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|---|---|
| **Project title:** | **Hardy nursery stock:**<br>**Examination of techniques to raise humidity in mist houses** |
| **Project number** | **HNS 76** |
| **Project leader** | **Dr R.S. Harrison-Murray** |
| **Annual report** | **March, 2001**<br>**(years 1 and 2, covering stage one of the project)** |
| **Previous reports** | **None** |
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| **Location of project:** | **HRI-East Malling, West Malling, Kent**<br>**ME19 6BJ**<br>**Phone: 01732 843833; Fax: 01732 849067** |
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| **Date completion due:** | **28 February, 2002** |
| | **Key words: humidity, mist, fog, evaporation, transpiration, environment, water balance, hardy nursery stock, propagation, rooting, cuttings** |

The results and conclusions in this report are based on an investigation conducted over two years. The conditions under which the experiment was carried out and the results obtained have been reported with detail and accuracy. However because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results especially if they are used as the basis for commercial product recommendations.

CONTENTS

# PRACTICAL SECTION FOR GROWERS

This project is investigating ways in which nurserymen can achieve the sort of environmental conditions required for the cuttings of stress-sensitive species which require maximum environmental support to achieve high rooting percentage (e.g. soft cuttings of *Garrya elliptica* 'James Roof' or large cuttings of *Cotinus coggygria* 'Royal Purple' suitable for 'designer liner' production).

## Commercial benefits of the project

Progress in this project is expected to have the following commercial benefits:

- Reduced wastage: about 200 million HNS cuttings are taken every year and while failure rates vary from nursery to nursery and from crop to crop, it has been estimated to be at least 25% overall. Optimising the rooting environment could contribute to reducing this wastage.
- Cost savings: See cost benefit analysis below.
- Increased ability to respond to a sharp rise in demand when a particular plant becomes fashionable.

## Background and objectives

The purpose of this project is to provide reliable information on how to achieve optimal environmental conditions for stress sensitive cuttings. It is intended to complement the information from earlier HDC funded projects that showed how much rooting potential can be lost if the propagation environment does not restrict water loss from cuttings sufficiently. Sensitive cuttings need a combination of generous leaf wetting and an atmosphere that is almost saturated with water vapour (i.e. 100% rh).

A good fog system can achieve this but the equipment is technically more difficult to maintain and control than mist. Polythene-enclosed mist can achieve almost as good results but tends to suffer extremely high temperatures. Furthermore, it is not favoured by many growers because polythene covers over each mist bed makes it difficult to monitor the condition of cuttings.

This project is investigating a number of alternative approaches, including the combination of mist and fog in one system, aiming to combine the best of both systems.

## Summary of results and conclusions

We have now completed the first stage of the project, which investigated the factors controlling the build up of temperature and humidity in polythene enclosures for propagation. The main emphasis was on the influence of the shape and size of the enclosure. Industry experience suggested enclosures covering a large area suffer higher temperatures than small-scale enclosures, such as a polythene tent over a single mist line. This was broadly consistent with physical principles which predict that temperature lift will depend on the ratio of the external surface (through which heat will be lost) to floor area (where solar radiation is intercepted). As the enclosed area increases it becomes impractical to increase height proportionately and the 'External to Floor Area Ratio' (EFAR) therefore tends to decrease.

The results do ***not confirm these expectations*** and open up new practical possibilities. Additional experiment and analysis suggest further exciting possibilities:

- The effect of EFAR on temperature lift was much smaller than predicted.
- Our more detailed theoretical analysis indicated that increased heat storage in the floor and cooling by radiation exchange probably explain why the effect of EFAR was smaller than expected.
- There was no evidence of any advantage of the traditional approach to polythene enclosed mist, i.e. low tunnels over single mist lines, which make access difficult. Instead, air temperature and humidity were slightly more favourable in a structure of 'walk-in' height.
- It may be possible to reduce temperatures in some propagation enclosures, and maintain higher humidities, by maximising radiative cooling. This depends on

finding ways to minimise the presence of strong absorbers of thermal radiation (e.g. water and glass but not polythene) between cuttings and sky.

- Our theoretical analysis pointed up the potential for further modelling of high humidity propagation systems and further work to develop a robust model is needed. The objective is a tool for optimising the design of propagation facilities, taking account of local conditions (e.g. whether under glass or polythene).
- Temperature lift increased by about 6 °C per $kWm^{-2}$ of solar radiation.
- The correlation of temperature lift with radiation level was less close than expected, indicating that unidentified factors are having an important influence.
- The humidity in the enclosures was close to 100% rh at night but dropped during the day to as low as 70% rh.
- There was a strong link between high radiation and low humidity in the enclosure.
- Condensation was a very unreliable guide to humidity in the enclosure.
- Even a very small leak in an enclosure can result in substantial decrease in humidity (e.g. a hole representing 0.13 % of the surface area increased vpd by 50%) but has little cooling effect.

## Action points for growers

It is too early to give any conclusive recommendations at this stage but a number of points have emerged of immediate practical relevance:

- If using a polythene enclosure to raise humidity, always ensure that it is well sealed. Even a small opening can dramatically reduce humidity.
- Try to ensure that surfaces within a high humidity enclosure, including access paths, are kept wet. Either arrange that they are misted or cover with water retentive material and hose down occasionally. Otherwise, temperature will rise and humidity will fall.
- If you are thinking of trying some of the more stress-sensitive subjects, consider whether you could erect a walk-in polythene enclosure around a section of existing high-mounted mist. Our results suggest that a walk-in enclosure should work at least as well as a tent over an individual mist line.

- Insulation under the mist bed is liable to lead to higher daytime temperatures. This could be offset to some extent by using a deep layer of sand (~10 cm of fine water retentive sand) over the insulation to provide some thermal buffering.

## Anticipated practical and financial benefits

This research should allow growers to exploit existing knowledge on the benefits of a highly supportive rooting environment for more difficult cuttings by making it possible for them to create, on a commercial scale, the sort of environments that have proved highly effective at a research level. In particular, it will benefit growers attempting to use larger than normal cuttings to shorten the time from cutting to saleable plant (i.e. the designer liner concept).

**Cost benefit analysis**

Estimate of number of cuttings that fail to make saleable liners

= 25% of 200M cuttings p.a.

= 50M cuttings p.a.

At an average price of £0.20, the value of this lost production

= 50M x 0.2 = £10M

Making the conservative estimate that improvement in propagation environment could reduce losses by 5% (equivalent to increasing average rooting percentage by just 1%) then the value of lost production saved

= 5% of £10M

= £500K

Total cost of the project is approximately £120K, therefore the cost of the project will be recouped in less than a year.

Over a ten year period, the ratio of benefit to total cost

= 500 x 10 / 120 = 41.7

# SCIENCE SECTION

## Introduction

### *Purpose*

This project aims to meet the need for reliable information on how the design of propagation facilities influences the environment created and thus how well cuttings are protected from two stress factors: water stress and high temperature. Ventilated wet fog, such as the Agritech house at HRI-East Malling, achieves a suitable environment on a research scale, but for many reasons is not appropriate for most nurseries. Polythene enclosed mist often gives similar results but is prone to very high temperatures. This project is investigating alternative approaches and is designed to deliver:

- a set of **practical rules or guidelines** for improving an existing mist system or for designing a new propagation house from scratch.
- identification and explanation of the underlying principles (which apply equally to every type of facility from a fog system to a simple polythene tent).
- insights into the effect of the structure, shape, and size of a propagation unit on the problem of high temperature associated with restricting ventilation to raise humidity
- evaluation of the relative merits of three main alternatives:
  - polythene enclosed mist
  - ventilated mist with background fog to raise humidity of incoming air
  - ventilated mist with some form of passive humidification such as moist pads or curtains

### *Basic requirements of the environment for stress-sensitive cuttings*

Leafy cuttings have a fundamental weak point: to be effective at photosynthesis their leaves inevitably tend to lose water yet, in the absence of roots their capacity for water uptake is severely restricted. However, the nurseryman can do much to mitigate this problem by creating an environment in which evaporative demand is minimised while still being favourable for photosynthesis. Earlier HDC-funded work showed that successful rooting of many difficult subjects (e.g. *Garrya elliptica* 'James Roof' and *Cotinus coggygria* 'Royal Purple') depends on the combination of generous wetting and high humidity, together with appropriate shading (Harrison-Murray *et al.*, 1993a and 1998). In practice, this is a difficult combination to achieve. In particular, reducing ventilation to raise humidity tends to lead to excessively high temperatures (e.g. air temperatures > 40 °C), forcing the propagator to ventilate on days when fine weather make damaging water stress most likely. What is needed now is reliable information on how the design of propagation facilities influences the environment achieved. In particular, the following questions need to be answered:

- What factors control the temperature which develops in polythene enclosures (such as are used in polythene-enclosed mist) - e.g. shape, size, how well sealed, air movement around?
- What factors control the humidity around cuttings in polythene enclosures, and are there important gradients in conditions?
- Are there any fundamental reasons why polythene-enclosed mist has traditionally been operated with small covers over individual mist lines rather than more conveniently large walk-in enclosures?
- Can the theoretical advantage of the combination of fog (for humidification of incoming air) and mist (for uniform leaf wetting) be realised in practice?

***General background***

Sizes of propagation facilities vary greatly among nurseries, and the types of structure vary from simple polythene tunnels to large climate-controlled glasshouses. Furthermore, in view of the large number of more robust species which can tolerate relatively stressful conditions (Harrison-Murray *et al.*, 1998), generally it will make sense to upgrade only part of the house, to be used for the sensitive subjects. By identifying the principles that are operating, the aim is to produce rules of design that can be applied to any system.

This work addresses a number of the HDC’s stated objectives, particularly the exploitation and development of new opportunities. It will help unlock the proven benefits of highly supportive propagation environments and thus contribute to exploitation of the 'designer-liner' concept (HNS 69). That concept calls for the use of larger than normal cuttings that tend to require a more 'supportive' rooting environment.

***Previous studies***

Conventional mist systems provide wetting but the relative humidity drops rapidly during the intervals between mist bursts (Grange and Loach, 1983) so that cuttings prone to water stress, such as soft cuttings of *Garrya elliptica* 'James Roof', fail to root (Harrison-Murray *et al*., 1993a). By contrast, a good fog system can keep the humidity close to 100%, but it is difficult to ensure **uniform wetting** of foliage (Harrison-Murray *et al*. 1993b). There may therefore be benefits in combining fog and mist in the same system, using mist nozzles to evenly wet the foliage, and fog nozzles to raise the humidity. At first sight, this appears a very expensive approach but the majority of nurseries have existing mist facilities, and upgrading this mist by the addition of fog nozzles to raise the ambient humidity (i.e. 'background fog') may be economically more attractive than replacing the mist with a fog system.

Apart from 'background fog', there are other methods of raising the humidity under mist which deserve further investigation (Loach, 1987). Enclosing individual mist beds under polythene is effective in raising humidity (Grange and Loach, 1983), but it can result in excessive temperature build up and also restricts access to the cuttings. As a result it has not been widely adopted by the industry. The work of Grange and Loach in the early eighties established a firm foundation for the study of the microclimate of propagation environments but many questions remain to be addressed. For example, it is not clear exactly what determines how high the temperature rises when mist is enclosed under polythene and the influence of the shape and size of the enclosure, in particular, requires investigation. Recent developments in the technology of plastic films, particularly the advent of a material that reflects strongly in the near infrared part of the solar radiation spectrum (Visqueen, Luminance THB), may bring practical benefits in this area.

Cuttings vary greatly in their dependence on environment to restrict water loss by transpiration and for many it is sufficient to enclose them in some kind of polythene tent to raise humidity. A group based at the Institute of Terrestrial Ecology (ITE), Edinburgh, have shown that a simple development of this approach is appropriate for many tropical tree species. Their 'non-mist propagator' combines a polythene enclosure with simple arrangements for keeping the substrate moist and appropriate shade to achieve an environment that is acceptable for many species (Leakey *et al.* 1990). For developing countries, it has the great advantage of not depending on mains electricity or a piped water supply.

Studies of the microclimate inside the non-mist propagators showed that the leaf-to-air vapour pressure difference (LAVPD, i.e. the driving 'force' for transpiration) rose substantially as soon as the lid was opened and also tended to increase with increasing irradiance (Newton and Jones, 1993a). Remarkably, there was no consistent difference in water status between cuttings in the non-mist propagator and a polythene enclosed mist system (Newton and Jones, 1993b). Furthermore, LAVPD was reported to be greater in the enclosed mist system than in the non-mist propagator, a surprising result and one that differs from the findings of other groups (Grange and Loach, 1983, and Mudge *et al.* 1995).

The disparity between these reports probably reflects the difficulty of making reliable comparisons of the microclimate in different systems. In addition to the technical difficulty of measuring accurately leaf temperature and atmospheric humidity, practical constraints generally limit replication of the systems being compared and the number of locations within each system where measurements are made. Another problem associated with this area of research is difficulty in defining some aspects of the propagation system, such as the behaviour of the equipment regulating output of mist and how effectively polythene enclosures prevent any ingress of drier air from outside.

In contrast to polythene enclosure, 'background fog' offers the potential to combine high humidity with control of temperature by ventilation. The fog droplets present such a large surface area for evaporation that incoming dry air can be humidified before it reaches the cuttings. However, this will only be achieved if the fog generating system has sufficient capacity to meet the most demanding weather conditions without creating other problems such as excessive local wetting near the nozzles. There is a need for reliable design criteria, provided in a form that growers and their advisors can readily apply. There is virtually no scientific literature in this area beyond comparisons of the advantages and disadvantages of alternative types of equipment for creating fog (Loach, 1988).

***Approach adopted***

The approach adopted involved three stages:

1. Studies of the microclimate of polythene enclosures to determine the effects of shape and size on temperature and humidity at cutting height.

2. Experimental scale trials of 'walk-in' polythene-enclosed mist and/or background fogging (i.e. combination of fog and mist), depending on the results of stage 1.

3. Nursery scale 'proof of concept' trials of the best system

***Theory relevant to stage one***

A polythene enclosure causes the temperature to rise because it imposes a resistance to the loss of the energy gained when solar radiation passing through the polythene is absorbed by the ground or the cuttings. This resistance applies to the loss of energy by the movement of air, known as convection (either 'free' due to local heating or 'forced' by a fan or natural wind) and by evaporation (i.e. loss of energy as latent heat). In a tightly sealed enclosure there can be no energy loss by evaporation, though evaporation and condensation can transport energy from the ground to the polythene. Convective loss depends on the indirect effect of cooling of the polythene by the air outside it. The temperature within the enclosure therefore rises until the lift of temperature above that of its surroundings is large enough to establish a balance between energy gain and energy loss. As such, it is similar to a very well sealed polythene greenhouse. It differs from a glasshouse in that the polythene does not restrict the loss of energy as outgoing long wave radiation (the classical 'greenhouse effect').

Since convective heat loss to the surroundings occurs across the surface of the polythene, it was reasonable to expect that the larger this surface area the more readily heat would be lost in this way. By contrast, we expected that the amount of energy absorbed into the enclosure would depend on the solar irradiance within the enclosure (i.e. amount of radiation per unit area of ground) and the area covered by the enclosure. On this hypothesis, and assuming that convection would remain a major component of heat loss, we predicted that temperatures in polythene enclosures would depend on the ratio of the surface area of the enclosure (i.e. area of polythene) to the area of ground covered (i.e. footprint). We coined the term 'External to Floor Area Ratio' (EFAR) for this ratio. It was expected that temperatures would tend to rise with increasing footprint area, but would fall with increasing height of the enclosure (because the extra height would increase the area of polythene for any given footprint).

It was more difficult to make any prediction about whether the overall scale of the enclosure would have an additional effect, independent of EFAR. To test the hypothesis, three enclosures were constructed with very different EFAR and, to investigate the effect of scale, two of them were reproduced at half-scale. Details are given in the next section.

## Materials and Methods

### Stage 1: effects of size and shape of polythene enclosure

#### *The experimental facilities*

*The house*

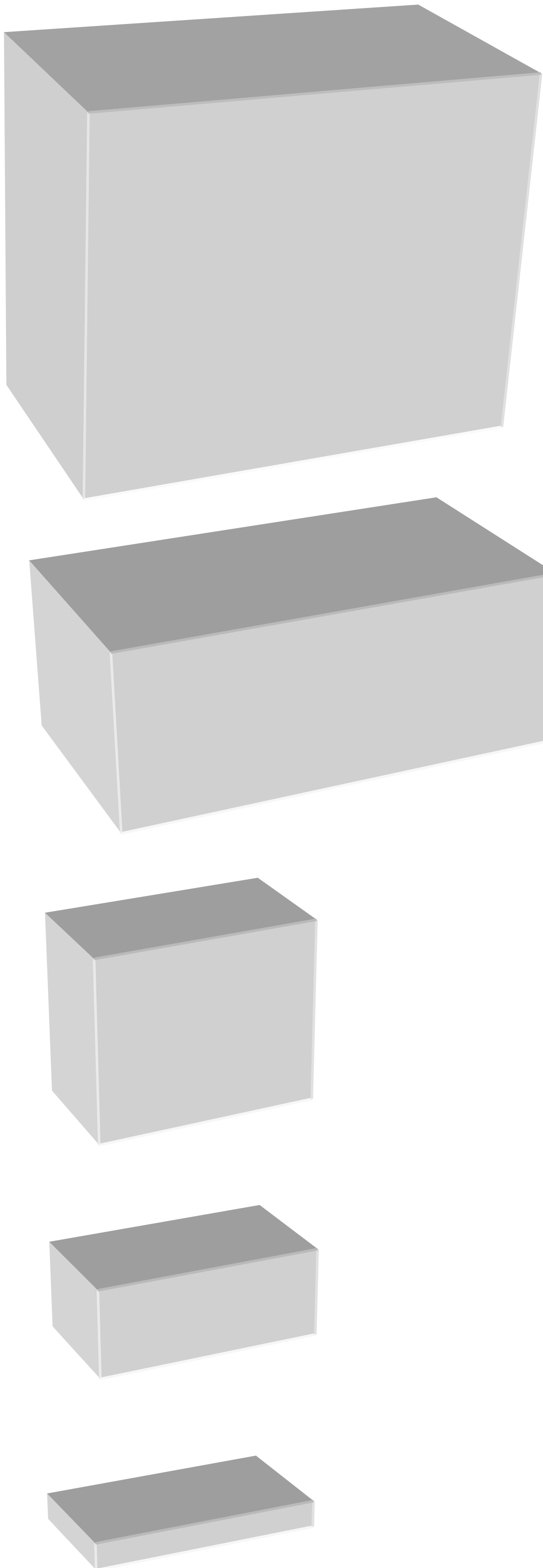
Experiments conducted so far have been inside a polythene greenhouse (Clovis Lande tunnel, type HLX 18, 14 x 5.5 m, with adjustable low level side vents) equipped with six independently controllable mist lines and heating beds.

A drained sand bed (4 x 11.25 m, with 100 mm depth of fine sand) defined the usable area. Additional tubular steel framework was fixed to the original tunnel framework to deflect upward air coming through the side vents. This limited local draughts and thus made conditions more comparable to those in a larger structure typical of a commercial propagation house. Otherwise, flapping of the polythene on the experimental structures would have been excessive.

Construction of a larger vertical-sided twin-span house with high level ventilation has been erected for stage 2 of the project. It provides an unrestricted propagation area >16 x 4.5 m within a house of 12.8 x 19.5 m, so that conditions will be much closer to those of a typical commercial facility. Unfortunately, planning consent and difficult site conditions meant that this facility was not available for year 2 as expected.

*The experimental enclosures*

The shape and dimensions of the structures are illustrated in Fig.1



Enclosure 1 (E1)
(a small "walk-in" enclosure)

| | |
|---|---|
| Height | 2.1 m |
| Width | 1.5 m |
| Length | 2.5 m |
| EFAR | 5.5 |

Enclosure 2 (E2)
(equivalent to a conventional single mist line enclosure)

| | |
|---|---|
| Height | 1.0 m |
| Width | 1.5 m |
| Length | 2.5 m |
| EFAR | 3.1 |

Enclosure 3 (E3)
(half-scale of E1)

| | |
|---|---|
| Height | 1.05 m |
| Width | 0.75 m |
| Length | 1.25 m |
| EFAR | 5.5 |

Enclosure 4 (E4)
(half-scale of E2)

| | |
|---|---|
| Height | 0.5 m |
| Width | 0.75 m |
| Length | 1.25 m |
| EFAR | 3.1 |

Enclosure 5 (E5)
(equivalent to contact polythene)

| | |
|---|---|
| Height | 0.15 m |
| Width | 0.75 m |
| Length | 1.25 m |
| EFAR | 1.6 |

**Figure 1 Diagram to show the shapes and dimensions of the experimental polythene enclosures. E1 an E2 were erected in situ on tensioned nylon monofil; E3, E4 and E4 were timber framed. EFAR = External to Floor Area Ratio**

Additional framework fitted to the house structure provide an adaptable means of constructing polythene enclosures to almost any design, using tensioned nylon monofil to support the polythene. The smaller experimental enclosures were constructed around a timber framework.

For one experiment, the vents and doors of the greenhouse were kept closed so that the tunnel itself became one of the enclosures under study.

***The environmental measurements***

The sensors were as follows:

- Six psychrometers (type WVU/2 with PT100 thermometers, Delta-T Devices, Cambridge). These miniature units are fan-ventilated and double screened against from radiation effects, but are unfortunately no longer manufactured. They measure air temperature and humidity (which can be expressed as relative humidity (rh), vapour pressure deficit (vpd, a measure of the drying power of the air), and water vapour partial pressure (vp, which serves as a measure of the concentration of water vapour). They were therefore of central importance.
- Six thermistors for soil temperatures (a pair being installed in the sand bed at 5 and 35 mm depth to provide an estimate of heat flux into the soil)
- Met station (PAR, temperature, humidity and wind speed)
- Thermocouple arrays for temperature gradients

These were monitored with a Delta-T data logger (type DL2 with four-wire inputs for platinum resistance temperature sensors (Delta-T Devices, Cambridge). Configuration varied but usually involved logging the psychrometers at 30 min intervals, after the fan had run for at least 1min.

In addition to these logged data, a hot wire anemometer was used for spot measurements of air movement within the tunnel. To measure light transmission a pair of PAR (quantum) sensors was monitored using integrators (Delta-T Microvolt Integrators, type MV1).

### ***The Experiments***

Data was collected almost continuously over the period July to December in 1999 and 2000. A preliminary examination of the data was made every few days. On the basis of this examination, changes were made either to the enclosures, to address different questions, or to the monitoring equipment, to improve the precision of the data. For ease of reference, the stream of data has been divided into sections that focus on more or less discrete topics. The essential features of each of these 'experiments' are listed below:

*Year 1*

*Experiment 1: Effects of shape and size of enclosure, within a heavily shaded greenhouse*

- Greenhouse shaded with reflective external shade (Ludvig Svensson OLS60, giving ~80% reduction in solar radiation within the house)
- All vents and doors open (wide but not fully)
- Sand bed watered and raked thoroughly before the psychrometers were put in place using inverted pots to support them at cutting height.
- Exposed sand bed around the enclosures watered daily

*Experiment 2: Effects of shape, size and re-wetting of enclosures, in a non-ventilated greenhouse*

- All greenhouse vents and doors kept closed.
- All shade removed midway through the experiment.
- Sand watered but not raked, as it was found that raking lead to drying of the sand 'peaks'.
- Watering of the bed and surrounding concrete path varied from day to day to test the effect on humidity and temperature.
- E3 and E4 moved to a different part of the house midway through the experiment to test for local variation within the tunnel.
- Pots supporting the psychrometers covered in Al foil to reduce radiant warming.

- First occurrence of some 'rogue' data in the logger's output. This caused intermittent problems in many subsequent experiments before it was established that it was due to malfunction of the logger at extreme temperatures (either high or low). This required rogue data to be identified and replaced by 'missing values' before analysis.

*Experiment 3: Effects of shape, size and re-wetting of enclosures, in a well ventilated greenhouse*

- Greenhouse vents and doors fully open
- No shade
- Daily watering of sand around the enclosures
- Otherwise similar to experiment 2

*Experiment 4. Investigation of ways to improve the reproducibility of psychrometer measurements of humidity*

At the start of the project the psychrometers were cross-calibrated under laboratory conditions and found to be within specification (±3% rh, ±0.2 °C). In view of the small differences recorded between the enclosures in experiments 1 to 3, cross calibration was repeated under the conditions of the experiment. When all the psychrometers were placed side by side in E2 it was evident that differences were larger than seen in the laboratory and were greatest in the middle of the day. A series of modifications were made to half of the psychrometers to identify sources of errors and means of mitigating them. Eventually, all psychrometers were modified accordingly and cross calibration rechecked. This showed that the modifications had virtually eliminated the errors, particularly if several measurements were averaged.

In order to be able to use averaging, the psychrometer fans must be run continuously. For measurements in very still air, there is a possibility that continuous operation of the fans could substantially modify the environment one is trying to measure. However, subsequent investigations have shown that the need for averaging is due to instability in the loggers measuring circuits rather than the psychrometers themselves.

It is likely that the problem could be avoided by using a different manufacturer's logger for critical applications in future.

*Experiment 5: Effects of limited ventilation of enclosures*

The effect of limited ventilation, such as will often occur in practice when polythene is used to enclose a propagation bed, was studied by creating a well defined small opening in E2 which was then enlarged in stages over several weeks. The other enclosures remained tightly sealed for comparison. The stages were as follows:

i. 0.13% vent (1 x 150 cm) at one end of the roof panel
ii. 1.3% vent (10 x 150 cm) at one end of the roof panel
iii. 1.9% vent (15 x 150 cm) at one end of the roof panel
iv. Two 1.9% vents (15 x 150 cm), one at each end of the roof panel

*Year 2*

The results obtained in year 1 indicated no fundamental reason why polythene enclosed mist should not work well in large walk-in chambers, as long as the enclosure was well sealed and there were no dry areas of floor. Unfortunately, the delays in the erection of the twin-span tunnel, which were referred to earlier, prevented the planned rooting experiments. Instead, we extended the study of the behaviour of the experimental enclosures used in year 1, measuring horizontal and vertical gradients within the enclosures and in the sand beneath them. The purpose was to increase our understanding of the control of temperature in polythene enclosures. We hoped that it would explain why EFAR had a smaller effect on temperature than expected but, more importantly, it would help provide a basis from which to develop reliable practical guidance to growers. The focus was on why.

*Experiment 6: Horizontal gradients within enclosures*

- Psychrometers mounted in retort clamps fixed to a horizontal bar to avoid any local modification of the environment by a supporting pot.
- Psychrometers concentrated in a comparison of E1 and E2, testing for differences between the centre and edges (10cm from polythene) of the enclosures.
- Greenhouse doors and vents fully open.
- No shade.

*Experiment 7: Vertical gradients within enclosures and the sand under them*

- Psychrometers concentrated in a comparison of E1 and E2, testing for vertical differences in temperature and humidity associated with the heavy condensation that formed on the root of all the enclosures.
- Testing the effect of direction of air movement through psychrometers on measurements made close to the roof of an enclosure.
- No shade.
- Greenhouse doors and vents fully open.
- Daily watering of sand around the enclosures.

*Experiment 8: Effects of shape and size of enclosures (incorporating improvements in methodology over earlier experiments)*

- Comparison of all enclosures except E5
- Using improved radiation shielding and support arrangements developed in experiment 4
- No shade
- Greenhouse doors and vents fully open
- Daily watering of sand around the enclosures

*Experiment 9: Measurements of temperature gradients within the boundary layer*

Arrays of thermocouples were constructed and used to measure temperature gradients close to the sand and the polythene to help identify patterns of heat flux. Thermocouples were manufactured from 0.2 mm diameter type T thermocouple wire (twisted pair) by twisting tightly and soldering. The small size of the resulting couple (~ 0.4 mm) made them relatively insensitive to radiation so that they could be used to measure air temperature without a ventilated screen. Thus, in contrast to the psychrometers, it was possible to make meaningful measurements within the boundary layer (i.e. near to sand and polythene surfaces, where air movement is restricted by frictional interaction with the solid). This experiment is being done under controlled conditions and is continuing.

## Results and Discussion

Analysis of the data generated a large number of graphs, tables and statistics for each experiment and sometimes for individual days within an experiment. This section presents the distillation of all this analysis using examples to illustrate the features that emerged in the complete data set.

### Factors affecting air temperature in enclosures

***Shape***

Temperatures were remarkably similar in all the enclosures. The small differences evident in Fig. 2 (< 1 °C) are not large enough to be of practical significance. However, the slightly higher temperatures in E2 that E1, and in E4 than E3, are consistent with the hypothesis that a large EFAR favours lower temperatures. This means that tall enclosures will generally tend to be slightly cooler at cutting level than low ones. The differences were not entirely consistent between experiments so that uncontrolled (and unknown) factors were of equal importance.

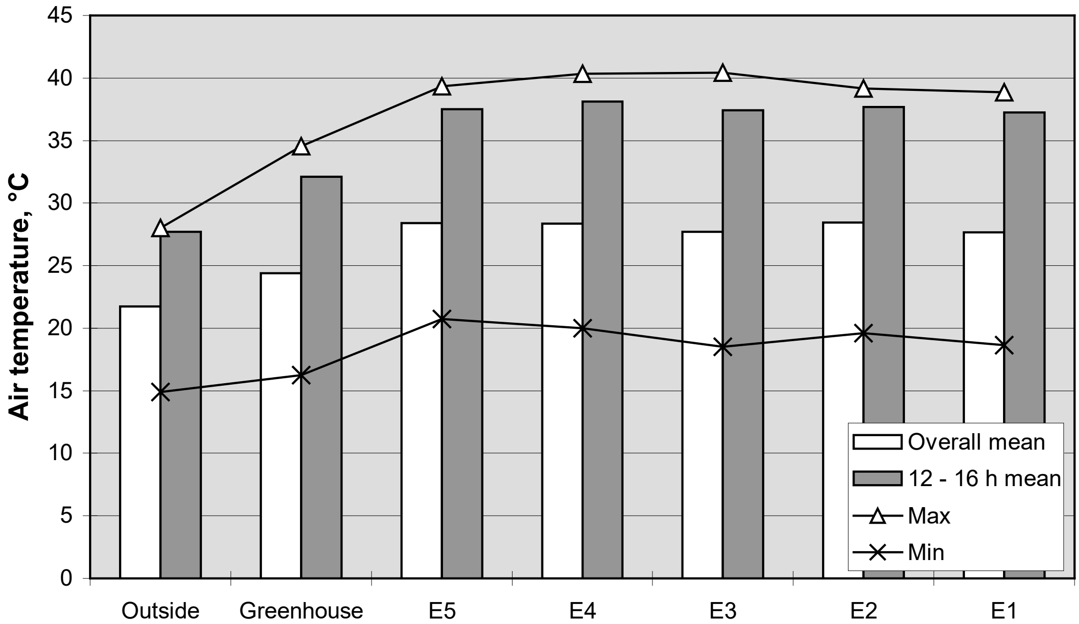



***Figure 2. Typical air temperatures in the different enclosures (E1 to E5) compared with the greenhouse air around them and the air outside. Values are means of 3 days data in experiment 3.***

In those experiments that included E5, which had the lowest EFAR, the highest temperatures were not observed in that enclosure. It was noted that condensation on the polythene formed more rapidly and heavily in E5 than any of the other enclosures. Measurements of light transmission showed that this reduced the proportion of solar radiation that reached the sand in E5 compared to the other enclosures. This prevented fair comparison with the other enclosures and was the reason that E5 was excluded from the later experiments.

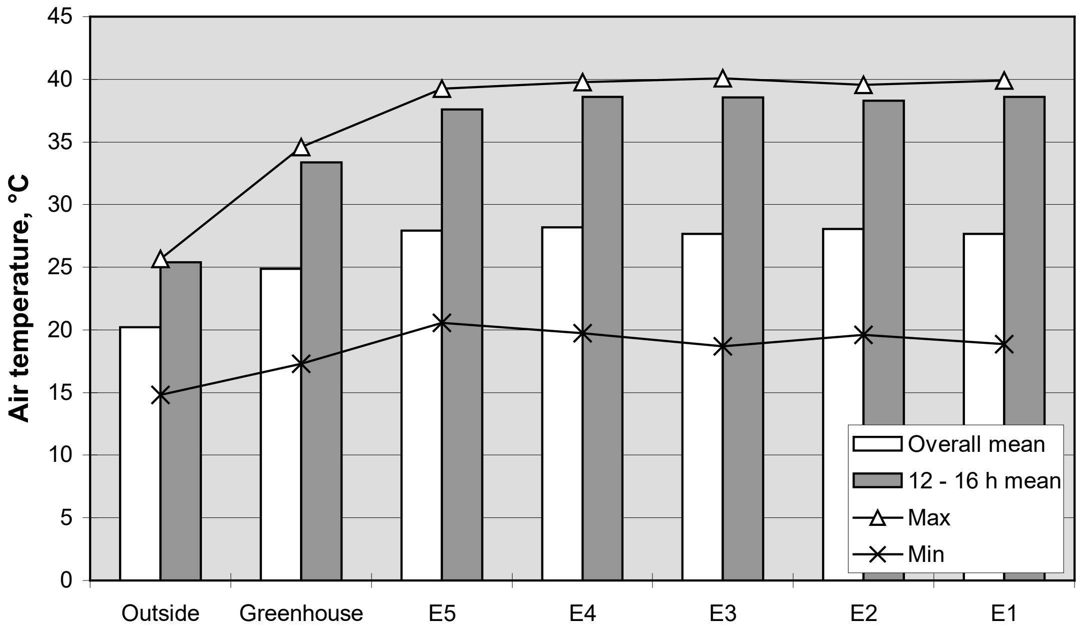



***Figure 3. Summary of the air temperatures recorded in different enclosures in experiment 2. For this experiment the greenhouse doors and vents were closed. Notice that the rise in temperature from the outside to the greenhouse is greater that the further increase within the experimental enclosures (E1 to E5)***

***Size***

The data in Fig. 2 also indicate that size had no substantial effect on temperature. The temperature in E1 was almost identical to its half-scale replica E3, while that in E2 was very similar to that in E4.

When ventilation of the greenhouse was closed (Experiment 2), the temperature rise in the greenhouse relative to outside air was larger than the additional temperature rise in the experimental enclosures (Fig. 3). While this might appear to be evidence for an effect of scale, it is more likely a consequence of the more vigorous convective heat exchange outside, which would have provided greater opportunity for reduction in heat exchange. In effect, the presence of the sealed greenhouse reduced the opportunity for an enclosure to restrict heat loss further – a case of the law of diminishing returns. Consistent with this explanation, when the greenhouse vents were fully open it still lifted temperature approximately as much as the non-ventilated enclosures within it (Fig. 2). More robust evidence will come from measurements in larger scale enclosures within the new twin-span house.

***Radiation***

Since radiation provides the energy that drives the rise in temperature within an enclosure, it is obviously a crucial factor in determining how high the temperature rises. Indeed the daily cycle of temperature always showed a clear parallel with the radiation cycle (e.g. Fig. 4). However, plots of temperature against radiation generally showed quite a wide scatter around a regression line (e.g. Fig. 5) indicating that there were other sources of variation.

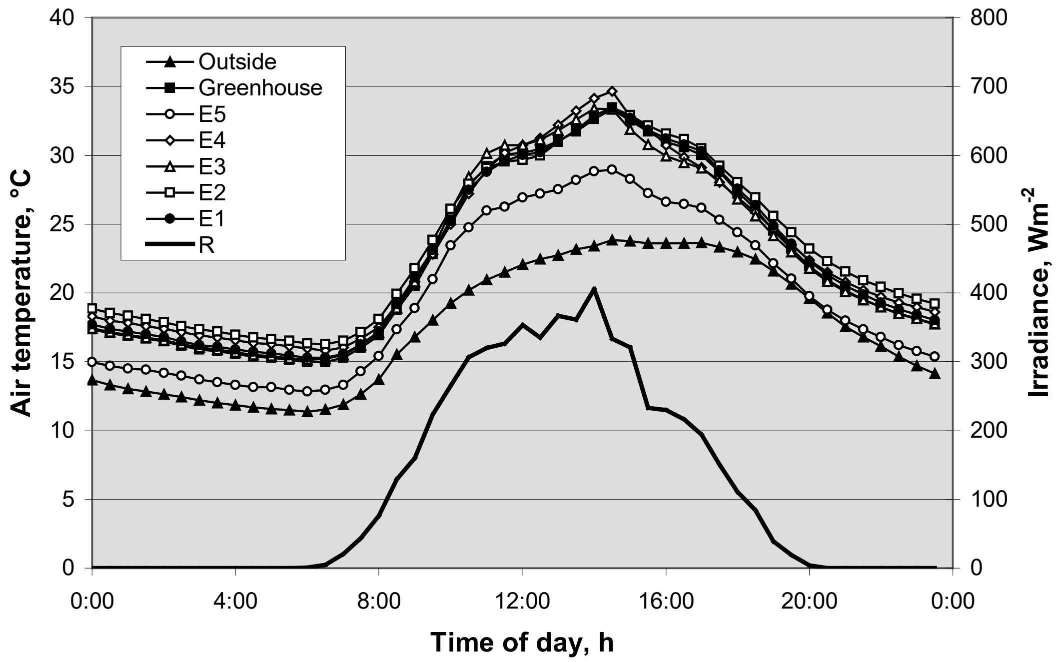



***Figure 4. Diurnal cycle of temperatures within the enclosures (E1 to E5) and the greenhouse as a whole. Notice the parallel with the diurnal cycle of incoming solar radiation (R), and that the parallel is less marked for the outside air temperature. Values are means from 6 days in experiment 8.***

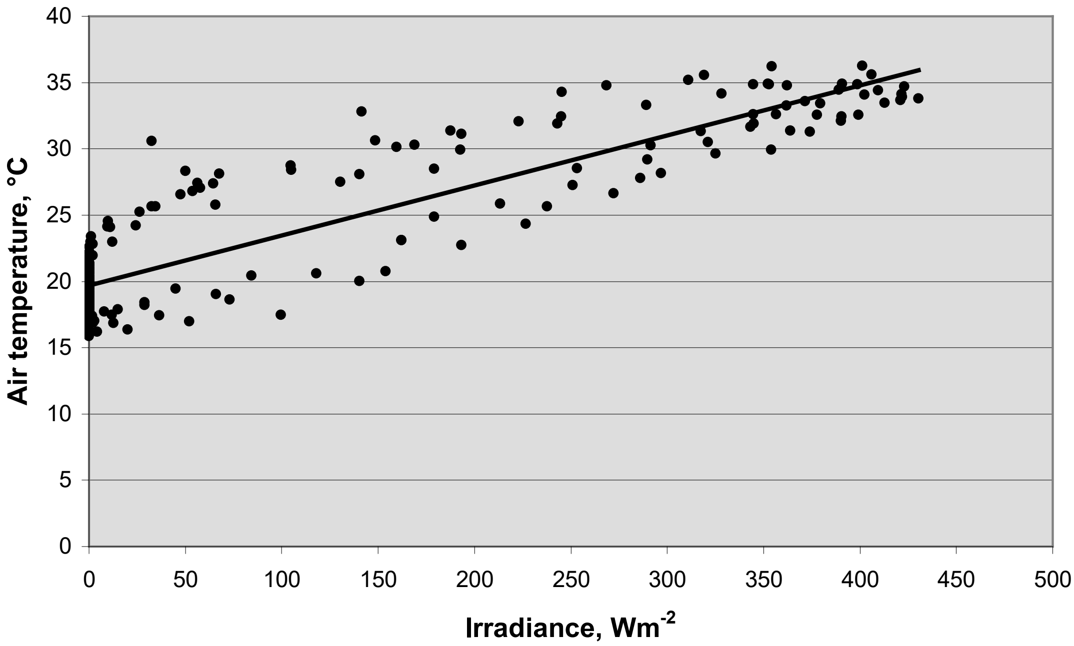



***Figure 5. The relationship between air temperature and incoming solar radiation in enclosure E1, based on data from four days in experiment 5.***

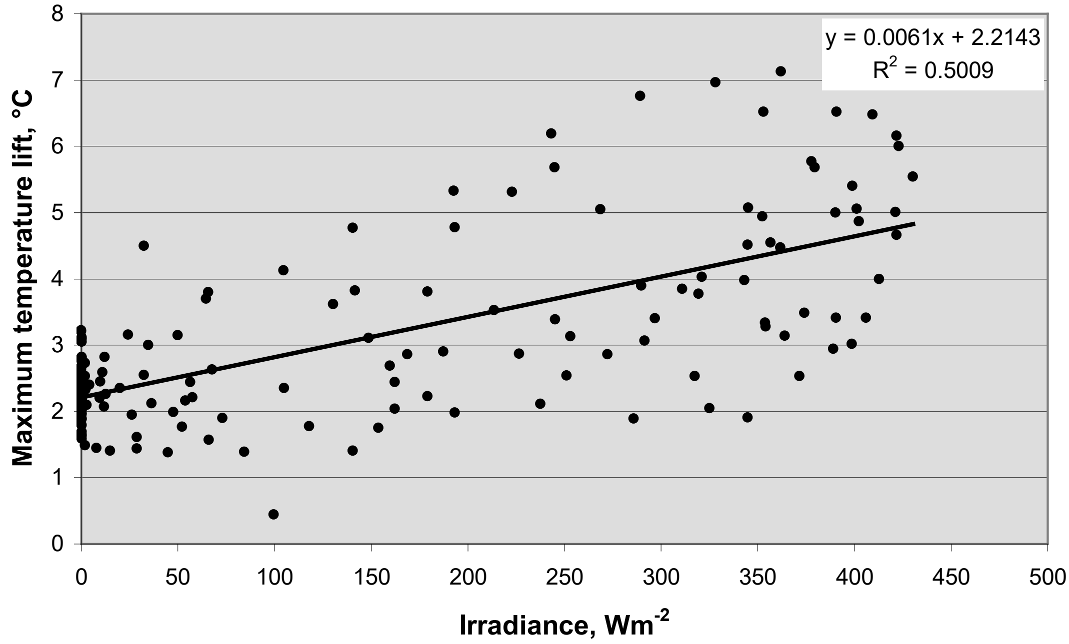



***Figure 6. The relationship between the temperature lift due to enclosure E1 and incoming solar radiation, based on data from four days in experiment 5.***

A more serious problem with Fig. 5 is that the observed relationship could be largely attributable to the effect of the radiation on outside temperatures. As such, it could not provide the basis for sensitive comparisons of different types of enclosure or for prediction of the best type of structure to minimise the problem of high temperature. To look specifically at how the warming effect of an enclosure depends on radiation level, the data were converted into values of temperature lift relative to the surrounding air. When temperature lift was plotted against radiation it was clear that it increased significantly as radiation level increased (Fig. 6). The equation of the fitted line provides a useful summary of the data:

$$y = 0.006x + 2.2.$$

The slope term (0.006) indicates that temperature lift increased by about 0.006 °C per W m-2 (or 6 °C per kW $m^{-2}$), while the constant term indicates that temperature was raised by 2.2 °C even in the dark. Such figures are clearly useful for predicting the benefit of shading in limiting air temperature within enclosures and illustrate the potential benefits of simple predictive models. However, the scatter around the regression line was even greater than that for the absolute temperatures (compare Fig. 6 with Fig. 5), some points being almost 3 °C away from the line. This suggests that other components of the energy balance were also varying sufficiently to have a large effect on temperature lift. The need to be able to *predict* how hot it is likely to be in a particular enclosure is central to this project, and work on the development a predictive model is covered further in a later section.

Interestingly, the temperature lift created by the ventilated greenhouse, relative to temperature outdoors, tended to show a greater scatter of points and a much more variable slope. This reflects that differences in factors such as windspeed and humidity can influence the energy balance of a ventilated enclosure much more than that of a non-ventilated one, so that the effect of radiation is less dominant.

***Limited Ventilation***

With a 1 cm wide gap at one end of the roof of E2 (equal to 0.13% of the polythene area) there was no detectable reduction in temperature compared to the non-ventilated enclosures. When this was increased to 10 cm (i.e. 1.3%) there was a small but detectable effect (Fig. 7). Therefore, minimal ventilation of an enclosure will not generally be an effective way to avoid excessive temperatures on hot days.

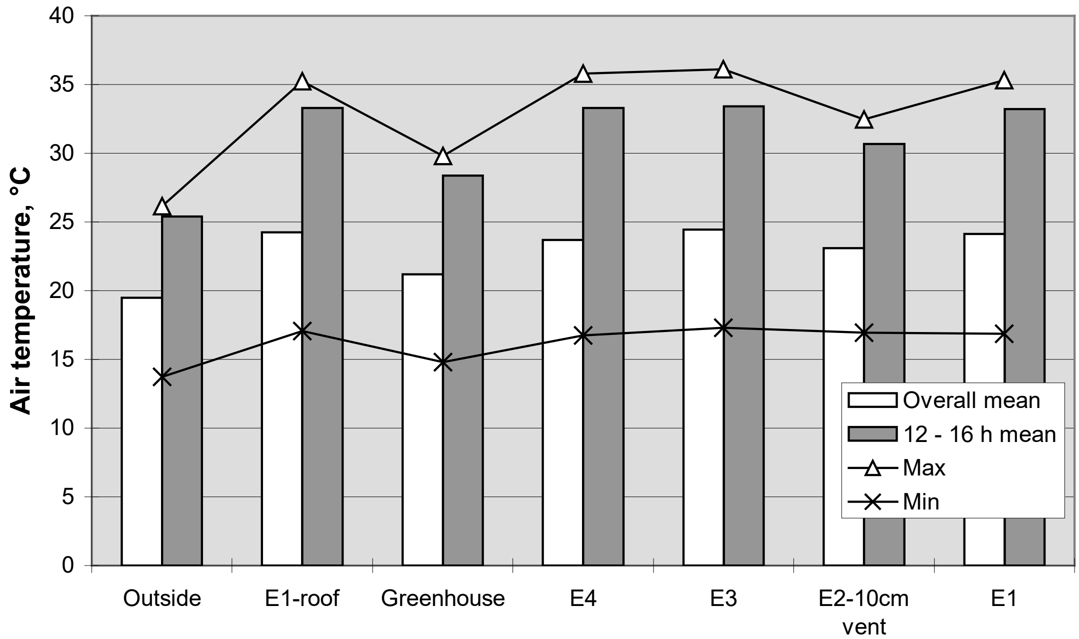



***Figure 7. Mean temperatures in the different enclosures showing the effect of opening a 10 x 150 cm vent (=1.3% of surface area of the enclosure) in the roof of E2***

***'Wetting down'***

In experiment 2, the procedure of daily wetting down the greenhouse was varied from day to day to determine its effect. A short-lived reduction in temperature was observed when the concrete path was included but not when it was only the sand bed that was wetted. This indicates that the effect of the hosing operation itself was minimal but extending the floor area from which heat could be lost by evaporation, by wetting the concrete path, reduced the temperature. It did not take long for the path to dry so that the effect was short-lived and could not be quantified precisely. To do this it would be necessary to set up enclosures in which the area of floor kept continuously moist (e.g. a moist sandbed) is varied.

## Factors affecting humidity in enclosures

Humidity is more complex than temperature because there are various different measures of humidity each of which is useful in a particular context. Here I shall refer to three of these:

- **relative humidity (rh)** – a measure of the degree to which the atmosphere is saturated with water vapour
- **vapour pressure (vp)** – a measure closely related to the concentration of water vapour in the air. This is important because it is gradients of concentration that drive movement of water vapour by diffusion (i.e. from regions of high to regions of low concentration).
- **vapour pressure deficit (vpd)** – how far below the concentration of saturated air is the current vp. As such, it is a measure of the driving force for evaporation from a wet surface at air temperature. However, it is important to recognise that, in practice, evaporating surfaces are often significantly below air temperature, due to evaporative cooling, or above air temperature, due to absorption of radiation. Therefore it does not completely describe the evaporative demand of an environment. However, it is much more appropriate than rh in this context, especially because it takes account of the effect of air temperature.

All these variables can be calculated from the wet bulb and dry bulb temperatures measured by the psychrometers. However, humidity is notoriously difficult to measure accurately. A change of just 0.1 °C in wet bulb depression (i.e. the difference between wet bulb and dry bulb temperature) is equivalent to a change of relative humidity of 1.5%. The results of experiments 1 to 3 showed that the differences between the enclosures were small and that special measures would therefore be needed to ensure that the observed differences were real. The results of experiment 4 pointed to inadequate radiation shielding as the main source of discrepancies between the psychrometers, and performance was greatly improved by applying a layer of reflective foil to the outside of the radiation shields. Special mounting arrangements were also adopted to avoid local warming of the air as it was drawn into the instrument. The results in this section are therefore based, as far as possible, on data collected after these improvements were made.

***Shape and Size***

Relative humidity consistently dropped during the day, usually to about 80% in the enclosures and to 40 – 60% outside and rose close to 100% at night.

Because of the differences in temperature between environments, vpd provides a more accurate basis for evaluating evaporative demand. Comparisons amongst the enclosures E1 to E4 in Fig. 8 reveal no consistent effect of shape but suggest that vpd was greater in the small scale enclosures, E3 an E4. No data were collected from E5 after the improvements to the psychrometers but earlier data indicated slightly lower vpd in E5 than in E1 to E4. The data for vp, in Fig. 9, show that the lower vpd in the larger enclosures (E1 and E2) was the result of higher vapour pressure. It is not clear why this should have been. It is possible that it was an artefact of the experiment: the slight reduction of the area of moist sand, caused by the wooden framework used for the small scale enclosures, might have been enough to reduce the total quantity of water evaporated and thus the vp.

The effect of the greenhouse itself was completely different. The mean vpd was about 50% greater than outside, despite the measurements being made 10 cm above the moist sand bed. In contrast, vp was almost identical to that outside. This indicates that air moving into the house from outside was increasing in temperature rapidly but picking up extra moisture much more slowly. The rise in vpd was entirely attributable to the increase in temperature.

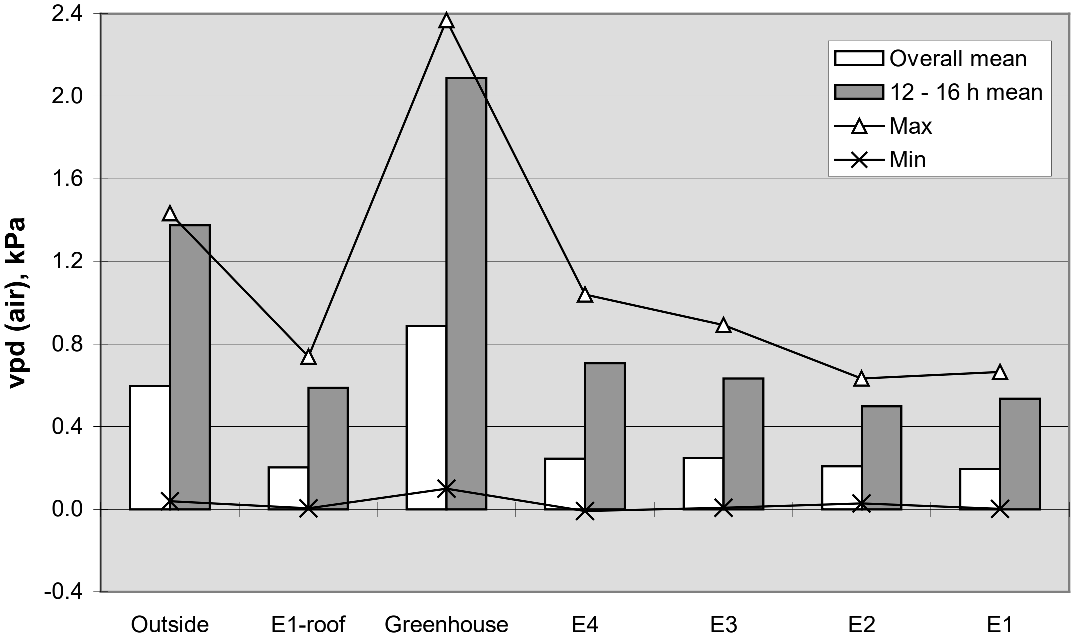



***Figure 8. Mean vpd of the air in the different enclosures (E1 to E4), in the ventilated greenhouse, and outside, averaged over six days in experiment 8. All psychrometers were mounted at 10 cm above the sand except for 'E1-roof', which was mounted just below the condensation laden polythene roof in E1.***

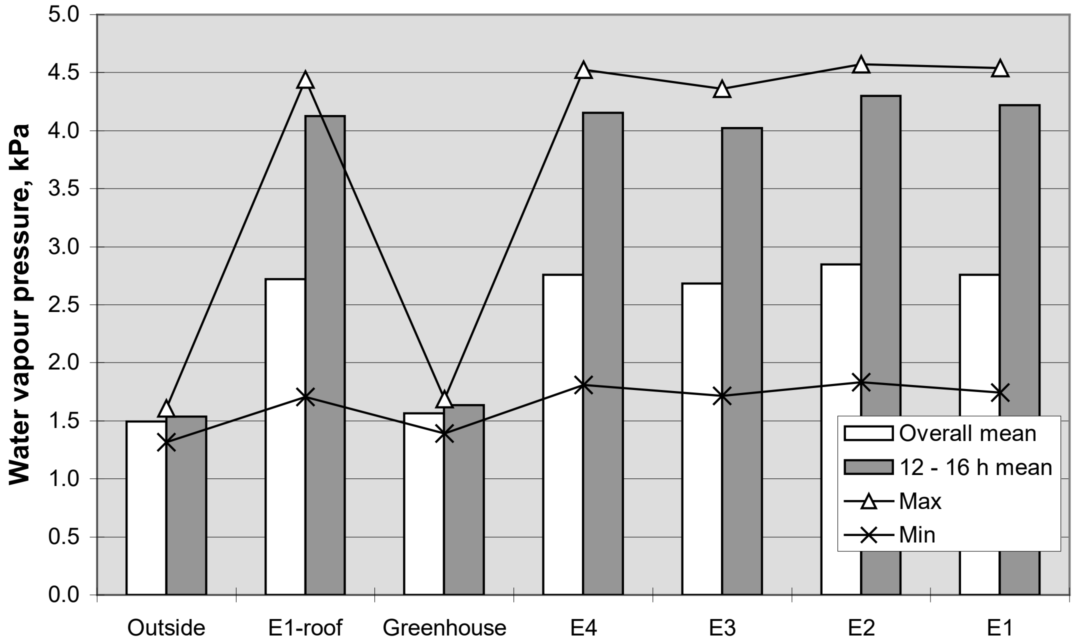



***Figure 9. Mean water vapour pressures in the different enclosures (E1 to E4), in the ventilated greenhouse, and outside, averaged over six days in experiment 8. All psychrometers were mounted at 10 cm above the sand except for 'E1-roof', which was mounted just below the condensation laden polythene roof in E1.***

### *Radiation*

Plotting vpd against radiation showed a close linear correlation (Fig. 10). The regression equation indicates that, in E1, vpd rose by 1.7 Pa for every additional $Wm^{-2}$ of solar radiation that reached the enclosure. For comparison, the value for E3 was slightly higher (2.0 Pa / $Wm^{-2}$), reflecting the slightly higher mean in Fig. 9, while that for the air outside was about three times as great (5.2 Pa / $Wm^{-2}$). The $R^2$ statistic indicated that radiation accounted for about 90% of the variation in vpd within the enclosures, compared with 85% of that for the air outside, and only 50% of the variation in temperature lift (Fig. 6).

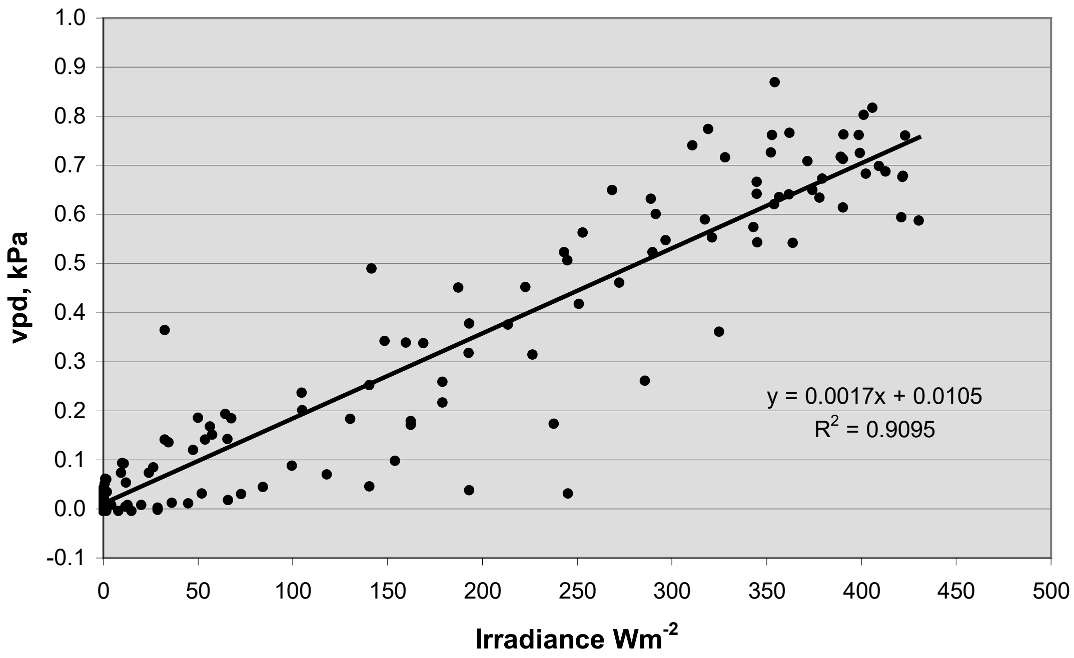



***Figure 10. Data from four days in experiment 5 showing the relationship between the vpd and incoming solar radiation in enclosure E1.***

### *Limited Ventilation*

The data in Fig. 11 show that a single 10 cm vent in E2 allowed enough ventilation to increase vpd to almost that of outside air, in marked contrast to the modest effect on temperature (Fig. 7). Even a 1 cm-wide vent increased vpd by about 50% (data not shown). Interestingly, the enclosures remained heavily covered with condensation except within a few centimetres of the vent. This shows how the presence of heavy condensation is no guarantee that a polythene tent is maintaining a relative humidity near to 100%, nor vpd close to zero.

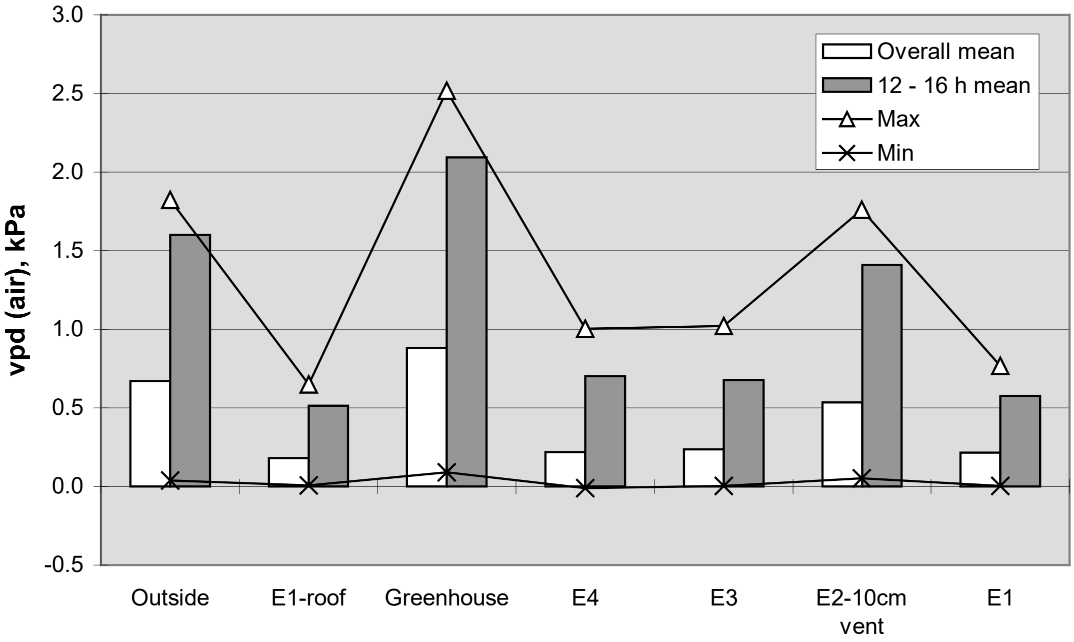



***Figure 11. The effect of ventilation on vpd. The data are means of 4 days in experiment 5 and show the large increase in vpd due to a 10 x 150 cm vent (representing 1.3 % of surface area) made in the roof of enclosure E2. All psychrometers were mounted at 10 cm above the sand except for 'E1-roof', which was mounted just below the condensation laden polythene roof in E1.***

## Gradients of temperature and humidity within enclosures

In year 2, attention focussed on gradients within enclosures, partly because of the practical relevance of non-uniformity in facilities and partly to identify the points of high resistance to heat transfer.

The measurements from experiments 6 and 7, summarised in Tables 1 and 2, show that the temperature was almost uniform throughout the enclosures. The largest difference observed, in either the vertical or horizontal planes, was 0.46 °C. The temperature difference between the inside and outside of the enclosures (3.0 °C for E1) must therefore have been concentrated close to the polythene. This implies that there was enough air movement within the enclosures to ensure thorough mixing, except in the boundary layer where air movement is reduced by frictional interaction with the stationary polythene.

The mixing of the bulk air within the enclosures was probably driven by free convection. The polythene was taught and minimal movement was visible except on exceptionally windy days. However, the possibility cannot be excluded that there was, in effect, some transfer of air movement 'through' the polythene.

Free convection results from buoyancy of warmer, less dense air, relative to cooler air. The surface of the sand, where the majority of the solar radiation would have been absorbed, would generally have been the warmest surface within the enclosure during the day. Heat transfer to the air in contact with the sand would have warmed a thin layer of air while evaporation would have increased its water vapour content. That would have made it slightly less dense and therefore liable to rise to be replaced by cooler air from above. The slightly higher temperature at the mid-height in E1 (Table 1) suggests that the upward movement of warm air may have stalled before it reached the roof of the tall enclosure. It is surprising that, in both E1 an E2, temperature was very slightly higher near the edge of the enclosure than in the centre. It is possible that this was caused by a convective eddy, upwardly moving warm air being pulled down again by the stream of cool air flowing down the walls of the enclosure. However, an alternative explanation is that slightly more radiation reached the sand towards the edges of the enclosures because condensation made the roof more reflective than the walls. Condensation occurred on the walls but tended to run off under gravity so that the walls were less uniformly covered with reflective droplets.

***Table 1. Vertical gradients of temperature and humidity over moist sand in enclosures E1 and E2. Air intake of the psychrometers were at the indicated height above the sand, in the centre of the enclosure A height of 185 in E1 or 85 in E2 required that the psychrometer was just touching the roof. Values are means for the period 12:00 to 16:00 BST of data collected over four days***

| Height, cm | Temperature, °C | | vpd, kPa | | vp, kPa | |
|---|---|---|---|---|---|---|
| | E1 | E2 | E1 | E2 | E1 | E2 |
| 10 | 26.95 | 27.41 | 0.34 | 0.36 | 3.34 | 3.42 |
| 85 | 27.41 | 27.77 | 0.50 | 0.48 | 3.30 | 3.41 |
| 185 | 27.19 | | 0.45 | | 3.29 | |
| greenhouse | 23.89 | | 1.43 | | 1.62 | |

***Table 2. Horizontal gradients of temperature and humidity over moist sand in the enclosures E1 and E2. Air intakes of the psychrometers were at 10 cm above the sand, including one outside the enclosure in the greenhouse. Values are means for the period 12:00 to 16:00 BST of data collected over four days in experiment 6.***

| Distance from edge, cm | Temperature, °C | | vpd, kPa | | vp, kPa | |
|---|---|---|---|---|---|---|
| | E1 | E2 | E1 | E2 | E1 | E2 |
| centre | 30.73 | 31.84 | 0.81 | 0.82 | 3.66 | 3.94 |
| edge | 30.90 | 31.99 | 0.94 | 0.92 | 3.57 | 3.88 |
| greenhouse | 24.54 | | 1.91 | | 1.20 | |

## Modelling the control of temperature and humidity

### *The original model*

At the start of this project, a hypothesis was put forward based on a simple conceptual model of the factors controlling temperature in polythene enclosures. The model envisaged that the temperature reached would depend on the balance of energy gained from solar radiation and the energy lost to the surroundings through the polythene. It was envisaged that, for a given solar radiation level and ambient air temperature, energy gain would be proportional to ground area, whereas energy loss would be proportional to the surface area exposed to external air, that is the area of polythene.

This model predicts that the temperature at equilibrium will increase as the external to floor area ratio (EFAR) decreases. The results provide some support for the hypothesis, those in Tables 1 and 2 being particularly reliable since they were obtained after the improvements to the psychrometers. Table 1 shows that the temperature in E2, with EFAR of 3.1, was about 0.5 °C higher than in E1, with a EFAR of 5.5. This difference is in the predicted direction but is much smaller than predicted. The model requires that the temperature lift be inversely proportional to EFAR, that is

$$Tl_2 / Tl_1 = EFAR_1 / EFAR_2$$

so that

$$Tl_2 = EFAR_1 / EFAR_2 \times Tl_1$$

$$= 5.5 / 3.1 \times (26.9-23.9)$$

$$= 5.3$$

(where $Tl_1$ and $Tl_2$ = temperature lift in E1 and E2 respectively
and $EFAR_1$ and $EFAR_2$ = the external to floor area ratios of E1 and E2 respectively)

This would have required that the temperature in E2 would have been 29.2 °C (i.e. 23.9 + 5.3) instead of the observed 27.4 °C. For the period covered by Table 2, when radiation levels were rather higher, the predicted temperature was 35.5 °C instead of an observed of 31.8 °C. These discrepancies are well outside the possible experimental errors and therefore indicate that the model is not close enough to reality to be of practical use. Further, the concepts underlying the model must be flawed. This is not unusual in modelling exercises which often help identify areas where current knowledge is incomplete or ideas incorrect. We therefore need to examine the assumptions implicit in our simple model to help identify where it is failing.

***Location of resistance to heat flow***

A major assumption was that the main resistance to heat loss would be the polythene and its boundary layers. In year 2 we examined temperature gradients within the enclosures to test whether air movement inside the enclosures might be so sluggish that this assumption was invalid. The extremely small temperature differences observed indicate that the resistance to transfer from the centre to the periphery was small and the original assumption was therefore correct. Ongoing experiments are using non-screened thermocouples, under controlled conditions and artificial light, to determine the temperature gradients within millimetres of the polythene and the sand. Preliminary assessment indicates that the measurable temperature gradient is confined to about 2 cm from the wall.

***A complete energy balance model***

Another assumption was that this was the only route for energy loss from the enclosures. In fact, some energy flux by other routes is expected but can generally be ignored for practical purposes. Some energy flows into the ground, resulting in soil warming. When averaged over 24 hours it can usually be disregarded but in the short term it could significantly reduce the temperature lift in the hottest part of the day. Other simplifications inherent in the original model are that the sand absorbs all incident radiation (i.e. no reflection) and that there is no net exchange of long wave radiation with the surroundings. To gain further insights into the underlying processes, and hopefully to explain the unexpected result, we attempted to estimate these terms.

*Soil heat flux*

In later experiments, soil temperature was measured at two depths in E1. The data from experiment 6, illustrated in Fig. 12 show that the temperature at 0.5 cm depth reached a maximum slightly above that of the air (measured at 10 cm above the sand surface) and slightly later in the day. The maximum at 3.5 cm depth was about 2 °C lower than at 0.5 cm, but the difference was reversed during the night. Extrapolating the temperature gradient to the surface yielded an estimated surface temperature between 12:00 and 16:00 h of 28.13 °C, which is 1.2°C above the average air temperature shown in Table 1. This difference is indicative of resistance to heat transfer through the boundary layer in contact with the sand surface.

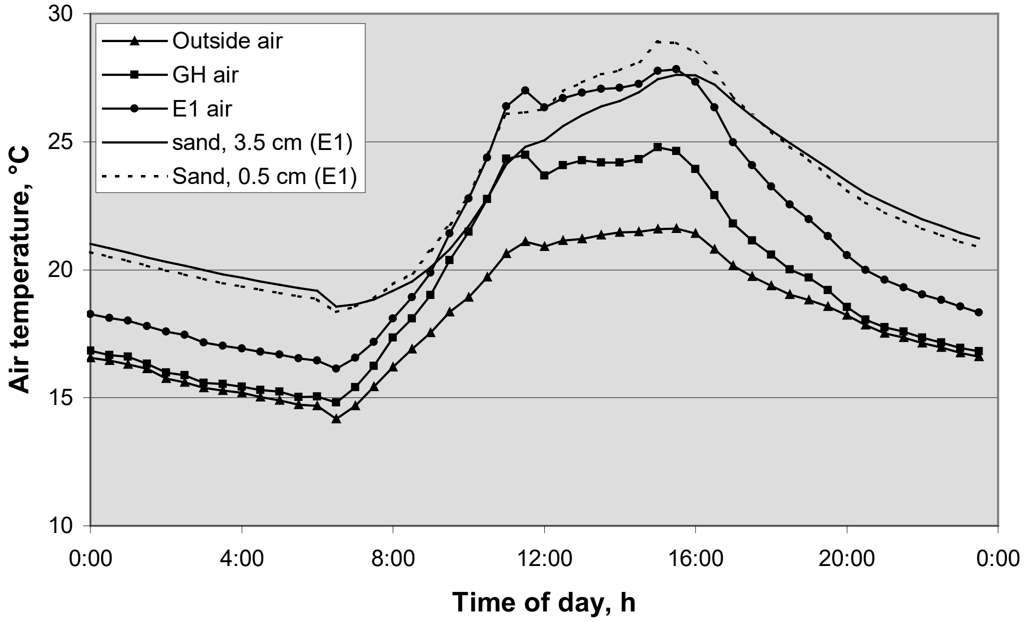



***Figure 12. Mean diurnal cycle of temperatures at depths of 0.5 and 3.5 cm below the surface in the sand under enclosure E1, compared with air temperature in the same enclosure, in the surrounding greenhouse air, and in the air outside. Based on four days from experiment 7.***

From the vertical temperature gradient in the sand it is possible to estimate heat flux into the sand. Assuming a thermal conductivity (k) of 1.8 W $m^{-1}$ $°C^{-1}$ (the value given for a sandy loan at 20% volumetric water content by Van Wijk and de Vries, 1963) and steady state conditions (not strictly true, but unlikely to incur large errors), then heat flux into the soil, G, is given by

$$G = k\ dT/dz$$

Values of this term are plotted in Fig. 13 along with other components of a full energy balance. The derivation of these terms is detailed below, using data for the period from experiment 7 summarised in Table 1.

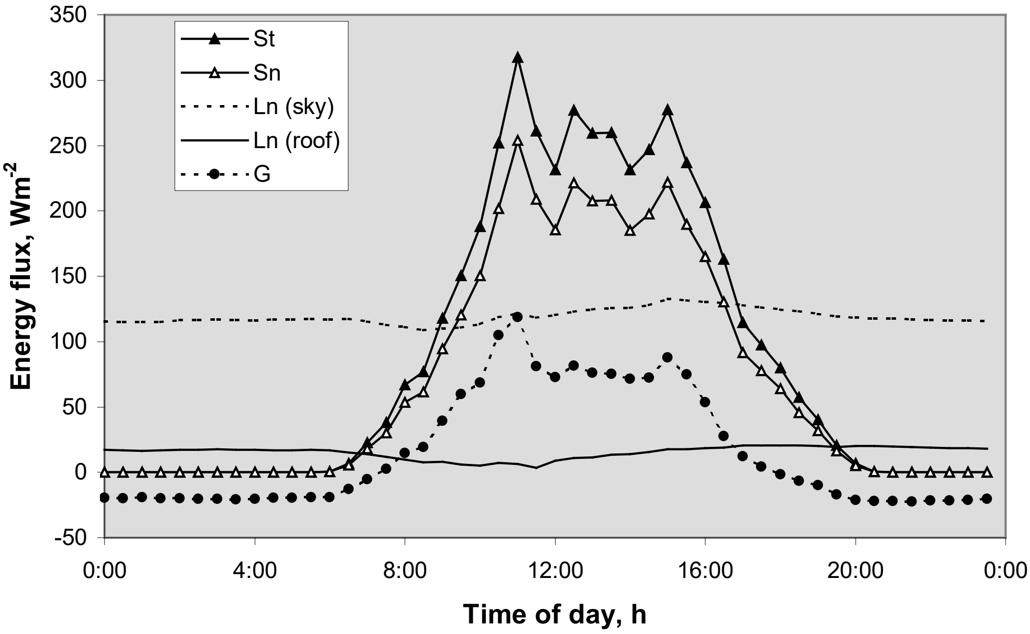



***Figure 13. Diurnal variation in components of the energy balance in enclosure E1. $S_t$ is the total incoming solar radiation, $S_n$ the solar radiation absorbed by the sand. $L_n$ is net long wave radiation loss to the surroundings based on two alternative main sources of downward long wave radiation into the enclosure (clear sky or the water condensed on the roof of E1, representing the extremes of what is likely to occur in practice). G is heat flux into the sand. The energy to be lost by convection is set by the difference between $S_n$ and the sum of all the other components. It is therefore highly sensitive to the actual value of $L_n$ within the two extremes shown. Plotted values are means based on four days in experiment 7.***

For the period covered by Table 1,

$$G = 1.8 \times (28.0 - 26.9) / 0.03 = 66 \text{ Wm}^{-2}$$

*Reflection of solar radiation*

Other components of the full energy balance that are not considered in our simple model are the loss of solar radiation due to reflection (r) from the sand, which is likely to be of the order of 20%. For the period in question, the estimated net solar radiation energy absorbed, $S_n$, is

$$S_n = (1\text{-}r) \times S_t$$
$$= 0.8 \times 221 = 177 \text{ W m}^{-2}$$

*Long wave radiation balance*

The contribution from long wave (thermal) radiation exchange to the energy balance is more difficult to estimate. Outgoing radiation from the sand ($L_u$) can be estimated accurately from its surface temperature using Stephan's law. For the period under examination,

$$L_u = \sigma T^4 = 5.57 \times 10^{-8} \times (28.1+273)^4$$
$$= 458 \text{ W m}^{-2}$$

where $\sigma$ = Stephan Boltzmann's constant

and T = the temperature of the radiating surface

The incoming radiation depends on which source of radiation in the surroundings is supplying the majority of long wave radiation intercepted. For crops outside, it is the radiation from the lower atmosphere that dominates and empirical methods of estimating it are well established. Since most polythene does not absorb or emit long wave radiation strongly, in a polythene structure the same may apply. It is least when skies are clear and the humidity low. Then

$$L_d = 1.2 \times \sigma T_a^4 - 171 \qquad \text{(Swinbank's formula, Montieth, 1973)}$$
$$= 1.2 \times 5.57 \times 10^{-8} \times (21.23+273)^4 - 171$$
$$= 330 \text{ W m}^{-2} \text{ for the period under examination}$$

However, all the enclosures became covered in condensation and water is a strong absorber/emitter of long wave radiation. Therefore, emission from that water probably dominated the downward flux of long wave radiation into the enclosure. The temperature of that water is unknown, but if it is assumed to lie half way between the air temperatures inside and outside the enclosure, then

$$L_d = \sigma T_a^4$$
$$= 5.57 \times 10^{-8} \times ((23.89+26.95)/2 + 273)^4$$
$$= 442 \text{ W m}^{-2} \text{ for the period under examination}$$

By subtraction, these figures lead to two alternative net losses of long wave radiation:

(i) if clear sky dominates $L_d$ then $L_n = 458 – 330 = 128$ Wm$^{-2}$

(ii) if condensed water dominates Ld then $L_n = 458 – 442 = 12$ Wm$^{-2}$

*Convection and conduction through the polythene*

This, in turn, leads to two estimates of the amount of energy to be lost by convection and conduction, C, through the polythene:

(i) if clear sky dominates $L_d$ then C = 177 – 66 – 128 = -17 Wm$^{-2}$

(ii) if condensed water dominates $L_d$ then C = 177 – 66 – 12 = +99 Wm$^{-2}$

These estimates of C indicate the energy that would have to be lost by convection to achieve energy balance to be consistent with the estimates of the other terms. The wide range of these estimates (chosen to represent extreme possibilities) shows how sensitive the system is to the long wave radiation balance and thus to which surface(s) dominate the downward emission of radiation into the enclosure.

***Implications of the analysis***

These figures, and the diurnal cycle shown in Fig. 13, illustrate the extent to which the original model was a simplification of reality, and point to important practical implications of understanding the long wave radiation balance more thoroughly. For example, any steps that can be taken to ensure that the enclosure 'sees' the long wave radiation from the sky rather than from the relatively warm surroundings of the greenhouse, will help maintain low temperatures in the enclosure. Such steps should also assist in maintaining a high humidity by reducing the temperature difference between the air in the enclosure and the polythene. It may sometimes be possible to achieve lower temperatures by using a twin skin on the roof of an enclosure so as to prevent condensation and thus maintain a long-wave window to the sky. Whether this could work would depend on other components of the system. Glass absorbs (and emits) long wave strongly, so that it would be inappropriate to in a glasshouse. Similarly, many shade materials may be incompatible with this approach.

The figures also indicate the potential importance of heat storage in the substrate. Insulation is widely used under propagation beds to reduce heat loss when bottom heat is operating.  This analysis shows that it may exacerbate the problem of high temperatures, particularly if there is no sand above the insulation to act as a short term thermal buffer.  However, when cuttings are in place, heat flux into the substrate will be more restricted so that the importance of this thermal buffering is likely to be less than suggested by Fig. 13, from which it follows that the temperatures experienced are likely to be higher.

More than anything else, this analysis demonstrates the potential practical value of attempting to summarise what we know in the form of a simple mathematical model which can be tested experimentally.

***An explanation of the small effect of EFAR ?***

Whilst the above analysis reveals the degree to which our original model was a simplification, it has not necessarily explained why the observed differences in temperature between E1 and E2 were not as large as predicted by the simple model. There is no reason to expect that heat lost by the alternative routes (i.e. by long wave radiation and heat flux into the ground) will be directly affected by EFAR, but it will increase as temperature rises in response to the restriction on heat loss by convection and conduction through the polythene.  It is impossible to determine whether these increases would be sufficient to provide an explanation without more precise data about these two pathways.  In particular it is important to determine whether the condensation on the roof of the enclosures does dominate long wave radiation exchange, and if so how its temperature relates to others in the system.

Only with such additional information, will it be possible to develop a more complete model, one which could be used to predict, for example, the effect of insulation under the propagation bed, or heat input during the night period, or the use of polythene with a different absorption spectrum, such a Luminance THB.  By further refinement, it should be possible to explain some of the details of the observed data that are lost in the summaries of Tables 1 and 2.  For example, Fig. 14 shows that the diurnal cycle of temperature lift in E1 and E2 lags behind that in their half-scale equivalents which in turn lags behind that of the greenhouse as a whole.  The more closely  a model fits all available data , the more confidence we can have in extrapolation to other situations.

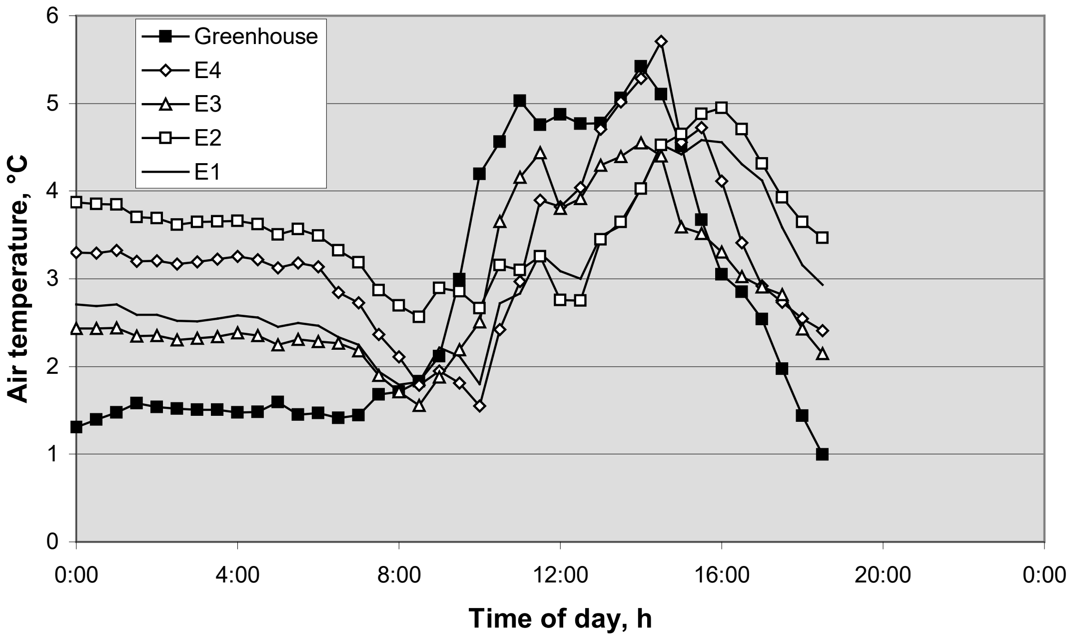



***Figure 14. Diurnal variation in temperature lift in enclosures E1 to E4, compared to that in the ventilated greenhouse around them, showing a phase shift of the cycle in E1 and E2 compared to their half-scale replicas E3 and E4, and the greenhouse. Plotted values are means based on 6 days of experiment 8.***

*Modelling humidity*

So far, no consideration has been given to the humidity component. The presence of condensation on the polythene indicates that some transfer of energy from the sand to the polythene is in the form of latent heat, i.e. heat absorbed when liquid water evaporates from the moist sand that is later released as it condenses on the polythene. Once a parcel of air has given up its water vapour to the walls and moved back into the bulk air, there is no opportunity for it to pick up more water vapour until it passes over the wet sand. For this reason, the bulk of the air in the chamber can be well below saturation. The close correlation of vpd and radiation seen in Fig. 10 suggests that the more energy that is transferred in this way, the more severe is the drying effect despite, presumably, heavier deposition of condensation.

However, since the movement of water vapour involves the same pathway and the same physical mechanisms as convective transfer of heat, the distinction between latent and sensible heat is of not major importance for the energy balance model for *sealed* enclosures. The same does not apply to a ventilated enclosure, and a more sophisticated model will be needed to predict the effect of ventilation in terms which can be applied to any structure, e.g. number of changes of air per hour. It is quite clear from experiment 5, that there is no opportunity to achieve significant reduction in temperature by ventilation without incurring massive loss of humidity. The opportunity to counteract this using injection of fog, will be examined in the next stage of the project.

## Conclusions

The main conclusions from stage 1 of the project are as follows:

- The temperature lift caused by a well-sealed polythene enclosure increases as its EFAR (external to floor area ratio) decreases. A decrease in EFAR is characteristic of increasing the size (i.e. the floor area) of a house or an enclosure.
- The effect of EFAR on temperature lift was much smaller than predicted of the grounds of a simple energy balance concept.
- A more complete analysis of the energy balance suggested that increased losses due to heat storage in the floor and long wave radiation exchange probably mitigate the effect of low EFAR on heat loss by convection and conduction.
- Further work to develop a robust model is needed. It will allow us to test whether our ideas about the processes controlling conditions in the propagation environment are correct. It will also provide a tool for optimising the design of structures for propagation that takes account of local conditions (e.g. whether it is to operate within an existing glasshouse, an existing polythene house, or is being designed from scratch with no constraints).
- There was no evidence of any advantage of the traditional approach to polythene enclosed mist, i.e. low tunnels over single mist lines, which make access difficult. Instead, air temperature and humidity were slightly more favourable in a structure of 'walk-in' height.
- Temperature lift was correlated with radiation level but the relationship was less close than expected ($R^2 = 0.5$). Further work is required to identify the other factors that are influencing the relationship.
- The humidity in the enclosures was very close to saturation at night but dropped during the day to as low as 70% rh (vpd = 2 kPa).

- There was a strong positive correlation between vpd within the enclosure and radiation ($R^2 = 0.9$). This implies that the more condensation was deposited on the polythene the *drier* was the bulk air inside.
- There was no reliable evidence that the scale of an enclosure (independent of EFAR) had any substantial effect on temperature or humidity.
- The temperature lift due to a 14 x 5.5 m polythene tunnel with all doors and vents closed was larger than that of the smaller experimental enclosures within it. This is attributed to more vigorous forced convection of the outdoor conditions against which it is compared.
- Any temperature or humidity gradients within the bulk air of an enclosure are minimal. Gradients are concentrated in the boundary layer very close to the walls and the floor.
- Hosing down inside enclosures did not in itself have any lasting effect on temperature or humidity. However, where previously completely dry surfaces (e.g. a concrete path) were generously wetted, temperature was reduced and humidity increased until the water had evaporated.
- Opening a vent which represented 0.13 % of the surface area of an enclosure (1 x 150 cm) increased vpd by 50% while having very little effect on temperature.
- Limited ventilation cannot be used to limit temperature rise unless some measure is taken to humidify incoming air, e.g. fog injection.

## Plans for future work

The results from **stage one** clearly indicate that the testing of a relatively large-scale walk-in version of polythene-enclosed mist should be the starting point for **stage two**. However, it is unlikely that misting alone will be enough break the correlation of vpd with radiation that was identified in stage one. Therefore, the potential for further improvement in the environment by supplementary fog should also be investigated as soon as possible.

The complexities of the environmental physics, and the technical difficulties that can arise in collecting high quality data, were amply revealed in stage one. However, the insights obtained are likely to have far reaching implications and it is important that this analysis is pursued further because an understanding of the fundamentals is the best foundation for reliable practical guidance. In addition to continuing to refine the model for the 'simple' enclosure (i.e. without cuttings or mist), and extending it to incorporate the effect of mist and fog, there is an additional factor that needs to be considered when cuttings are involved. This is the leaf-to-air temperature difference which, combined with vpd data, allows the leaf-to-air-vapour-pressure-difference (LAVPD) to be determined. LAVPD is the concentration gradient driving transpiration and accurately quantifies the evaporative demand perceived by the cuttings.

In outline, the experiments required for **stage two** are as follows:

- Measure temperature and humidity in a walk-in enclosed-mist system, covering ca. 4 x 8 m of an insulated sand bed. This will provide an initial check on the conclusions from stage 1 and an opportunity to ensure the system is working well before introducing cuttings to the system.
- Rooting experiments comparing the walk-in mist with the Agritech ventilated fog. Environmental monitoring systems to be extended to include thermocouples for measurement of leaf-air temperature differences on a representative sample of leaves in each environment and the temperature of the polythene/condensate.
- Add fog as a supplement (i.e. 'background fog') to the walk-in mist system and repeat the rooting experiments and environmental assessments.
- Continue the development of models to permit extrapolation of results to other situations. Amongst many components that need clarification, measurements with solarimeters and net radiometers to quantify the radiation environment in detail are the most important. Measurements will be made in the presence and absence of condensation, under a variety of atmospheric conditions, and shading arrangements.

# TECHNOLOGY TRANSFER

This project was outlined to growers at the Propagation Workshops held at HRI East Malling on 22-23 September, 1999. Certain aspects were discussed in workshops on grower holdings in 2000.

# GLOSSARY : terms, abbreviations and products used

**boundary layer** – the layer of air in contact with a surface within which flow of air is slowed down by friction between the airstream and the surface. The existence of the boundary layer phenomenon is evidenced by an increase in rate of air movement with distance away from a surface but there is no sharp distinction that defines the edge of the boundary layer.

**EFAR** – External to Floor Area Ratio

**evaporative demand** - an imprecise term referring to the power of an environment to evaporate water. It differs from humidity in that it takes account of the many other factors that influence evaporation, such as irradiance. For a more precise definition it is necessary to specify a particular evaporative surface e.g. a leaf - see also potential transpiration.

**irradiance** - a scientific term to describe the quantity of light, or other form of radiant energy, falling on unit area of a flat surface per unit of time, which in this report has usually been replaced by the lay person's term **light level**. The scientific term *light intensity* is often used incorrectly in place of irradiance. (Intensity refers to the quantity of light emitted by a source of radiation per unit solid angle.)

**long wave radiation** – (also known as terrestrial and thermal radiation) the radiation emitted by surfaces in our terrestrial environment. Being much cooler than the surface of the sun the wavelengths are much longer, mainly between 3 and 100 µm, with a peak at about 10 µm. The intensity of long wave emissions increases with temperature but also varies between materials and surfaces. Materials that have high emittance always have correspondingly high absorbance.

**PPFD** - Photosynthetic Photon Flux Density. A measure of irradiance confined to the wavelengths of light that are active in photosynthesis (i.e. 400 to 700 nm) and in the units that relate to its action in photosynthesis (i.e. quantum units).

**rh** – relative humidity is the water vapour pressure in the atmosphere expressed as a proportion of the vapour pressure of a saturated atmosphere at the same temperature. It is usually expressed as a percentage.

**solar radiation** – the short wave radiation that we receive from the sun, mainly between wavelengths of 0.3 to 3 µm. About 50% of it is in the visible waveband (0.4 to 0.7 µm). It reaches a maximum irradiance of about 800 W $m^{-2}$, with short-term peaks to about 1000 associated with reflection from clouds.

**stomatal conductance** – A measure of the ease with which water vapour can diffuse out of the lower surface of a leaf, and a function of the size of the stomatal apertures.

**temperature lift** – the difference in temperature between air in an enclosure and the air immediately outside it (i.e. temperature inside – temperature outside the walls of the enclosure). It can also be applied to a greenhouse and in many other contexts.

**vp** – vapour pressure, i.e. the partial pressure of water vapour in the atmosphere or other gas mixture

**vpd** – vapour pressure deficit, i.e. the difference between the water vapour pressure and the saturated vapour at the same temperature

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