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CONTRACT REPORT

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WINTER HARDINESS OF HARDY ORNAMENTAL NURSERY STOCK

G.E. Bowman

September 1989

Head of Physics Division : W. Day

AFRC INSTITUTE OF ENGINEERING RESEARCH

WREST PARK

SILSOE, BEDFORD, MK45 4HS

PUBLICATION

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Work carried out for:

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Summary

The physical conditions for container grown plants on nurseries are assessed in order to define ways to delay the freezing of the root ball and hence reduce the risk of damage to or loss of nursery stock.

Calculations are given for the time to freeze pots of various size and moisture content. Times ranged from under 5 hours for a 2 l pot at 10% moisture content in a 4.5 m/s wind to 60 hours in still air for a 7.5 l pot at 50% moisture content. Experiments agreed well with calculations.

Insulation with 8 mm thickness foam can double time to freezing. Surrounding an array of pots by an outer row of filled but unplanted pots will give some insulation to the inner pots. Artificial snow is unlikely to be a cost-effective method of insulating nursery stock plants.

Attention to the detail of windbreaks on the nursery can provide valuable protection and significant delays to freezing. A computer study of the effect of windbreaks on air speed and heat exchange is described.

The provision of suitably designed windbreaks offers the simplest and most economical method of reducing the risk of frost damage. The permeability or percentage free area of the windbreak is its most important attribute and should be close to 50%. This implies the need for occassional maintenance of living windbreaks.

Windbreaks provide the best protection over a distance of about ten times their height. Some claims made for the effectiveness of commercial artificial windbreak materials are based on unrepresentative conditions in wind tunnel experiments and should be treated with caution.

The forces on windbreaks will increase more rapidly than the square of their height. Arrays of windbreaks between 1 and 2 m high and separated by

between 8 and 16 m appear to offer the best protection whilst being relatively small structures. The best protection within the array is in the lee of the first windbreak.

Some practical implications of the study are presented and suggestions of areas where further work may be justified. It should be noted though that sustained protection against frost damage during persistent spells of severe weather is impossible out of doors. Under these conditions movement to the shelter of a building or other protective structure is the only way of preventing plant loss.

1 Introduction

Within the last decade or so, there has been an increase in the number and varieties of hardy ornamental plants grown in containers. Demand for the more delicate species has increased - perhaps as a result of wider foreign travel. However, during this period there have been seven abnormally mild winters, perhaps giving growers an optimistic impression of the winter hardiness of at least some of these species. The problems are most acute in the case of evergreen subjects, since a bright day in winter promotes the loss of water from leaf tissue by transpiration,demanding water from a root system which cannot supply it if the root ball is already frozen. Sustained root ball temperature below -5°C will kill Magnolia stellata, whereas Picea omorika is not harmed unless the temperature falls below -23°C(1).

In practice, all simple, inexpensive countermeasures can only serve to delay the rate at which cooling takes place during a prolonged spell of cold weather. It will still be necessary to move the most suseptible plants of high value to the safety of a building or other protective structure should severe weather be sufficiently prolonged. However there are a number of steps that the nurseryman can take in order to to get best advantage in cold weather, and this study has attempted to put numbers to these advantages.

2.1 Heat loss from containers

The rate at which the outer surface of a container loses heat depends upon several factors such as surface area, wind speed, cloud cover and the difference between air and surface temperature. The time taken for the compost in the container to become fully frozen depends on further factors such as compost mass and moisture content, and the extent to which the container may be in thermal contact with the ground. From the point of view of the physics of the process, a sand capillary bed offers better thermal contact with the ground than does a gravel bed - but apart from being more expensive to instal, control of disease may be a problem. Under a given set of conditions, large containers take longer to freeze than small ones, partly because their mass is greater, and partly because the ratio of exposed surface to enclosed volume is smaller and thus more favourable. However, increasing the container size puts up the production cost and presents the customer with a bulkier and heavier item to carry home. Since most nurserymen accept the need in extreme circumstances to move containers into the protection of a building, it was important at the beginning of this study to establish the time taken for isolated containers to become entirely frozen in typical winter weather, and to identify those parameters which the nurseryman could alter in order to gain a useful delay in the freezing time.

A simple one-dimensional heat flow model was used to study the transfer of heat from the container to the air. The times taken for the whole of the compost first to reach freezing point, and then to become completely frozen, were calculated for various combinations of container size, compost moisture content and wind speed. The necessary physical properties were taken from published data(2, 3, 4). A sudden fall in air temperature from 2.5°C to -2.5°C was assumed. Heat exchange with the ground was ignored: this is justifiable for containers standing on free-drained gravel beds which are used by the majority of growers. The times for freezing of the entire root ball was found to vary from just under five hours for a 2 litre pot of 10% wet basis moisture content in a 4.5 $m\ s^{-1}$ wind, to sixty hours for a 7.5 litre pot at 50% moisture content in still air. The results are given in Table 1: for all combinations of pot size, compost moisture content and wind speed, the times to reach freezing point are much less than those needed to attain complete freezing. The dominant feature is latent heat exchange, ie the heat needed to convert liquid water into solid ice. In order of both effectiveness and likely preference to the grower, the options are to reduce wind speed, ensure moist compost, insulate the pots, use larger pots.

A more elaborate two-dimensional thermal model, applied to pots in a temperature-controlled greenhouse, identified air movement as an important factor influencing the root zone temperature(5). The exact mathematical solution of problems of melting and freezing in cylindrical or tapering bodies is difficult, and for some cases not possible(6). Empirical formulae exist for calculating the depth of frost penetration into soil(7), and there is also a published method of forecasting the formation and melting of ice on surface waters(8).

2.2 Experiments with pots

These theoretical expectations were then checked by experiments in which pots containing compost of known moisture content and initially at room temperature, were suddenly introduced into a small wind tunnel at -10°C from a room at about 20°C. The temperatures of concentric zones within the compost, and of compost in contact with the inner surface of the pot, were monitored with miniature thermocouples.

When pots were introduced into the cooled wind tunnel, it was noticed that the rate of heat loss from the surface of the pot was not uniform: that part facing the air stream lost heat less rapidly than the sides, and the greatest rate of loss of heat occurred from the leeward surface. Further measurements with sensitive anemometers placed 10 mm from the surfaces in question showed that apart from some differences in mean air speed, there were also differences in the extent to which the air flow was turbulent. The rate of heat loss was least at the windward face of the pot, where the turbulence (ie the root-mean-square value of the unsteady component of air speed) was lowest, and the leeward face of the pot showed the greatest rate of heat loss where the turbulence was a maximum.

Figs 1 - 5 show the results of these measurements, which are in broad agreement with the calculated times after allowing for the greater temperature differences in the experiments. For the first stage, ie the fall from room temperature to freezing point, the temperature difference was nominally 20°C or 8 times that used in the model: for the second stage, completion of freezing of the compost, the temperature difference was 10°C or 4 times the model value. Hence one may expect cooling to freezing point to be accomplished in one eighth of the time indicated by the model, and the subsequent complete freezing to occur in a quarter of the model time.

Earlier experiments on pine bark compost, for both freezing and melting sequences, have demonstrated a substantially linear dependence of time to freeze or thaw on the moisture content of the compost(9). In that work, all pots contained 0.8 l compost and were in still air.

In practice, pots are set out in arrays, and the thermal behaviour of the array is different from that of a single pot. In a closely packed array of circular pots, in which the rim of an inner pot is in contact that of each of its six neighbours, only the boundary pots have most of their curved surface exposed, and the average rate of heat loss per pot from the whole array is about one third of that from an isolated pot - but precise calculation is extremely difficult. In experiments on arrays of pots, compost temperature in sparsely arranged pots responded more rapidly to changes in solar radiation than that in closely packed arrays(10): presumably this was due to the greater pot surface exposed to the sun when pots were spaced apart. The wind tunnel was of necessity built inside a deep-freeze cabinet and had a cross-section only 30 cms square, too small to accommodate arrays of pots.

2.3 Methods of reducing heat loss

There are two principal ways of reducing heat loss: by increasing thermal insulation, or by reducing forced convection, ie wind speed.

2.3.1 Insulation

The calculations quoted in 2.1 were repeated, assuming an insulating layer of cellular foam 8 mm thick on the curved sidewalls of the pots. The results are given in Table 2, showing that the time to attain complete freezing is double that of uninsulated pots. Thicker insulating layers would result in even longer times, but at additional cost.

Artificial snow offers another possible way of increasing insulation and from data on likely weather conditions we can calculate the probable efficiency of such machines. Snowmaking machines operate by spraying water droplets through the air. As a droplet moves through the air, heat is lost from its surface by forced convection if the air is colder than the droplet ("sensible" heat loss). If the air is not saturated with water vapour, ie the relative humidity is less than 100%, some water evaporates from the surface, reducing the droplet temperature still further ("latent" heat loss). The total rate of heat loss is the sum of these two processes. The ability of the air to freeze water dropltes can be calculated using equations given by Monteith(11) in terms of dry bulb temperature and water vapour pressure deficit. For practical engineering purposes, the water vapour pressure deficit may be regarded as being proportional to (100-RH%). Thus the sum H of the sensible and latent heat losses from the surface of a droplet moving through the air can be shown to be

$$H = A(\Delta T + 9.94 - (1.63 * vp))$$

where ΔT is the difference in °C between air temperature and freezing point, vp is the water vapour pressure in millibars and A is a constant. It is convenient to express the combined effect of sensible and evaporative cooling in terms of an "effective" temperature: this will be equal to the dry bulb temperature if the air is saturated with water vapour (100% RH) - since no evaporative cooling is possible. If the relative humidity is below 100%, then evaporative cooling will occur and the effective temperature will be lower than the dry bulb temperature, to an extent dependent on the ability of the air to absorb water vapour.

Fig 6 shows the relationship between humidity, dry bulb temperature and effective temperature. For completely dry air, the effective temperature is 0°C when the dry bulb temperature is just under 10°C, implying that snow formation is possible. But in UK conditions, humidities are usually high enough to prevent snow formation at air temperatures appreciably above freezing point.

Unfortunately, because artificial snow consists of spherical ice particles ("graupel"), and not the finely branched hexagonal crystals seen in naturally generated snow, its insulating value is only one third that of the natural product. This is largely a consequence of the greater bulk density of graupel (0.32 to 0.48 kg/l) compared with freshly fallen natural snow (0.1 to 0.2 kg/l). Furthermore, snow generators are expensive, both in capital and in running costs. A small 35kW machine costs about £20k, a 50kW Diesel-powered machine some £50k and crawler-mounted machine powered by twin turbo-charged 130 hp Diesel engines about £200K. Fig 7 shows the snowmaking performance of the three machines in terms of effective temperature. Their performance is best at a low effective temperature, ie at low air temperature and low humidity: these conditions rarely prevail in a UK winter. Suppose we have saturated air at -5°C: this has an effective temperature of -10°C (from fig 6). Under these conditions, the smallest 35 kW machine in 12 hours would generate snow cover to a depth of 10 cm (4") over one acre, consuming 420 kWh of electricity in the process. There is a machine made by Suga Test Instruments in Japan which can generate hexagonal snow crystals of good thermal insulating value, but only at the rate of 10 kg in 24 hours(12). This is equivalent to only 50 l or $4 * 10^{-5}$ acre-feet in 12 hours, a snow thickess over one acre of just less than half of a thousandth of an inch. Overall, artificially generated snow does not offer an attractive means of providing protection for containers.

Chemically generated foam may be another possibility but here, apart from cost, there is the further possible problem of phytotoxicity.

2.3.2 Windbreaks

Reduction of wind speed by means of artificial windbreaks or by shelter belts of trees is already a feature of many commercial nurseries and appears to offer the cheapest way of reducing the rate of heat loss. Much has been published on the performance of single windbreaks, but it is not practical to consider a single windbreak for protecting large areas, since the zone of effective leeward protection at ground level only extends to about ten times the windbreak height when the wind is incident at right angles to the windbreak plane(13,14,15,16). For oblique incidence,the degree and lateral extent of the shelter is reduced(17).

It was therefore considered important to assess the merits of multiple windbreaks, particularly as some growers already employ them.

3 Modelling of windbreaks

Measuring the protection afforded by real windbreaks is both expensive and time-consuming(18), apart from the necessity of having to wait for the occurrence of appropriate wind speeds and directions.

Wind tunnels offer an alternative means of investigating the problem, but few tunnels are designed to provide correctly scaled vertical profiles of horizontal windspeed, or appropriate turbulence in the incident air stream. Turbulence is that part of the wind energy associated with random fluctuations in the wind: under most circumstances it is a minor component of the total wind energy. Improper use of data obtained in wind tunnels has led in some cases to performance claims for windbreak materials which cannot be realised in practice(19), particularly that wind speed reduction and extent of shelter are greatly exaggerated.

Mathematical modelling is a further possibility: the windward and leeward spaces on each side of a wind break of defined free area or porosity can be divided into several elementary zones and the equations of fluid flow solved at boundaries of each zone. Such a scheme for calculating the flow of liquids or gases is known as a fluid dynamics computational program, several examples of which are available commercially. One of these, "PHOENICS" (Cham Ltd.) is installed on the VAX computer network at Wrest Park, and has been used to model air flow through and around windbreaks.

3.1 The computation

The modelling was for wind incident at right angles to the windbreak which allowed the computations to be in only two dimensions: even so each run required up to six hours of computer time. The space enclosing the windbreak was divided into 31 vertical zones and 156 horizontal zones, giving rise to a total of 4836 regions or cells in which the detailed movement of the air was calculated. The equations used were based on those developed by Richards during the course of his work in New Zealand on the design of windbreaks for the protection of kiwifruit(14). In particular, the vertical profile of incident wind speed, and the degree to which it was turbulent, matched real conditions. The zones or cells were of unequal size: near the ground, and in the vicinity of the windbreak, a large number of small cells were used. This was necessary to allow sufficiently detailed calculation where patterns of air movement are subject to rapid change. Such unequal spacing allows the best use to be made of computer memory and the shortest run time. The zone for which the computations were made represented a real space 25 m in height and 128 m in length, with up to eight windbreaks 1 m high at 8 m centres. Fig 8 shows the grid or arrangement of cells: the lines overlap where the cell size is small. The output file from PHOENICS consists of tabulated values of air pressure, horizontal and vertical components of air velocity and turbulence energy for each cell. A separate program called PHOTON allows these quantities to be plotted graphically as velocity vectors or isopleth contours. A velocity vector takes the form of an arrow, the length of which represents magnitude, eg air speed, and the angle the direction in which air movement occurs. An isopleth is a line, usually curved, which joins all places having the same value of a particular quantity, eg turbulence energy. (For example, map contours are isopleths of altitude above sea level). In PHOTON, vectors and isopleths are plotted from the centre of each cell.

3.2 Single windbreaks

As a test of the validity of the model, runs were made for a single windbreak for different values of windbreak porosity or "free area". For example, an array of flexible plastic strips 50 mm wide, fixed at 100 mm centres has a porosity of 50%: if fixed at 60 mm centres, the porosity would be only 10%. Figs 9 - 12 show the velocity vector plots for windbreaks of 70%, 50%, 30% and 10% porosity. The 30% plot reveals the onset of a reverse flow vortex in the lee of the windbreak, which becomes strongly developed when the porosity is reduced to 10%. In the latter case, reverse flow at ground level in the lee of the windbreak (region A in Fig 12) is faster than that to windward: this means that in practice a very dense windbreak is a definite disadvantage because it will increase the rate of heat loss from plant containers.

Figs .13 -16 show turbulence energy contours: as may be expected, generation of turbulence increases as windbreak porosity decreases. Also, note that the zone of low turbulence in the lee of the windbreak is reduced in length at ground level as the porosity of the windbreak is reduced. Overall, the results suggest that a reasonable compromise between the reduction of wind speed at ground level and the generation of turbulence is given by a porosity or free area of about 50%. This is in general agreement with the results of practical trials by ADAS on full-scale windbreaks(20). The leeward distance over which protection is effective depends upon the magnitude of speed reduction considered acceptable: for the maximum practicable speed reduction of 60%, the protected zone extends to about eight times the windbreak height in open countryside of normal surface roughness. More extensive protection, up to twelve windbreak heights, would be given if the wind fetch were over an aerodynamically smooth surface such as submerged marshland(19). These values apply only to a wind incident at right angles to the windbreak: in general, for obliquely incident wind, the zone of protection will be halved.

3.4 Array of windbreaks

The PHOENICS program was run for arrays of up to eight windbreaks. In all cases the vertical components of velocity near the ground were 1% or less of the corresponding horizontal values, allowing these vertical components to be ignored in the calculation. Since one of the effects of a windbreak is to modify the profile of velocity above the ground, as distinct from merely multiplying it by a constant factor, it is not immediately obvious how the change in wind speed resulting from the presence of the windbreak is best expressed. Richards quotes data at half the height of the windbreak(19) which is appropriate when considering orchard trees. In our case we are interested in heat loss from containers up to perhaps 30 cm tall, so the data presented is averaged over zones extending 8 m horizontally and 31.2 cm vertically. The upper edge of these zones is the boundary between the third and fourth row of vertical cells in the PHOENICS program: it will be recalled that cells are not of uniform size and averaging can only be performed over an integral number of cells.

Table 3 is the result for eight windbreaks in series, expressed as percentages of the incident wind speed at the same level above ground. The greatest protection is obtained in the lee of the first windbreak, and worthwhile speed reduction still occurs even after the eighth windbreak. As the wind passes each successive windbreak, more turbulence is generated (Fig 17), but the proportionate increase is not enough to cause a significant increase in the surface heat transfer coefficient.

Table 4 shows the results for a single windbreak, and for two windbreaks spaced at 8, 16, 24 and 32 m. It will be seen that good protection is obtained in the immediate lee of all windbreaks, but little speed reduction occurs to windward of widely spaced windbreaks. The greatest speed reduction close to the ground occurs between two windbreaks 8 m apart, but this is not the case for a succession of windbreaks at the same spacing. A series of windbreaks constitutes a gross increase in surface roughness, which has the effect of modifying the vertical profile of wind velocity so as to reduce the protection(19).

For a large area, the best compromise would appear to be a series of windbreaks, spaced not less than 8H, but not more than 16H, where H is the windbreak height (see Table 5).

3.5 Mechanical forces on windbreaks

The constructional cost of a windbreak is likely to be related to the mechanical forces developed on it, in particular the total turning moment at ground level which must be resisted by the support posts (or tree trunks). From PHOENICS output data giving the pressure at the centre of each computational cell, the net pressure difference across each element of windbreak surface can be calculated. If we divide a windbreak into narrow horizontal zones, the total turning moment about the base can be calculated by summing the moment due to each zone. It is clear that even if the pressure on each zone were identical, the total moment will depend upon the square of the height of the windbreak: as height increases there are more zones and each is further from the ground. In reality, the upper zones also experience higher windspeeds that the lower ones, leading to proportionately higher pressures on those zones furthest from ground level and thus even greater leverage.

Table 5 shows the moments developed at ground level (in SI units Nm) by a single windbreak 1 m high, an array of eight windbreaks 1 m high, spaced 8 m apart, and single windbreaks 8 m and 10 m high. In all cases, a constant wind speed of 1 m s^{-1} incident on windbreaks of 50% permeability at 1 m above ground level, was assumed. The turning moment on the first of the eight windbreaks is slightly less than that on the single one, and the load on the second of the eight windbreaks is just less than half of that on the first. Subsequently, the loads successively increase, but even that on the eighth is still little more than half that on the first. The practical implication is that economies can be made in the support structure for intermediate windbreaks in a series, only the outermost windbreaks requiring support to the same standard as that needed for a single one. In gusty conditions, the forces developed would be about three times greater. The single 8 m high windbreak will give comparable wind speed reduction at ground level to that given by the array of eight 1 metre windbreaks, and require the same area of permeable material - but the cost of providing adequate structural support would be much greater because of the need to resist a much larger turning moment.

Compared with a 1 m high windbreak, the 8 m windbreak generates a turning moment 132 times greater: a factor of 64 resulting from greater height, and a further factor of 2.07 due to increased wind speed with height. For the 10 m windbreak, the comparable values are 221, 100 and 2.21 respectively. As may be expected, the factor arising from wind pressure is greatest for the tallest windbreak because of the vertical wind velocity gradient.

It would seem appropriate to use trees as windbreaks around the boundary of a nursery, but to use smaller artificial windbreaks within the planted zone to secure immediate protection without the need for maintenance or significant loss of light.

3.6 Practical implications

* Keep pots moist (if other cultural considerations allow)

* Arrange pots in compact groups, with unplanted, dry, compost-filled pots around periphery to provide thermal insulation at edges

* Use largest acceptable pot

* Protect with windbreaks about 2 m high, spaced apart 16 - 32 m

* Establish encircling belt of trees

* Place particularly delicate subjects in immediate lee for prevailing winter wind

* Ensure easy access to all pots to facilitate transfer to a building during abnormally prolonged cold periods

* Make use of weather forecasts to plan pot transfer

3.6 Further research opportunities

PHOENICS could be used to investigate a number of air flow problems associated with windbreaks eg

(1) For windbreaks of less than 50% permeability, it may be possible to inhibit the formation of a leeward vortex by increasing the permeability of the windbreak close to ground level. It would be of particular interest to establish to what extent this could be achieved in the case of a series of windbreaks.

(2) A study of three-dimensional flow could be used to investigate the appropriate geometry for an encircling windbreak, in particular to establish the aerodynamic behaviour of different forms of corner. Right-angled corners may be undesirable.

(3) Three-dimensional flow could also be used to study novel forms of multiple windbreak, eg windbreaks arranged on a hexagonal or square ground plans. In principle, such arrangements would offer the same protection regardless of wind direction.

Methods to predict the timing of the onset of freezing and completion of freezing in containers could be developed. Where nurseries already have weather stations and microcomputers for greenhouse control, software could be developed to give rapid warning of potential problems.

The layout of windbreaks and the need to be prepared to move some material rapidly into protected areas suggests that joint assessment of windbreaks and automated pot handling would be valuable.

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Table 1

Freezing times for uninsulated pots, in relation to pot size, compost moisture content and wind speed

2 litre pots	Time to reach freezing point, hours	Time to freeze entirely hours
50% wet, 0 ms^{-1}	1.03	37.2
50% wet, 4.5 $m\ s^{-1}$	0.34	12.4
10% wet, 0 m^{-1}	0.42	14.8
10% wet, 4.5 $m\ s^{-1}$	0.14	4.9
7.5 litre pots		
50% wet, 0 $m\ s^{-1}$	1.65	60.0
50% wet, 4.5 $m\ s^{-1}$	0.55	20.0
10% wet, 0 $m\ s^{-1}$	0.66	23.8
10% wet, 4.5 $m\ s^{-1}$	0.22	7.9

Table 2

Freezing times for pots insulated with foam 8 mm thick, in relation to pot size, compost moisture content and wind speed

2 litre pots	Time to reach freezing point, hours	Time to freeze entirely hours
50% wet, 0 ms^{-1}	2.05	74.0
50% wet, 4.5 $m\ s^{-1}$	0.95	34.7
10% wet, 0 m^{-1}	0.84	29.5
10% wet, 4.5 $m\ s^{-1}$	0.39	13.7
7.5 litre pots		
50% wet, 0 $m\ s^{-1}$	3.28	119.4
50% wet, 4.5 $m\ s^{-1}$	1.54	56.0
10% wet, 0 $m\ s^{-1}$	1.31	47.4
10% wet, 4.5 $m\ s^{-1}$	0.62	22.1

Table 3

Average normalised wind speed over 8 m horizontal regions, expressed as a percentage of speed of wind incident from left. Vertical lines indicate the pressence of windbreaks. Only the first three zones are shown: their centres are 3, 12 and 25 cm respectively above ground level indicated by the horizontal line. The upper boundary of the highest zone is 32 cm above ground.

```
wind ->
            | 36.0 | 37.4 | 39.7 | 40.9 | 41.9 | 42.7 | 43.8 | 51.4
            | 36.7 | 38.8 | 41.6 | 43.1 | 44.3 | 45.3 | 46.5 | 54.8
            | 46.3 | 46.9 | 50.8 | 52.9 | 54.5 | 55.9 | 57.5 | 66.5
------------------------------------------------------------------------
```

Table 4

Percentage of incident windspeed for windbreaks at different spacings, averaged over 8 m horizontal zones. The significance of vertical and horizontal lines is as in Fig. 3, as are the vertical divisions

```
Single windbreak
wind ->
            | 31.0   70.8
            | 39.7   73.2
            | 41.1   63.1
------------------------------------------------------------------------

Two windbreaks 8 m apart
wind ->
            | 31.6 | 38.7   72.4
            | 31.0 | 38.5   75.5
            | 31.3 | 40.6   80.8
------------------------------------------------------------------------

Two windbreaks 16 m apart
wind ->
            | 38.0   58.4 | 43.1   74.9
            | 37.8   59.4 | 45.8   78.1
            | 38.9   62.2 | 46.6   83.3
------------------------------------------------------------------------

Two windbreaks 24 m apart
wind ->
            | 39.1   68.5   71.7 | 44.2   76.3
            | 39.1   69.4   72.7 | 44.7   79.4
            | 40.4   75.4   72.6 | 47.7   84.6
------------------------------------------------------------------------

Two windbreaks 32 m apart
wind ->
            | 39.5   70.0   83.5   77.9 | 43.5   73.9
            | 39.5   72.2   85.6   77.7 | 43.9   76.9
            | 40.8   76.7   88.0   77.4 | 46.5   81.9
------------------------------------------------------------------------
```

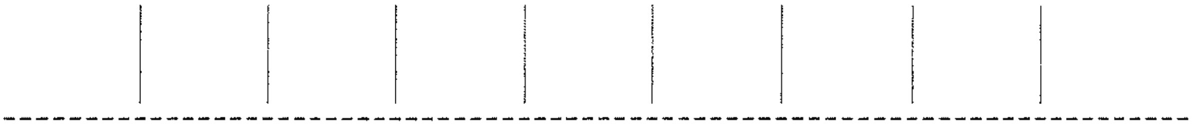
Table 5

Ground level turning moments in Nm for windbreaks. Windbreaks are represented by vertical lines, the ground by horizontal lines

Single 1 m windbreak
wind ->

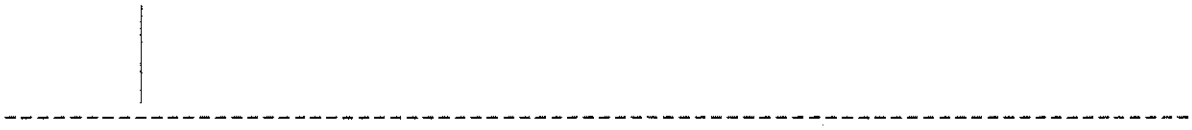
0.259

Eight 1 m windbreaks
wind ->



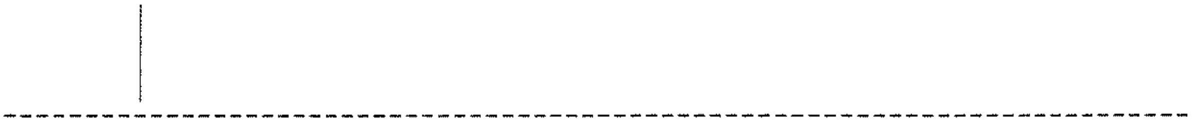
0.231 0.115 0.120 0.121 0.123 0.125 0.127 0.133

Single 8 m windbreak
wind ->



34.40

Single 10 m windbreak
wind ->



57.44

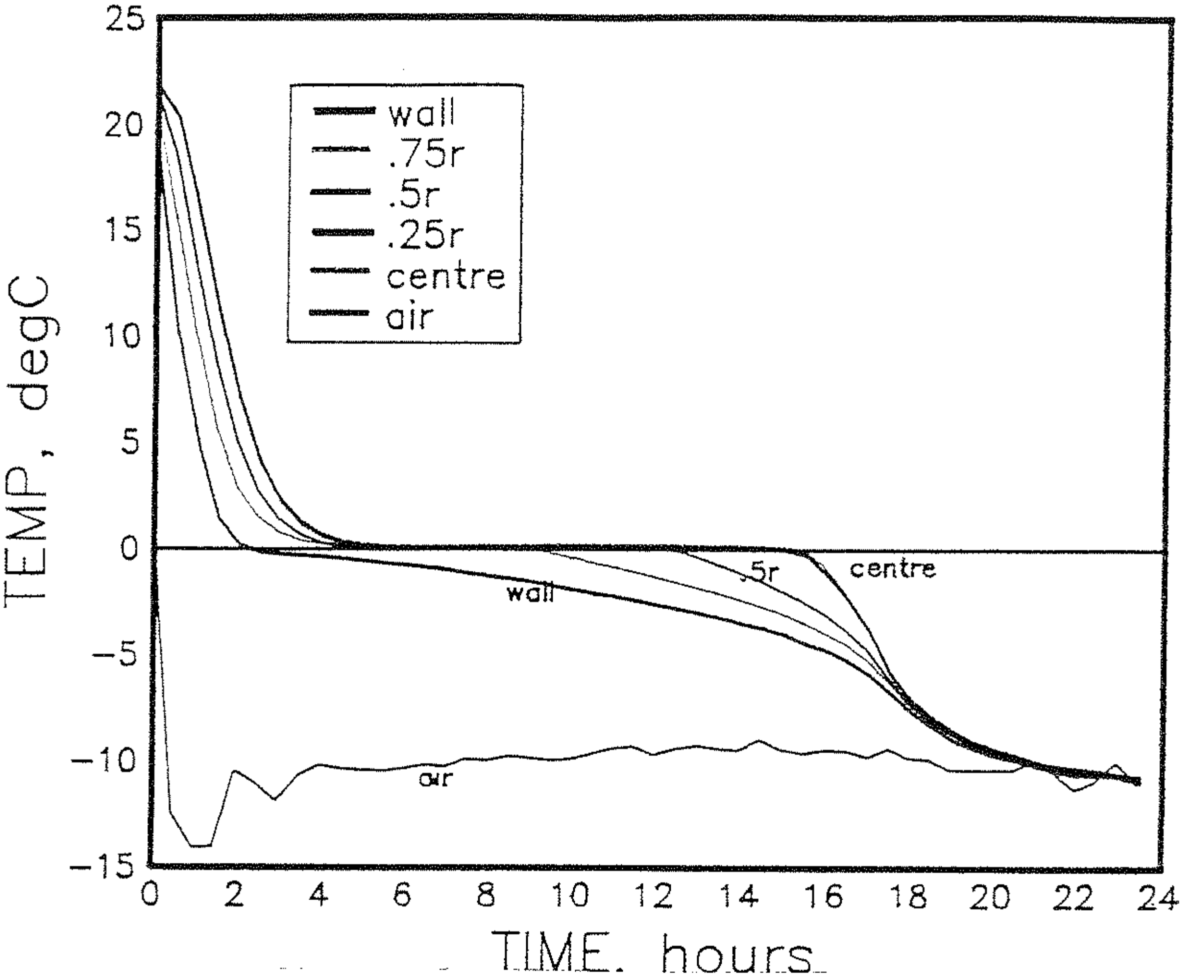


Figure 1 Time/temperature curves for a 2 litre pot, filled with 62% wet basis compost, in an air stream of 0.9 m s^{-1}. Five thermocouples were inserted to half compost depth at equal radial spacing: the sixth thermocouple measured air temperature. The centre and 0.75 radius traces are almost indistinguishable. Freezing of the entire pot contents took 16 hours

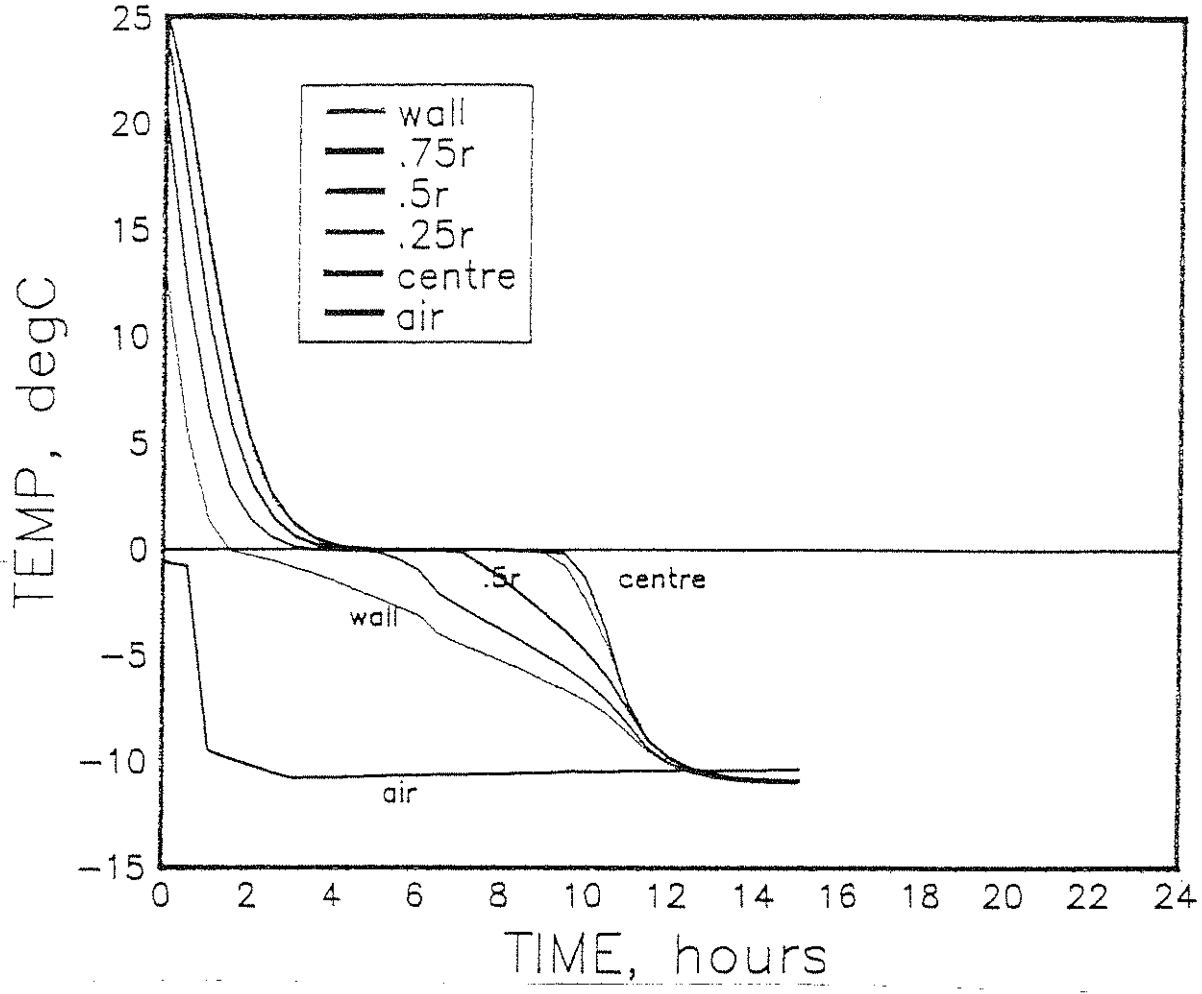


Figure 2 Time/temperature curves for a 2 litre pot, filled with 62% wet basis compost, in an air stream of 2.7 m s^{-1}. Five thermocouples were inserted to half compost depth at equal radial spacing: the sixth thermocouple measured air temperature. The centre and 0.75 radius traces are separated. Freezing of the entire pot contents took 10 hours

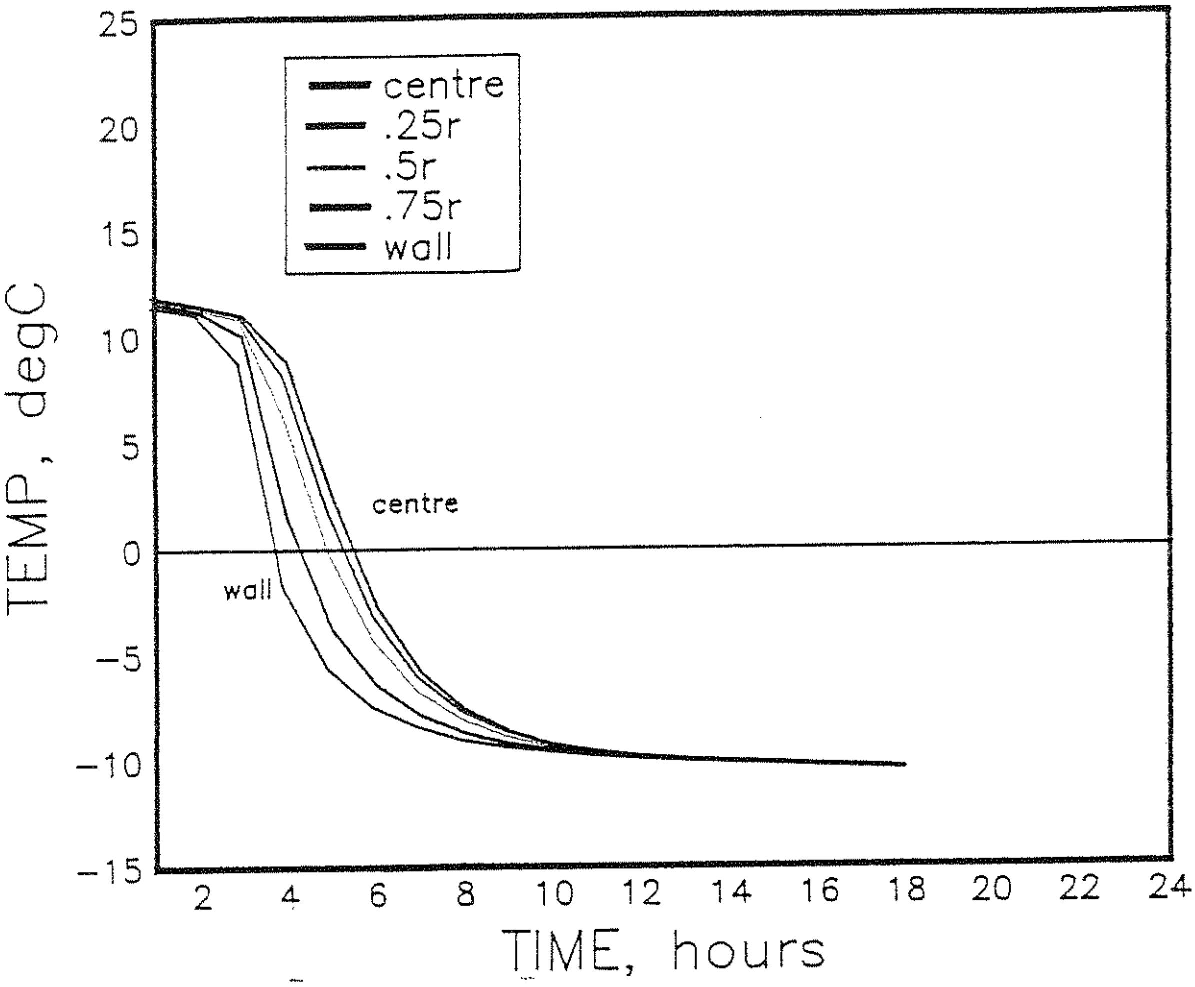


Figure 3 Time/temperature curves for a 2 litre pot, filled with dry compost, in an air stream of 2.7 m s^{-1}. Note that there is no dwell at freezing point, because no ice was formed

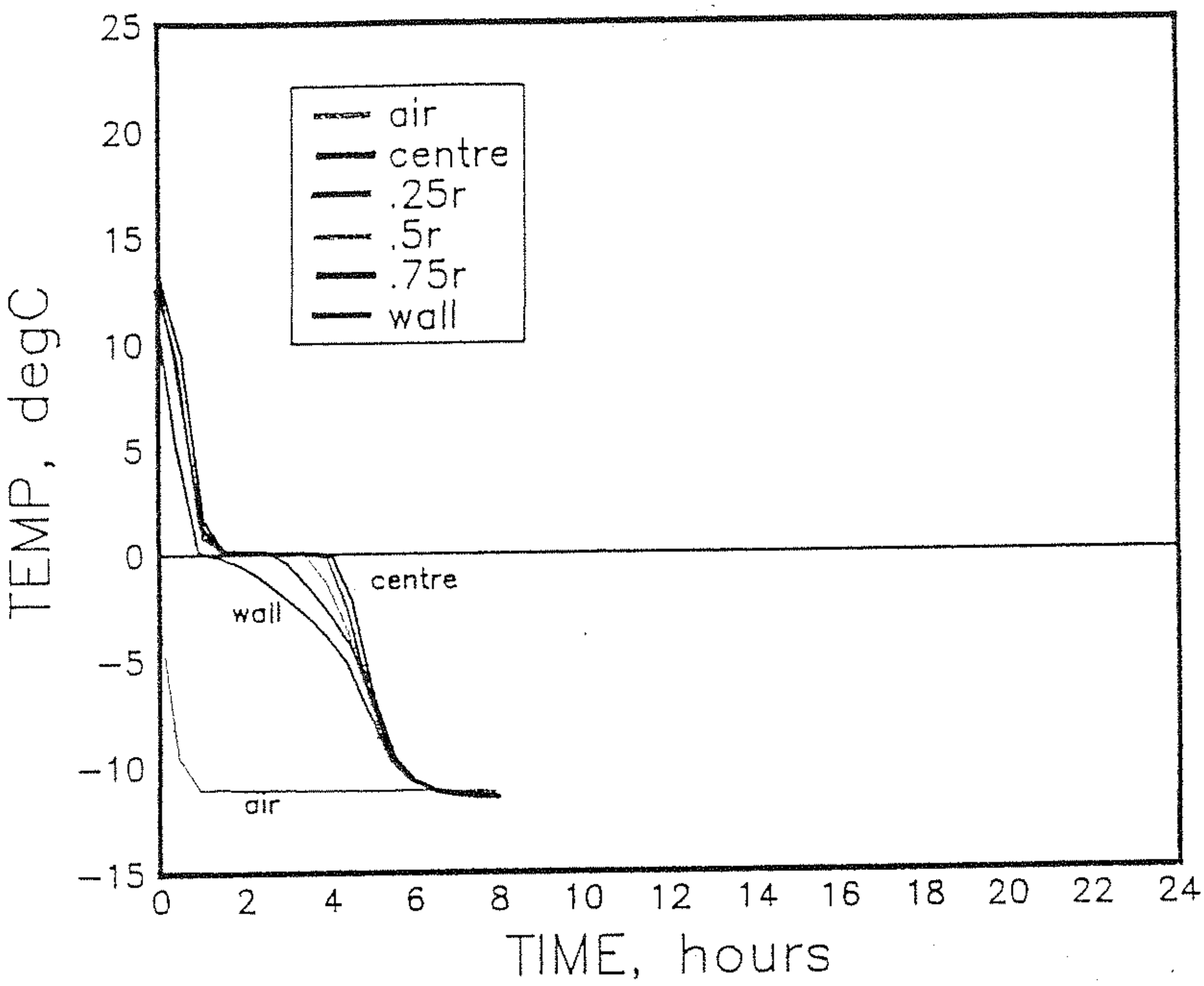


Figure 4 Time/temperature curves for a 2 litre pot, filled with 19% wet basis sand, in an air stream of 2.7 m s^{-1}. Note that the dwell at freezing point is about one third of that obtained for 62% wet compost. Freezing of the entire pot contents took 4 hours

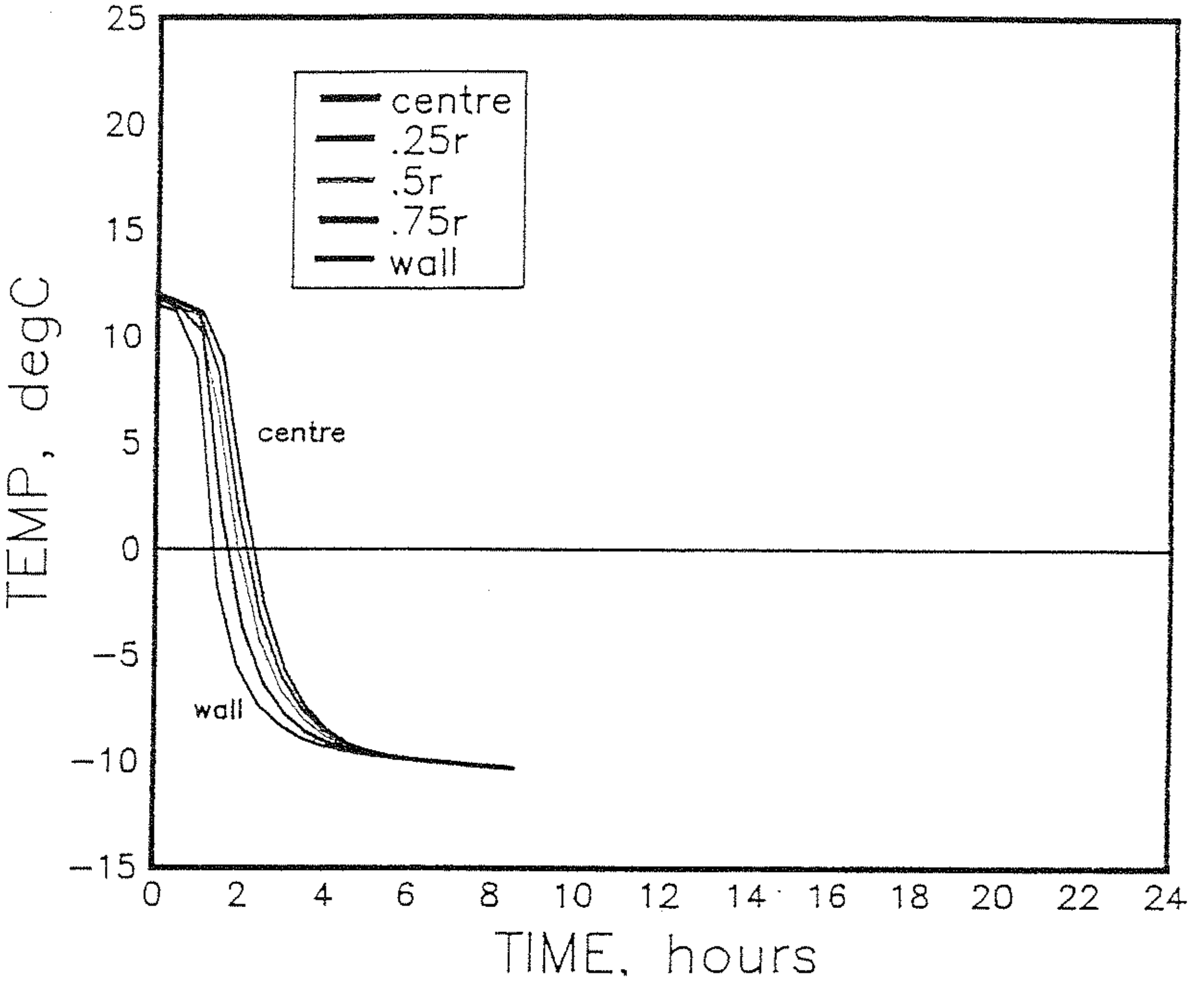


Figure 5 Time/temperature curves for a 2 litre pot, filled with dry sand, in an air stream of 2.7 m s^{-1}. Note that there is no dwell at freezing point, because no ice was formed. The rate of temperature fall is greater than that for dry compost because the thermal conductivity of dry sand is greater than that of dry compost

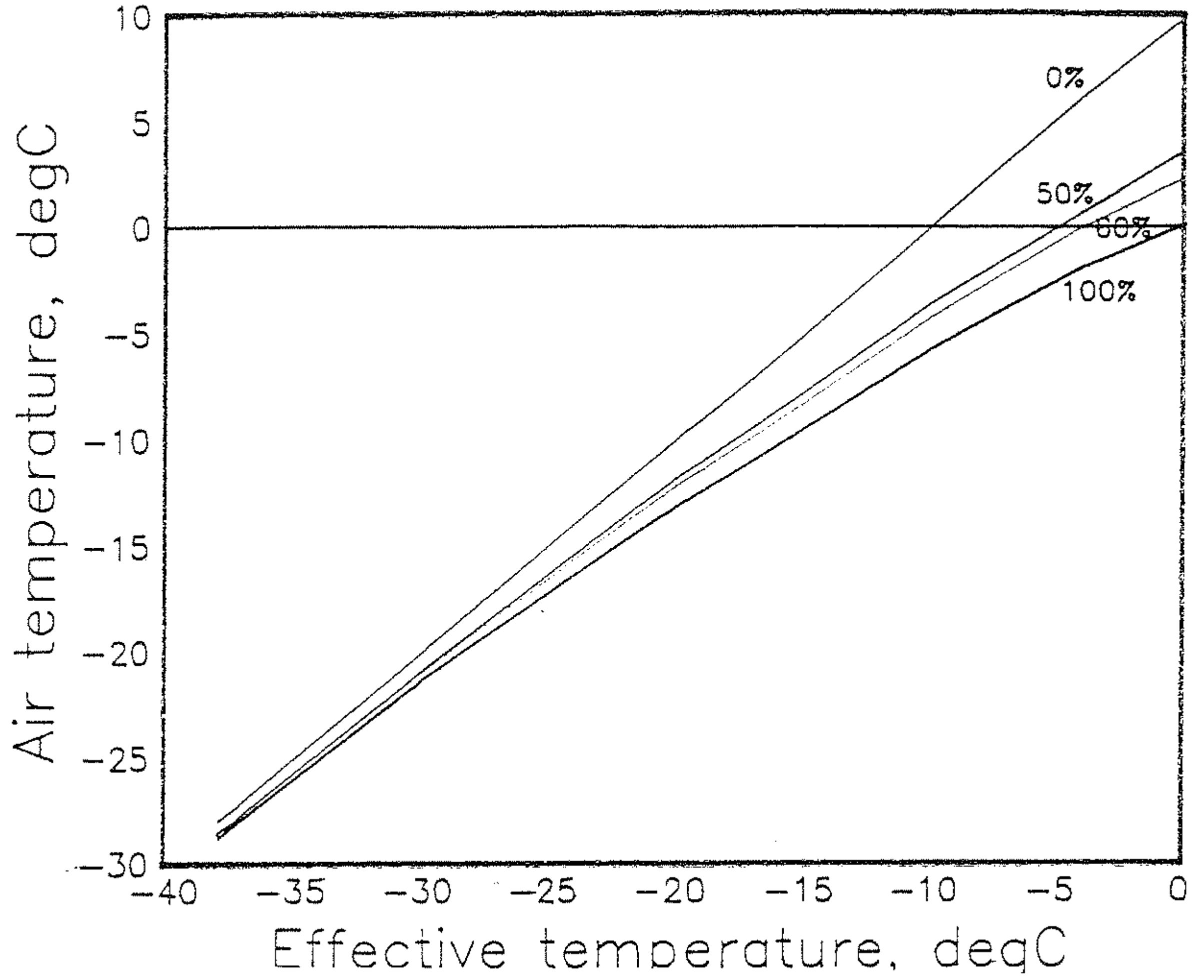


Figure 6 Relationship between atmospheric humidity, dry bulb temperature and effective temperature, based on Monteith's equation

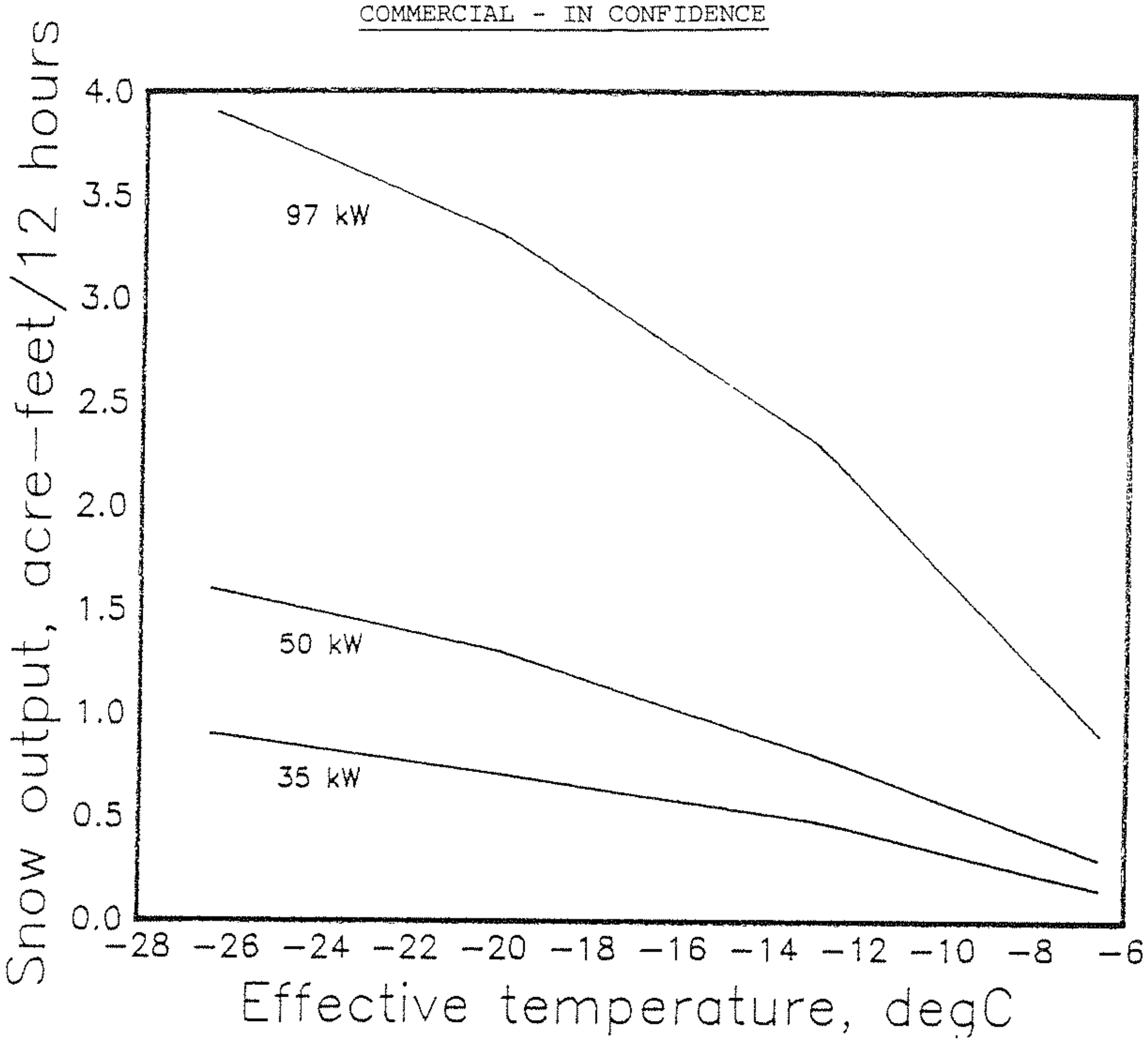


Figure 7 Performance of machines for making artificial snow, in terms of effective temperature

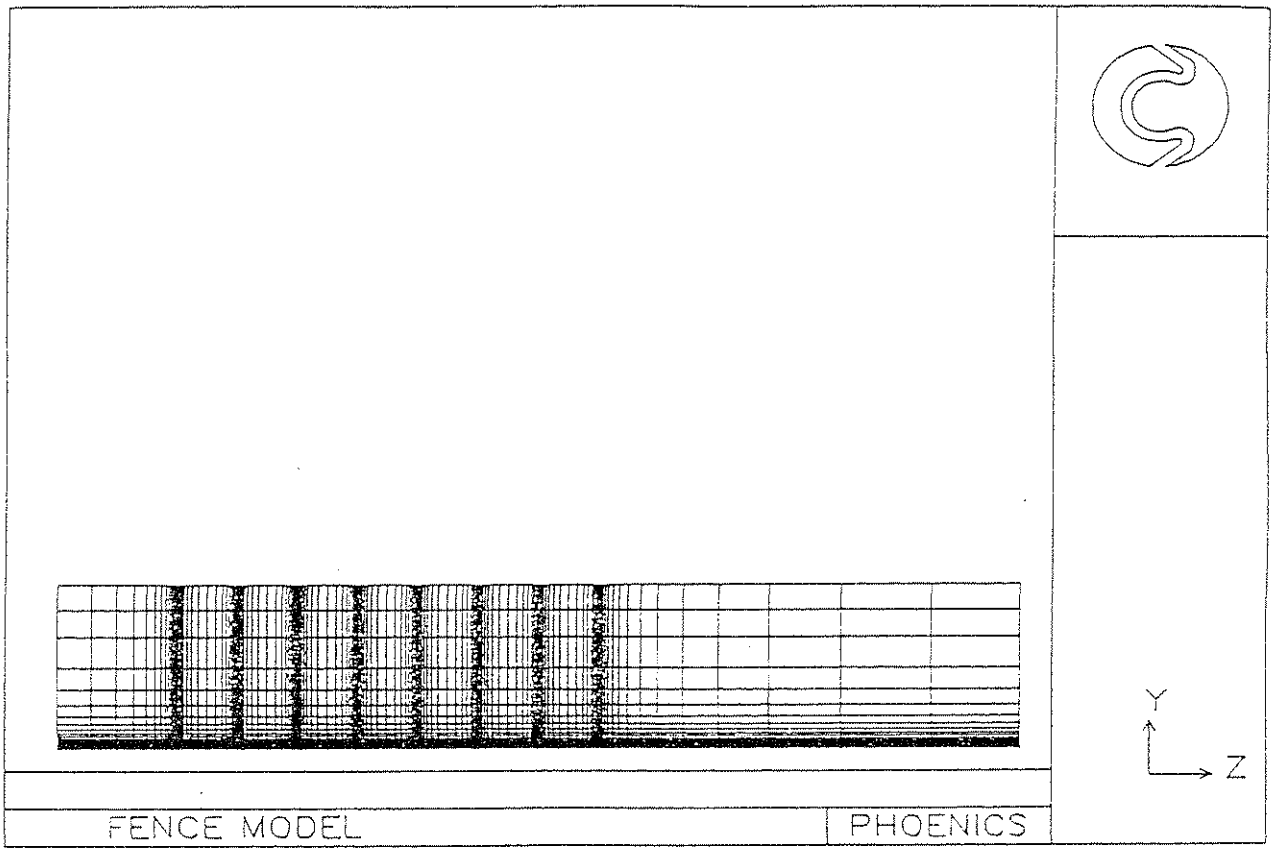


Figure 8 Extended PHOENICS grid for windbreak computation. The Y-axis represents a vertical height of 25 m and the X-axis a horizontal distance of 128 m. Grid lines overlap in regions where the cell size is small, i.e. near windbreaks and near the ground. The windbreaks are 1 m high

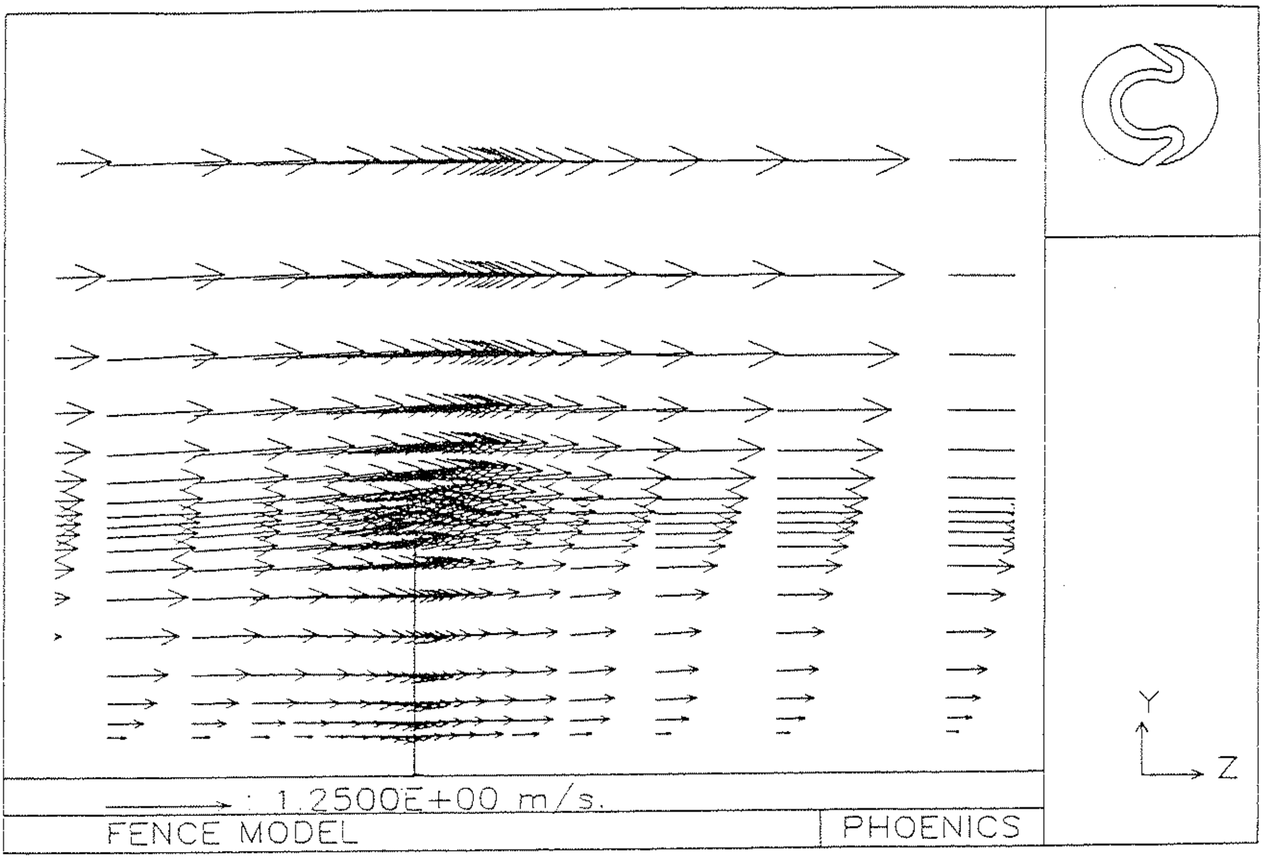


Figure 9 Velocity vector plot near a windbreak of 70% permeability. Windbreak position is indicated by a solid vertical line

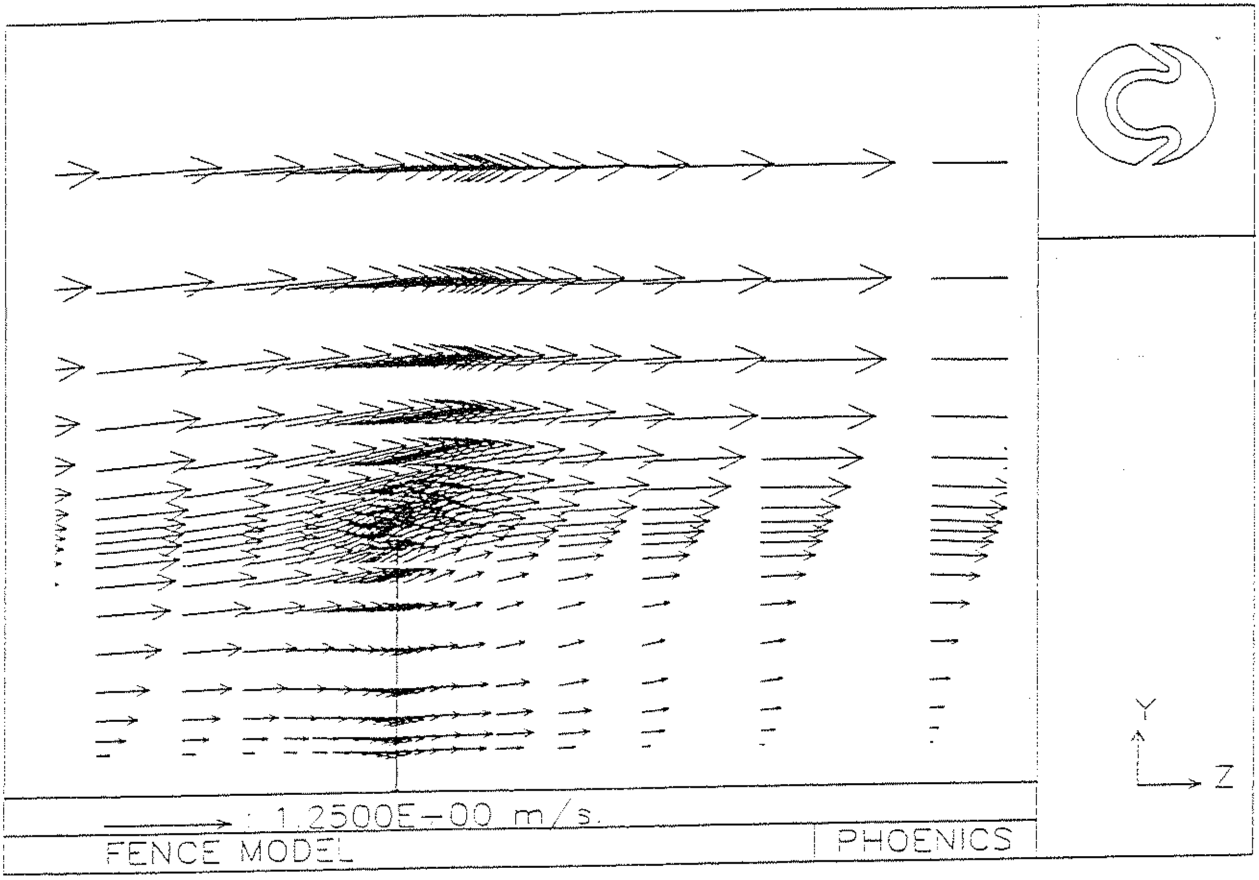


Figure 10 Velocity vector plot near a windbreak of 50% permeability. Windbreak position is indicated by a solid vertical line

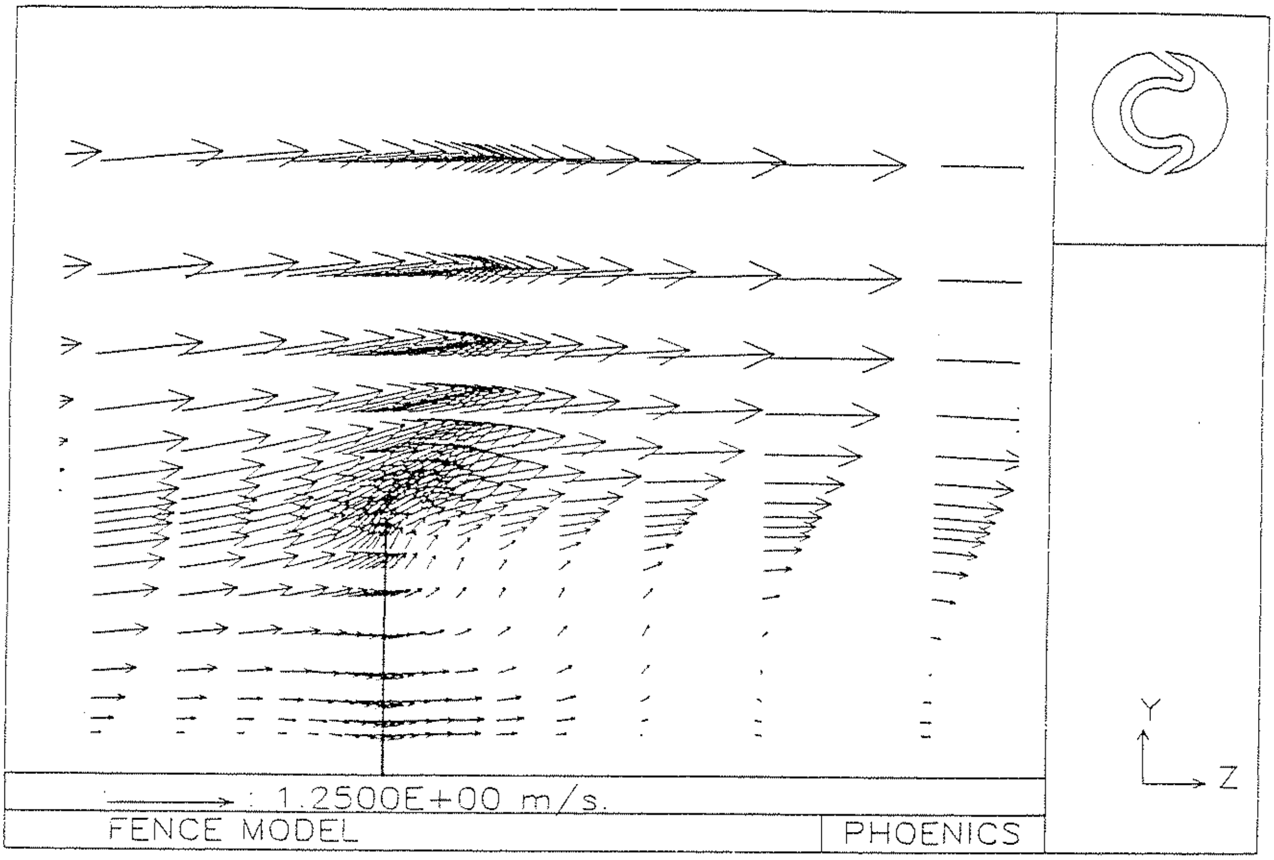


Figure 11 Velocity vector plot near a windbreak of 30% permeability. Windbreak position is indicated by a solid vertical line

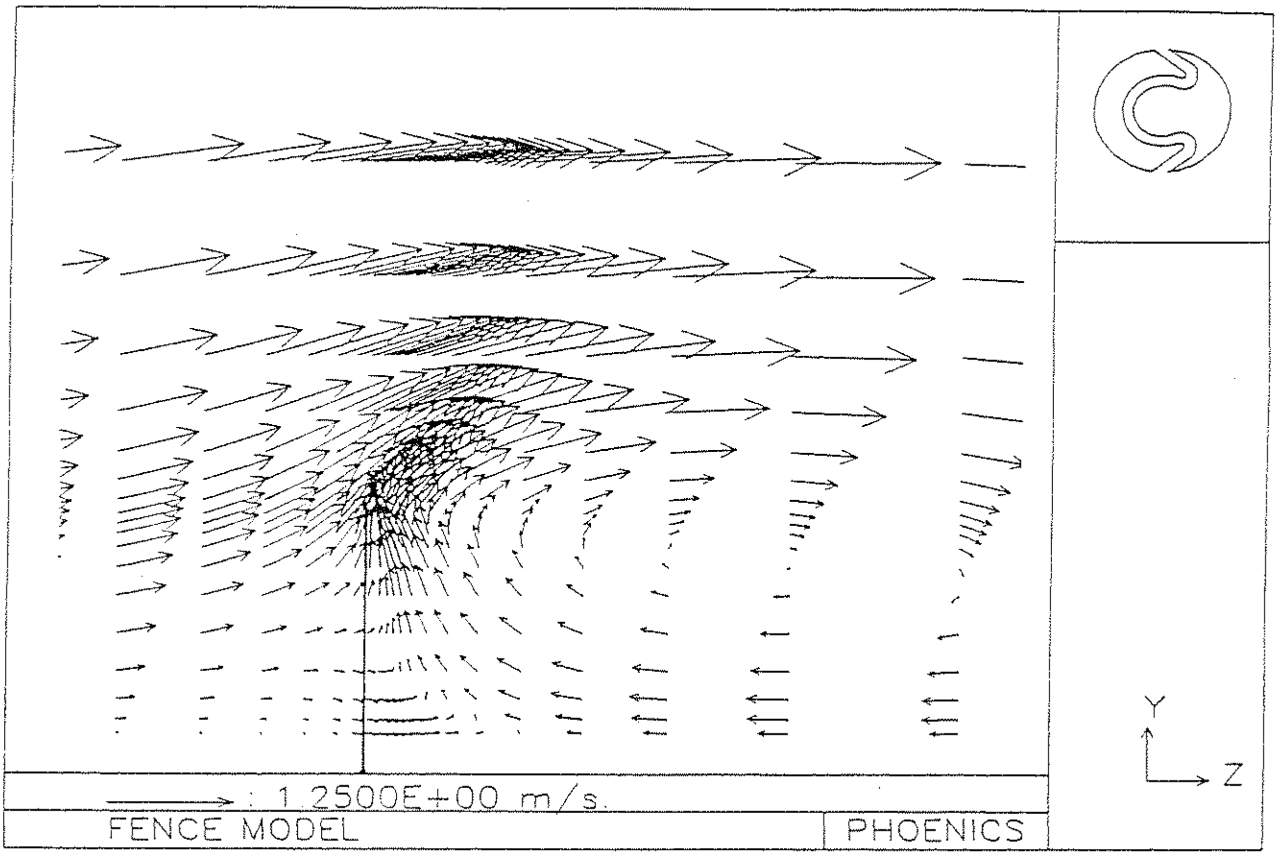


Figure 12 Velocity vector plot near a windbreak of 10% permeability. Windbreak position is indicated by a solid vertical line

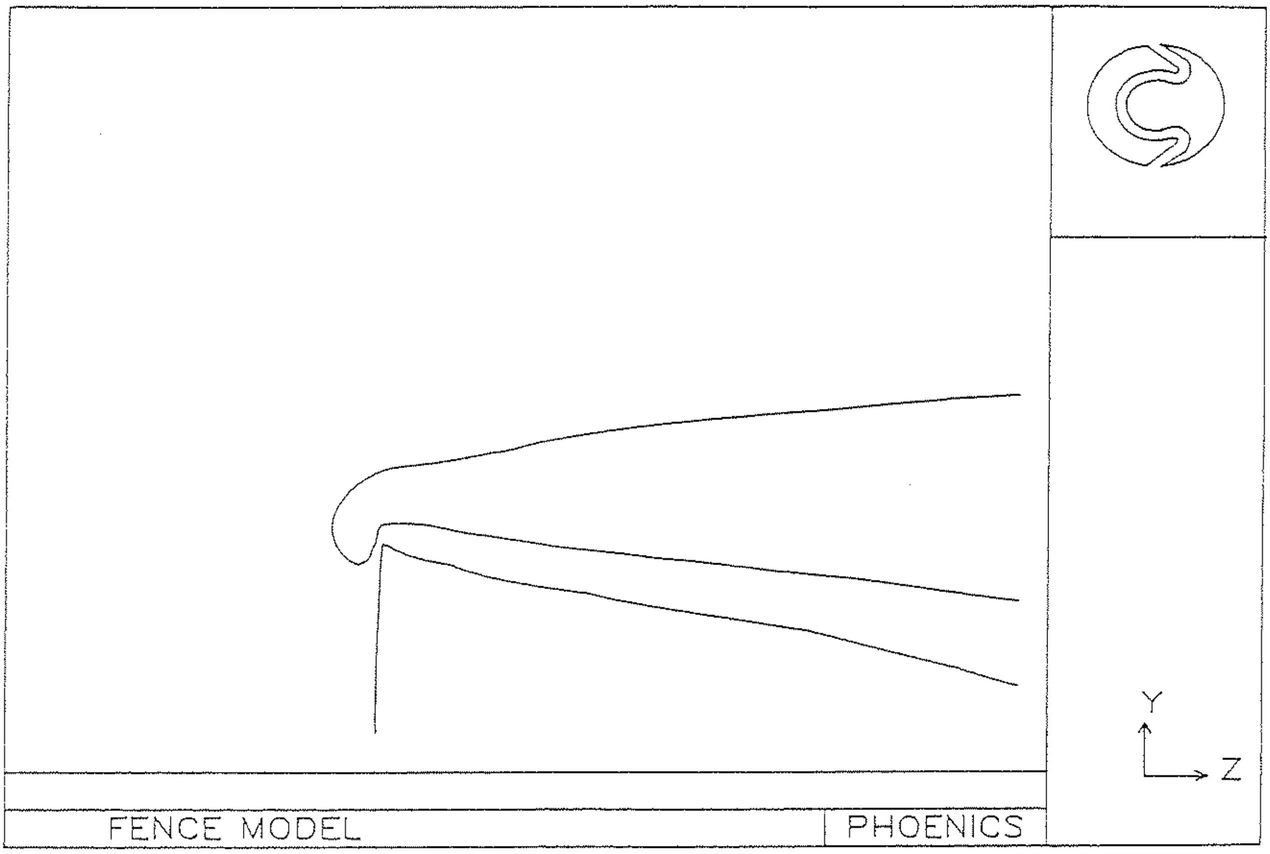


Figure 13 Turbulence energy contours for a windbreak of 70% porosity. The windbreak is just to the right of the vertical contour. Contour interval is 0.125 m^2s^{-2}. Notice the gentle slope of the first leeward contour: below this there is low turbulence

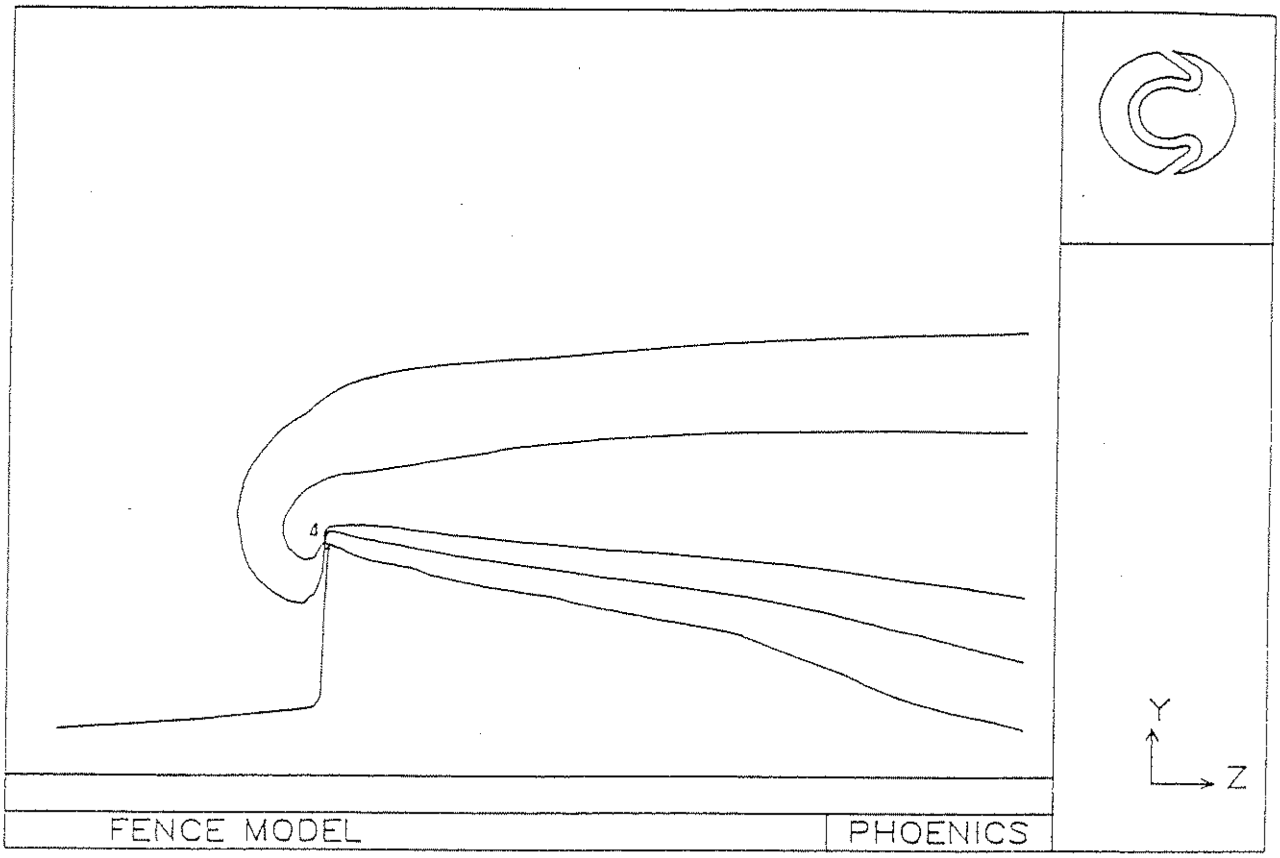


Figure 14 Turbulence energy contours for a windbreak of 50% porosity. The windbreak is just to the right of the vertical contour. Contour interval is 0.125 m^2s^{-2}. Notice that the slope of the first leeward contour suddenly increases after a horizontal distance equal to two windbreak heights, thereby curtailing the zone of low turbulence

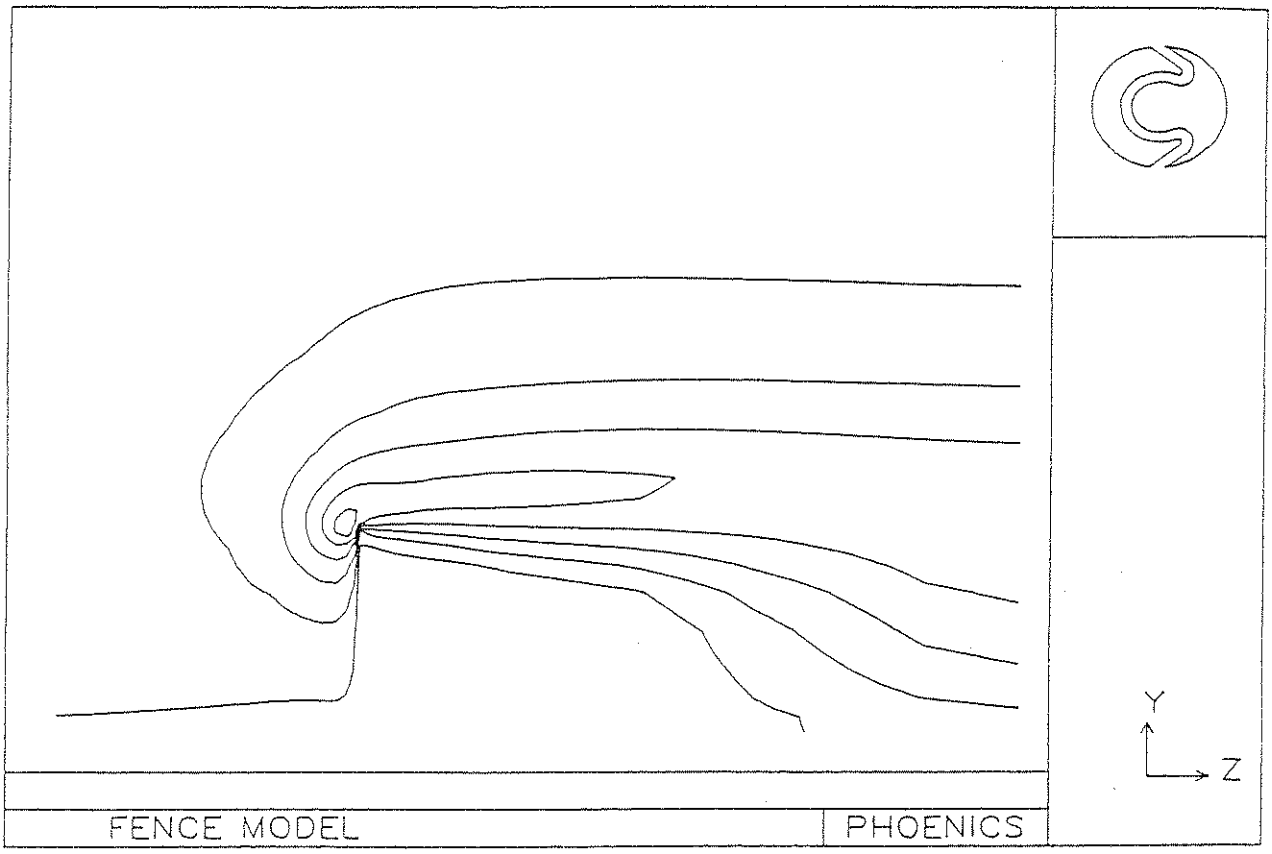


Figure 15 Turbulence energy contours for a windbreak of 30% porosity. The windbreak is just to the right of the vertical contour. Contour interval is 0.125 m^2s^{-2}. Notice the development of strong turbulence near the top of the windbreak, and that the leeward zone of low turbulence is further curtailed

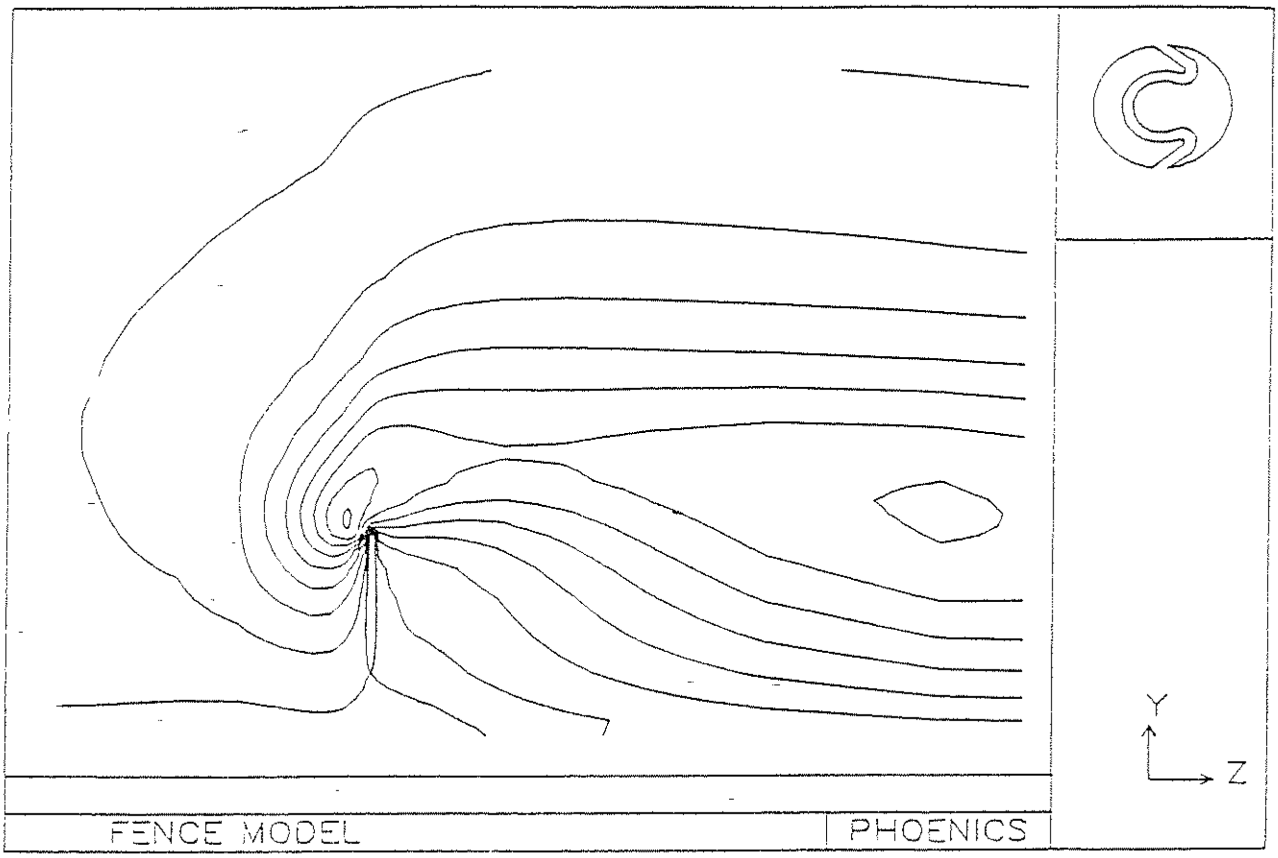


Figure 16 Turbulence energy contours for a windbreak of 10% porosity. The windbreak is between the vertical contours. Contour interval is 0.125 m^2s^{-2}. Notice that the zone of low leeward turbulence is now less than one windbreak height, and that strong turbulence exists just to windward of the upper edge of the windbreak

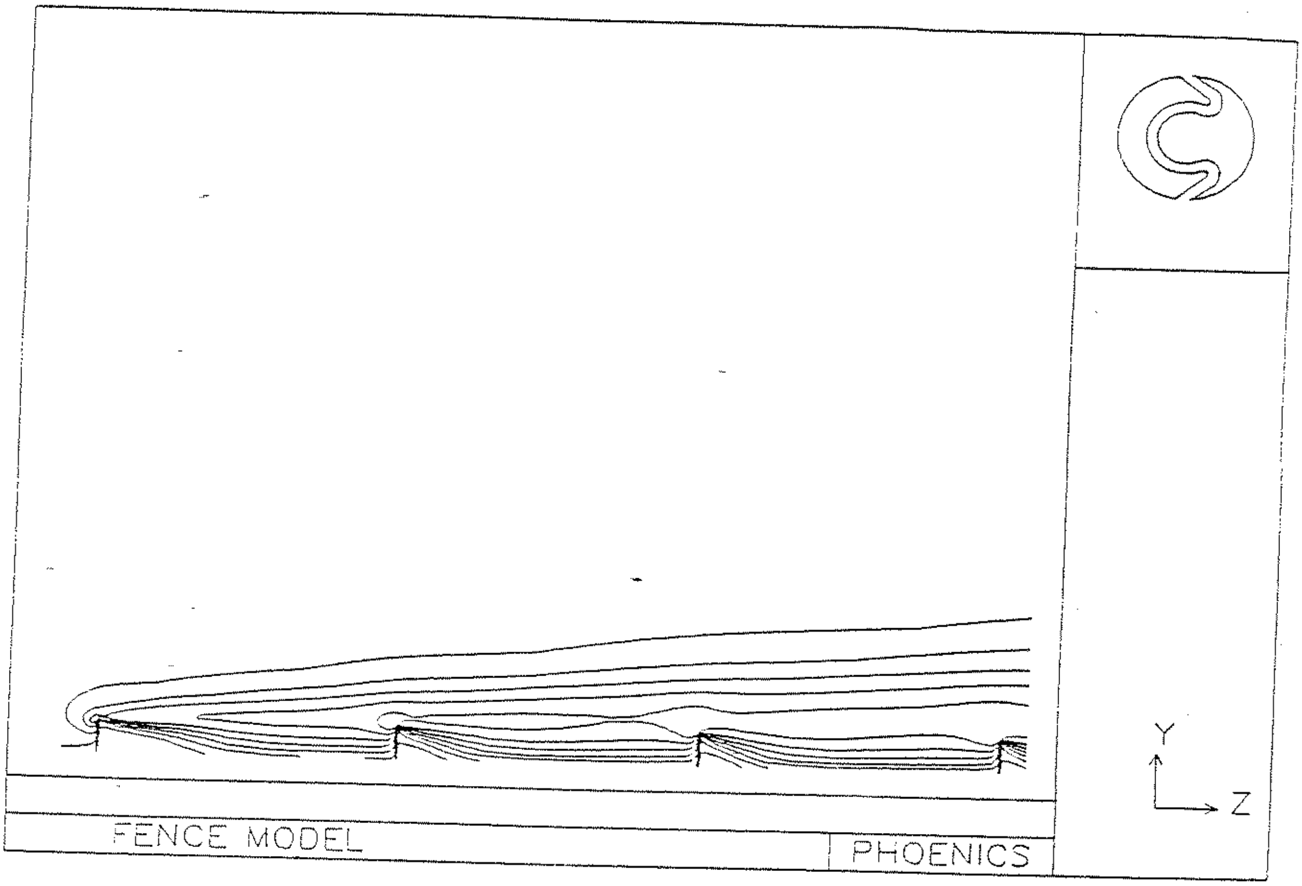


Figure 17 Turbulence for the first four of eight windbreaks in series. Wind is incident from the left: contour interval is 0.125 m^2 s^{-2}. Notice the longer leeward zone of low turbulence after the first windbreak, compared with successive ones