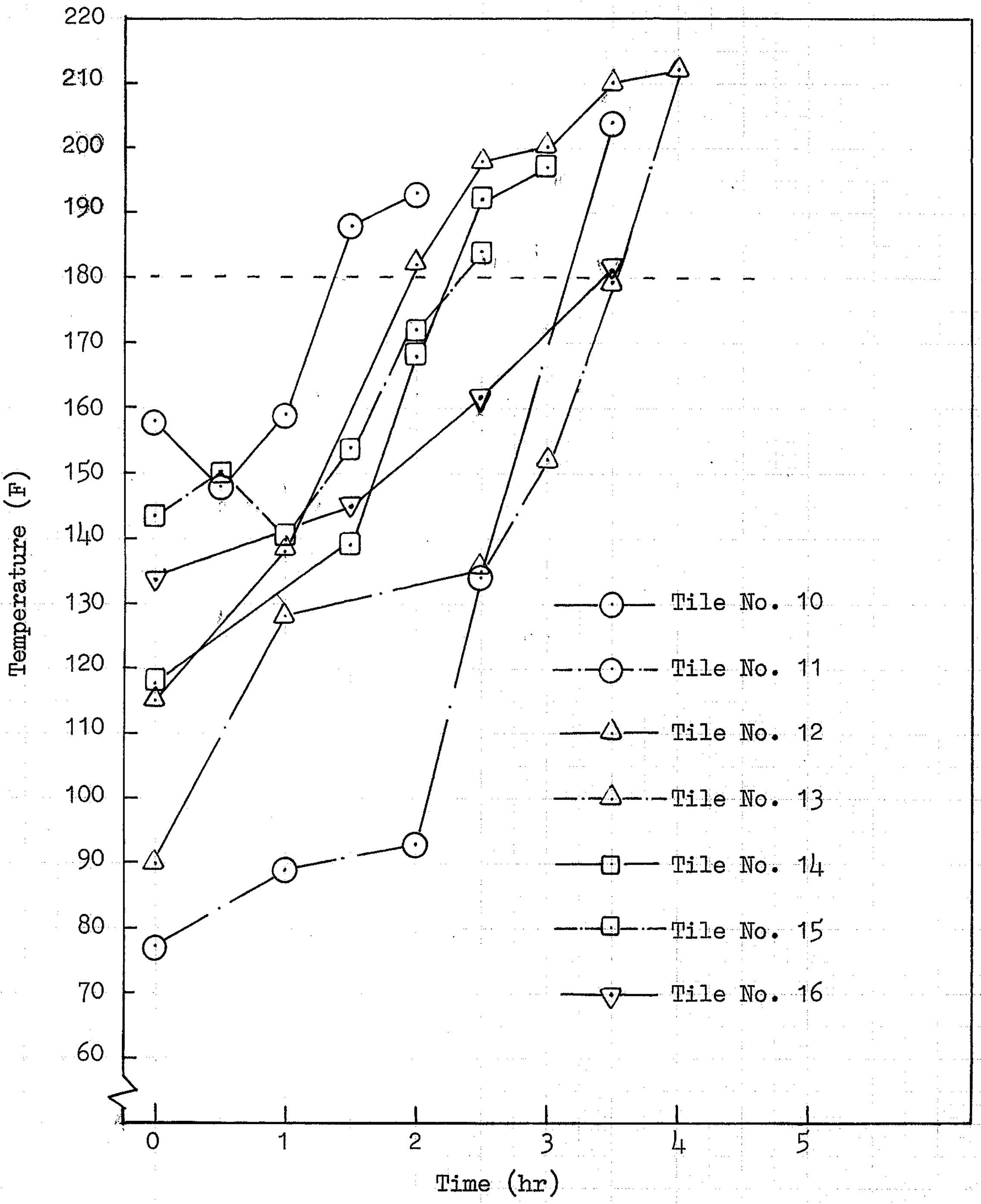

FIGURE A-4 Average Soil Temperatures Versus Steaming Time for Estimating Column 7 of Table 5-1 (Tile Nos. 10, 11, 12, 13, 14, 15 and 16)