# OVERWINTERING CONTAINER SEEDLINGS USING UNDERGROUND HEAT

Noval Enterprises[1]
1988

#64

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# ABSTRACT

This pilot study was undertaken to investigate the potential for ameliorating low root temperatures often associated with overwintering container tree seedlings. An instrumented experimental plot, part of which was heated from below the container, was assembled using various containers at the Noval Enterprises greenhouse, Joffre, Alberta.

The heating was found effective for increasing mid-winter root temperatures significantly, with a very small operating cost. Plant moisture stress was monitored through part of the winter using a pressure chamber and various comparisons were made between containers, heated-vs-unheated sections, and polyethylene covered and uncovered areas.

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# LIST OF SYMBOLS

| SYMBOL | MEANING | S1 | IMPERIAL |
|---|---|---|---|
| $x$ | Length | m | ft |
| $c$ | Specific Heat | J/kg°C | BTU/lb°F |
| $d$ | Density | $kg/m^3$ | $lb/ft^3$ |
| $T$ | Temperature | °C or °K | °F or °R |
| $A$ | area | $m^2$ | $ft^2$ |
| $K$ | Thermal Conductivity | W/m°C | BTU/hrft°F |
| $Q$ | Heat Transfer/Time | W | BTU/hr |
| $q$ | Heat Transfer/Time/Area | $W/m^2$ | $BTU/hrft^2$ |
| $h$ | Convection coefficient | $W/m^2{}^\circ C$ | $BTU/hrft^2{}^\circ F$ |
| $U$ | Overall heat transfer coefficient | $W/m^2{}^\circ C$ | $BTU/hrft^2{}^\circ F$ |
| $\Delta$ | Difference<br>eg; $\Delta T$ is temperature difference | | |
| $\partial$ | Partial Differentiation | | |
| $u$ | Viscosity | kg/ms | lb/hrft |
| $v$ | Velocity | m/s | ft/s |
| $a$ | Thermal Diffusivity | $m^2/s$ | $ft^2/s$ |
| $S$ | Stephan-Boltzmann Constant of Radiation | $5.669 \times 10^{-8} W/m^2{}^\circ K^4$ | $1.714 \times 10^{-7}$ $BTU/hrft^2{}^\circ R^4$ |
| $e$ | Emissivity | | |

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# 1.0 INTRODUCTION

Overwintering of container-grown tree seedlings carries with it the risk of damage and mortality. This risk is an important consideration to many nursery operators, especially for those who need to carry a crop outside over the winter period.

The primary damage mechanisms are low container root temperatures and dessication. This study was undertaken to examine root temperatures associated with overwintering in an outdoor compound, to review the literature to obtain information on root temperatures at which reduced seedling viability results and to evaluate the potential of underground heating for ameliorating container temperatures. Winter moisture stress was also considered.

A literature search was undertaken to assess the state of knowledge of lethal and damaging root temperatures and the role of moisture stress in winter damage. A search was undertaken with regard to analyses of ground and vegetation temperatures under various conditions. References which provided a framework for heat transfer analysis were also investigated.

A test plot was set up over the 1987-88 winter at the Joffre nursery of Noval Enterprises, a commercial producer of tree seedlings. The plot was roughly 20 feet square and a centre area was heated from below by an electric heater. The heater was turned on as a result of low plug temperatures that occurred as ambient temperatures fell. Moisture stress was monitored using a pressure chamber.

Since silviculture and heat transfer analysis are not often formally linked, the report gives an appreciation of the basic methods of heat transfer. These basics are followed by a discussion of their application in a forest or nursery environment. Publications which provide insights are noted. The forest environment is included because it, rather than the nursery situation is the one into which the trees evolved.

To duplicate as much as possible the situation in forested areas, weather tapes were obtained from Environment Canada for Lacombe and Peace River, Alberta. These tapes included daily average air ambient, snow depth and temperatures at various depths below ground.

The capital and operating cost of an underground heating is assessed for its suitability as an ongoing technique system in a production nursery.

## 2.0 HEAT AND MASS TRANSFER CONSIDERATIONS

The various mechanisms by which heat can be transferred are discussed very briefly in this chapter. The application of these mechanisms to ground and to container tree temperatures are also discussed.

### 2.1 Modes of Heat Transfer

Heat is transferred by conduction, convection and radiation. These mechanisms are described in many general books such as Holman (1972), Lienhard (1981) and the ASHRAE Handbook (1985). Each mechanism is discussed in the following sections, and the concepts of specific heat and latent heat are introduced.

### 2.1.1 Conduction

Figure 2-1 shows a slab of thickness ΔX and surface area A which is undergoing heat transfer from left to right through a temperature difference $T_1$ to $T_2$. Fourier's law of heat conduction gives the heat transferred, Q, as:

$$Q = -KA \frac{\partial T}{\partial X} \qquad (2\text{-}1)$$

where K is termed thermal conductivity given in BTU/hrft°F (W/m°C).

K is often considered to be constant and values are published for many materials. If K is assumed constant and the area is constant, then the partial derivative of Equation 2-1 becomes:.

$$Q = -KA \frac{(T_1 - T_2)}{\Delta X} \qquad (2\text{-}2)$$

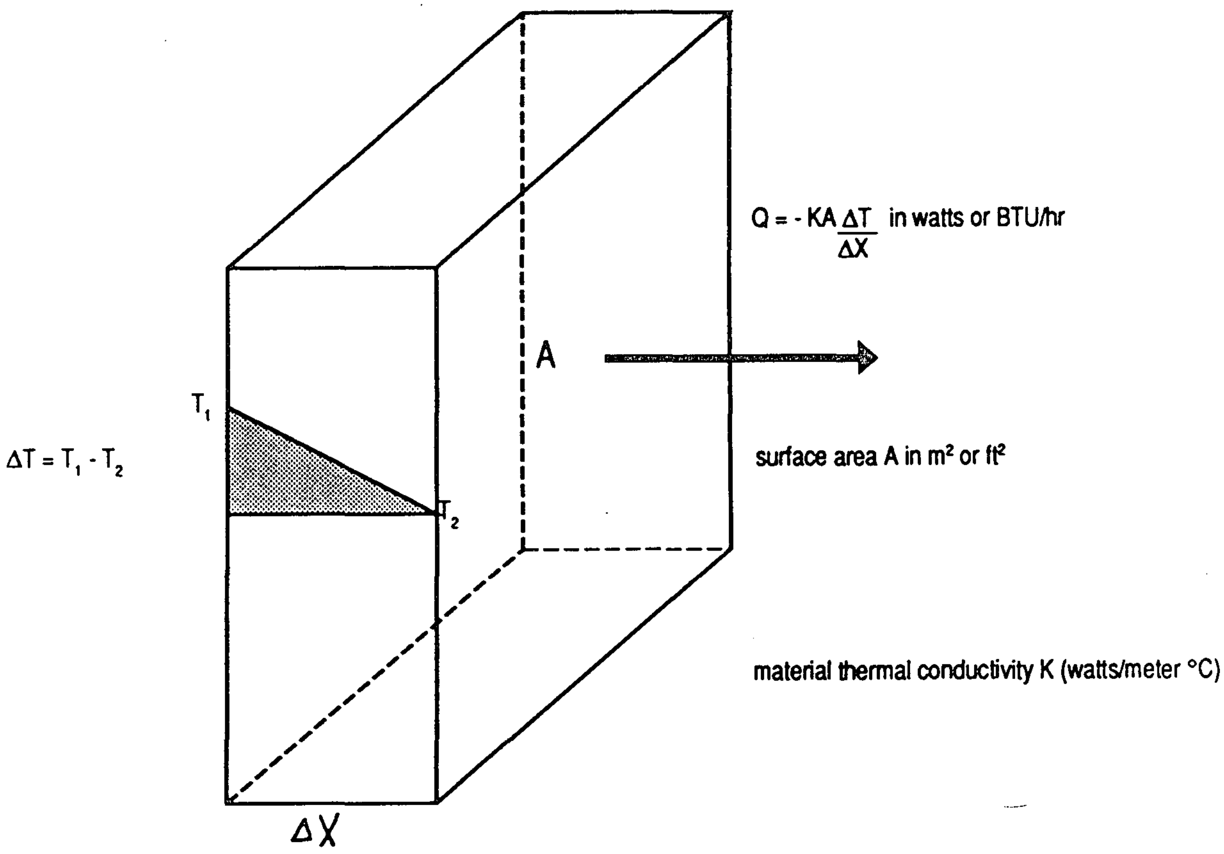


Figure 2-1
Steady State Heat Conduction Through a Large Slab of Constant Conductivity

Conduction heat transfer requires a gaseous, liquid or solid substance through which the heat can move, the transfer being via molecular motion, and in some cases with solids, via electrons.

### 2.1.2 Convection

As an example of convection, Figure 2-2 shows a wall, at temperature $T_w$, across which is flowing air at a lower ambient temperature $T_a$. Heat is transferred from the wall to the air by conduction at the layer close to the wall. The movement of the heated air transfers heat away from the wall and this is termed convection. The movement and mixing of the air allows re-introduction of cold air to the wall area for close contact. This re-introduction of air maximizes the temperature gradient of Equation 2-1 close to the wall, and enhances the transfer. Stationary air itself is a poor conductor of heat (as demonstrated by various insulators which work by trapping small pockets of air).

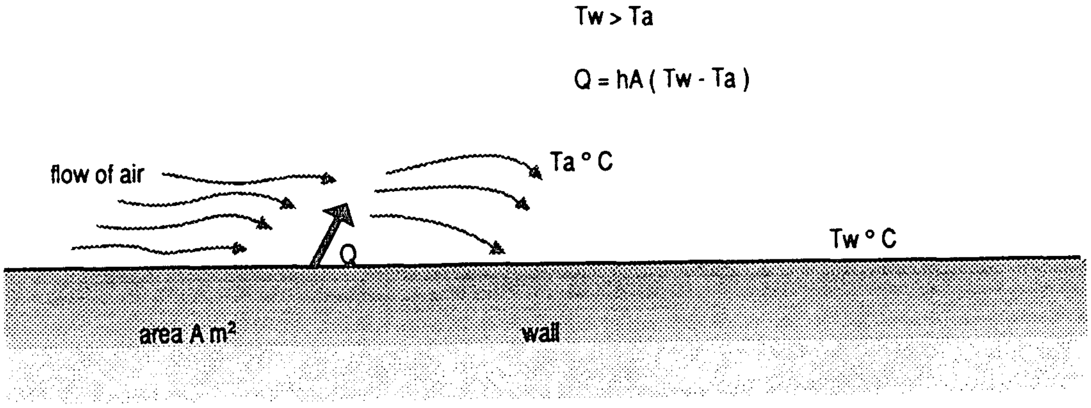


Figure 2-2
Heat Convection from a Wall

Referring to Figure 2-2, the heat transfer is given by

$$Q = hA\ (T_W - T_X) \qquad (2\text{-}3)$$

where h is the convection coefficient in BTU/hrft²°F (W/m²°C). This coefficient depends on the air velocity, thermal conductivity, heat capacity, viscosity and density.

Convection can be classed as forced or free (also termed natural). Free convection occurs where temperature gradients cause buoyancy effects which create air motion. If the wall of Figure 2-2 is heated, the air above it is heated, and, as a result, it rises. Cooler air replaces the rising air and a convective flow is set up.

Forced convection occurs where, for instance, wind or fan power causes the velocity.

The distinction between free and forced convection is important when the coefficient is to be calculated.

### 2.1.3 Thermal Radiation

Thermal radiation heat transfer is by electromagnetic radiation at wavelengths from infrared through visible light to ultraviolet, and is distinct from conduction and convection in that it can operate in a vacuum with no transfer medium.

For a surface at temperature $T_W$ °K or °R (absolute temperature scale, 273°K = 0°C). The total emitted energy per unit time is

$$Q = ST_W^4 \qquad (2\text{-}4)$$

if the surface is a perfect "black body" emitter. The quantity S is the Stephan-Boltzmann constant and equals $1.74 \times 10^{-7}$ BTU/hrft²°R$^4$ ($5.669 \times 10^{-8}$ W/m²°K$^4$).

Whereas conduction and convection are linear functions of temperature difference, radiation depends on the fourth power of absolute temperature. Radiation, therefore, becomes increasingly important as absolute temperatures go up.

As well as emitting radiation, surfaces can have incident radiation which affects the overall transfer. Real surfaces have radiation properties as follows:

a - absorptivity - the fraction of incident radiation absorbed.
t - transmisivity - the fraction of incident radiation transmitted.
r - reflectivity - the fraction of incident radiation reflected.

By definition $a + t + r = 1$, and in many cases $r = o$.

These properties become very important in forestry and nurseries where solar energy is an input variable.

The analysis of Equation 2-4 assumes emission of a "blackbody", which is defined as a body of absorptivity $a = 1$. Real surfaces have an absorptivity of less than one.

Emission is defined by another property:

e - emissivity - the ratio of actual radiation to that of a black body at that temperature.

From a discussion of energy equilibrium, it can be shown that absorptivity a = emissivity e, which is termed Kirchoff's identity. Emissivity is quoted in many heat transfer references for various practical surfaces.

### 2.1.4 Solar Radiation

Solar radiation is of paramount importance to heat transfer in environmental systems, and has the same basic theoretical treatment as thermal radiation, with a particular emphasis on wavelength. Emitted energy, as characterized by Equation 2-4, is summed over a spectrum of wavelengths. As emitting source temperature rises, the spectrum of wavelengths shifts to shorter (i.e., higher energy photons). The sun being a hot body has a spectrum which meteorologists term short wave. Some of this short wave radiation is converted into long wave radiation by scattering in the atmosphere.

Of the net short and long wavelength radiation incident on the surface, some fraction is reflected. This reflected fraction is termed albedo. Table 2.1 gives the albedo for various types of surfaces. This table is taken from Climate Canada (Hare and Thomas 1979), as is much of the preceding explanation.

TABLE 2-1
ALBEDO FOR VARIOUS SURFACES

| TYPE OF SURFACE | SUMMER | WINTER |
|---|---|---|
| snow freshly fallen | _ | over 0.8 |
| old snow | _ | 0.4 to 0.7 |
| vegetation types | | |
| tundra | 0.2 | 0.8 |
| open woodland | 0.2 | 0.6 |
| coniferous forests | 0.1 | 0.3 to 0.4 |
| grassland, growing crops | 0.2 | 0.4 to 0.6 |

## 2.2 Specific Heat and Latent Heat

The specific heat c of a gas, liquid or solid is the amount of heat required to increase the temperature of a unit of mass by a unit of temperature. The specific heat of water at 0°C is 1 BTU/lb°F (4187 J/kg°C).

Latent heat is the heat given off or absorbed when a substance changes phase. The latent heat associated with freezing or vapourization is extremely important in heat transfer. This is particularly true of the systems dealt with in this report, largely because of the water phase change. Latent heat of fusion of water to ice is 143.4 BTU/lb (334 kJ/kg), and the latent heat of vapourization of water to steam is 970 BTU/lb at 212°F (2.26 MJ/kg at 100°C).

Latent heat can be seen to be extremely important in storage of heat. The energy stored in the change of 1 lb of water to ice is the same as would be stored by a change in water temperature of 143.4°F, which has an important effect on frost penetration into the ground. Similarly, transpiration as a manifestation of the latent heat of evaporation, has a strong effect on heat transfer from plants.

## 2.3 Application of Heat Transfer to the Forest and Nursery

The various mechanisms of heat transfer have been discussed in general and will now be described as they apply to heat transfer at ground level in the forest and nursery.

The overall heat balance is described in Chapter 4 of Permafrost Engineering, Design and Construction by Goodrich and Gold (1981), and in Geotechnical Engineering for Cold Regions by Harlan and Nixon (1978).

The ground surface heat balance is as follows:

Q ground + Q radiation + Q convection + Q latent = 0 (3-1)
(note: all heat flows are chosen positive going to the surface)

where - Q ground is the heat flow at the surface.

- Q radiation is the net short and long wave radiation incident and reflected and long wave radiation re-emitted. This net radiation depends on the following parameters:

  a) angle of the surface to the sun.
  b) snow cover as it effects albedo.
  c) vegetation and other surface characteristics, as they effect albedo (see Table 2-1).

- Q convection is the net heat transfer between the air and the ground. This depends on the following parameters:

  a) temperature difference between air and ground.
  b) air speed and turbulence, which affect the convection coefficient h. The extent to which a site is exposed to the wind will be important.
  c) the insulating effect of snow.
  d) vegetation as it effects local air movement and snow accumulation.

- Q latent is heat transfer associated with evaporation (minus condensation) which depends on the following parameters:

  a) surface temperature.
  b) the extent of plant evapotranspiration.

  In winter conditions of frozen ground and hardy foliage, Q latent is much less important than in summer.

- Q ground is the transfer into or out of the ground. Referring back to Equation 2-1,

$$Q \text{ ground} = -KA \left.\frac{\partial T}{\partial X}\right|_{x = 0} \qquad (3\text{-}2)$$

  where x is the depth into the ground.

Of major importance in the present investigation is the ground temperature further below the surface where the tree roots occur. In winter, the temperatures at depth depend on the gradient at the surface; on soil properties - thermal conductivity and heat capacity; and the role of latent heat and phase change.

In analyzing temperatures at depth, Equation 3-1 might serve as a boundary condition, but as noted by Goodrich and Gold (1981), usually is not. Ground heat flux is often smaller than the other fluxes, and inferring it from the energy balance of 3-1, can lead to major errors because other fluxes are often not precisely known. Instead, ground temperatures are calculated using an assumed boundary condition of surface temperature or seasonally varying temperature. This does not, however, mean that Equation 3-1 is not useful. Given some generally understood regional ground temperature conditions, the effects of soil moisture content, snow depth or incident solar angles can be studied as an aid to nursery design or tree replanting strategy.

In summary, it can be stated that Equation 3-1 identifies the various parameters affecting heat transfer and hence is correct. The difficulty comes in making the equations yield useful results, since many solutions become very complicated even after simplifying assumptions. One usually falls back on partially empirical data to be sure that the field situation is adequately described.

## 2.4 Literature Search - Ground Temperature

Much of the information included here has to do with local effects and variations. Each of the references cited gives insight into some aspect of the forest or nursery heat transfer situation, and in some cases mathematical models are presented and solved.

Harlan and Nixon (1978) describe phenomena particularly as applied to permafrost studies, an area where considerable ground temperature analysis has been done.

Discussed in this reference are:

a) the fundamental modes of heat transfer with details of application to the ground.

b) thermal properties of soils. This was one of the best references found on conductivity and heat capacity as a function of water content for various types of soils.

c) Energy balance at the ground surface and the effect of various site specific phenomena. Snow depth was shown to be of particular importance with deep snow inhibiting depth of frost penetration and also slowing ground thawing in the spring.

d) Detailed mathematical analysis of ground temperature for a variety of situations are provided. The Stefan and Neumann solutions to ground freezing and thawing, and an introduction to numerical methods are included.

e) Thawing and freezing indices are described which enable temperature data for a region to be used for ground design purposes in that region.

Johnston et al. (1981) produced a reference with considerable information on structure and thermal properties of frozen and unfrozen soils. Goodrich and Gold (1981) cover similar material to that of Harlan and Nixon (1978) with considerable useful theoretical analysis.

The references described so far are clearly oriented towards permafrost studies, but the information sheds considerable light on the problems in non-permafrost situations. Care is, of course, required in applying results from one situation to another.

Agricultural research has examined ground temperature and the effect of tillage on soil temperature  Benoit and Mostaghimi (1984). Tillage influence soil thermal properties, and determines the extent of surface vegetation which influences snow trapping. Reference is made to dry soils freezing deeper than wet ones, presumably because of the latent heat of fusion effect.

A numerical model of the ground field thermal system was written and compared to actual results in Minnesota. Daily actual temperatures were used to drive the model and agreement to results was good for freezing and less good for thawing.

Civan and Sliepcevich (1985) provide a mathematical solution to the freezing and thawing of soils, with considerable detail of methods and assumptions. Sheppard et al. (1981) reported on freezing experiments which were performed in an agricultural plot. A redistribution of water to the freezing interface was shown to occur.

Other references as follows were found to be of general interest and are noted in the bibliography: Anderson, Ruschand, Penner (1978), Grace and Dixon (1985), Hayhoe, Topp and Edey (1983), Kattelman (1987), Kawaniski (1986), Sauland Potts (1986).

The references from Rutgers University (Roberts et al. 1985; Roberts and Mears 1984a,b, 1980), are helpful in examining the thermal characteristics of a layer of vegetation. Heated floor systems of various designs have been analyzed. These floors provide root zone heating in greenhouses and some heating of the air above the plants. Proper design requires measurement of conduction through and convection from bare floors and floors with bedding plant flats on them. The conduction and convection can each be considered to have a certain resistance to heat transfer, and the resistances can be added. As a result of this addition, an overall coefficient can be established.

This coefficient is $U = Q/(T_w - T_a)A$
where $T_w$ is heating water temperature to the floor
$T_a$ is air temperature above the floor
$A$ is floor or plant area
$Q$ is total heat from the floor to the air.

Table 2.2 from Roberts and Mears (1980) is the result of measurements taken in a greenhouse with heated water running through pipes in porous concrete and sand floors. The role of greater amounts of moisture is evident. These results were obtained under equilibrium conditions at night to avoid the thermal disturbance of solar gain. (Note - these results will give some general indication of U values in a heated tree compound, but are not the same containers or temperature regimes.)

TABLE 2.2

OVERALL HEAT TRANSFER
COEFFICIENTS FROM RUTGERS FLOORS
U VALUE

| Porous Concrete | W/m²°K | BTU/hrft²°F |
|---|---|---|
| Embedded Pipe 15 cm spacing - Bare Floor | 4.2 | 0.74 |
| Embedded Pipe 15 cm spacing - Dry Flats | 2.9 | 0.51 |
| Embedded Pipe 30 cm spacing - Bare Floor | 3.5 | 0.62 |
| Embedded Pipe 30 cm spacing - Dry Flats | 2.7 | 0.48 |
| Embedded Pipe 30 cm Dry Floor - Wet Flats | 3.1 | 0.55 |
| Embedded Pipe 30 cm Wet Floor - Wet Flats | 3.4 | 0.60 |
| Embedded Pipe 46 cm - Bare Floor | 2.9 | 0.51 |
| Embedded Pipe 46 cm - Dry Flats | 2.6 | 0.46 |
| Embedded Pipe 46 cm Dry Floor - Wet Flats | 2.5 | 0.44 |
| Embedded Pipe 46 cm Wet Floor - Wet Flats | 2.8 | 0.49 |
| Sand | | |
| Dry Sand 15 cm spacing | 5.2 | 0.92 |
| Dry Sand Covered with plastic | 4.0 | 0.70 |
| Wet Sand flooded plus cover | 9.2 | 1.62 |
| Wet Sand plus cover | 9.2 | 1.62 |

## 3.0 SEEDLING OVERWINTERING CONSIDERATIONS

This section will discuss two primary areas of winter injury: 1) low-temperature injury to tops and roots; and 2) winter dessication. There can also be problems with disease over the winter period, but this study was designed to examine reducing losses due to the first two areas. Diseases can generally be controlled by proper sanitation and treatments of the seedling before going into the winter period.

Useful information has been produced by Dymock and Dendwick (to be published) on the use of weather records for nursery purposes. They outline the type of weather information commercially available and its potential uses. Of particular interest is the dynamics of hardening as related to actual weather conditions, and the potential for damage. The use of weather records in a post mortem analysis of a problem is also an interesting idea.

### 3.1 Low-Temperature Injury

There are many differences among plant species in terms of cold hardiness as well as differences among tissues on the same plant. (Smith and Beattie 1986). As pointed out by Dormling (1987) and Mattsson (1986), among others, the cessation of height development and initiation of bud dormancy are not synonymous with cessation of root growth. Roots do not actually develop dormancy; rather their growth is inhibited during winter with its low temperatures, but they always manage some growth as the temperature rises. Because of these differences the following discussion has been divided between tops and roots.

#### 3.1.1 Tops

The successful overwintering of containerized nursery stock is very closely linked to proper dormancy and cold hardiness of the species involved (Dymock and Dendwick 1987). Colombo *et al.* (1982a) reported that a primary cause of winter damage in Ontario is that containerized seedlings are hardened off outside under existing weather conditions. These plants are then susceptible to frost injury until sufficiently cold hardened in response to short daylengths and colder temperatures. Unfortunately, every fall does not feature ideal hardening temperatures with gradually decreasing temperatures as the days get shorter. Often, the temperature drops to below the frost hardiness level, and injury occurs to the seedlings. In response to this problem, a technique called "Extended Greenhouse Culture" was introduced in Ontario in an attempt to better harden spruce container seedlings (Colombo *et al.* 1982a,b; Colombo *et al.* 1984). In brief it involves keeping seedlings in the greenhouse and manipulating daylength and temperature under more controlled conditions to ensure seedlings are hardened sufficiently before moving them outside for overwintering.

Early spring is another problem time in which frost damage can be substantial (S. Navratil, CFS, pers. comm., 1987). Gouin (1985) states that "once dormancy requirements have been satisfied, plant shoots exposed to temperatures above freezing rapidly lose their cold tolerance". What can, and often does, occur in Canada's prairie region especially is that temperatures can easily drop below the cold hardiness level of the actively expanding seedlings. Glerum (1985) reports that actively growing trees are not frost hardy and can suffer frost injury when temperatures drop.

Frost injury can also occur during the remainder of the winter period, particularly if seedlings are not properly cold hardened and/or if the plant's genetic capacity to acclimate to freezing temperatures is insufficient (Glerum 1985). With both of the preceding factors maximized, the difference in hardiness of some plants at the extreme opposite ends of their two growth stages can be as much as 190°C (Green and Fuchigami 1985). In a study limited by a freezing chamber which only went down to -40°C, Glerum (1973) reported a maximum winter frost hardiness of something colder than -40°C for potted three to four year old seedlings of white, red and jack pine as well as for white and black spruce and tamarack. The maximum for Norway spruce was around -40°C. Smit-Spinks *et al*. (1985) found that six to twelve month old *Pinus sylvestris* seedlings in tube paks (similar to Spencer-LeMaire containers) obtained a maximum hardiness of greater than -40°C.

Clearly, if everything is done correctly, seedling tops can withstand some very cold air temperatures. Unfortunately, seedlings often do not have everything going correctly for them and winter injury occurs at some point. Considerable work has been done, and continues to be done, in an attempt to maximize plant dormancy and cold hardiness to minimize low-temperature injury.

### 3.1.2 Roots

Low-temperature injury to roots is a major problem in the overwintering of container grown plants because the roots are significantly less cold hardy than shoots (Green and Fuchigami 1985; Lindstrom and Mattsson 1987). As pointed out earlier, shoots of *Pinus sylvestris* L. seedlings were tolerant at least to -40°C; however, the maximum hardiness of these seedlings' roots was -15°C (Smit-Spinks *et al*. 1985).

Under natural conditions seedlings are able to survive well because soil temperature seldom get as low as air temperatures during the winter. Working with bare root nursery material in Rhinelander, Wisconsin, W. Rietveld (U.S. Forest Service, pers. comm., 1987) reported a temperature of -1 to -2°C as being a "normal" temperature at the soil surface under a cover of 45 cm of snow. With 45 cm of snow cover he expects the soil temperature to average 7°C in the upper 15 cm of soil in his geographic location. The importance of cover is very clear as indicated by J. Scarrett (CFS, pers. comm., 1987). He reported that a surface soil temperature of

-15°C with no snow cover will move up to 0°C in a week or less when 15 cm of snow cover is added.

During winter cold periods, the temperature can get much lower in containers than in the soil. Wiest et al. (1976) found that over an air temperature range of 15 to -30°C, the soil temperature at 8 cm varied from 12 to -6°C and in the centre of an 8.8 L container, the corresponding temperatures ranged from 15 to -15°C. Studies by Desjardins and Chong (1980) and Tinus (1982) also show that seedlings in containers are subjected to lower temperatures than those grown as bare root stock in nursery beds.

This discussion raises the question of the tolerance level of container seedling roots to cold temperatures. Green and Fuchigami (1985) point out that root hardiness is a function of temperature; low temperatures promote root hardiness and warm temperatures promote loss of hardiness. It is important to note that, since roots do not go dormant and the development of root cold tolerance is directly related to root growth activity, cold injury can occur at any time of the year. W. Rietveld (U.S. Forest Service, pers. comm., 1987) stressed that root growth will be initiated at 3.8 to 4.4°C. J. Scarrett (CFS, pers. comm., 1987) pointed out that "abnormal" warm temperatures in the middle of winter will cause roots to lose hardiness and the change back to colder, "normal" winter temperatures will cause low-temperature root injury. As reported by Green and Fuchigami (1985), the entire root hardiness level can be lost within a 24-hour period. Once this happens, the re-acquisition of cold tolerance may require a longer time than is generally available in winter, especially in Canada's prairie provinces.

Attempts have been made to dampen, or "take the edges off rapid and drastic temperature changes" by using various coverings (C. Glerum, Ont. Min. of Nat. Res., pers. comm., 1987). This is the idea behind the "Extended Greenhouse Culture" technique in Ontario (Colombo et al. 1982a,b) and the work with seedling coverings by the Canadian Forest Service in Sault Ste. Marie (J. Scarrett, CFS, pers. comm., 1987). This is also the impetus behind thermal blanket, polyethylene and microfoam research as described by many (Smith and Beattie 1986; Smith and Treaster 1980, 1986; Wynstra and Smith 1984; Rizzo et al. 1979; and McNeil and Duncan 1983).

In Sweden it has been common practice to have seedlings remain on pallets raised in the air to promote air pruning of roots and aid in the mechanical handling of seedlings (Lindstrom, 1986a). Questions about the potential harmful impacts of this method of winter storage led to several studies by Lindstrom (1986a,b) to assess temperatures in these elevated conditions and the effect of those temperatures on root growth capacity. In studying Norway spruce the lowest air temperature recorded was -22°C and the lowest container temperature was -15°C in the treatment with seedlings 20 cm above ground and no snow cover (Lindstrom, 1986a). In the Scotch pine part of this study, the minimum temperature recorded in containers placed on the ground was -11°C and -16°C for the treatment 10 cm above the ground. Temperature differences of 4 to 8°C were observed between treatments. The author felt that the actual lethal root temperature was probably not reached for either species in this study; however, seedling roots were still damaged in treatments with the lowest container temperatures. Working with white spruce (Picea glauca) and Siberian spruce (Picea omorika), Havis (1976) found that -23.3°C was the temperature at which more than 50% of the root system was killed and top growth reduced. Laboratory freezing tests have shown that dormant Norway spruce roots can tolerate temperatures lower than -20°C (Lindstrom 1986a). Lindstrom's report indicates that the lethal point for one year old Scotch pine was found to be about -20°C in the laboratory. This report also states what a number of others have also reported, that lethal temperatures for young roots are considered to be substantially higher than for mature roots. Smit-Spinks et al. (1985), however, dispute this as they reported that roots with and without white tips did not differ significantly in their hardiness.

In trying to determine lethal temperatures it should be remembered that under natural conditions the duration of the low temperatures is longer than in the laboratory. Research has shown the duration to be significant and thus lethal root temperatures under natural conditions would be expected to be higher than those determined under laboratory conditions.

Lindstrom (1986b) reported that root growth capacity was significantly reduced when he dropped the temperature in the root zone of one year old Scotch pine and Norway spruce from -6°C to -11°C, with four and eight hours of exposure, and again when the temperature was lowered from -11°C to -16°C. He found almost no root growth after exposure to -20°C, especially in Scotch pine. He concluded that Scotch pine roots were severely injured at -16°C and -20°C and he questioned their survivability if outplanted. Even a temperature of -10°C resulted in the lower parts of the roots suffering cold injury.

Lindstrom and Nystrom (1987) pointed out the seasonal variation in the cold hardiness of Scotch pine, Norway spruce and lodgepole pine seedlings. A September temperature of -5°C was sufficient to kill more than 50% of the seedlings while in October temperatures of -10 to -15°C were required. In November the temperatures required were in the -15 to -25°C range. By mid-April temperatures of -10°C would again cause death of more than 50% of the seedlings.

### 3.1.3 Summary

After reviewing the preceding literature and telephone discussions with C. Glerum (Ontario Ministry of Forests), J. Scarrett and I. Edwards (Canadian Forestry Service), A. Lindstrom (Swedish University of Agricultural Sciences) and W. Rietveld (U.S. Forest Service) it was decided that, for this preliminary study, an attempt would be made to have the heating source become active at -8°C. Based on the available information it was felt that a target minimum temperature for the medium in the container of -5 to -7°C should minimize the temperature to which the roots would be exposed and in turn would minimize low-temperature injury to seedling roots.

## 3.2 Winter Dessication

Another primary cause of winter injury to container grown seedlings is dessication (Green and Fuchigami 1985). The problem of dessication is generally viewed as indirect winter injury and is not usually directly related to low winter temperatures since a disturbance of "plant water economy" can occur during winter whether the soil is frozen or not (Ebermayer 1901). It can also be a problem when the tree tissues are also frozen and water is lost from the needles and cannot be replenished quickly enough (Baig and Tranquillini 1980).

The extent of injury is a factor of the amount of moisture stress and the duration of time that the stress is imposed (Smith and Beattie 1986). As these authors explain, if the relative humidity is high, air temperature and leaf temperature are low, then the vapour pressure deficit between the leaf (or needle) and the air is low, resulting in a limited amount of moisture loss. If, however, as can happen in mid-winter, the relative humidity of the air is low and air and leaf temperatures are high, the vapour pressure deficit is high resulting in excessive moisture loss.

As described by Green and Fuchigami (1985), there are at least four situations where dessication can occur. The first is where changes occur in the roots. Roots do not become truly dormant, but their growth is inhibited by low temperatures. In this situation roots mature and as the root tissue matures its water uptake ability is greatly reduced. The second situation where dessication can occur is where there is a change in the viscosity of water. When the temperature drops, the viscosity of the water increases and the rate of water uptake decreases, especially in the soil system. A third situation is where there is ice in the system. As the water in the container freezes, water uptake is completely shut down while transpiration may continue in the foliar tissue. The fourth situation is created by the environment above the ground. With increased solar intensity, decreasing relative humidity, increasing temperature and/or increasing wind speed, transpiration increases as does the possibility for dessication injury.

Green and Fuchigami (1985) also point out that some plants are well adapted to controlling transpiration by producing cuticular waxy surfaces. However, being able to get the cuticle to form completely may be a problem, especially in container systems. Working with <u>Picea abies</u> needles, Lange and Schulze (1966) reported that it took three months from the time of shoot elongation to the time when needles reached their final thickness. Research in Ontario has found that the cuticle is often not complete when seedlings are placed outside (C. Glerum, Ont. Min. of Nat. Res., pers. comm., 1987). Their work is currently focussing on techniques to get the cuticle to form completely to reduce dessication problems, especially as they may relate to the technique of "Extended Greenhouse Culture" (Colombo et al. 1982a,b).

Another method of reducing the potential for winter dessication is to reduce air movement through the leaf canopy (Smith and Beattie 1986) or by eliminating soil frost (Havis 1965). The work done by Havis (1965) involved artificially heating the soil to prevent its freezing. He reported a definite reduction in winter dessication in the Rhododendron used in this study.

Reduction of air movement through the seedlings has been attempted using a variety of techniques. Wood (1987) reports satisfactory results from placing containers on the ground, surrounding them with empty container trays and erecting snow fencing to catch and hold snow over the seedlings. Lindstrom (1986) found that insulating below the pallets raised soil temperature several degrees. Wynstra and Smith (1984) stated that results of their study showed lower maximum average air temperatures were lowest in white polyethylene covered structures while the relative humidity was significantly higher in aluminum film covered structures. A study by McNiel and Duncan (1983) found that foam-type covers were superior to poly-covered frames for overwinter container stock protection. Results of preliminary work by the Canadian Forest Service in Sault Ste. Marie indicates that a white, perforated polyethylene covering works best to date to reduce transpiration (J. Scarett, CFS, pers. comm., 1987).

One of the problems with winter dessication is its measurement. It can be indirectly approached by monitoring the soil moisture status, but relating this information to the plants' moisture status is very difficult. A much better approach is to measure plant moisture stress (McDonald 1984). This is because plant moisture stress (or plant water potential) integrates soil moisture tension in the root zone, the resistance to water movement within the seedlings, as well as the water demands from transpiration as affected by the environment (relative humidity, heat loading, wind, air temperature, etc. (Cleary and Zaerr - not dated). The techniques for evaluating water potential (or plant moisture stress) of plants include the use of thermocouple or thermistor psychrometers, dyes, gravimetric vapour exchange, freezing point determination and the pressure chamber (Day 1980).

The pressure chamber (or pressure bomb) is a relatively new instrument for assessing the internal plant moisture status and, as pointed out by Day and Walsh (1980), it was the first instrument "to provide a simple, accurate, rapid and practical means of measuring plant moisture stress". Actually, the concept is not new as the first pressure chambers were constructed in 1914 by H.H. Dixon (1914). The first ones were made of glass and were truly pressure "bombs" as they would sometimes explode! This approach was subsequently abandoned and later revived in the 1960's by P.F. Scholander and his team of researchers at the Scripps Institution of Oceanography at the University of California (Scholander et al.

1965). The revised pressure chambers were constructed of metal. Pressure chambers as a tool for forestry use have been developed and tested in Ontario by G. Pierpoint and C. Glerum, Research Branch, Ontario Ministry of Natural Resources and R.J. Day of Lakehead University in Thunder Bay, Ontario (Colombo 1985).

With respect to the author's study and pressure chambers, the literature is very limited with regard to the monitoring of plant moisture stress over the winter period. Even in the growing season the method has not been researched enough to establish a direct relationship between plant moisture stress readings and the performance of tree seedlings after planting (Colombo et al. 1984). Data interpretation has to take into account that plant moisture stress varies throughout the day as well as over the year (Cleary and Zaerr, not dated).

In terms of when to measure plant moisture stress, the most common time during the growing season is pre-dawn (Day and Walsh 1980; Cleary and Zaerr, not dated). This is the time when the moisture status within the plant is changing slowly as the seedlings have had an overnight period for relief from atmospheric demand and a time for moisture to be absorbed from the soil to allow the plant to "catch up" on the moisture needs. This is the time plants are closest to equilibrium with soil moisture. The next best time to take measurements is called the "mid-day measurement" (Cleary and Zaerr, not dated) or "On the Afternoon Plateau" (Day and Walsh 1980). This is when plant moisture stress is reasonably stable and usually is at its highest point. The maximum reading provides an indication of whether the seedling is under sufficient stress to impair processes such as photosynthesis or cell elongation.

## 4.0 RESULTS OF GROUND TEMPERATURE INVESTIGATION

Environment Canada keeps computerized data for ground and air temperatures generally taken for agricultural purposes on a grassed site which attempts to represent an open field. Two sites in Alberta where this information is measured are Lacombe and Peace River. A computer tape was obtained with data for these sites from Environment Canada's Downsview, Ontario office and this was loaded to NOVA's mainframe system. Peace River was chosen as somewhat representative of climate in a forested area, and Lacombe because it is close to Joffre.

For ease of data manipulation and display, this mainframe data was downloaded to an IBM-AT personal computer configured with a "Bernoulli Box" removeable hard disk. In the downloading process, the data from the mainframe was converted to binary, with each piece of data being stored as a two byte integer number, which required much less disk storage than the one byte per character on the original tape. The downloading process was performed by Evan Mulcaster of NOVA's Computer Services Dept. The data was manipulated using Microsoft Fortran software and program listings can be obtained from the authors by interested parties. The Fortran programs were used to put the data into an output file on disk. Files were read into a Lotus 123 Spreadsheet for production of the graphs presented.

The data collected and examined was for the winter months for Lacombe and Peace River, 1980 - 1983. Cold temperature data and interesting data were selected for graphing.

Data collected is as follows:

| | |
|---|---|
| daily mean temperatures | °C |
| daily snow depth | cm |
| temperature at 5 cm | (2 inch) depth |
| temperature at 10 cm | (4 inch) depth |
| temperature at 20 cm | (8 inch) depth |
| temperature at 50 cm | (1.64 feet) depth |
| temperature at 100 cm | (3.28 feet) depth |
| temperature at 150 cm | (4.92 feet) depth |
| temperature at 300 cm | (9.84 feet) depth |

Graphs include data for 5, 10, 20 and 100 cm depth. The x - axis is for days starting at the beginning of the month noted and the y - axis is in °C except for the snow depth which is in cm.

January and February 1980 data for Peace River (Figure 4-1) shows the dramatic effect of snow cover on ground temperature. Approaching day ten, average air temperatures were near -35°C. A 6 cm snow cover helped keep the 5 cm depth temperature above -10°C. Approaching day 30 as ambients reached -25°C with very little snow cover, the 5 cm temperature reach -12.8°C. The effect of no snow cover was again evident on days 45 to 50.

Temperatures immediately after day 30 show the response at 20 cm to be slightly slower than 5 or 10 cm. Response at the 100 cm depth is very slow.

January and February 1981 data for Peace River (Figure 4-2) is interesting for the even behavior underground. This is due to the snow cover which is maintained close to 20 cm.

November 1981 to February 1982 data for Lacombe (Figure 4-3) reinforce the snow cover effect. The instance of low ground temperature coincided with cold temperature and little snow cover after day 60.

FIGURE 4-1

**GROUND TEMPERATURE FOR PEACE RIVER**

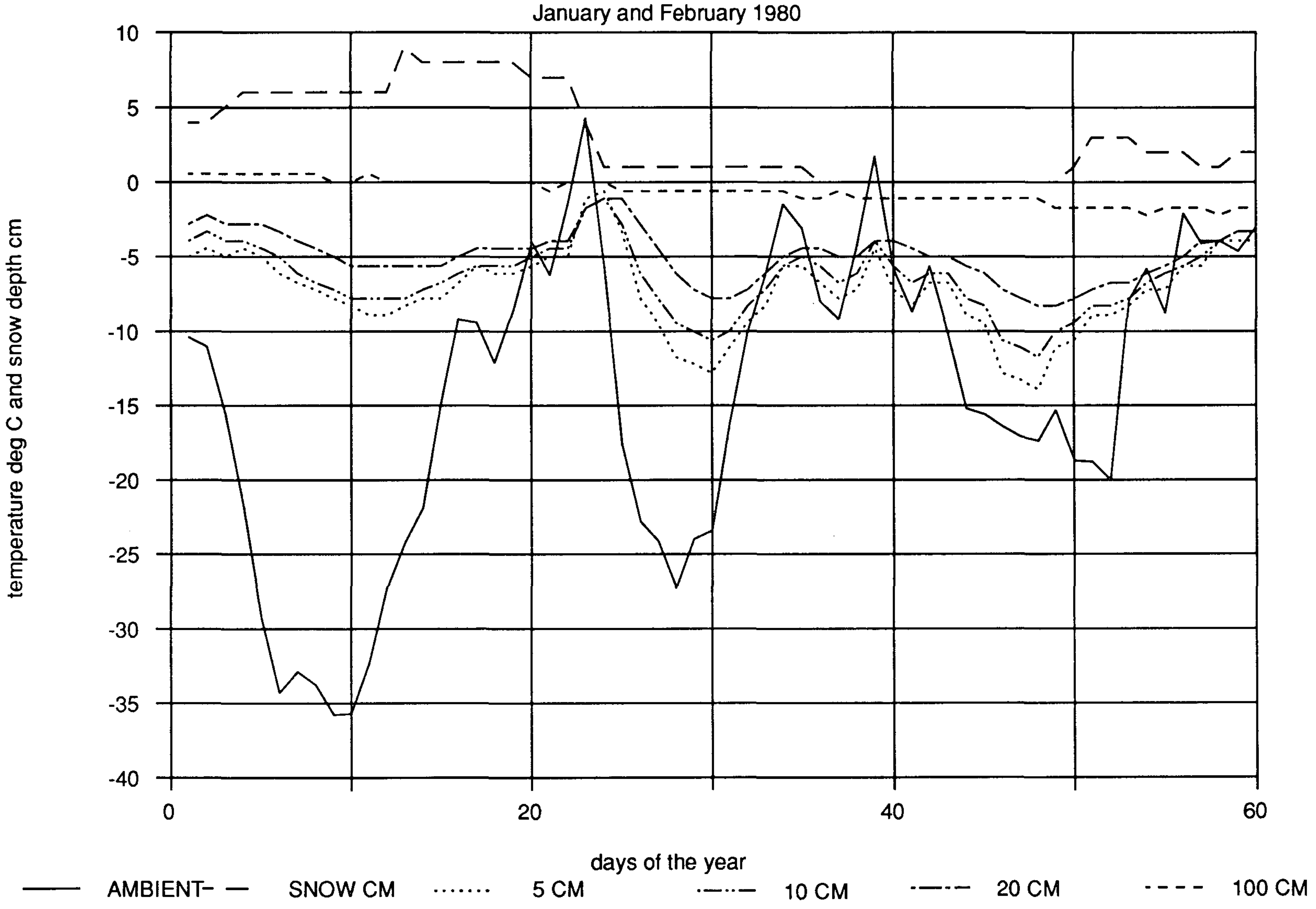


FIGURE 4-2

# GROUND TEMPERATURE FOR PEACE RIVER

January and February 1981

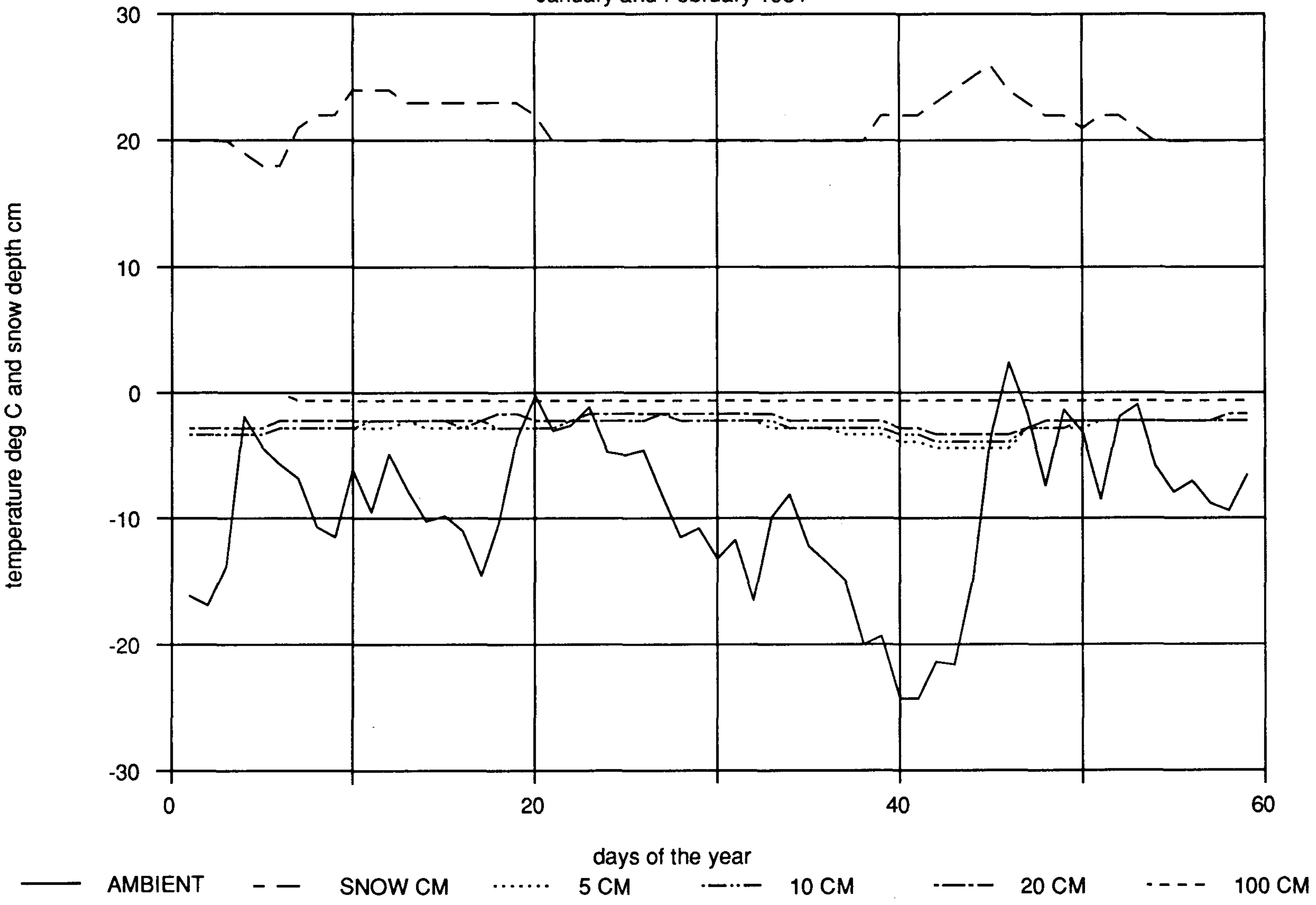
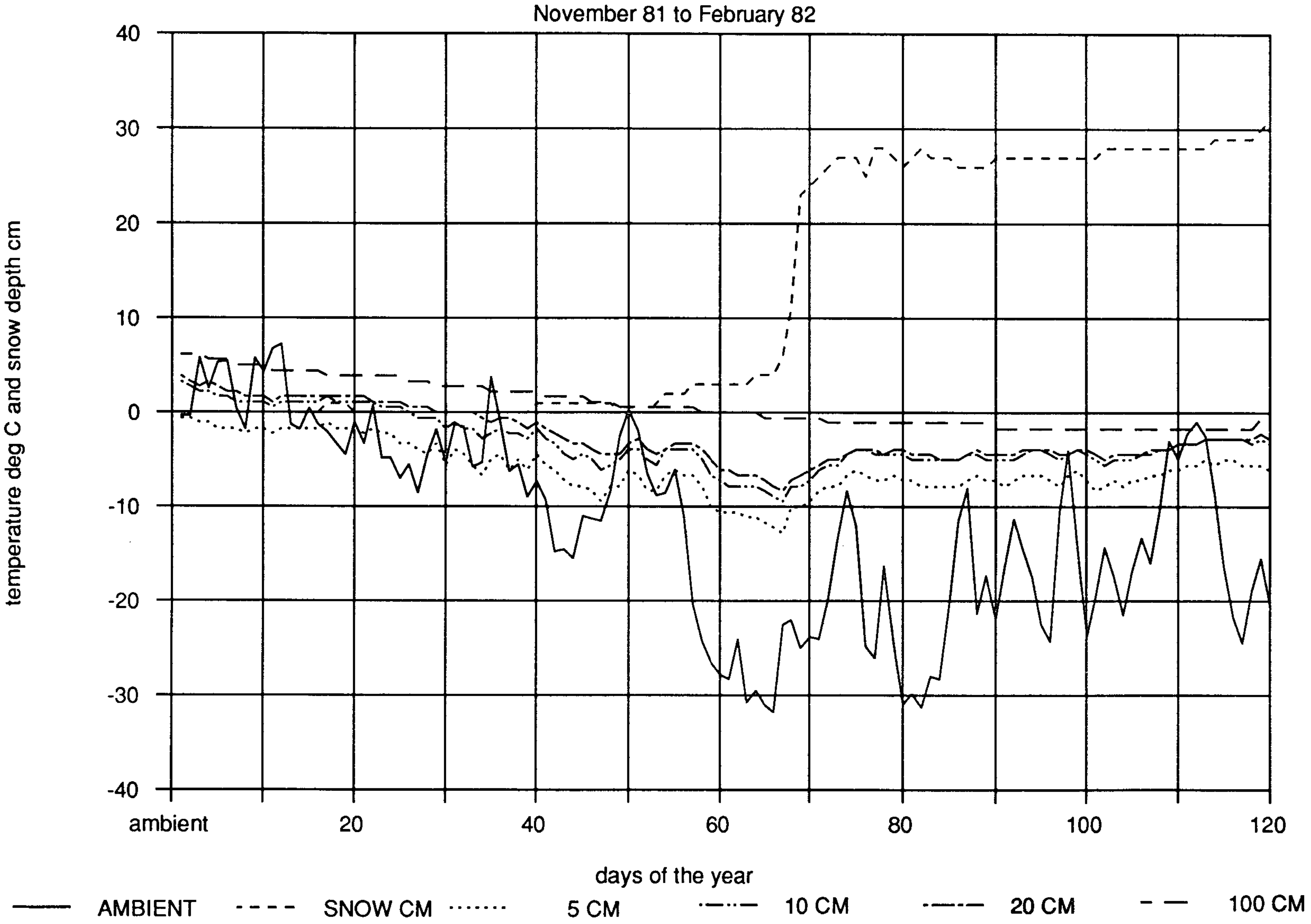


FIGURE 4-3

# GROUND TEMPERATURES FOR LACOMBE



# 5.0 EXPERIMENTAL METHODS

## 5.1 Heat Transfer

To assess the concept of underground heating of containers, an experimental plot was established in preparation for the winter of 1987-1988. The test seedlings consisted mainly of white spruce in Beaver Plastics' Styroblock containers (Econoblock 160 and Styroblock 5). These trees were left over from Noval Enterprises' commercial orders. Smaller numbers of blue spruce, lodgepole pine and Scotch pine in Styroblocks were also placed in the test compound. The Alberta Forest Service kindly provided 11 trays of Spencer-LeMaire sixes of pine containers and 16 trays of spruce in sixes from the Pine Ridge Nursery. In total, the test compound included about 30,000 trees.

All Styroblock trees were seeded in January or February of 1987 and were to be grown to a height of 4 to 10 inches (10 to 25 cm). In general they were from containers that did not have a large enough diameter by the shipping date of early August. They generally were at the smaller end of the height range.

Figure 5-1 and Figure 5-2 show the compound as it was in the fall. The underground heating system was an 810 watt electric heating cable of the type normally used in a greenhouse propagation area for seed germination. The heated area was 8 feet by 8 feet (2.4 m x 2.4 m) and the heating cable was buried 2 inches (5 cm) deep on 6 inch (15 cm) intervals. Figure 5-3 shows the cable prior to being buried. The right centre of the photograph shows a pipe rising out of the ground. This pipe contained temperature sensor wires and carried them indoors to the computer (to be described).

Temperatures were taken using three separate systems: a computer, which also performed a control function, and two Campbell Scientific portable data loggers, a CR21 and a 21X. Figure 5-1 shows the compound and placement of these sensors. Figure 5-4 shows the three positions of the sensors as follows:

A) - in the foliage at the top face of the container
B) - in the root plug in a central location
C) - under the container

Sensors were brought into their respective position, from the side instead of above or below. This was done to minimize erroneous readings due to heat conduction along probe wiring (i.e., much of the heat flux and therefore temperature difference is in a vertical rather than horizontal direction). For the B position, holes were made in the containers before insertion of the probes.

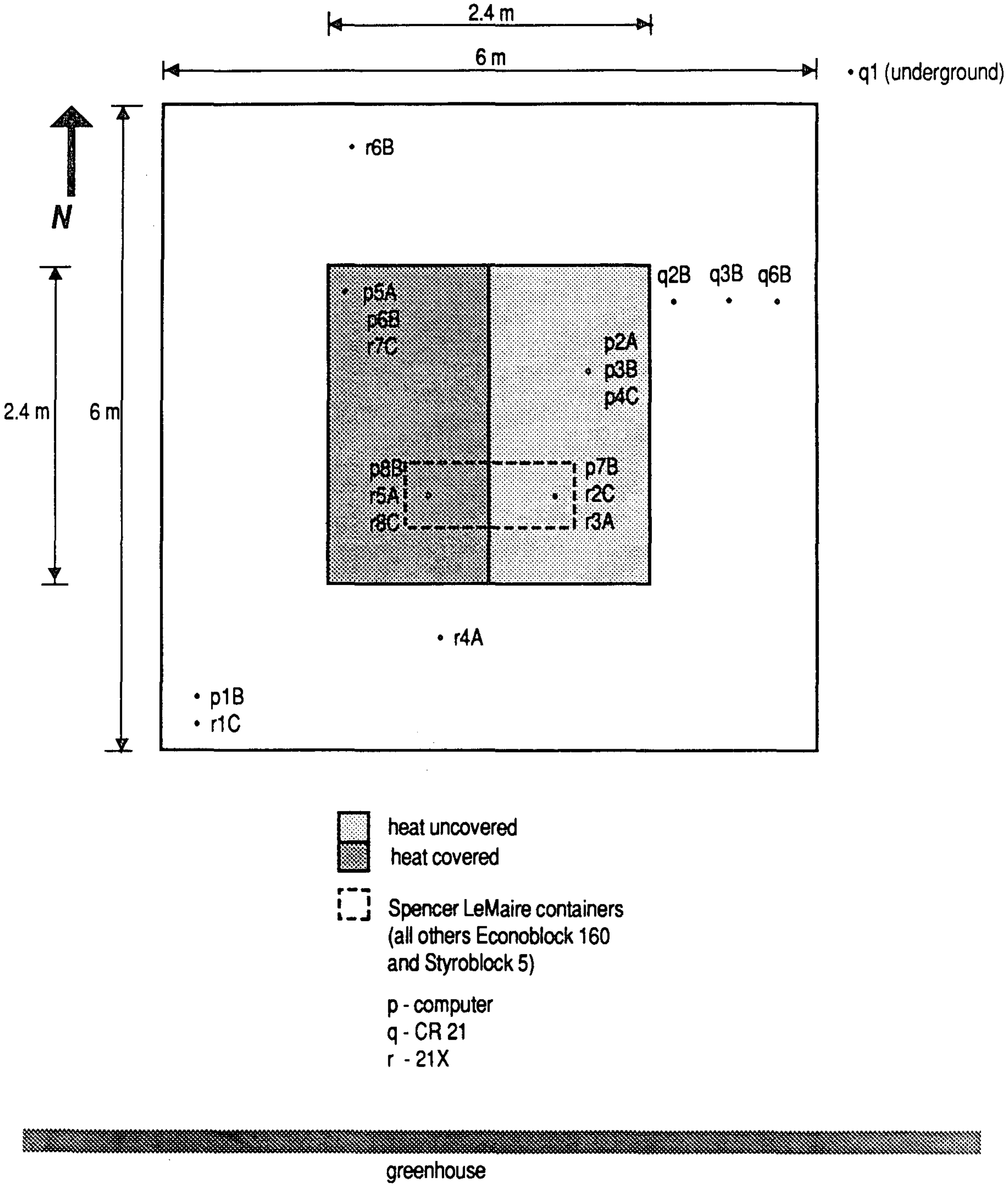


Figure 5-1
Outline of Test Compound (not to scale)

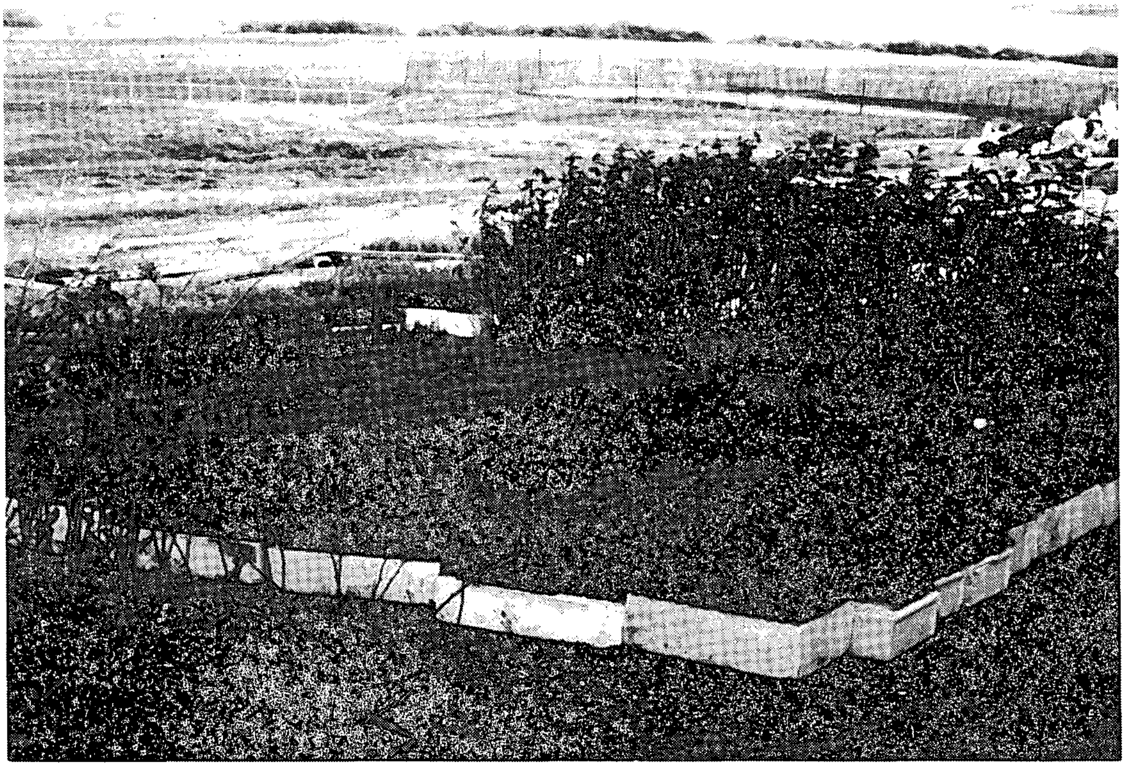


FIGURE 5-2
OUTDOOR TEST COMPOUND, FALL 1987

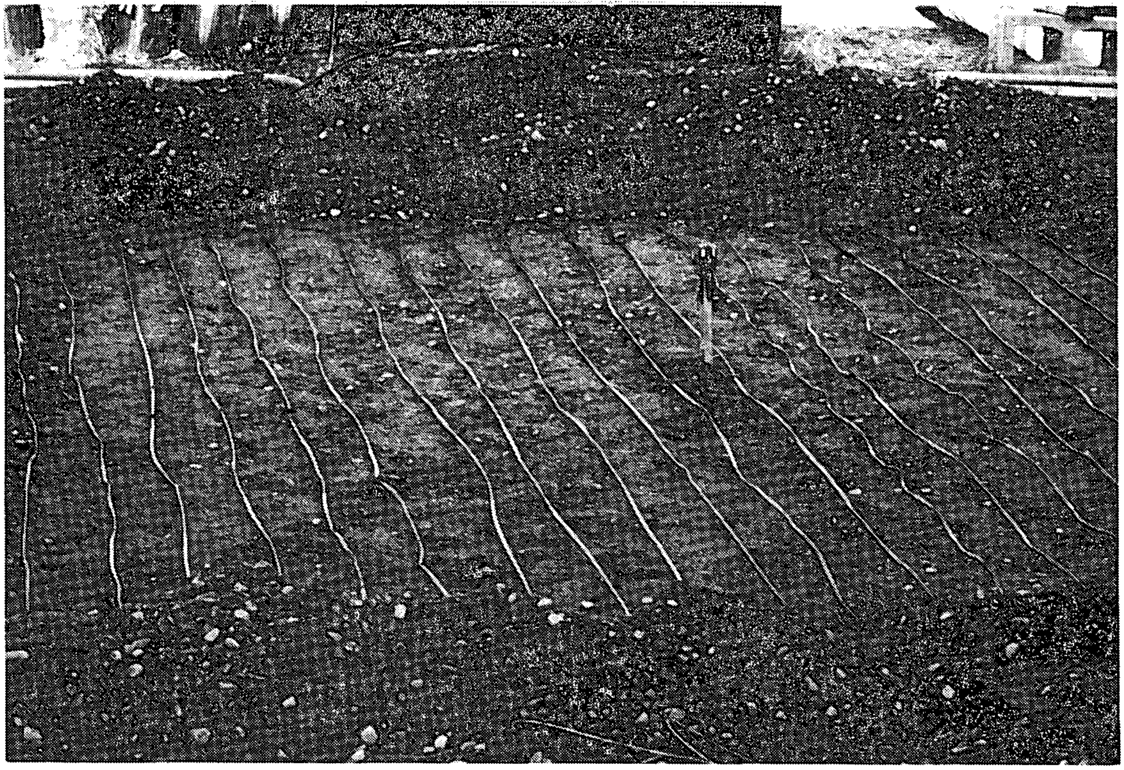


FIGURE 5-3
HEATER CABLE

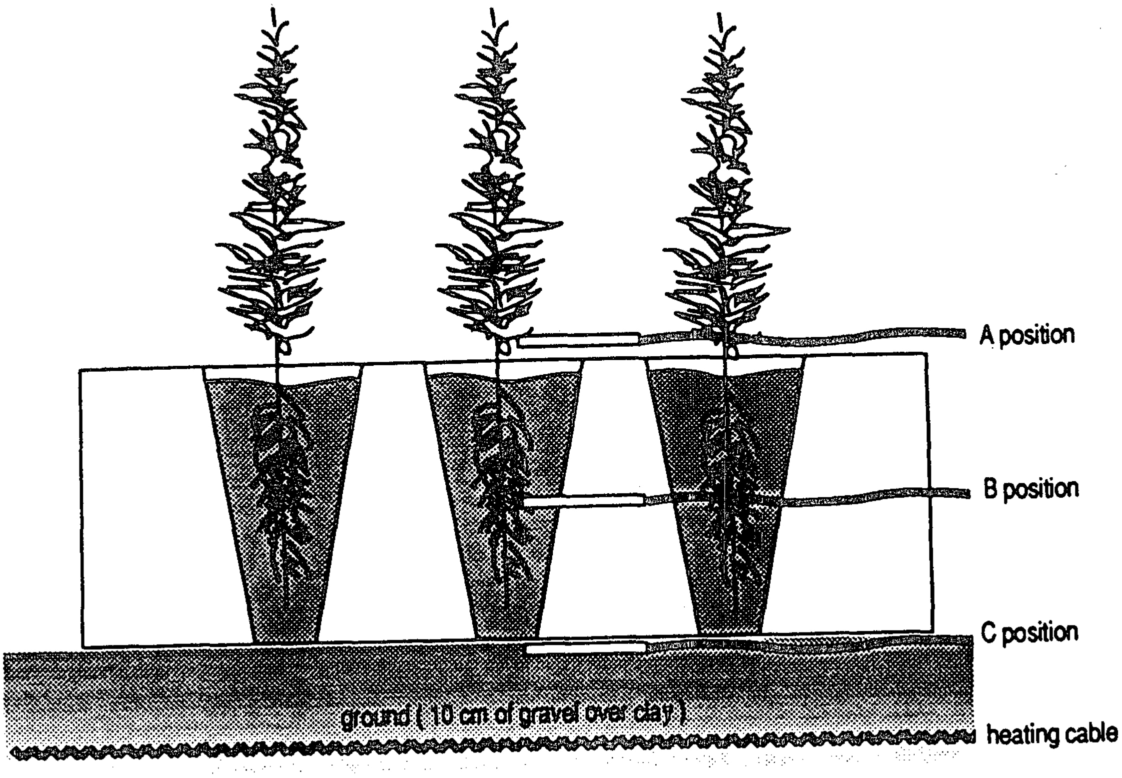


Figure 5-4
Probe and Electric Heater Position

There were five different areas in the compound as follows:

1) Heated Styroblocks (all Econoblock 160) with no plastic cover.
2) Heated Styroblocks (all Econoblock 160) with a plastic cover.
3) Heated Spencer-LeMaire with no plastic cover.
4) Heated Spencer-LeMaire with plastic cover.
5) Surrounding the 8 x 8 ft. heated area of 1) to 4), was an unheated section which expanded the compound to 20 x 20 ft. (6.1 m x 6.1 m). All the unheated containers were Styroblock 5's or Econoblock 160's.

The personal computer system was a Packard-Bell XT equivalent with a fixed hard disk. Two Data Translation input boards were attached to this computer which allowed analogue and digital input as well as analogue and digital output. One input board was for the sensors used in association with the operation of the Joffre greenhouse and waste heat system. The other board was for eight temperature sensors used for data acquisition in the overwintering experiment. These sensors were semiconductor devices accurate to about 1°C.

The software used was Lab-Tech Notebook which allowed acquisition of data and calculation and logical processes. Sensor #3 in the heated uncovered Styroblock, B position (see Figure 5-1) was used as a control. This sensor was monitored, and if its output was -8°C or lower, a digital output channel was triggered. This in turn activated a relay and the underground heater was turned on. When the temperature sensor output went to -5°C, the heater was turned off. It is important to note, therefore, that one particular area of the uncovered Styroblock study area was controlled. The other three heated areas received much the same heat generation from below, so at least, in theory, their temperature control was less exact.

All eight sensors and data from a ninth ambient air temperature sensor were archived on disk every hour. Data from the disk was later transferred to a Lotus 123 Spreadsheet for graphing and analysis.

Two Campbell Scientific recorders, CR21 and 21X, were also used to improve the total coverage of points. Data from these devices was read to storage and transferred to disk by either Campbell Scientific in Edmonton or by the University of Alberta Soil Science Department. The information on these disks was later merged with the rest of the data.

The intent of placement of sensors was to achieve information on each set of conditions, rather than duplication of a particular set of readings. Confirmation of correctness of a particular reading was by initial and final calibration of sensors.

## 5.2 Seedling Evaluation

### 5.2.1 Moisture Monitoring

There are a number of techniques to use when attempting to evaluate seedling moisture status. Few of them, however, are useful when dealing with frozen soil and seedlings. Soil moisture monitoring was discarded due to frozen container plugs and the problems associated with thawing them out and accounting for moisture loss while thawing, as well as the initial problem of extracting them from the containers.

For this study a pressure chamber was used to try to evaluate actual plant moisture stress. This was made possible by the loan of a pressure chamber to the authors by Dr. I. Edwards, Northern Forestry Research Centre, Canadian Forestry Service. The pressure chamber used was a PMS Instrument Co. model with a remote compressed nitrogen cylinder as a pressure source. Details of the equipment and how to operate it are found in Cleary and Zaerr (not dated).

Using the instrument to assess plant moisture stress over winter presented a problem of how to handle frozen seedlings. The literature is devoid of information on this topic. In conversations with E. Harvey (formerly CFS, Edmonton, pers. comm. 1987), Professor R.J. Day (Lakehead University, pers. comm., 1987) and Dr. B. Cleary (PMS Instrument Co., pers. comm., 1987) it became clear there is not a well defined approach for using the pressure chamber during the winter period. In this study, the January 27 and March 2 readings were done by clipping these seedlings, putting them in a moist, cooled, plastic bag and taken inside the greenhouse for five to ten minutes before measuring. The other readings were all taken outside near the experimental compound. Seedlings were measured in this manner because the intent was to measure the current moisture status of the seedling and not after the plug had thawed and moisture status had time to change. As well, this was a preliminary study and an attempt was being made to evaluate treatments relative to one another. All readings were taken between 11:45 a.m. and 3:45 p.m. in an attempt to cover the warmest time of day, theoretically the maximum moisture stress period.

### 5.2.2 Miscellaneous Monitoring

Some means of evaluating seedlings is necessary to assess the impact of bottom heating on seedlings, especially the root plug. Therefore, root counts were done on May 18 using a modification of the method described by Dymock and Dendwick (1987). The container plugs were divided into three equal sections from the top to the bottom, and the number of white root tips visible on the outside in each was counted and recorded. The container plug seedling roots were not washed; only the roots visible on the outside were counted and no attempt was made to measure their length. This approach was used in an attempt to gain some general information without expending a lot of labour. Root counts may be a useful tool for evaluating bottom heating if a controlled experiment follows this study.

Seedling diameters were also measured on May 18 in an attempt to determine if any differences were noticeable between treatments. Of particular interest was the covered and uncovered heated seedlings. No baseline measurements were made at the start of this experiment, as this measurement was designed to add some general information for potential use if a truly controlled experiment were to be set up following this preliminary study.

Moisture contents were determined once in February by destructive sampling of tops and roots. This was a simple weighing separately of the top and root plug, oven drying to 221°F (105°C), re-weighing and then calculating moisture content.

## 6.0 RESULTS

### 6.1 Heat Transfer

The winter of 1987-88 was a relatively warm one, so unfortunately the computer seldom called for the heater to be turned on. Data is presented in graph form for the two occurrences of cold weather.

Figure 6-1 shows data from December 17 to January 6 for an uncovered Styroblock. Shown are air temperature, foliage or A position, centre of plug or B position and underblock or C position. It can be noted that the B position indication is a smoother indication than the A or C. The B position of the uncovered styroblock is sampled by the computer every minute in order to perform its control function. The graphed output is therefore a calculated hourly block average for that minute-by-minute data. The ambient air temperature is also a calculated average. The other computer channels record values taken once per hour.

The legend for the graphs is follows:
first letter = h - heated or u - unheated
second letter = u - uncovered or c - covered
third letter = A, B, C - representing probe position
fourth and fifth letters if used = Sp - Spencer-LeMaire
or St - Styroblock

Thus, for example, huBSp represents a heated uncovered B position probe in a Spencer-LeMaire container.

From 0 to 300 hours, C position readings were close to 0°C and ambient air temperatures were mild. B position readings were mainly above -5°C with -7°C being the lowest reported. After hour 300, much cooler weather occurred and this generally lowered the C position temperature to about -2°C and the B position temperature to -7°C.

At about hour 400, a few days of cooler weather occurred, and the control B probe turned on the heater and the C position probe rose sharply in temperature against a rapidly dropping ambient air temperature. The B position temperature remained above -8°C, but that was partly due to an estimated 2 inches (5 cm) deposit of snow on January 5 and 6.

Figure 6-2 superimposes the A and B positions for the covered Styroblocks and shows some differences. The A position results for both the covered and uncovered Styroblocks followed the air temperature reasonably well until hour 300. After hour 400, the two A position temperatures deviate, especially after the estimated 2 inches (5 cm) of snow at the end of the period. The covered B position had temperatures much lower than those for the uncovered B position, possibly due to the presence of snow.

Figure 6-3 shows that Spencer-LeMaire B positions are cooler for the cold period after hour 400.

The bulk of the information of this report is for the period January 27 to February 17 which included the period of coldest weather of the winter. During this period, the 21X recorder and, intermittently, the CR21 recorder were used to obtain data, but for December 17 to January 6 they were unavailable.

Figure 6-4, for an uncovered Styroblock, shows ambient air temperatures going down to -30°C. As the B position probe sensed -8°C, the heater turned on and the C position indicator clearly registered that fact. At hour 160, the heater turned off and the C position dropped sharply, ambient air temperatures fell and the heater again turned on.

The B position temperature fell as low as -13.7°C as a result of a 24-hour period with near -30°C ambient air temperature. After hour 350, the ambient air temperature rose and the pattern of C positions near freezing and the B position above -5°C re-emerged.

One tree in a block at the south-east corner of the compound was measured as being 14.6 cm (5-3/4 in.) high. Snow depth was measured and was 9.5 to 12.7 cm (3-3/4 to 5 in.) after February 9 (hour 300). Drifting occurred throughout the plot, depending on tree height, proximity to the covered area, and proximity to the greenhouse wall.

Unfortunately, wind ripped the white polyethylene cover over the plot, and some snow undoubtedly drifted into that area. The damage was repaired February 6, but much of the covered data is suspect.

Figure 6-5 for the covered Styroblock, Figure 6-6 for the uncovered Spencer-LeMaire and Figure 6-7 for the covered Spencer-LeMaire are offered without comment. The remaining graphs in Chapter 6 facilitate more effective comparisons.

Figure 6-8 shows C position results for various situations. Of particular interest is the unheated Styroblock which maintained -4°C to -5°C for the cold weather. The other heated sensors maintained temperatures with the same general trend. The uncovered Styroblock with its snow cover would have had the greatest resistance to heat flow and therefore the highest C position temperature. The uncovered Spencer-LeMaire tray showed a marked lowering of the temperature around hour 300, indicating a close thermal coupling between the B and C position.

Figure 6-9 shows B position readings for various situations. The unheated Styroblock had a much lower temperature than other blocks, reaching -22°C. This probe was r6B (see Figure 4-1) at the north end of the compound on an outside block. (Comparison of q2B, q3B and q4B indicated that temperature did not drop off severely at the edges.) Trees from this block showed substantial mortality in the spring.

During heating from below, the Spencer-LeMaire containers, both covered and uncovered, tended to remain warmer than the Styroblocks because of their expected lower thermal resistance to conditions below. Thermal resistance above is dominated by foilage, snow or covering rather than from the container.

Figure 6-10 shows A position readings. These generally followed air temperatures. The heated, uncovered Spencer-LeMaire container was markedly higher than other sensors between 80 and 210 hours. These blocks were slightly lower than others surrounding it, so drifting into that area was likely. Even a small variation in snow depth seems to have a very important effect on plug and under block temperatures.

On February 11, several seedlings were removed in a frozen condition from their container. These were from a Styroblock 5 container at the edge of the compound. Seven plugs were separated from the container and were transplanted to a sealed jar in the still frozen condition.

Moisture content was determined to be 71.6% by weight of the total and as such the thermal conductivity K and specific heat were calculated to be close to that of ice. Thermal conductivity was estimated from Figure 3.10 (p. 117) of Geotechnical Engineering for Cold Regions (Harlan and Nixon 1978).

Assumed values are as follows for frozen peat at 71.6% moisture:

$K = .347$ BTU/hrft°f (.6 W/m°C)
$c = .472$ BTU/lb°F (1.97 J/kg°C)

Assuming that the plugs were 90% full (a rough estimate), density was calculated as:

wet $d = 30.274$ lb/ft$^3$(485.6 kg/m$^3$)
dry $d = 8.61$ lb/ft$^3$ (138.1 kg/m$^3$)

Figure 6-11 shows a plug being removed by breaking the Styroblock. A mass of roots with air spaces and little peat is evident. This gap at the bottom of the plug contains quiescent air and will have a clear effect on heat transfer into the block.

Figure 6-12 shows mortality at the perimeter of the compound, and Figure 6-13 shows the result of a spring flush and good survival in the central heated area. Figure 6-14 shows the plot in early spring with considerable snow drifting, much of which occurred after February 17.

## 6.2 Seedling Evaluation

Pressure chamber readings were taken five times during the study (Table 6.1). Measurements started in late January and continued at irregular intervals through the study with the last one conducted on May 18. No statistical analysis has been done other than to determine the means and standard deviation for each treatment. The variability within treatments was too high in most cases, to attempt any determination of significance between treatments. Simply put, the number of samples was not generally large enough.

The data in Table 6.1 is consistent with the expected values in that values are higher in January and generally decrease into April and May. There is an interesting, apparently treatment related, difference in the plant moisture stress levels between the covered and uncovered seedlings in the January data. The readings for covered seedlings averaged 17 to 20 bars with no reading over 26 bars while the uncovered seedlings averaged 26 to 33 bars with three seedlings having values of 43 bars or greater. These latter seedlings were considered to be dead, based on comments from Dr. B. Cleary (PMS Instruments Co., pers. comm., 1987). He suggested that over the winter period he would consider 40 to 50 bars to be lethal and that 20 to 25 bars is most likely non-threatening. The status of values in the 30 to 35 bar range is not clear as to whether these are too high or not, although, based on readings on March 2, it looks like they may not be lethal. By this date, all treatments were under essentially the same amount of plant moisture stress (14 to 15 bars average).

TABLE 6.1
RESULTS OF PRESSURE CHAMBER READINGS
FOR WHITE SPRUCE SEEDLINGS

| TREATMENT | AVERAGE PRESSURE CHAMBER READINGS (BARS) | | | | |
|---|---|---|---|---|---|
| | Jan. 27 | Mar. 2 | Mar. 17 | Apr. 6 | May 18 |
| Unheated, uncovered styroblock | 30.4 ± 4.9<br>(9,1)* | 15.6 ± 4.6<br>(11,2) | 19.5 ± 6.4<br>(11,1) | 9.7 ± 2.3<br>(12,0) | 14.8 ± 5.0<br>(12,0) |
| Heated, uncovered styroblock | 25.9 ± 8.5<br>(10,0) | 15.6 ± 5.2<br>(10,0) | 20.6 ± 5.1<br>(11,0) | 11.6 ± 3.0<br>(12,0) | 14.9 ± 3.7<br>(10,2) |
| Heated, covered styroblock | 17.2 ± 4<br>(10,0) | 15.5 ± 5.7<br>(11,0) | 15.5 ± 3.8<br>(12,0) | 8.6 ± 2.5<br>(12,0) | 13.0 ± 3.1<br>(12,0) |
| Heated, covered Spencer-LeMaire | 21.0 ± 3.5<br>(5,0) | 14.0 ± 3.4<br>(7,0) | 12.9 ± 4.9<br>(7,0) | 14.6 ± 4.0<br>(7,0) | 9.7 ± 1.6<br>(7,0) |
| Heated, uncovered Spencer-LeMaire | 33.2 ± 4.5<br>(3,2) | 14.3 ± 5.9<br>(7,0) | 19.6 ± 4.7<br>(7,0) | 11.5 ± 3.5<br>(6,1) | 11.6 ± 3.2<br>(7,0) |

*The first number is number of readings used for averaging; the second number is number of seedlings considered dead (reading generally greater than 40 bars).

There is another interesting aspect to the values in Table 6.1 and that is the large drop in the readings between January 27 and March 2 for the uncovered, heated and unheated treatments. Over this period of approximately one month, plant moisture stress apparently dropped by about 50%. The change was not nearly so large for the covered seedlings. Caution is required in putting too much emphasis on this change and, for any future detailed study, it is recommended that pressure chamber readings should be undertaken as soon as the study is initiated in the fall and maintained at two to four-week intervals.

The results of the white root counts on May 18 shows an interesting point (Table 6.2). The average number of white roots is in the order of 55 to 69% higher for white spruce in the uncovered Styroblock treatments. The number of samples for lodgepole pine is very limited; however, even for this species in the Spencer-LeMaire containers, the heated uncovered treatment has about 38% more white roots.

There is also a substantialy higher number of white spruce white roots in the Styroblock containers versus the Spencer-LeMaire containers. This difference would not appear to be due necessarily to a difference in root plug surface area as the numbers for lodgepole pine in Spencer-LeMaire are also higher than for the white spruce.

The average seedling diameters shown in Table 6.2 show an increase of about 0.25 mm for the heated covered treatment versus the uncovered white spruce in Styroblock containers. The white spruce in Spencer-LeMaire containers have exactly the same caliper. Lodgepole pine seedlings, again a very limited sample size, showed a difference in caliper size. In this case the difference in the average was about 0.9 mm higher for the heated covered Spencer-LeMaire containers.

## TABLE 6.2
## RESULTS OF ROOT COUNTS AND SEEDLING DIAMETER MEASUREMENTS
## MAY 18, 1988

| Treatment | White-Tipped Root Count (ave no./plug) | Ave. Seedling Diameter (mm) |
|---|---|---|
| Unheated Styroblock (SW) | 27.5 ± 18.3<br>(12)* | 2.76 ± 0.34<br>(12) |
| Heated, uncovered Styroblock (SW) | 42.7 ± 21.5<br>(12) | 2.76 ± 0.38<br>(12) |
| Heated, covered Styroblock (SW) | 25.2 ± 8.3<br>(12) | 3.05 ± 0.60<br>(12) |
| Heated, covered Spencer-LeMaire (SW) | 4.4 ± 4.1<br>(7) | 2.25 ± 0.23<br>(7) |
| Heated, uncovered Spencer-LeMaire (SW) | 7.6 ± 6.0<br>(7) | 2.25 ± 0.28<br>(7) |
| Heated, Uncovered Spencer-LeMaire (Pl) | 20.7 ± 1.1 | 2.40 ± 0.09 |
| Heated, covered Spencer-LeMaire (Pl) | 12.7 ± 5.9<br>(3) | 3.32 ± 0.54<br>(3) |

* number in parenthesis is sample size

FIGURE 6-1

# TEMPERATURE OF UNCOVERED STYROBLOCKS

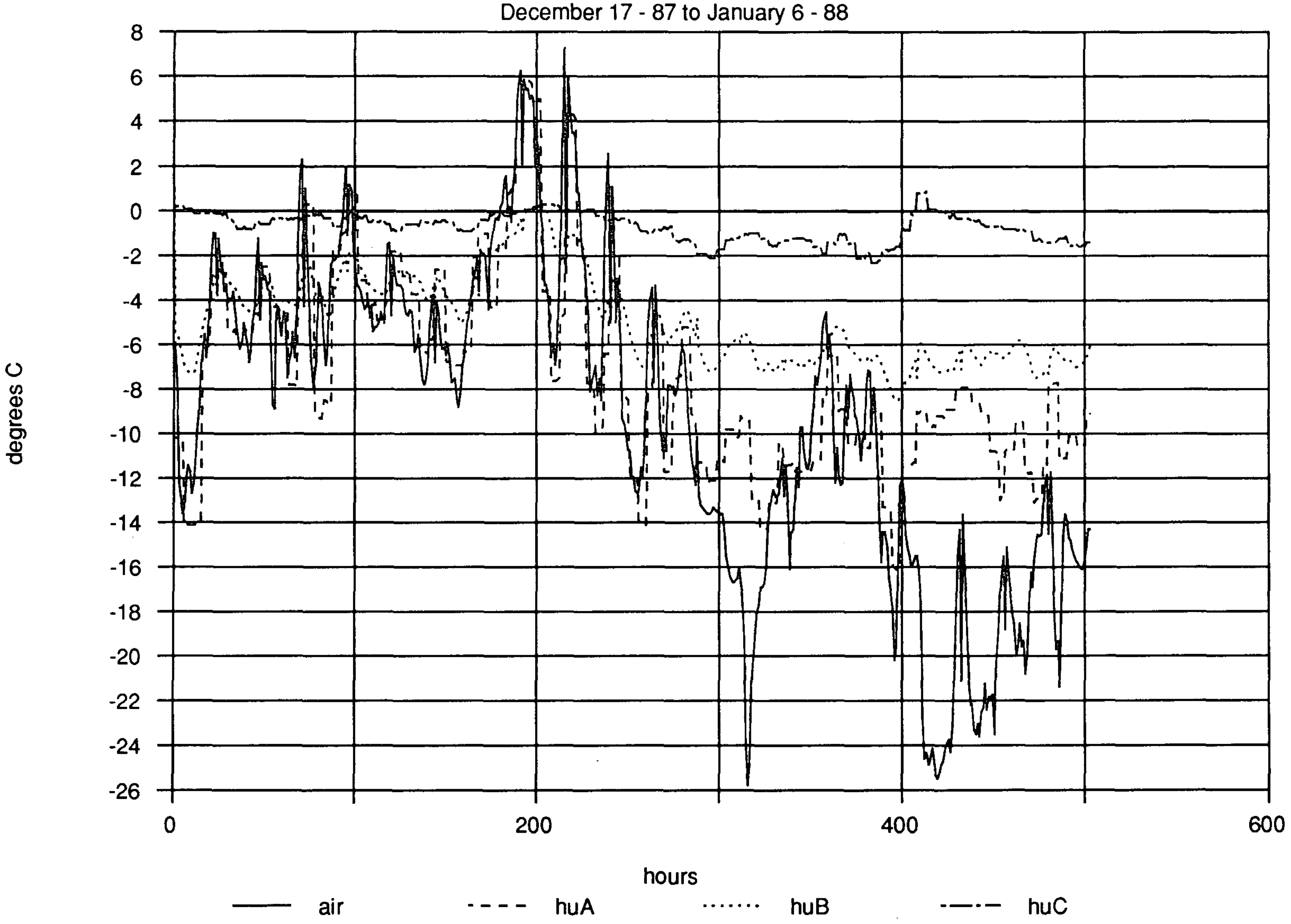


FIGURE 6-2

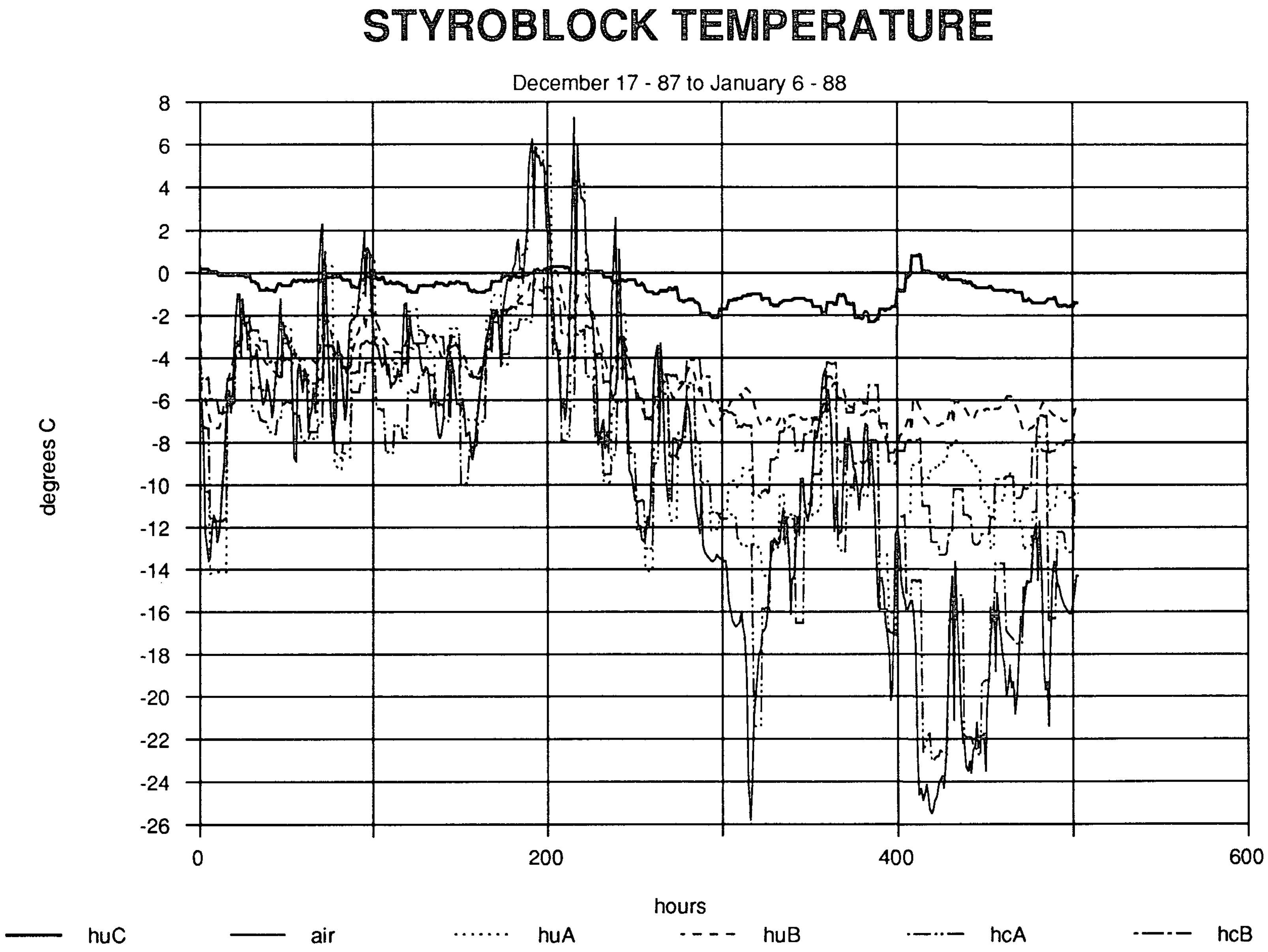

STYROBLOCK TEMPERATURE
December 17 - 87 to January 6 - 88
degrees C
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
0
200
400
600
hours
huC
air
huA
huB
hcA
hcB

FIGURE 6-3

# SPENCER AND STYROBLOCK ROOT TEMPERATURE

December 17 - 87 to January 6 - 88

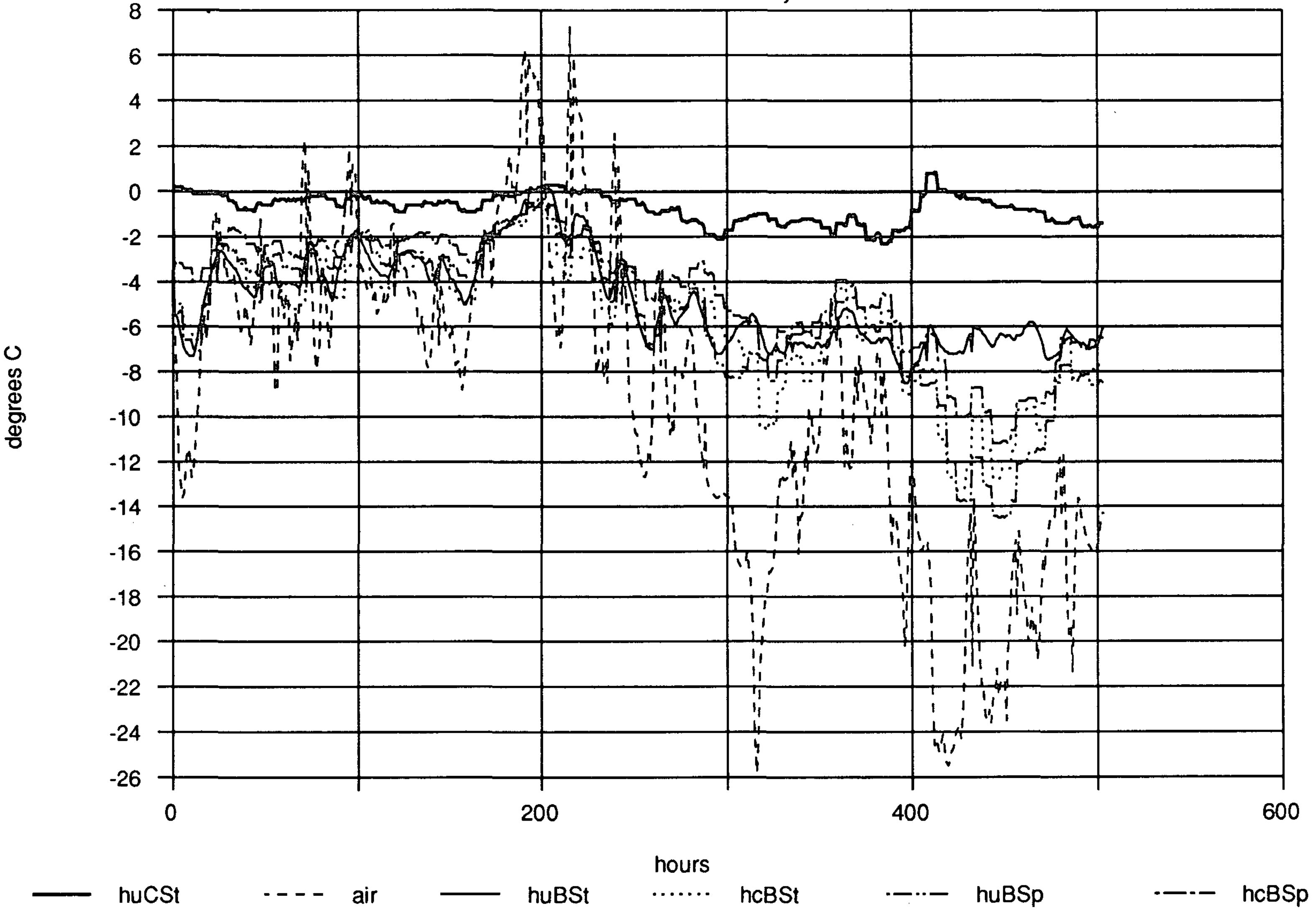


FIGURE 6-4

TEMPERATURE OF UNCOVERED STYROBLOCK

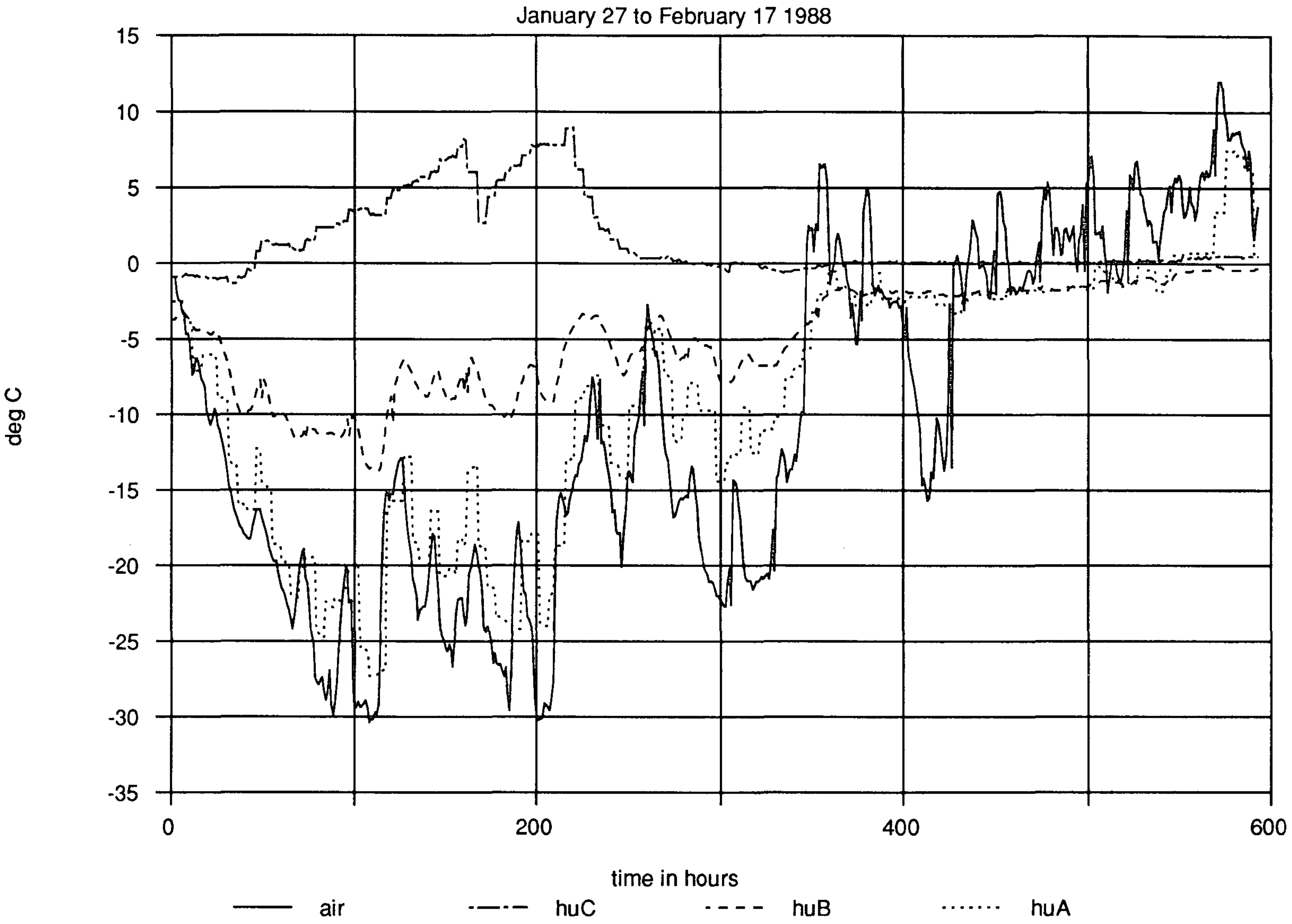


FIGURE 6-5

# TEMPERATURE OF COVERED STYROBLOCK

January 27 to February 17 1988

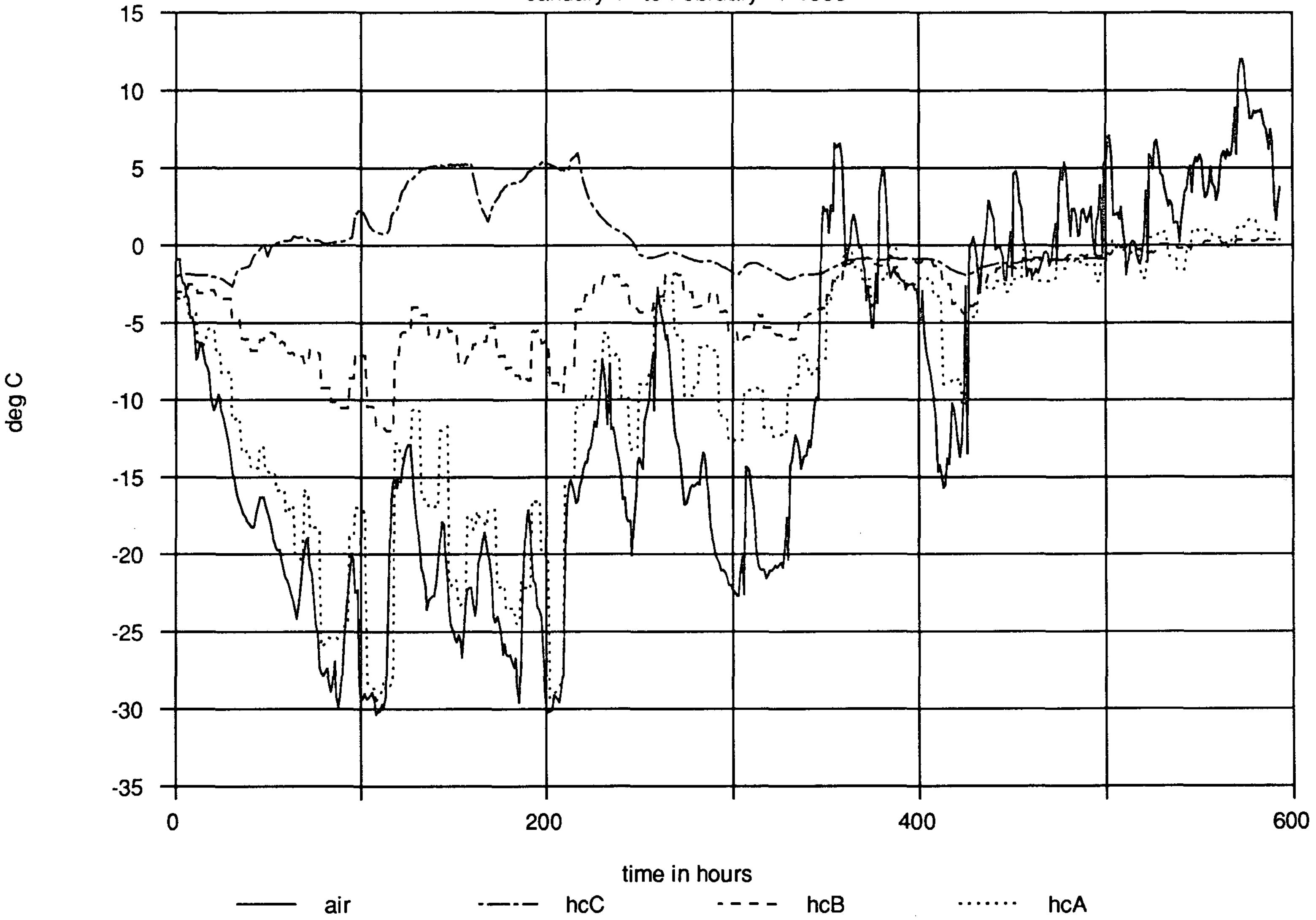


FIGURE 6-6

# TEMPERATURE OF UNCOVERED SPENCER

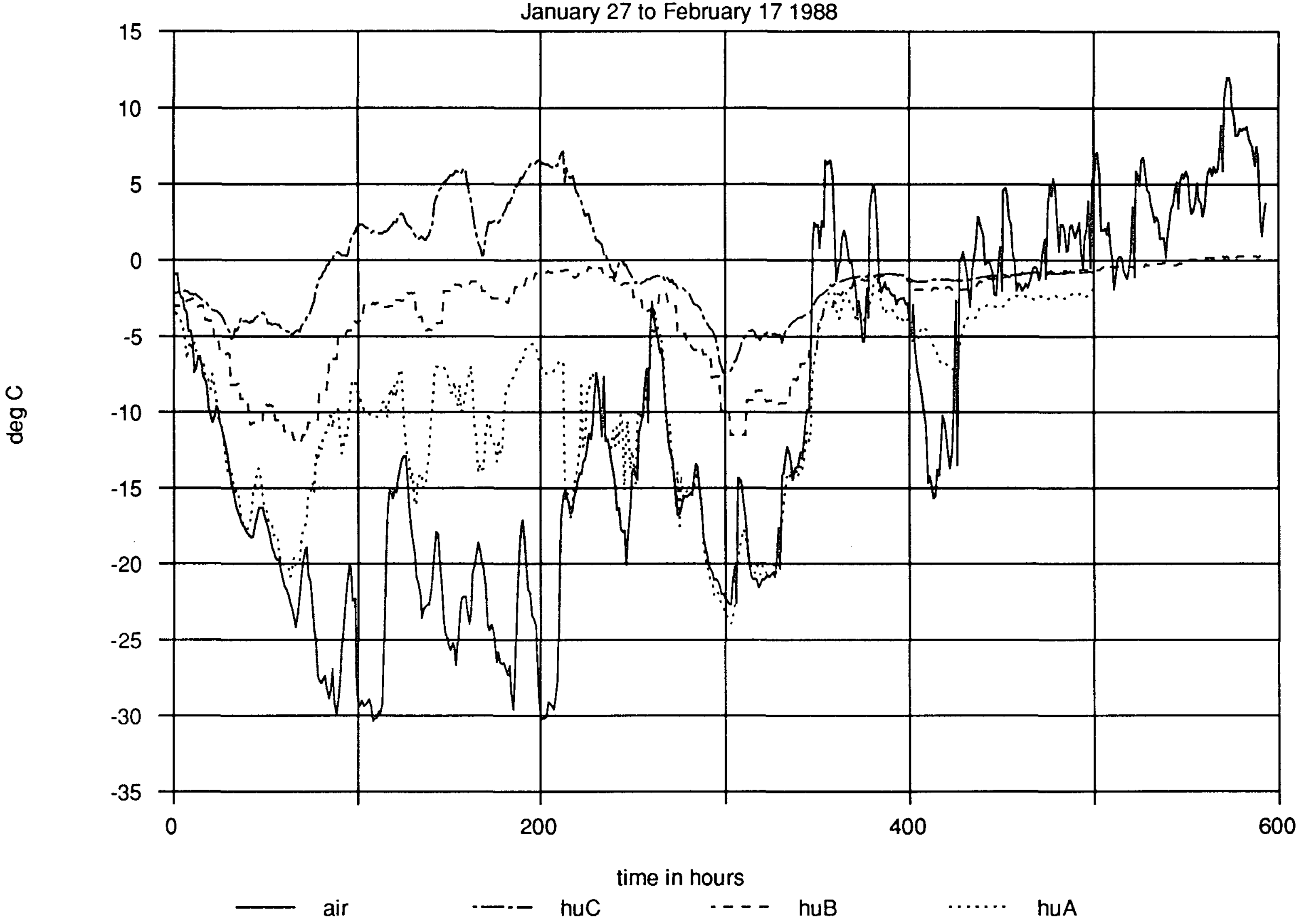


FIGURE 6-7

# TEMPERATURE OF COVERED SPENCER

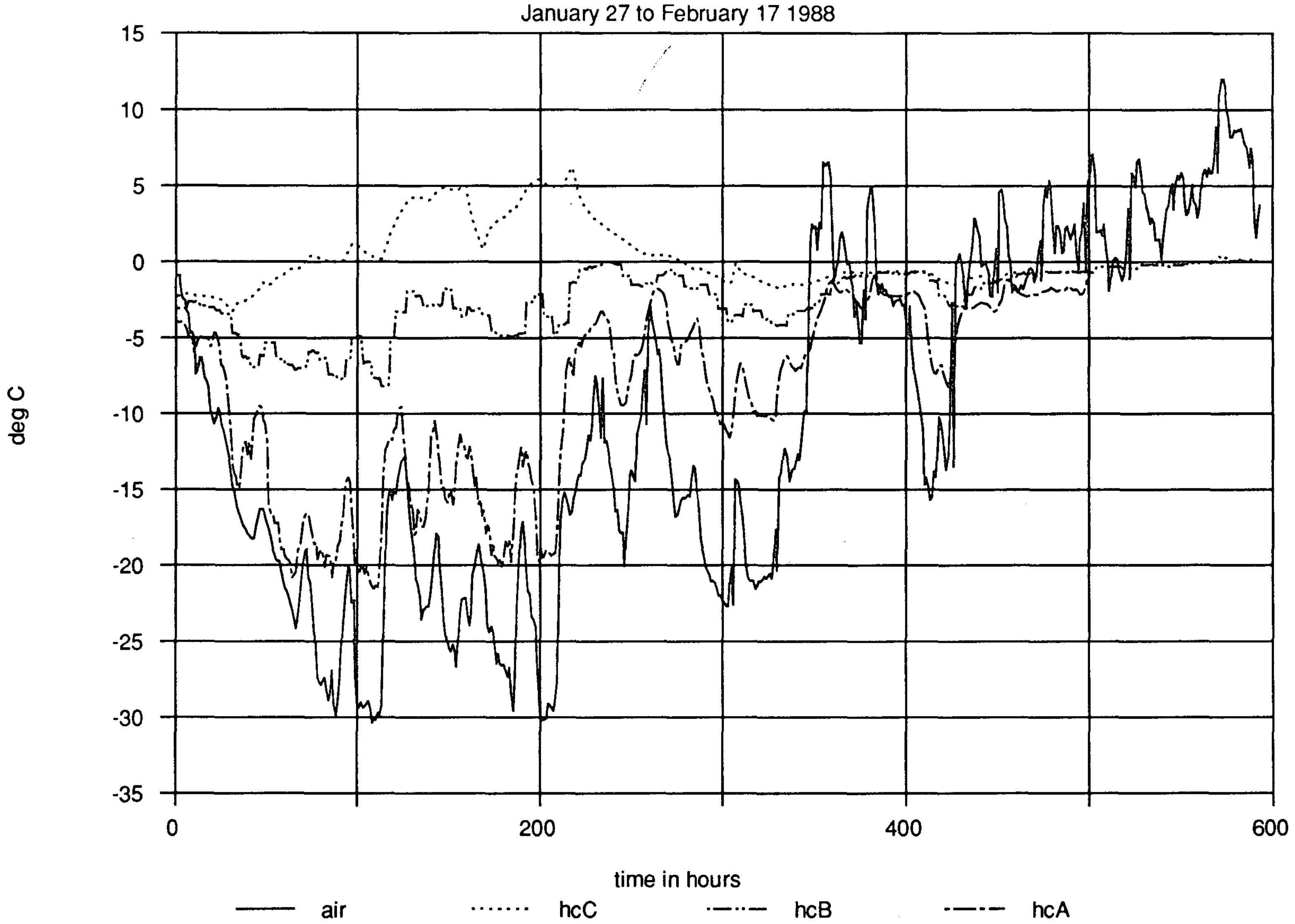


FIGURE 6-8

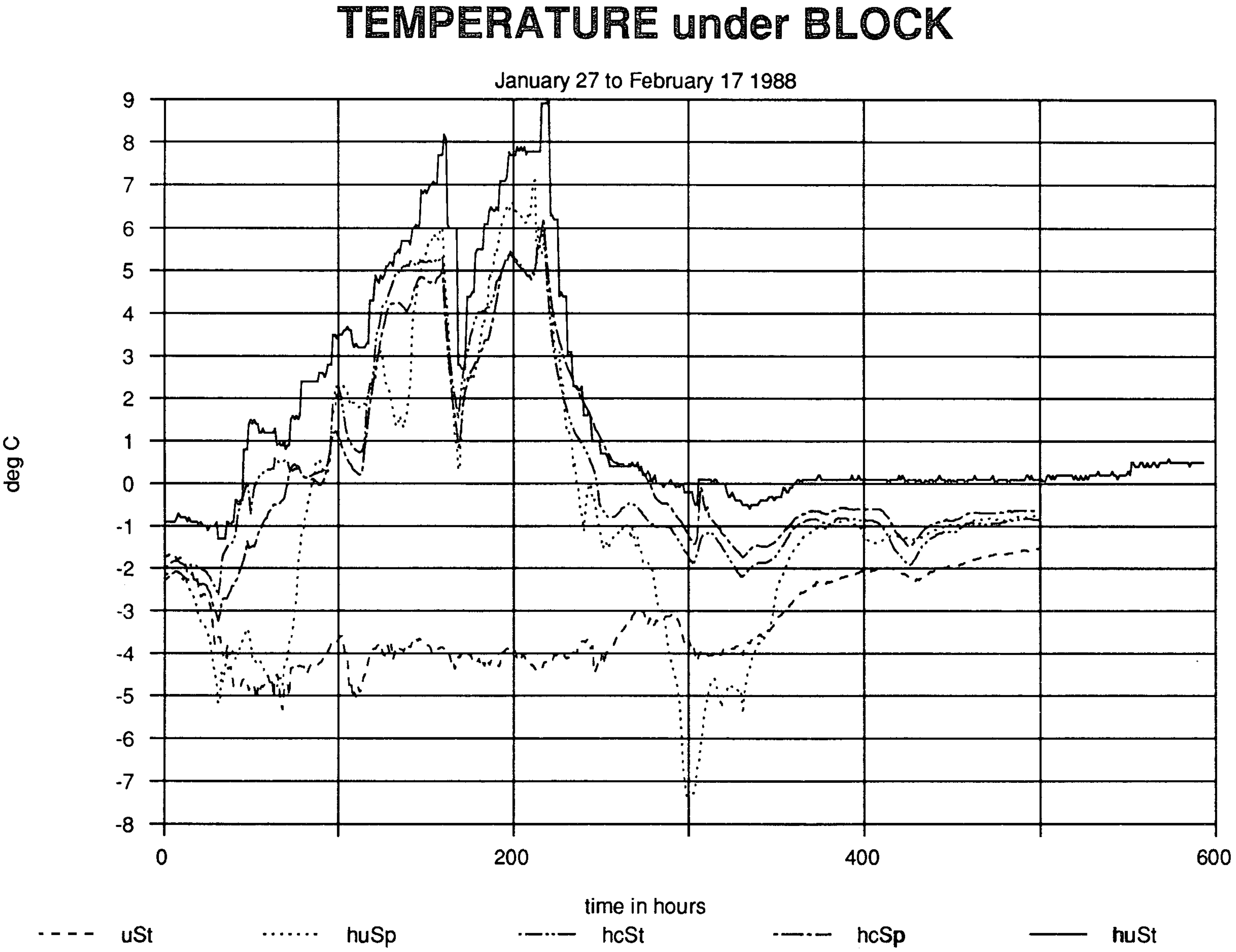

TEMPERATURE under BLOCK
January 27 to February 17 1988
deg C
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
0
200
400
600
time in hours
uSt
huSp
hcSt
hcSp
huSt

FIGURE 6-9

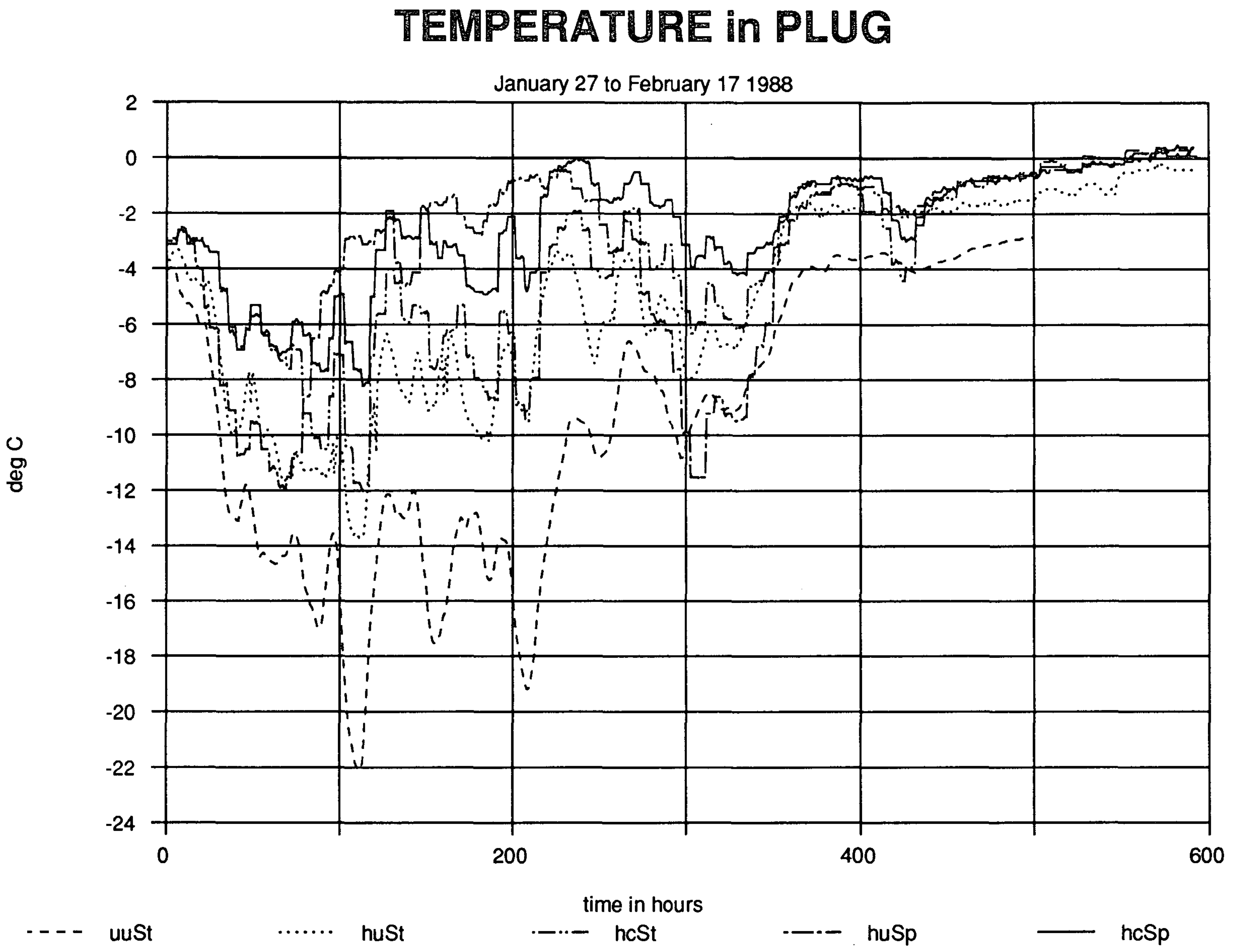
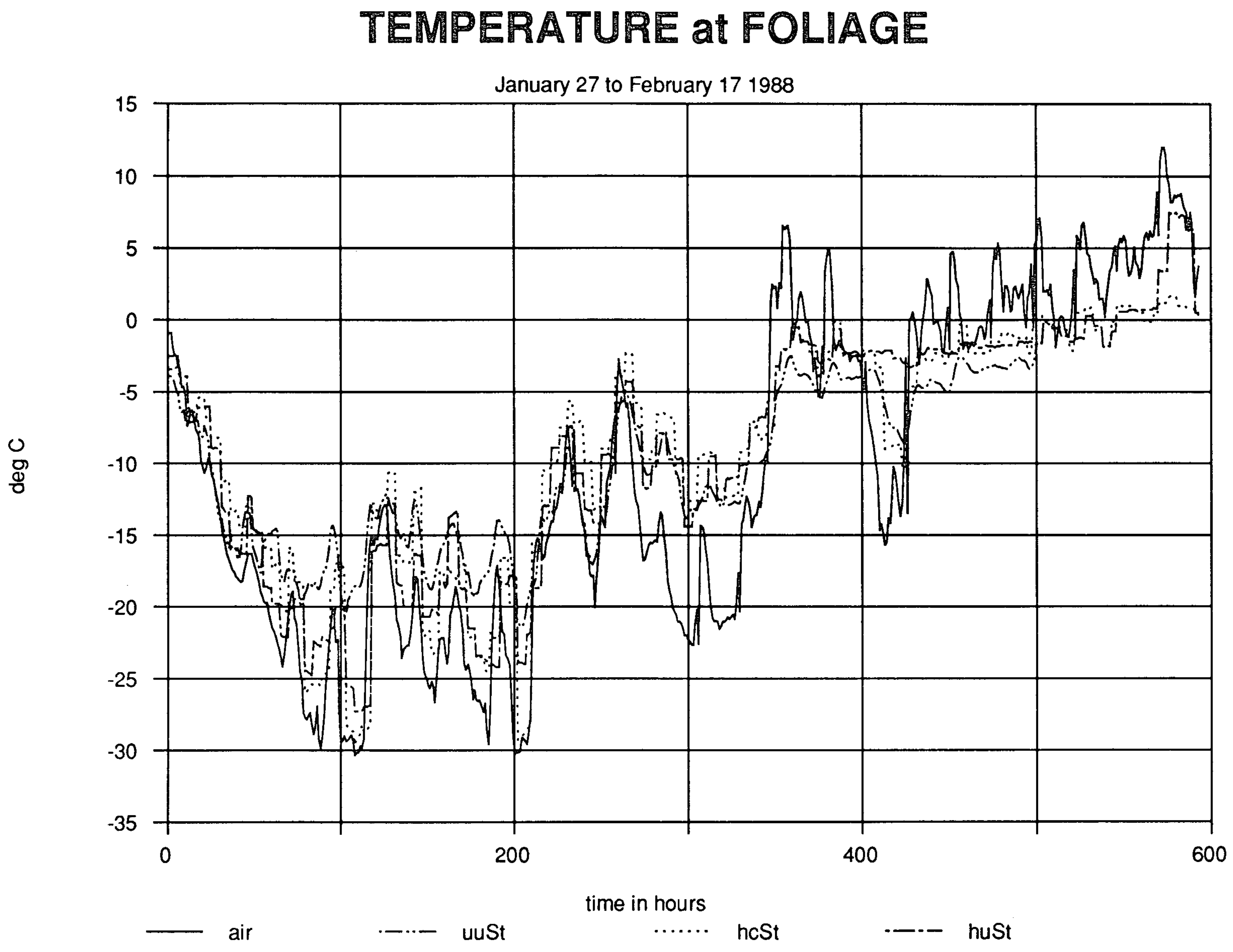

TEMPERATURE in PLUG
January 27 to February 17 1988
deg C
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
0
200
400
600
time in hours
uuSt
huSt
hcSt
huSp
hcSp

FIGURE 6-10


TEMPERATURE at FOLIAGE
January 27 to February 17 1988
deg C
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
0
200
400
600
time in hours
air
uuSt
hcSt
huSt

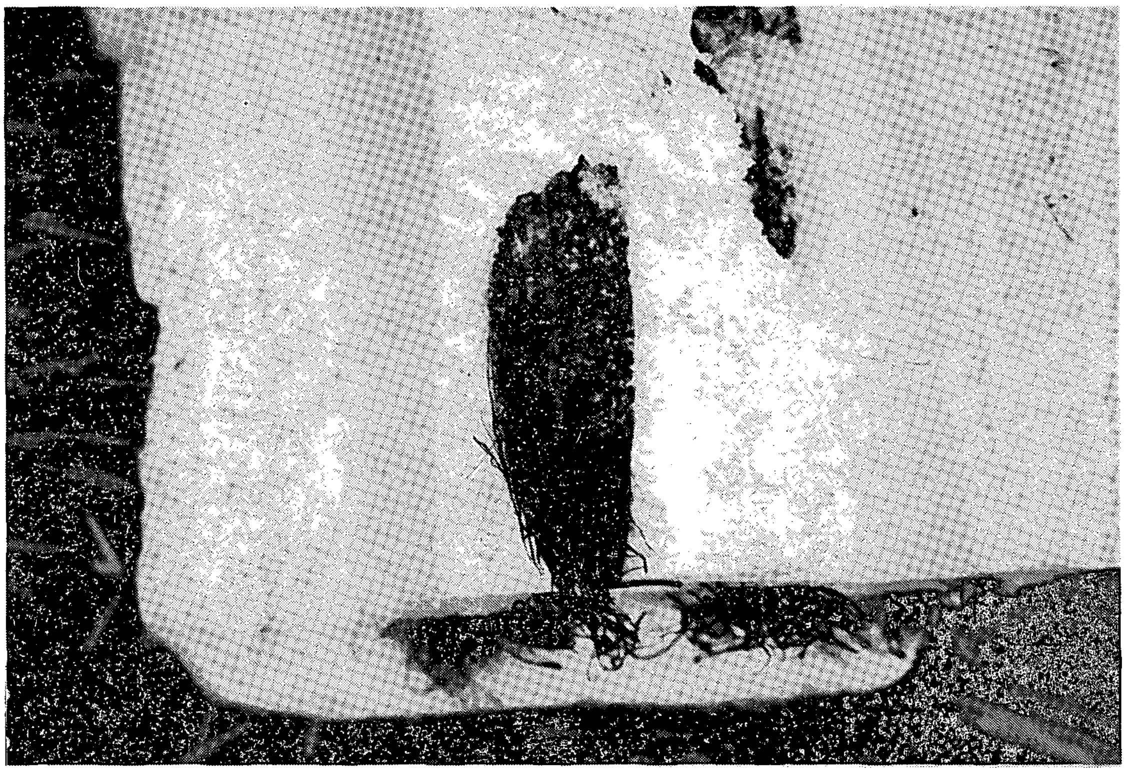


FIGURE 6-11
FROZEN PLUG BEING REMOVED FOR MOISTURE MEASUREMENTS

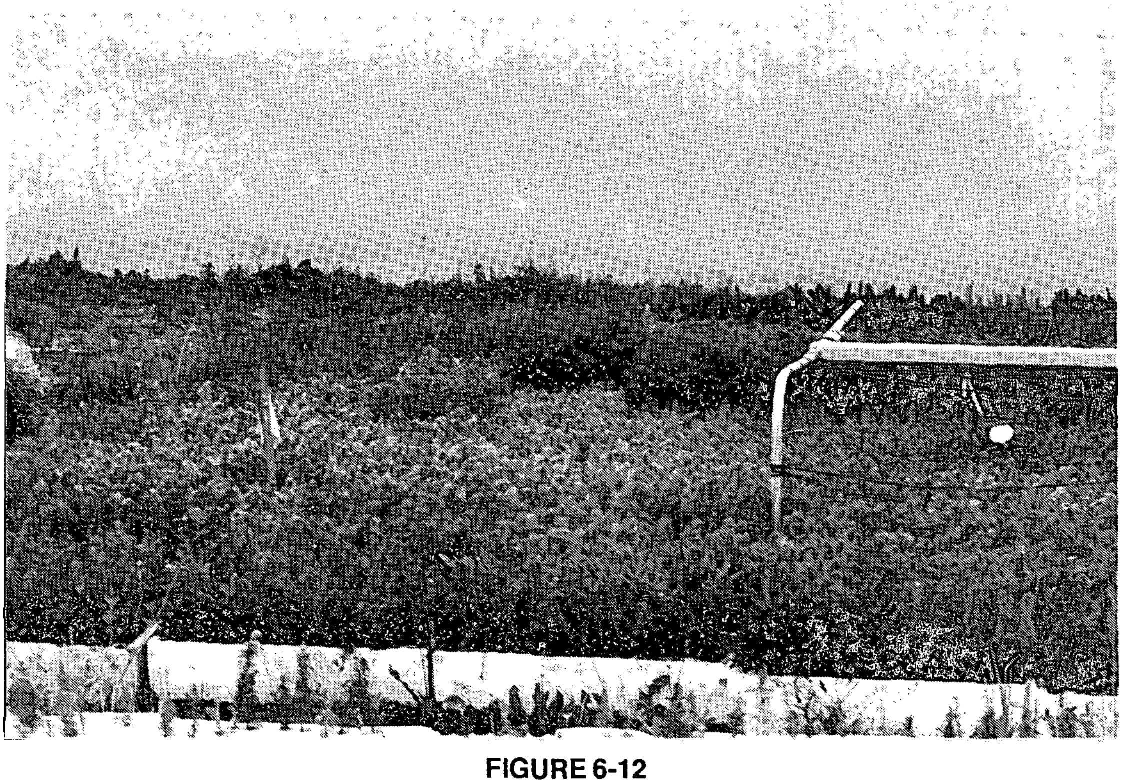


FIGURE 6-12
PLOT IN LATE SPRING

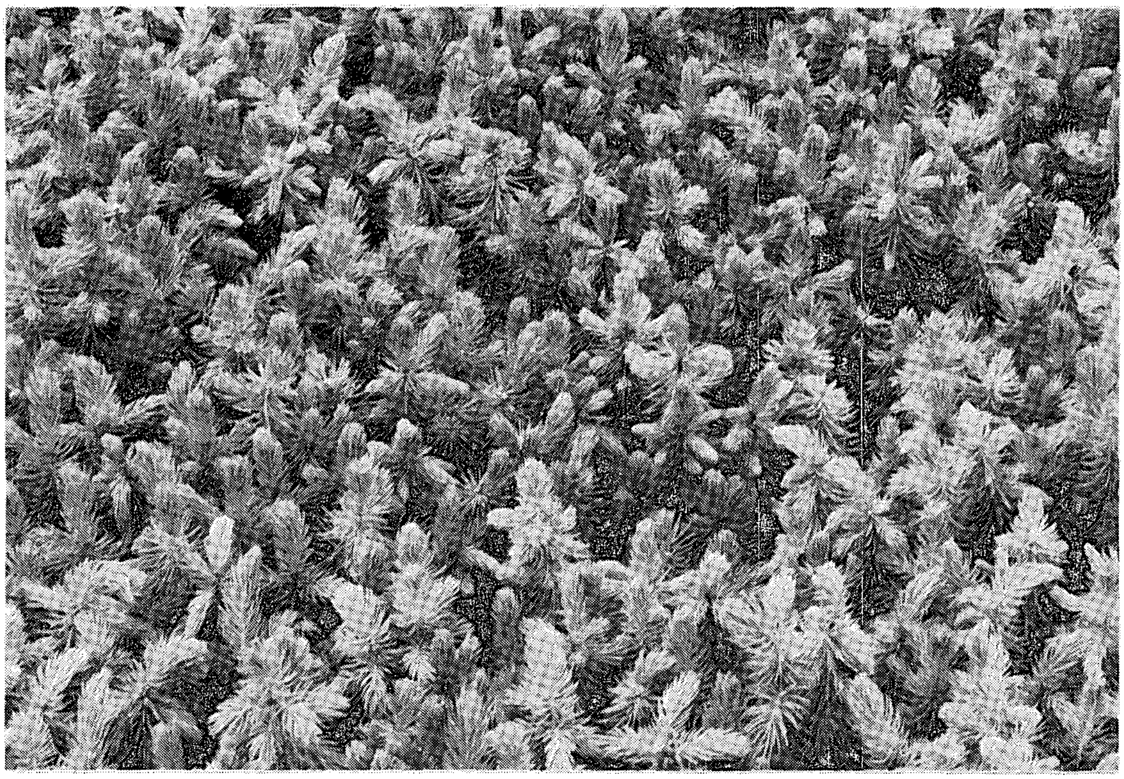


FIGURE 6-13
CENTRE OF HEATED AREA - GOOD FLUSH

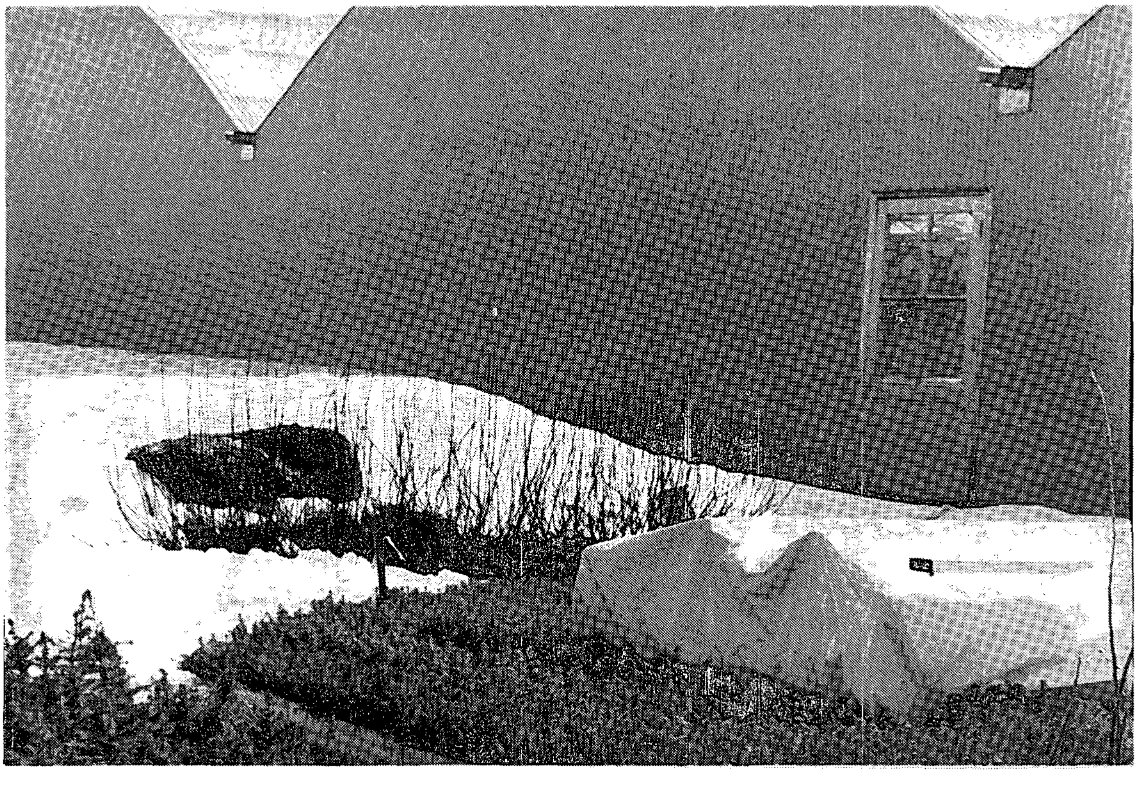


FIGURE 6-14
PLOT IN EARLY SPRING SHOWING COVER AND EXTENSIVE SNOW DRIFTING

## 7.0 DISCUSSION

### 7.1 Heat Transfer

Figures 7-1 to 7-3 show a heat flow through a Styroblock. As $T_{air}$ gets colder, so do $T_a$ and $T_b$. Since the cross section area is reduced nearer the ground, it is harder for the plug to get heat from the ground. Assuming steady state conditions, heat transfer through the frozen plug is by conduction given by $Q = -KA(x)\ \partial T/\partial X$ where x is depth. Thus, for a given heat flow, the temperature difference needed is greater for a smaller cross section. Under the assumed steady state condition the temperature difference is therefore not linear with temperature (as was shown in Figure 2-1 for constant area).

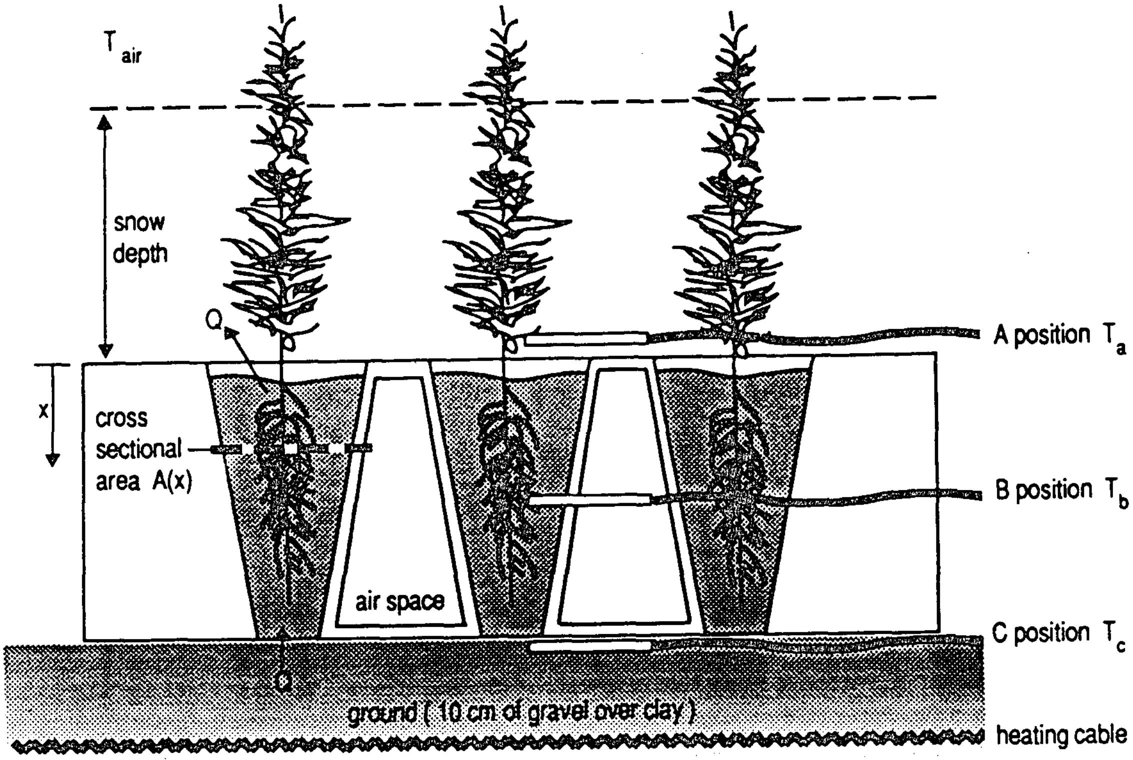
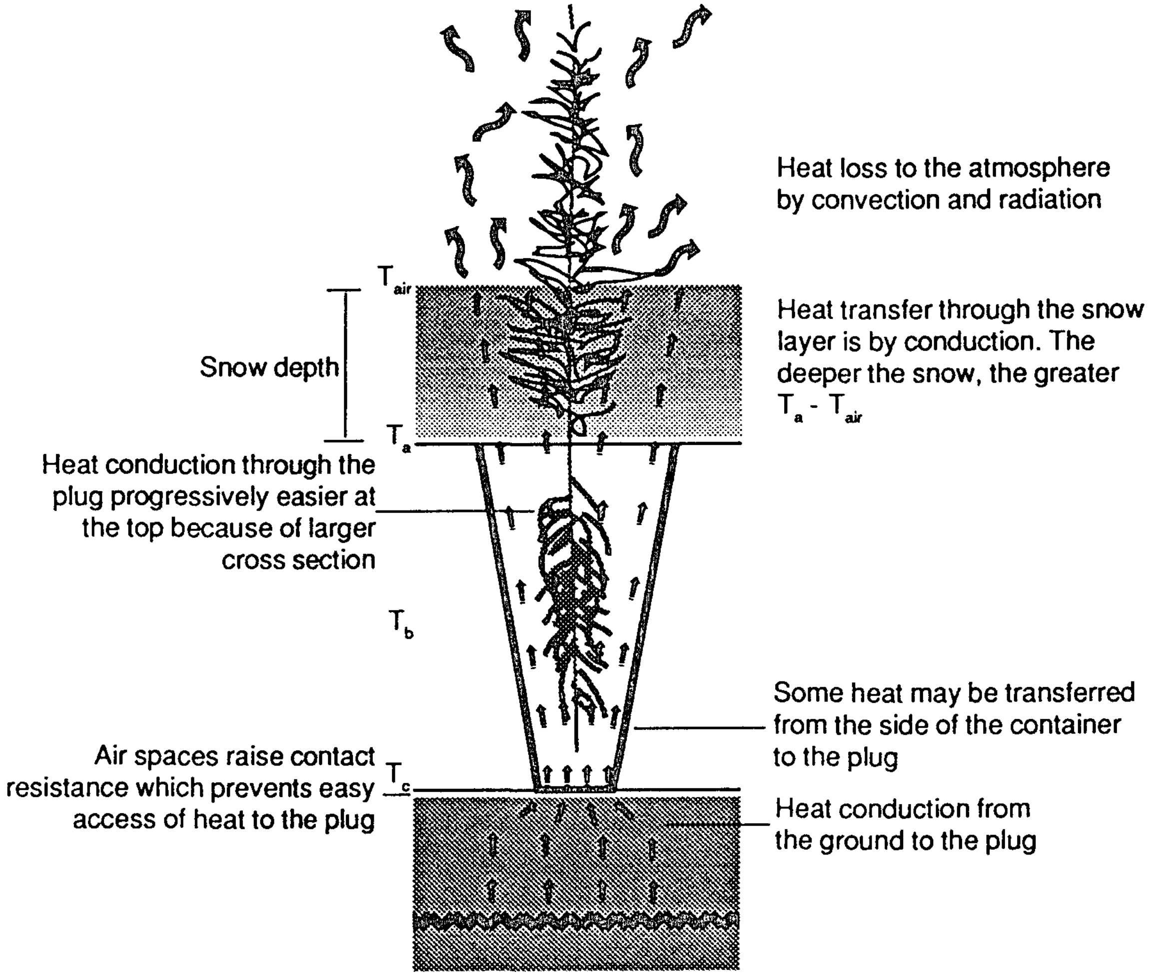


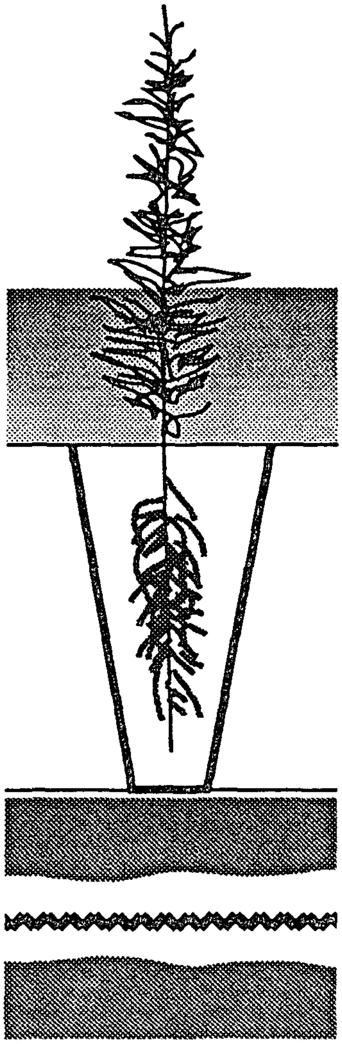
Figure 7-1
Heat Flow Through a Styroblock

Underground heating to $T_c$ = 8°C raises the total heat flow by increasing the temperature difference $T_c - T_a$ which raises the intermediate temperature $T_b$.



Assumptions
- Decreasing ambient and plug temperature
- Heater is not on
- Plug and ground (at shallow depth) are frozen
- Solar radiation is not included

Figure 7-2
Heat Flow Through a Plug



As heating progresses, ice around the heater melts which initially acts as a heat sink.

Heater is turned on and the plug begins to warm.
Mechanisms of heat transfer are as per figure 7-2 except as noted.

Figure 7-3
Heat Flow Through a Plug

The effect of snow is to increase the temperature difference between $T_a$ and $T_{air}$. For a given $T_{air}$, greater snow depth raises $T_a$, and for a given $T_c$, heat flow is reduced. The effect of turning on a heater is to produce a certain Q (i.e., a certain watt output results), and a greater buildup of temperature at C and therefore at B.

Mathematical solutions to predict plug temperature are difficult for the following reasons:

(a) Time dependent as opposed to steady state analysis is required. The results showed that, at cold ambients, plug temperature was not often steady.

(b) As heating occurs at C position, temperatures rise above freezing and a melting phase transformation travels up the plug. This transformation affects the rate of temperature change, and a numerical solution is probably needed.

(c) In the air space, some heat transfer occurs by convection and radiation. This heat then travels by conduction through the cell wall. The convection in particular is difficult to predict.

Appendix 1 gives properties of various materials associated with the experiment. Polystyrene and air have particularly low values of K. One ramification of low K for air is that any space between the bottom of the block and the ground has an important effect on the thermal contact and B position temperature. Lindstrom (1986b) noted a temperature a few degrees higher between blocks placed on sand rather than gravel. This effect was attributed to the better thermal contact between the container and the finer particles of sand.

The results obtained are useful guidelines for temperatures in an outdoor compound. It is, however, clear from the results in Chapter 6 and the Environment Canada weather data for Lacombe and Peace River, that snow cover is extremely important to the temperatures obtained. The foliage of the trees was seen to act to trap snow. The compound was on the north side of a greenhouse and in the low light months snow tended not to melt. In addition, the compound was in an area where the building caused drifting snow.

Spencer-LeMaire results can be considered as only qualitative in nature. Too few blocks were used to properly eliminate edge effects. The comparisons are of interest, however, because they show the relative ease with which Spencer-LeMaire containers can be heated as compared to Styroblocks.

It is clear from the results that C position temperatures can be raised from -5°C to +8°C and higher if necessary. The unheated Styroblock (B position temperature) in Figure 6-8 went to -22°C while the heated one got as low as -13.7°C. Edge effect has had some impact on reducing the unheated block temperature.

The unheated B position readings showed considerable variation with respect to one another (due to snow drifting and edge effects). Several CR21 sensors were monitoring the B position, but unfortunately this recorder was unavailable much of the time. Spot checks of data do, however, make it clear that the heater was effective in raising plug temperatures several degrees.

## 7.2 Seedling Evaluation

The results obtained from the seedling evaluation raised more questions than answers. However, some interesting items were identified which should be pursued in any future research.

As pointed out by Dr. B. Cleary (PMS Instruments Co., pers. comm. 1987), readings in the 40-50 bar range are apparently lethal, however, what readings mean in the 30's is not clear and should be further investigated.

There appears to be less plant moisture stress in the covered seedlings versus those not under the polyethylene covering. This is despite some rips in the polyethylene prior to January 27. This appears to be a real difference as it occurred in both the Styroblock and Spencer-LeMaire seedlings. The better seedling moisture contents under the covering should be a benefit to the seedlings; however, more work needs to be done to quantify these results. Measurements should be done over the entire study period.

The influence of the covering on the number of white roots is interesting and may be related to seedling diameters. The uncovered seedlings appear to have more active roots, while the covered seedlings exhibited larger average diameters. Uncovering seedlings earlier may provide for a more active root system which may be more desirable if they are going to be directly outplanted. However, if seedlings require more caliper before shipping, keeping them covered may allow the grower to obtain better diameters. Again, this aspect requires further evaluation.

Casual observation while doing root counts revealed the presence of fungal mycelium on five out of 14 Spencer-LeMaire white spruce seedlings. In some cases the entire outside of the plug was covered and, in others, only the bottom half of the plug. This situation was not evident on the lodgepole pine seedlings in the Spencer-LeMaire nor in the Styroblocks. The significance of this is not known; however, it could be an effect of the heating and should be evaluated in any further heating experiments.

## 8.0 UTILITY COSTS AND UNDERGROUND HEATING EQUIPMENT

The 810 watt heater was turned on for about 200 hours for the test winter of 1988-89, a mild winter. In an effort to assess a more normal winter, Figure 8-1 shows the cumulative probability of various temperatures occurring at Red Deer, Alberta. This data is taken from multi-year Environment Canada published data and means, for instance, that the probability that a temperature of -10°C or less will occur is 12.6%.

It appears from the data that the heater turned on at ambient air temperatures between -15°C and -20°C. The cumulative probabilities for these values is 7.1% and 3.5%. Based on a year of 24 hours x 365 days, this results in 622 hours and 307 hours, respectively, as the time the heater would be expected to be operating.

Table 8-1 shows the cost to heat with electric power and with natural gas.

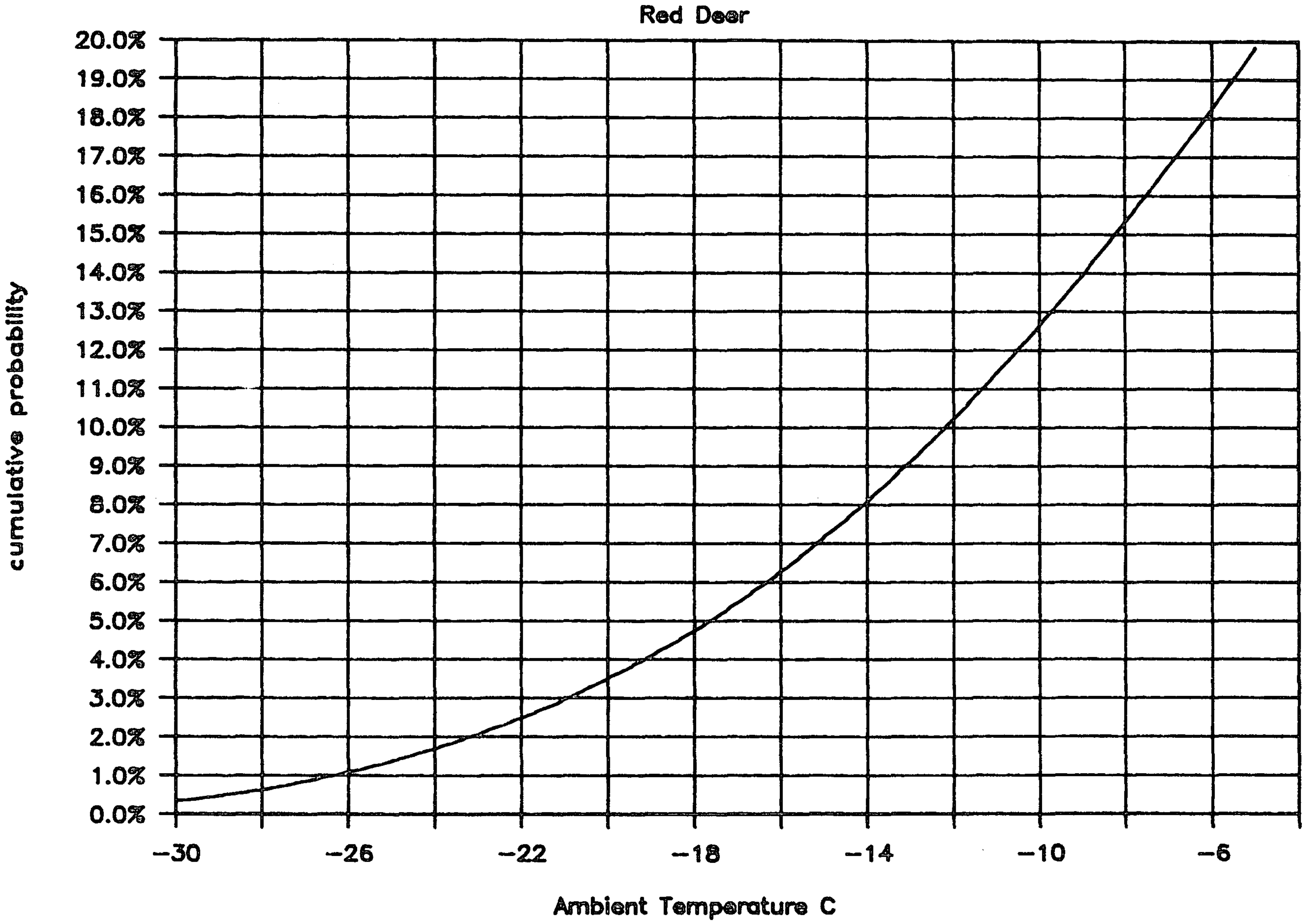
TABLE 8-1
UTILITY COST OF UNDERGROUND HEATING

| | Actual Test | Trigger at Long Term Average for -20°C | Trigger at Long Term Average for -15°C |
|---|---|---|---|
| operating time | 200 | 307 | 622 |
| cost at 5¢/KW-hr for test plot | $8.10 | $12.42 | $25.19 |
| cost at $3.00/MMBTU for test plot | $2.07 | $3.18 | $6.45 |
| cost/acre at $3.00/MMBTU | $1,411 | $2,163 | $4,389 |
| cost/tree at 2,470,000/acre (Econoblock 160) | .057¢ | .087¢ | .177¢ |

The predicted operating costs are subject to a number of uncertainties such as fuel cost, tree spacing and operating hours. The cost will, however, certainly be modest.

FIGURE 8-1

CUMULATIVE TEMPERATURE PROBABILITY



The electrical heater used for the experiment was chosen largely for cost savings and convenience for a small scale test. In a commercial sized operation, a fossil fuel boiler or waste heat system would be used to heat a heat transport fluid. A system similar to that used in Noval Enterprises' greenhouse could be employed. This system to provide bottom heat in the greenhouses was based on a method outlined by Ohio State University (1985). Detailed design and construction of the Noval system was done by T.D. Ellis, one of the authors of the present work.

The system consists of buried 3/4 inch polyethylene tube at 1-foot lateral intervals and at a depth of 3 inches to 1 foot. The heating fluid is water in a closed loop which is heated indirectly across a heat exchanger by waste heat. Cost of the system based on an area of 150,000 $ft^2$ at Joffre was roughly $0.60 per square foot installed complete with the heat exchanger, controls and all pumps. (Please note - no new building was needed to house any of this equipment.)

The system could be readily adapted to an outdoor system to provide a heating fluid at a controlled -10°C to +15°C. A computer such as the Packard-Bell used to control the test heater, could also be used to control such an outdoor system. The heating fluid should be an antifreeze solution rather than water.

The capital cost for heating a one acre compound would require a site specific design and estimate, but might be roughly $60,000 including all installation and a computer system. Not included are a utility room for the heat exchanger or a computer room. Also not included is a boiler to provide the heat since the boiler might already exist as part of the nursery facility. It is assumed that all added systems would fit within existing nursery buildings and that no major additions to the electrical system would be required.

The capital and operating cost of the heating system can be compared to that of cold storage, that being another method of avoiding winter damage. Information presented by the BC Ministry of Forests during its recent nursery privatization gives cold storage costs as $7.50 per carton in the north of that province. Southern cold storage can be half that amount because of greater year round facility usage. Based on 475 trees per carton, this translates to costs of about 0.8¢ to 1.5¢ per tree in the south and in the north.

Based on $60,000 capital cost per acre for the heating system, and 2,470,000 trees per acre, a capital cost per tree is 2.43¢. Based on a five-year depreciation of the system and a 0.1¢ annual operating cost, costs per tree is about 0.6¢. The lifetime of the system should certainly exceed ten years, so the 0.6¢ cost is certainly conservative.

The foregoing calculation shows that underground heating should be cheaper than cold storage, however the comparison may not be entirely valid. Cold storage is a useful technique to ensure that a seedling grown to specification and hardened can be protected until later planting. The major value of the underground heating system is that it provides winter protection for trees being grown for two years. Based on typical selling prices, if use of the system results in reduced winter mortality of 4%, the capital and operating cost will be offset.

## 9.0 CONCLUSIONS

One of the questions driving this research was the feasibility of heating containers using an underground heating system. This pilot study demonstrates that the capital cost for an underground heating system is relatively modest and the operating costs are expected to be quite small.

Several facts stand out in this research in terms of temperatures, containers and heat transfer. They are:

- Snow cover is extremely important in ameliorating container plug temperatures and also ground temperatures.
- Spencer-LeMaire containers are more sensitive to temperature change (especially from below) than are Styroblocks. Heating costs would be different for the two containers.
- Plug temperatures can be raised several degrees C by heating from below. This resulted in temperatures under the containers of above +5°C.
- Temperatures in the unheated containers reached temperatures much lower than those encountered at the corresponding depth in heated containers.
- Temperature measurements should be considered as essentially qualitative in nature because of the variability in plug temperatures due to edge effects and snow drifting.

Plant moisture stress results are as follows:

- Plant moisture stress levels appear to be less in January under the polyethylene-covered seedlings than for uncovered ones.
- Uncovered, heated seedlings did not appear to differ much from the uncovered, unheated seedlings in terms of January plant moisture stress.
- The pressure chamber technique showed potential as a means of monitoring plant moisture status as related to treatment during the course of the study, however, readings must be initiated earlier and continued at a regularly scheduled interval of two to four weeks until about April 1.
- Polyethylene-covered seedlings exhibited a larger average diameter, while uncovered seedlings appeared to have more active root growth.

It is re-stated that these are preliminary conclusions based on this pilot study. Most of the results need to be substantiated by a more detailed and controlled experiment.

The authors feel this approach is one which can have considerable commercial applicability. It has potential for reducing root injury due to:

1) early fall cold temperatures before roots are properly acclimatized;

2) to low over-winter temperatures as a result of a lack of snow cover, extremely low temperatures which surpass maximum low root temperatures or unseasonably high temperatures followed by a quick return to colder temperatures; and

3) late cold temperatures in the spring after roots have become deacclimatized.

Reduced root injury in any of these seasons assists the grower in producing a better quality seedling for outplanting.

## 10.0 FULFILLMENT OF CONTRACT

The terms of contract 10K45-7-0067 are restated here and comments are made with respect to achievements of objectives.

10.1 Review literature on frost tolerance and cold hardiness overwintering procedures to determine threshold temperature at which freezing damage occurs in lodgepole pine and white spruce seedlings.

Comment - An extensive review was performed and information presented on any tree species thought to provide insights (see Chapter 3).

10.2 Review literature on heat transfer characteristics of container materials, air, growth medium, and plants to determine the feasibility of application of heat transfer principles to overwintering containerized seedlings in an outdoor compound. Define the parameters and dynamics of heat transfer among containers in an outdoor environment.

Comment - Literature directly giving heat transfer characteristics of the container system was sparse, however much related information was found and presented in Chapter 2. Parameters of heat transfer were defined.

10.3 Develop a heat transfer model of an outdoor storage compound for Spencer-Lemaire and Styroblock containers using a fluid mixture such as ethylene glycol-water as the heat source. The model should represent, mathematically, the dynamics of heat transfer between the circulating heated fluid and containers, growth medium, plants, and ambient environment.

Comment - The basic physical parameters and analysis techniques were presented in Chapters 2 and 7. Neither a closed form or computer solution was presented because of the inherent complexity of the problem. The approach was to identify parameters to support analysis of experimental results in a semi-empirical fashion.

10.4 Test the model by conducting suitably controlled and replicated experiments at Joffre, Alberta, using lodgepole pine and white spruce seedlings that are equivalent to second crop seedlings, i.e., late-spring sown, greenhouse grown, and are 15-20 weeks old. Refine the model based on results of the test. Monitor weather data, e.g., temperature, precipitation, wind, relative humidity, and solar radiation as well as temperature gradients across the plant-environment interface and determine the effect of weather on heat transfer within the system. The objective should be minimal warming to prevent frost damage. Monitor the temperature of roots and shoots beginning with outdoor placement and continuing throughout the winter and into the spring.

Comment - The experiments were conducted and heat transfer analysis adjusted based on actual results. Solar radiation was not measured, and trees available for the experiment were somewhat older than 15-20 weeks. Neither deviation is thought to be critical to the results obtained and inferences drawn.

10.5 Computer all heat and pumping cost for the system and compare these with the cost of packaging and/or cold storage of seedlings.

Comment - Capital and operating costs were determined and compared to cold storage costs in Chapter 8.

10.6 Prepare a scientific report discussing the heat transfer model developed and the feasibility of using heat to prevent frost damage to seedlings that are overwintered outdoors.

Comment - The report was prepared.

# BIBLIOGRAPHY

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 1985. ASHRAE Handbook 1985 Fundamentals. Am. Soc. of Heating, Refrig. and Air-Cond. Eng., Inc., Atlanta, Georgia.

Anderson, D.M., R. Rusch and E. Penner. 1978. Physical and thermal properties of frozen ground. Pp. 37-103. *In* Geotechnical Engineering for Cold Regions. O.B. Andersland and D.M. Anderson (eds.) McGraw-Hill Book Company, Toronto, Ont. 566 p.

Baig, M.N. and W. Tranquillini. 1980. The effects of wind and temperature on cuticular transpiration of *Picea abies* and *Pinus cembra* and their significance in dessication damage at the Alpine Treeline. Oecologia (Berl.) 47:252-256.

Benoit, G.R. and S. Mostaghimi. 1984. Modelling soil frost under conservation tillage systems. Paper No. 84-2505, Am. Soc. of Agric. Eng. Winter Meeting, New Orleans, Louisiana, Dec. 11-14, 1984.

Civant and Sliepcevich, C.M. 1985. Comparison of the Thermal Regimes for Freezing and Thawing of Moist Soils, *In* Water Resources Research 21:407-410.

Cleary, B. and J. Zaerr (not dated). Guidelines for measuring plant moisture stress with a pressure chamber. PMS Instrument Co., Corvallis, One.

Colombo, S.J. 1985. Interpreting the significance of plant moisture stress by means of the pressure-volume technique. Pp 58-65. *In* Nurserymen's Meeting Swastika Forest Station June 18-21, 1984. Ontario Ministry of Natural Resources, Toronto, Ontario.

Colombo, S.J., C. Glerum and D.P. Webb. 1984. Frost hardiness testing: an operational manual for use with Extended Greenhouse Culture. For. Res. Rept. No. 110, Ontario Tree Imp. and For. Biomass Inst., Min. of Nat. Res., Maple, Ont. 14 p.

Colombo, S.J., D.P. Webb and C. Glerum. 1982a. Bud development in black spruce container stock. Forestry Res. Note No. 32, Ontario Ministry of Natural Resources, Maple, Ontario, 5 p.

Colombo, S.J., D.P. Webb and C. Glerum, 1982b. Cold hardiness and bud development under short days in black spruce and white spruce seedlings. Pp 171-176. *In* Proceedings of the Canadian Containerized Tree Seedling Symposium, J.P. Scarett, C. Glerum and C.A. Plexman (eds.). COJFRC Symp. Proc. O-P-10, Canadian Forestry Services, Environment Canada.

Day, R.J. 1980. Effective nursery irrigation depends on regulation of soil moisture and aeration. Pp 52-69. *In* Proceedings North American Forest Tree Nursery Soils Workshop, L.P. Abrahamson and D.H. Bickelhaupt (eds.). Coll. Environ. Science and Forestry, State University, New York, Syracuse.

Day, R.J. and S.J. Walsh. 1980. A manual for using the pressure chamber in nurseries and plantations. Silv. Rept. 1980-2. School of Forestry, Lakehead Univ., Thunder Bay, Ontario. 49 p.

Desjardins, R.L. and C. Chong. 1980. Unheated environments for overwintering nursery plants in containers. Can. J. Plant Sci. 60:895-902.

Dormling, I. 1987. Dormancy and dormancy release in seedlings of *Picea abies* (L.) Karst. and *Pinus sylvestris* L. *In* Proceedings Seminar on Frost Hardiness and Overwintering of Forest Tree Seedlings. Joensuir, Finland, Dec., 1986.

Dymock, I.J. and F.M. Dendwick. 1987. Monitoring viability of overwintering container stock. Pp 21-35. *In* Proceedings of the 1986 Prairie Federal-Provincial Nurserymen's Meeting. E.M. Harvey (comp.). Info. Rept. NOR-X-287, No. For. Centre, Can. For. Serv., Edmonton, Alberta. 54 p.

Ebermayer, E. 1901. Zur Schuttekrankheit der Kiefler. Allg. Forst. Zahdztg. 77 Jkg: 309-314.

Glerum, C. 1973. Annual trends in frost hardiness and electrical impedance for seven coniferous species. Can. J. Plant Sci. 53:881-889.

Glerum, C. 1985. Frost hardiness of coniferous seedlings: Principles and applications. Pp 107-123. *In* Proceedings: Evaluating Seedling Quality: Principles, Procedures, and Predictive Abilities of Major Tests. M.L. Duryea (ed.). Workshop held Oct. 16-18, 1984. For. Res. Lab., Ore. State Univ., Corvallis, Ore. ISBN 0-87437-000-0.

Goodrich, L.E. and L.W. Gold. 1981. Ground Thermal Analysis. Pp 149-172. *In* Permafrost Engineering Design and Construction. G.H. Johnston (ed.). John Wiley & Sons, Toronto, Ontario. 540 p.

Gouin, F.R. 1985. Resolving problems with the structureless thermo-blanket system for over-wintering container grown ornamentals. Maryland Nurseryman's News, March-April. Pp 4-6.

Grace J. and M. Dixon, Convective Heat Transfer from Leaves. Progress in Biometeorology. Vol. 21985: 1-16.

Green, J.L. and L.H. Fuchigami. 1985. Overwintering container-grown plants. Ornamentals Northwest 9(2): 2-12.

Hare, F.K. and M.K. Thomas. 1979. Climate Canada. 2nd ed. John Wiley and Sons Canada Limited, Toronto, Ontario. 230 p.

Harlan, R.L. and J.F. Nixon. 1978. Ground thermal regime. Pp 103-163. In Geotechnical Engineering for Cold Regions. O.B. Andersland and D.M. Anderson (eds.). McGraw-Hill Book Company, Toronto, Ontario. 566 p.

Havis, J.R. 1965. Dessication as a factor in winter injury of Rhododendron. Proc. Am. Soc. Hort. Sci. 86: 764-769.

Havis, J.R. 1976. Root hardiness of woody ornamentals. Hort. Sci. 11:385-386.

Hayhoe, H.N., G.C. Topp and S.N. Edey. 1983. Analysis of measurement and numerical schemes to estimate frost and thaw penetration of a soil. Canadian Journal of Soil Science 63: 67-77.

Holman, J.P. 1972. Heat Transfer. 3rd ed. McGraw Hill Book Company. Toronto, Ontario. 462 p.

Johnston, G.H., B. Ladanyi, N.R. Morgenstern and E. Penner. 1981. Engineering characteristics of frozen and thawing soils. Pp 73-147. In Permafrost Engineering Design and Construction. G.H. Johnston (ed.). John Wiley & Sons, Toronto, Ontario. 540 p.

Kattelmann, R. 1987. Snow Compaction Effects on Nighttime Freezing. presented at the Western Snow Conference.

Kawanishi, H. 1986. Numerical analysis of forest temperature diurnal variations. Ecological Modelling 33: 315-327.

Lange, O.L. and E.D. Schulze. 1966. Untersuchungen uber die Dickenentwicklung der Kutikularen Zellwandschichten bei der Fichtennadel. Forstwiss Zentralbl 85:27-38.

Leinhard, J.H. 1981. A Heat Transfer Textbook. Prentice-Hall Inc., New Jersey. 516 p.

Lindstrom, A. 1986a. Freezing temperatures in the root zone - effects on growth of containerized Pinus sylvestris and Picea abies seedlings. Scand. J. For. Res. 1:371-377.

Lindstrom, A. 1986b. Outdoor winter storage of container stock on raised pallets - effects on root zone temperatures and seedling growth. Scand. J. For. Res. 1:37-47.

Lindstrom, A. and A. Mattsson. 1987. A method for artificial freezing of roots. In Winter storage and root hardiness of containerized conifer seedlings. A. Lindstrom (ed.), Dept. For. Yield Res., Swedish Univ. of Ag. Sci., Garpenburg, Sweden.

Lindstrom, A. and C. Nystrom. 1987. Seasonal variation in root hardiness of container grown Scotch pine, Norway spruce, and lodgepole pine seedlings. In Winter Storage and Root Hardiness of Containerized Conifer Seedlings. A. Lindstrom (ed.), Dept. of For. Yield Res. Swedish Univ. of Ag. Sciences, Garpenburg, Sweden.

Mattsson, A. 1986. Seasonal variation in root growth capacity during cultivation of container grown Pinus sylvestris seedlings. Scand. J. For. Res. 1:473-482.

McDonald, S.E. 1984. Irrigation in forest-tree nurseries - monitoring and effects on seedling growth. Pp 107-121. In Forest Nursery Manual: Production of Bareroot Seedlings. M.L. Duryea and T.D. Landis (eds) Martinus Nijhoff/Dr. W. JunK Publishers, Boston, Mass. 386 p.

McNiel, R.E. and G.A. Duncan. 1983. Foam tops poly for overwintering container stock. Am. Nurseryman, Dec., 1983. Pp 94-101.

Ohio State University. 1985. Soil heating using subsurface pipes - A decade of research results. Res. Bull. 1175, Ohio State Univ., Wooster, Ohio.

Rizzo, C.F., E.M. Smith and T.A. Fretz. 1979. An evaluation of microfoam on plant quality following overwintering of container-grown woody ornamentals. Pp 18-20. In Ornamental Plants - 1979: A Summary of Research. Res. Circ. 246, Ohio Agric. Res. and Dev. Centre, Wooster, Ohio.

Roberts, W.J., J.W. Bartok, Jr., E.E. Fabian and J. Simpkins. 1985. Energy conservation for commercial greenhouses. Rept. NRAES-3, Northeast Regional Agric. Eng. Service. 40 p.

Roberts, W.J. and D.R. Mears. 1980. Floor heating of greenhouses. Paper No. 80-4027, Am. Soc. of Agric. Eng. Summer Meeting, San Antonio, Texas. June 15-18, 1980.

Roberts, W.J. and D.R. Mears. 1984a. Floor heating and bench heating for greenhouses. Rept. E-047, Co-operative Extension Service, Cook College, Rutgers Univ., New Brunswick, N.J. 13 p.

Roberts, W.J. and D.R. Mears. 1984b. Heating and ventilating greenhouses. Rept. E-046, Co-operative Extension Service, Cook College, Rutgers Univ., New Brunswick, N.J. 19 p.

Saul, L.A. and D.F. Potts. 1986. Spatial and temporal variability of forest soil frost development in western Montana. Presented at the Western Snow Conference

Scholander, P.F., H.T. Hamonel, E.D. Bradstreet and E.A. Hemmingsen. 1965. Sap pressure in vascular plants. Sci. 148:920-922.

Sheppard, M.I., B.D. Kay,, J.P.G. Loch. 1981. The coupled transport of water and heat in freezing soils: a field study. Canadian Journal of Soil Sci. 61: 417-429

Smith, E.M. and D.J. Beattie. 1986. Principles of overwintering container-grown landscape plants. Pp 1-13. In Principles, Practices and Comparative Costs of Overwintering Container-Grown Landscape Plants. D.J. Beattie (ed). Southern Co-operative Series Bulletin 313, Agricultural Exp. Sta., Penn. State Univ., University Park, Penn. 32 p.

Smith, E.M. and S.A. Treaster. 1986. A comparison of Armin and Ethyl Visqueen while copolymers for overwintering landscape plants. Pp 18-20. In Res. Circ. 289, Ohio Agric. Res. and Dev. Centre, Ohio State Univ., Wooster, Ohio.

Smit-Spinks, B., B.T. Swanson and A.H. Markhart III. 1985. The effect of photoperiod and thermoperiod on cold acclimation and growth of *Pinus sylvestris*. Can. J. For. Res. 15:453-460.

Tinus, R.W. 1982. Successful overwintering of container-grown seedlings. Pp 26-44. In Proceedings of the 1981 Intermountain Nurserymen's Association Meeting. Info. Rept. NOR-X-241. Can. For. Serv., Edmonton, Alberta.

Wiest, S.C., G.L. Good and P.L. Steponkus. 1976. Analysis of thermal environments in polyethylene overwintering structures. J. Amer. Soc. Hort. Sci. 101:687-692.

Wood, B. 1987. Pine Ridge Forest Nursery procedure for overwintering containerized seedlings. Pp 18. In Proceedings of the 1986 Prairie Federal-Provincial Nurserymen's Meeting. E.M. Harvey (Compiler). Info. Rept. NOR-X-287, No. For. Centre, Can. For. Serv., Edmonton. 54 p.

Wynstra, J.R. and E.M. Smith. 1984. A comparison of white vs aluminum poly for overwintering woody ornamental landscape plants. Res. Circular 279. Ohio Agricultural Resources and Development Centre, Ohio State University, Wooster, Ohio. 21 p.

# APPENDIX

# APPENDIX 1

## THERMAL PROPERTIES OF MATERIALS

| | k<br>W/m°K | k<br>MJ/hr°K | c<br>MJ/m³°K |
|---|---|---|---|
| water | 0.602 | 0.00216 | 4.18 |
| ice | 2.22 | 0.00799 | 1.93 |
| air | 0.024 | 0.000086 | 0.00126 |
| snow - fresh | 0.105 | 0.000378 | 0.209 |
| snow - compacted | 0.335 | 0.001206 | 0.419 |
| polystyrene | 0.029 | 0.000104 | 0.0586 |
| peat - frozen | 0.6 | 0.00216 | 1.97 |

| | k<br>BTU/hrft°F | c<br>BTU/ft³F |
|---|---|---|
| water | 0.347 | 62.4 |
| ice | 1.282 | 28.8 |
| snow - fresh | 0.0606 | 3.12 |
| snow - compacted | 0.1935 | 6.25 |
| polystyrene | 0.016 | 0.874 |
| peat - frozen | 0.34 | 29.48 |

at % moisture measured