Energy Conservation in Protected Agriculture and the Future of the UK Glasshouse Industry

by

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Abstract

The glasshouse industry in the UK faces severe problems of rising fuel prices and foreign competition. Greater efficiency in the use of energy would improve the outlook for the industry. Low temperature growth strategies and organisational approaches to energy saving are being investigated but methods that involve changing the physical aspects of the system are being more widely used. Further development of these physical methods is hampered by the cost of trials and the time needed to carry out the experimentation. Accordingly a computer model of the thermal behaviour of a glasshouse was produced for use as a tool to investigate methods of energy conservation.

The model (GHFORSM) was constructed in a modular form allowing routines to be added or amended with ease. It uses a series of component layers to simulate a representative square metre in the middle of a glasshouse array. The flows of energy into through and out of the system were modelled to allow the component temperatures and internal environmental conditions to be calculated. The model user can assign values to any of more than one hundred system parameters. A double glazed roof, a thermal screen and a heater designed to maintain the inside air temperature at a level defined by a bluprint regime can also be simulated. Unlike previous glasshouse models GHFORSM can be used to examine a wide range of physical conservation methods and assess the benefits of different management strategies. The model can use external meteorological data and can produce output ranging from a single measure of daily heat requirement to a detailed listing of more than one hundred environmental variables. Thus GHFORSM can show the effects of conservation methods not only on the daily heat requirement but also on other components of the internal environment.

Several runs of the model were carried out to investigate the effects of changing some of the system parameters on the heat requirement. It was found that changing the emissivities of the cladding material and of the soil surface, and also the inside convective transfer coefficient had the greatest effect. Changes to the air leakage rate and the outside convective transfer coefficient had an effect but not as large as those listed above. The cladding extinction coefficient was altered to show that the model was capable

of detecting small changes. Finally, several runs were undertaken using ten year weather data from two sites (Kew in London and Eskdalemuir in Scotland) to compare the benefits of using combinations of thermal screens, double glazing and low emissivity glass. It was found that energy conservation methods save more energy under conditions at Kew, but the higher energy requirement at Eskdalemuir makes the installation of these methods more attractive in terms of investment. A thermal screen saved more energy than double glazing for longer during the year at Eskdalemuir than at Kew.

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Introduction

The technologies currently available for harnessing solar energy such as flat plate collectors and photovoltaic cells are often thought to be of only limited use in the UK. The relatively low intensity of solar radiation and the changeable weather ensure that these devices are not as widely used in this country as they are in others, such as Israel. It is possible to find a few buildings and houses with collectors clustered on their roofs but until a device is developed which can work efficiently in our climate, the use of solar energy collectors will be limited and the widespread belief that solar energy is only of use elsewhere in the world will persist. However, agriculture has been successful in using solar energy profitably, and since the middle of the nineteenth century the glasshouse industry has used solar energy not only for photosynthesis but also for heating the growing environment. In 1981 glasshouse growers produced goods valued at some 60 million which might otherwise have been imported (Financial Times, 24 November, 1981)

The glasshouse environment is controlled so that crops can be harvested for much longer than their outdoor counterparts and some crops are grown in glasshouses which could not be grown outside, exposed to the UK weather. The sun plays a major part in this process; as well as the direct use of solar radiation by the plants in photosynthesis, the sun's radiation is trapped within the confines of the structure and heats up the growing space. But the glasshouse industry is now in decline, having faced severe problems since the early nineteen seventies, and the whole future of the UK and Channel Islands industries is in doubt.

The most important problems have been increasing fuel costs and stiff foreign competition. These are of serious concern to most industries, but for the glasshouse grower whose fuel bill represents up to forty percent of the costs of production, such problems can be the death knell. One consequence is that growers need rapid and precise advice on how energy savings can be made. Here computer models of the thermal behaviour of a glasshouse can be of use in providing quick evaluations of different possible physical alterations. I have produced such a model in order to investigate the benefits of such energy conservation techniques as thermal screens, double glazing or alternative cladding materials such as low emissivity glass, or new heating or management strategies.

The model simulates the thermal behaviour of a representative square metre inside a glasshouse by examining the energy exchanges between the various component layers which make up the system. Each component the roof, inside air and floor for example, can be defined by the model user who assigns values to the parameters of the system. The model makes use of external meteorological data and can be altered to accept such data at different time intervals, but it can also generate its own solar radiation figures if required. The model, GHFORSM, contains the facility for including a secondary cladding layer and/or a thermal screen, and heating can be applied to provide the correct amount of heat to maintain the inside air at a given blueprint temperature.

Computer modelling is becoming a much more widely applied research tool as the cost of computing decreases. A discussion of computer modelling in general and the problems of validation is included in the thesis and the applicability of this type of modelling to the glasshouse problem is considered. Also, the future of the industry is examined in the light of the limited amount of investment which is likely to take place.

Previous Work

Previous work involving computer models can be divided into three categories: 1) investigation of the general glasshouse environment, 2) studies of specific energy transfer or conservation techniques and 3) studies of glasshouse climate control routines.

The general glasshouse environment

Bot (1980), Bot and van Dixhoorn (1979) and Bot Van Dixhoorn and Udink ten Cate (1978) produced a computer model of the glasshouse climate dependent upon the outside weather conditions. The important physical processes were quantified and linked together but in the absence of a complete knowledge of the heat transfer processes in the glasshouse it was found that some of the parameters had to be estimated. This is a problem often encountered in glasshouse modelling work which is heightened because the parameters pertaining to one site or one type of glasshouse may well be unique; forced convection coefficients are a good example of this.

The nocturnal heat loss of a plastic clad greenhouse was modelled by Garzoli and Blackwell (1981). This model would probably have had difficulty in simulating the ground heat flux as it did not include any solar radiation input. They assumed that a fixed inside air temperature was the main plant requirement. However, the ability of a model to detect other environmental changes such as humidity level is important as well. During the course of their work they found a wide range of values for some of the parameters which describe the heat transfer processes.

A model produced by Kimball (1973) used an energy balance approach. It generated its own solar radiation data but could not use measured values directly, in order to investigate the effects of shading and evaporative cooling methods on the internal glasshouse environment for conditions found in Arizona. There was also no facility included for providing heating to the inside air. As conditions in the south-western USA are so unlike those of northern Europe the results of this study are of little benefit to growers here, where heating rather than cooling is required. The study was more concerned with finding methods of keeping excess energy out of the glasshouse rather than trying to reduce heat loss.

Van Bavel et al. (1979) described a glasshouse computer model which, as in the model described in this thesis, simulated a representative square metre in the middle of an infinite glasshouse. However, its use was restricted to investigating the behaviour of a hollow roofed structure with a fluid circulating between the roof layers that would act as an energy storage medium. Further work was reported by Damagnez et al. (1980). In this system the glasshouse was considered to be a large solar collector: the fluid in the roof allowed those wavelengths of solar radiation required by the plant to be transmitted, whilst the energy of some of the non-photosynthetically active radiation was stored for later release. However, the heat transfer coefficient between the roof and the outside air which they used was inappropriate for the windspeeds with which the model was tested (Iqbal and Khatry, 1977). The model was also used to investigate conditions in the south-western USA and has been used to simulate glasshouses under conditions found in France. However, the model can not readily be used to investigate different energy conservation systems apart from the fluid roof case for which it is specifically designed.

A model used to predict the energy savings which might be made through the use of fuel conservation systems such as thermal blankets and solar energy storage devices was developed by Rotz et al. (1979). They used ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers) heat transfer relationships. An overall heat loss coefficient for the glasshouse was derived but no mention of heat exchange with the soil was made. They also state that at night the only heat flows modelled are those due to conduction through the cover and air leakage. By ignoring exchange with the soil at night they are possibly over-estimating the amount of heating required.

A simulation model to describe greenhouse energy flows was developed by Duncan et al. (1981). However, only readily available weather data and greenhouse parameter values are required and thus the ability of the model to simulate a wide range of energy conservation methods is limited. For example, an average value of glasshouse transmittance to solar radiation was used and U values were increased to take account of transmission of thermal radiation by plastic cladding. They found that their model results compared quite well with measured data but the simulated heating requirement was some 8.9% lower than when calculated from conventional degree-day data.

Finally, Seginer and Levav (1971) reported on the work carried out in the first year of an investigation into the possibilities of using laboratory and computational models to aid greenhouse design, a study which was discontinued. They discuss the equations describing the heat exchange in glasshouses and then describe some tests which they made on a sealed greenhouse model to measure some of the energy balance values required by the computer model. They found that some of the measurements were an order of magnitude different from those found in the literature and could find no apparent explanation for this.

Specific energy transfer and conservation models.

The approach used in this area is to identify a specific area of interest and model it in detail, disregarding other energy transfer pathways or incorporating them in as simple a way as possible. In this way Caffell and McKay (1980) developed a computer model of a heat storage system using mud, designed to simulate the requirements of a glasshouse in eastern Canada. The model was used to determine the size of heat store, dependent upon the glasshouse design, operating temperature and presence of a thermal screen. Their simulations did not include heat loss to the ground and only modelled one transfer pipe, although they do mention that the design and layout of the 150 or so pipes which might be needed in practice, would be important in the consideration of heat loss. Yianoulis (1980) investigated a similar problem in simulating a solar energy heat storage system under Mediterranean conditions. The glasshouse heat losses were derived from average values and although this was suitable for the sort of investigation he was carrying out, it would not provide detailed information on the inside environment.

A number of researchers have investigated the transmission of light into glasshouses. Critten (1983) developed a model which calculated the daily light integral and transmissivity of a greenhouse, including multiple reflections, attenuation by glazing bars and shadowing. Excluding the internal structure, reflection from the floor attenuation in the glass, and dirt on the cladding, the model gave a light transmission curve which compared well with the measured data. but was some 15% higher. Inclusion of a subsidiary model which handled the blockage of light by the internal structure gave a much closer fit with the measured data. As an investigation of glasshouse transmission this work appears to have been successful, but the computer model was detailed and took several hours to run. Such a detailed consideration of the overall glasshouse climate would not be possible if the model was to run in a realistic time. and for this work to be included in more general models it would have been useful if Critten had identified a set of transmission coefficients for different shaped structures and sky conditions.

The amount of radiation present inside a glasshouse as a function of its shape, orientation and cladding material was modelled by Kirsten (1973). He found that glasshouses positioned in the east-west direction had the greatest transmissivity and saddle or shed roofed structures also had a small advantage in this respect. In winter, the free-standing single ridge glasshouse had superior radiation characteristics than the multi-ridged block. Kozai and Kimura (1977) also investigated the light transmission of glasshouses finding that the east-west orientation gave a greater flux, whereas the north-south orientation gave an overall reduced flux but more even radiation distribution.

Ventilation inside a glasshouse has been studied by Kozai and Sase (1978) and Kozai, Sase and Nara (1980) using both computer and physical models. Glasshouse ventilation depends upon a number of factors such as wind velocity and the shape position, number and opening angle of the vents and their model compared well with recorded data but could not be used to study varying wind speed conditions, and contained no natural convection inside the glasshouse. They suggest that a sub-model approach to glasshouse modelling might be a good way of investigating the problem of glasshouse design. Tantau (1980) developed a general model to investigate the dynamic behaviour of the glasshouse system with a view to investigating control strategies. One problem was that of modelling the non-linearity of heat transfer by ventilation. For control purposes it is important either to model such areas well, or understand where deficiencies in the model are likely to cause problems.

Glasshouse heating has been modelled by Kanthak (1970). Like other models simulating heating systems a large number of energy transfer factors were included. Kanthak was particularly interested in pipe and air heating at different levels inside the glasshouse, finding that the use of heating pipes at crop height required about 25% more heat than pipes sited at ground level which gave a better heat circulation amongst the plants themselves. However, there is no indication that his model could be used to investigate different blueprint temperature strategies and it may be that it is more important to find a heating system which can maintain a bluprint regime efficiently rather than trying to find which system loses energy the most readily.

A model was used by Manning and Mears (1981) in the design of a heating system for a glasshouse which used waste heat from a power station. They found the use of a model valuable because it helped them to identify the benefits of various innovative heating system configurations and control strategies. The heating system was required to maintain a fixed temperature above that of the outside air and again there was no indication of how efficiently it might cope with meeting a varying blueprint regime. A similar study was carried out by Rotz and Aldrich (1979). Their work mainly involved the study of heating systems and of the economics of the various strategies. It was found that three of the systems provided good cost savings (ranging from 37 to 51%) and pay-off times which varied from 4.8 to 6.6 years. These figures do make such schemes appear attractive but there are other factors such as the continuity of supply and the maintenance of backup systems to consider as well. Waste energy use will be discussed in a later chapter.

Glasshouse climate control

The third class of models have been used to study glasshouse climate control. Some have already been referred to (Tantau (1980), Manning and Mears (1981) and Bot et al. (1978 and 1980)). Bot et al. (1978 and 1980) used a systems approach to study the plant production process and suggested that the system can be controlled to produce 'optimal' performance. Much of the work in this field has been carried out by Dutch workers and Udink ten Cate (1983) has recently reviewed the control problem. The rapid introduction of glasshouse computers in the Netherlands, in contrast with other areas of the world, can be explained by the high level of automation in glasshouse control which is already present. The constantly changing weather conditions have meant that vent and heating system settings have to be altered often if a blueprint temperature strategy is to be maintained. As glasshouse growing is carried out on such a large scale in the Netherlands high levels of automation reduce the man-power needed. When control procedures became widely used, expense of analogue control mechanisms and the decreasing cost of computer equipment paved the way for widespread computer installation. Udink ten Cate reviewed some of the simple glasshouse environment models and suggested that software packages for glasshouse climate models should be developed and he stressed that these should include latent heat fluxes.

Bot, van Dixhoorn and Udink ten Cate (1978) outlined a general opinion on potential computer applications in glasshouses. Control methods can be applied to affect the the instantaneous glasshouse climate, the short term plant growth and the long term crop development. The instantaneous glasshouse climate affects the crop growth and the grower aims to control this instantaneous climate so that both the short term crop growth and the long term crop development are optimized. Before analogue and computer control the climate would have been controlled by the grower himself by setting heating blueprint values and opening vents to what he considered the correct amount. By implementing new blueprint strategies as the crop developed and the season progressed, he would try to produce a healthy crop and a good yield at the right time of the year. Now, the computer can handle the control of the glasshouse climate and the discussion is about the sort of algorithms which are most efficient at doing the job. The immediate problem with which Udink ten Cate et al. (1978) were faced was that knowledge of the dynamic behaviour of the glasshouse system was very limited. Even advanced controls tended to be based on rough and ready relationships and on growers' experience and this sometimes has meant that the controller behaves unpredictably in unforseen circumstances. Too often it has been thought that control algorithms can be developed from existing knowledge, whereas in their experience of glasshouse control this is not the case.

In the same paper (Udink ten Cate et al. 1978) models which simulate some facet of the system mentioned in the preceeding paragraph are also discussed. Although knowledge of the physical interactions of the glasshouse climate is required for thorough work to be done, there appear to be 'blind spots' in this knowledge. One task a model might be able to perform would be to point out the significance of measurements made on components which are not commonly measured, cladding temperature for example, either for the development of new measuring strategies or to discover factors of importance to crop growth.

Hashimoto (1980) referred to earlier Dutch work and studied the 'speaking plant' approach to climate control. This method requires measurements such as the electrical capacitance of the stem (to determine the water content) to be made on the plant. By monitoring the plant's responses to changes in the climate, the short term plant growth can be maintained at an optimum level. He suggested that leaf transpiration could be controlled instantaneously by the use of one small computer, running fairly simple software. Seginer (1980) considered the overall control of the glasshouse environment and suggested that discussion about control of the aerial environment has often been limited to air temperature. Although important other factors, such as CO_2 concentration and relative humidity, are also important. Seginer maintained that there were two stages to the optimisation process: 1) calculating the economically optimal set of environmental conditions (if the grower is trying to maximise his return) and 2) developing a control algorithm which would adequately maintain the settings calculated in step 1.

The control programs designed to manage the glasshouse environment appear to be in their infancy. Some of the Dutch work (Udink ten Cate 1983) develops routines which try to force the inside air temperature to follow sharply stepped curves, of the sort indicated on blueprint temperature strategies. An easier approach in computing and heating terms would be one of trying to follow smoother temperature blueprint curves as it is more difficult for a smaller computer to handle abrupt changes in direction.

Relevant work not specifically carried out for glasshouses

In addition to the work outlined above much work has been carried out for purposes other than the study of the glasshouse environment but may be relevant. Thus Gimmestadt et al. (1982) modelled the convective radiative and conductive heat exchange between a body and its environment. Waggoner and Reifsnyder (1968) studied the temperature, humidity and evaporation from a leaf canopy. Luxmoore et al. (1981) studied the sensitivity of a soil-plant-atmosphere model to changes in the dew point, air temperature and solar radiation. Littler (1979) investigated the thermal balance on heat reflecting windows, and quoted figures of U values of various combinations of double glazing surface coatings and gases between layers. Parton and Logan (1981) developed a model of the diurnal variation of temperature in the soil and air, based on average values of climactic temperature. Wolf et al. (1981) studied flat plate collectors, carrying out dynamic simulation and parametric sensitivity studies on them. They sum up modelling neatly, saying that the building of physical models is generally expensive but once validated, a computer model can save time and money and allows the user to study the effects of a change in value of a single parameter. The important phrase here is 'once validated' and this problem will be considered in more detail in a later chapter.

Mention will also be made in later sections of this thesis of other relevant glasshouse work which has not involved computer modelling to any great degree. Looking at the more specific conservation and heat transfer models, we find again that much of it has been aimed at investigating one particular problem, under specific conditions for certain parts of the world (Caffell and McKay, 1980; Yianoulis, 1980; Kozai and Sase, 1978; Kozai et al., 1980 Manning and Mears, 1981; Rotz and Aldrich 1979). Output in these cases was often in the form of costs and pay-back times. Other results might have been difficult to apply to glasshouses in general, without a fuller consideration of the heat transfer interaction between all of the components of glasshouse system. The Japanese workers who investigated glasshouse ventilation understood such problems inherent in their models and suggested that the sub-model approach to modelling would be sensible. In this way each section could be handled in as much detail as was considered necessary or current knowledge allowed. For models with heating systems no indication was given as to how the heaters behaved when a varying inside temperature was required and it is not clear whether any of these models would allow various heating strategies to be investigated.

Discussion

It is difficult to say, merely from reading the references, how complete many of these models were and how much output they produced both in terms of volume and variety. There seems to have been a general interest in modelling the temperature of the inside air which is understandable because this is probably the most important factor. However, as Seginer (1980) points out, other factors are also important and should be considered in more detail than is generally found.

The model presented in this thesis was designed to simulate the thermal behaviour of a glasshouse system. It was written in a modular way as suggested in work by Kozai et al. (1978 and 1980) so that each section of the heat transfer could be handled separately, and other parts of the system could be slotted in as required. This approach made the checking of the program easier because each routine could be developed before being included within the overall framework of the model itself.

The major differences between this model and the others I have reviewed is that it was specifically designed to enable several different energy conservation methods to be tested; any of over 100 system parameters can be altered. The heating system provides the amount of energy needed to meet a definable blueprint temperature regime. This allows such regimes to be tested in conjunction with any of the energy conservation methods and is thus useful in the examination of control methods. The other great advantage of this model is that it has been developed for use on a large mainframe computer. Taking advantage of the speed and computing power of these machines enables the model to use real weather data in the simulations rather than having to use generation routines. An advantage of the large number of parameters which can be set is that other types of structure such as warehouses can be investigated quite easily.

One other difference concerns the information produced by the model. Although one sometimes has an intuitive idea of how a particular energy conservation technique is going to affect the environment, this is seldom known in detail and so the model was designed to produce output covering almost every environmental factor. The user can cause the values of over one hundred variables to be printed out by calling the various print subroutines at the end of a run. Such a complete print section was included both to aid verification and validation and to show how the whole environment may be altered by the introduction of some conservation measure. The importance of environmental factors other than the inside air temperature has been considered by Seginer (1980) and Udink ten Cate et al. (1978) in the references discussed above.

The problems of finding correct parameter values which were outlined by Bot (1980) has meant that some parts of the system are modelled more fully than others. This was inevitable given the present state of knowledge and the limited measuring programmes which have been carried out. The time and computer space available was also a limiting factor. For example, Critten's (1983) light transmission model required a long time to run, involving integration over hemispheres, and it would be difficult to construct an overall glasshouse model to this same degree of complexity given the time and space available. As discussed in later sections of the thesis, parts of this modelling approach were more successful than others, but one of the important results of the work has been the development of a framework for a glasshouse model. Some areas of the framework have been 'filled in' more satisfactorily than others but future work, both in modelling and in the measuring of parameter values, might carry the work further than has been possible at this time.

The thesis begins with a general background to the history of glasshouses and the present state of the industry. The energy transfer pathways are described and the general equations that make up the model are presented. Then the verification and validation process is discussed and the results and conclusions are presented.

Chapter One

The Glasshouse Industry

Protected cultivation has been used in Europe since the sixteenth century, although in the early days this amounted to little more than putting plants in sheds or heated houses during the winter. In the seventeenth century the construction of orangeries began and some of these had stove heating and vertical glass panes in the southern wall (Muijzenburg, 1980). After industrial methods of sheet glass manufacture were developed protected cultivation began to expand from the mere forcing of crops in the gardens of the landed gentry, but it was not until the mid-nineteenth century that commercial glasshouse use began in the Lea valley, at Hampton in Middlesex, at Swanley in Kent and at Worthing on the South Coast of England. (Spedding, 1983; Winspear and Canham, 1974).

Throughout the twentieth century the industry has developed dramatically and the glasshouse structure has changed as new materials have become available and new ideas have been implemented. Glazing bars and structural members are now made of aluminium rather than wood, ventilating systems are operated automatically with the aid of sophisticated electronics rather than by hand, and some crops are not even grown in soil at all.

To produce early crops, glasshouses have to be heated during the coldest months, and earlier in this century this was done using coal fired boilers. Now, of the total heated glasshouse area in this country, about 1471 ha, over 80% are oil fired and the remainder burn gas. However, a growing number are returning to coal burning (Schaffer and Clarke, 1984). One Guernsey grower used coal originally but switched over to oil in the days of cheap fuel; now he has changed back to using coal again. This change back to coal is not yet common although many growers are giving it consideration. The Channel Islands glasshouse industry has unique problems which will be considered later.

The UK industry has come a long way since the early times, but now, despite the prevalence of technological innovations such as micro-processor control and the nutrient film technique it faces decline. Why is this so and what can be done to help it?

The Use of Glasshouses

On the majority of farms the yield from outdoor crops, and thus the farmers' livelihood, depend upon the vagaries of nature (although it might be said that the the farmers' well being depends more upon the EEC Common Agricultural Policy than anything else). Too much rain and the crops may rot in the fields too little rain and the yields are low an untimely frost or pest infestation can cause thousands of pounds of damage. Using glasshouses the grower can almost completely control such environmental factors as the temperature, the water supply, the nutrients, the humidity and the carbon dioxide concentration and under the protective cover pests and disease can be controlled and treated thus keeping the crop healthy. By controlling these conditions the grower can produce his crop at the best time so that his produce reaches the market when the prices are best. Consumers are willing to pay much more for some out of season glasshouse crops than for the same crop 'in season'. Glasshouse tomatoes for example, are often larger and 'better looking' than their field counterparts, although many people would say that they do not taste as nice.

Whilst it is technically possible for the grower to control the crop's growing environment completely, in practice, were he to install all the latest equipment to control every last detail of the environment he would find the cost prohibitive. The grower has to decide which combination of equipment is best suited to his needs, allowing him to make a reasonable return on his investment. The type of equipment that he installs depends upon the crop he intends to grow. For example, whilst it might be sensible to have artificial lighting and shading for flower production for the Christmas market this would not be justified for the tomato crop. Further, if he wished to remain flexible in the crops he was able to produce, then he would have to decide which equipment would give him this freedom.

The Problems of the Glasshouse Industry

In the UK in the nineteen-eighties the glasshouse industry faces two problems common to much of the rest of British industry; rising energy prices and foreign competition. Included with this discussion of the UK industry's problems will be a consideration of the Channel Islands horticulture industry because Jersey and Guernsey, the two major producers face problems similar to those faced by the UK industry. In the past the islands have been successful at exploiting their slight geographical advantage and have sold their produce on the UK market for good returns. However, their problems are somewhat more severe because all fuel has to be imported, and their non-membership of the EEC makes their trading position precarious. Furthermore, the establishment of the islands as world financial centres has meant that agriculture has lost some of its importance to the islands' economies and the free flow of EEC produce into the UK has limited the size of their market. To illustrate the extent of the decline, a fully automated, five year old vinery (the local name for a glasshouse 'farm') was put up for auction in Guernsey recently and the only bid received was one of £10,000, less than the value of the glass alone. This year only about 250 acres of tomatoes are being planted in Guernsey compared with about 1000 acres in past years (Financial Times, 16 February, 1983).

Returning to the problems of the UK industry, we can look in more detail at both the rising energy prices and the foreign competition. Agriculture in all forms accounts for about 3-4% of the annual UK energy requirement but produces approximately 50% of the nation's food. The glasshouse industry uses about one third of the agricultural petroleum requirement the remainder being used by tractors and other farm equipment (Bailey, 1979; Spedding, 1983). About 45% of the UK tomato consumption is now produced in this country. As glasshouse production is so energy intensive, and because the vast majority of growers use oil to heat their houses, the oil price rises of the early seventies affected glasshouse growers more than farmers who produce outdoor crops. Taking the price rises of recent years into account, and notwithstanding the fall in the price of oil in early 1983, the total energy bill can now represent up to 40% of the total cost of tomato crop production (Bailey, 1979; Wass, 1982).

The whole problem is highlighted still further when one considers that glasshouses have been designed for maximum light penetration and the conventional single layer of glass cladding means that heat retention is poor (Bailey et al. 1976). The industry developed in the age of cheap fuel when all the grower had to do in a cold season was to burn a little more oil, at small additional cost to maintain the required temperatures. Once a crop has been planted, the air temperature must be maintained at a certain minimum level in order to keep it alive, and if the grower wants any reasonable return then he must follow certain blueprint heating strategies to ensure that the crop thrives. If he has to stop heating in February because the oil company will not extend any more credit for example the crop may die and all will be lost

As energy prices rise the problems of the industry will increase as there are alternative sources of supply for most of the crops. During winter and spring tomatoes from Morocco and the Canary Islands. and new potatoes from Egypt and Cyprus are on sale in this country. Since these are produced outside. the only fuel related cost increases are transportation costs. which are lower than those which the glasshouse grower incurs. For the glasshouse grower, cost and availability of fuel will remain the major problem and energy efficiency will have to be maintained (Spedding 1983). However. amidst all this gloom, it is important to point out that during the seventies the fuel problem was tackled well by the UK growers and tomato production rose from 108,000 tonnes in 1970 from 1020 hectares to 134,000 tonnes in 1979 from 960 hectares. This represents an increase from 31% to 45% of the UK demand (Winspear 1980). Oil consumption has also been reduced by 21% since 1973, achieved through improvements in control and optimisation, reduction of heat loss from the structures and overall improved efficiency (Spedding, 1983).

Rees and Hand (1980) suggest that future improvements in efficiency of production will determine the future profitability of the glasshouse industry since it is unlikely that the increased production costs (an 8-9 fold increase in the price of fuel oil during the seventies) can be recovered from the market-place alone. That such improvements in efficiency of the industry are possible can be seen from the figures quoted above.

Foreign Competition

The problem of importation applies not only to outdoor crops competing with UK glasshouse crops but also to foreign glasshouse crops being brought into this country. The main source of imported glasshouse produce is The Netherlands and since the nineteen-fifties nearly one quarter of the world's acreage under glass has been sited in that country. In its physical characteristics the Netherlands differs little from the UK but the Dutch industry does have an advantage derived from its geographical position near to the large, prosperous markets of Western Europe. There are good land-based communications links with these markets (road and rail networks) and this ready market for its produce has encouraged the Dutch to expand. As the industry has grown in size it has become an increasingly important part of the Dutch economy and its future prosperity and survival has been given a high priority by the Dutch government.

The UK industry is much smaller, producing goods mainly for home consumption, and is not so important to the UK economy. Consequently the long history of governmental support and aid which the Dutch industry has enjoyed has not been reflected in the UK. In recent years Dutch support for the industry has manifested itself in the form of fuel subsidies. Growers in the Netherlands have been able to buy natural gas cheaper than their UK counterparts have been able to buy heavy fuel oil, thus benefiting not only from the reduced cost of this energy but also from the greater efficiency with which natural gas can be burnt. As well as subsidies, the Dutch growers have received support in the form of good state advisory, teaching and research services, and the co-operative auctioneering system has enabled them to specialise on small numbers of varieties and still be certain of selling their crops (Muijzenberg 1980). In the UK advisory and research services exist but Dutch growers seem to be more willing to try new ideas such as introducing computer control into glasshouses. In fact, so successful has this been in recent years that by the middle of 1979 over 1000 units had been sold to growers (Valentin et al., 1979) and by 1983 over 2500 glasshouse computers were in operation. These ranged from central minicomputers with many user functions to smaller units which replaced more conventional equipment (Udink ten Cate, 1983). Taking all this into consideration it is not surprising that the Dutch industry is flourishing. A measure of its success is that it can afford to produce tomato crops in the Netherlands and transport them across Europe to Italy, at a profit.

Although at present the main foreign competition in the UK comes from the Dutch, this may soon change. It has been estimated that in energy terms the cost of transporting an outdoor crop from Spain to London is about one tenth of the amount required to grow the same crop under glass in this country (Winspear 1980). As the EEC expands to include both Spain and Portugal, the situation could become more difficult for the UK grower, and it would appear that already there are some Dutch growers showing an interest in Spain with a view to producing there. It also seems unlikely that there will ever be anything other than limited government aid to growers in the UK (Winspear, 1980) and the research going on at present may be too little and too late to be of any benefit to some growers

Remedies

It is not easy to decide which factor, rising energy prices or foreign competition, presents the greatest threat to the UK industry; both have to be overcome. The more traditional ways of dealing with foreign competition, import tariffs and restrictions, are not acceptable between members of the EEC and so the competition has to be overcome by other means. It can be argued therefore that tackling the rising energy price with improved productivity and greater efficiency is the only way of trying to overcome competition. But it is certain that the Dutch will be striving towards these goals as well.

The EEC Commission has brought pressure to bear upon the Dutch government to reduce fuel subsidies to its growers, which it has agreed to do in a phased manner In order to go part of the way to reducing the advantage gained by the Dutch from this subsidy the EEC Commission has agreed to allow member countries to subsidise their own horticultural industries in a limited way. Accordingly, the British government granted a sum of £5.5 million to reduce the 1981 price of fuel oil by 5 pence per gallon, and that of gas oil by 8 pence per gallon, the maximum allowed by the Commission. For 1982 these subsidies were reduced to 3.5 and 4.7 pence per gallon respectively, as the Dutch subsidies had been reduced as well (Financial Times, 24 November, 1981).

Jersey growers received the same subsidy as their UK counterparts but this did even less to help them. The only oils imported into the Channel Islands are the lighter more expensive grades, and so subsidies at the same level as those offered to UK growers proved to be even more limited in reducing costs. However, although the major oil companies have always insisted that heavy fuel oils were not suitable for the Islands' glasshouse industries and have never imported it, Guernsey growers have set up a growers' co-operative, Guernsey Fuel Oils, to import and market the heavy oil. More than forty of the island's growers have switched from using the lighter grades to using the heavier one which is more widely used in the UK. There are also loan subsidies available from the States (the Guernsey government) to help growers to convert their boilers to heavy oil burning (Financial Times, March 2nd 1983). In Jersey, growers who bought their own relatively small quantities of oil did not qualify for any bulk discounts, but now it has been proposed that the States bulk-buy the oil for the growers and pass on the discount they would receive. It is uncertain yet exactly what sort of savings this would provide for the grower and whether it would match the subsidies to which they are entitled at present (Gurdon, 1983).

Subsidies provide short term aid to the industry but they cannot be maintained forever and are not the long term answer to the industry's problems. The solution lies in improving the efficiency of crop production so that yields increase at little or no extra cost to the grower.

Approaches to Energy Saving and Efficiency

Ideas abound for improving the efficiency of glasshouses by reducing the fuel requirement and these fall into three general categories or approaches. These approaches can be termed biological, physical and organisational. The biological approach attempts to produce new strains of plants which can withstand lower temperatures without loss of yield. The development of new, low temperature growth regimes for crops already being cultivated would also fall into this category. The nutrient film technique NFT, whereby plants are grown in a nutrient solution rather than directly in the soil is a good example of this and is already widely used in Jersey. By using NFT it may be possible to warm the roots by heating the nutrient solution at the same time as reducing the air temperature in the glasshouse to lower and levels without detriment to the crop.

The physical approach to energy conservation involves altering the structure to improve the way heat is retained by the system or improving the way in which fuel is used in the boiler and the way heat is distributed throughout the glasshouse array. This approach includes the use of thermal screens, glass coatings, double glazing and alternative cladding materials and will be discussed in more detail below.

The organisational approach is less well defined but includes such things as 'good house-keeping' and good farming practice. The good farmer will ensure that broken windows are replaced, his thermostats will be correctly set and, if he has had any say in designing the layout of the farm, the boiler house will be sited in the proper place, close to the houses so that the heat does not have too far to travel. The good farmer will be aware of new developments which might benefit him and will use his local advisory service. Goldsberry states that research is not needed in areas such as fuel efficiency (and presumably good farming practice) as such things have been known about for years but were disregarded in the days of cheap oil. Improvements can be made merely by better education and advice (Goldsberry, 1979).

This organisational approach is something the grower will learn by experience if he does not already practice it. If he does not learn then he will probably fail as there is little room in the industry for inefficiency of this kind. This approach is largely one of common sense and the grower can benefit immediately given good advice. With the new methods of control and production which are now being used this organisational problem might benefit from a study using a systems approach. Such a study would show the strong and weak points of management techniques and might identify where improvements might be made. However, this thesis will not be concerned with the organisational problem except when different management strategies might improve energy conservation.

A study of the present state of the industry would suggest that it would be unwise for new growers to enter the industry, but how should an established grower with the necessary capital and freedom of choice decide the best course of action? His overwhelming concern is to remain in business and make money. Generally he requires a reliable fuel supply for his boiler, sufficient water during dry summers, a general knowledge of the local climate, a market for his produce and some idea of what the future holds in store. He must decide what sort of glasshouse structure would make him more efficient, although of course the established grower has little choice in these matters, and he has to decide what crop or crops he will grow and the method of cultivation he will use.

The biological methods of improving efficiency are being investigated by the Experimental Horticultural Stations (EHS) around the country and by such places as The Glasshouse Crops Research Institute (GCRI) at Littlehampton. This work is carried out season by season with the energy input and yield, amongst other factors, being measured and recorded as more energy efficient growing regimes are sought. An integrated glasshouse environment/crop growth model would be of great help in this work but none are available at present and although models of the growth of glasshouse crops are being developed, these can only offer limited help at present. This is because the absence of a complete understanding of the crop processes and responses to changing environmental conditions makes the modelling both difficult to carry out to validate. The work of the research stations is of necessity slow. However, the grower can make use of new information as it reaches him each season to improve his growing technique and crop yield, and in this way progress should be made steadily over a number of years rather than in large jumps at intervals.

The physical methods of improving efficiency are being investigated by chemical and glazing companies as well as the EHS and the National Institute of Agricultural Engineering (NIAE) at Silsoe. When one considers the number of theories there are for improving the structure of the glasshouse then it is clear that were each to be tested over a full season it would require much time, money and space. Even more if all the combinations of methods, such as double glazing and thermal screen use in the same house. were to be tried. However, time, money and space are not available to the industry in any great measure so rather limited experimentation is carried out. There is no apparent system or programme which is being followed nationally and research stations carry out work in whatever direction is of interest or is regarded as important at that time.

The Value of Computer Modelling

Testing energy conservation methods in different seasons causes problems when it comes to comparing results as weather conditions vary from year to year. It is at this stage that the idea of a computer model becomes attractive. If it were possible to model the energy flows within a glasshouse system and predict the energy requirement for a season, then energy saving techniques could be introduced mathematically into the model and tested with standard weather data. The possibility that a simulation model of the glasshouse environment might be able to predict energy usage is a major justification for using computer modelling techniques as savings in time and money, and benefits from testing under identical conditions would result. Of course the problem is not simple as there are still factors concerning the crops' interaction with the glasshouse environment which are not fully understood. Also it is very difficult to model the external weather conditions fully. For example, the problem of modelling rainfall inclined at an angle which might hit four of the six glasshouse surfaces (for a single structure) is not an easy one to solve.

Given these constraints, and others involving computer size and time available, the modeller has to decide the objectives of the exercise. He may decide to produce a model which will indicate only in general terms which broad methods are likely to be worth pursuing. For example, the model may say that strategies A,B and C are worth considering and field trials should be conducted, D and E might be useful under certain conditions and G,F and H are not going to be useful under present conditions. Models which are capable of dealing accurately with specific conservation techniques are likely to be more complex and will require much time to develop and test.

The original aim of the work described in this thesis was to construct a computer model of the glasshouse environment which would allow energy conservation methods to be investigated. Although other models have been produced to investigate the general glasshouse environment or specific types of energy conservation (see sections above), this model would allow a wide range of conservation strategies to be examined using real weather data. It would do this by allowing the investigator to change any of the parameters which describe the glasshouse system and the inclusion of a heating system would allow the energy savings to be compared.

After discussion with Dr. B J Bailey of the National Institute of Agricultural Engineering (NIAE) during the second half of 1980, it was decided that the main objective of the project would be to construct a simulation model of the thermal behaviour of a glasshouse system under UK weather conditions, which could include a double roof layer and a thermal screen. This would complement work on thermal screens and natural light intensity which had been, and still was, continuing at NIAE at that time.

Upon completion it was hoped that the model could be used to investigate specific energy conservation techniques and it was thought necessary to construct it in as detailed a way as was possible. The effects of different conservation methods on the system might be small and a detailed model would be required to detect differences in effect of similar conservation methods; small changes in the heat requirement can mean large costs to the grower. After the model was produced an investigation involving the use of thermal screens and double glazing was carried out. The use of thermal screens is becoming more widespread now and double glazing can greatly reduce heat loss from glasshouses. Glasshouses are found all over the country and it may be that thermal screens and double glazing may be more effective in one area than in another. Using GHFORSM's ability to use weather data and simulate long time periods several runs were carried out simulating the use of screens and secondary cladding, singly and together, using ten years of weather data from Kew in London and from Eskdalemuir in Scotland.

Chapter Two

Environmental Conditions Inside the Glasshouse

A model of the thermal behaviour of a glasshouse, called GHFORSM, was produced and will be described in the following chapters. A listing of the model and a full description can be found in the appendix. This chapter describes the environmental conditions found within the glasshouse

Glasshouses are used for cultivation because conditions inside can be made more favourable for crop growth, improving profitability for the grower.

The Principal Environmental Factors

Air Temperature

The air inside a glasshouse is warmer than the outside air. The amount of increase in air temperature above that of the outside air depends primarily upon the volume of the structure. This is because volume is proportional to radius^3 and exchanges through the surface enclosing the volume occur through the area bounding the volume which varies with radius^2, thus smaller volumes exchange proportionately more energy through their bounding areas than larger volumes. An example of this temperature variation with volume is given by Seemann (1974). During one year the mean monthly outside air temperature increased from 12.8°C in May to 16.5°C in June and the corresponding rise in a small glasshouse (37m^3) was from 16.8°C to 23.6°C, whereas the rise in a larger glasshouse (289m^3) was 15.1°C to 18.1°C.

The air temperature inside is also dependent upon the type of cladding material used to cover the framework. Glass does not transmit longer wavelength radiation and so energy passing into the glasshouse in the form of short-wave radiation is then transformed to longwave energy and cannot directly escape. This is commonly termed the 'greenhouse effect' and is less pronounced in plastic clad structures which transmit thermal radiation more readily. Variation of temperature also depends upon such factors as the orientation and shape of the glasshouse, the thickness of the cladding material and the number of cladding layers. In addition, the inside air temperature is affected by the temperatures of all the other interior glasshouse components. For example there is sensible heat exchange between the inside air and the soil (Whittle and Lawrence, 1960; Seemann, 1974).

The temperature of the inside air shows little variation with height except for the air layer a few centimetres above the floor. In this region the air temperature drops quite sharply with increasing height over a few centimetres, but above this the temperature remains much the same, being slightly warmer near the roof than at a point at mid-height. Glass, the most widely used material, is relatively good at maintaining high temperatures throughout the vertical structure of the glasshouse. However, the variation in temperature with height is changed if the glasshouse is heated since the temperature distribution then depends upon the type and positioning of the heating system as well as upon the amount of mixing that takes place (Kanthak, 1970).

Soil Temperature

The soil temperature plays an important part in the thermal picture of the glasshouse since most of the thermal mass of the system is located in the soil. Because the soil or floor surface is not exposed to winds and because the radiation properties of the glass do not allow the soil to have a direct long-wave radiation exchange with the sky, the soil inside the glasshouse is warmer than that outside. Towards the edge of the covered area soil temperatures fall slightly, the amount of the fall being dependent upon the area (Seemann, 1974). The flow of heat into and out of the soil inside the glasshouse is interesting and will be discussed later but in general, heat flows into the soil during the day, mainly due to solar radiation, and flows out into the air during the night. This flow of heat has a smoothing effect on the air temperature fluctuations inside the structure.

Plant Temperature

Plant and leaf temperatures generally run in parallel with the surrounding air temperature. Solar radiation or radiation from heating systems will tend to raise the plant temperature above that of the surrounding air, while transpiration will tend to bring the plant temperature down. If transpiration is hindered by high inside relative humidity or water stress then damage may be caused if the plant temperature rises too high. This has important implications for energy conservation techniques which might be applied; those which reduce ventilation and raise relative humidity may save energy but could damage the crop. The crop canopy exchanges long-wave radiation with the floor and the cladding material, and not directly with the outside environment if the roof is of glass.

Inside Air Humidity

The inside air humidity differs significantly from that of the open air. The variation in the absolute humidity inside the glasshouse is closely related to the soil temperature (if there is an open soil surface); with evaporation rising and falling with temperature. Ventilation is important since when the vents are opened the difference between the inside and outside air humidities is decreased. The type and positioning of the heating system also has an effect; a blown air system tends to produce a drier atmosphere, whereas a radiant type, which will heat up the soil, increases the evaporation from the soil and hence increases the humidity.

When soil forms the floor and when it is adequately supplied with water, the evaporation is comparable to evaporation from open water. Plants release water by transpiration whereby water is evaporated mainly through the stomata on the leaf surfaces. Such stomatal transpiration occurs at the greatest rate during the day when the stomata are open and this helps to maintain the plant at the optimum temperature. Close relationships for example have been found between the amount of incoming radiation and the transpiration of a lettuce crop (Morris et al., 1957).

Carbon Dioxide Concentration

Carbon dioxide is essential to the photosynthesis of plants. In an unventilated glasshouse the atmospheric supply of carbon dioxide may be depleted to such an extent by the crop that growth is hampered. However, opening the vents and allowing free exchange between the inside and outside air may be insufficient to halt the fall in CO_2 concentration. Some other active system may need to be installed to draw air into the structure and to maintain the concentration to suitable levels on still, warm days. Many farmers introduce CO_2 artificially into the glasshouse air, usually from bottled sources or by burning propane. Of course, if the farmer is artificially increasing the level of concentration then he will keep the vents closed. However, at some point during the day the vents have to be opened to keep air temperatures from getting too high and harming the crop. The grower thus has to balance his actions of ventilating and increasing CO_2 concentration in such a way that the crop benefits.

Radiation

The amount of shortwave or solar radiation present inside the structure is affected by the type of cladding and amount of structural material present. The solar radiation flux is extremely important for photosynthesis and growers like to ensure that the internal downward flux is maximised. Glass is a good transmitter of visible radiation with transmission coefficients of 0.9 or more at normal incidence, but it is important for the grower to keep the surfaces clean, as dust deposition can decrease the transmissivity considerably. Inside the glasshouse there are normally a large number of structural elements and solar radiation nearly parallel to surfaces is often kept out of the glasshouse by the shading effect of these. Of course, even after striking such elements much of the solar radiation is still effective in the glasshouse as diffuse radiation but some is lost by reflection back out to the environment. In the older, wood-framed glasshouses the amount of blockage was much greater than in the more modern aluminium structures.

The Glasshouse System Model (GHFORSM)

The general environmental conditions have been discussed in the previous pages but in order to model the glasshouse system the heat transfer pathways have had to be defined and the remainder of the chapter is devoted to this. In the course of the following discussion reference is made to GHFORSM and system model is first briefly described.

At the outset of this work the intention was to produce a model which simulated the thermal behaviour of a three-dimensional glasshouse structure of conventional construction. It soon became clear that such a structure would not be very easy to model if the aims of allowing many different conservation methods to be tested were to be met. The problems of devising routines which would calculate the solar radiation incident upon and transmitted through the various roof and wall surfaces would be formidable and a detailed treatment of other facets of the problem would use more computer time and space than was available. It was decided therefore to model a representative square metre somewhere in the middle of a large glasshouse array in a similar manner to that taken by Van Bavel et al. (1979). Figure 2-a shows this representative square metre section taken from the roof to the soil below the floor.

This approach is not as crude as it sounds and it makes the computing task much more straightforward. The computing difficulties which arise in a treatment of the problem of a three-dimensional structure are mainly due to the edge effects near and beyond the side walls. When a square metre in the middle of the glasshouse is modelled these edge effects can be ignored and the problem can be considered as one of one-dimensional energy exchanges through the vertical structure of the glasshouse. Such a model would not be an accurate representation of small glasshouses as the edge effects play a large part in the thermal behaviour. However, as the floor area is increased, the roof area becomes greater and greater in proportion to the side-wall area, and a greater proportion of the glasshouse is well represented by the square metre in the middle. The edge effects become less significant as the area is increased. If a knowledge of the side-wall heat losses is at hand then it may still be possible to use the single square metre approach for simulating

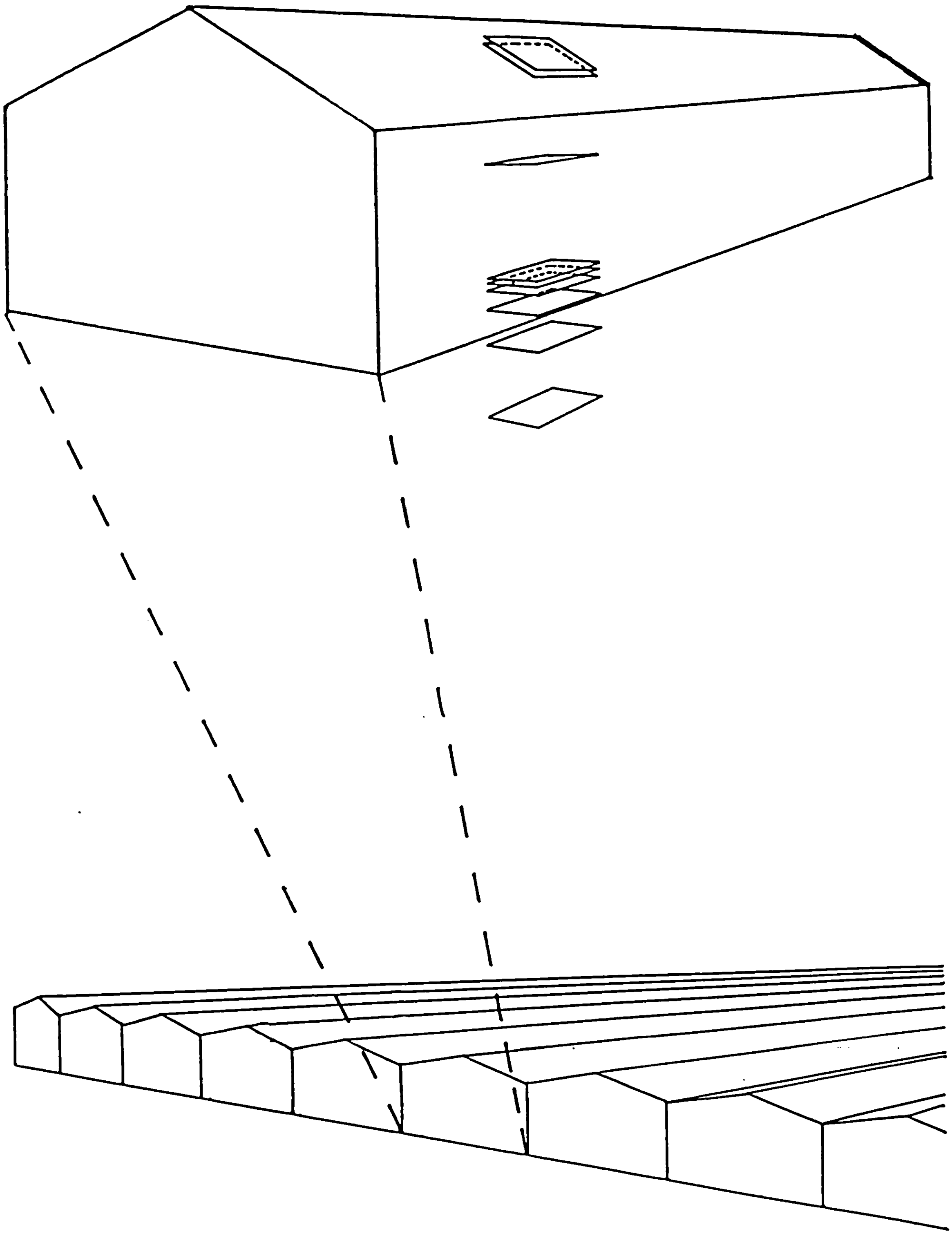


Fig. 2-a
The glasshouse system modelled by GHFORSM

smaller glasshouses by altering some of the parameters which describe the exchange processes between the roof and the air. However, a different approach to longwave radiation transfer between surfaces would have to be included in the smaller glasshouse case.

The model was constructed as a series of layers or components (figure 2-b). These include the outside air, roof layers, inside air, floor and soil layers, each identified by odd numbers. This numbering system was employed for two reasons. Firstly, by using this method other layers could be inserted between existing ones and the sequential numbering system could still be used unaltered. Secondly, and perhaps more importantly, when considering the heat exchange pertaining to components it is often the surface of each component which is important. For example, longwave radiation exchange and convective transfer processes occur from surfaces, and some components have two of these. With this numbering system it was usually possible to define the relevant heat transfer coefficients using both odd and even numbers so that the components to which the exchange referred could be easily identified. For example CHT(2), a convective heat transfer coefficient, applies to convective exchange between the outside air, 1, and the top roof, 3.

Another important factor of such a system definition is that not all of the components are in the simulated system at the same time. For example, only when a thermal screen is present will components 9, 11 and 13 be part of the system and component 15 will be absent but with the screen withdrawn, 15 will be present and 9, 11 and 13 will not.

The Heat Exchange Process

I now consider the heat exchange processes of the glasshouse in relation to the model. In the glasshouse energy is exchanged with the environment by radiation, conduction and convection, ventilation and by latent heat loss. Each layer or component within the glasshouse exchanges energy with the other components of the system, but only certain layers exchange energy with the external environment. Radiation exchanges involve shortwave or solar radiation and longwave or thermal radiation. The shortwave exchange is one-sided as the glasshouse acts purely as a receiver to such radiation but the

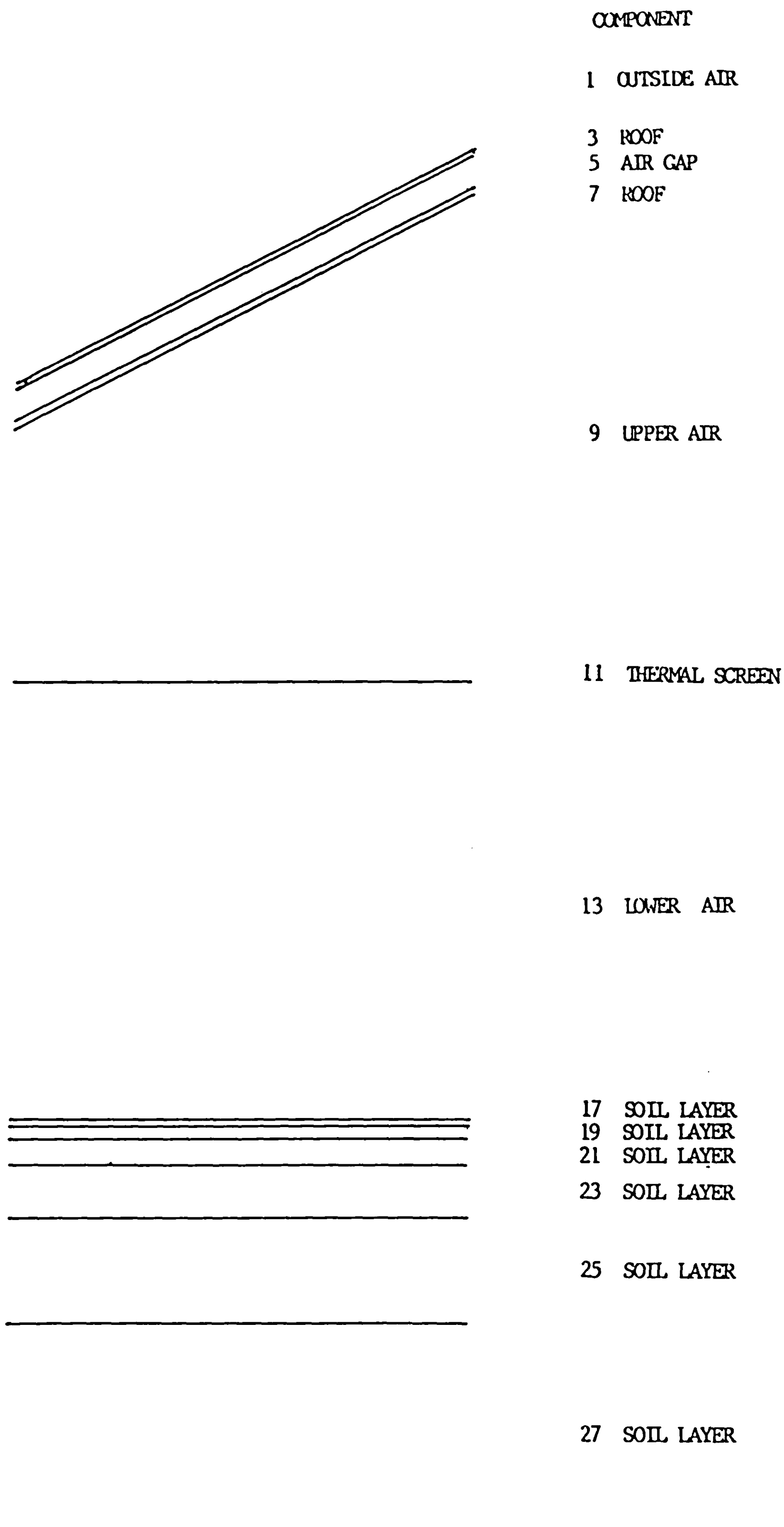


Fig. 2-b
The components of the system

longwave radiation exchange is more complicated as all of the component surfaces are longwave emitters.

Conduction of heat occurs through the glasshouse components and most notably through the soil beneath the floor of the structure. Convection takes place between component surfaces and the air, and an important exchange is that which occurs between the outer cladding surface and the outside air as this is a large source of heat loss. Both active and passive ventilation occur involving heat exchange between the inside and outside air. This will be described in more detail later. Passive ventilation is commonly referred to as leakage. Latent heat exchange also occurs in glasshouses and comprises the transfer of heat to and from the glasshouse environment by the evaporation of water from the ground or the crop which subsequently condenses on the cladding or is lost via ventilation.

Convection

In convective heat transfer, energy is exchanged between a component surface and a fluid above or below it. In the glasshouse case an example of this is the exchange between the outside air and the upper surface of the cladding material which can be described by the following equation:

$$q = h * (T_{air} - T_{gl})$$

In this equation q is the heat transferred and h has units of W/m^2K, indicating that heat is exchanged between the glass surface and the air at a rate of h W/m^2 for each °K difference between them (the variables used are listed at the end of the chapter). This energy exchange also depends upon the wind velocity; on a calm day heat loss is by free convection but in windy conditions the air moves over the roof surface, and the heat loss is by forced convection. Convective exchange takes place at all the surface/air interfaces inside the glasshouse, but it is assumed that these transfers are all of the free convection type.

For the glasshouse the problem lies in deciding upon a value for h which is suitable both for the system and the conditions being simulated. There is some controversy in the literature as to which values should be used and a wide range are presented. This does not mean that some are correct and others are not, but is an indication of how the value may change with different conditions. The convective transfer is dependent upon a number of different factors such as wind speed and direction, the type of surface from which convection is occurring, whether it is smooth or covered in dust and dirt, and the topography of the site being considered. The degree of turbulence in the air flow above the surface is also important. McAdams (1954) and Duffie and Beckman (1980), who quote McAdams, assign a value for h as follows

$$h = 5.7 + 3.8 * v$$

The problem with using this value is that the equation is based on measurements made on a plate of area 0.5 m^2, and probably includes radiative exchange. This equation is widely used in calculations of heat transfer in many different situations, but as GHFORSM considers radiative exchange separately, its use here would not be appropriate. Duffie and Beckman (1980) also give an equation which excludes radiation:

$$h = 2.8 + 3.0 * v$$

However, this gives somewhat lower values than others and probably also comes from measurements taken on a plate of small surface area. Duffie and Beckman (1980) also describe the work of Mitchell who conducted wind tunnel tests on various shapes of structures and showed that many such shapes can be represented by a sphere with diameter equal to the cube root of the volume of the shape being considered. His work suggests that for solar collectors, the minimum heat transfer coefficient should be 5 W/m^2C for a temperature difference of 25 °C, and 4 W/m^2C when the temperature difference is 10 °C. For forced convection over buildings the transfer can be expressed as:

$$h = 8.6 * v^{0.6} / (V_{gh}^{1/3})^{0.4}$$

Statham (1975) suggests that the value of the heat transfer coefficient should lie somewhere between 4.0 and 8.0 W/m^2K, with the higher value being applied when the windspeed is about 6.0 m/s. Duffie and Beckman state that the calculation of wind induced heat transfer coefficients is not well established and they report McAdams suggestion that where both free and forced convection occurs, coefficients of heat transfer should be calculated for both cases and the larger value used. Mitchell suggests that for outdoor conditions, the values should be increased by some 25%. Although these suggestions may be be applied to get a rough idea of the convective transfers which might occur, for more detailed work values of h based on measurements of systems more nearly like those being simulated ideally should be used.

Another approach to convective heat transfer is the use of the U value. Here the heat transfer coefficient is of a slightly different nature in that it describes the heat flow through a component rather than exchange from the surface of the glazing to the air. For example ordinary window glass has a U value of approximately 6.0 W/m^2K which means that heat is exchanged through the glass at a rate of 6 W/m^2K. Davies (1980) uses the film resistance approach when calculating the U value of a double glazed window. taking the outside film resistance as 0.055 m^2K/W, the cavity resistance as 0.18 m^2K/W, and the inside resistance as 0 123 m^2K/W. This gives an overall U value for the double glazing of 2.8 W/m^2K. The use of 0.055 m^2K/W for the outside film resistance corresponds to an outside transfer coefficient of about 18 W/m^2K, much greater than values shown above.

Sheard (1976) gives a total heat transfer coefficient value of 7.95 W/m^2C for a whole glasshouse, but he also gives a wind related U value of:

$$U = 4.06 + 0.65 * v$$

For single skin plastic structures, and inflated roof structures he suggests that the U values are:

$$U = 4.76 + 0.52 * v$$

and

$$U = 4.06 + 0.25 * v$$

respectively. These figures do compare well with the accepted U values for transfer through glass and related cladding materials but when considering loss from surfaces the problem of finding a suitable h value still remains. However, these equations do provide a means of checking the values chosen by using the method employed by Davies (1980) described above.

Iqbal and Khatry (1977) conducted wind tunnel tests on model glasshouses and showed that the external surface transfer coefficient is higher under such conditions than those measured for parallel flow over flat surfaces. The value of h depends upon the direction of the wind, degree of turbulence and shape of the structure, and they present a wind related transfer coefficient valid for wind speeds greater than 4.0 m/s and less than 20 m/s:

$$h = 17.9 * v^{0.576}$$

This equation gives values rather higher than others (39.77 W/m^2C evaluated at v = 4.0 m/s) and this can partly be explained by the fact that they measured the temperature of the outside surface. Other workers may have considered the roof layer to be isothermal which would suggest that the difference in temperature between the upper roof surface and the outside air was greater than it actually was. Also their measurements were made on a scale model of a glasshouse in a wind tunnel using spires to create suitable suitable wind velocity profiles which should have given more realistic values than those measurements made on vertical plates and uniform wind flow. In the model produced by Van Bavel et al. (1979) this equation is used despite the fact that the modelled wind speed never exceeded 4.0 m/s. However, the use of this equation with its high values, even at wind speeds of less than 4.0 m/s is probably better than using those equations derived from measurements made on plates of small area.

Kimball (1973) also uses large values for the outside transfer coefficient but found that these were consistent with the small observed temperature differences between the upper roof surface and the outside air. As in the work by Iqbal and Khatry, Kimball uses the outer roof surface temperature and does not treat the roof as isothermal.

Under conditions whereby free convection alone is taking place, the heat transfer coefficient can be described by equations containing the temperature difference between the component and the air. Considering transfer between the lower side of the roof and the inside air, Bailey (1975) gives h a value such that:

$$h = 0.8 * (T_r - T_{air})$$

McAdams (1954) gives a value for the transfer between the inside air and the cover of:

$$h = 1.38 * (T_r - T_{air})^{1/3}$$

The problem of convection coefficients is discussed by Garzoli and Blackwell (1981) who state that in the absence of precise values for the internal and external heat transfer coefficients, it is common practice to use those given by McAdams. They go on to reiterate the statement made by Iqbal and Khatry (1977) that the surfaces of the glasshouses are very much larger than the areas of the plates for which the relationships given are valid, and that the transfer coefficients for plates were often derived from streamlined air flow parallel to the surface, a situation which is not always true for flow close to the ground. They say that for accurate analysis of the heat transfer situation, relationships should be calculated for a range of conditions. Whilst other work shows a wide variation in the values of heat transfer coefficient used they continue by saying that the value used in their work is that recommended by ASHRAE (The American Society of Heating, Refrigeration and Air Conditioning Engineers) for calculating the heating requirement of buildings

$$h = 8.3 + 3.8 * v$$

The first term on the right-hand side, 8.3, is used as the free convection coefficient for the inside transfers as well as for the outside surface transfers when the wind speed is zero. However, this relationship does include transfer by radiation and consequently should be smaller when radiation exchange is calculated separately. In their model the use of this value resulted in an overestimate of heat loss of 13.2% (they calculated radiation separately), whereas the use of the suggested McAdams values gave an underestimate by some 28%. The value of h which best fitted the data was found to be

$$h = 7.2 + 3.8 * v$$

where h = 7.2 W/m^2K could be used for the inside transfer coefficient.

After studying the work listed above is clear that no single value of h can be chosen as being the correct one to use for a range of different situations. The convective heat transfer depends upon so many different factors that at best, a collection of values can be chosen to describe particular situations. However, the references suggest that transfer coefficients for glasshouses are significantly higher than those measured for plates of small surface area under conditions of parallel air flow. The values in the more recent work, when evaluated at a wind speed of 4 0 m/s, range from 19 to nearly 40 W/m^2K and are shown below:

39.77	Iqbal and Khatry (1977)
19.0	Gimmestadt et al. (1981)
22.4	Garzoli and Blackwell (1981)
20.92	Seginer and Levav (1980)
>20.0	Kanthak (1970)

Taking these into account, it was decided that when GHFORSM was complete, the outside transfer coefficient used in the simulations should be similar to these but a range of values would be used to test the sensitivity of the model to changes in this variable. As there is less uncertainty in the inside transfer coefficients it was decided that Garzoli and Blackwell's (1983) value of 7.2 W/m^2K would be used, but the sensitivity of the model to this could also be tested.

Conduction

Conductive heat transfer takes place between the soil layers of the glasshouse floor The amount of heat transferred depends upon the relative temperatures and the thermal conductivities of these layers. At some depth below the surface it must be considered that the heat has escaped from the system, but this depth has no definite position and will vary from place to place and season to season. In general heat is transferred during the day into the soil from the air in the glasshouse above where it is conducted to deeper and deeper layers. At night, when the inside air and roof temperatures may fall below that of the soil, heat is transferred back into the air in the glasshouse. Relatively little actually escapes the system by conduction (Sheard, 1976). The flow of heat is proportional to the temperature gradient and k, the constant of proportionality, is called the thermal conductivity. For transfer between two adjacent soil layers (17 and 19) the rate of heat flow can be represented as:

$$q = -k * A * (T_{17} - T_{19}) / z$$

where k is the thermal conductivity, A is the area across which flow occurs and $(T_{17} - T_{19}) / z$ is the temperature gradient. The conductivity k has units of W/mK, and its value varies in soils of differing composition and moisture content.

Soil is a mixture of both organic and inorganic materials with spaces between the particles. These spaces may be filled with either air or water; saturated soils have water-filled spaces whilst very dry soils contain much more air. The relative amounts of air, water and particulate matter which comprise the soil, affect the value of the thermal conductivity k. Kanthak (1970) gives values of 1.867 - 0.117 W/mK depending on the porosity and moisture content whilst Carslaw and Jaeger (1959) quote the following values:

Soil Type	Density kg/m^3	k W/mK
Average soil	2500.0	0.96
Sandy, dry soil	1650.0	0.26
Sandy, 8% moisture	1750.0	0.59

Ingersoll et al. (1955) give a wide range of values for more specific soil types:

Soil Type	Density kg/m^3	k W/mK
Calcareous earth 43% water	1670.0	0.712
Quartz sand, medium fine dry	1650.0	0.264
Quartz sand, 8.3% moisture	1750.0	0.586
Sandy clay, 15% moisture	1780.0	0.921
Soil, very dry		0.167-0.335
Wet soils		1.256-3.350
Wet mud	1500.0	0.837

Hanks and Ashcroft (1980) give a value of 1.68 W/mK and Caffell and Mackay (1980) give a range of 0.2 - 3.5 W/mK. They suggest that 2.0 W/mK would be applicable to a deliberately water saturated soil (their work is concerned with the storage of heat in mud). Van Bavel et al. (1979) use a value of 1.0 W/mK for k and Russell (1973) gives values of k for air (0.024 W/mK), water (0.586 W/mK) and for soil solids (1.674 W/mK) and he points out that for more compact and/or wet soils (a clay soil for instance), the thermal conductivity is greater than for the drier and less dense soils (sandy soils for example).

In GHFORSM the floor and the soil beneath is split into a number of layers with the thickness of each layer increasing with depth. The increase in thickness with depth was included for reasons of mathematical stability as the temperature variation through time is less for the thicker layers at the bottom. The particular thicknesses were chosen so that the temperature variation of the bottom layer is small (less than 1 °C). Each layer is assumed to be of uniform temperature and composition, and heat flows from the centre of one layer into the centre of the next. In the model these soil layers can be defined individually so that the top three might be made of concrete for example, whilst the remaining ones might be soil. The heat transfer coefficients and the temperature rise index are more fully described in the program description.

Ventilation

Ventilation is the exchange of air between the external environment and the internal glasshouse environment. Passive ventilation is the natural exchange of air which occurs through small gaps in the covering material of the structure, whilst active ventilation is the deliberate air exchange which takes place when the ventilators are opened.

Passive exchange, or leakage, is the same as that which occurs in any non-air tight structure: air leaks in and out between the glazing bars and cladding material, through cracks in the glass and through gaps in the structure due to ill fitting doors and vents. A well maintained structure will have a lower leakage rate than a poorly maintained one but the air exchange rate will vary due to the different characteristics of cover materials and mechanisms for holding the cladding in place. For example a glasshouse employing clips to hold the glass to the glazing bars is likely to lose more heat due to leakage than one which uses putty to secure the glass (Kanthak, 1970). The rate of air exchange due to passive ventilation is described in the literature by a widespread range of values. Kanthak (1970) reports the work of Flachsbart, Hiller and Heisner who proved and confirmed the linear relationship between the quantity of air exchanged and the wind velocity. This work also shows that whilst the relationship appears to be linear, the exchange does not tend to zero at low or zero wind speeds, due to a thermal buoyancy effect, due to the lower density of warm air compared to that of colder air. Warm air, rising to the top of the glasshouse, escapes through the vents and is replaced by cooler air, but at higher wind speeds, air is blown into the glasshouse and currents are set up in the inside air. Bot (1980) also points out that the expected relationship between wind velocity and air exchange rate is linear as do Kozai and Sase (1978) and Kozai et al. (1980).

Active ventilation is carried out by growers for a number of reasons, the foremost being to keep the inside air temperature from getting too high in summer. Also, by ventilating, the grower can keep the inside air humidity at reasonable levels and can maintain the carbon dioxide concentration at a level which is beneficial to plant growth (Sase et al., 1980; Statham, 1975). Indeed, the active ventilation itself can be divided into two categories, natural and forced ventilation. Natural ventilation occurs when the air exchange takes place through open windows or vents, and forced ventilation takes place when some air distribution method, such as a fan system, is employed within the structure. When the vents are open the rate of exchange depends upon several different factors; the extent of window opening wind speed and direction, and the temperature difference between the inside and outside air (Tantau, 1980). Tantau also points out that there is no linear relationship between window opening and heat exchange.

Recent Japanese work has concluded that the ventilation problem is complex and the rate of air exchange depends upon the positioning of the vents and the shape of the structure as well as on the window opening, wind velocity and temperature difference. In their experiments it was found that at wind speeds greater than 2 m/s, the rate of exchange was proportional to the wind speed but at lower wind speeds the rate was governed by the temperature difference (Kozai and Sase, 1978). It was also found that the rate of air exchange through vents open to the leeward of the glasshouse was not the same as those exchanges through vents open to windward (Kozai et al., 1978; Sase et al., 1980 Kozai et al., 1980).

The amount of ventilation can be expressed as: air changes per hour, m^3/s or m^3/m^2s. Udink ten Cate (1983) gives a wide range of values, showing the sort of rates of air exchange which can occur. He says that in the average glasshouse in winter, the number of air changes per hour will be between 0.5 and 10.0. During the summer this figure increases dramatically to between 0.5 and 100.0 as more ventilation is required to keep temperatures lower in the warmer weather. Kozai and Sase (1978) found that for a four span glasshouse with open vents under a 2 m/s wind, the rate of air exchange was between 30 and 40 changes per hour. This rose to about 80 changes per hour as the wind speed increased to about 5 m/s. Kozai, Sase and Nara (1980), say that in a house with vents open along the side walls, the temperature difference between the inside and outside air can be as great as 25°C. In houses with open vents in various configurations on the roof, the air change rate varied from 22 to 47 changes per hour, with the temperature difference ranging from 4.8 to 8.5°C between the inside and outside air. In these cases the angle of opening of the vents was set at 10° and 20° in different experiments.

In the house with side wall vents, the ventilation rate was found to be proportional to the wind speed regardless of vent opening angle and wind direction. With roof based vents, it was found that only at speeds above 2 m/s was the exchange rate proportional to the wind speed. Kozai et al. (1980) found that at wind speeds of about 5 m/s, exchange rates of up to 200 changes per hour could be achieved, depending upon the wind angle and the configuration of the vents.

The model glasshouse which they were using had a volume of 577 m^3 which gives values of air exchange in the range 3.52 - 7.53 m^3/s. When divided by the floor area, this becomes 0.018 - 0.039 m^3/m^2s. The upper value is in accordance with the value used by Van Bavel et al. (1979) for the active ventilation rate. Statham (1975) states that in the warmest of summers in Britain, the rate of air exchange needs to be between 300 and 400 m^3/s per hectare, i.e. about 0.03 - 0.04 m^3/m^2s.

Looking at the actual exchange of heat due to air exchange, and ignoring the loss due to latent heat flow at present, Kanthak (1970) uses the following equation:

$$q_v = z * V_{gh} * d_{air} * C_{air} * (T_{in} - T_{out})$$

q_v = heat flux due to air exchange, W
z = number of air changes per 'time', /s
V_{gh} = glasshouse volume, m^3
d_{air} = density of air, kg/m^3
C_{air} = heat capacity of air, J/kgK
$T_{in/out}$ = air temperature inside/outside, K

Van Bavel et al. (1979), however, use:

$$q_v = 2.0 * (T_{in} - T_{out}) * C_{air} * d_{air} * V_{gh} * z / A_{gh}$$

This is the same as that shown above except that the result is divided by the floor area which gives units of W/m^2. However, the use of the factor of 2.0 in this treatment is questionable as it is not required for a simulation of leakage. If their model did include a forced venting system then two equations would be needed: one for the leakage through the roof which does not require this factor of 2.0, and one for the forced venting. As the model only contains one equation, that using the factor 2.0 then they assume the exchange due to leakage is twice as great as it really is. The justification for the use of the factor of 2.0 for forced ventilation simulation is found in the treatment by Seginer and Levav (1971) who consider a slice of glasshouse taken along the x-axis and assume that air enters this slice at a temperature of $T_{ave} - T'$ and leaves the slice at $T_{ave} + T'$. The 2.0 arises from the temperature difference between the incoming and outgoing air being 2T'. If the variation in temperature along the glasshouse is small, then the heat flux by ventilation can be written as:

$$q_v = d_{air} * C_{air} * u_{air} * b_{air} * 2.0 * (T_{in} - T_{out}) / x$$

u_{air} = air speed m/s
b_{air} = air thickness m
x = length of glasshouse m

In GHFORSM the ventilation is considered to be by leakage and by exchange through open ventilators; no forced system for moving air along the house is simulated since such forced systems are not commonly used by tomato growers in the UK. As an initial parameter value a passive ventilation rate of 0.002 m^3/m^2s, corresponding to about two air changes per hour, and an active one of 0.04 m^3/m^2s, about forty changes per hour, were chosen.

Latent Heat Exchange

Part of the energy which is available to the crop inside the glasshouse is used in evaporating water which thus tends to increase the relative humidity of the inside air. There may be evaporation from the soil itself directly into the inside air, but this can be restricted if polyethylene sheeting is laid on the ground to alter the reflection and absorption properties of the floor to short-wave radiation. The water vapour may condense on the roof or walls of the structure or on the thermal screen if conditions are suitable, thereby returning its energy to the environment. Alternatively, some of the water vapour may be lost in the air exchange by ventilation, although if the outside air humidity is greater, then there will be a net increase in the moisture content of the inside air

Rothwell and Jones (1961) measured the water requirement of a tomato crop and found that between 24 and 74% of the solar radiation available was used in evaporating water, depending upon the state of the crop. In the first eight weeks of growth it was found that the water loss was related to crop height. Hand et al. (1970) show that the energy used in evaporation can be calculated as 56% of the solar radiation available on a horizontal surface in the glasshouse. and 76% of the total energy available to the crop. The approach they use is as follows

$$E_c = I_{tot} + L_{pipe} - r_c I_{tot} - L_{c,gl} = q_{lat} + q_{sen} + q_{soil}$$

E_c = the net energy available to the crop
I_{tot} = the total solar radiation entering the glasshouse
L_{pipe} = the longwave radiation supplied by the pipe heating system
r_c = the reflection coefficient of the crop
$L_{c,gl}$ = the net longwave radiation from the crop to the glass
q_{lat} = heat transfer by evaporation
q_{sen} = amount of sensible heat transfer
q_{soil} = heat transfer to the soil

During the summer months the crop is well established and transpiration occurs at its greatest rate, solar radiation being at its most intense during this period. Also, at this time, L_p will be small, and $L_{c,g}$ can be ignored as there is little temperature difference between the leaves of the crop and the underside of the roof glazing. The reflection coefficient from the crop, r_c, has been measured as 0.26 for tomatoes and so the equation can be reduced to:

$$E_c = 0.74 * I_{tot} = q_{lat} + q_{sen} + q_{soil}$$

They had previously measured q_{lat} and found it to be equivalent to 0.56 I and when this is combined with the above equation gives a measure of how q_{lat} is related to the total energy, E_c, available to the crop:

$$q_{lat} = 0.76 * E_c$$

Morris et al. (1957) use a similar value and Forsdyke (1974) states that about 70% of the solar radiation goes into evaporation and the remainder is used in heating the glasshouse. These figures seem to be rather high but much of the energy is regained when condensation takes place on the walls and roof surfaces. Adams (1980) measured the water uptake of a cucumber crop and found that the uptake increased in relation to light intensity and was greatly reduced on dull, wet days.

The effects of humidity on crops are still under investigation and there is renewed interest in this field following the increased use of thermal screens in glasshouses. The use of such screens provides an extra resistance to the flow of heat out of the glasshouse and reduces the amount of fuel which needs to be burnt. However, many of these screens are made up of plastic or plastic laminates which are impermeable to air and water vapour and it has been found that there is often an increase in the relative humidity of the air under the screen at night. It is uncertain yet whether or not this has a detrimental effect on crop growth either by affecting the growth directly, or indirectly by promoting fungal growth on the crop. Bailey (1978, 1979, 1981) and Statham (1975) briefly discuss the problem of raised humidity levels, suggesting that high humidity levels are not considered to affect plant growth directly, but condensing water can fall onto the crop, promoting the growth of fungal diseases such as Botrytis. Furthermore, there is a purely mechanical problem in that condensation on a thermal screen increases its weight, making it more difficult to move.

In the studies that have been made on crop transpiration, relatively few have concerned themselves with conditions inside the glasshouse. Morris et al. (1957) found that the transpiration rate depends more upon the solar radiation than any other factor. Seemann (1974) notes that their work has indicated a correlation between the solar radiation and the transpiration rate, but says that this is not the only parameter which affects it. As transpiration is an evaporative process, then the important factors are the amount of water which is available for evaporation from the plant and the area over which evaporation can occur. There are two types of transpiration which can occur; cuticular and stomatal transpiration. The stomata open and close, regulating the exchange of materials into the inside of the leaf depending upon the state of the plant and the local environmental conditions. For example, outdoor crops may become water stressed and the stomatal aperture will remain small, minimising further water loss. Under high radiation conditions the stomata will open up, allowing greater transpiration to take place and CO_2 exchange to occur. In the glasshouse, there is usually ample water available for the crop and it is safe to assume that it will not be water stressed.

Milburn (1979) gives values of the cuticular and stomatal resistances (R_{cu} and R_{st}) which can be thought of in the electrical analogue sense as being in parallel. R_{cu} usually lies somewhere between 3700 - 38000 s/m, whereas R_{st} is less, between 38 - 1600 s/m. Overall, the resistance can be calculated as:

$$1/R = 1/R_{cu} + 1/R_{st} \text{ or } R = R_{cu} * R_{st} / (R_{cu}+R_{st})$$

The minimum value for R would be just under 38 s/m.

Rose (1966) considers the water use by a crop as the movement of water through a series of resistances from the soil to the atmosphere. In still air conditions the stomatal resistance is usually more than an order of magnitude smaller than the air boundary layer resistance (Rutter, 1972) and in the glasshouse the stomatal resistance controls transpiration only when nearly closed. This is reflected by Van Bavel et al. (1979) in their calculation of the latent heat exchange of the crop with the air. They consider only the stomatal resistance and the boundary layer resistance as the important factors in the latent heat exchange and the stomatal resistance is calculated depending upon the incident, photosynthetically active, radiation and the leaf water potential. The boundary layer resistance is set at 250 s/m in their model, and is added to the stomatal resistance to give an overall resistance to latent heat exchange. The latent heat exchange with the air is calculated as:

$$q_{lat} = (H_{air,in} - H_{sat,leaf}) * W_{lat} / R$$

where q_{lat} is the heat exchange, $H_{air,in}$ is the inside air humidity, $H_{sat,leaf}$ is the humidity of saturation at the leaf temperature and W_{lat} is the latent heat of vaporisation of water.

Solar Radiation

The most important energy input to the glasshouse system is the short-wave solar radiation. In terms of heat exchange the glasshouse plays a passive part as it is not a source of radiation at these wavelengths. However, any radiation absorbed causes the glasshouse to heat up and energy is lost by conduction, convection and re-radiation at long wavelengths. As well as being an important source of heat, short-wave radiation is vital to the photosynthetic process of plants.

The most important aspect of the design of the glasshouse structure has always been the amount of light transmitted through the cladding material. The short-wave radiation is incident upon the glasshouse skin as both direct beam radiation from the sun and as diffuse sky radiation. The amount transmitted through the cladding depends upon the physical properties and dimensions of the material and the angle of incidence of the beam. Having struck the covering, the radiation is either reflected away, back to the environment, absorbed in the covering or transmitted into the inside of the structure. Once inside, the major part of the radiation is absorbed by the structure, plants and floor (Kirsten, 1973), but part is lost as some radiation is transmitted out through the covering after secondary or multiple reflections from the many internal surfaces. Such reflections can cause bright spots on the floor or crop canopy (MacKinnon, 1977). A relatively small amount of the radiation is actually used by the crop in photosynthesis, and more goes to heating up the glasshouse and evaporating water in the evapo-transpiration process.

The angle of incidence of the direct beam radiation can be calculated from equations such as those shown by Duffie and Beckman (1980). A knowledge of the position of the sun in the sky and the orientation of the receiving surface are all that is required for this and then the angle of refraction can be calculated by using Snell's law. From these two angles, along with the extinction coefficient and thickness of the covering material, the reflection, absorption and transmission coefficients can be calculated. For example, if i is the angle of incidence of the radiation upon the surface, then b, the angle of refraction is calculated as:

$$\sin(b) = RI_{air} * \sin(i) / RI_{gl}$$

where Ri represents the refractive index. Using the Fresnel relationships, the reflection of unpolarized light passing through one medium to another is:

$$r_{perp} = \sin^2(b-i) / \sin^2(b+i)$$
$$r_{par} = \tan^2(b-i) / \tan^2(b+i)$$

where 'perp' and 'par' are the perpendicular and parallel components of polarised light respectively. The initial value of r, r', is then calculated by averaging the two components

$$r' = 0.5 * (r_{perp} + r_{par})$$

The absorption of the radiation in the medium is assumed to be proportional to its intensity and the distance travelled in the medium:

$$dI = I * K * dx$$

where dI is the amount absorbed, I is the intensity, dx is the path length and K is a constant of proportionality called the extinction coefficient. The total path length inside the medium is:

$$x = z_{gl} / \cos(b)$$

where x is the total path length and z_{gl} is the thickness of the material. By integrating along the path length an intermediate value of t' ($=I_{in}/I_{out}$) can be calculated which is the transmittance of the medium taking absorption losses only into account (Duffie and Beckman, 1980; Agarwal and Verma, 1977):

$$t' = e^{-K*x}$$

Finally, the transmittance, reflectance and absorptance of the material can be calculated as follows:

$$t = t' * (1-r') / (1+r') * (1-r'^2) / (1+r'^2*t'^2)$$
$$r = r' * (1 + t' * t)$$
$$a = 1 - r - t$$

where t, r and a are the transmission, reflection and absorption coefficients.

After calculating such values for the second glass layer, if one is present, and using albedo values for the crop and soil, the amount of radiation absorbed by the components can be calculated. Amhadi and Glockner (1982) used the following equation to describe the radiation absorbed by the cover:

$$I_{a,cov} = a_{cov}*(1+r_c*t_{cov})*I_{dir}*\cos(i) + a_{cov}*r_c*t_{cov,dif}*(I_{dif}+I_{gr})$$

where

$I_{a,cov}$ = radiation absorbed by the cover
A_{cov} = cover absorption coefficient
r_c = crop reflection coefficient
t_{cov} = cover transmission coefficient to direct radiation
$t_{cov\ dif}$ = cover transmission coefficient to diffuse radiation
I_{dir} = direct radiation intensity
I_{gr} = Intensity of radiation reflected by surrounding ground
I_{dif} = Intensity of diffuse radiation

Similar treatments lead to the amount absorbed in other cladding layers and the floor inside.

There are many values of transmission coefficients for cladding materials and average values for glasshouses to be found in the references cited. Hand et al. (1970) used a mean glasshouse transmission coefficient for direct and diffuse light of 0 70 whilst Critten (1983) measured the transmission in a four-span venlo house under overcast conditions and found that between 65 and 70% of the light was transmitted. Kozai and Kimura (1977) produced the following transmission coefficients for 3 mm thick glass, having a refractive index of 1.526 and an extinction coefficient of 7.6 m^{-1}:

Angle of Incidence	0	10	20	30	40	50	60	70	80	90
Transmission coeff.	.86	.86	.86	.85	.85	.82	.77	.65	.40	.00

Godbey et al. (1979) list the transmission coefficients of various cladding materials

Material	Thickness /mm	Transmission Coefficient
Polyethylene	0.101	.888
Fibre glass: flat	0.636	.831
flat	1.016	.729
corrugated	1.016	.792
Polyester	0.127	.865
Glass	3.175	.878
Polycarbonate	1.588	.844
Polyvinylfluoride	0.076	.910

Measurements made by Agarwal and Verma (1977) show that heat absorbing glass absorbs 53% of incident radiation, transmits 41% and reflects the remainder. Nisen (1979) gives values of 0.92 transmitted for 0.1 mm PVC, 0.91 for 3 mm horticultural glass and 0.90 for 1.1 mm layered polyester. Kirsten (1973) states that for silicate glass, 86% of radiation between the wavelengths 0.35 - 2.8 microns is transmitted, but he does mention the important problem of soiling. As an average figure, he assumes that about 10% of the light incident on the outer surface of the covering is blocked by dirt deposits. He suggests that this figure could be higher if the glass is not regularly maintained or if it is located near industrial regions.

Melinex, a covering material produced by ICI which is double skinned at night and single skinned by day, has a transmission coefficient of 83% in its deflated or single skin form. When it is inflated to form the double layer, the transmission drops to 77% but in both cases the absorption losses are approximately 3%. Using the Melinex highlight film the transmission coefficients increase to 91.6% and 88.7% in the deflated and inflated states respectively and absorption losses are also decreased. The reduction in transmission at night is not a problem of course. ICI state that in the best modern glasshouses, 10% of the light is lost by reflection and absorption in glass, and 20% more is lost through the structure and overlapping of the glass, giving an overall loss at the plant level of about 30% (ICI, 1981).

Statham (1975) also discusses losses due to the structure of the glasshouse, stating that up to 40% of the diffuse radiation can be lost by shading from the structure. He goes on to say that the semi-cylindrical and wide-span structures offer the best transmission although there is quite a rapid deterioration in the plastic skin which should be changed every two years. Hanan et al. (1978) note that the transmittance of polyethylene decreases from 83% to 72% in about one year and Mastalerz (1977) states that the transmittance of glass does not vary with age. This also has implications for energy conservation methods which concern alternative cladding materials. For crops where light intensity is important, a cladding material which had decreased transmittance over short times might prove costly to replace at regular intervals and glass might be the better alternative. Mastalerz continues by saying that, in general, glasshouse glass is changed every 15 to 20 years in houses where putty holds the glass to the frame and has to be renewed but with the use of aluminium frames, and good glass maintenance, the life of the glass is longer. He also considers the shape and orientation of the glasshouses and found that the best light transmission is achieved in hemispherical domes, and an east-west ridge orientation in a glasshouse with roof angle 26° gives better transmission than a north-south orientation.

There is general agreement that an east-west orientation gives better transmission than the north-south one (Harnet et al., 1979; Statham, 1975; Kozai and Kimura, 1977; Kirsten, 1973), but the north-south orientation does give a more even distribution of the radiation over the crop inside. It has been found that the non-uniformity in the distribution of radiation inside an east-west oriented house is due in part to the glass itself, and not solely to the structural pieces in the way (Kozai and Kimura, 1977). Kirsten (1973) also considers glasshouse designs and etched glass surfaces which will increase the winter transmissivity of the structure. However, as radiation levels in winter are low, the actual amount of extra radiation reaching the crop inside may not warrant the extra expense or trouble which such designs may cause.

In the model itself the user can choose to have the glasshouse oriented in whatever direction he wishes. The optical coefficients used in the model are calculated according to the method given by Duffie and Beckman (1980) which is outlined above. An average value of 16.0 m^{-1} was used for the extinction coefficient but this was altered during the course of the test runs to see the effect on the heat requirement. The albedo of the floor can also be set by the user to simulate bare earth, black or white polyethylene, or concrete for example. For the solar radiation input, GHFORSM can use data values at regular intervals daily values which are then integrated around a sine curve or it can generate its own values according to a method given by Privett (1979).

Longwave Radiation

The short wave radiation flux constitutes a net gain to the glasshouse under all daylight conditions but the longwave radiation picture is very different as the glasshouse plays an active part, being an emitter at these wavelengths. Long-wave or thermal radiation exchange occurs between the glasshouse and the external environment, as well as between the internal glasshouse surfaces. The net flux of radiation between surfaces depends upon such things as the temperatures of the surfaces, their emissivities and the shape and orientation of each with respect to the other. For a grey surface the energy emitted as longwave radiation is:

$$E = e * s * T^4$$

E = energy emitted

e = emissivity

s = sigma (the Stephan-Boltzmann constant = $5.67 * 10^{-8}$ W/m^2K^4)

T = surface temperature of the emitter

Radiation exchange between surfaces is dealt with by McAdams (1954) and he shows that such an exchange can be represented as:

$$q_{1-2} = A_1 * s * T_1^4 \ / \ (1/e_1 + 1/e_2 - 1)$$

where 1 and 2 represent the two surfaces and thus q_{1-2} stands for the energy lost from surface 1 to surface 2. Similarly

$$q_{2-1} = A_2 * s * T_2^4 \ / \ (1/e_2 + 1/e_1 - 1)$$

For surfaces of infinite area $A_1 = A_2$, and combining the two equations gives the net flux for either surface:

$$q_1/A = -q_2/A = s * (T_2^4 - T_1^4) \ / \ (1/e_1 + 1/e_2 - 1)$$

The more general case is shown by McAdams (1954) and Duffie and Beckman (1980), amongst others:

$$q_1 = s * (T_2^4 - T_1^4) \ / \ ((1-e_1)/(e_1*A_1) + 1/(A_1*F_{12}) + (1-e_2)/(e_2*A_2))$$

Once again, $q_1 = -q_2$. F_{12} is called the view factor and is defined as the fraction of energy which leaves surface 1 which is intercepted by surface 2. When $A_1 = A_2$ and $F_{12} = 1$, this equation reduces to that of the infinite parallel plane (all radiation leaving surface 1 is intecepted by surface 2). Another special case is that of an object radiating to a much bigger enclosure, consider a horizontal glasshouse roof (3) radiating to the sky (1) for example. The general equation can be re-written as:

$$q = A_3 * s * (T_1^4 - T_3^4) \ / \ ((1-e_3)/e_3 + 1/F_{31} + A_3*(1-e_1)/(A_1*e_1))$$

In this case, F_{31} is again 1, and A_3/A_1 is 0 (A_1 is very much greater than

A_3), which gives:

$$q/A_3 = e_3 * s * (T_1^4 - T_3^4) \text{ W/m}^2$$

Gimmestad et al. (1982) give a similar equation for radiation heat exchange between a flat plate and the sky:

$$q/A_{plate} = - e_{plate} * s * (T_{plate}^4 - T_{sky}^4)$$

The - sign is included here to maintain the convention that q is the net radiation to a surface of temperature T_{plate} and emissivity e. Thus, if T_{plate} is greater than T_{sky}, then q is negative, indicating a loss from the surface in question. T_{sky} is the 'effective' sky temperature which Gimmestad et al. related to the outside air temperature T_{air}:

$$T_{sky} = D * T_{air}$$

The value of D varies between 0.93 and 1.0 as the sky condition changes from clear to heavily overcast.

Kanthak (1970) goes into rather more detail and considers the lower six air layers which contribute most to the atmospheric radiation. The lowest layer, some 87 m thick, accounts for about 72% of the radiation, which originates from water vapour, CO_2, O_3 and dust. However he does use a similar equation for radiation exchange between the sky and a surface:

$$Q = e * s * (T^4 - T_{air}^4 * (.82 - .25 * 10^{-.126} *p))$$

where p is the water vapour pressure in the outside air in mm of mercury.

In GHFORSM the floor and the screen are both assumed to be parallel, as are the upper and lower roof layers (should both be present) and so a parallel plane exchange equation is used (view factor = 1.0). For the exchange between the sky and the upper roof surface, as well as the exchanges between the roof and the screen or floor, the general equation which includes a view factor is used. Radiation from the sky includes a contribution from the water vapour in the air as does that modelled by Van Bavel et al. (1979). The emissivity values of the surfaces can all be altered but in the first runs the sky, the glass cladding and the floor were all assumed to have emissivities of 1.0.

These are the general equations which govern the transfer of heat in the glasshouse. The equations used in the model are given in the next chapter with a description of FORSIM, the integration package used with the model.

Name	Description	Units
A	Area	m^2
a	Absorption coefficient	
b	Angle of refraction	Radians
c	Heat capacity	J/kgK
D	Gimmestadt's coefficient (1982)	
d	Density	kg/m^3
E	Energy	J
e	Emissivity	
F	View factor	
H	Humidity	kg/m^3m^2
h	Heat transfer coefficient	W/m^2K
I	Solar radiation	W/m^2
i	Angle of incidence	Radians
K	Extinction coefficient	m^{-1}
k	Thermal conductivity	W/mK
l	Wavelength	m
L	Long-wave radiation	W/m^2
N	Number of air changes	s^{-1} or h^{-1}
p	Vapour pressure	mm of Hg
q	Heat transferred	W or W/m^2
R	Resistance	s/m
Ri	Refractive index	
r/r'	Reflection coefficient	
s	Stefan-Boltzmann coefficient	W/m^2K^4
T	Temperature	K
T'	Small temperature difference	K
t/t'	Transmission coefficient	
U	U value	W/m^2K
u	Inside air speed	m/s
V	Volume	m^3
v	Wind speed	m/s
x	Path length	m
z	Height or thickness (z-axis)	m

Subscripts	Description
air	Air
b	Black body
c	Crop
cov	Cover
cu	Cuticular
dif	Diffuse
dir	Direct
f	Floor
g	Glass
gh	Glasshouse
gr	Ground
in	Inside
l	Wavelength
lat	Latent heat
leaf	Leaf
n	net
out	Outside
pipe	Heating pipe
par	parallel
perp	Perpendicular
s	Soil
sat	saturation
sen	Sensible heat
sky	Sky
st	Stomatal
tot	total
v	Ventilation
w	Water

Chapter Three

GHFORSM: A Glasshouse Model

Having looked at the environmental conditions and heat transfer pathways to be found within the glasshouse, a general description of the model and the integrating package (FORSIM) can be given.

GHFORSM models the thermal behaviour of a glasshouse by calculating the energy flows within and through the system and it predicts the the temperatures of all the glasshouse components as well as the amount of heat required to maintain the inside air temperature at a given, blueprint level. The numbering system which defines the components has been described in the preceding chapter. In more detail, numbers 3,5 and 7 are the roof components, and if the roof is to be double glazed, then all of these are present. If the roof is to be single glazed, then only component 3 is needed. Components 9, 11, 13 and 15 make up the inside of the structure between the roof and the floor surface. Usually, and always during daylight hours, only component 15 is present, but when the thermal screen is drawn over the crop then there are two distinct air layers, one above and one below the screen and in this case components 9, 11 and 13 are present but 15 is not. Component 17 is the top floor layer and its upper surface is the interface between the floor and the inside air. Subsequent layers are deeper and thicker and component 29 is considered to be external to the glasshouse structure which means that it acts as a path for heat to flow into and out of the glasshouse, but plays no part in the heat capacity of the system as it is defined. The system configurations showing the components present at any given time which GHFORSM can model are shown in figure 3-a, with those on the left representing daytime configurations, and those on the right are for night. Thus, the top two systems are identical with a single glazed roof and no thermal screen; in the next row a screen has been added for use at night; the third set shows the use of a double glazed roof and the last shows a system which contains both a double glazed roof and a thermal screen at night.

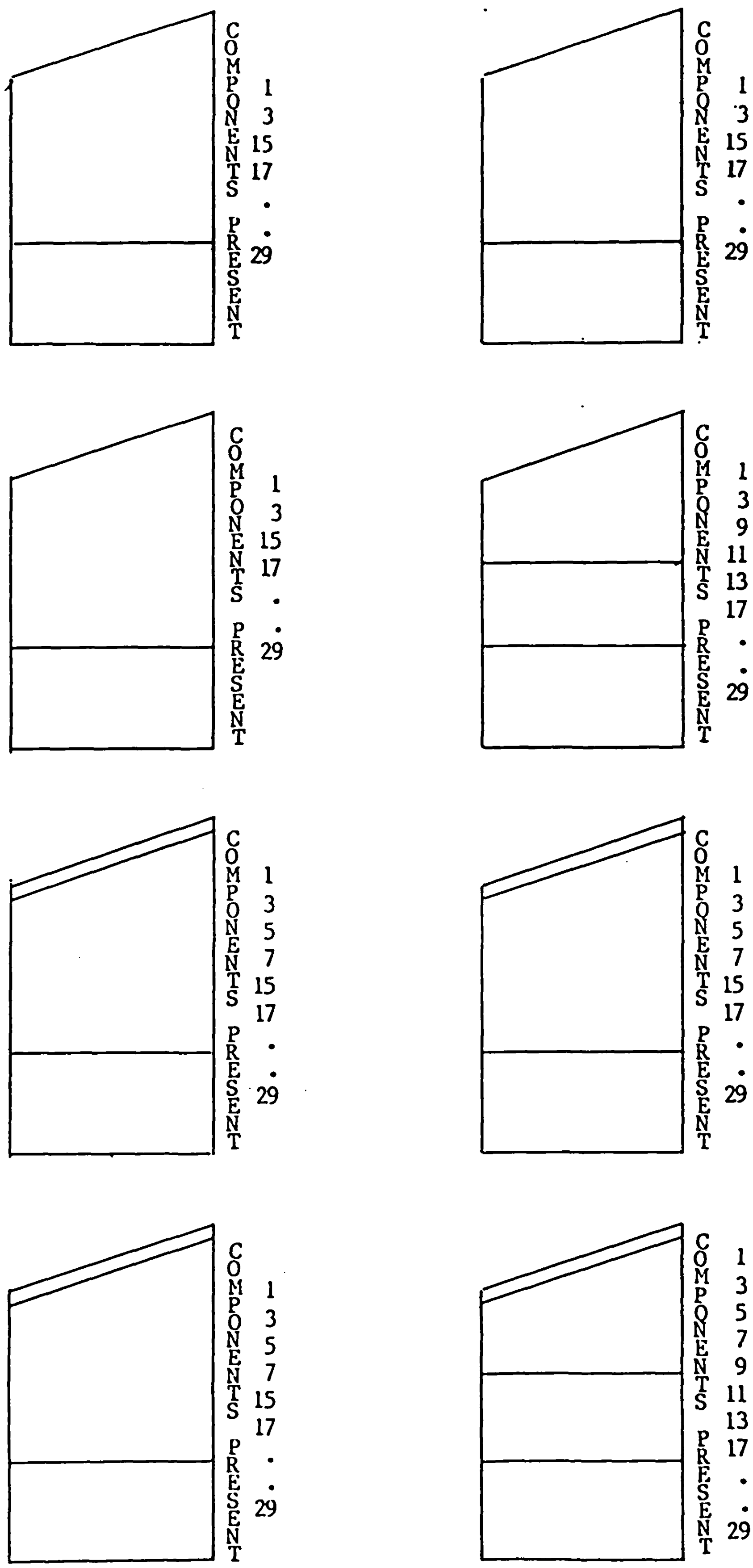


Fig. 3-a
The system configurations which GHFORSM can model, showing which components are present at any given time

The model is set out in sections with each major routine being assigned its own section or subroutine and a full listing can be found in the appendix. An advantage of this system is that it allows routines to be switched in and out of the model as required, as well as allowing alterations to be made quickly. For example, the thermal screen equations are only included in the model if the screen flag, SCREEN, is assigned a value of 1.0 and if the user wishes that the screen should behave in a different manner, then he would need only to change the screen section in order for it to do so.

FORSIM

FORSIM, the main calling program may require to run through UPDATE, the actual model, many thousands of times and to save computer time routines which are only needed once during the run are put into separate subroutines. For example, the system parameters need only be loaded once into the program and the print routines are only required at the end of the run.

FORSIM handles the integration required in GHFORSM. It was decided to use this because it seemed to be the most suitable package available. CSMP which is a simulation package used by some other workers was not available and FORSIM was recommended as an alternative. An important factor in the choice of FORSIM was that it was fully supported by the College computer centre and advice would be easy to obtain. However, although the model in this form uses FORSIM, the majority of the routines would require only slight alteration to allow them to be used either with some other integration package, or with integration routines which were included as part of the model itself.

FORSIM is a program developed by Atomic Energy of Canada Limited (AECL), and comprises a set of subroutines for the continuous integration of a system of differential equations. The package allows the user to write his equations in FORTRAN, into one or more subroutines which are compiled and handled by the main FORSIM control routine. In subroutine UPDATE, the subroutine which contains the modeller's main routines, FORSIM receives instructions for the simulation. The names of the variables to be integrated are listed in the COMMON block labelled /INTEGT/, whilst the names of the derivative equations are listed, in the same order, in the block marked /DERIVT/.

It is important to allow FORSIM to gain convergence of the equations in an efficient manner by whatever means are at its disposal and so some variables are under FORSIM's sole control, but there are others which the user can set. The /RESERV/ block contains the time and method of integration variables. The original FORSIM package contained several different integration methods, but the current version contains variations on only two algorithms which proved both 'robust and reliable' in the past. METHOD 1 is a Runge-Kutta-Fehlberg routine, METHOD 2 is a fixed step length Runge-Kutta method and METHOD 3 is a fixed step Euler method. These last two are the only fixed step length methods available and can give no indication of the error sizes. METHODs 4 to 8 are Adams routines and 9 to 13 are Gear backward difference methods for stiff equation sets. A more complete discussion of these METHODs can be found in the FORSIM manual and in the references cited therein. METHOD 4 was used in GHFORSM because it required less computer time for execution than METHOD 1. METHODS 2 and 3 were not used as these were fixed step length methods and would not make use of FORSIM's ability to find the most efficient step length as the run progressed.

The /CNTROL/ block contains variables which are made available to the user to help in finding out how well the simulation is progressing and to allow the user to control the flow of the program under certain conditions. The most important variable listed in this section is INOUT which takes on different values as integration proceeds. For example, at the start of a run, when FORSIM encounters a *MYCONS* statement which indicates the presence of data, INOUT is given a value of -3 by FORSIM. The user may then call any initialisation subroutines by directing FORSIM to execute certain program lines subject to INOUT having a value of -3.

There are three stages in the execution of a FORSIM simulation. Firstly, in the input and initialisation stage, FORSIM receives instructions about which variables are to be integrated, it accepts any data which may be required for the run, and assigns initial values to the variables. This is carried out by several sweeps through the user's routines in UPDATE at time T = 0. Secondly, during the integration stage, T is advanced and sweeps through UPDATE are made as required by the integration method chosen to meet the error criterion set by the user. During this period the value of T will pass through user specified printout times and at such moments the INOUT variable is given a value of 1 and routines in UPDATE can then direct the program control to the print or other subroutines. Finally, when a termination condition has been satisfied, the simulation finishes after the next converged step. Having ceased integration, a final pass through UPDATE is carried out to allow the last printout of any required information to be made (Carver et al. 1978).

A description of GHFORSM

The remainder of this chapter describes the model and the more important equations, using the terminology described in the previous chapter. Figure 3-b shows the energy exchanges which would be present in a system with no thermal screen and a single glazed roof.

In sections 1 and 2 of GHFORSM all the arrays are named and dimensioned and the COMMON blocks required by FORSIM are listed. Section 3 assigns some of the parameter values for a particular run, indicating for example whether the roof is single or double glazed and whether the heater is to be used. In section 4 all of the initial values required once only at the beginning of the run by FORSIM are set and any data is read into storage arrays.

Section 5 deals with the flow of time in GHFORSM and FORSIM. During a run the time variable T in FORSIM runs from 0.0 to 10.0 FORSIM seconds (FS) regardless of the number of days actually being simulated. This section divides this length of time into units of equal length which will represent single days in GHFORSM. In Section 6 T is changed from FS to hours and minutes of real time

Section 7 is used to interpret the data read in section 4. External meteorological data may be entered by the user as discrete points but as FORSIM will deal with small time steps, a method of deriving continuous values from the data points had to be chosen. A linear interpolation method is used and the outside air temperature can be used as an example of this:

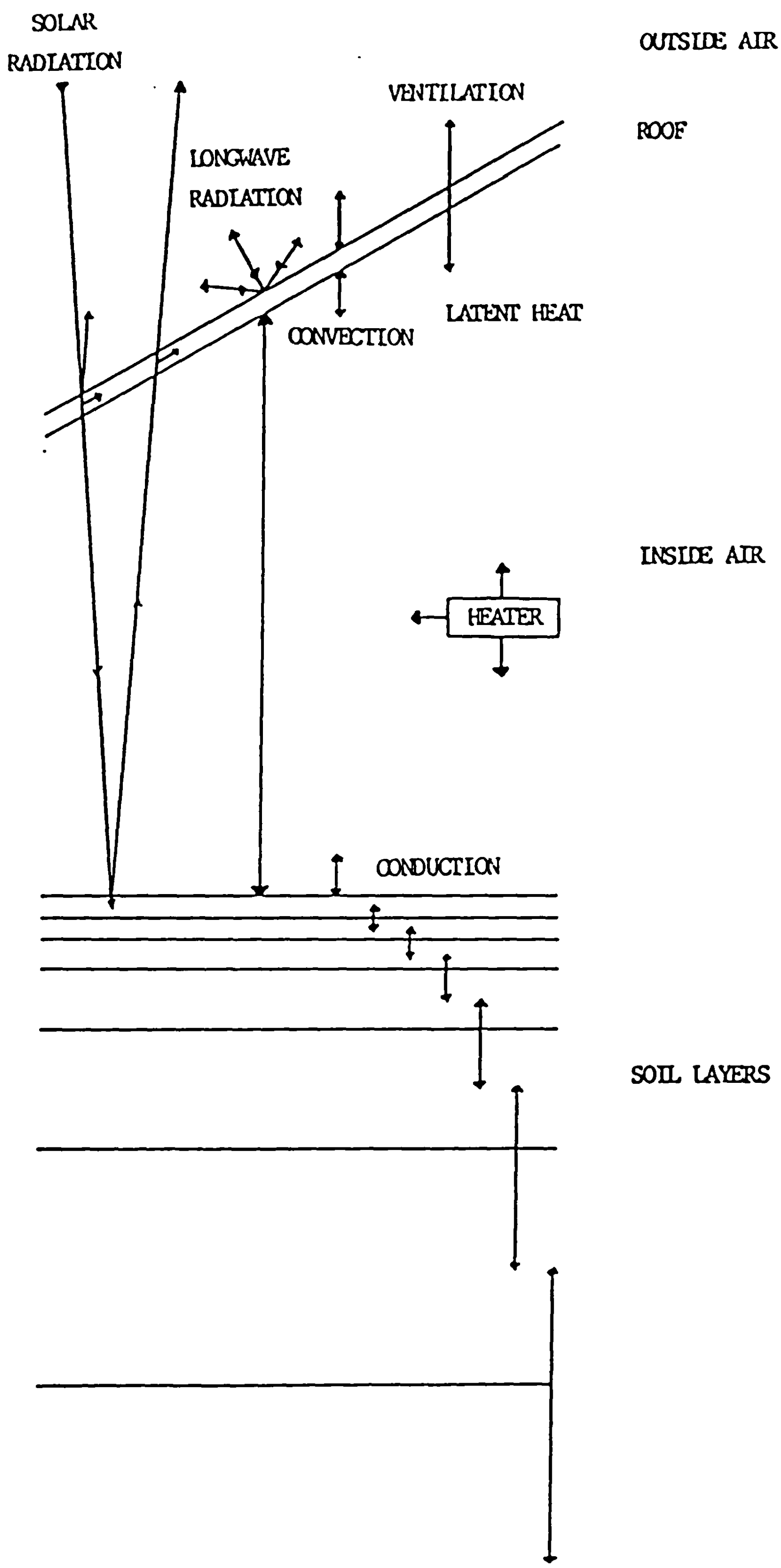


Fig. 3-6
The heat transfer pathways included in the test runs.

$$T_1(t) = T_1(K) + [(T_1(K+1) - T_1(K)) * f(t)] + 273.16$$

In this example (t) means 'at time t' and (K) denotes a storage array position and f(t) is the time elapsed since the previous data point time, represented as a fraction of the interval between data points. The outside air humidity, heater setpoint and solar radiation are all treated in the same way (although the solar radiation can be generated continuously by routines in the model).

Section 8 deals with the solar radiation part of the model. There are several paths which may be followed by solar radiation striking the top of the roof. The coefficients of reflection (r), transmission (t) and absorption (a) are calculated for any given time by the model in accordance with the equations shown in chapter three. The intensities of radiation reflected, transmitted and absorbed by the various components of the system (all in W/m^2) are calculated as follows:

$$I_{t,3} = I * t_3$$
$$I_{a,3} = I * a_3 * (1 + I_{t,3} * r_7) + I_{17} * r_{17} * t_7' * (1 - r_3')$$
$$I_{t,7} = I_{t,3} * t_7$$
$$I_{a,7} = I_{t,3} * a_7 + I_{17} * r_{17} * a_7' * t_7'$$

Here, $I_{t,3}$ is the solar radiation transmitted through component 3. Factors such as r_7' represent the coefficients which need to be used for diffuse radiation reflected from the floor.

Air exchange between the inside and outside air takes place via leakage (passive ventilation) or through open vents (active ventilation). Section 9 of GHFORSM takes both of these into account and the overall ventilation rate is calculated as follows:

VENT(K) = 0.002 + VTOPEN(K) * VDELTA

where VENT(K) is the ventilation rate and 0.002 is the leakage rate, both in m^3/m^2s, and VDELTA * VTOPEN(K) is the extra exchange due to the degree of opening of the vents. The 0.002 and the other values used to define the temperature range over which the vents open and to define VDELTA (the increment in the amount of air exchange due to a 1% increase in the vent opening) can all be set by the user before the run starts.

The longwave radiation emitted from the sky and the various glasshouse surfaces is calculated in accordance with the methods shown in chapter two and are specified in section 10 of GHFORSM. For radiation from the sky Van Bavel's (1979) equation is used which includes a contribution from the water vapour in the air.

$$L_a = e_1 * (s * T_1^4) * (0.605 + 0.0408 * \ (1370 * H_{out}))$$

For radiation between the two roofs (if two are present) the following equation is used which assumes that the roof surfaces are square metre sections of infinite parallel planes:

$$L_{3,7} = s * (T_7^4 - T_3^4) \ / \ (1/e_4 + 1/e_7 - 1)$$

where e_4 is the emissivity of the lower surface of the top roof and e_7 is that of the upper surface of the lower roof. For the exchange between a roof surface and the thermal screen or the floor the equation is a little more complex as a view factor (F) is needed. The view factor is defined as the amount of radiation leaving one surface which arrives at the other. The exchange between the roof and the floor can be represented as:

$$L_{7,17} = \frac{s * (T_{17} - T_7)}{(1-e_{17})/(e_{17}*A_{17}) + 1/A_{17}*F_{7,17} + (1-e_8)/(e_8*A_7)}$$

If we take the floor area to be 1 m^2 then the roof area directly above this will be 1 / COS(b_r) where b_r is the roof slope angle. The view factor can be represented as 1 / (2+COS(b_r)). In section 10 the humidity of saturation of the inside air also calculated and this is done as follows:

$$H_{sat}(T_{15}) = 1.323 * \exp(17.27 * (T_{15}-273.16) \ / \ (T_{15}-35.86)) \ / \ T_{15}$$

Section 11, 12 and 13 all deal with the heat balance equations for the components and the different stages in the daily cycle of the glasshouse require different sets of equations to be used. Section 11 handles the thermal screen and 12 deals with the period of time just after the screen has been removed when the air layers are mixed. Section 13 contains the equations which deal with the heat balance without the thermal screen, and all three sections can include a double glazed roof and heating. For the sake of brevity the following examples will show the energy balances for a single roofed glasshouse during daylight hours (i.e. there is no thermal screen). For the roof (component 3) the change in temperature is given by:

$$T_3(t)-T_3(t-1) = G_3 * (h_2 * (T_1-T_3) - h_4 * (T_3-T_{15}) + L_{a,3})$$

which is the energy exchange by convection between the outside air and the roof and that between the inside air and the roof (in units of W/m^2) plus the radiation term $L_{a,3}$ which is expanded below:

$$L_{a,3} = L_1 * e_3 - L_{3,1} + L_{3,17} + I_{a,3}$$

This is the longwave radiation absorbed from the sky less that emitted to the sky, plus the exchange between the roof and the floor inside the glasshouse. The last term is the shortwave radiation absorbed by the roof. The sum of all these terms is multiplied by G which converts the W/m^2 into a temperature rise per second. G can be represented as:

$$G_3 = 1 / (c_3*d_3*V_3) \quad K/(W/m^2)s$$

In the model itself there is an extra term in this to convert time measured by FORSIM in FS to real time. The balance for the floor also contains convective and radiative terms as well as a conductive one:

$$T_{17}(t)-T_{17}(t-1) = G_{17} * (h_{16} * (T_{15}-T_{17}) - h_{18} * (T_{17}-T_{19}) + L_{a,17}$$

The conductive term is formulated in the same way as the convective term with h_{18} being the conductive transfer coefficient between components 17 and 19. The radiation term consists of the longwave exchange with the roof and the solar radiation absorbed by the floor:

$$L_{a,17} = L_{3,17} + I_{a,17}$$

The inside air temperature change is more complex and can be represented as:

$$T_{15}(t)-T_{15}(t-1) = G_{15} * (h_5 * (T_3-T_{15}) - h_{16} * (T_{15}-T_{17}) - E_{vent} + E_{heater})$$

The first terms can be recognised as convective exchanges. The E_{vent} term is the ventilation loss and is shown below

$$E_{vent} = (T_1 - T_{15}) * h_{15} * VENT(K)$$

The final term is the gain from the heating system if the heater is switched on, which exactly matches the losses from the inside air:

$$E_{heater} = h_5*(T_{15}-T_3) + h_{16}*(T_{15}-T_{17}) + E_{vent} + (T_{set}-T_{15}) * V_{15} * c_{15} * d_{15}$$

The first terms of this are the losses due to convection and ventilation and the last terms alter the heater power so that the the heater setpoint temperature is maintained. In the model the extra heat which forces the inside air temperature to follow the setpoint may be added slowly so that large jumps which need more computer time to be handled by FORSIM are not required.

Section 14 handles the balance for the deeper soil layers which only exchange heat by conduction. In the model the floor and the soil beneath is split into a number of layers with the thickness of each layer increasing with depth. Each layer is assumed to be of uniform temperature and composition, and heat flows from the centre of one layer into the centre of the next. These soil layers can be defined individually so that the top three might be made of concrete for example, whilst the remaining ones might be soil. The increase in thickness with depth was included for reasons of mathematical stability as the temperature variation through time would be less for the thicker layers at the bottom. The particular thicknesses were chosen so that the temperature variation of the bottom layer would be small (less than 1 °C). The heat transfer coefficients and the temperature rise index are more fully described in the appendix but the heat transfer coefficient is derived by combining the thermal conductivity and the distance between the centres of layers. Considering layers 17 to 27 inclusive in more detail, the thickness of each layer and the distance between centres is:

Layer Number	17		19		21		23		25		27
Thickness (metres)	0.01		0.02		0.04		0.08		0.16		0.32
Distance between centres		.015		.030		.060		.120		.240	

The h variables are coefficients of heat transfer between components and they are called CHT(x) in GHFORSM. A more complete description of their action is given in the appendix but as an example, their method of calculation is shown here. They are calculated by dividing the thermal conductivity by the distance between centres in accordance with the equation shown below:

$$h(n) = k/((THICK(n)+(THICK(n+1))/2)$$

where n is the layer number. The values for each of the soil variables are listed below and are obtained using a k value of 1.0 W/mK for each layer.

$$h(18) = 1.0 \ / \ .015 = 66.67 \ W/m^2K$$
$$h(20) = 1.0 \ / \ .03 = 33.33 \ W/m^2K$$
$$h(22) = 1.0 \ / \ .06 = 16.67 \ W/m^2K$$
$$h(24) = 1.0 \ / \ .12 = 8.33 \ W/m^2K$$
$$h(26) = 1.0 \ / \ .24 = 4.17 \ W/m^2K$$

The heat exchange involving layer 21 can be used as an example:

$$T_{21}(t)-T_{21}(t-1) = G_{21} * (h_{20} * (T_{19}-T_{21}) - h_{22} * (T_{21}-T_{23}))$$

Section 15 contains the routines used to find out how well the model was functioning. A record of the number of sweeps through UPDATE was kept and the maximum and minimum values of the derivative variables were stored with the time at which these occured. When problems in the running of the model are found, this routine shows when the rates of change of the derivative values are at their highest, indicating the times at which FORSIM is having the most difficulty. Section 16 calculates the heat stored in the layers of the system and section 17 deals with the relative humidity. In GHFORSM the method used to calculate the inside air humidity is similar to that employed by Van Bavel et al. (1979). Water is evaporated across a resistance which is determined by the solar radiation and the air boundary layer resistance to flow. The amount of transpiration is also affected by the leaf area index which is a measure of the leaf area per unit floor area and this is also included in the model. The exchange of water vapour due to the ventilation between the inside and outside air is included as well. The inside air humidity change can be expressed as:

$$H_{in}(t-H_{in}(t-1) = (H_{sat}(T_{leaf})-H_{in})*A_{leaf} \; / \; R(K) \; - \; (H_{in}-H_{out}(K))*VENT(K)$$

Section 18 calculates the heat losses from the system via the roof and soil. and through ventilation. Also the net solar gain and heat flux are calculated. In section 19 the temperatures calculated by FORSIM from the derivative values are assigned to their respective arrays and the program returns for another sweep unless it is required to finish. At the end of the run the print subroutines are called from section 20.

A full listing and an accompanying description of the model can be found in the appendix. The equations listed above are those concerned with the energy transfers of the system and comprise the main part of the model. The following chapter describes the verification and validation of GHFORSM.

Chapter Four

Modelling, Verification and Validation

Modelling

Simulation can be broadly defined as the use of abstract or physical models of real situations; as such, simulation is now a part of mankind's way of life, having developed throughout his history (Lewis and Smith, 1979). We test imaginary situations in our minds, formulate some opinion about their outcome and govern our actions according to our understanding.

A model is a simplification of the system or phenomenon it is designed to simulate. Whilst models of physical processes can give an insight into behaviour, the gravitational attraction of two masses for example, they are usually only 'good enough' representations of a particular situation or range of situations. Newton's laws of motion for example, are a 'good enough' description of forces and behaviour of objects at velocities encountered in everyday life. But these laws are not sufficient to describe motion at high speeds, where relativistic equations are required. Models only approximate reality and cannot be expected to provide information on every aspect of a system. Models of physical situations may be sufficiently good to get man to the moon, but knowledge of their limitations is just as important (Lewis and Smith, 1979).

Descriptive modelling

The simulation described above is classed as descriptive modelling and is the most widely used by the general population. More formally, general ideas and principles are conveyed by means of descriptive word models, and answers to 'what if...?' type questions are sought by recourse to a body of opinion, knowledge or judgement. Problems in the use of descriptive models arise when ideas are communicated to people of different backgrounds who may have different definitions for the words being used. The method of prediction in these models is not a formal process but is internal to the modeller and so this type of model can never be used in the same way twice in succession or by two different people. However, this type of modelling is inexpensive and, as the processes are second nature to most people, it is widely used in decision making (Emshoff and Sisson, 1970).

Physical modelling

Physical models, motor-car prototypes for example, are a good means of communicating ideas as they can be used to explain different facets of the same problem to people of differing backgrounds and abilities. However, with this type of model physical changes have to be made if different situations are to be investigated which is often both time consuming and expensive (Gordon 1969).

Symbolic modelling

Symbolic models may be of an explicit mathematical nature or more abstract but are relatively easy to communicate to people of similar technical background as the modeller himself. These models are often useful in focusing attention on one particular aspect of the situation, or in helping to define the processes and interactions which comprise the system. Generally their cost is low relative to the system they simulate and to a physical model of the same situation.

Symbolic models and simulation techniques are often used for system management and design problems where manipulation of physical models is either too dangerous, too costly, too time consuming or impossible. Examples of this are the models used in the design process for aircraft where building full scale prototypes for each new design idea would be very expensive, time consuming and dangerous for the test-pilot.

Computer modelling

Modelling has been used as a scientific tool for centuries and early scientists built physical models in the belief that the knowledge needed to do this would enable them to understand the real process itself. As mathematical methods were developed, physical models were replaced by mathematical ones as ideas could be expressed with a clarity and precision which the use of words does not allow (Jeffers, 1982). The advent of the computer has changed modelling yet again and computer simulation is becoming a much more widely applied research tool as the cost of computing continues to fall.

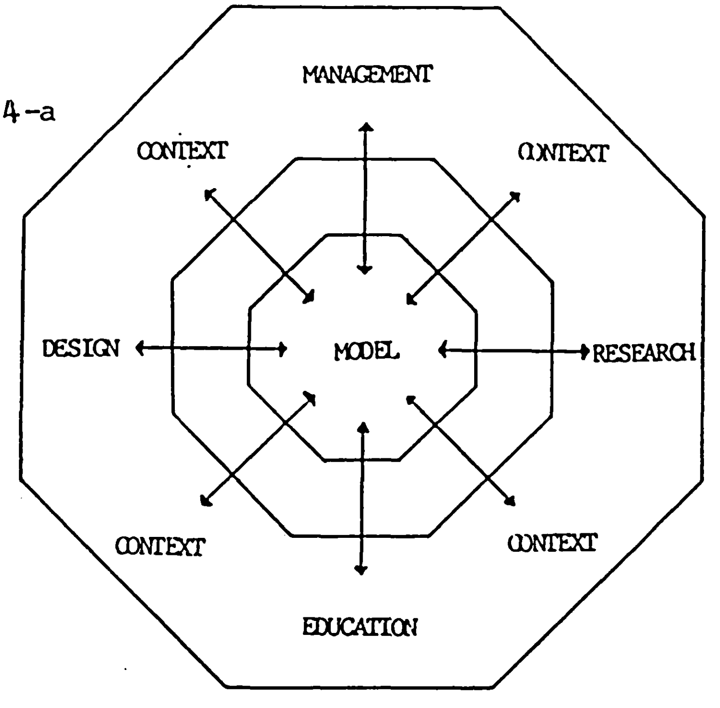
The computer has enabled researchers to develop models of much more complex systems than before. For example, some of the world's most powerful computers are dedicated to weather forecasting, predicting the circulation of the atmosphere on a global scale, a task which would have been impossible on any useful timescale only a few years ago. However, it is the development of the inexpensive and relatively powerful computers which has revolutionised modelling: there is widespread use of spreadsheet and financial modelling packages in business today which was non-existent ten years ago, and the low cost computer is now available to nearly every scientist whatever his field.

Computer models may be as simple or as complex as the situation requires. They may be very specific representations of well-defined and understood processes designed to solve a range of related problems. In this sense they may be likened to a book of tables to be consulted whenever a suitable problem arises. Alternatively a computer model can be designed to simulate some real life situation, the interactions of which can be observed directly or indirectly but cannot be predicted with accuracy. Such models try to break down the system into its component parts and simulate the interactions between them. By using these models the researcher hopes to learn about the system and understand what affects it. Different models of the same system may be produced by analysts interested in different aspects of the system and a modeller may well devise several different models as his understanding and knowledge changes (Gordon, 1969).

This second type of model may be a collection of models knitted together in a framework with linkages that represent the interactions between components; these may be the theories of the modeller himself. Some of these links may be correct representations of the real world but the modeller will be less sure of others. However, he must be aware that a model with incorrect links may give a correct answer, correct at least when judged by the criteria used in establishing accuracy.

A well designed model can provide useful information to users of a range of different disciplines and might be represented thus:

Fig. 4-a



Here a model is surrounded by a broad range of context and users of different backgrounds and abilities some with overlapping interests might all benefit from it. For example, a well tried and trusted model might be used by the researcher to investigate new techniques, by the designer in development, by someone wishing to learn about the system and by the manager as part of the decision making process.

The modelling process is made up of many different stages and one definition of the way to proceed is outlined below in figure 4-b.

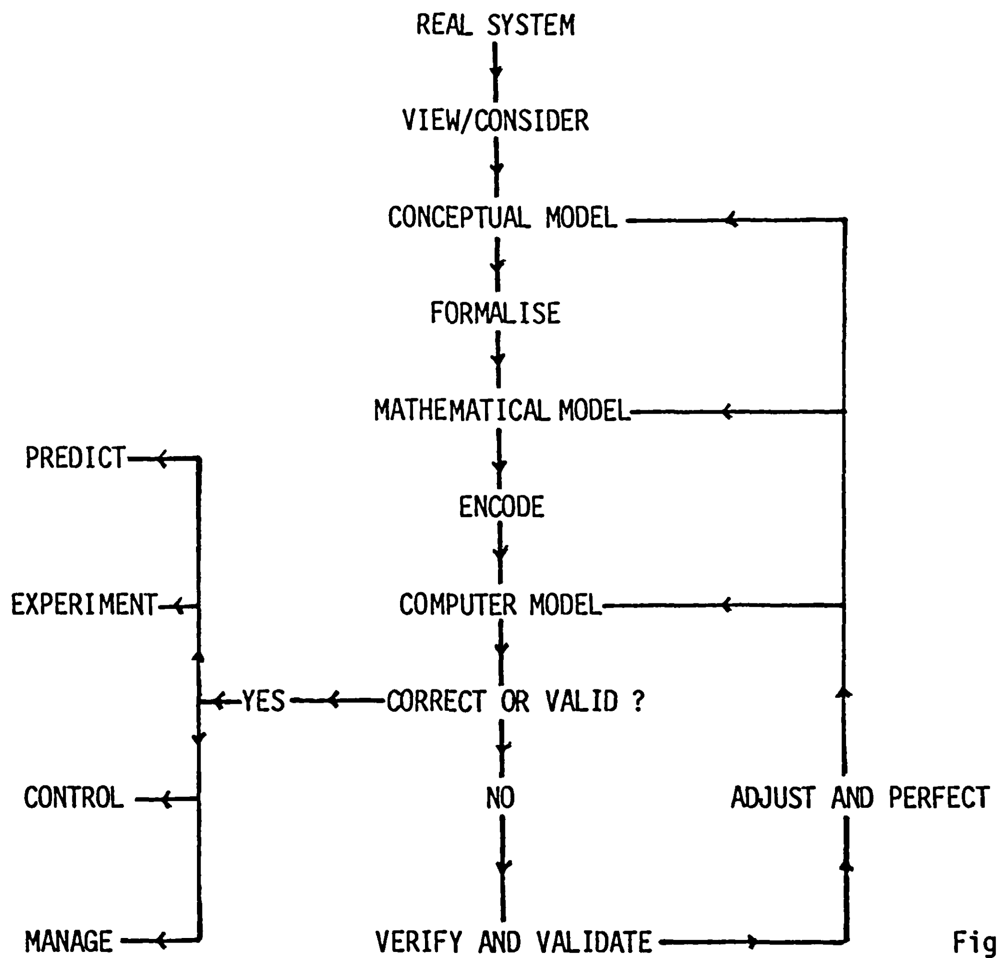


Fig. 4-b

Given a real system to model, the first stage is to consider the problem and develop some conceptual model of how the system operates. Where possible this stage should involve physically looking at the system to see what immediate problems come to light, and to get some idea of what modelling approach might be tried. Once completed, this model can be formalised into a mathematical one comprising the equations which describe the system. Then, this mathematical model can be encoded and fitted into a computer model framework which will handle the flow of information into and out of the model. Verification and validation are the next stages and involve testing to see that the computer model is a true representation of both the conceptual and mathematical models and to see how it compares with the real world. This process is repeated and the model is adjusted until the validation criteria have been met. Complete failure, when the model fails to predict the real world at all, may require returning to the conceptual model stage and altering that until it is sufficiently correct and complete.

Verification

The words verification and validation are used in this thesis to mean different things. Verification is the process of ensuring that the program coding is correct and that the model performs as intended, whilst validation is the process of seeing how well the model output compares with some reference data. Jeffers (1982) considers that the process of verification is one of comparing the behaviour of the model with the behaviour of the system being simulated. If the processes of the model are broadly similar to those of the real system then this does give the modeller a degree of confidence in the results produced. Models or sub-models which do not behave as expected have to be investigated and the modeller has to decide if the fault lies in the coding or in the reasoning behind the model. In verifying a model the question which should be asked is of the type: "does the programme operate correctly?" (Lehman, 1977).

Verification is the easier of the two processes to carry out. It is not difficult to check a program for coding errors although this is sometimes a tedious process. If a model is a combination of sub-models, then the links between each one and the output should also be examined (Martin, 1968).

The Verification of GHFORSM

The verification of GHFORSM began as soon as the first routines of the model were written. The modular nature of the program enabled testing of the routines to be carried out before each was included in the main program and then the inputs and outputs were checked to verify correct operation by extensive printing of the variables. Once complete, further tests were carried out on the whole program to ensure that it was working as intended and these verification or sensitivity tests are described below.

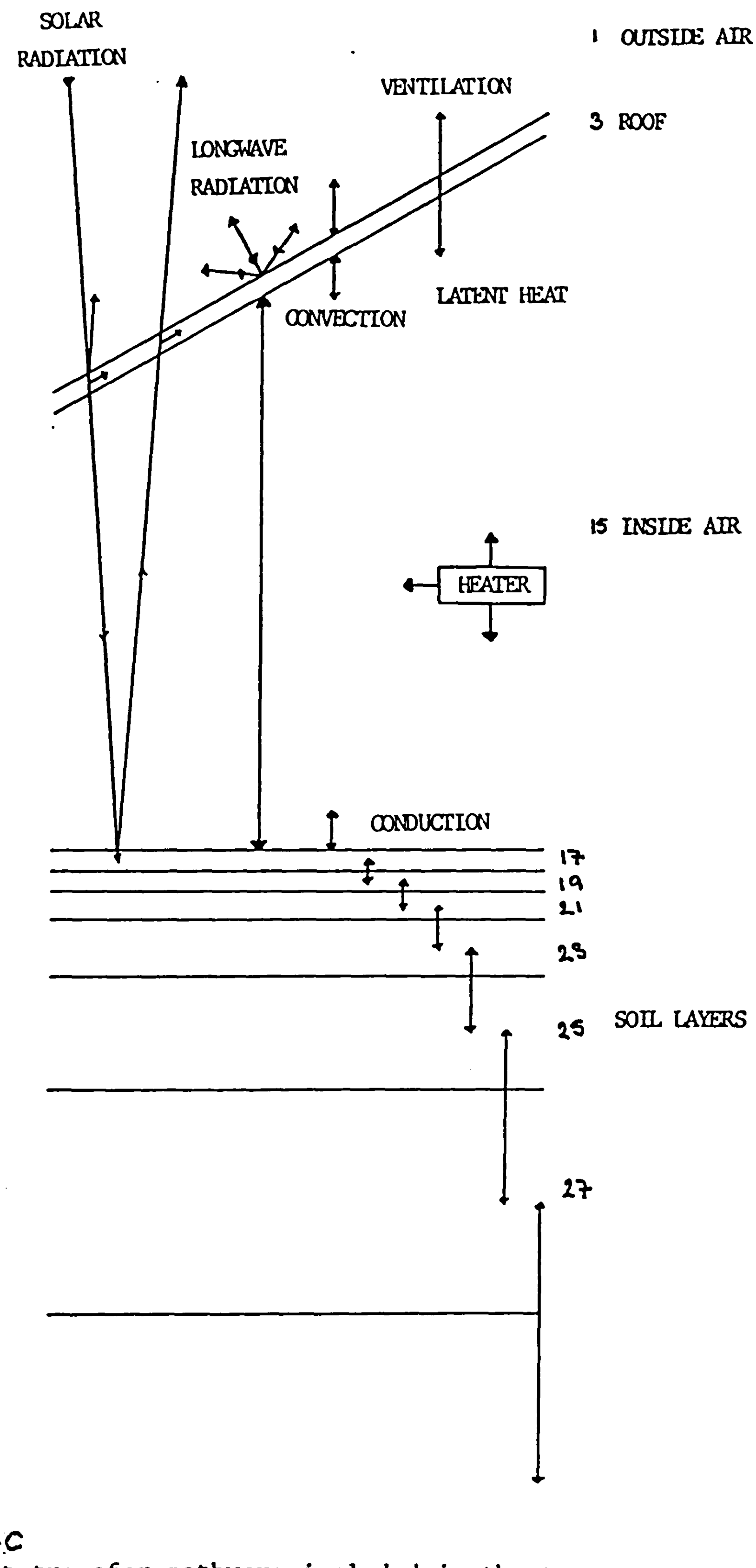


Fig. 4-C
The heat transfer pathways included in the test runs.

Firstly the model was set up to simulate a glasshouse operating over a period of twenty identical days; the same input data and daynumber were used for each day of the run. Next the final temperatures and rates of change of temperatures of the components from this run were used as the initial values for a series of runs to investigate the effects of altering some of the coefficient values. The first twenty day run was used to allow the model to approach an equilibrium point so that the subsequent sensitivity runs would not waste computer time going through this process. The first of the runs was a ten day continuation of the original twenty day run and the results of this acted as a reference against which the other runs could be tested.

As this run was the reference, it will be described in some detail, with a full list of the coefficient values used. The day of the year simulated was day number 82, which gave a declination value of just greater than 0.0, and about twelve hours of daylight. For this run the roof was single glazed and no thermal screen was used and so there will be no references in the following lists to a screen or a second roof layer. Figure 4-c illustrates the system simulated as well as the heat transfer pathways included.

Parameter values

The following section lists the values of the parameters which were used, as well as values quoted in some references. The numbers refer to the components, thus DENSITY(1) is the outside air density for example.

<u>DENSITY</u> kg/m^3

DENSITY(1 AND 15) AIR 1.293

In the references Tennent (1976) quotes 1.293; Carslaw and Jaeger (1959) give 1.29 and both Udink ten Cate (1983) and Seginer and Levav (1971) give a value of 1.2.

DENSITY(3) GLASS 2600

Butler and Classen (1980) use 2489 Carslaw and Jaeger (1959) give 2400; Doremus (1973) quotes values in the range 2000-6000 and Seginer and Levav (1971) and Tennent (1976) give 2600.

DENSITY(17 to 27) SOIL 1500

Carslaw and Jaeger (1959) give values of 1650-2500 for soils ranging from sandy dry to average soils and Seginer and Levav (1971) use 1500. The values quoted here and for other soil properties depend upon the type of soil in question.

EMISSIVITY

EMLR(3) GLASS 0.94

Both Bailey (1981) and Kanthak (1970) use 0.94 and Van Bavel et al. (1979) use 1.0

EMLR(17) SOIL 1.0

Van Bavel et al. (1979) use a value of 1.0; Kanthak (1970) gives a range of values, 0.945-0.968, for wet and dry sandy soils and Seginer and Levav (1971) give a value of 1.0.

HEAT CAPACITY J/kg°K

HEATCAP(1 and 15) AIR 1008

Carslaw and Jaeger (1959), Kozai et al. (1980) and Seginer and Levav (1971) give values of 1008 whilst Udink ten Cate (1983) quotes a value of 1000 and Van Bavel et al. (1979) use a value of 1194 from an equation: 1154.9*303 16/(T+273.16) at T=20°C.

HEATCAP(3) GLASS 840

Butler and Claassen (1980) give 754; Carslaw and Jaeger (1959) and Seginer and Levav (1971) use 840; Doremus (1973) gives 987 and Tennent (1976) gives a value of 670.

HEATCAP(17 to 27) SOIL 1500

Carslaw and Jaeger (1959) give values ranging from 798-1650 for sandy, dry to moist soils. Hanks and Ashcroft (1980) give 840; Privett (1979) uses 2520; Seginer and Levav (1971) use 1050 and Van Bavel et al. (1979) use a value of 1333 derived from : [$2*10^6$ J/m^3K]/density).

REFRACTIVE INDEX

RI(1 and 15) AIR 1.0

Duffie and Beckman (1980) quote a value of 1.0.

RI(3) GLASS 1.526

Duffie and Beckman (1980) give a value of 1.526 Butler and Claassen (1980) quote 1.518 and Doremus (1973) gives 1.520.

THICKNESS m

THICK(3) GLASS .003

Godbey et al. (1979), Kanthak (1970), Kimball (1973) and Seginer and Levav (1971) all use values in the range 0.003-0.004 m.

THICK(15) AIR 4.0

This value was used as the average height of the glasshouse.

THICK(17)	SOIL	0.01
(19)	SOIL	0.02
(21)	SOIL	0.04
(23)	SOIL	0.08
(25)	SOIL	0.16
(27)	SOIL	0 32

Van Bavel et al. (1979) use a similar arrangement of soil layers in their model (although they use more of them) and the increasing thickness with depth improves the mathematical stability of the model.

CONVECTIVE HEAT TRANSFER W/m^2K

CHT(2) OUTSIDE AIR TO GLASS 27.9

The value used here is derived from 25.0/COS(roof slope) but there is a wide range of different values quoted in the references:

39.77 Iqbal and Khatry (1977) from $17.9*V^{.576}$ with V=4.0 m/s

11.0 Gimmestadt et al. (1982) from (3+4*V) with V=2 m/s

14.8 Garzoli et al. (1981) from (7.2+3.8*V) with V=2

12.89 Seginer and Levav (1980) from (5.635+3.82*V) with V=2

13.42 Kanthak (1970)

U values are quoted in many references:

.35-6.0 Littler (1979) for single and double glazing with combinations of coatings/gas fillings

5.8 Kozai et al. (1980)

2.8-4.5 Manning and Mears (1982) for double plastic with screens

4.6-8.5 Privett (1979) for double/single glazing

4.56-7.96 Sheard (post 1975) for inflated and single roofs

4.5-6.8 Simpkins et al. (1976) for double polyethylene and single glass

4.13-6.0 Wass (1981) for day and night U values respectively

The value chosen for the above coefficient (27.9) favours the higher values quoted above. This is because measurements made on real glasshouses or models of real glasshouses are considered to reflect the true value better than the smaller values derived from measurements made on flat plates under conditions of parallel wind flow. Note that there is a difference between the two sets of values quoted above, the first set being surface transfer coefficients and the second set being U values, for flow through components.

CHT(4-16) Component to Inside Air 7.2

Once again there are many values quoted for this set of coefficients:

5.0 Bot et al. (1978

3.5 Bot et al. (1978) for air to soil

5.0 Bailey (1981) for natural convection

3.0 Gimmestadt et al. (1982)

7.2 Garzoli et al. (1981)

7.0-9.33 Kanthak (1970) for glasshouses with radiant or air heating systems

3.15-3.85 for air to soil transfers

4.2-5.25 for glass to air transfers

5.1 Manning and Mears (1982) for warm concrete floor

3.21 Seginer and Levav (1971) from: $1.491*(T_i-T_a)^{1/3}$ with $(T_i-T_a)=10$

THERMAL CONDUCTIVITY W/mK

SOIL 1.0

Bot et al. (1978) use a value of 2.0 for a moist soil; Carslaw and Jaeger (1959) give values in the range .264-.963 for sandy dry-average soils; Kanthak (1970) uses values in the range .05-1.75 for soils of varying porosities and moisture content and Van Bavel et al. (1979) use a value of 1.0

The heat transfer coefficients for conduction between the soil layers were calculated using the thickness of each layer and the thermal conductivity of the soil. The method used to do this in the model has been described previously.

The V array contains the parameters that describe the system being modelled and the following values were used in this run. Not all of these values apply to the system containing only a single glazed roof and no thermal screen they are listed here for the sake of completeness.

V(1) degrees 26.5
- 26.0 Bot et al. (1979)
- 28.0 Hand et al. (1970)
- 25.0 Kanthak (1970)
- 27.1 Kimball (1973)

V(2) degrees 0.00

V(3) m^{-1} 16.1
- 6.10 Davies (1980)
- 4.0-32.0 Duffie and Beckman (1980) good white to poor glass

V(4) 0.9
- 0 9 Kirsten (1973) for dust deposits
- 0.95 Kanthak (1970) for glazing bars
- 0 9 Kimball (1973) for structure/dust

V(5-6) .8/.2

V(7-8) m^3/m^2s .002/ 04
- .11 Udink ten Cate (1983) from 100/hour 4m high roof

V(9) 0.2
- 0 1 Kimball (1973) for a crop
- .15-0.1 Van Bavel et al (1979) for photo/non-photo synthetic radiation

V(10) K 288.0

V(11) K 297.0

V(12) K .04

V(13) hours 26.0 (no special

V(14) hours 26.0 time data)

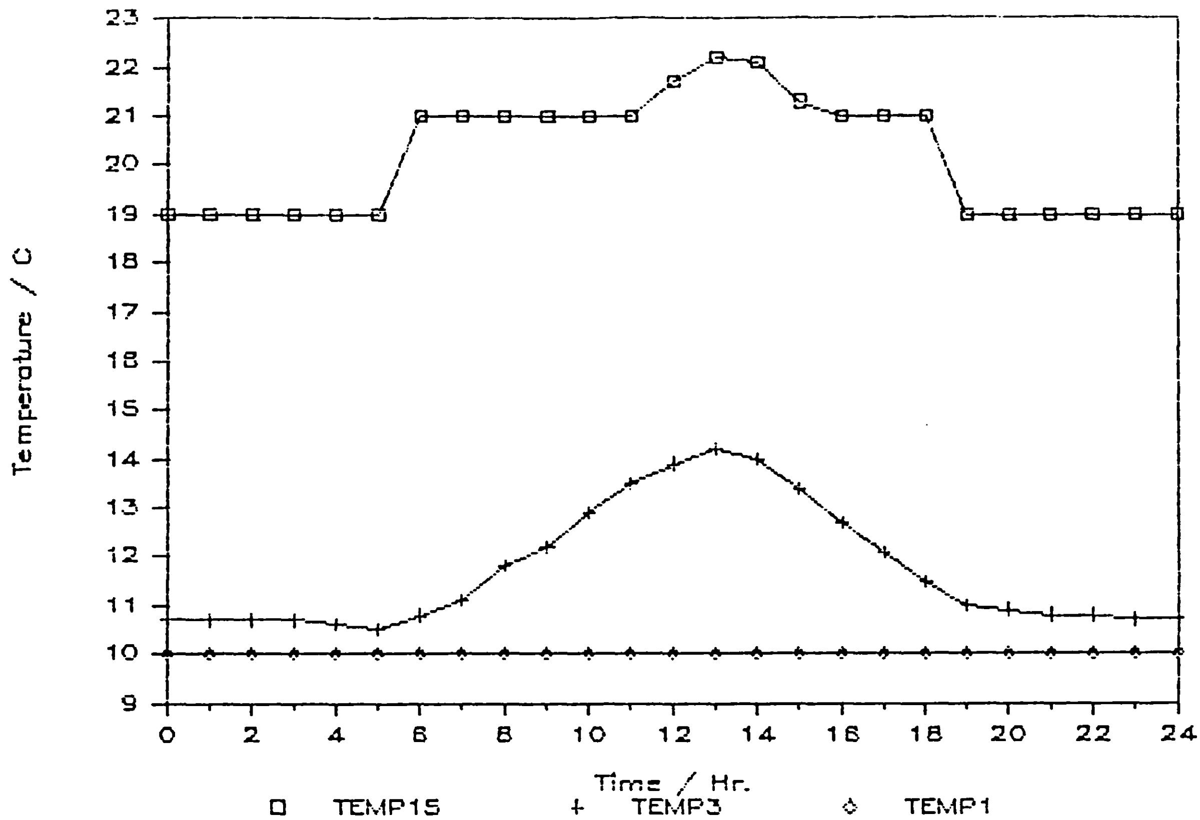
V(15) degrees	52.0	V(30) degrees	0.0
V(17)	0.56	V(31) mins.	1.0
0.56 Hand et al. (1970)		V(32) days	82
V(18) s	5000	V(33) days	0.0
5000 Van Bavel et al. (1979)		V(34)	0.1
V(20) s	50	V(35) mins	45.0
50 Van Bavel et al. (1979)		V(36) mins	15.0
V(21) s	55	V(37) K	20
V(22) K	variable	V(38)	1.5
V(23) s	45.0	V(39) degrees	60.0
V(24)	43.2	V(40) mins	5.0
V(25) s/m	333	V(41) K	.02
V(26) unused		V(42)	Cos(V(1))
V(27) J/MJ	10^6	V(43) m^2/m^2	0.0
V(28)	2.0	V(44) degrees	26.5
V(29) degrees	0.0		

Results

The results of this run were in the form of over 100 columns of numbers which are not reproduced here. Instead, the important of results are displayed as graphs and are discussed below.

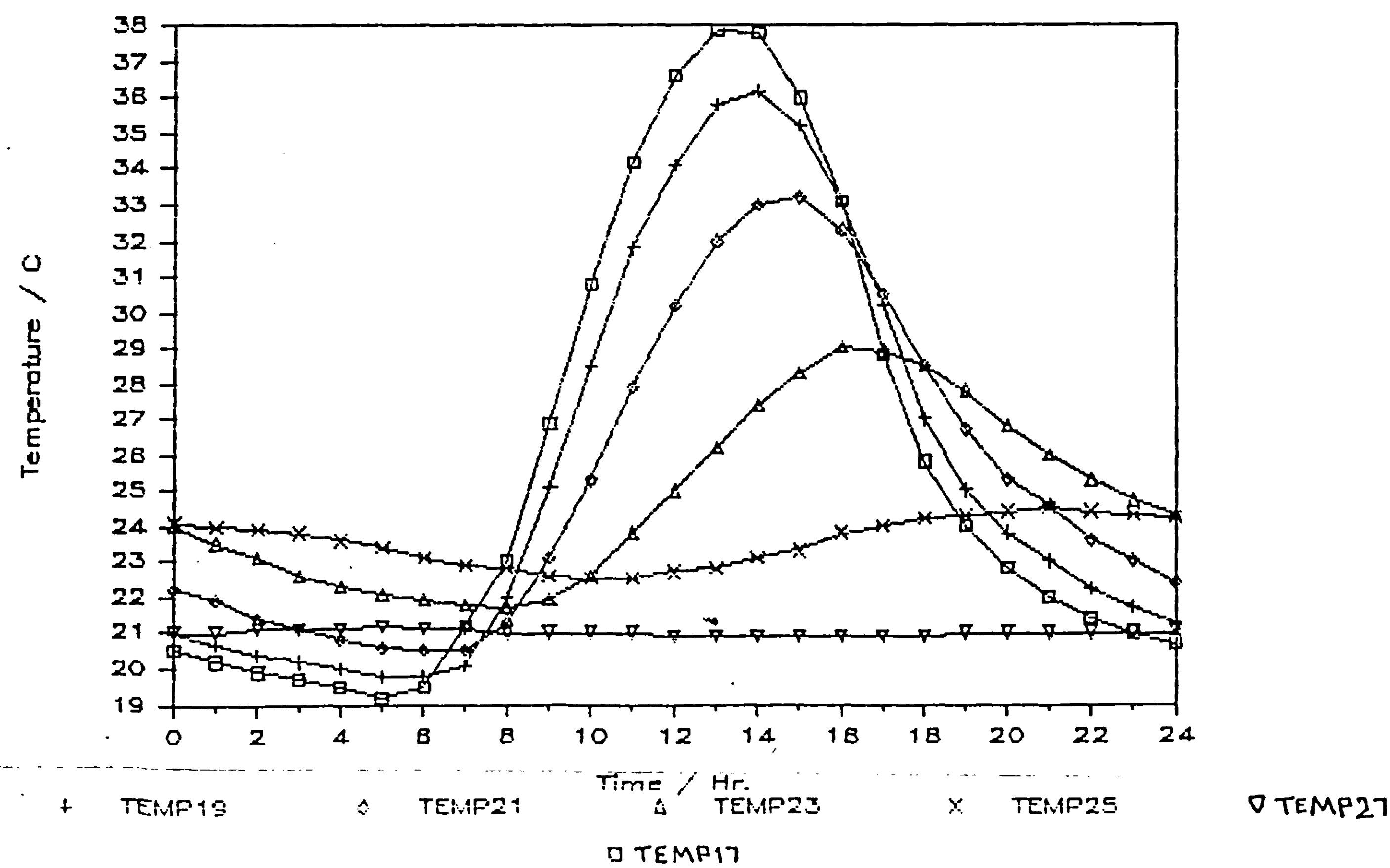
In this relatively simple configuration the upper components of the model were the outside air, the single roof, the inside air and the top soil layer. The corresponding temperatures were TEMP1, TEMP3 TEMP15 and TEMP17. As shown on figure 4-d, the outside air was constrained to remain at a temperature of 10.0°C throughout the day and night and the inside air temperature was controlled by the heater and was not allowed to fall below 19.0°C between sunset and sunrise, or below 21.0°C at other times. Between 11.00 and 16.00 h. TEMP15 was higher than 21.0°C as the solar contribution to the heating forced the temperature upwards. TEMP3, the roof temperature remained just higher than TEMP1 during the night although it fell throughout this time. At dawn TEMP3 began to rise as TEMP15 had reached its daytime setting of 21.0°C. It continued to rise as the solar radiation increased, reaching a peak at 13.00 h from which it fell steadily until 19.00 h, and then more slowly until

Fig. 4-d



23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
Temperature / C
0 2 4 6 8 10 12 14 16 18 20 22 24
Time / Hr.
TEMP15
TEMP3
TEMP1

Fig. 4-e



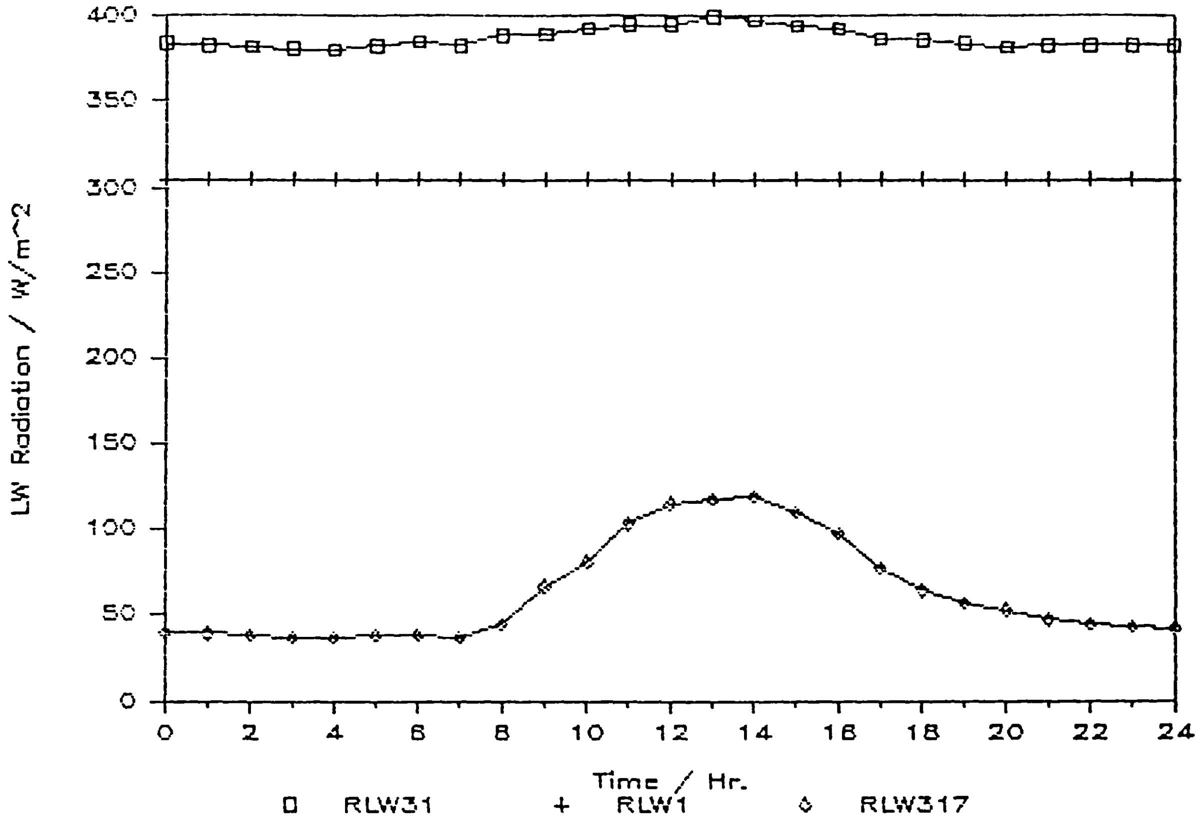
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
Temperature / C
0 2 4 6 8 10 12 14 16 18 20 22 24
Time / Hr.
TEMP19
TEMP21
TEMP23
TEMP25
TEMP27
TEMP17

mid-night when the cycle began again. The top floor layer, component 17, was at a lower temperature than the inside air between 1.00 h and 8.00 h, but TEMP17 rose sharply as the solar radiation increased, reaching a maximum at 13.00 h. The plot is shown on figure 4-e. The large fluctuation in TEMP17 was due to the large absorption of solar radiation in this relatively thin layer, 0.01 m. These temperatures behaved as expected under the conditions set for this run.

TEMPs 17 to 27 were the soil layer temperatures with 17 being the topmost and thinnest layer, and 27 being the deepest and thickest. Below component 27 the soil temperature was maintained at a constant temperature of 15°C. The large fluctuation in TEMP17 has been explained above and it can be seen that the shape of the TEMP17 vs. time curve is similar to that of the solar radiation curve, with TEMP17 reaching its maximum value at about 13.00 h following the peak in the solar radiation. In the deeper layers the maximum temperatures occurred later and later in the day as the temperature wave penetrated deeper. The thicker layers showed less fluctuation in temperature and TEMP27 varied by less than 0.25°C. Figure 4-e shows the progress of this temperature wave with time and illustrates the flow of heat into and out of the soil system. For example, at 13.00 h the temperature of each layer was greater than those of the layers beneath and heat was flowing downwards into the soil. At midnight the temperature of each layer was greater than the one above, excluding the deepest layer, and heat flowed upwards towards the surface. However, heat only reached the air from the soil by convection when TEMP17 was greater than TEMP15. In this case, this condition was true between 8.00 h and 24.00 h.

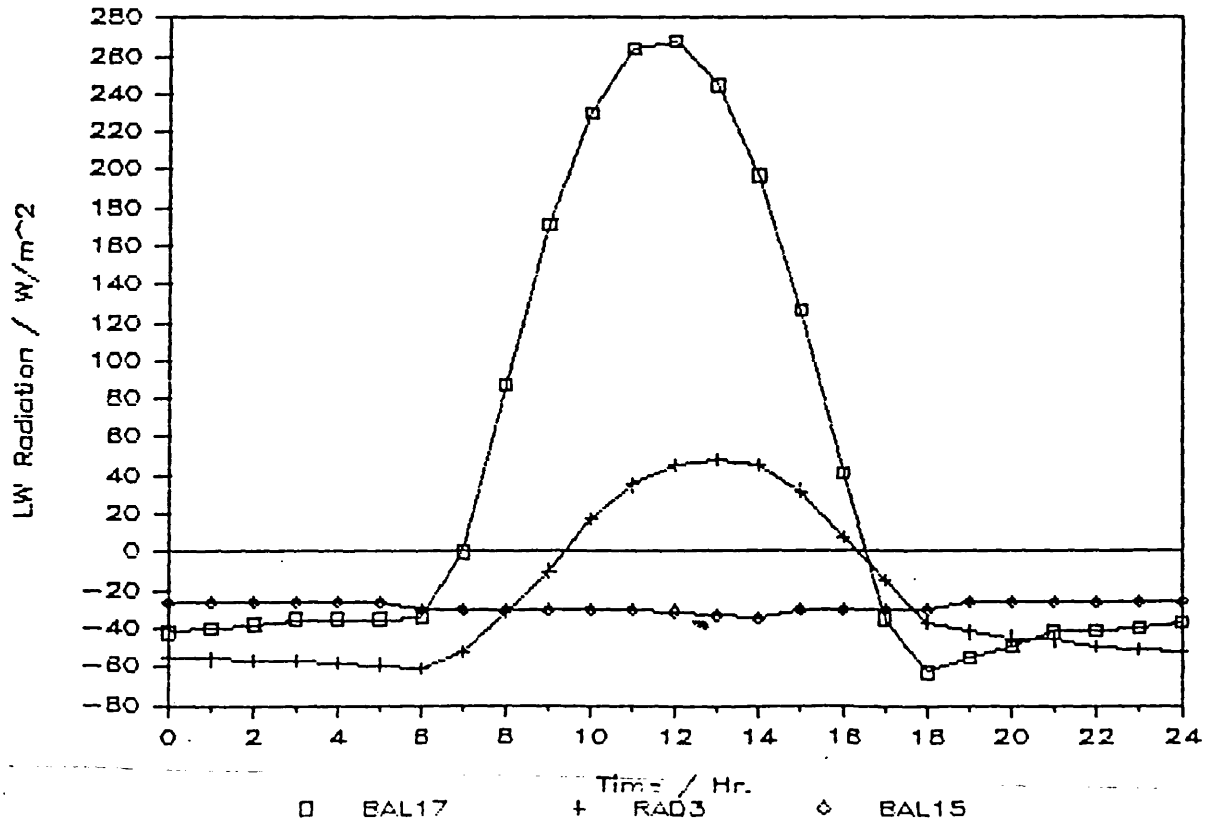
For this run with no double glazing or thermal screen, the longwave radiation exchanges were limited to those between the sky and the roof, and the roof and the soil surface. As figure 4-f shows, radiation from the sky, RLW1, remained constant at 304.772 W/m^2 as the outside temperature did not vary. The loss from the roof to the sky, RLW31, varied with the roof temperature, reaching a peak at 13.00 h when TEMP3 was at a maximum. Since TEMP1 was constrained to remain constant, the net loss from the roof to the sky was larger than it would have been had the air temperature varied through the day. The roof lost energy in the form of longwave radiation to the sky

Fig. 4-f



400
350
300
250
200
150
100
50
0
LW Radiation / W/m^2
0 2 4 6 8 10 12 14 16 18 20 22 24
Time / Hr.
□ RLW31 + RLW1 ◇ RLW317

Fig. 4-g



280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
−20
−40
−60
−80
LW Radiation / W/m^2
0 2 4 6 8 10 12 14 16 18 20 22 24
Time / Hr.
□ BAL17 + RAD3 ◇ BAL15

at all times under the conditions met in this run, and considering the equations used to calculate both of these values. the outside air temperature would have to be considerably higher than the roof temperature (some 18 K higher) before the roof-sky exchange would result in a net gain to the roof. Such conditions are extremely unlikely to occur and it may be assumed that the roof always loses thermal radiation to the sky.

RLW317 was the radiation exchange between components 3 and 17 with a positive value indicating a net flux from 17 into 3. By comparing TEMP3 and TEMP17 it is clear that the floor temperature was always greater than the roof temperature and so there was always a net flow from the floor to the roof. This is a realistic result as solar short-wave radiation heats up the floor maintaining it at a higher temperature than the roof. Once again the maximum was reached at 13.00 h, when the temperature difference between components 3 and 17 was at its greatest

BAL15, shown on figure 4-g, was the heat exchange between the inside and outside air by ventilation, a negative value indicates a net loss of energy from the inside air. As TEMP15 never reached the active ventilation temperature of 24.0°C, all ventilation losses were due to leakage. BAL17 was the radiation balance for the top floor layer and comprised the gain from solar radiation as well as the longwave exchange with the lower roof surface. From just before sunset until just after sunrise BAL17 was negative, indicating a net loss. This was to be expected as there was little or no solar gain and continual longwave loss to the roof (consider RLW317). During the day BAL17 became sharply positive since it received large amounts of solar radiation in the absence of a crop. and it reached a maximum value at 12.00 h when the solar radiation was also at its highest. RAD3 was the net gain to the roof due to radiation; other exchanges such as convective losses are discussed later. The roof gained longwave radiation from the sky and floor at all times in this example. and lost it by emitting to the sky. Between sunset and sunrise the roof lost energy but during the daylight hours solar radiation heated up the floor layer causing more radiation to be emitted by the floor to the roof. At about 9.30 h the net radiation balance on the roof was 0.0 and from then until just after 13.00 h the roof gained energy as the emission from the floor increased. It also gained a small amount of energy from the absorption of solar radiation as it passed through the glass (ABSRAD3 shown in fig 4-i). This picture of the net radiative energy exchange by the roof is sensible as far as the conditions simulated here are concerned but the radiation could be altered depending on the state of cloud cover in the sky or the type of cladding material being used.

Figure 4-h shows the variation in the reflection, transmission and absorption coefficients for the solar radiation incident on the south facing roof. As expected, the reflection coefficient was high at times close to sunrise and sunset when the angle of incidence was high, and it was much lower during the middle of the day when this angle was smaller. The shape of the transmission coefficient curve shows that TRANCO3 was low in the morning and late afternoon, and high during the middle part of the day. ABSCO3, the absorption coefficient, remained quite small throughout the day, having maxima early in the morning and late in the afternoon.

Graph 4-i shows solar radiation flows. SUNRAD was the flux of radiation incident upon the roof surface and TRARAD3 was the amount of this radiation transmitted through the cladding. The remainder was reflected away or absorbed (ABSRAD3). SUNSOIL was the amount of radiation absorbed by the floor and its small magnitude needs explanation. SUNRAD was the flux upon the roof which slopes at an angle of 26.5° towards the south and it would be expected that this flux would be greater than on a similar horizontal surface. For example, on day 82 at mid-day let us suppose that the intensity of radiation upon a surface normal to the direction of the sun receives 1000 W/m^2. On the sloping roof this would be reduced to about 900 W/m^2 and on a horizontal surface this would be about 615 W/m^2. This explains about two-thirds of the decrease and the remainder was due to reflection and absorption in the roof and reflection of some radiation by the floor.

SUNGAIN (shown on figure 4-j) was the total gain to the glasshouse system from the solar radiation flux, including the absorption in the glass. All of these radiation figures reached their maximum values at 12.00 h as the incident intensity was at its greatest.

Fig. 4-h

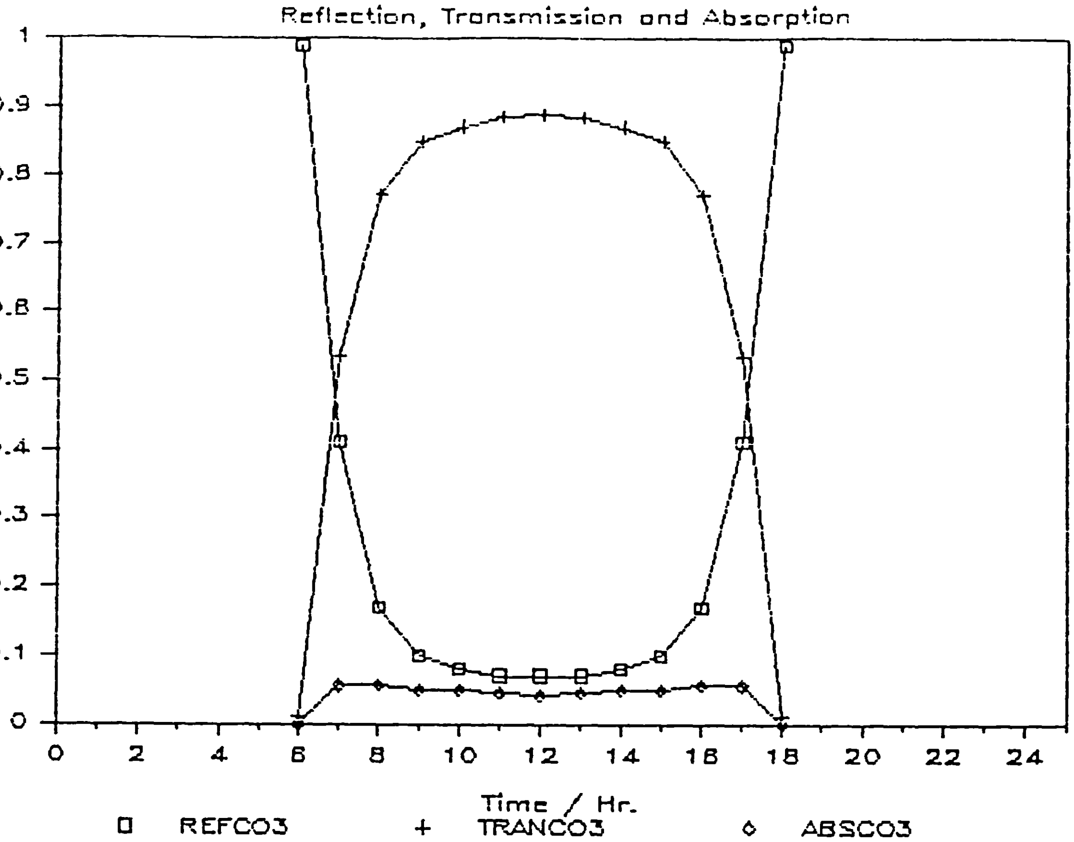
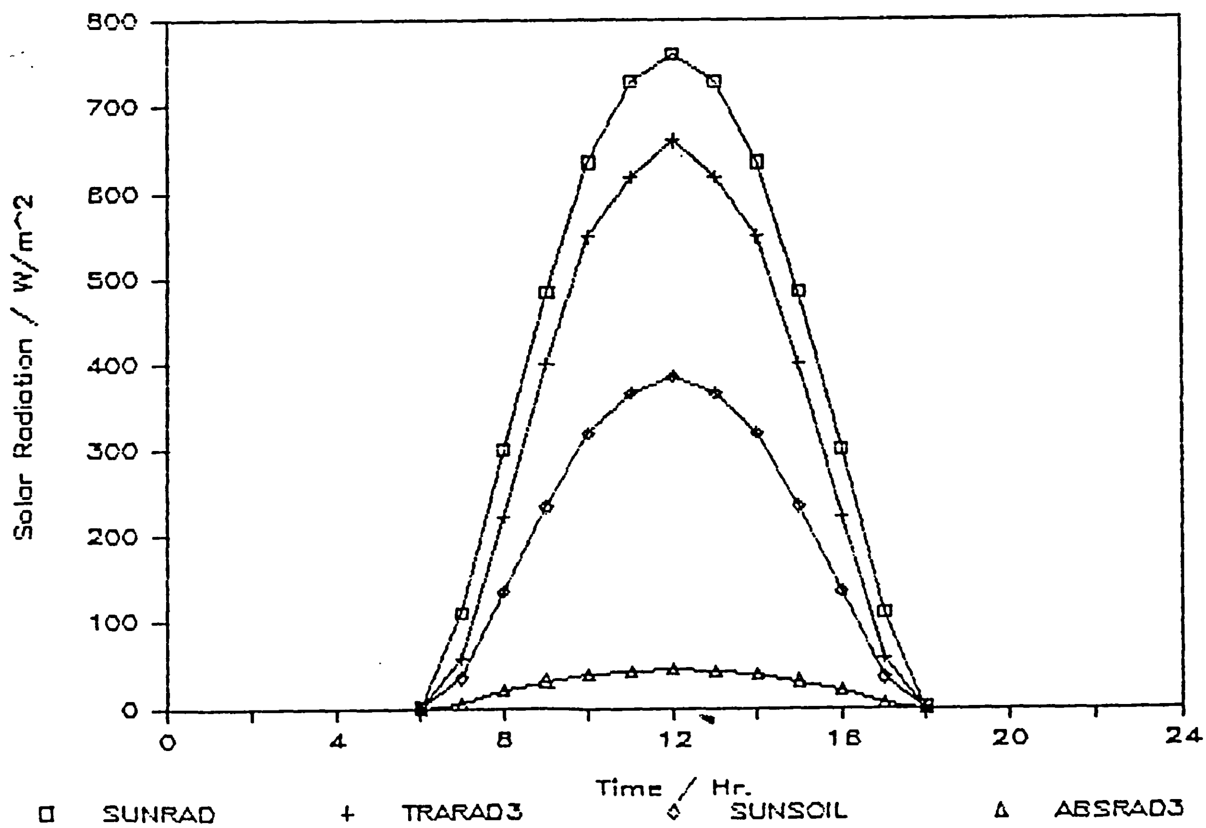

Reflection, Transmission and Absorption
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Time / Hr.
REFCO3
TRANCO3
ABSCO3

Fig. 4-i


800
700
600
500
400
300
200
100
0
Solar Radiation / W/m^2
0
4
8
12
16
20
24
Time / Hr.
SUNRAD
TRARAD3
SUNSOIL
ABSRAD3

HTPWR, the heater power, is also shown on figure 4-j. The heater supplies exactly the amount of energy needed to maintain the air temperature at the blueprint setting. Between 0.00 h and sunrise the heater output rose slowly from about 90 to 100 W/m^2. At sunrise it rose sharply to raise the air temperature from its night time setting of 19°C to the day setting of 21°C. The output then fell until reaching a value of 0.0 W/m^2 at 12.00 h indicating that the air was receiving enough energy to maintain the setpoint level without needing any from the heater. Until 15.00 h the heater was not needed but after this until sunset HTPWR increased sharply as the solar energy decreased. The fall in heater output just after sunset can be explained by the lowering of the blueprint temperature setting to its night time level of 19°C. Only when the air temperature fell to below this setting did the heater switch on and the output increased slowly through the night. The sharp rise and fall during the late afternoon and early evening is an interesting phenomenon which does occur in glasshouses and can be altered by the heating management practices which are used. The implications of this will be discussed in a later chapter.

The same graph shows the radiative (RHLR), convective (CHLR) and ventilative (VHLR) exchanges through the roof and the conduction (CHLS) exchange through the soil. These were exchanges between the external environment and the glasshouse system and the negative values shown here indicate that these were all losses. The exchanges included in HFLUX were the longwave radiation (RLW31) and convection loss (CHLR) from the roof, conduction loss through the soil (CHLS), the ventilative loss (VHLR) and the gain from the sun and from the heater. In this run with no vegetation, there was no loss by evapo-transpiration and EVAPHT was 0.00 W/m^2. The total flux, HFLUX, was calculated as the sum of all the gains less the losses as shown by the following equation:

$$HFLUX = SUNGAIN + HTPWR(K) - RHLR(K) - CHLR(K) - VHLR(K) - CHLS(K)$$

The graph of HFLUX against time shows that the system lost heat between 0.00 h and 7.00 h, and then gained heat as the solar contribution increased, and lost again from 15.00 h until midnight. At 18.00 h the system lost heat sharply in the absence of both sun or heating, until the heating switched on.

Fig. 4-j

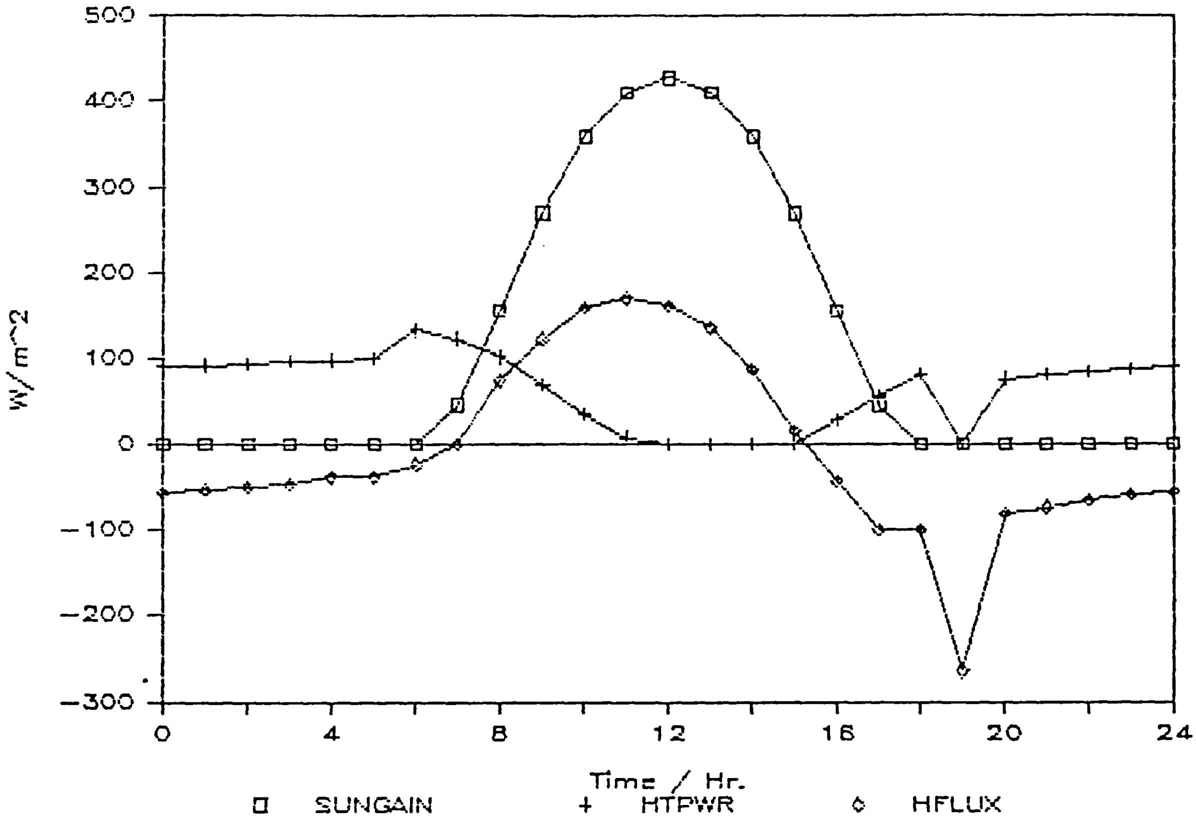


Fig. 4-j(i)

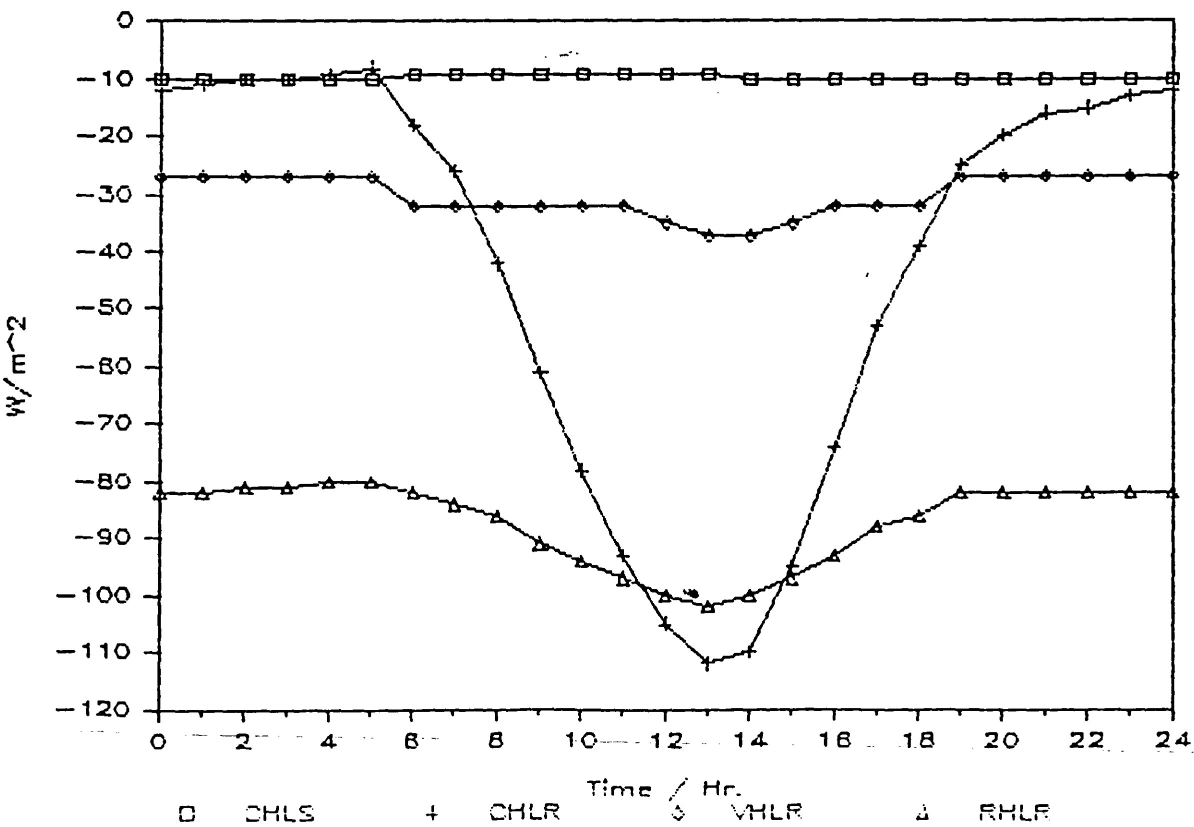


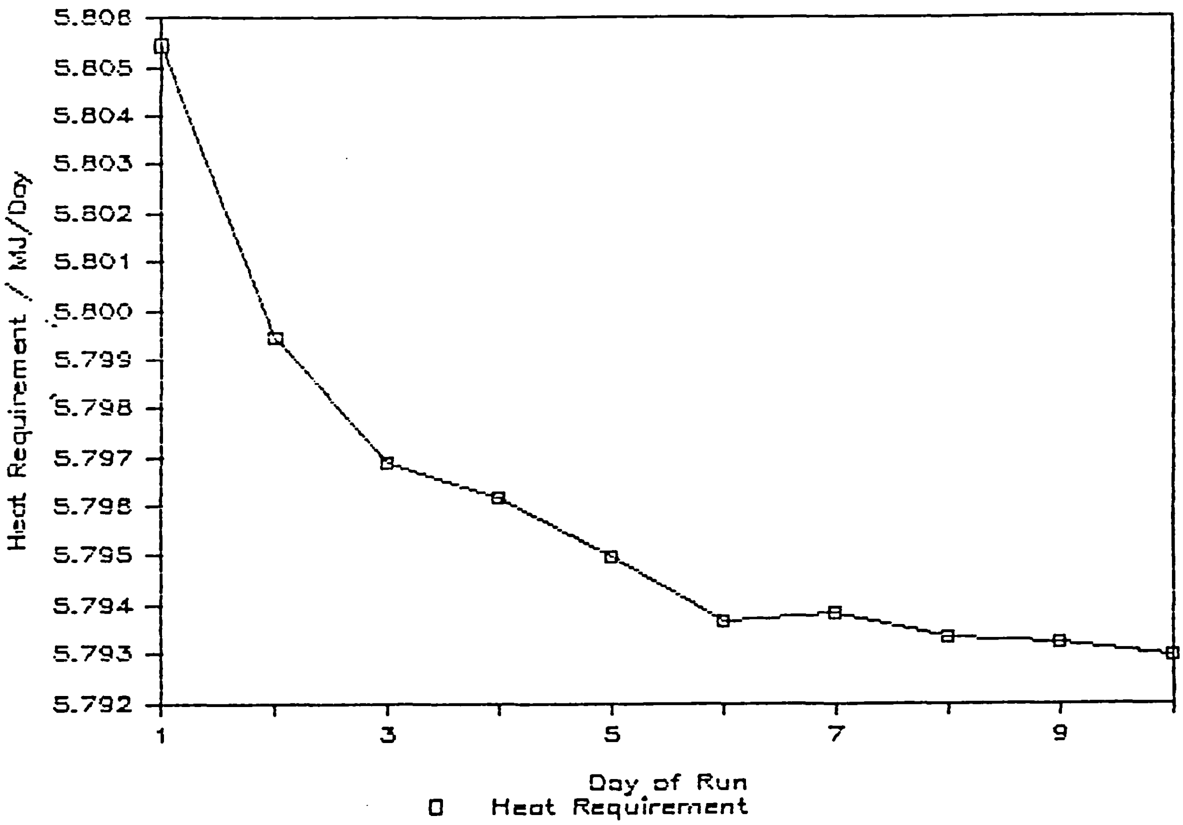
Figure 4-k is a graph showing the total heat supplied by the heater for each day of this ten day run. The heat required reached an equilibrium of about 5793 kJ/m^2 and fluctuated around this level with variation of about 0.2-0.3%. The equations used by the model are calculated to a level of accuracy defined by the EMAX constant and whilst it would be possible to reduce the value of EMAX until the heat requirement was the same for each day of the run, the cost in computing time would be prohibitive. Also, the calculation of heating requirement is purposely made less accurate to save even more computer time. The equilibrium is approached as the temperatures of the floor and deeper soil layers reach their equilibrium values. A good first approximation of these values could be determined by linear interpolation of the temperature between that of the floor and that of the soil beneath the system.

This reference run gave values for the ten days (really the last ten days of a thirty day run) as follows:

DAY OF RUN	DAY OF YEAR	HEAT REQUIREMENT kJ/m^{2}DAY
1	82	5805.447
2	82	5799.438
3	82	5796.884
4	82	5796.152
5	82	5794.972
6	82	5793.650
7	82	5793.851
8	82	5793.326
9	82	5793.242
10	82	5792.974

When the initial temperature values have been chosen carefully the heat requirement approaches its equilibrium point quickly. In simulations where the initial temperatures are unknown or are not chosen carefully then it may take a run of thirty days or more before the heat requirement approaches an equilibrium. However, even when similar situations with large changes in parameter values are run, the heat requirement may still be approaching the equilibrium point after ten days. The first test runs were all made using

Fig 4—k



ten identical days. It was found that the differences between successive values of heat integrals were between 60 70% of the preceding difference This arises because the average temperatures of the soil layers change slowly with time as they reach their respective equilibriunm values. This 60-70% change was used to estimate the equilibrium value of the heat requirement in runs where this point was still being approached after ten days.

For the test run shown above the heat requirement for the first day was 5805 kJ/m^2 and it decreased in the four following days to a value of around 5793 kJ/m^2. The values then fluctuated in the 5792-5794 kJ/m^2 range, probably due to the intentional lower accuracy mentioned above (see figure 4-k). In accordance with the above listing a value of 5793 kJ/m^2day was used as the reference.

Test Runs

The user can set the values of more than one hundred parameters to describe the system and the total number of variables used in the model is even greater than this. An attempt to change each of these and observe the effect on the output from the model would be impossible, so, because of the limitations of computer time and space, only a few of these could be investigated. The variables which might be altered by the user in the course of investigating energy conserving materials, and others which were thought to be important or had a wide range of values in the references were varied in the runs described below.

These test runs were carried out for a number of different reasons. Firstly, to see how changes in these parameters would change the output. This would give some idea of which energy conservation techniques might be more promising than others. Secondly, the runs showed that the model could produce reasonable results over a range of conditions and although no level of accuracy could be assigned to the output at that stage, it could be seen that the results produced after each change were consistent with the original alteration. Thirdly, to show that the model could cope with changes without requiring an excessive amount of computer time. Fourthly, the runs gave a means of predicting how the user should set the initial conditions in the model in order to economise on his use of computer time. Finally, carrying out a number of these runs and finding that the results produced by the model were sensible gave a certain degree of confidence in the model. In modelling, this is not only heartening, but is sometimes the only means of a rough validation of the model which is available at a particular time.

The important output section for these runs was the daily total of heat supplied by the heater. This was the figure used to ascertain the effectiveness of an energy conservation strategy. Since simulations of a very simple case were carried out, constant outside air temperature and cloudless days, the results of the tests will not be examined in as great detail as might be justified in a more realistic case. The results will be discussed in this chapter solely in terms of the verification of the model; the implications to energy conservation will be discussed in the results chapter.

a) Convective Heat Transfer from the Roof

The first set of runs was an investigation into the effect of altering the convective heat transfer coefficient between the outer roof surface and the outside air. As discussed in a previous chapter, there is a wide range of values for this coefficient to be found in the literature. Because of this, it was important to investigate the stability of the model to changes in this parameter (CHT(2)). On those days when the roof temperature was greater than that of the outside air, it would be expected that as CHT(2) was decreased, the heat requirement would decrease also. The values assigned to CHT(2) over the next four runs, and the resulting final heat requirements are shown on figure 4-1.

These results show that relatively large changes in CHT(2) have only a small effect on the daily heat integral. A doubling in value from 10.0 to 20.0 or 15.0 to 30.0 W/m^2K leads to an increase in the heat requirement of some 8%. During the night the temperature difference between the roof and the outside air remained small which meant that only a small heat loss occurred, but during the middle of the day when this temperature difference was at its greatest, the inside air was at a temperature greater than the prescribed level and no heating was required. The results show that the model is quite stable to changes in CHT(2). A change in heating requirement of a few percent may not seem to be very much but to a grower, changes in heat requirement of this order represent large increases in the fuel bill and the implications of this will be discussed in the next chapter.

TEMP3 would be expected to increase with a decrease in CHT(2), causing greater loss via longwave radiation. When CHT(2) was varied over the range 25.0 to 10.0 W/m^2K the longwave radiation increased by 4%. A higher TEMP3 would mean that the difference between the inside air and roof temperatures was smaller and so less heat would flow into the roof from the inside air. The increased longwave loss and the reduction in heat flow from the inside air would tend to limit the size of roof temperature increases.

The direct effect of altering CHT(2) was to change the component temperatures. As CHT(2) was reduced, the temperatures of the components increased with the largest increase being to TEMP3 itself. The decrease in CHT(2) over the range mentioned above led to an increase in the floor temperature of about 0.9°C at 13.00 h, when TEMP17 was at a maximum. This small increase was enough to ensure that heat flowed from the soil into the inside air for nearly another hour during the night, rather than from the air into the soil.

b) The Emissivity of the Roof

The second series of runs investigated the effects of altering the longwave emissivity of the upper and lower roof surfaces. The roof surfaces were taken to be identical and the changes were applied to both surfaces simultaneously. As TEMP3 is greater than TEMP1, it would be expected that a decrease in EMLR(3) and EMLR(4) which would result in a lower net radiative loss, would decrease the heat requirement of the inside air.

Changing these two parameters had a large effect on the heating requirement (see fig. 4-m). The heat integral changed by more than 20% over the range of alteration (0.6 to 0.94). Reductions in the emissivities led to a warmer roof through the day, but only warmer by 0.5°C when the emissivities were both set at 0.60. More noticeable was the rise in the inside air and floor temperatures which increased by more than 1.0°C and just less than 3.0°C, respectively, during the middle of the day. From these runs, it was shown that for the particular baseline system being investigated, when the emissivities were decreased to between 0.7 and 0.8, TEMP17 remained greater than TEMP15 at all times, and no heat was lost by convection into the floor from the air. The reduced emissivity means that less longwave radiation is absorbed by the roof from the sky, but this is more than offset by the reduction in longwave loss from the roof. As the soil surface emissivity was kept at 1.0, component 17 remained able to absorb all the longwave radiation incident upon it, but as the roof emissivities decreased, less radiation from the soil could be absorbed by the roof. This was shown as a decrease in the value of the RLW317 variable. As the emissivities decreased, the net gain to the roof from floor radiation fell also.

Fig 4-l

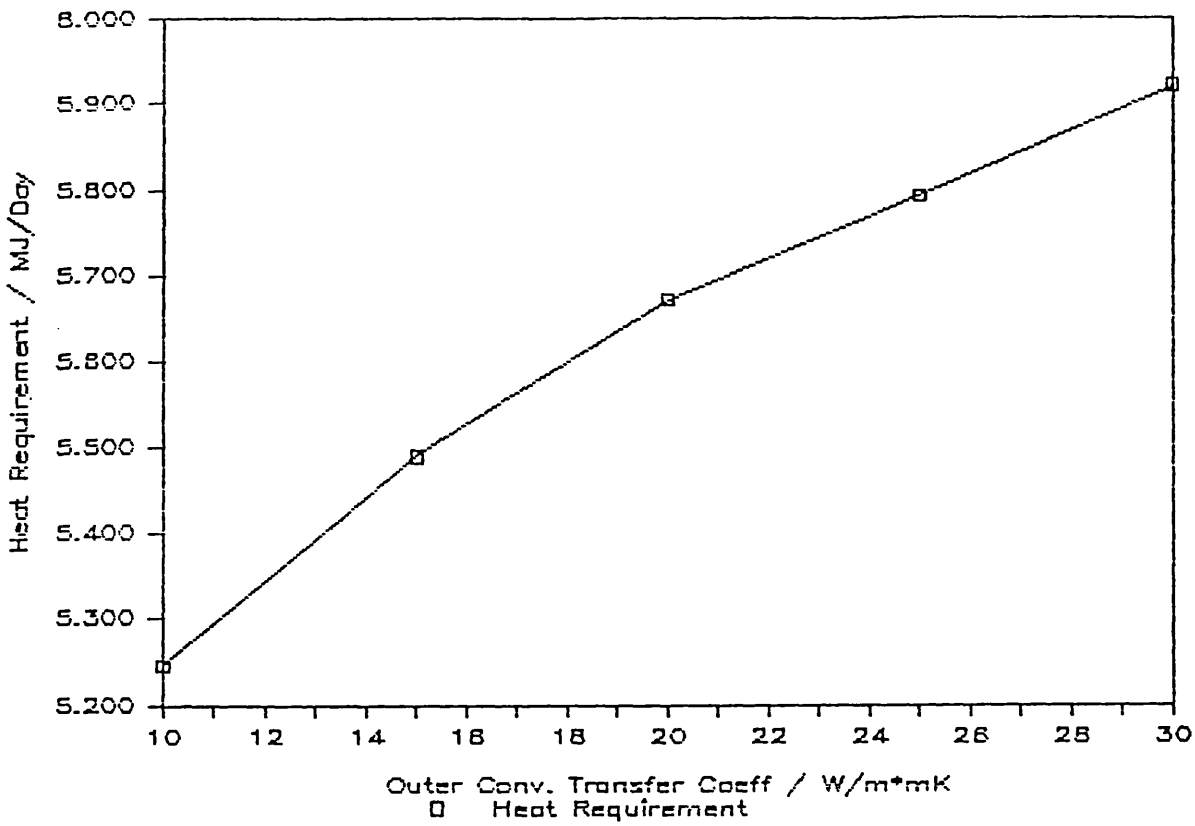

8.000
5.900
5.800
5.700
5.800
5.500
5.400
5.300
5.200
Heat Requirement / MJ/Day
10
12
14
16
18
20
22
24
26
28
30
Outer Conv. Transfer Coeff / W/m*mK
Heat Requirement

Fig 4-m

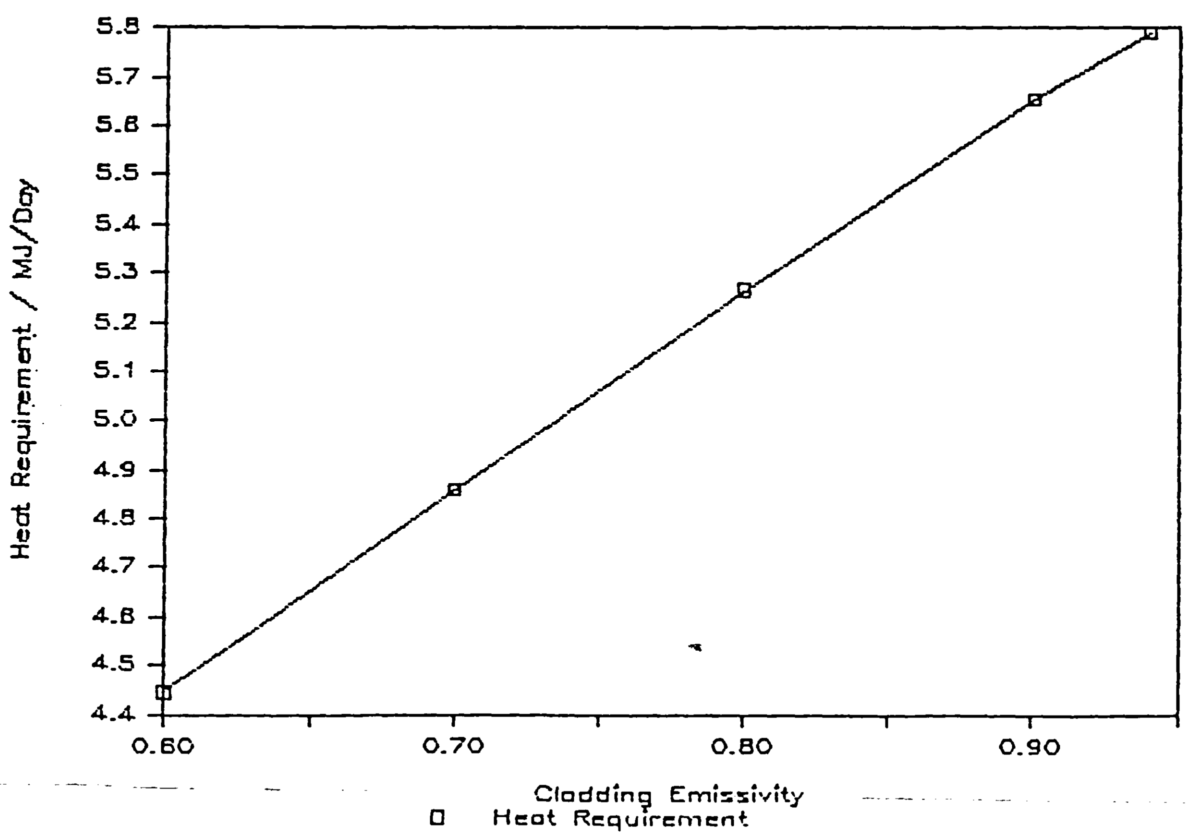

5.8
5.7
5.8
5.5
5.4
5.3
5.2
5.1
5.0
4.9
4.8
4.7
4.8
4.5
4.4
Heat Requirement / MJ/Day
0.60
0.70
0.80
0.90
Cladding Emissivity
Heat Requirement

Fig 4—n

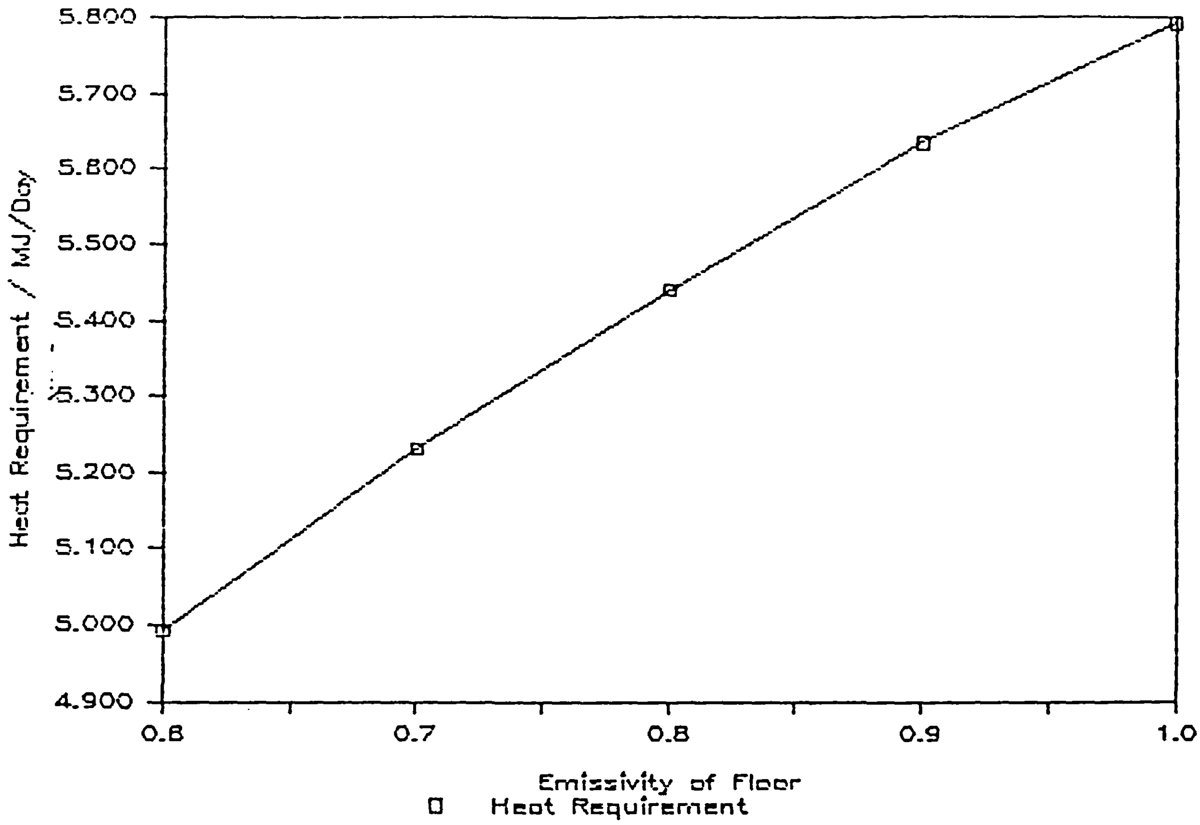
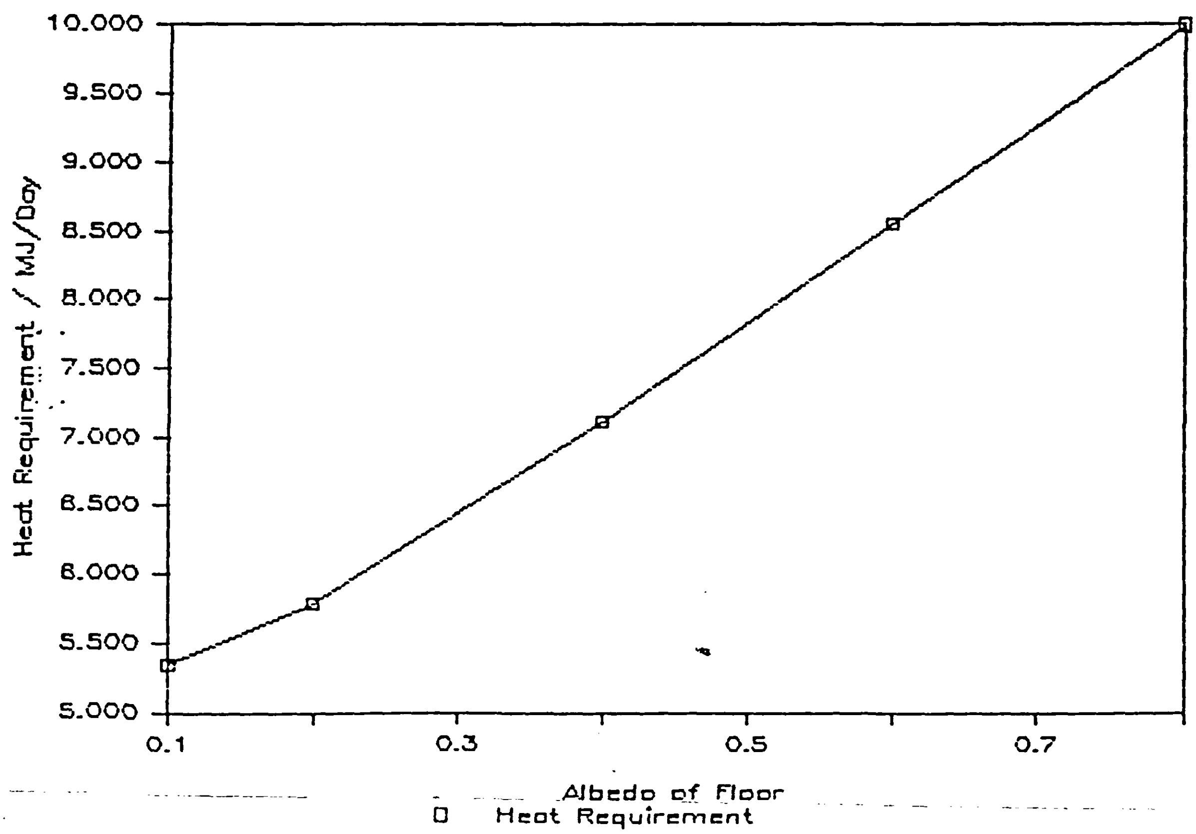

5.800
5.700
5.800
5.500
5.400
5.300
5.200
5.100
5.000
4.900
Heat Requirement / MJ/Day
0.8
0.7
0.8
0.9
1.0
Emissivity of Floor
Heat Requirement

Fig 4—o


10.000
9.500
9.000
8.500
8.000
7.500
7.000
6.500
6.000
5.500
5.000
Heat Requirement / MJ/Day
0.1
0.3
0.5
0.7
Albedo of Floor
Heat Requirement

c) The Soil Surface Emissivity

The next series of runs investigated the effects of changing the emissivity of the soil surface. This was important because most growers use some sort of covering on the floor of their glasshouses and the emissivity could vary from a value of about 1.0 for open soil, to about 0.6 for some synthetic materials. The expected result of reducing EMLR(17) would be a reduction in the heat requirement as the resulting higher value of TEMP17 would lead to greater convective gain to the inside air.

As with the changes to the cladding emissivity, the change in heat requirement with a decrease in floor surface emissivity was large (see figure 4-n). The increase was not as great in this case as over the same range of change in the roof emissivity but even a moderate reduction in EMLR(17), to 0.8, was enough to maintain the floor temperature above that of the inside air at all times. TEMP17 remained at between 2.5 and 3.0°C higher throughout the day when EMLR(17) was 0.6, compared with the standard run results. The maximum value of TEMP17 occurred later in the day as EMLR(17) was decreased, being nearer to 14.00 h than 13.00 h when EMLR(17) was 0.6. Since the top soil layer was warmer throughout the day, the deeper soil layers were also warmer in comparison with the standard run, and less heat was lost through the bottom soil layer as EMLR(17) was increased. The amount of heat loss through the bottom soil layer varied between about 9.7 and 10.0 W/m^2 in the standard run and this increased to a range of 11.9 to 12.2 W/m^2 when EMLR(17) was set at 0.6. The increase in heat loss through the soil was approximately 20% over the range in variation of EMLR(17), but as this heat loss was small when compared with the other forms of loss the implications of this increase are not so important. The inside air was found to be warmer when EMLR(17) was reduced and RLW317 decreased indicating a reduction in the amount of longwave radiation transferred to the roof from the soil despite the increase in temperature of the layer.

d) The Albedo of the Floor

The albedo of the floor can take a wide range of values since different coverings may be used on the soil surface. However, the empty glasshouse, containing no crop, will be much more influenced by changes in the floor albedo than the glasshouse complete with a fully grown crop.

Variation in the albedo value gave rise to large changes in the heat requirement as shown in figure 4-o. In GHFORSM solar energy is absorbed either by the glass or the soil and any which is reflected or transmitted away does not provide heat to the system. Increasing the albedo of the floor caused more radiation to be reflected by the soil surface, and the majority of that was then transmitted away through the roof as the amount absorbed by the glass is small. As the albedo was increased in value, the temperature of the top soil layer, and subsequently the lower layers, fell as less radiation was absorbed. Since less was absorbed during the day, the temperature of component 17 fell below that of the inside air earlier in the night, and heat flowed from the air into the soil requiring the heater output to be increased to counteract this loss.

e) The Passive Ventilation (leakage) Rate

The next runs investigated the passive ventilation of the glasshouse which under normal conditions occurs at a rate of about two air changes per hour. As expected, a decrease in the passive ventilation rate gave a decrease in the heat requirement as the heat loss from the inside air was lessened (see figure 4-p).

f) Convective Transfer Inside the Glasshouse

The next runs were used to look at the effect of altering the convective heat transfer coefficient of the surfaces inside the glasshouse. As with the external coefficients there are a wide range of values to be found in the references. The changes made in these runs were applied to all of the inside surfaces at the same time. The heat requirement fell as the inside convective heat transfer coefficient was decreased (see figure 4-q). The effect of lowering these coefficients was to increase the floor temperature, allowing heat to flow from the floor into the inside air later into the night, and to lessen the amount of heat lost from the inside air to the roof. This loss resulted in a drop in the temperature of the roof, TEMP3, causing it to fall below TEMP1 at times and this meant that heat was flowing from the outside air to the roof, into the system rather than away from it. In a specific study of the effects of changing these coefficients a more realistic outside air temperature should be used.

g) The Outside Air Temperature

Changes to the outside air temperature would affect the heat requirement and in the next runs TEMP1 was altered and the results are shown on figure 4-r. A lower value of TEMP1 had the immediate effect of reducing TEMP3, thus increasing the rate of convective heat transfer from the inside air. There was a greater net flow of longwave radiation from the floor to the roof and these two effects raised the demand on the heating system. At the lowest temperature tested the heater was switched on all day but at the other extreme tested, the higher value of TEMP1 caused an increase in TEMP3 which reduced the demand on the heating system.

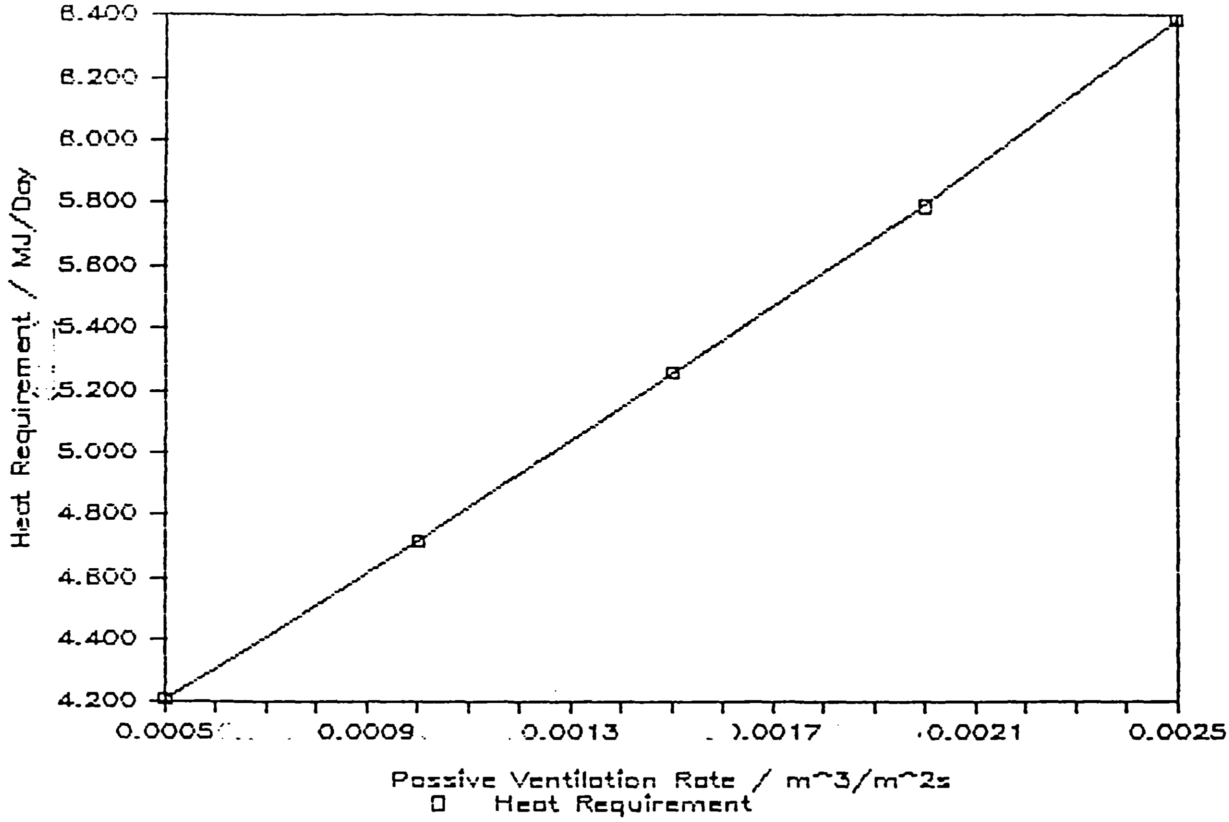
h) The Cladding Extinction Coefficient

A change in the extinction coefficient of the cladding material alters the amount of solar radiation absorbed. The size of the effect is small leading to a low solar radiation absorption by the glass about 5%. The graph, figure 4-s, shows that the effect was small when this coefficient was changed; a doubling of V(3) led to a 0.9% rise in the heat requirement. These runs were carried out to demonstrate that GHFORSM is sensitive enough to detect changes of this size.

i) The Day of Year

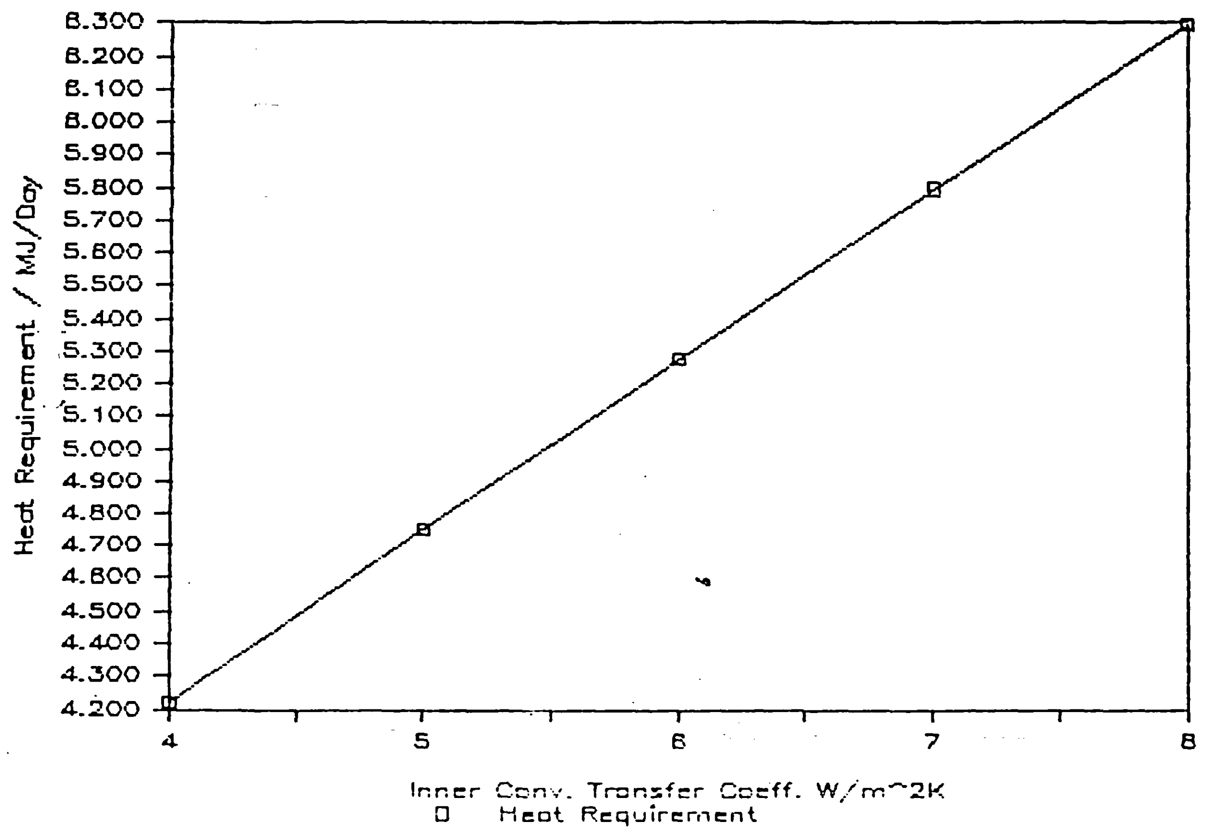
The next set of runs was used to check that the program would simulate different days of the year. It was run five times with daynumbers corresponding to December 21st, February 4th, March 21st, May 5th and June 21st the outside air temperatures were also altered. The results are shown on graph 4-t and whilst the values which described the weather conditions were not very realistic, the model behaved as expected with less heat being required as the outside air temperature increased as the year progressed.

Fig 4-p



Heat Requirement / MJ/Day
0.0005
0.0009
0.0013
0.0017
0.0021
0.0025
Passive Ventilation Rate / m^3/m^2s
□ Heat Requirement

Fig 4-q



Heat Requirement / MJ/Day
4
5
6
7
8
Inner Conv. Transfer Coeff. W/m^2K
□ Heat Requirement

Fig 4-r

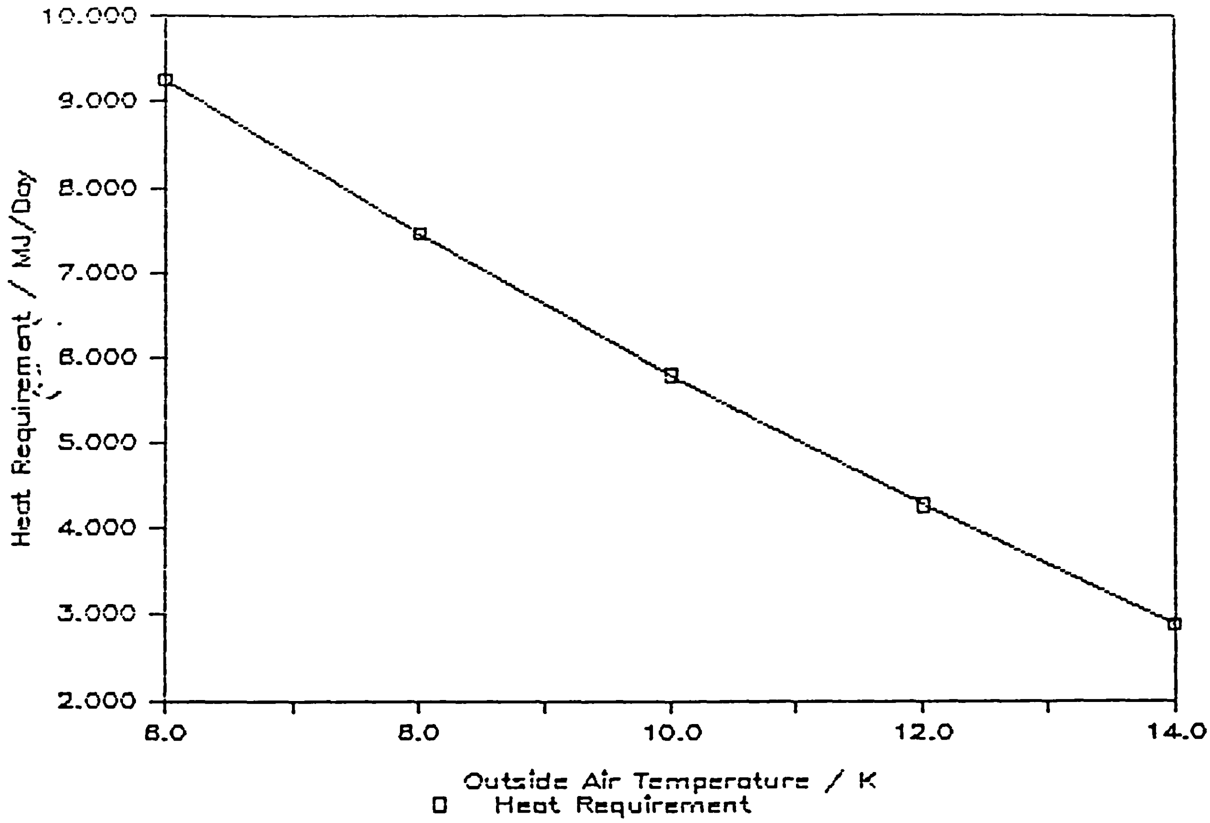

10.000
9.000
8.000
7.000
6.000
5.000
4.000
3.000
2.000
Heat Requirement / MJ/Day
6.0
8.0
10.0
12.0
14.0
Outside Air Temperature / K
Heat Requirement

Fig 4-s

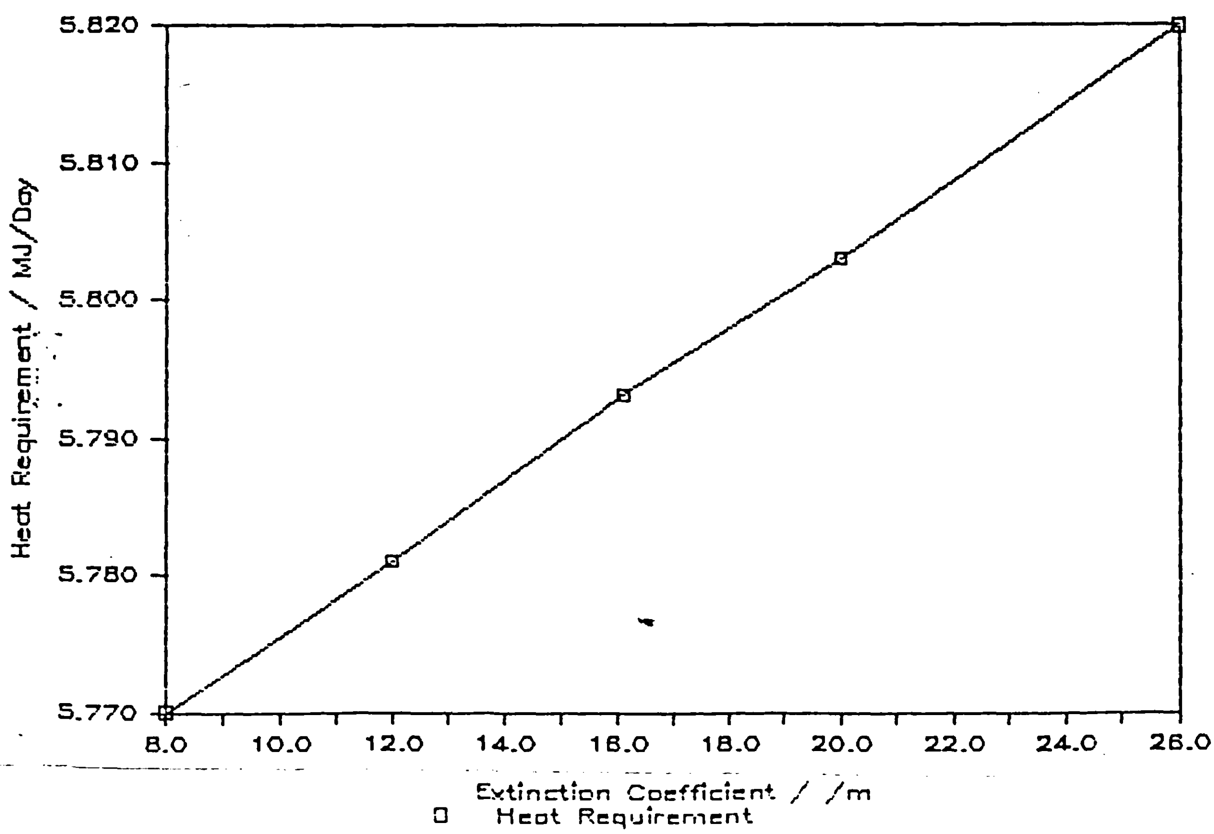
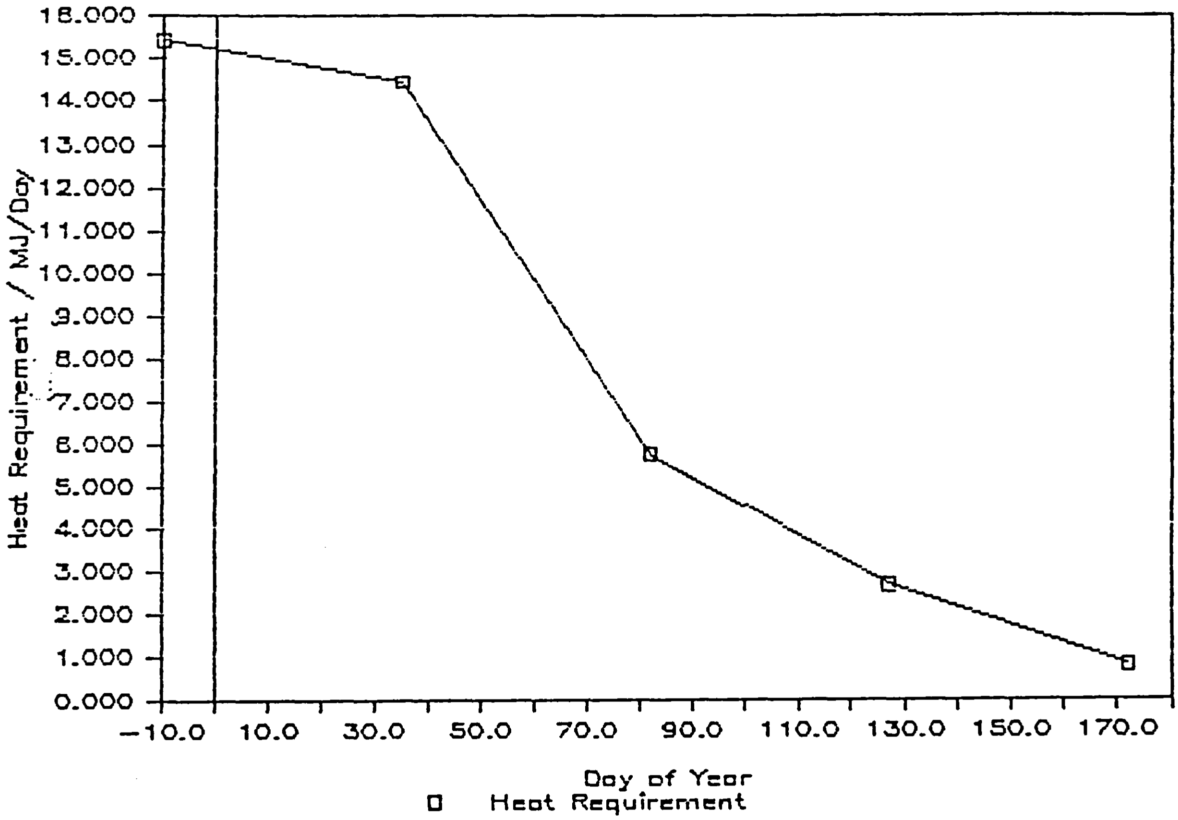

5.820
5.810
5.800
5.790
5.780
5.770
Heat Requirement / MJ/Day
8.0
10.0
12.0
14.0
16.0
18.0
20.0
22.0
24.0
26.0
Extinction Coefficient / /m
Heat Requirement

Fig 4—t



j) Sharp Changes in Weather Data

A final set of verification runs tested the ability of GHFORSM to handle changes in the weather data. Three runs were carried out with the heater switched off. The first of these used steady solar radiation data between 12.00 and 12.30 h (200 W/m^2) and the second used very spiky' sunshine (0 and 387 W/m^2 on alternate minutes). The total energy received by the system was identical in these cases but for the third run the amplitude of the 'spikes was increased to 1000 W/m^2, a more severe test of the routines. The results of interest in these cases were the relative amounts of computer time required by each run.

The execution times required for these runs were 38, 58 and 69 seconds respectively, the third run taking about 80% longer to complete that the first. This shows that when sharp changes occur in the solar radiation data the computer time required to handle these is lengthened. Using real meteorological data, the wind speed and the solar radiation may vary sharply over short time periods, on windy days with fast moving clouds for instance, and other changes such as variation in air temperature will take place more slowly. The computer time needed to handle real weather data will increase as the number of weather variables increases. The above results show that GHFORSM, using FORSIM and a large mainframe computer, can handle sharp changes to solar radiation data very quickly, but the results also indicate that smaller machines might have more difficulty. Routines available for microcomputers are unlikely to be as sophisticated as those which make up FORSIM, so that not only would the steady state run take longer to execute, but the 'spiky' data runs would take more than 80% longer to complete, if they worked at all.

These test runs do not constitute a complete set but were sufficient to verify that GHFORSM functioned as intended. This fact in itself allows the user to have a certain degree of confidence in the model. As a result of these runs it can be seen that changes to a number of variables such as the albedo of the floor and the passive ventilation rate, have a marked effect on the heat requirement. If the model can be validated so that these results can be considered correct, these test runs suggest several avenues of further investigation which might be carried out and these are discussed later in the chapter.

Validation

The process of validating a simulation model is recognised as being extremely important but often difficult. Anand et al. (1979) provide a definition of model validation, stating that it is the comparison of model outputs with some reference: real world observations or output from some other model. The availability of a validated model allows parameter optimisation for example, to be carried out with confidence and at minimum cost.

Lehman (1977) states that agreed criteria for validation of models have not been developed, and also says that the validity depends upon the purpose for which the model is intended. It is in this statement that the difficulty becomes apparent; the widespread use of modelling and simulation in varied fields causes problems in the development of validation criteria. The questions to ask in validation are of the type "does the program represent the model and the real world accurately?". Lewis and Smith (1979) discuss the difficulties of validation stating that few known techniques exist which might guarantee a program's correctness. Both Smith (1968) and Kobayashi (1978) say that validation is straightforward in principle but difficult in practice.

Naylor et al. (1966) consider that the problems of validation involve many practical, theoretical, statistical and even philosophical complexities. They continue by stating that it is the very possibility that simulation models may be able to predict, that is the major source of justification for using simulation as a tool of analysis. Despite the complexities they manage to define the problem quite succinctly, saying that in general two tests of a model apply:

1) how well does a model compare with historical data?
2) how accurate are future predictions?

Validation is more than just quantitatively comparing a model's predictions with the measured behaviour of some real system, and more than extended verification. There are three areas to consider according to Lantz and Winn (1979) and these are

1) the evaluation of the quality of the input and comparison data
2) the evaluation of the model's assumptions and model logic
3) the evaluation of the model's predictive capability.

The assumptions in (2) are required in the modelling process to define the problem in a form that can be handled by a computer.

Whilst a model may be compared with the real world, such comparisons make no evaluations of the adequacy of the underlying theory itself, or indeed of the model as a representation of the theory (Lehman, 1977). Emshoff and Sisson (1970) state that the common method of validation is to compare output of a model with historical data but problems occur with management type models. The justification for the use of such models is that they have provided correct predictions in the past. This puts the new model in a difficult position since there is no past performance record to fall back on. These authors outline five approaches to validity which may help in the process and can certainly be used as a definition of the problem:

1) Internal validity
With no change in input values the results obtained from separate runs should be the same, within the definable error limits. For models which involve stochastic processes, only slight changes in output should be expected.

2) Face validity
Does the model appear to be a correct representation of the real system? This is more of a verification stage, testing the behaviour of the model and 'seeing' if it gives reasonable results

3) Variable/parameter validity
This too is a verification stage, and is a check to ensure that the simulation's parameters compare with those of the real system. This is a most important process because almost any model can be made to give the correct results for a given situation by assigning values to parameters which bear no resemblance to the real ones. Seldom however, will such a set-up provide correct results for different situations. A sensitivity analysis can be included in this stage.

4) Hypothesis validity
This is a check on the relationships between sub-models within a main model to see how they compare with the real world.

5) Event validity
This is validation in its most widely used form. In other words a test of how well the model predicts observable events.

Stages one to four are important in assuring the modeller that the process is worth continuing but a model can only be considered truly valid after stage five has been completed.

Anand et al. (1979) produced guidelines for a validation methodology for solar heating and cooling models. They classified models into two categories; the detailed type which can accept data in short time interval form and have considerable flexibility in the configuration of systems they simulate, and the more simplified approaches which predict monthly and yearly system performance. They note here that even in a somewhat limited subject, these two approaches to modelling, with their inherent differences in detail, assumptions, flexibilities and capabilities, make it inappropriate to develop a single methodology of validation. They present an overall perspective which takes account of both types of model. For the more detailed type of program, they suggest that the first step is to consider the question "what effect do unmodelled physical phenomena have on the accuracy of the simulation?"

Whilst many models are based on physical laws and properties which are quite well understood, experimental data is needed to back up the results of a simulation in which models of physical laws are linked together by less well understood pathways. The simplifying assumptions, often used in the modelling of responses to weather, never provide a complete picture and can lead to unacceptable errors in the final output. The simplifying assumptions made in combining two parameters, or in modelling the system responses to change for example, can give errors which cannot be accounted for merely by examining the model's parameters. This level of validation, really a combination of verification and validation, is designed to identify these errors. A similar process can be carried out for the simpler type of models and such an analysis should give the modeller some idea of how well his model will predict the system given accurate input data. The next level of validation must account for the variability of design parameters and the effect this variability might have on the model's performance. For example, a glasshouse model or a solar heating device model must be able to cope with variable weather data and alterations in the parameters describing the system. This level establishes confidence limits on the model's performance.

Finally, they suggest that real system data can be compard with model prediction

Smith (1968) also acknowledges the importance of good quality data in the validation of a model. A suitable set of data should be long enough to test the model fully, but be fairly constant in the first instance. In practice, there is often a lack of sufficiently long time run data which is complete enough for validation purposes. Data is often difficult to obtain but some validation process should be carried out whatever the state of the data available, because it will provide a check on the larger errors at least. As a last resort, turn to common sense. For instance, do small input changes give small output changes where required? (Lewis and Smith, 1979).

The validation of GHFORSM

The previous discussion suggests that the validation of a computer model is very important to try to achieve, but is seldom easy. GHFORSM is capable of providing large amounts of output on a wide range of environmental variables and this capability was provided for two reasons. Firstly, as the model was developed, the large amounts of output data provided a means of checking that the various routines were acting as intended, it gave a method of verifying the correct coding and correct action of the model. Secondly, it was hoped that large amounts of output would facilitate the eventual validation of the model.

It became clear that the sort of complete data necessary for a more thorough validation of the model would be difficult to come by, despite the fact that it had been expected that a suitable supply of data would be available at the required time.* Complete data would include measurements of the physical characteristics of the glasshouse as well as measurements of component temperatures, radiation levels, air humidity and energy used in heating over a number of days and under different conditions. After writing

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* A measuring programme at NIAE was cancelled during 1983 due to the installation of a new computer system.

and visiting various research stations, universities, manufacturers and growers around the country, it was apparent that although most people were willing to provide any data which they did have, there was little which was of real use. No one had or intended to make a complete set of measurements of the environmental conditions in a glasshouse.

Despite these drawbacks I am extremely grateful to all those who were able to provide data but particularly to Dr J M Penman of the South-West Energy Group at Exeter University, and Mr S Wass of MAFF in Bristol who sent me two papers concerning a model which he has developed.

Without the means of carrying out the sort of validation which had originally been intended, other methods had to be found. Three approaches were used. The first was to compare the inside air and solar radiation output from the model with real measurements made in glasshouses which were either provided as data or found in references. This approach disregarded the heat requirement and was designed to see if the modelled temperatures matched the real ones. The second approach was to see if heat use in the model matched the limited data which was available and to see how well this model output corresponded to that of other models. Thirdly, in several of the references, figures are quoted for the reduction in heat requirement when particular conservation measures were applied and GHFORSM was used to simulate the use of these same measures and the required heat reduction was compared.

a) Comparison of GHFORSM with a Model by Kimball (1973)

For the first stage of validation comparison was made between GHFORSM and measured inside and outside temperature and radiation values recorded by B A Kimball (1973). In his paper Kimball described a model which simulated the energy balance of a glasshouse. Comparison was also made between results produced by Kimball's model and GHFORSM using the same input data as far as possible. The recorded measurements were made in a glasshouse in Arizona and although conditions there can hardly be likened to those found in the UK, they provided a good test of how well the model could withstand varied meteorological data. Included in Kimball's paper was a list of parameters which pertained to the glasshouse in which the measurements were taken, and although this was not a complete list, it was useful in the absence of similar lists in other references. Several graphs were presented showing the measured data and his model's predicted data. Two runs of GHFORSM were undertaken, one using the measured solar radiation data for June 23, 1970 and the second using solar radiation data generated by the model. The values of parameters and coefficients which were used in the model runs are given below. Generally the values given by Kimball appear first and the values used in GHFORSM appear afterwards, on the right hand side of the page.

The dimensions of Kimball's glasshouse were as follows:

Width	= 10.52 m		
Length	= 15.64 m		
Height	= 4.71 m		
Roof slope angle	= 27.1°	V(1)	= 27.1°
Average air thickness	= 6.1 m	THICK(15)	= 6.1 m

The glass thickness and radiation reduction are shown below. The same values of density and heat capacity of glass used in the standard reference run were used here.

Glass thickness	= 0.0037m	THICK(3)	= .0037m
Radiation reduction by dirt etc.	= 10%	V(4)	= 0.9

Specific mention is made of the number of air changes per hour by natural ventilation and using this with the dimensional data allowed a value of the ventilation rate in m^3/m^2s to be calculated.

Passive ventilation rate	= 0.22/hr	V(7)	= .00037 m^3/m^2s

The floor albedo for solar radiation is shown below:

Floor albedo	= 0.1	V(9)	= 0.1

The floor and cladding emissivities used were:

Floor emissivity = 0.96	EMLR(17) = 0.96
Cladding emissivity = 0.93	EMLR(3),(4) = 0.93

The values for the soil parameters shown, allowed the heat transer coefficients to be calculated using a value of 1500.0 kg/m^3 for the soil density.

Soil thermal conductivity = 1.26 W/m°C

Soil heat capacity = 840.0 J/kg°C

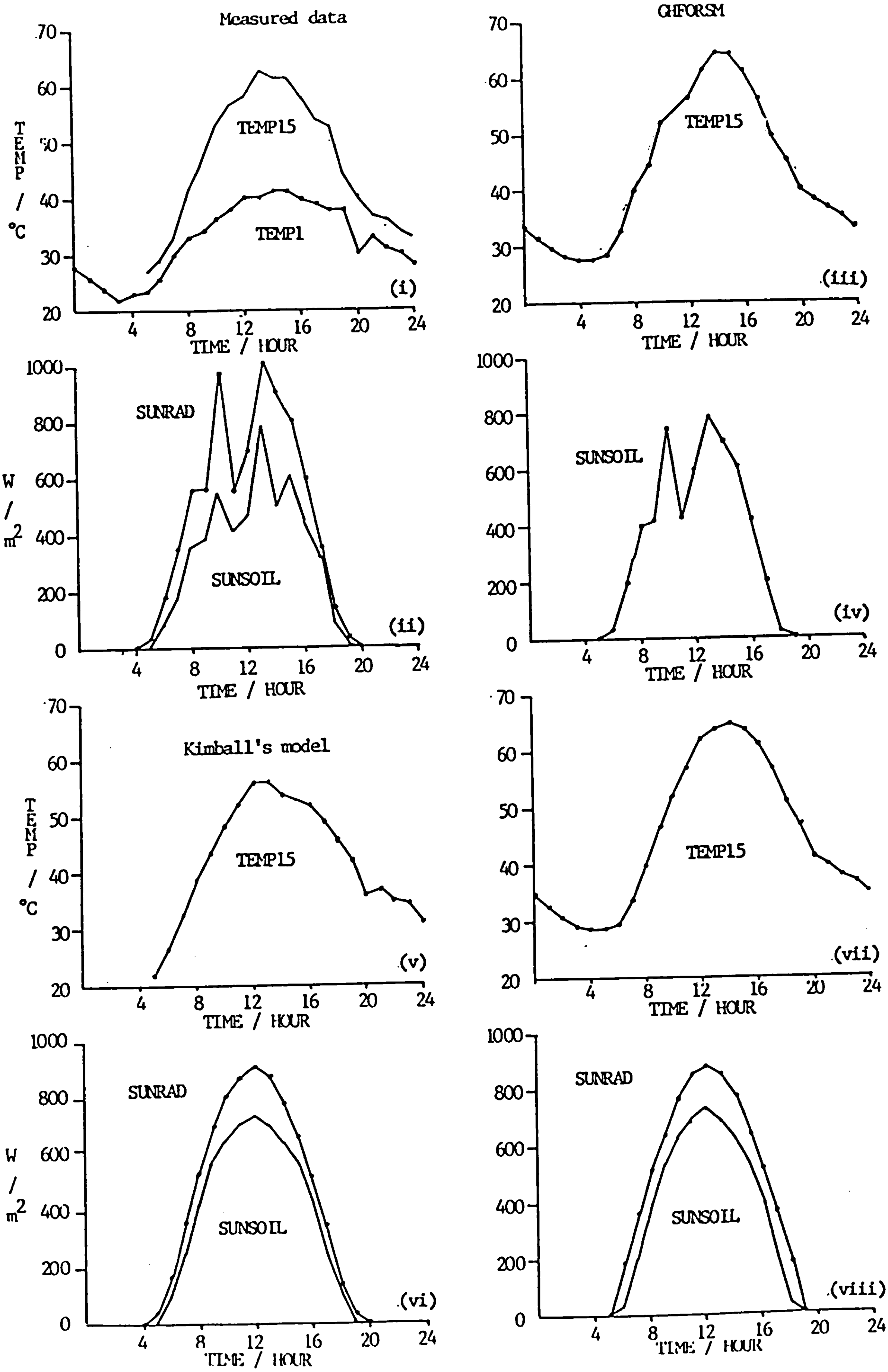
The heat transfer coefficients for the soil used in GHFORSM were derived from the above thermal conductivity value and are shown below:

CHT(18) = 84.0 W/m^2°C
CHT(20) = 42.0 W/m^2°C
CHT(22) = 21.0 W/m^2°C
CHT(24) = 10.5 W/m^2°C
CHT(26) = 5.25 W/m^2°C
CHT(28) = 2.625 W/m^2°C

The soil beneath the system had a temperature as indicated:

Deep soil temperature = 34°C	V(10) = 34.0°C

The results of these runs are shown in figures 4-u(i) to 4-u(viii). 4-u(i) shows the outside air temperature (TEMP1) variation against time and these figures were used as an input to GHFORSM. The second curve on the graph shows the measured inside air temperature (TEMP15) in an unventilated, unshaded glasshouse. Figure 4-u(ii) shows the solar radiation curves, one measured outside the glasshouse (SUNRAD) and the other inside (SUNSOIL). This particular day appeared to be intermittently cloudy as there is variation in measured values between 9.00 h and noon. Figure 4-u(iii) shows TEMP15 simulated by GHFORSM and these values were very similar to the measured values. The best fit occurred in the early morning and in the afternoon. Figure 4-u(iv) shows the amount of radiation reaching the floor, equivalent to the solar radiation inside the glasshouse shown in figure 4-u(ii). In



Figs. 4,-u(i),u(ii),u(v) and u(vi) after Kimball, 1973 this case the fit is not quite as good as before but the general shape of the curve and the maximum values are nearly identical. Differences in specific values at various times of the day may be attributed to the structural members of the glasshouse partially blocking the radiation.

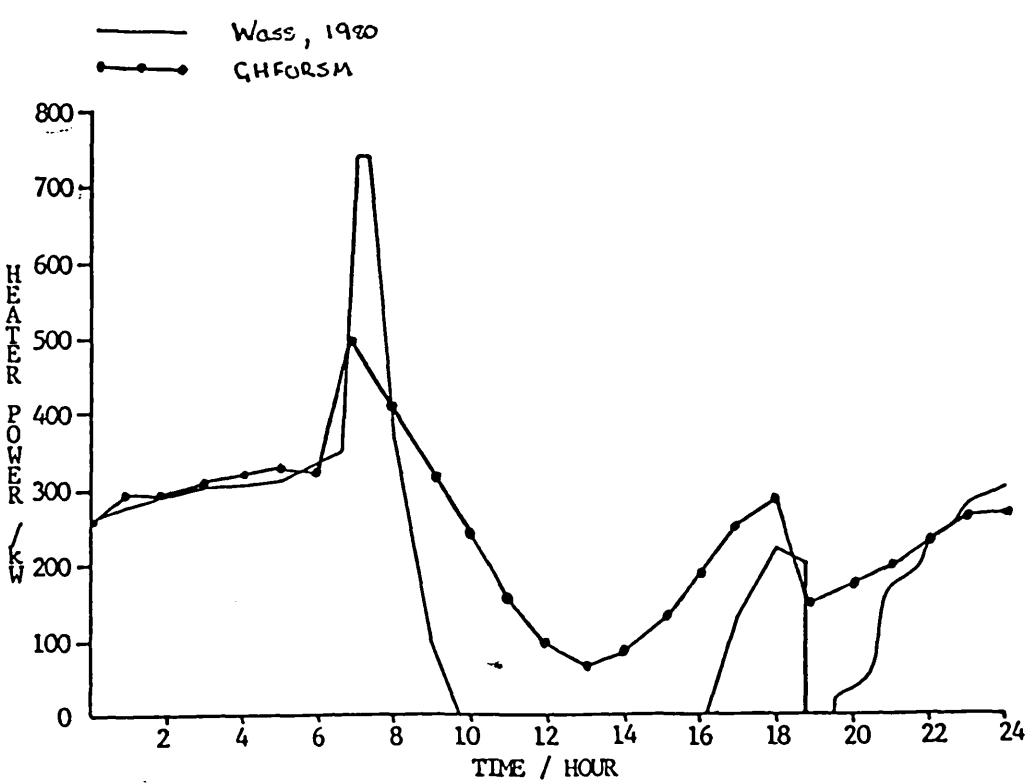
Figures 4-u(v) to 4-u(viii) are results from Kimball's model and GHFORSM, both set up to generate solar radiation data. Figure 4-u(v) was the inside air temperature produced by Kimball's model. Although this reached a peak at the same time as the recorded data (see fig. 4-u(i)), the maximum value was lower by about 7°C. This graph also shows that the temperature fell to a low value of about 22°C just before sunrise when the measured value was approximately 27.5°C. Figure 4-u(vii) shows the inside air temperature calculated by GHFORSM which again reached a maximum of 64°C at about 14.00 h. Figures 4-u(vi) and 4-u(viii) show the solar radiation outside and inside the glasshouse as calculated by both models. These are practically identical as similar generation techniques were employed.

The results shown here were extremely encouraging as they showed that GHFORSM produced reasonable values. A more complete knowledge of the system in which the measurements were taken, or more frequent data would probably improve the fit still further in the first case where recorded data values were used as input. In the second case it can be argued that GHFORSM produced results closer to the recorded data than Kimball's model did. Furthermore, these runs show that GHFORSM is flexible enough to handle a range of meteorological data and can cope with temperatures and radiation values recorded in Arizona. However, even though these results were encouraging, they must be seen in perspective. All that GHFORSM was required to do here was produce a roughly sinusoidal output curve using roughly sinusoidal input data. If this was to be its sole task, a much simpler model would be all that was required. However, the inclusion of a heating system and blueprint temperature strategies changes the response of the inside air temperature and a more complex model is needed. A sinusoidal model may be satisfactory under conditions of steady sunshine where the main external energy input to the system follows a sinusoidal path, but under less steady conditions, intermittent clouds for example, more complexity in the model is needed to handle the sharp changes and simulate the inside environment more closely.

b) Comparison of Heater Output from GHFORSM with Wass (1980 and 1981)

Wass (1980 and 1981) prepared a model of the fuel requirement of a glasshouse heating system in collaboration with workers at the National Institute of Agricultural Engineering (NIAE) The model included the use of a U value in estimating the transmission losses from the inside air and the ability to include heat gained from the burning of propane or paraffin for CO_2 enrichment Using similar meteorological data and knowing the area of glasshouse which Wass' model was simulating it was possible to set up a similar run for the same day on GHFORSM. The two models are of different types and the sort of detailed data required for GHFORSM was not available and so estimates for many of the parameters had to be made.

Fig. 4-V



The shapes of the heater output curve are similar although results from GHFORSM are plotted at hourly intervals so that some of the variation may be masked and some of the peaks and troughs have been smoothed out. The curves indicate that the heater in GHFORSM did not switch off at any time time during the day (see figure 4-v). One reason for this was that during the day the heat derived from CO_2 enrichment in Wass' model was provided by the heater in GHFORSM. However, taking the final heat output results it can be seen that there was a good correspondance between the two. Wass produced a figure of 5000 kWh consumption. plus 631 kWh derived from CO_2 enrichment. The figure from GHFORSM is 5775 kWh which is 2.5% higher than the total requirement simulated by Wass' model.

It is very tempting for a modeller to say that such a good correspondance shows that his model is a valid representation of the real world, but the figures compared above were results from two models. It is encouraging to see such similar results but it is possible that this comparison is partly due to good fortune in estimating the system parameters. In the absence of detailed information there is no way of checking this result but it does show that GHFORSM does produce reasonable heat requirement figures.

c) Comparison with Data Recorded by the South-West Energy Group

The South West Energy Group based at Exeter University have been working on a glasshouse simulation model and some measurements of environmental conditions in a real glasshouse have been made. Data on solar radiation, wind speed and direction, inside and outside air temperature, heating water temperature and firing times of the two boilers have been recorded. The structure was oriented along a North-South axis, and the dimensions of the glasshouse in which these measurements were made are:

Length	= 30.45 m
Width	= 6.16 m
Height to Eaves	= 1.82 m
Height to Apex	= 3.48 m

These figures give the roof slope angle as 28.3°. The data provided was in the form of hourly readings some of which were less reliable than others. The heating system of two boilers were originally intended to heat three identical houses. When the data was recorded, only one of the houses was being heated and the boilers were working at a fraction of the normal load. This reduced their efficiency which was estimated at somewhere between 30 and 50% based on measurements of fuel flow through the burner nozzles which were subject to an error of about 15%. The simulations carried out on GHFORSM using the measured meteorological and structural data for two days were difficult to compare with such uncertain heating requirement figures. The boilers (1 and 2) burned fuel at a rate of $1.38*10^7$ and $7.8*10^6$ J/min respectively. The standing losses from the heating system have been calculated at $17.5*10^8$ +/- $3*10^8$ J/day (South West Energy Group Annual Report, 1982/83). Using the data for this particular glasshouse was rather a coarse way in which to test the validity of the model; the uncertainty in the measured energy consumption figures provided a broad band of error. Coupled with this was the fact that this glasshouse of some 187 m^2 in area was rather small, and was not of the sort of size which GHFORSM was intended to simulate; the inside longwave radiation exchange would be different for example. Once again, many of the parameter values which were required in the model had to be estimated, providing a further source of error in the simulation. The measured energy consumption figures and the modelled heat requirement are shown below:

Day 82	Burner 1 fired for 196 minutes	= 2548 MJ
	Burner 2 fired for 93 minutes	= 725.4 MJ
	Total	= 3273.4 MJ
	Subtracting the standing losses gives that the real energy requirement lies in the range	1223 to 1823 MJ
	GHFORSM heat requirement output	= 8.885 MJ/m^2
	multiplied by floor area	= 1667 MJ

This result compares well with the recorded value.

Day 95	Burner 1 fired for 194.4 minutes	= 2572.2 MJ
	Burner 2 fired for 82.8 minutes	= 645.84 MJ
	Total	= 3218.04 MJ
	Subtracting the losses gives	1168 to 1768 MJ
	GHFORSM heat requirement output	= 9.726 MJ/m^2
	multiplied by floor area	= 1824 MJ

This figure is greater than the maximum value of the range shown above.

The results are of the correct magnitude and show once again that the model behaves as intended and does produce heat requirement figures which are of reasonable value, even if some of the parameter values might not be correct.

Each of the runs described so far in this section give an indication of validity for specific instances, but when the results are considered together, they do give the user a degree of confidence in the model; three different glasshouse simulations using different input data produced results which were very close to the measured data in two of the cases.

d) Comparison of GHFORSM Results with Energy Conservation Data

The final set of validation tests were designed to simulate energy saving techniques investigated by other researchers to see how the results produced by GHFORSM compare. These were used not only for validation but also as a verification of the thermal screen routines. The use of thermal screens can give heat savings of between 26 and 57% (Rebuck et al. (1977); Simpkins et al. (1976); Rotz et al. (1974)) Research was conducted by Bailey (1975, 1976, 1977, 1979, 1981) into the use of thermal screens and during the course of his work he measured the optical and longwave radiation properties of many screen materials (Bailey, 1981). Black polyethylene, clear polyethylene and aluminised polyester screens were among those that he tested and GHFORSM was set up to simulate the use these. Since the conditions under which they were tested were again somewhat artificial (unchanging outside air temperature for example) the results will not be discussed in great detail.

The runs will be described briefly first, and then the results will be given in a table afterwards. The first run was conducted without a screen present and produced a reference heat requirement figure. When black polyethylene was simulated, the emissivities of the upper and lower surface were set at 0.77, and the longwave transmission through the screen was 0.18 (Bailey 1981). The clear polyethylene screen was simulated by setting the emissivities to 0.12 and the transmission to 0.85 (Bailey, 1981). Cam-Therm is an aluminised polyester. laminated to a black polyethylene layer with the aluminium protected by a layer of lacquer. For this simulation the emissivity of the top layer was taken to be 0.06, for the aluminium, whilst that of the the lower layer was 0.95 (Bailey (1981) does indicate that there are different values of emissivity for polyethylene depending upon the density), and the longwave transmission was 0.0 (Bailey and Cotton, 1977). The results are shown below

Screen Material	Emissivity EMLR(11)	EMLR(12)	LW Trans. V(34)	Heat Required W/m^2	Simulated Reduction %	Measured Reduction %
No Screen	-	-	-	2892	-	-
Black poly	0.76	0.76	0.18	1426	51	32-44
Clear poly	0.12	0.12	0.85	1589	45	33-50
Cam-Therm	0.06	0.95	0.0	1258	57	51-65

The range of values given in the 'Measured Reduction' column were recorded by Bailey at wind speeds ranging from 0.0 to 6.0 m/s. GHFORSM was set to simulate light wind conditions of about 2-3 m/s. It would appear from these results that the black polyethylene screen simulation gave too great a reduction whilst simulations of the other types of screen materials gave a good agreement with the measured data and other simulations of aluminised screens gave similar results.

e) Comparison of GHFORSM Results with Tests on Commercial Glasshouses

Bailey (1979) also conducted some screen tests on commercial glasshouses. In one experiment a screen made of an impermeable film of aluminised polyester laminated to black polyethylene, Peritherm, was used in a 0.22 ha glasshouse. Peritherm has upper and lower surface emissivities of 0.07 and 0.91 respectively. An identical glasshouse was kept unscreened and the fuel consumption in each was compared daily. For the period around March 21st 1979, the fuel savings in the screened glasshouse were between 50 and 60% of the fuel used in the unscreened house. GHFORSM was set up to simulate similar growing conditions using the average outside air temperatures for this time period. With the screen in place at night the model simulated savings of about 57% in the heat requirement compared with the unscreened simulation. Although data about the glasshouse system and external conditions was again scanty, the measured results were made in a large glasshouse, more similar to the type which GHFORSM was intended to simulate than the small experimental compartments in which many of the other screen measurements had been made. This test shows a good agreement between the model and the measured data.

This was the limit to which validation of the model was taken and it was thought unreasonable to carry out further validation work until more measured data was available. None of the above tests alone could be regarded as a true validation of the model as they could all be considered as special cases. Taken as a whole however, this set of results does show that the model is unlikely to produce wildly inaccurate results for the systems tested so far, and in some cases the agreement between the simulated and real systems was very good.

Chapter Five

Results

During the course of the project many runs of the model were made for verification and validation purposes. The first test runs were made on simple systems having single roofs and constant outside air temperatures. Later runs tested the double glazing and thermal screen routines. These have already been discussed in terms of verification and validation but in this chapter I re-examine them from the point of view of energy conservation Finally, a set of runs was carried out to investigate the effects of using thermal screens, double glazing and low emissivity glass in two different areas of the country

Energy Conservation Strategies

The graph of the heater power for the reference run (fig. 4-j) shows an increase in power requirement late in the afternoon. As described in the previous chapter this was due to the heater having to maintain the daytime setpoint temperature as the solar radiation intensity decreased. Keeping the air temperature at the daytime setpoint for the last two hours of the afternoon is expensive and wasteful since much of this energy is allowed to escape at sunset when the lower night-time setpoint is used. Little growth occurs under the relatively low light conditions of late afternoon, and the grower might save energy by implementing the night setpoint earlier, or by using an intermediate value.

a) In the test runs, altering the value of the floor albedo from 0.1 to 0.8 gave an increased heat requirement of 87%. In the presence of a crop this result would have been different since little direct radiation would have reached the floor after the plants had developed. The use of white polyethylene sheeting by growers increases reflection from the floor to increase the light available to the crop. To save heat, a low albedo covering in good thermal contact with the floor would be desirable when the leaf area index was low and the heating demand was greatest. Later in the year a high albedo covering would be beneficial to increase the amount of light in the crop canopy. However, the grower has to opt for one option or the other at the beginning of the growing season, most use white polyethylene.

b) When the passive ventilation rate was altered from one air change per hour to two the heat requirement increased by 22%. This suggests that the grower should reduce the leakage rate as much as possible. However, there are other factors to be considered. The leakage rate should not be reduced to such a level that active ventilation is required to maintain the CO_2 concentration during the cold months of the year since more heating would be required to warm the inside air. Direct firing is one alternative to active ventilation to increase CO_2 concentration but this can also cause problems. Nitrogen oxides and unburnt hydrocarbons from direct firing, and the use of chemical compounds such as wood preservatives and coatings for plastics can all damage crops. Inadequate ventilation can lead to dangerously high concentrations of these chemicals and crop damage amounts to £2 million per year in Britain (New Scientist, 25-8-83). Clearly it would not be sensible for the grower to try to save energy if his losses in reduced crop yield outweighed the energy savings. Another consideration is that a well sealed glasshouse might not allow enough moist air to escape and the humidity would increase. It is still uncertain as to whether high humidity levels are directly detrimental to plant health but falling condensation might increase the risk of disease. So the degree of reduction in the passive ventilation rate has to be balanced; conditions for plant growth must be acceptable, whilst not too much heat is wasted through poor cladding.

c) The longwave radiation characteristics of the system have a large effect on the heat requirement of the glasshouse. An increase of 50% in the emissivities of the upper and lower surfaces caused an increase in the heat requirement of 27%. The same increase in floor emissivity raised the heat requirement by 13%. However, in this case there was no crop present to hinder the longwave radiation exchange between the floor and the roof. The longwave exchanges involving the floor are not of primary importance, the grower will decide on a method of crop production and will cover the floor with an appropriate covering. The effect of changes in floor emissivity is difficult to quantify without a crop. For the roof the energy benefits of low emissivity cladding are clearer. However, the presence of dust and condensation will affect the emissivity and thus the heat exchange.

d) Raising the value of the inside convective heat transfer coefficients by 50% gave an increase in the heat requirement of 25%. Although the grower can alter the longwave characteristics of the glasshouse cladding and floor by installing a low emissivity glass or a different sheeting on the floor, altering the convection coefficients is more difficult. The most significant inside convection exchange is that between the inside air and the cladding and to reduce the overall convective loss to the roof an indirect approach has to be applied. The introduction of a second cladding layer adds an extra resistance to the system and reduces the flow of heat from the inside air. The use of a thermal screen has a similar effect but causes no reduction in light transmission since it is withdrawn during the day. The simulated use of a screen with an aluminised upper surface gave a heat saving of 57% shown in the previous chapter. In another run of GHFORSM a double glazed roof and no active ventilation reduced the heat requirement by 70%. The absence of active ventilation meant that this run simulated slightly different conditions from previous ones and it was carried out to see the level of component temperatures that would arise under these conditions. The results shown in figures 5-a,b,c and d also demonstrate one way in which the model can be used. A user investigating the amount of ventilation required for a glasshouse with a double glazed roof can compare results from runs using varying degrees of active ventilation against this one.

The heat saving which resulted from the use of a double glazed roof was high (figs. 5-a,b) and at first sight it might appear that it was higher than it should have been. The presence of an extra roof layer might be expected to double the resistance to convective heat transfer under free convection conditions and the heat requirement would be expected to fall by 50% if this were the sole mode of loss from the system. Using the full printing capabilities of GHFORSM it is possible to see where the extra saving arises and also where problems which might not have been immediately obvious occurred.

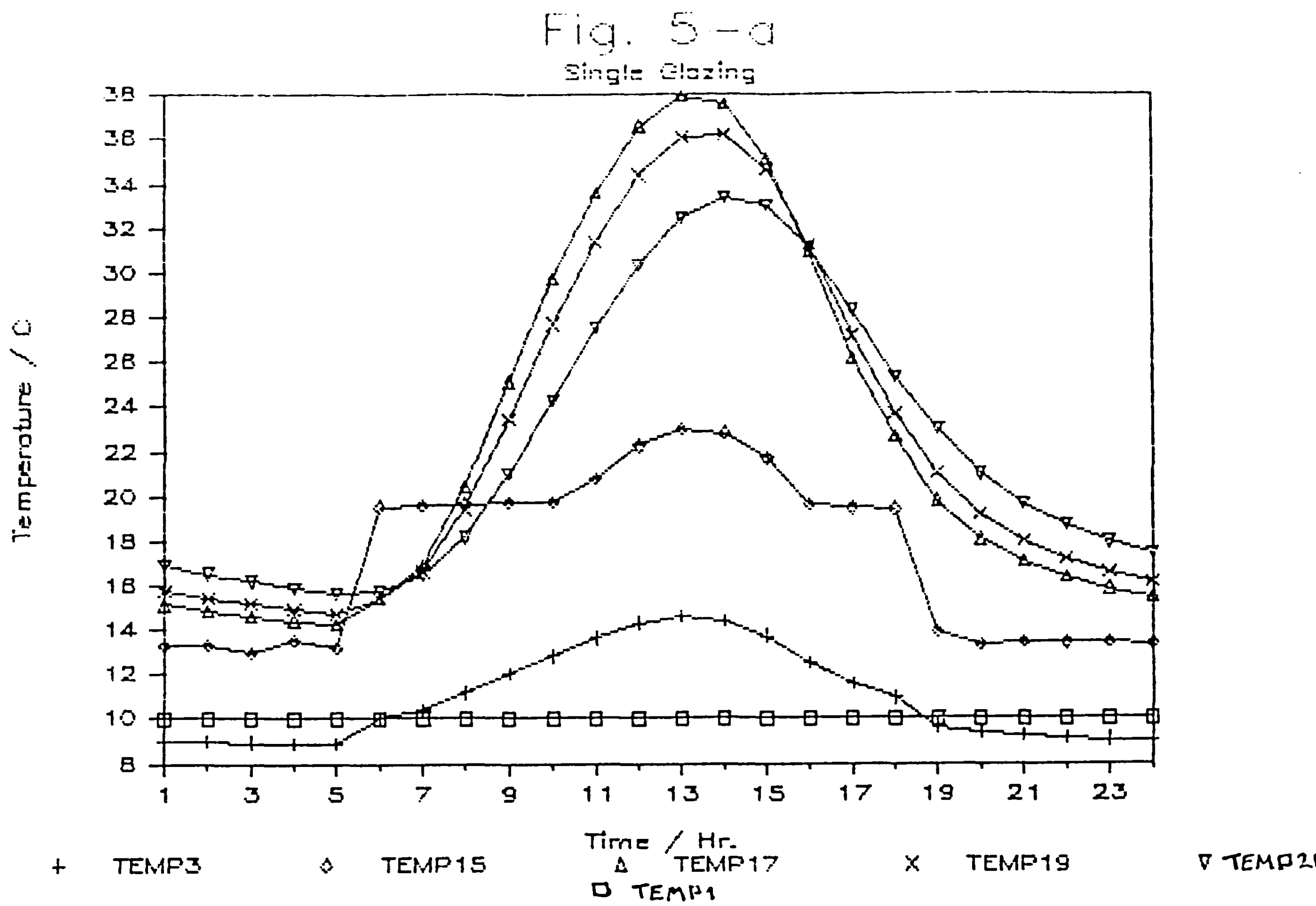


Fig. 5-a
Single Glazing
Temperature / C
Time / Hr.
+ TEMP3
◊ TEMP15
Δ TEMP17
X TEMP19
∇ TEMP21
□ TEMP1

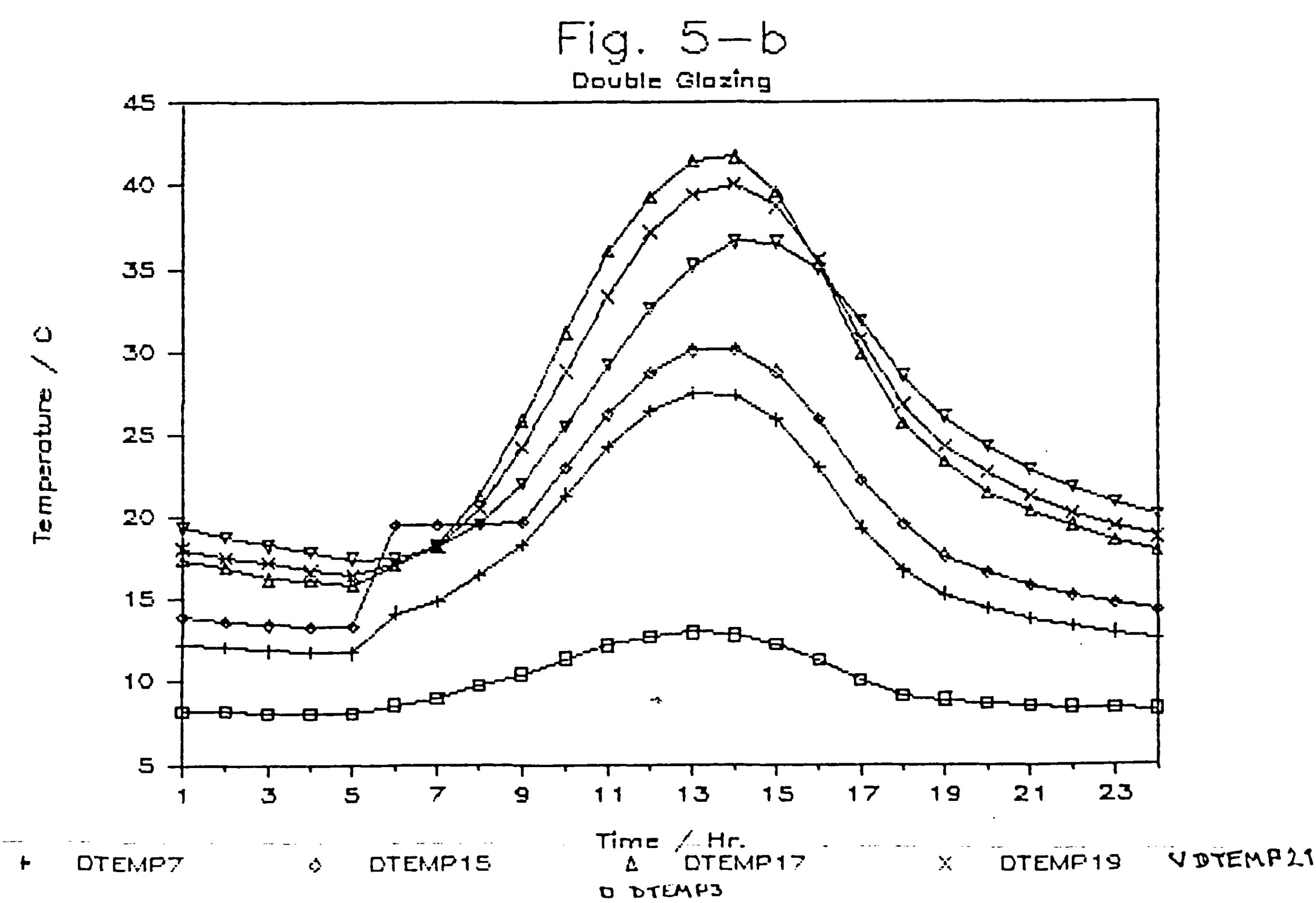
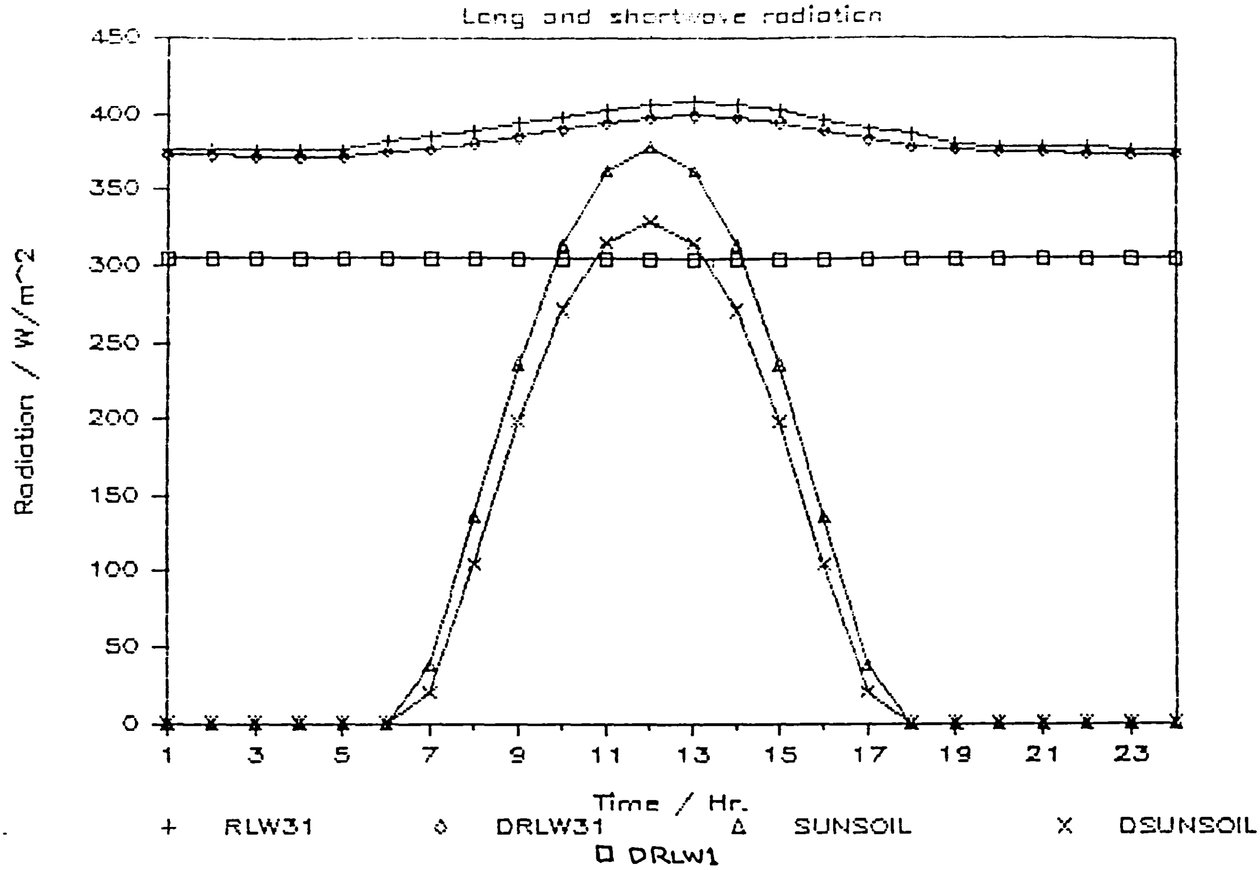


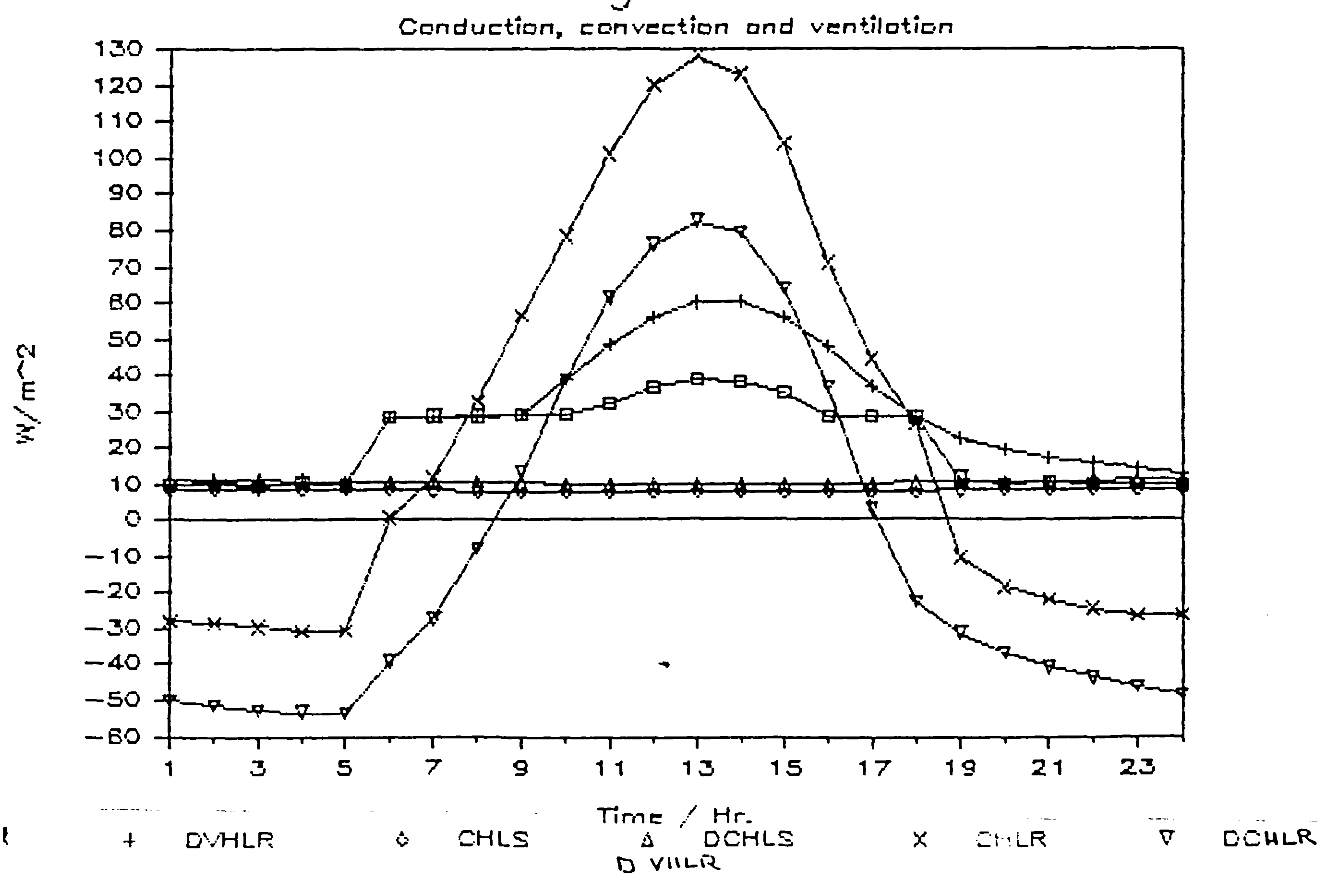
Fig. 5-b
Double Glazing
Temperature / C
Time / Hr.
+ DTEMP7
◊ DTEMP15
Δ DTEMP17
X DTEMP19
∇ DTEMP21
□ DTEMP3

Fig. 5-c



Long and shortwave radiation
Radiation / W/m^2
450
400
350
300
250
200
150
100
50
0
1
3
5
7
9
11
13
15
17
19
21
23
Time / Hr.
+ RLW31
◇ DRLW31
Δ SUNSOIL
X DSUNSOIL
□ DRLW1

Fig. 5-d



Conduction, convection and ventilation
W/m^2
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
1
3
5
7
9
11
13
15
17
19
21
23
Time / Hr.
+ DVHLR
◇ CHLS
Δ DCHLS
X CHLR
∇ DCHLR
□ VHLR

The outside roof surface has a lower resistance to convective heat transfer than the inside surface due to the wind. Therefore the inclusion of a lower roof layer more than doubles the overall roof resistance. The two runs were carried out using the same environmental conditions, a constant outside air temperature of 10.0°C and inside day and night temperatures of 19.6 and 13.3°C respectively. The EMAX variable was set at a fairly high value of 0.005 which explains the variation in both TEMP15 and DTEMP15 around the setpoint values. A smaller value of EMAX would have ensured that any variation in TEMP15 was much less, smaller than the third decimal place displayed here but would have needed more computer time.

Under double glazing the upper roof temperature, DTEMP3 (fig. 5-b), remained lower at all times than TEMP3 (fig. 5-a) under single glazing. Whenever either of these was less than TEMP1, 10.0°C, the roof gained heat The CHLR variables (Convective Heat Loss from the Roof) show that in the double glazed case the roof gained energy (indicated by a negative value) for longer than in the single glazed case. When losses occurred during the middle of the day, these were 30-40% lower in the double glazed case. The lower roof, component 7, remained at a lower temperature compared with TEMP15 but the difference in temperature between these two components never rose above 2.9°C. The corresponding difference between TEMP3 and TEMP15 in the single glazed case never fell below 4.0°C, and rose to nearly 9.0°C at times. Thus heat was lost from the inside air by free convection to the roof at a greater rate in the single glazed case. Figures 5-a and b show the time of day that heat was saved under the double glazing. The shape of the DTEMP15 curve (fig. 5-b) shows that after 9.00 h no heating was required until 4.00 h the next morning

The longwave radiation losses from the upper roof surface, RLW31 and DRLW31 (fig. 5-c) for the single and double glazing respectively, show that only 1-2% more was lost by the single glazed roof. The gain to the system, RLW1, remained constant and the net longwave loss from the system was a maximum of 8% higher in the single glazed case. Other results (fig. 5-d) show that the conductive losses through the soil (CHLS) and the ventilative losses (VHLR) were affected, both being higher for the double glazed case. DCHLS in the double glazed case was 30% more than in the single glazed run but the actual loss was only 2-3 W/m^2. The ventilative losses for both runs were similar during the night, and were practically the same from about 4.00 to 9.00 h However, the passive ventilation was treated in the same way for the double glazed case as for the single case which may have been unrealistic. With two roof layers it might be expected that the leakage of air would be reduced. During the middle of the day, DTEMP15 in the double glazed case (fig 5-b) reached over 30°C and loss of air at this temperature via passive ventilation resulted in a ventilative heat exchange about 60% higher than calculated for the single glazed run. Overall, these results show that the reduction in heat requirement under the double glazed roof can be accounted for by reduced convection.

However, other important factors also became apparent. A closer study reveals that temperatures of the inside air, floor and deeper soil layers under the double glazed roof were several degrees higher than under the single roof for the same incident solar radiation. The intensity of the radiation reaching the floor was about 13% lower under the double glazing during the middle of the day (fig. 5-c). However, the maximum value of 330 W/m^2 would be higher under a cloudless summer sky and active ventilation would be required. When this was included, it was found that the inside air temperature was kept well within the venting range and that the heat loss via ventilation was a little higher. The other exchanges were similar, but overall, the heat requirement was higher in the vented case than in the non-vented one.

The results also show the difference between the inside air and floor temperatures (figs. 5-a,b). In both cases the floor remained at a higher temperature than the inside air except for a short time just after dawn. This difference was twice as great during the night in the double glazed run compared with the single glazed one which meant that the air was receiving heat from the floor at a greater rate, thus reducing the heating needed. During the day the temperature difference in the single glazed case was approximately 15°C compared with about 11°C in the double glazed run. So the air received more heat from the floor during the day in the single roof case. The temperatures of some of the deeper soil layers show that under double glazing the layers were warmer than under the single roof.

Energy Conservation at Kew and Eskdalemuir

The lack of suitable data made GHFORSM difficult to validate and the use of the model to find absolute values of heat requirement could thus not be justified. However, models such as this may be used to compare the effects of different conservation methods, since any errors should be common to results from all runs.

Two methods of energy conservation already installed in some glasshouses are thermal screens and double glazing. The use of low emissivity cladding is not yet widespread but the test runs showed that its use can save substantial amounts of energy. Weather conditions in different parts of the country might mean that one of these methods saved more energy in one area of the country than in another, or that one method was more effective during the colder months. To test this several runs of GHFORSM were carried out using ten years (1959-1968) of weather data for Kew near London (51.47° N) and Eskdalemuir in Dumfries (55.32°N). Daily values of solar radiation in MJ and average wind speed were available in addition to the daily maximum and minimum temperatures. Solar radiation was calculated by fitting a sine curve to the data value and the wind speed data was used to determine the roof convective transfer coefficient using the equation shown by Garzoli and Blackwell (1981).

The outside air temperature was derived using a method developed by Parton and Logan (1981) from the maximum and minimum temperature values. Using this method it was assumed that during daylight hours the temperature follows a sinusoidal path and then decreases exponentially from sunset until the following sunrise. Two runs were carried out to test the outside air temperature routine. The first used twelve days of hourly data measured at Kew in 1964. One day was chosen for each month of the year and included both sunny and cloudy days. The second runs used the maximum and minimum temperature values for these same days. Figures 5-e and 5-f show the simulated and measured temperatures for two of the sunny days with more direct solar radiation. Figures 5-g and 5-h show the temperatures on two cloudy days. These show that the best fit occurred on days of higher direct solar radiation, but the difference was never greater that 1.5°C. Although using

Fig. 5-e

Jan 1, 1984

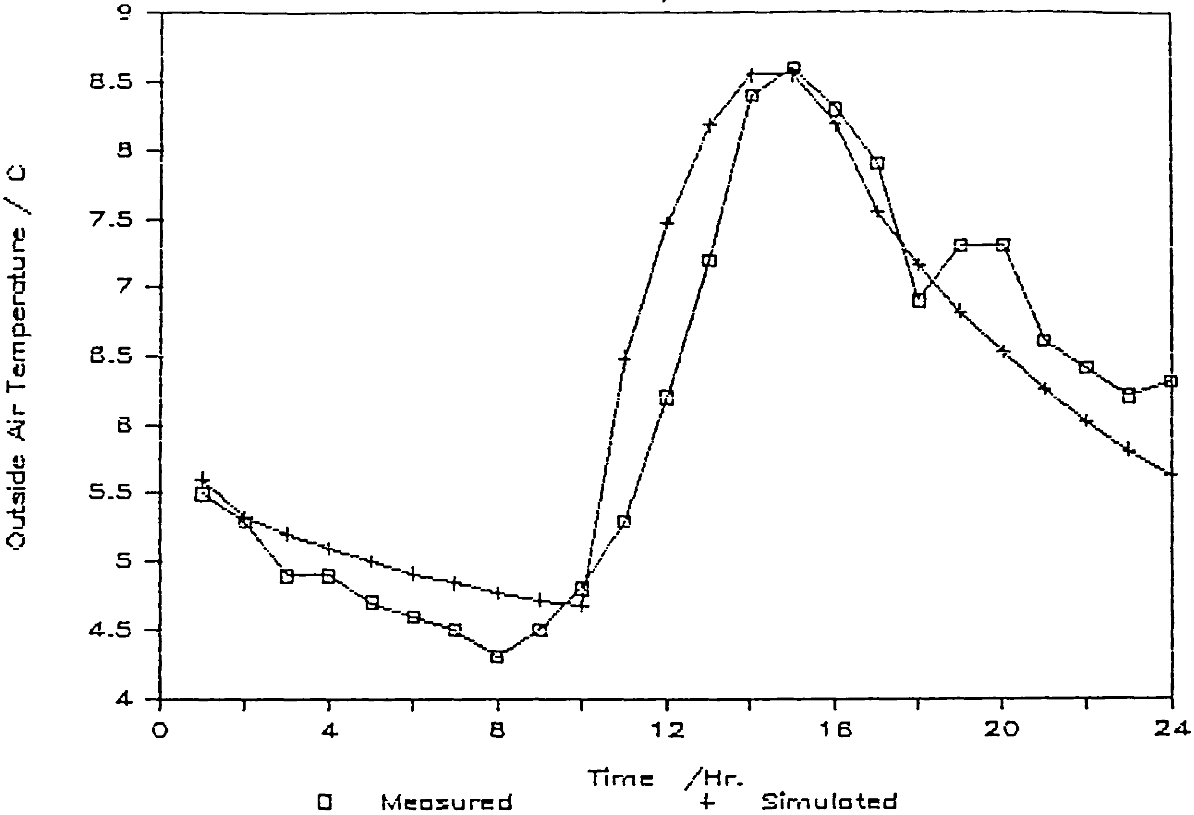


Fig. 5-f

May 12, 1984

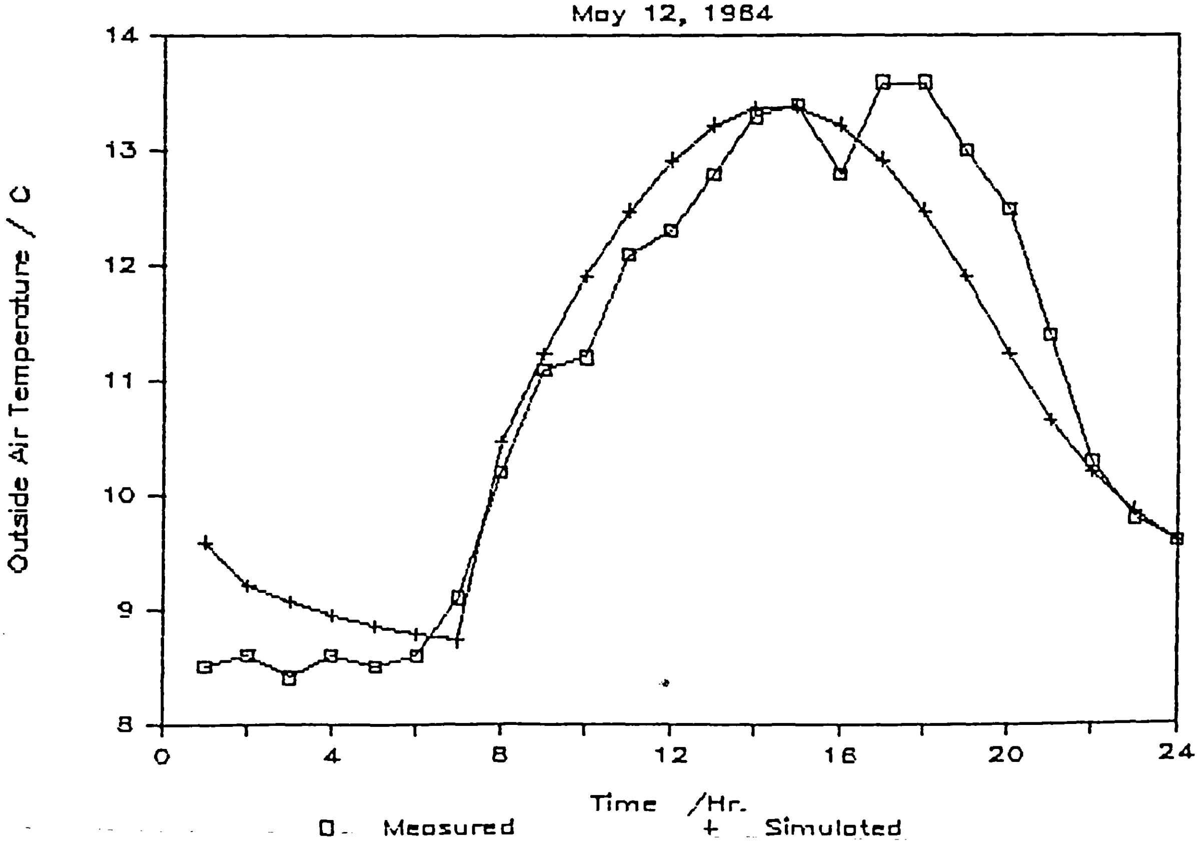


Fig. 5-g

June 18, 1984

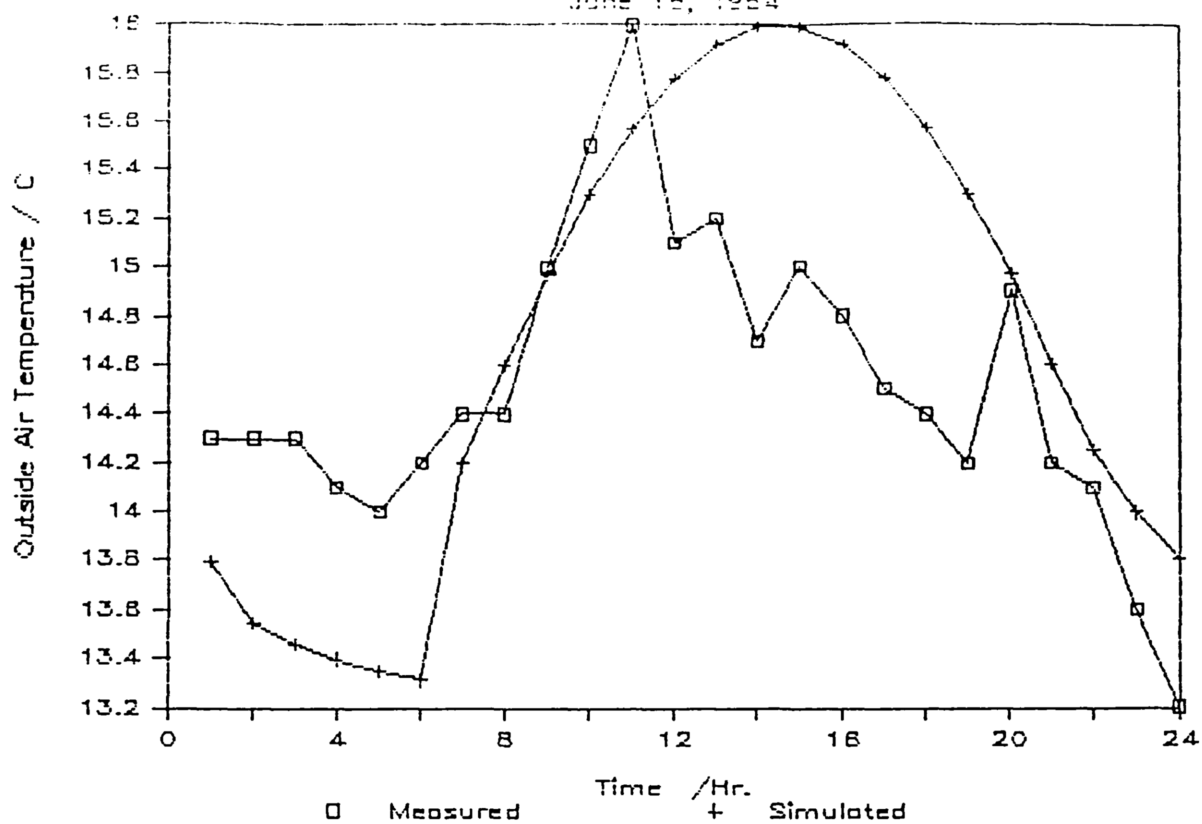
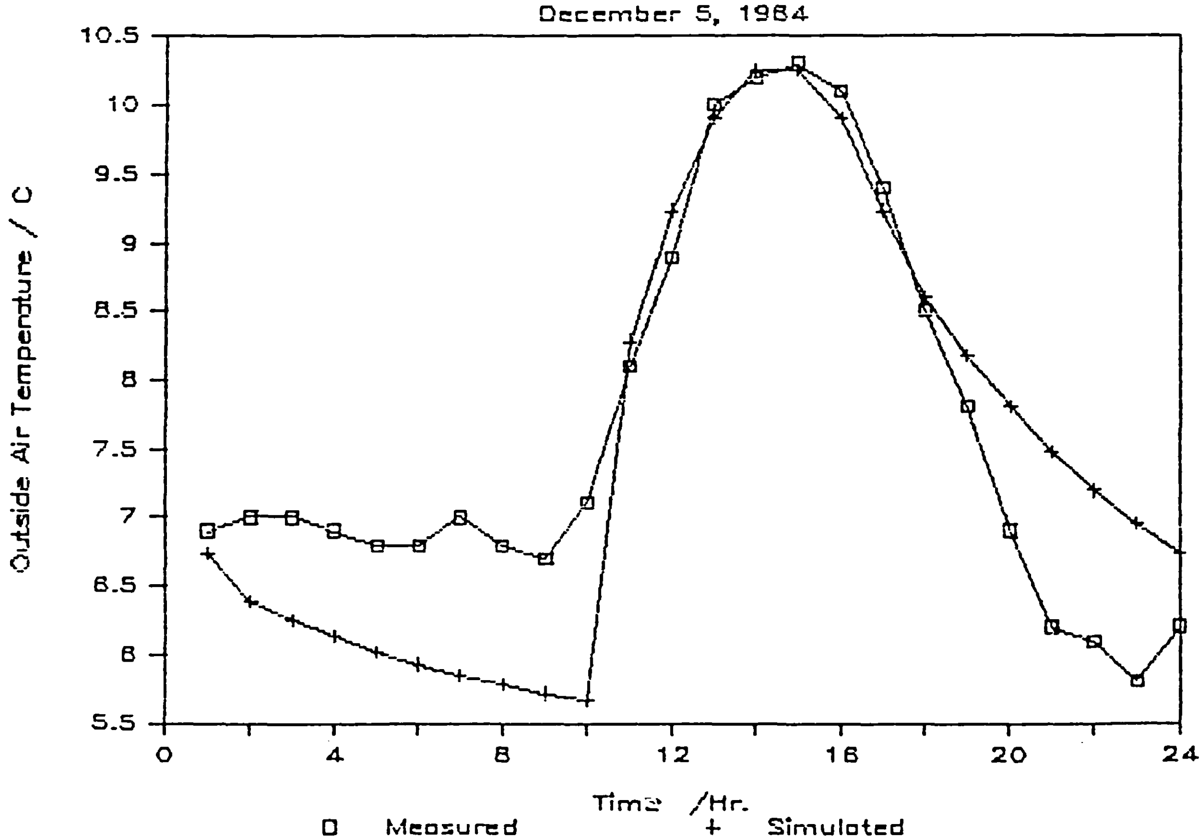


Fig. 5-h

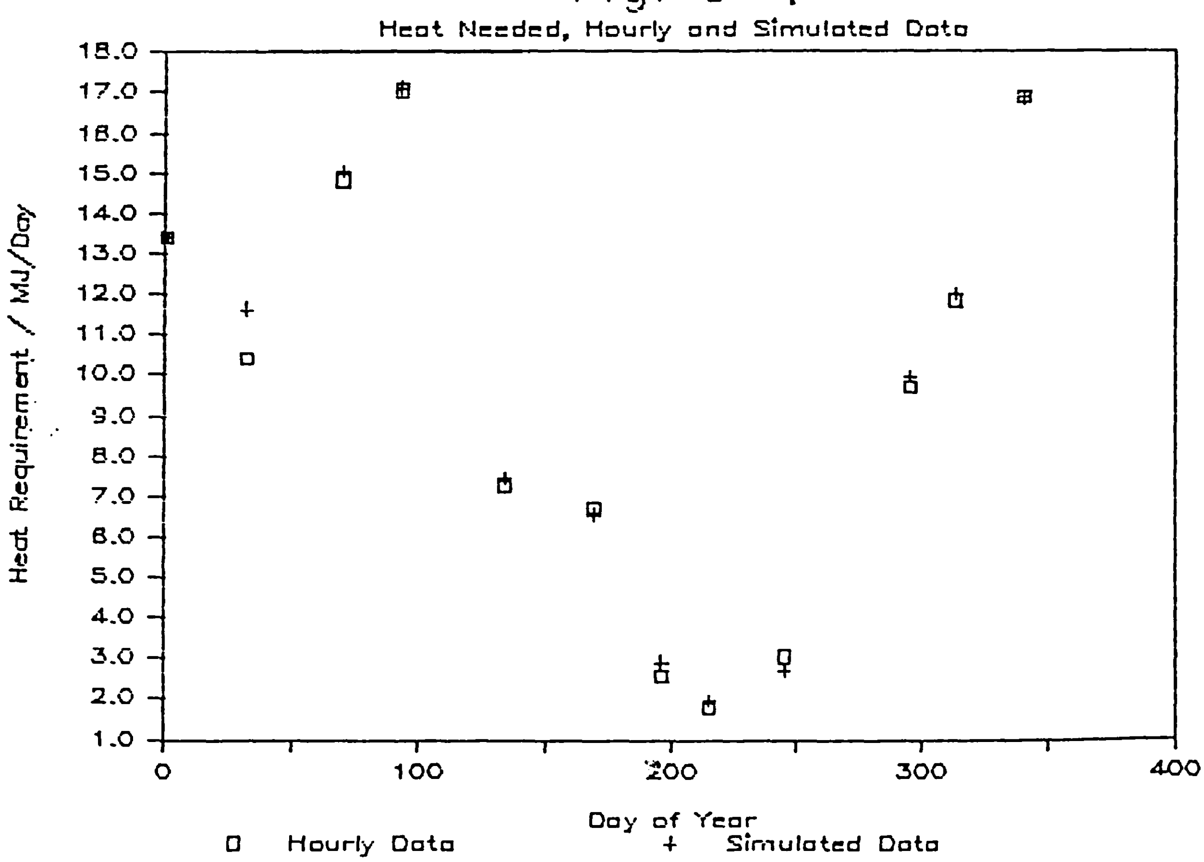
December 5, 1984



this method some of the simulated days would compare very badly with real measured data (if any was available), the use of averaged data and long time runs would reduce the importance of this.

The heat required on each of these twelve days is shown on figure 5-i and shows that the use of maximum and minimum values produced heat requirements which compared very well with those calculated from the real data. The exception was the simulated day in February which over-estimated the heat requirement by about 12%. That particular day was chosen because the outside air temperature rose throughout the twenty-four hour period and reached a maximum during the night. The simulated temperature for that day was completely different and this day was included as an example of one of the worst possible cases which might have arisen.

Fig. 5-i



The daily data was averaged to produce 120 average days one for each month of the ten year period. Too much computer time would have been required to run the model twelve times over ten years of daily data and only two runs covering one year using daily data were carried out. Figures 5-j(i) and 5-j(ii) compare the monthly heat requirement for a single glazed, unscreened glasshouse using averaged data from Kew and Eskdalemuir for 1960 with the monthly requirement derived from running the model using daily data The figure for January using the daily data was artificially high in both cases since the model was approaching an equilibrium range during the first part of the month. The monthly average figures were taken from the 120 month run and so the January results were normal. At both sites the use of the averaged data overestimated the heat requirement during the first half of the year and underestimated it during the second half although the difference between the two was small. The first half year results suggest that the variability of the daily data lost in the averaging process provides more gain to the system than when using the averaged data. The switch from over- to underestimation during the second half of the year is difficult to explain but may have been due to the fact that both runs had to be carried out in two parts for computing reasons. The model was run from January to June, and then from July to December for the two sites. Had it been possible the runs would have been carried out in one go over a full year.

Using 1960 as a representative year, figures 5-k,l and m show the heat requirement month by month for the simulations at both sites. Figure 5-m shows the heat needed by the 'base-line' cases glasshouses with single roofs and no thermal screens. The figure shows that more heat was needed at Eskdalemuir. Upon examining the weather data it was found that the average windspeed at Kew was higher than that measured at Eskdalemuir. Conditions at Eskdalemuir may be more sheltered than in the glasshouse areas in the north of England the coastal region near Preston for example. If this is the case then the true heat requirement will be greater than simulated here, and the curves should be further apart.

Fig. 5-j(i)

Monthly average vs. Daily data Kew, 196?

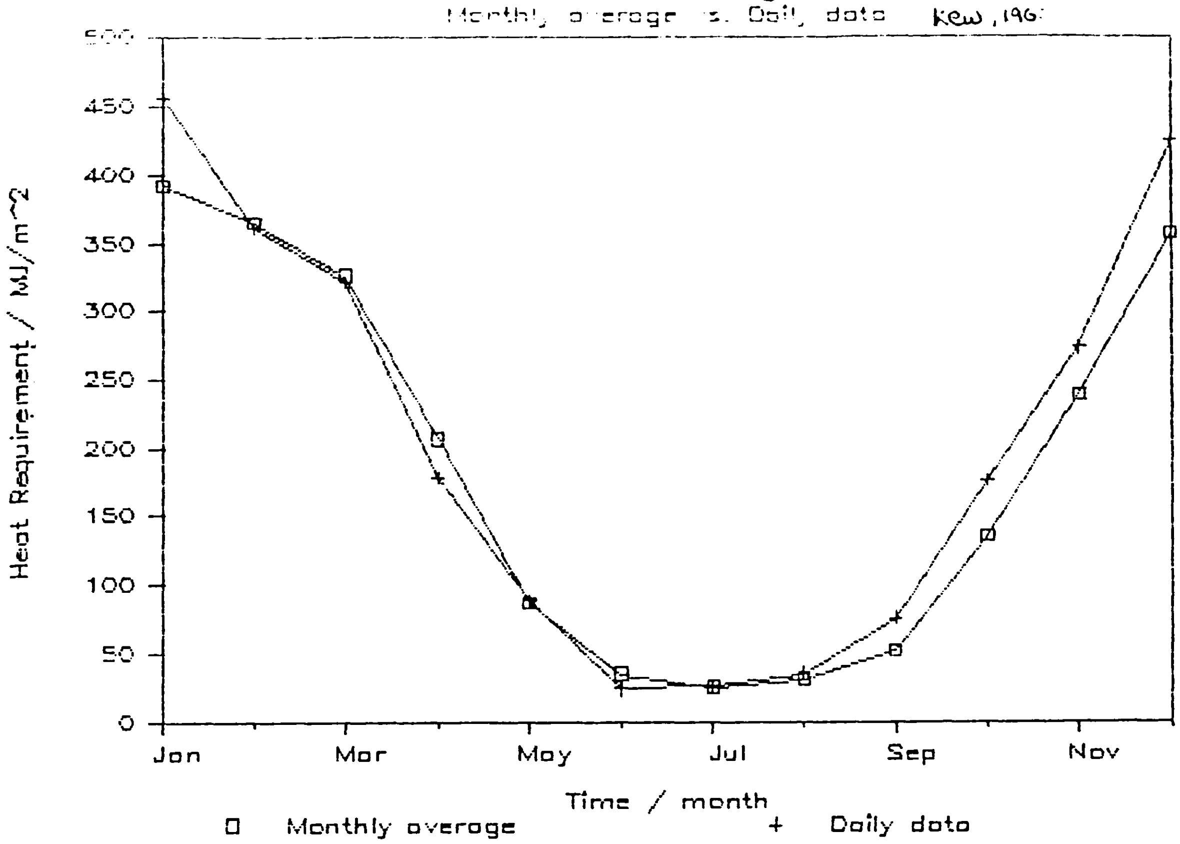


Fig. 5-j(ii)

Eskdalemuir, 1980

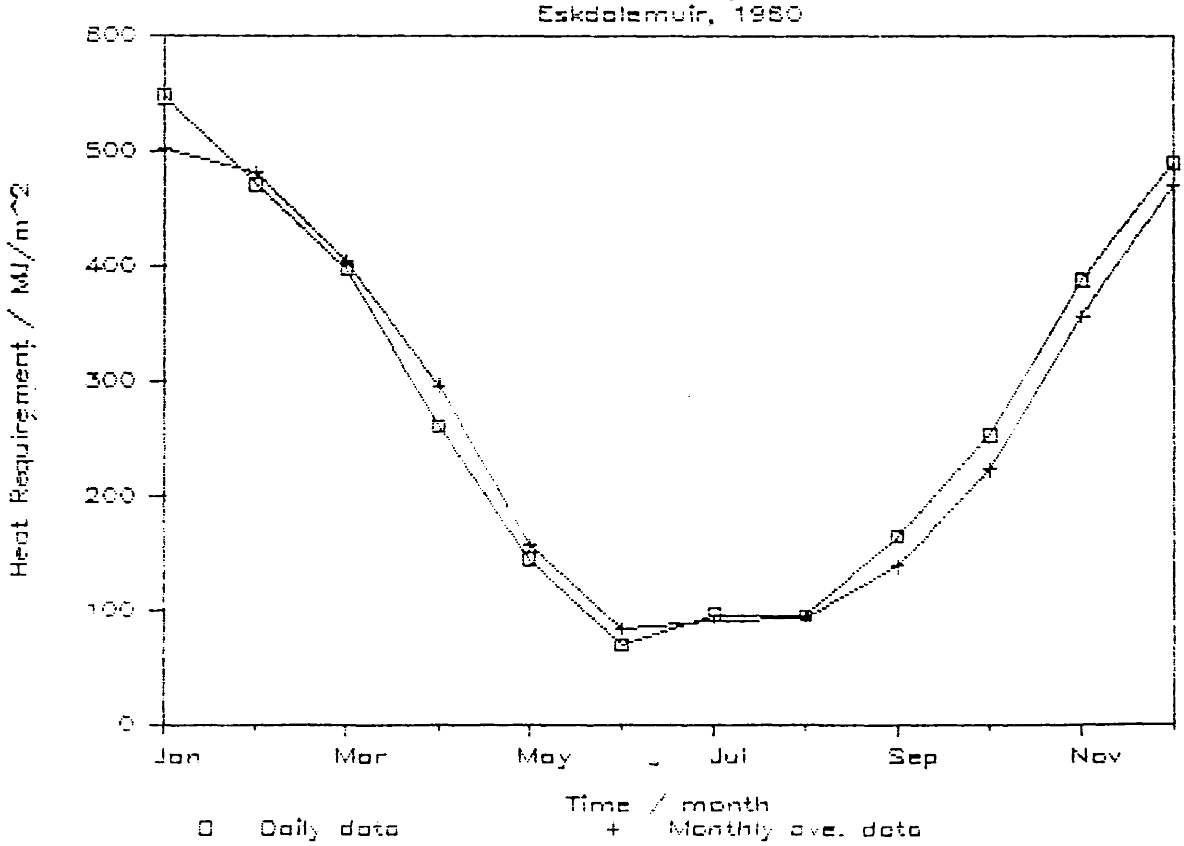


Fig. 5-k

Eskdalemuir, 1960

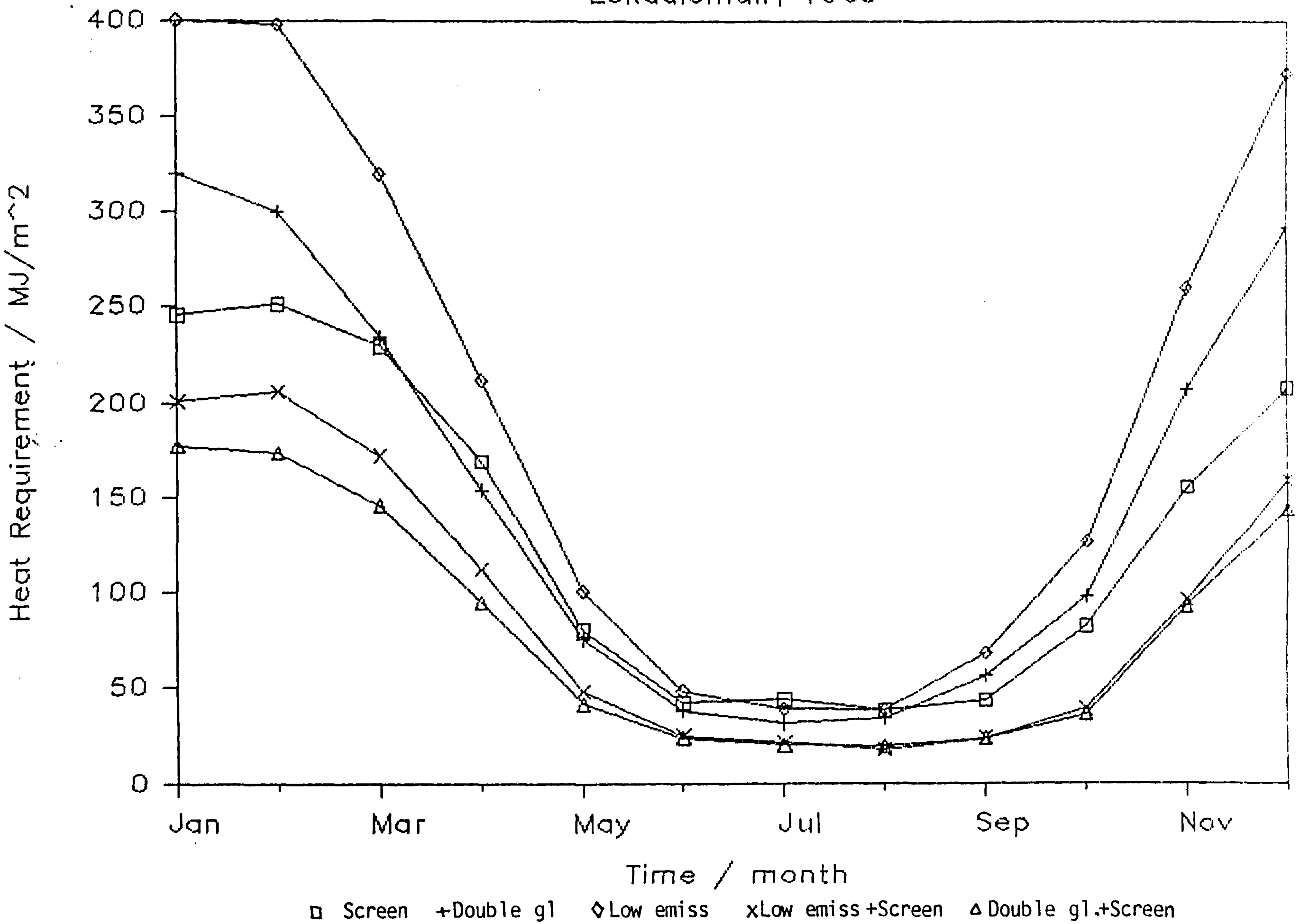


Fig. 5–1

Kew, 1960

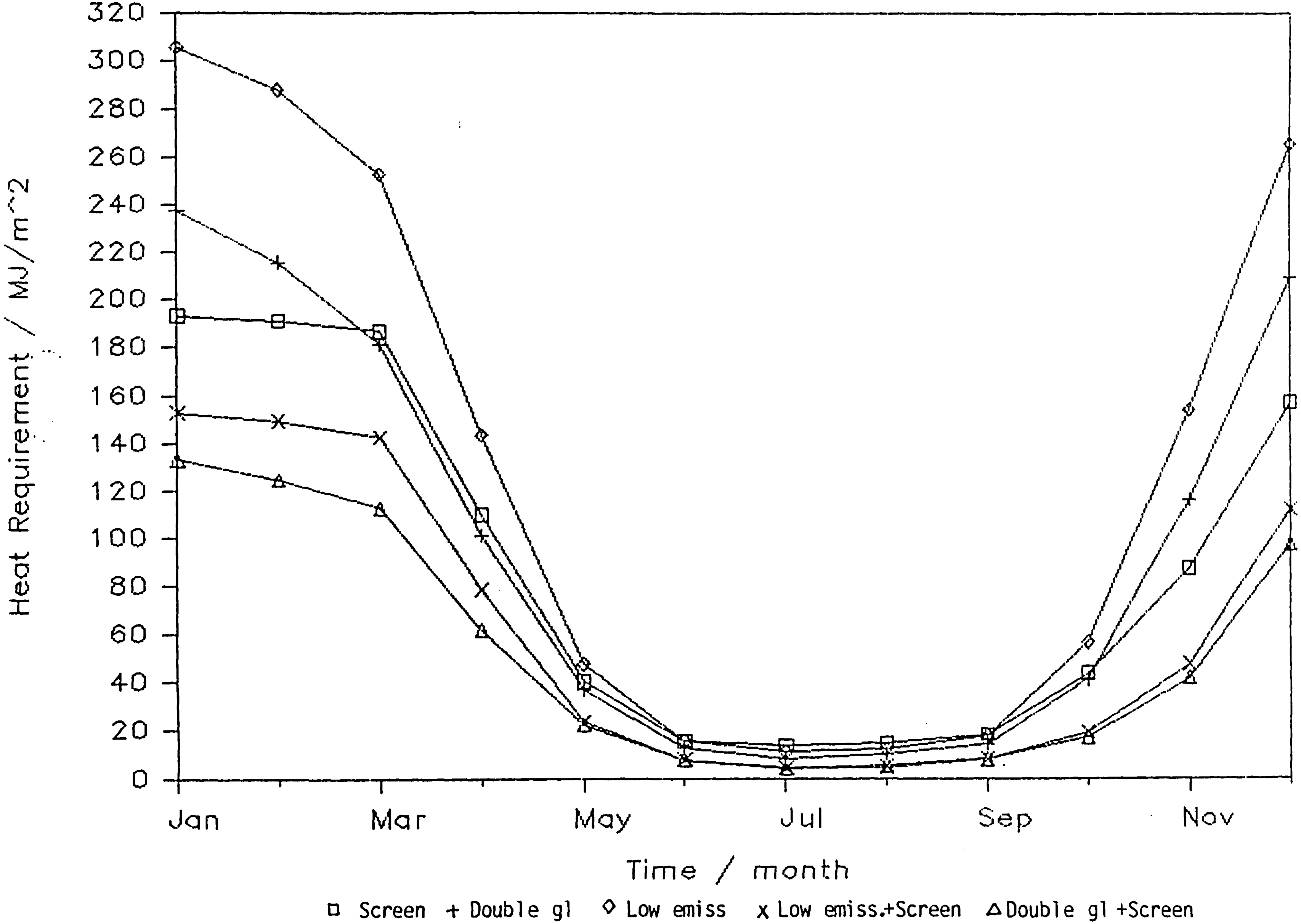


Fig. 5-m

Single glazed and un-screened

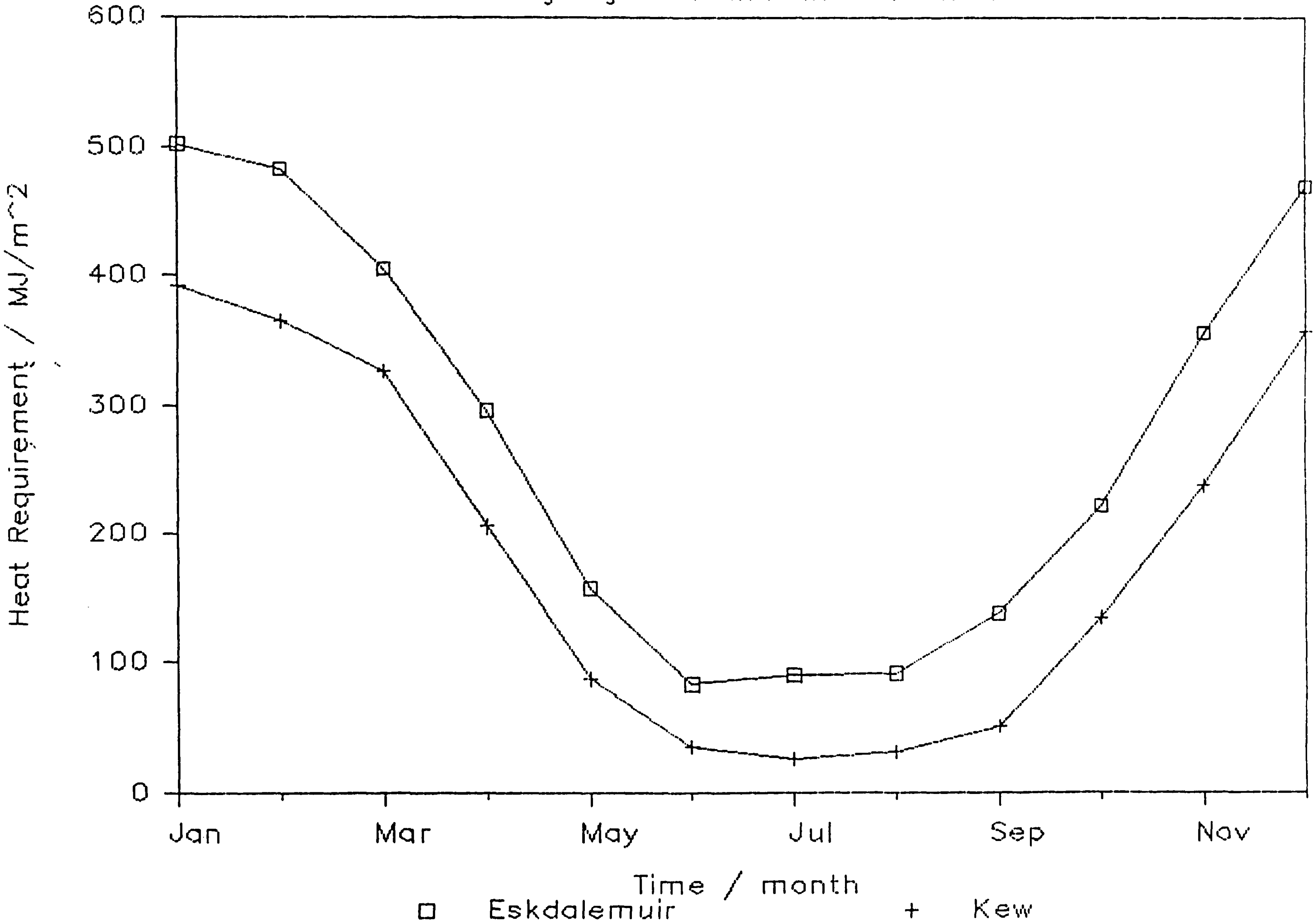


Figure 5-k shows the heat requirement for the glasshouse at Eskdalemuir using the five different combinations of energy conservation methods Combinations that included the use of the thermal screen were more effective and the thermal screen with double glazing gave the greatest reduction. The same result is shown on figure 5-1 for the glasshouse at Kew.

An interesting result can be seen by comparing the heat required for the glasshouse with single glazing and thermal screen with the double glazed one. At both sites the screen saved more energy than the double glazing during the winter, January, February, November and December at Kew and January, February, March, September, October, November and December at Eskdalemuir. During the other months the double glazing was more efficient. This result was generally true throughout the ten year period and is summarised in figure 5-n. A K indicates that at Kew the thermal screen saved more heat than the double glazing during a month and an "E" represents the same for Eskdalemuir.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1959	K E	K E	E		K				E	E	K E	K E
1960	K E	K E	E						E	E	K E	K E
1961	K E	K E	K E						E	E	K E	K E
1962	K E	K E	K E						E	K E	K E	K E
1963	K E	K E	E						E	E	K E	K E
1964	K E	K E	E						E	K E	K E	K E
1965	K E	K E	K E						E	K E	K E	K E
1966	K E	K E	K E		K				E	E	K E	K E
1967	K E	K E							E	E	K E	K E
1968	K E	K E	K E	K					E	E	K E	K E

Fig. 5-n. Months when the thermal screen saved more energy than the double glazing. K=Kew, E=Eskdalemuir

At Eskdalemuir the screen saved more for longer during the year only from April to August was the double glazing better. At Kew the reverse was true although during March April and October these methods saved about the same amount of heat. and in some years the screen was slightly better than the double glazing. In May of 1959 and 1966 the screen was also slightly more effective at Kew than the double glazing. Examination of the data showed that these months had a greater range of temperature (more than 9.45 and 9.35°C respectively) than the average for May during the other years (7.6°C).

The switch over in efficiency can be explained by the change in daylength through the year. Double glazing is in position throughout the twenty-four hours whereas the screen is removed during the day, and only saves energy at night. Thus the screen would be expected to save most when the nights are longest, during winter. The difference in the timing of the switch can be explained by the different latitude of the sites and the lower solar radiation in the north. Double glazing reduces the solar gain to the system and because of the lower sun angle in the north more solar radiation is lost by reflection from the roof. The reduced solar gain during the day will mean that the screen will save more energy for longer during the year until the greater solar intensity and higher solar angle reverse this.

The overall heat requirement figures are shown on figure 5-o and more heat was required under conditions at Eskdalemuir; the lower ambient air temperatures gave an increased rate of loss from the glasshouse and lower solar radiation intensity reduced the gain. In all cases the heat saved at Kew was greater than under the Eskdalemuir conditions. However, in percentage terms the heat saved by the screens at both sites was very similar (51 13 and 52.87% for Eskdalemuir and Kew), but the double glazing saved rather less energy at Eskdalemuir than at Kew (44 38% and 47.26%). The low emission cladding was also less efficient at Eskdalemuir, saving 25.41% compared with 29 21% at Kew.

Another way of analysing the results of these runs is in terms of the reduction in heater power requirement. Although these runs gave no indication of the peak heating requirement, the single glazed, un-screened glasshouses at both sites required much more energy during the year than those runs with energy conservation. Figure 5-p(i) to 5-p(x) compare the two base line cases (glasshouses with no energy conservation) with the runs using conservation. The histograms show the number of months over the ten year

Fig 5-o

Eskdalemuir

Year	Single Gl. No Screen kJ	Single Gl. With Screen kJ	Double Gl. No Screen kJ	Low Emiss. No Screen kJ	Double Gl. With Screen kJ	Low Emiss. With Screen kJ
1959	2964398	1364980	1621418	2148365	832586	979011
1960	3296254	1592503	1843211	2386126	992522	1122371
1961	3308857	1630088	1845564	2452364	1014084	1186235
1962	3574612	1737251	1981846	2696810	1067139	1275959
1963	3624984	1769790	2030790	2745508	1104303	1321477
1964	3413405	1699629	1938344	2495215	1075921	1244648
1965	3560953	1742912	1994622	2656683	1084187	1265042
1966	3493164	1741089	1950788	2620295	1088818	1296685
1967	3355220	1662066	1833353	2554886	884202	1249951
1968	3437251	1688654	1886678	2624587	997017	1253574
Mean	3402910	1662896	1892661	2538084	1014078	1219495
% reduction		51.13	44.38	25.41	70.20	64.16

Kew

Year	Single Gl. No Screen kJ	Single Gl. With Screen kJ	Double Gl. No Screen kJ	Low Emiss. No Screen kJ	Double Gl. With Screen kJ	Low Emiss. With Screen kJ
1959	2051874	929228	1068001	1432467	543626	649731
1960	2250243	1071840	1184522	1569625	635228	749318
1961	2125364	991126	1118356	1458557	589406	666393
1962	2561343	1227137	1361065	1851661	731356	890140
1963	2641953	1276336	1422809	1934033	844355	907047
1964	2384031	1147078	1273516	1702747	514593	802118
1965	2370229	1108380	1237584	1706692	672557	805052
1966	2283481	1084604	1191786	1609138	576180	755085
1967	2199964	975337	1133262	1527549	643049	685871
1968	2322737	1118363	1241017	1625595	684426	776166
Mean	2319122	1092943	1223192	1641806	643478	768692
% reduction		52.87	47.26	29.21	72.25	66.85

Fig. 5-p(i)

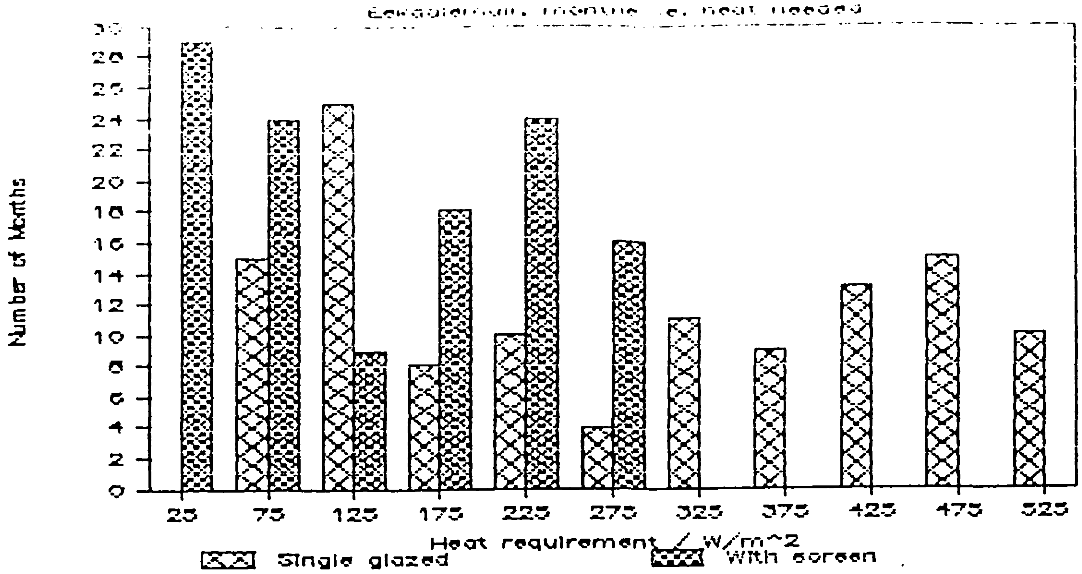


Fig. 5-p(ii)

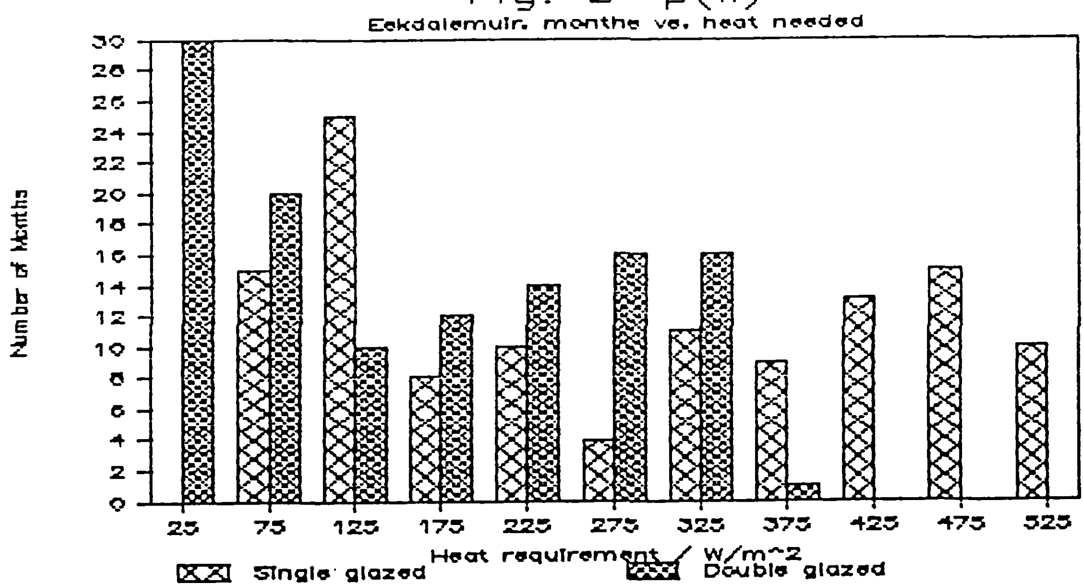


Fig. 5-p(iii)

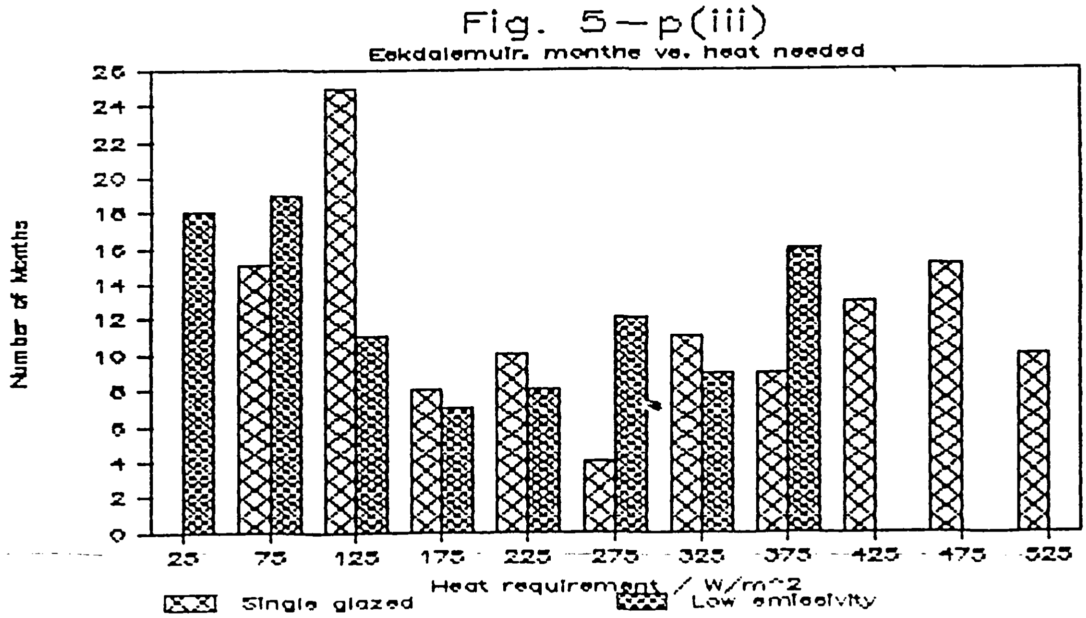


Fig. 5-p(iv)

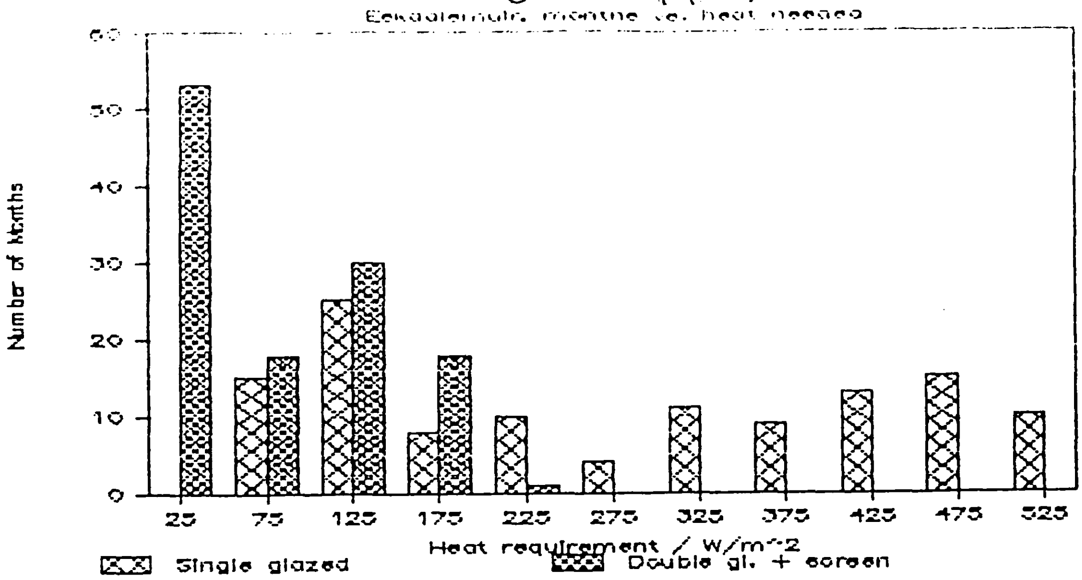


Fig. 5-p(v)

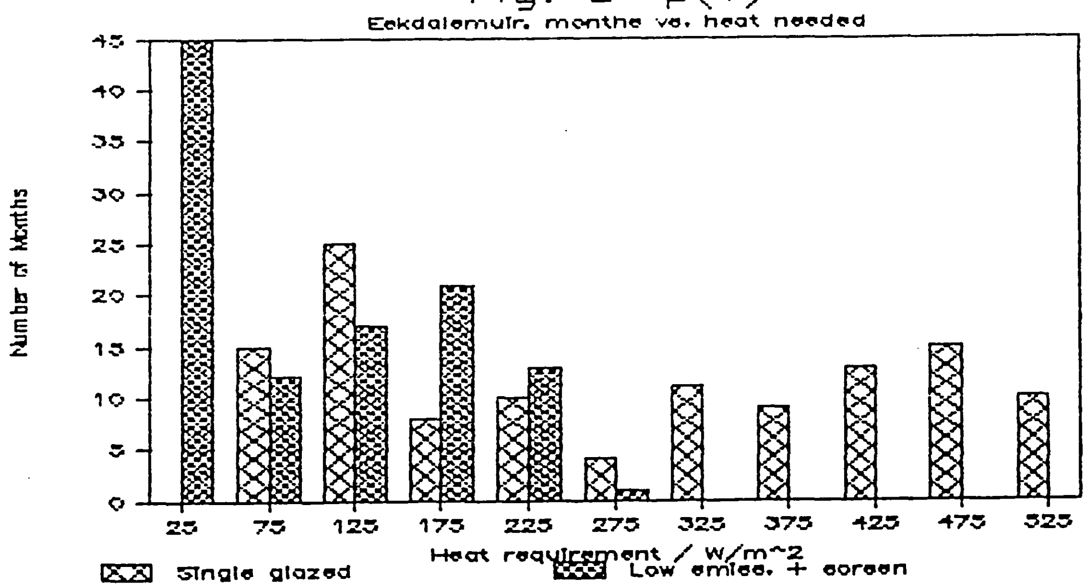


Fig. 5-p(vi)

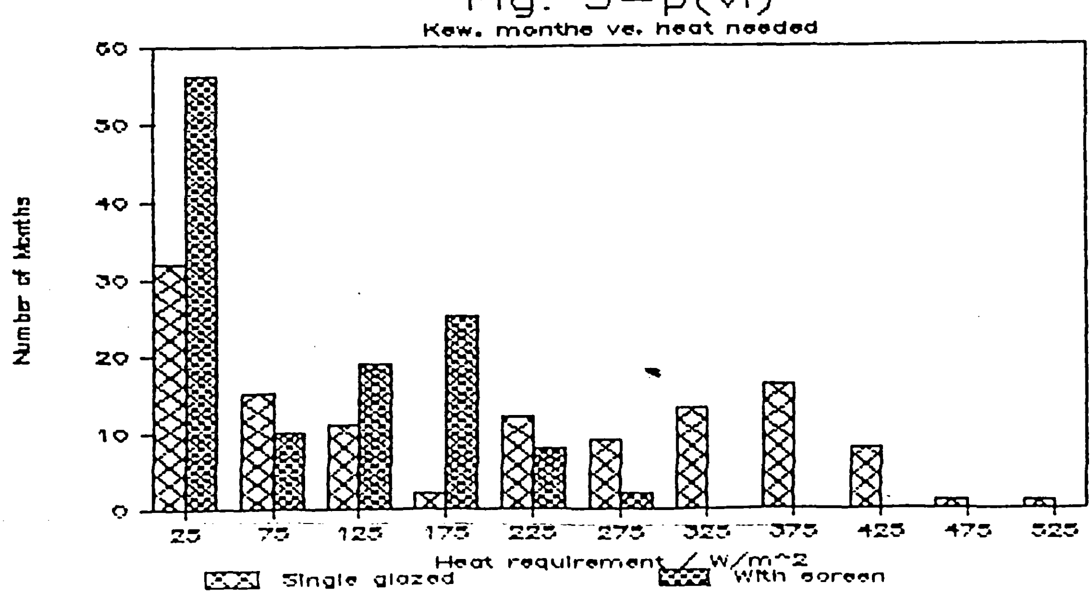


Fig. 5—p(vii)

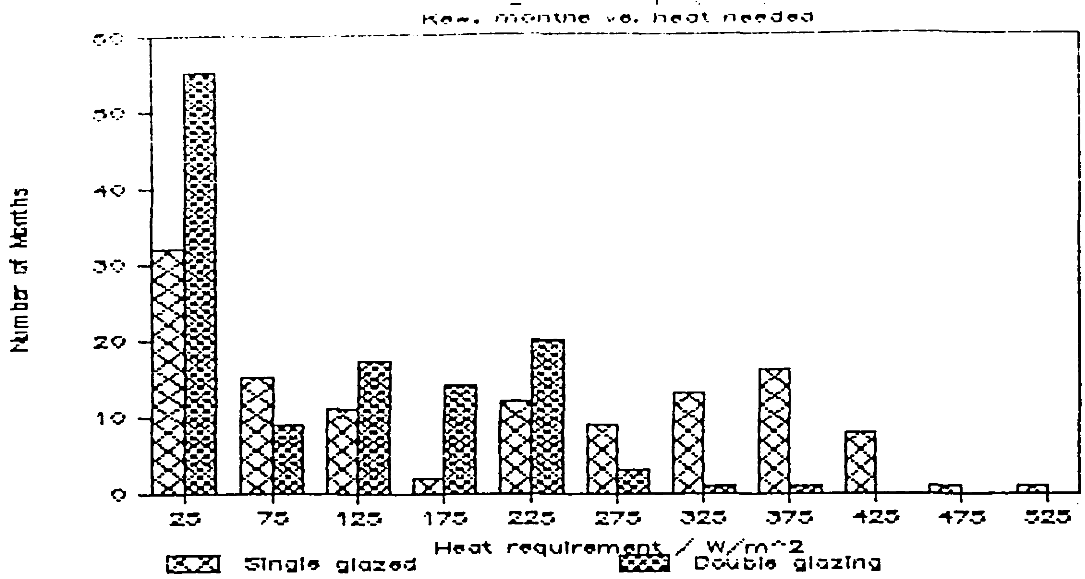


Fig. 5—p(viii)

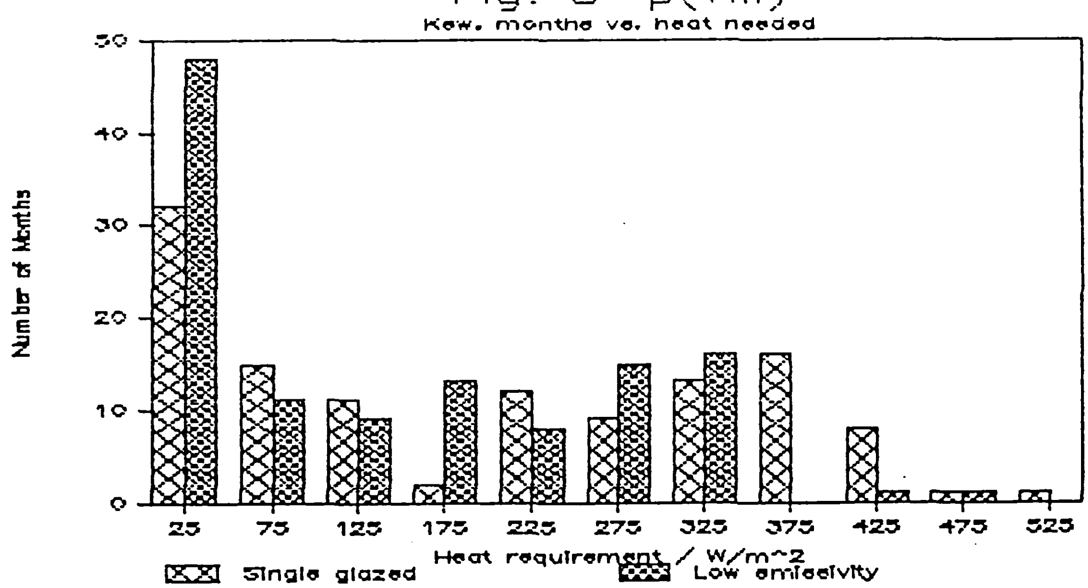
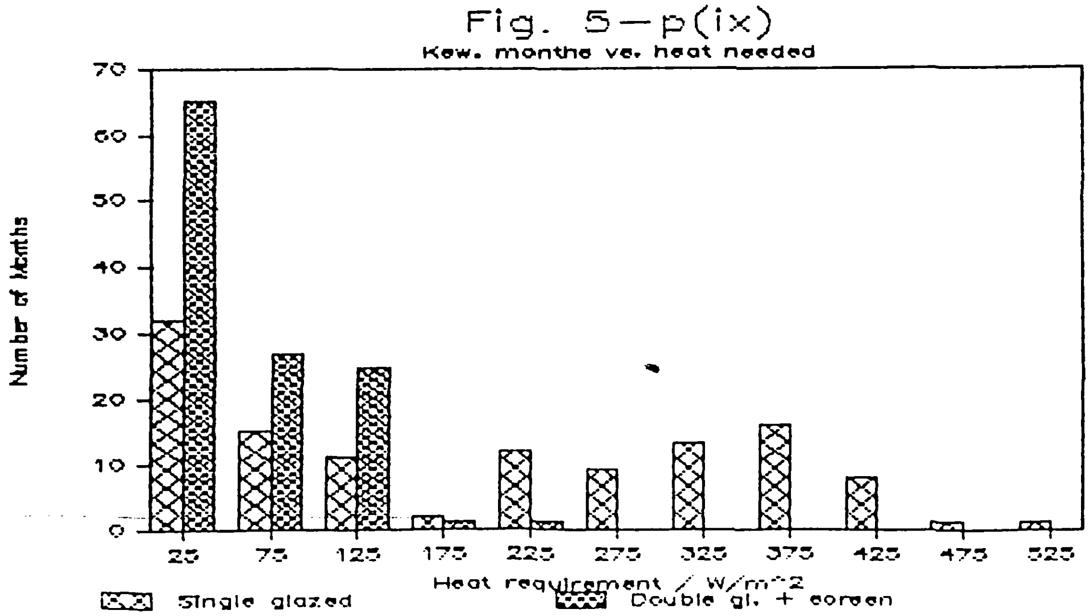
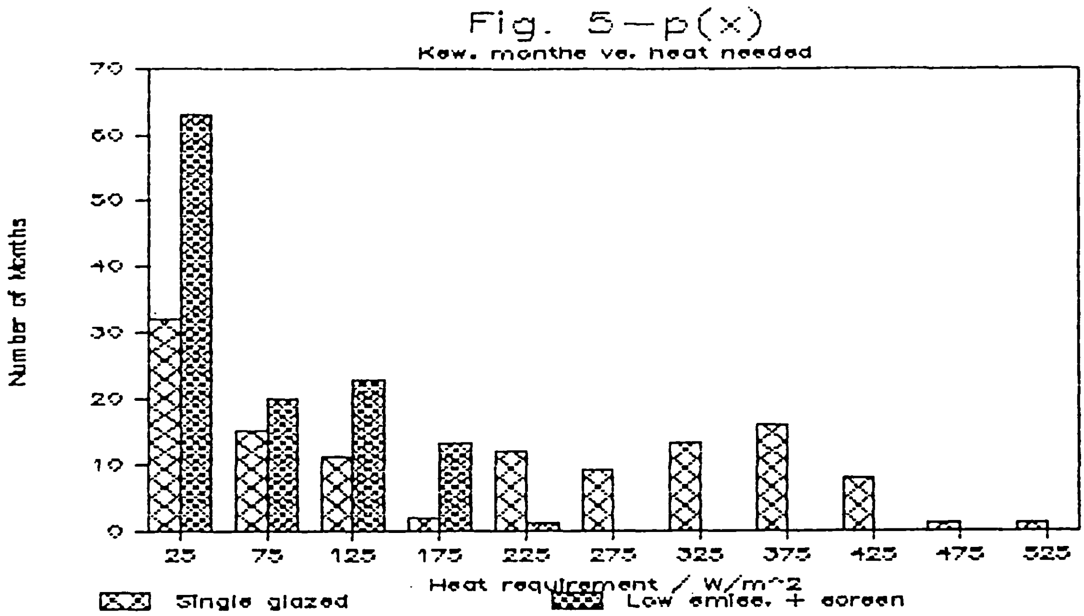


Fig. 5—p(ix)





period that certain levels of heating were required. Thus in figure 5-p(i) it can be seen that for the unscreened glasshouse at Eskdalemuir during fifteen months the heat required was between 50 and 75 MJ/m^2. The actual values on these graphs are not as important as the overall shapes. When any conservation measures were applied large amounts of heat were needed during fewer months. Whilst there was a wide spread for the single glazed, unscreened glasshouses the results for the houses with conservation were clustered lower down the scale. Further runs would be needed to ascertain whether the peak power requirement from the heater was reduced by these conservation measures. The implications for the grower will be discussed in the next chapter. The most effective conservation system, thermal screen and double glazing, reduced the maximum monthly demand the most. At both sites in only one month of the ten years did the demand exceed 200 MJ/m^2 using this conservation method.

Chapter Six

The Future of the Glasshouse Industry

The future of the UK and Channel Isles glasshouse industries is uncertain but the problems outlined at the begining of this thesis can be overcome if the will (and money) to do so is present. However the cost may be too high, whether this be measured in economic or political terms.

The Role of Subsidies

In the Netherlands the government has supported the glasshouse industry not only by subsidising fuel, but also by providing funds for research, advisory services and education in the horticultural field. Succesive UK governments have been more modest in providing aid, probably because glasshouse produce is far less important to the UK economy. In the UK money has been provided in the form of fuel subsidies and the government has indicated that it is keen to promote the re-development of the glasshouse industry into a more efficient state . The 1983 Conservative manifesto stated that the glasshouse industry would be helped to sell more fruit and vegetables, and to make use of the best possible arrangements for heating and insulation. The intention is to make sure that British agriculture and horticulture continue to make the 'greatest possible contribution to our economic success. However, in the light of current government spending it seems that government aid is likely to be limited. Furthermore, the rules of the EEC do not make the policy of providing subsidies to glasshouse growers very easy. Even the Channel Isles, not members of the community, have to be careful not to fall foul of the regulations (Nicholson, 1980). The proposed bulk buying of fuel oil by the States of Jersey, and the formation of a company in Guernsey to import heavy fuel oil for the islands respective glasshouse industries show two ways in which aid can be provided. But these are short term measures and a more long term plan is needed.

The trend of recent years suggests that glasshouse acreage will fall, especially in the Channel Islands, as foreign competition increases. It can be argued that we should not be too concerned with the decline of an industry that uses increasingly precious fuel reserves to produce foodstuffs that can be obtained elsewhere at a lower energy cost. Needless to say this is not a popular view with the industry itself and if such a decline was brought about by government policy or inaction, the results would be detrimental to the country s balance of payments. However, in a world which will become increasingly concerned with energy and energy supply problems, the glasshouse grower will find that his ability to obtain resources such as fuel will fall.

Marketing

Regardless of whether or not governments find the money to follow through their proposed courses of action there is much that the glasshouse industry can do for itself. In one particular area the marketing of produce the Dutch have been extremely successful. The pattern of buying tomatoes in this country has changed in recent years and is still changing as traditional shops disappear to make way for supermarket chains. These chains are keen to 'bulk-buy' goods and it would be to the advantage of the UK industry to opt for some marketing strategy that exploits this policy to the full. The Dutch and Channel Islands growers have co-operative systems which are quite successful but there are suggestions that an increased and more diversified wholesale trade system the traditional UK marketing method. could cope with the changing pattern of purchasing (Nicholson, 1980). Were the industry to aim at the 'bulk-buy' market, it could help itself by improving the quality of the produce and ensuring that the grading system provides supplies of consistent quality to the purchaser.

Research and Advice

The grower has little influence on his crop once it has left his farm and poor packaging, storage or transport systems may affect demand. Inefficiencies at any of these levels may cause prices to be higher than necessary. Nicholson (1980) discusses these in more detail but here I will concentrate on the policy and developments which have a more direct effect on the grower. One area of potential improvement is that of research and advice.

There is an active advisory service in the UK and money allocated to research is spread amongst many research establishments around the country. It may be that such research, covering a wide variety of fields of interest may be just as effective in the long run as spending more money on fewer projects. It is probably true however, that by spreading the money thinly a certain amount of work is needlessly repeated.

A specific area of potential improvement is in information technology related to glasshouse research. For example, at the research establishments better control might have been exercised in recent years over the policy for computer purchase. All manner of different machines have been bought in the past few years with the result that programs developed in one station are often of little use to other stations with different computers, or even to different departments within the same station. This is a difficult problem researchers have benefitted from the wider availability of relatively powerful micro- and mini-computers and it would not have been sensible if 'better control' had left the research establishments stuck in the era of mainframe computing, unable to benefit from distributed computing. Better control should allow researchers access to smaller computers but should ensure that software from one station would run on machines elsewhere around the country. This criticism of computer purchasing policy can be levelled at many establishments in this country not just those concerned with agriculture and horticulture.

The diverse work and mediocre communications also make it impossible for a researcher to know everything that is going on around the country that may be relevant to his particular line of work. He may know about similar work being carried out, but sets of data initially used for some unrelated purpose may be discovered too late or never at all. This is wasteful and matters might be improved if a register were to be kept in which data sets and their availability for general use were described. Such a register could be run from the Agriculture and Food Research Council, employing an information scientist to manage and update the information. It would also be useful if complete data sets were recorded; all too often recording work is limited to measurements of interest to single or small groups of workers when others need additional data. Often the excuse is that not enough hardware is available and one researcher working for the States of Jersey was given enough money to build experimental glasshouses, but could not get any funds to buy data logging equipment.

The present operation of research stations has proved useful in the past and growers are aware of the useful work that they carry out but with the computer and communication revolution which is currently occurring it is now time to assess their future operation. These centres could be linked by large scale computer networks, and information from around the country could be made available within seconds both for the researcher and the interested grower. More general information on pest warnings for example, is already available via Prestel. One or more stations could be set up solely as monitoring and recording centres as the use of micro-computers increases and as more simulation programs are written. Computer software could be made available to growers both for educational and management purposes and could be kept at the local research station to be collected either on tape or disc, or to be transferred to the user's machine over the telephone line. These links need not be one way; growers with computers can provide data to the stations, enormously increasing the size of the database available. The added benefit of this is that data measured at a research station is often recorded on small scale sites (small glasshouse compartments for example) whereas on a farm the measurements would be made under the very conditions that the researcher is trying to understand or improve. The technology needed to do this is available now but money is needed to get it started.

Energy Efficiency

With little or no capital to spend on improvement, the grower has to ensure that his farm operates as efficiently as possible. Growers are finding that the older style glasshouses are becoming uneconomic to use. Modern houses can be three time more energy efficient. One Jersey grower has stopped producing crops which require supplementary heating in his older houses and stores imported house-plants in them for eventual re-sale (Stein, 1984). It may be that the individual grower will keep going by changing his pattern of horticulture in this way, or he may decide that there is no future and sell his land or develop it for something else.

If the industry is to survive then the long term aim should be to make it efficient and profitable. In order to do this money should be spent in areas designed to help it combat the present and the likely future problems, or to help it change in such a way that the major problems are avoided altogether. As energy comprises a large part of the industry s costs the government should encourage conservation, but to do this it must know which methods are the most effective, and must know which ideas should be passed on by the advisory service. Money should be provided for wide ranging research into both the physical and biological methods of improvement. For example, it might be sensible to try to develop cultivars which can withstand the higher levels of pollution associated with CO_2 enrichment of the inside air in more air-tight structures without loss of yield.

As the future energy supply is far from certain thought should be given to research in this area. At present there is an oil glut but it is likely that this will soon disappear as demand increases with the end (or lessening) of the world recession. The best immediate alternative fuel sources for glasshouses are coal and waste heat as little or no new technology is required for their deployment. The UK has good coal reserves but if growers are to switch to coal burning the government will need to make funds available to aid the transfer. The switch from oil to coal is not as straightforward for the grower as it might appear. Oil is an extremely convenient fuel to use; it is a concentrated energy source, it is liquid and can be stored in tanks that directly feed the boiler, and there is little or no residue to be handled after combustion. When using coal, space is required for its storage, and it is more difficult to arrange for its transfer from the point of storage to the burner. It cannot be switched on and off in the same way as oil. After combustion there is the removal and disposal of quantities of ash and clinker to be arranged.

The total heating consumption for the 1471 ha (1982 figures) of heated glasshouses in this country is equivalent to about 500 000 tonnes of coal per annum (Schaffer and Clarke 1984). Eighty percent of this heat is derived from oil and a change from using heavy fuel oil to burning coal can give a fuel cost saving of about 22%. The saving is even greater if the grower switches from gas oil to coal, about 40%. However, capital costs are higher for coal firing equipment, extra labour is required and coal is less convenient to use. Consequently, oil burning may continue to be the more economic alternative for the small grower with oil fired boilers still in good condition (Smith 1984). Some 45% of the heated area under glass comprises holdings equal to or greater than one hectare in area and it is in this sector that it is thought that a switch to coal would be beneficial (Schaffer and Clarke, 1984).

The Coal Firing Scheme is intended to provide aid to industries wishing to change over to modern coal burning technology and the scheme is now set to end in December of 1984. Some glasshouse coal conversions have attracted grants under this scheme and reductions in costs of around 42% have been achieved by a daffodil grower on a two acre site. This same grower has found the by-products of the combustion, ash and clinker, useful, as they can be distributed around the site on the pathways. The payback time associated with the purchase of coal fired plant has been calculated to lie in the range of two to three years (after the grant) even less if the replaced equipment was old and due for change anyway (Energy Management, January,1984).

The attractions of coal are such that the country's largest producers, Van Heyningen Brothers Ltd., are to switch to coal firing. However, the whole problem must not be underestimated. One grower who produces four million chrysanthemums and 250 tonnes of maincrop tomatoes each year, has recently achieved a saving of some £30,000 by switching to coal, a move which incurred a capital cost of about £120 000 but attracted a grant. His reason for switching to coal was stated as simply a means of trying to remain in business, it will not answer all his problems (Energy Management Focus on Heating for Horticulture, January,1984).

Combined heat and power and waste energy utilisation schemes are being given more consideration now than they have in the past. Many industrial and energy generating processes produce large quantities of low grade heat so called because it is at too low a temperature for use in many of the procedures of industry and cannot be converted back into a high grade useable form very cheaply. The energy itself is usually tied up in large quantities of air or water and is most often just 'dumped', possibly after being used once to pre-heat some other material. Despite all the recent attention given to the Energy Crisis, a modern 2000 MW power station often disperses about 3000 MW in the cooling water. The fact that this would be enough to heat the entire UK glasshouse industry is an indication that either the process of energy production is very wasteful, or that the UK industry is rather small (Rees and Hand, 1980).

The Central Electricity Generating Board and Express Dairy Foods Ltd have undertaken a joint venture to produce tomatoes in glasshouses heated by the waste heat from the Drax power station. This proved successful and they have increased the cultivated area under glass. The problems associated with using waste heat are considerable there must be a supply of heat available to the crop when required and if this is at all uncertain the grower will need to maintain an expensive backup heating system and fuel, ready for those occasions when the main supply is interrupted. It may be possible to include penalty clauses in any contracts joined by growers and heat suppliers so that the supplier would be required to pay if heat supplies were disrupted.

Sources of waste heat that might be appropriate include breweries cement works and petroleum refineries but sites suitable for these may not be suitable for glasshouses. Furthermore, increased concentration of gases which might be found in industrial areas can harm crops and deposition of particulates on the cladding can lower the light transmission and reduce the yield. Waste heat glasshouse schemes are finding favour in France, and in the USSR and Hungary total interaction schemes are being planned (Sheard, 1978). The inclusion of glasshouses or fish farms could become an approved or accepted method of cooling large industrial or energy production plants. The use of such a waste heat system either involves industry moving to established glasshouse areas or glasshouses being built around the factories. It requires large investment on someone's part to change the industry so drastically.

In the immediate future the smaller grower is going to have to help himself. The larger projects can only be undertaken by government or large concerns who may not care whether the small grower survives. One way in which he can help himself is by remaining flexible in the type of crops he is able to grow. Traditionally, the most important UK glasshouse crop has been the tomato, but if trading in this crop becomes increasingly more difficult, then the grower should be prepared to diversify and grow other things. In the Channel Isles there has been a noticeable swing away from tomato production towards crops such as peppers and early season potatoes, and flowers for the tourist and UK markets (Financial Times , December 21, 1982)

The future of the glasshouse industry in the UK depends upon investment. If it is to succeed against the background of a strong Dutch industry and increased competition from around Europe it needs to change. The smaller grower might be able to supply the local market but will probably end up growing a variety of diff rent crops for specialist markets, Kiwifruit for example. As for the industries of the Channel Islands, their outlook is the most gloomy. Faced with greater costs than their mainland competitors they have to fight for the same markets and the smaller scale of their operations and the reluctance of the islands' governments and business communities to invest in the industry will cause further contraction. The lack of interest in the sale of quite modern glasshouses is symptomatic of the degeneration With little industry on the islands there is small scope for waste heat projects with no indigenous coal or oil, all fuel has to be imported. The only advantage is their geographical position which allows crops to be produced slightly earlier, but this too will vanish when Spain Portugal and Greece start producing. The physical size of the islands means that land is at a premium and property prices have soared. As more housing is needed especially in Jersey. the Development Committee are looking more favourably on proposed developments of areas of land which have hitherto been 'protected', and the Guernsey States is keen to retrieve some of the open spaces which the glasshouse industry had taken. The astute grower might decide that the time had come to build on his land or sell it and turn his attentions elsewhere.

The Contribution of GHFORSM

For the grower or researcher the use of a computer model, GHFORSM for instance, can be helpful in deciding how efficient one glasshouse system is in comparison with another, in a particular area of the country.

Results

The results derived from GHFORSM discussed in the previous chapters can be considered in terms of their implication to the grower. The effects of changing parameter values and including thermal screens or double glazing can be neatly summarised as increases or decreases in the heat requirement. The annual fuel bill is between £3.00 and £5.00 per square metre (Smith, 1984) and the effect of a 1% increase will affect different growers in different ways depending upon the type and location of his glasshouse and on the efficiency of his heating system. For the tomato grower the fuel cost now represents about 40% of the total cost of production and a 1% increase in heat requirement will mean a greater than 0.4% increase in overall production costs (assuming a boiler system less than 100% efficient).

1) By reducing the emissivity of the cladding material from 0.94 to 0.6 a simulated saving of 23% in heat requirement was achieved, reducing the cost of heating to the range £2.30-£3.85/m^2. The cost of a coated glass cladding is between 50% and 300% more than the cost of conventional glass. Pilkingtons quote a price of £1.80 /m^2 for 3mm horticultural glass and the calculations in this chapter will assume a low emissivity glass cost of £2.70/m^2. This is the lower end of the scale but is justified since it should become cheaper as more is produced and used. Using a 1 ha glasshouse and assuming a cladding area of about 1.3 m^2 per 1 m^2 of floor and that the low emissivity glass will cost about £2.70 /m^2 then the cost per 1m^2 of floor area will be about £3.50. The payback time will range between three and five years. However this will be considerably less if it is installed with a new glasshouse at the time of building, or if the glass needed replacement anyway. Only the extra cost comes into the calculation and the payback time falls to between one and two years.

2) The emissivity of the floor surface was reduced from a value of 1.0 to 0.6 and gave a heat saving of 13.7%. However, with a crop present this figure would have been different, as the crop rather than the floor would have exchanged radiation with the roof. Maintaining the low emissivity of a floor covering would be very difficult inside the glasshouse under humid conditions.

A similar problem arises in trying to quantify the energy savings by reducing the shortwave reflection from the floor. High albedo coverings are widely used to reflect light into the crop canopy and these do not greatly increase the amount lost by re-transmission through the glass.

3) Reducing the leakage rate from two to one air change per hour gave a simulated heat saving of 18%. Sealing the laps between glass panes to reduce leakage can give energy savings of about 5% (Smith 1984) and would reduce the fuel cost to £2.85-£4.75/m^2. The cost of this option is about 15p/m^2 (Smith, 1984) which gives a pay-back time of under one year. Similar figures pertain to the savings and costs of fitting polyethylene to the side and end walls and for insulating the gutters.

4) A reduction in the outside convective transfer will reduce the energy requirement. The transfer coefficient is difficult to change but another factor the wind speed. can be altered. The highest rate of convective heat loss occurs in strong winds rather than during periods of cold temperatures (Sheard 1978). Shelters can cause a reduction in wind speed of 30% leading to a 10% reduction in heat loss. Their low cost (approximately 15p/m^2 for a natural wind break) can also be re-couped within one year.

5) The inside convective transfer can be lowered by using a secondary cladding around the walls of the glasshouse at a cost of 50p/m^2 for polyester and 75p/m^2 for glass. The installation of complete double glazing is much more expensive costing about £8 for double polyethylene, £20 for glass, £28 for acrylic and £30 for polyester (all per square metre). The high capital cost and reduced light intensity makes this option look less attractive but if new glasshouses were being installed, double glazing should be considered.

6) The use of thermal screens can reduce heat requirement by up to 65% Bailey and Cotton (1977). The heat savings of 45 to 57% simulated for different screens by GHFORSM could reduce the heating bill to about £1.50 to £2.50/m^2. The cost of screens lies in the range £2.00 to £5.00/m^2 and so the payback time should be between one and two years (Smith, 1984). However, when using screens, the grower must be aware of the possible danger of yield reduction which can be as much as 10%. This would lengthen the payback time.

7) For conditions at Kew and Eskdalemuir the runs showed that the thermal screens simulated were more effective at saving energy than the type of double glazing tested. Concerning the double glazing alone, the difference in the amount of heat saved at Kew (47.26% compared with 44.38% at Eskdalemuir) shows that double glazing is more effective at Kew than at Eskdalemuir. Overall energy reductions at Kew and Eskdalemuir from thermal screens were similar (52.87% at Kew and 51.13% at Eskdalemuir) although the screen was more effective than double glazing for longer during the year in the North.

The Kew and Eskdalemuir runs showed that overall, all of the energy conservation methods saved more energy at Kew than at Eskdalemuir. If we assume that the glasshouses were identical and that the grower under Kew conditions paid £3.00 /m^2 each year for his fuel for a single glazed, unscreened glasshouse then the heating costs at both sites for all the conservation techniques will be as shown below.

	Single Gl. No Screen	Single Gl. With Screen	Double Gl. No Screen	Low emiss. No Screen	Double Gl. With Screen	Low emiss. With Screen
Kew						
Fuel	£	£	£	£	£	£
cost	3.00	1.41	1.59	2.13	.84	.99
Saving	0.00	1.59	1.41	0.87	2.16	2.01
Esk.						
Fuel						
cost	4.38	2.16	2.46	3.27	1.32	1.59
Saving		2.22	1.92	1.11	3.06	2.79

Thus all of the conservation methods save the grower in the North more money and the payback times will be correspondingly less. Assume the following costs for the conservation methods (all /m^2 of floor area and the same for each grower):

Thermal screen	£ 3.50		
Double Glazing	£ 26.00	with Screen	£ 29.50
Low emiss glass	£ 3.50	with Screen	£ 7.00

The payback times will be:

	Single Gl. With Screen	Double Gl. No Screen	Low emiss. No Screen	Double Gl. With Screen	Low emiss. With Screen
Kew					
Years	2.2	18.4	4.0	12.0	3.5
Esk.					
Years	1.6	13.5	3.2	9.6	2.5

The payback times for the grower at Eskdalemuir are less. The life of double glazing and low emissivity glass cladding will be about 15 to 20 years although the heat saving effect of the low emissivity glass may be reduced by dust, dirt and water on the surface, and the coating may be worn away. Once in place, a double glazed glasshouse only needs replacement glass, not the whole supporting structure as well. A thermal screen however, will have a shorter life. Part of the expense of the screen is in the supporting structure and mechanisms which open and close it and so replacement of the screen itself will not incur the same initial cost. However, the payback time of the combination of double glazing or low emissivity glass used with a screen will be longer than shown above as the screen will have to be replaced.

The figures show that the installation of a thermal screen is a good option for both sites and low emissivity glass has a considerably better payback time at Eskdalemuir than at Kew. However, it would appear that the installation of double glazing represents a very long term investment and may not be a viable option at Kew, given the prices quoted above. Cheaper systems will make it much more attractive.

There are other, hidden benefits to using energy conservation. The overall reduction in heat requirement will mean that not only are the grower's fuel bills lower, but he will have to borrow less money to buy fuel during the early part of the year when he has little or no return from sales of his produce. Thus his interest payments will be reduced. Further runs would be needed to show the peak heater output for each of these conservation measures. If a reduction in these peak levels was brought about then the grower could use a smaller boiler with a lower capital cost. The peaks of heater output occur when the heating switches on to bring the air temperature from the night setting to the day setting and these could be smoothed if growers did not try to force the glasshouse air temperature to follow stepped blueprints. Raising the temperature slowly, starting an hour or more before sunrise should reduce the peak heating requirement.

The use of Computer Models for Glasshouses

A final set of points concerns the use of models to investigate glasshouse systems, and the lessons learnt from the modelling work carried out during this project.

When the project began a large mainframe computer and an eight bit microcomputer were available for use. Whilst the micro was used to a small extent for developing sections of routines, the model was written for use on the mainframe as it was thought that a detailed model would require large amounts of computer space; more than was available on the micro. The mainframe computer had a library of routines such as FORSIM that could be used and the other major benefits of using a large machine were the computing power and speed it provided. In conjunction with FORSIM, the mainframe could handle in fractions of seconds the work that might have taken a smaller computer minutes or even hours to accomplish when difficult areas of computation were reached, sharp changes in temperature for example the mainframe simply 'changed gear' and found the most efficient way of proceeding.

Of course the common drawbacks to using a mainframe computer were encountered as well. The mainframe was being heavily used and printout from runs was not available until the following day, despite having taken only a few seconds of actual computing time to complete. However, the mainframe was the only device then available on which the model could have been developed. Were the exercise to be repeated or continued there would be a strong case for adapting GHFORSM for use on one of the sixteen bit micros that are coming into more common useage. The advantage of a dedicated machine would be the ability to produce results whenever required. Moreover, the greater processing power, storage and speed of the sixteen-bit micros in comparison with the eight bit machines makes them competitive with mainframe computing.

GHFORSM has been used to investigate the effects of three energy conservation methods in two different parts of the country, but a hierarchy of other types of models can be defined, along with the type of machine on which such models might be written. Such a list might be as follows:

Type of Model	Machine
Simple measure of heat loss using U values for the heat transfer	Pocket calculator 8-bit microcomputer
A steady state model such as the simulation of nocturnal inside air temperature using simple heat transfers	8-bit microcomputer 16-bit microcomputer
A model which included diurnal variation of conditions estimating the temperatures of the air and the soil and the heat requirement. Generation of meteorological conditions by the program.	8-bit microcomputer with 64K bytes of memory. 16-bit microcomputer with a compiler for example
As above, using measured data designed to point out areas of interest for future study, showing where savings might be made for example	16-bit microcomputer with a library of routines a compiler and large storage space
A detailed model using routines to solve differential equations handling a range of measured weather data at various time intervals and providing output on many aspects in which the user might be interested	Mainframe computer

The correct choice of computer for simulation is important; the choice depends upon the type of model, and the objectives. Most of the model types listed above could probably be run on a small 8-bit microcomputer with sufficient memory space but the programs would take increasingly longer to run as the models became more complex. Wide ranging testing or use of the model would require much time to complete, which would be a severe constraint upon the modeller.

Time problems often occur in computer models when real meteorological data is being used. In areas of the world where the climate is more stable, the problem is not as great because continuous cloud cover, or clear, sunny weather is easy to model and does not present numerous sharp changes that have to be handled. In the UK, the changeable weather and broken cloud conditions give rise to sharp changes in the solar radiation intensity on a timescale of minutes or even seconds. GHFORSM can handle such sharp changes but microcomputers will be less suited to the task of running large models that incorporate 'weather', including outside air temperatures air humidities solar radiation (direct and diffuse), longwave radiation and so on. They would also have problems in handling models that included more detailed descriptions of heat transfers such as ventilation for instance. Models that used complex treatments could only be run on mainframes if results were required in a realistic time. A model of the same complexity as that described by Critten (1983) which takes several hours to complete on a PDP11 computer, could not be run on a small micro.

To meet the initial objectives of the project a mainframe computer was the correct choice for the job. The sole alternative an 8-bit micro would not have been suitable. GHFORSM simulates the glasshouse environment at speed and makes full use of the mainframes memory. It was kept as general as possible so that it could be used to investigate structures other than glasshouses in a similar way. One group has already used the model to simulate the thermal behaviour of a warehouse in a warm climate replacing the glass roof with solar energy collectors.

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Appendix I: Program Listing and Description

In the following description of the model a line by line listing of the program is presented. The model is written in Fortran and the program lines are indented and printed in capital letters. The description is given after each listing and some sections are split up into several parts of more manageable size. The "*" character is used in two different ways in the program. Firstly it is used as a multiplication operator, the standard Fortran command and secondly it is used at the beginning of a line to denote a continuation of the previous line.

SECTION 1 DIMENSION STATEMENTS FOR ARRAY VARIABLES

```
 COMMON/TEMP/ZTEMP1(98),ZTEMP3(98),ZTEMP5(98),ZTEMP7(98),ZTEMP9(98),
*ZTEMP11(98).ZTEMP13(98),ZTEMP15(98),ZTEMP17(98),ZTEMP19(98),ZTEMP21(98),
*ZTEMP23(98),ZTEMP25(98),ZTEMP27(98)
 COMMON/EM1/DN(98),HEATOT(98),HTPWR(98),TIMDEC(98),TIME(98).VENT(98),
*VTOPEN(98)
 COMMON/BALRAD/BAL9(98),BAL13(98),BAL15(98),BAL17(98),EVAPHT(98),HV(98),
*RAD3(98),RAD7(98),RAD11(98),RAD17(98)
 COMMON/STOREHT/HSTAIR(98),HSTORE(98),HSTOR1(98),HSTOR3(98),HSTOR5(98),
*HSTOR7(98),HSTOR9(98),HSTOR11(98),HSTOR13(98),HSTOR15(98),HSTOR17(98),
*HSTOR19(98),HSTOR21(98),HSTOR23(98),HSTOR25(98),HSTOR27(98)
 COMMON/RADIATE/ABSCO3(98),ABSCO7(98),ABSRAD3(98),ABSRAD7(98),PHOTRAB(98),
*R(98),REFCO3(98),REFCO7(98),SUNRAD(98),SUNSOIL(98),THETA1(98),THETA2(98),
*THETA4(98),TRANCO3(98) TRANCO7(98),TRARAD3(98),TRARAD7(98)
 COMMON/HUMHEAT/HMSAT3(98),HMSAT7(98),HMSAT11(98),HMSAT15(98),HUMROOF(98),
*RELHU11(98),RELHU15(98),ZHAI(98)
 COMMON/MISCEL/TEMDEL(98),TINCR(98),TMINSAR(98),TMP1DAT(98)
 COMMON/DAYHT/HEATDAY(98)
 COMMON/INIT1/DERIV(16),DERVAL(16,2),NUMBER(98),TM(16,2),TTOT(98),
*DTM(16,2)
 COMMON/READAT/TEMPONE(98),SUNREAD(98),OUTHUM(98),TEMCHEK(98)
```

```
 COMMON/LWRAD/RLW1(98),RLW31(98),RLW37(98),RLW311(98),RLW317(98),
*RLW711(98),RLW717(98),RLW1117(98)
 COMMON/EM2/CHLR(98),CHLS(98),DELT151(98),SUNGAIN(98),HFLUX(98),HLR(98),
*HLS(98),RHLR(98),VHLR(98)
 COMMON/INIT2/C(40),CHT(28),DENSITY(27),EMLR(17),FLUXTOT(98),HAO(98),
*HEATCAP(27),LHEAT(98),N(98),RI(7),THICK(27),TRI(27),V(45),COEFF(10)
```

This section contains all the dimension statements required by the program. The variables named here are storage arrays for values which can be printed out at the end of the run. A description of each can be found in the text which follows and also in the variable list.

SECTION 2 FORSIM CONTROL STATEMENTS

```
 COMMON/INTEGT/TEMP3,TEMP7,TEMP9,TEMP11,TEMP13,TEMP15,TEMP17,TEMP19,
*TEMP21,TEMP23,TEMP25,TEMP27,HAI,HEATIN
 COMMON/DERIVT/TEMP3T,TEMP7T,TEMP9T,TEMP11T,TEMP13T,TEMP15T,TEMP17T
*TEMP19T,TEMP21T,TEMP23T,TEMP25T,TEMP27T,HAIT,HEATINT
 COMMON/RESERV/T,DT,DTOUT,EMAX,TFIN,METHOD,DTMAX
 COMMON/CNTROL/INOUT
 DATA LK/0/
 DATA JN/0/
 DATA JM/0/
 DATA LM/0/
```

FORSIM is a program that solves differential equations and those variables that FORSIM is to integrate are listed in the INTEGT block. These are, in this case, all the component temperatures, the inside air humidity and the heat input from the heating system. The outside air temperature which is read in as data and the temperature of the air gap between the roof layers are omitted and reasons for this will be given later. The variables listed in the DERIVT block tell FORSIM under what name to find the derivative equations corresponding to those variables listed in the INTEGT block. Notice that all the names are the same except that the DERIVT variables have an extra T (denoting a time derivative) added to the end of each and that they appear in the same order as the INTEGT variables. Thus, TEMP3 is the temperature of component 3 and TEMP3T is the variable which takes on the value of the change in TEMP3 with time during sweeps through the program.

The RESERV block contains variables that will be common to both FORSIM and to subroutine UPDATE some of which can be set by the user within UPDATE FORSIM uses a time variable T which always runs from 0.0 to 10.0 FORSIM SECONDS (hereafter denoted by FS) for whatever length of real time the user wishes to simulate. DT is the time step which FORSIM will set when trying to gain convergence in solving the equations and the user has no control over this variable although he can use it in UPDATE routines. DT can lie anywhere in the range:

$$10^{-19} \leq DT \leq 10^{+19}$$

although this is generally modified using DTMAX to set an upper limit on DT (default value of 0.1) which it may not exceed. DTOUT is a variable which informs FORSIM when conditions are suitable for a printout. If DTOUT is set at 0.1 then over the full run from 0.0 to 10.0 FS we will get values printed out 10.0 / 0.1 = 100 times. Of course DTOUT can be set a little more subtly within UPDATE itself so that printout times need not be at regular intervals and this will be shown later. EMAX is the maximum relative truncation error allowed as FORSIM tries to gain convergence of the equations. Should this value be exceeded in any integrand FORSIM will reduce DT and repeat the step until the convergence is satisfactory. When all the errors are below the value of EMAX, DT will be increased so that the program may proceed as quickly as possible Only if DT falls below 10^{-19} FS, will the program continue to the next step after setting an internal flag indicating that one or more equations failed to converge at that point. EMAX can either be set in UPDATE by the user, or FORSIM will use a default value. TFIN can be specified by the user to set the finishing time of the run the default time is 10 FS.

Within the FORSIM routines there are several different means of carrying out the numerical integrations and the user can choose any of these by setting METHOD. The default value is 1 which is a Runge-Kutta method but in this example METHOD is set to 4 which is an Adams method. A fuller explanation of the METHOD variable and others described in this section can be found in the FORSIM manual (Carver et al , 1978). Finally in this section, the CNTROL block contains the variable INOUT which takes on different values (set by FORSIM) through the run denoting, for example the start of the run or that printout conditions have been met or that the end of the run has been reached. It is given a value by FORSIM depending upon the values of DTOUT and T at any given time during the run Usually INOUT has a value of 0 which indicates that the equations are converging smoothly but at intervals of DTOUT, every 0.1 FS for example, INOUT is set at 1. This value can then be used in the UPDATE routines to channel the program into the printout sections if so desired.

The four integer variables LK, JN, JM and LM are used as flags in UPDATE and help to control the pathway of the program. The DATA statements set each of them to 0 at the start of the run but their respective values change as the calculations progress and as each is encountered a description of its function will be given.

```
SECTION 3 CONTROL VARIABLES AND FLAGS

METHOD=4
EMAX=.0005
DAYS=10.0
ROOF=1.0
SCREEN=0.0
KMAX=24
DATAIN=0.0
HEATER=1.0
```

Section 3 contains some of the variables used to describe the glasshouse system and some which control FORSIM. In this example METHOD is set at 4 and EMAX at 0.0005 indicating that an Adams method of integration will be employed and the error limit is 0 0005. This model simulates the thermal behaviour of a glasshouse over a number of days and is set up in this example to print out the results for the final day only. Results in this context means temperatures, long-wave radiation, humidities etc. printed out for various times during the day. The model can be changed quite easily to print out the results after each day of the run but several pages of numbers printed out for each and every day are often of very little use and so the program stores values for each day in the arrays defined in Section 1. At the end of each day the program checks to see if there are any more days to be simulated and if there are, the storage arrays are overwritten with the new day's results. If however, there are no more days to be simulated the printing routines are called and the storage arrays are printed out. This method makes the best use of the computer memory available and also allows flexibility in printout times. It is sensible however, to save and print the heating requirement for each day of the run as this gives an indication of how well conservation methods are performing. In this example DAYS is 10.0 which means that we are simulating a glasshouse for 10 days and more will be said concerning this variable in later sections.

This model has the capability of incorporating both a single or double glazed roof and a thermal screen. In this example ROOF is set at 1.0 and SCREEN is 0.0 indicating the presence of a single glazed roof and the absence of a thermal screen at night. ROOF = 2.0 would indicate double glazing and SCREEN = 1.0 the use of a screen at night.

In order to write values to the storage arrays, UPDATE uses a variable called K (described in section 6 KMAX is a variable which defines the maximum value that K will take during a run and indicates the number of values to be printed out for the final day. For example, if KMAX were set at 96 we would expect 96 values of each variable to be printed whenever a print was called, one value for each variable every 15 minutes perhaps. In this example however KMAX is 24 and UPDATE controls the value of K so that it is incremented by one every hour. It is possible though to have KMAX set at 84 for example, and arrange that UPDATE should increment K by one every hour between 0.00h and 12.00h then by one every minute until 13.00h and finally by one every hour again for the remainder of the day. In this way, if the user had a particular interest in the behaviour of the glasshouse between 12 00h and 13.00h, results could be obtained every minute during this period.

The program can be set up to read in data or to create its own and a variable DATAIN, is used to tell the program whether or not data is available. If DATAIN is 1.0 then there will be data present, if it is 0.0 then it must create its own. HEATER is used to indicate whether or not the heating system will be employed during this run (1.0=on, 0.0=off)

SECTION 4 DATA INPUT...SUBROUTINE CALLS...INITIAL VALUES

```
   IF(INOUT.EQ.-3)
   GO TO 37
   GO TO 38
   37 CALL ASSIGN(DAYS,ROOF,RAD)
   CALL DATREAD
   CALL INITIAL(TEMP1,ROOF,KMAX,DAYS)
   CALL PARAOUT(RAD)
38 CONTINUE
   PI=C(30)
```

FORSIM carries out its work in three separate stages, the initialisation stage sets up all the starting conditions, the calculation stage calculates the results and the final stage prints out the results and ends the run At the beginning of the run, FORSIM sweeps through UPDATE to see if there are any instructions it must carry out before the simulation begins. If a *MYCONS* statement is found at the end of the program this indicates to FORSIM that data is present and must be read in before the run starts. Upon reading a *MYCONS* statement the program assigns a value of -3 to INOUT. A routine in UPDATE checks on the value of INOUT and if it is -3 then the initialisation subroutines, ASSIGN, DATREAD, INITIAL and PARAOUT, are called; if it is not -3 then UPDATE jumps to statement label 38 (CONTINUE) The subroutines will be described later on PI is a variable equated to C(30) which is assigned the value Pi in one of the initialisation routines. Rather than use C(30) in equations containing the value Pi, it was felt that it would be easier to understand the variable name PI more quickly.

SECTION 5 TIME CONTROL

```
    TDAY=C(4)/DAYS
    TOUR=T
100 IF(TOUR.GT.TDAY) GO TO 120 GO TO 140
120 IDAY=IFIX(TDAY)
    TOUR=TOUR-FLOAT(IFIX(TOUR/TDAY))*TDAY
140 CONTINUE
```

The program simulates the glasshouse for a number of DAYS and this section ensures that these DAYS will fit into the time limit of 10.0 FS. TDAY is the length of time of one day of simulation represented in FS, thus if DAYS = 10.0. TDAY will be 10.0 / 10.0 = 1.0 FS. It is much more efficient for a computer to handle named constants and variables which have been stored once during the initialisation procedure in a calculation, rather than for it to use numbers or values named each time the program is called. As FORSIM may call UPDATE many thousands of times during one run then any method of decreasing the number of lines the computer is required to execute will make a significant contribution to improving the efficiency. The C array is an array of constants containing those numbers frequently used by routines in UPDATE, and the V array contains parameter values that describe all aspects of the glasshouse system being simulated. A description of these arrays can be found in the Subroutines section which follows later. Whilst it would be easier to understand equations containing numbers and easily 'decipherable' variable names, it was felt that in most cases the need for improved efficiency outweighed the disadvantages.

Returning to the time control routine, once TDAY has been calculated a variable called TOUR, is set equivalent to T. The following lines compare the values of TOUR and TDAY and if TOUR is greater than TDAY then a multiple of TDAY is subtracted from TOUR until the value of TOUR is less than that of TDAY. In this way TOUR is constrained to run between 0.0 and TDAY for each separate day of the simulation. An example of this process is shown below. Given that TDAY = 1.0 and T = 3.4 at some stage during the run then TOUR is set as follows:

```
    TOUR = T                                          3.4
100 IF(TOUR GT TDAY) GO TO 120                        GO TO 120
    GO TO 140
120 TOUR=TOUR-FLOAT(IFIX(TOUR/TDAY))*TDAY             TOUR=3.4-(3*1)=0.4
140 CONTINUE
```

Thus TOUR has a final value of 0.4 indicating that the current time on the third day of the run is 0 4 FS.

SECTION 6 TIME CONVERSION

```
    HOUR=TDAY/C(5)
    TIMDE=TOUR/HOUR
    TMINVAL=TIMDE*C(8)
    IHOUR=INT(TIMDE)
    TMINS=TIMDE-FLOAT(IHOUR)
    IF(TMINS.GT.0 995) GO TO 155
    TIM=FLOAT(IHOUR)+(TMINS*C(11))
    GO TO 157
155 TIM=FLOAT(IHOUR+1)
157 DTMAX=TDAY/C(31)*V(40)
```

The use of FORSIM time is inconvenient when it comes to printing out results in an easily readable form. TEMP3 might be 19 316°C at T = 5.5 but it is not immediately clear exactly what time of day T = 5 5 is. This section converts time measured in FS to time represented by hours and minutes. Firstly, one hour of real time is converted to FS and by dividing TDAY by 24 0. This value, HOUR, is then used to calculated TIMDE, the current time in decimal hours followed by TMINVAL the current time in minutes since midnight. IHOUR is the whole number of hours since midnight and TMINS the fraction of the hour remaining after subtracting IHOUR from the current time. Next, if TMINS is greater than 0 995 then IHOUR is incremented by 1 and the time is assumed to be a whole number of hours past midnight. If TMINS is not greater than 0 995 then TIM (time) is calculated as IHOUR plus TMINS * 0.6 so we now have FORSIM time converted to hours and minutes. As an example of this calculation let DAYS be 1.0 and T be 5.5 Thus we have TDAY=10.0 and TOUR=5.5:

```
HOUR     = 10.0 / 24.0         = 0.41667 FS
TIMDE    = 5.5 / 0.41667       = 13.2 hours
TMINVAL = 13.2 * 60            = 792  minutes
IHOUR    = INT(13.2)           = 13 hours
TMINS    = 13.2 - 13.0         = 0.2  hours (TMINS is less than 0.995)
TIM      = 13.0 + (0.2 * 0.6) = 13.12 hours.minutes
```

The current time is therefore 13.12h

DTMAX is the maximum time step which FORSIM will be allowed to take in trying to gain convergence of the equations. V(40) is this time step in real minutes which is set by the user and DTMAX is the equivalent value in FS.

```
    IF(TIM.GE.V(13).AND.TIM.LE.V(14)) DTMAX=0.00003
    IF(TIM.LT V(13)) GO TO 110
    IF(TIM.GT V(14)) GO TO 112
    DTOUT=HOUR/C(8)
    K=INT((TOUR-(5.0/DAYS))/DTOUT)+IFIX(V(13))+1
    GO TO 130
110 DTOUT=HOUR
    K=INT(TOUR/DTOUT)+1
    GO TO 130
112 DTOUT=HOUR
    K=INT(TOUR/DTOUT)+IFIX((V(14)-V(13))*C(8)/V(31))
    TDAY1=TDAY-(TDAY/C(31)*C(4))
    IF(TOUR.GT.TDAY1) K=K+1
130 DTOUR=DT*C(2)*DAYS
    IF(TOUR.GE.C(4)) K=KMAX
    IF(K.LE.2.OR.K.GE.(KMAX-2)) GO TO 137
135 IF(K.LE.LK+1) GO TO 137
    K=K-1
    LM=LM+1
    WRITE(6,136)K,TIM,TOUR,DT,LK,LM
```

```
    136 FORMAT(2X,I4,2X,2F10.7,2X,F10.8,2X,I4,2X,I5)
        GO TO 135
    137 LK=K
        TIME(K)=TIM
        TMINSAR(K)=TMINS
        TIMDEC(K)=TIMDE
```

The second part of this section deals with the derivation of a value for the variable K. V(13) and V(14) are times (expressed in decimal hours) between which more specialised data minute by minute readings perhaps may be available and so we would wish to increment K by 1 for each minute passed during this time period as explained previously. If we have data for the entire run at hourly intervals, then V(13) and V(14) can be set at any value greater than 24 so that TIM will always be less than V(13) and the program will always follow the hourly increment path. If however, minute interval data is available for a certain period of the run between TIM = V(13) and TIM = V(14), and the current time (TIM) lies between V(13) and V(14) then DTMAX is set at a smaller value than before. This allows the program to run smoothly by ensuring that FORSIM is not allowed to take time steps greater than 1 minute of real time in length. If it were allowed to do so then the value of K might jump from 15 to 17 in one go for example which would cause problems in some of the routines and would mean that no values of variables at K = 16 would be available. One of the improvements which could be made to FORSIM would be to ensure that DTMAX, the maximum time step value, is passed on to all the FORSIM subroutines. Unfortunately this is not always the case so that when some of the routines are being used, time steps of greater value than DTMAX are taken causing the problems outlined in the previous paragraph. The next few lines of this section make sure that the value of K increases as it should and that no values are missed out. Two of the DATA variables, LK and LM are used in this process. LK is equated to K for each sweep through the program and on the following sweep, if K is more than LK + 1, i.e. if one value of K has been missed, then K is reduced by one and the test is carried out again. Every time this happens, LM is increased by one to give an indication of how many times this problem has occurred and the variables involved are printed out. The final lines assign things such as time and the number of minutes past the hour to their respective storage arrays.

SECTION 7 OUTSIDE AIR TEMPERATURE

```
    IF(TIME(K).LE.V(13).OR TIME(K).GT.V(14)) GO TO 301
    TMINVAR=TMINSAR(K)-TMINSAR(K-1)
    GO TO 305
301 TMINVAR=TMINSAR(K)
```

In this model, any data points to be included as inputs for the simulation are read in at the beginning of the run. This section handles any outside air temperature, heater setpoint or outside air humidity data which may be available and produces intermediate values by a linear interpolation method. In order to ensure that the program will be able to cope with a 'specialised' data section at some point during the run, it is necessary to split the interpolation routines into three distinct sections. If all data is of the hourly interval type, then only one pathway will be followed by the program through this section. The first lines set a time variable, TMINVAR, depending upon which pathway the program will follow. For example, if we have hourly data until mid-day, minute by minute data between 12.00h and 13.00h and hourly data thereafter, then before 12.00h and after 13.00h TMINVAR is assigned a value equivalent to that of TMINSAR(K) which is that fraction of the hour which has elapsed since the last whole hour. Between 12.00h and 13.00h its value is the difference between the current value of TMINSAR(K) and the previous value which in this case is the amount of time which has elapsed since the last whole minute. For example, given TIME(K) = 10.30h and V(13) = 12.00h then TMINVAR takes on the value of TMINSAR(K) which is 0.5 (=30 min./60 min.). At TIME(K) = 12h 30 min and 15 secs. TMINVAR is TMINSAR(K)- TMINSAR(K-1) which is 0.25 as the time now is 15 seconds since the last whole minute.

```
305 TEMDEL(K)=TEMPONE(K+1)-TEMPONE(K)
    TINCR(K)=TEMDEL(K)*TMINVAR
    TMP1DAT(K)=TEMPONE(K)
    HTDEL=TEMCHEK(K+1)-TEMCHEK(K)
    HTINCR=HTDEL*TMINVAR
    IF(DATAIN.NE.1.0) GO TO 307
    HUMDEL=OUTHUM(K+1)-OUTHUM(K)
```

```
      HUMINCR=HUMDEL*TMINVAR
      GO TO 309
  307 HAO(K)=0.009
      GO TO 311
  309 HAO(K)=OUTHUM(K)+HUMINCR
  311 TEMP1=TEMPONE(K)+TINCR(K)+C(15)
      V(22)=TEMCHEK(K)+HTINCR+C(15)
```

The data points for the outside air temperature, the heater setpoint and the outside air humidity are stored in arrays named TEMPONE(K), TEMCHEK(K) and OUTHUM(K) respectively. A description of the derivation of the outside air temperature can also be used as an example of the way the humidity and heater setpoint variables are calculated. At any given time, TEMDEL(K) is the difference in value between the previous data point value, TEMPONE(K), and the next data point value, TEMPONE(K+1). TINCR(K), the increment in temperature since the previous data point, is this value TEMDEL multiplied by TMINVAR, the time variable. Finally, in the line labelled 311, the value of TEMP1 is calculated as the sum of the previous data point and the temperature increment. For example, if TIME(K) = 10.30h and the value of TEMPONE(11) (the outside air temperature at 10.00h) is 10.0 °C and TEMPONE(12) (the next data point value at 11.00h) is 11.0 °C then TEMDEL(K) = 1.0 °C. As we are 30 minutes past the hour TMINVAR = 0.5 and TINCR is thus 0.5 * 1.0 °C = 0.5 °C. When added to the previous value TEMPONE(11) and C(15) (= 273.16 K) the current value of TEMP1 becomes 10.0 + 0.5 + 273.16 = 283.66 K.

This type of interpolation is employed to ensure that FORSIM does not have to deal with any 'steps' when changing from one data point to the next. There are other methods of calculating a 'current value' of TEMP1. One way would be to use the data point value, unchanged, from one hour to the next and the other would be to use an average value, again throughout the entire hour. Both of these give stepped data whereas the method used in GHFORSM gives a continuous curve. FORSIM handles the changes in direction which result when the temperature or data starts to fall after rising steadily, without trouble. The outside air humidity and the heater setpoint can both be calculated in a similar way, although the humidity does have a default value if DATAIN = 0.0 indicating that no data is available.

```
      IF(IHOUR.EQ.24) GO TO 313
      GO TO 320
  313 TEMPONE(KMAX+2)=TEMPONE(KMAX+1)
      OUTHUM(KMAX+2)=OUTHUM(KMAX+1)
      TEMCHEK(KMAX+2)=TEMCHEK(KMAX+1)
  320 CONTINUE
```

These final lines of the section set values for the temperature humidity and heating setpoint arrays at points two greater than KMAX. This is done to enable the interpolation routine to function during the 24th hour of any simulated day.

SECTION 8 SOLAR RADIATION GENERATION

```
      RAD=C(30)/C(9)
      RAD90=90.0*RAD
      RAD180=180.0*RAD
      PHI=V(15)*RAD
      DEC=C(16)*RAD*SIN((((C(17)+DN(5))/C(18))*C(19))*RAD)
      DECLIN=DEC/RAD
      DL=ACOS(-TAN(PHI)*TAN(DEC))/RAD*C(1)/C(20)
      TDL=DL*TDAY/C(5)
      TDLM=TDL/C(1)
      TMIDAY=TDAY/C(1)
      SUNRISE=TMIDAY-TDLM
      SUNSET=TMIDAY+TDLM
      SCROPEN=SUNRISE+TDAY/(C(5)*C(8))*V(35)
      SCRDRAW=SUNSET+TDAY/(C(5)*C(8))*V(36)
      SUNRI10=SCROPEN+(TDAY/C(31)*V(16))
```

This section deals with the solar radiation routines of the program and includes such things as the calculation of sunrise and sunset times, reflection, transmission and absorption coefficients and the solar radiation flux. The first part of the routine is concerned with the daylength. RAD is the number of radians per degree of arc and is used to convert angles measured in degrees to radians. RAD90 and RAD180 are 90.0° and 180.0° expressed in radians and PHI = V(15) * RAD is the geographic latitude (V(15)) of the glasshouse being modelled which is entered by the user in one of the initialisation subroutines in degrees. Multiplying by RAD gives PHI the same latitude, in radians. DEC is the solar declination angle and DECLIN is this angle expressed in degrees. DL is the day length in hours and TDL is DL expressed in FS. TDLM is the daylength divided by two which when subtracted from TMIDAY, the time in FS when noon occurs, gives the time of sunrise. Adding TDLM to TMIDAY gives the sunset time. SCROPEN and SCRDRAW are the times at which the screen opens and closes above the crop respectively. The screen opens when the time is sunrise plus a number of minutes, V(35), and closes at sunset plus V(36) minutes. SUNRI10 is the screen opening time plus a number of minutes, V(16), set by the user, in FS.

```
 IF(TOUR.LT.SUNRISE.OR.TOUR.GT.SUNSET) GO TO 380
 HA=ABS(TMIDAY-TOUR)*C(5)/TDAY*C(20)*RAD
 COSTHE1=SIN(DEC)*SIN(PHI)*COS(V(1))-
*SIN(DEC)*SIN(PHI)*SIN(V(1))*COS(V(2))+
*COS(DEC)*COS(PHI)*COS(V(1))*COS(HA)+
*COS(DEC)*SIN(PHI)*SIN(V(1))*COS(V(2))*COS(HA)+
*COS(DEC)*SIN(V(1))*SIN(V(2))*SIN(HA)
 IF(COSTHE1.LT.-C(6)) COSTHE1=-C(6)
 IF(COSTHE1.GT.C(6)) COSTHE1=C(6)
 COST1=SIN(DEC)*SIN(PHI)*COS(V(44))-
*SIN(DEC)*SIN(PHI)*SIN(V(44))*COS(V(2)+RAD180)+
*COS(DEC)*COS(PHI)*COS(V(44))*COS(HA)+
*COS(DEC)*SIN(PHI)*SIN(V(44))*COS(V(2)+RAD180)*COS(HA)+
*COS(DEC)*SIN(V(44))*SIN(V(2)+RAD180)*SIN(HA)
 IF(COST1.LT.-C(6)) COST1=-C(6)
 IF(COST1.GT.C(6)) COST1=C(6)
 IF(COST1.GT.COSTHE1) COSTHE1=COST1
 IF(COSTHE1.LE.0.0) GO TO 380
 COSTHE17=SIN(DEC)*SIN(PHI)*COS(V(29))-
*SIN(DEC)*SIN(PHI)*SIN(V(29))*COS(V(30))+
```

```
*COS(DEC)*COS(PHI)*COS(V(29))*COS(HA)+
*COS(DEC)*SIN(PHI)*SIN(V(29))*COS(V(30))*COS(HA)+
*COS(DEC)*SIN(V(29))*SIN(V(30))*SIN(HA)
 IF(COSTHE17.LT.-C(6)) COSTHE17=-C(6)
 IF(COSTHE17.GT.C(6)) COSTHE17=C(6)
 COSTHOR=SIN(DEC)*SIN(PHI)+COS(DEC)*COS(PHI)*COS(HA)
```

Having calculated the sunrise and sunset times, the routine then checks to see if the current time lies within the hours of daylight. If it does not then there is no need to calculate any of the reflection, transmission or absorption coefficients or the solar radiation flux and so the program jumps to statement label 380, by-passing the bulk of this section. If we are in daylight then the program calculates the solar hour angle which, with the declination, specifies the position of the sun in the sky. The next lines calculate the angle of incidence of solar radiation upon the glasshouse roof using the declination, the latitude of the site, the roof slope angle (horizontal or flat roof = 0), the roof azimuth angle (the angle it is facing, measured from south) and the hour angle. There are two roof surfaces through which solar radiation might pass to any particular area on the glasshouse floor. The next lines calculate the angle of incidence of solar radiation upon the second roof surface whose azimuth is assumed to be 180° different from that of the first roof. Then, whichever of these two values is the lesser is used as the cosine of the angle of incidence in subsequent calculations.

The angle of incidence of solar radiation upon the floor of the glasshouse is calculated in a similar manner using the floor slope angle and azimuth in the appropriate places. In case there are any slight errors in the computational routines used to calculate the cosines of the angles of incidence in the computer routines, both these values are checked and set to lie between -1 and +1. The cosine of the angle of incidence of the radiation upon a horizontal surface (COSTHOR) is also calculated for use here and is used later in the section for those occasions when radiation data measured upon a horizontal surface is handled.

```
      THETA1R=ACOS(COSTHE1)
      IF(TAN(THETA1R).GT.19.0) GO TO 380
      THETA1(K)=THETA1R/RAD
      SINTHE2=RI1(1)*SIN(THETA1R)/RI(3)
      THETA2R=ASIN1(SINTHE2)
      THETA2(K)=THETA2R/RAD
```

THETA1R is the angle of incidence of the solar radiation upon the glasshouse roof in radians and if this angle is large in this case greater than about 87° then it is assumed that no radiation actually gets through the roof due to the shadowing effect of the raised glazing bars, and the section is not executed. The next line calculates THETA1(K) which is the angle of incidence expressed in degrees. THETA2(K) is the angle of refraction of the light in the roof medium.

```
      DELTHET=THETA2R-THETA1R
      DELTHET=ABS(DELTHET)
      SUMTHET=THETA2R+THETA1R
      IF(SUMTHET.LT.0.00001) GO TO 333
      REFPERP=SIN(DELTHET)**2/SIN(SUMTHET)**2
      REFPAR=TAN(DELTHET)**2/TAN(SUMTHET)**2
      GO TO 334
  333 REFPERP=0.0
      REFPAR=0.0
  334 TAUALF1=EXP(-V(3)*THICK(3)/COS(THETA2R))
      TRPAR=TAUALF1*((C(6)-REFPAR)/(C(6)+REFPAR)*(C(6)-REFPAR**2)
     */(C(6)-REFPERP**2*TAUALF1**2))
      TRPERP=TAUALF1*((C(6)-REFPERP)/(C(6)+REFPERP)*(C(6)-
     *REFPERP**2)/(C(6)-REFPERP**2*TAUALF1**2))
      TRANC03(K)=C(21)*(TRPAR+TRPERP)
      REFC03(K)=C(21)*(REFPAR*(C(6)+TAUALF1*TRPAR)+REFPERP*
     *(C(6)+TAUALF1*TRPERP))
      ABSC03(K)=C(6)-REFC03(K)-TRANC03(K)
      IF(ROOF.EQ.1.0) GO TO 325
```

These lines calculate the reflection transmission and absorption coefficients for the upper roof, component 3 DELTHET is the difference between the angles THETA1R and THETA2R and SUMTHET is the sum of the two angles. Using the Fresnel relationships, the reflection of unpolarized radiation passing from one medium refractive index n_1, to another refractive index n_2 is:

$$r_{perp} = \sin^2(a_2-a_1) \;/\; \sin^2(a_2+a_1)$$
$$r_{par} = \tan^2(a_2-a_1) \;/\; \tan^2(a_2+a_1)$$
$$r = 05 * (r_{perp} + r_{par})$$

where perp is the perpendicular component, par is the parallel component and a_1 and a_2 are the angles of incidence and refraction respectively. The absorption of radiation is assumed to be proportional to the intensity and the distance travelled in the medium:

$$dI = I * K * dx$$

where dI is the amount absorbed, I is the intensity, dx is the path travelled and K is a constant of proportionality. The pathlength inside the medium is:

$$path = thickness \;/\; \cos(a_2)$$

Integrating along the length gives the value TAUALF1 which is the transmittance of the medium with regard to absorption losses only:

$$TAUALF1 = e^{-K*path}$$

The transmittance. reflectance and absorptance of a single roof can be calculated as follows using the parallel component as an example:

$$TRPAR = \frac{TAUALF1 * (1 - REFPAR)}{(1 + REFPAR)} * \frac{(1 - REFPAR^2)}{(1 + REFPAR^2 * TAUALF1^2)}$$
$$RF_{PAR} = REFPAR * (1 + TAUALF1 * TRPAR)$$
$$AB_{PAR} = 1 - RFPAR - TRPAR$$

For unpolarized radiation the transmission coefficient is found by averaging the values derived for the perpendicular and parallel components:

TRANCO3(K) = 0.5 * (TRPAR + TRPERP)

The absorption coefficient is assumed to be equal to:

1 - TRANCO3(K) - REFCO3(K)

as all radiation must be either absorbed, reflected or transmitted. The last line of this section is a check on the type of roof that is present If ROOF = 1.0 then all the required transmission coefficients have been calculated and control moves to statement label 325, but if a double glazed roof is present, then more coefficients, those pertaining to the lower roof have to be calculated.

```
 SINTHE3=RI(3)*SIN(THETA2R)/RI(5)
 THETA3R=ASIN(SINTHE3)
 SINTHE4=RI(5)*SINTHE3/RI(7)
 THETA4R=ASIN(SINTHE4)
 THETA4(K)=THETA4R/RAD
 DELTHE4=ABS(THETA4R-THETA3R)
 SUMTHE4=THETA4R+THETA3R
 REFPER4=SIN(DELTHE4)**2/SIN(SUMTHE4)**2
 REFPAR4=TAN(DELTHE4)**2/TAN(SUMTHE4)**2
 TAUALF2=EXP(-V(3)*THICK(7)/COS(THETA4R))
 TRPAR2=TAUALF2*((C(6)-REFPAR4)/(C(6)+REFPAR4)*(C(6)-
*REFPAR4**2)/(C(6)-REFPAR4**2*TAUALF2**2)
 TRPERP2=TAUALF2*((C(6)-REFPER2)/(C(6)+REFPER4)*(C(6)-
*REFPER4**2)/(C(6)-REFPER4**2*TAUALF2**2)
 TRANCO7(K)=C(21)*(TRPAR2+TRPERP2)
 REFCO7(K)=C(21)*(REFPAR4*(C(6)+TAUALF2*TRPAR2)+REFPER4*
*(C(6)+TAUALF2*TRPERP2))
 ABSCO7(K)=1-TRANCO7(K)-REFCO7(K)
```

```
      GO TO 326
```

There is no difference in the method employed to calculate the coefficients for the second roof layer so no further explanation is given. However the coefficients do need to be calculated separately because the two roofs may be made of different materials glass and plastic for example or they may differ in thickness say. The gap between the two layers, component 5, may be filled with a gas other than air, or even with some liquid and so will have a different refractive index.

```
  325 THETA4(K)=0.0
      TRANCO7(K)=1.0
      REFCO7(K)=0.0
      ABSCO7(K)=0.0
```

If only one roof is present then the storage values for the coefficients for the second roof are all equated to 0.0 except TRANCO7(K) which is equated to 1.0.

```
  326 COSZEN=SIN(PHI)*SIN(DEC)+COS(PHI)*COS(DEC)*COS(HA)
      ZENITHA=ACOS(COSZEN)
      SINSNAZ=COS(DEC)*SIN(HA)/SIN(ZENITHA)
      SUNAZ=ASIN(SINSNAZ)
      IF(DATAIN.EQ.0.0)GO TO 340
      IF(TIME(K).LT.V(13).OR TIME(K).GE.V(14)) GO TO 340
      SUNDEL=SUNREAD(K+1)-SUNREAD(K)
      SUNINCR=SUNDEL*TMINVAR
      SUNRAD(K)=(SUNREAD(K)+SUNINCR)*COSTHE1/COSTHOR
      SUNSOIL(K)=(SUNREAD(K)+SUNINCR)*TRANCO3(K)*TRANCO7(K)*(C(6)-V(9))
      GO TO 400
  340 SUNRAD(K)=(C(6)-(ZENITHA/RAD90)**4.42)*(0.9*(COS(ZENITHA)*COS(V(1))+
     *SIN(ZENITHA)*SIN(V(1))*COS(SUNAZ-V(2)))+*0.11*(C(6)-(V(1)/RAD180)))
      IF(SUNRAD(K) LT.0.0) SUNRAD(K)=0.0
      SUNRAD(K)=SUNRAD(K)*C(3)
      SUNSOIL(K)=((C(6)-(ZENITHA/RAD90)**4.42)*(0.9*(COS(ZENITHA)*
     *COS(V(29))+SIN(ZENITHA)*SIN(V(29))*COS(SUNAZ-V(30)))+0.11*
```

```
*(C(6)-V(29)/RAD180))))*TRANCO3(K)*TRANCO7(K)*(C(6)-V(9))
 IF(SUNSOIL(K).LT.0.0) SUNSOIL(K)=0.0
 SUNSOIL(K)=SUNSOIL(K)*C(3)*V(4)
 GO TO 400
```

These routines deal with the solar radiation and start by calculating the solar zenith and azimuth angles dependent upon the latitude time of day and day of year. If radiation data is available between V(13) hours and V(14) hours then DATAIN = 1.0. With data present, the amount of solar radiation, SUNRAD(K), is calculated by interpolation in a similar way to the outside air temperature but is altered because of the presence of a sloping roof. Data is usually in the form of measurements of global radiation upon a horizontal surface, and so needs some alteration to correct it for a sloping one. SUNSOIL, the radiation absorbed by the soil is calculated in a similar manner, but the radiation is assumed to have travelled through one roof layer (two if the structure is double glazed) before striking the floor.

If there is no data, then the program will generate its own, starting at the line labelled 340. The first two lines of the expression generate the direct beam component and the third generates the diffuse contribution for a bright, clear day. For a uniformly cloudy day part of the first two lines would be removed and the diffuse contribution would be increased so that we might have:

```
SUNRAD(K)=(C(6)-(ZENITHA/RAD90)**4.42)*0.4*(C(6)-(V(1)/RAD180))
```

This generation of SUNRAD(K) gives results in kilo-Watts and so must be multiplied by 1000.0, C(3) to change the result to Watts. Finally, the radiation absorbed by the soil is calculated using the equation listed above, with the radiation passing through the roof as before. Once again, the value must be multiplied by a factor of 1000.0 but it can also be multiplied by V(4), a factor which the user sets to reduce the radiation striking the floor. V(4) may represent radiation lost due to the structure or to dust deposits on the glass perhaps. The program then jumps to statement label 400.

```
380 SUNRAD(K)=0.0
    SUNSOIL(K)=0.0
    THETA1(K)=0.0
    THETA2(K)=0.0
    TRANCO3(K)=0.0
    REFCO3(K)=0.0
    ABSCO3(K)=0.0
    REFCO7(K)=0.0
    TRANCO7(K)=0.0
    ABSCO7(K)=0.0
    COSTHE1=1.0
    COSTH17=1.0
```

At night the program skips the preceding routines and jumps directly to line 380. All the relevant variables are then equated to 0.0 with the exception of the two cosines which are equated to 1.0

```
400 TRARAD3(K)=SUNRAD(K)*TRANCO3(K)
    ABSRAD3(K)=SUNRAD(K)*ABSCO3(K)*(C(6)+TRANCO3(K)*REFCO7(K))+
   *SUNSOIL(K)*COEFF(9)*V(9)*COEFF(1)
    ABSRAD3(K)=ABSRAD3(K)/V(42)
    IF(ROOF.EQ.1.0) GO TO 405
    TRARAD7(K)=TRARAD3(K)*TRANCO7(K)
    ABSRAD7(K)=TRARAD3(K)*ABSCO7(K)+SUNSOIL(K)*V(9)*COEFF(5)*COEFF(7)
    ABSRAD7(K)=ABSRAD7(K)/V(42)
    GO TO 410
405 TRARAD7(K)=0.0
    ABSRAD7(K)=0.0
410 PHOTRAB(K)=SUNSOIL(K)*V(17)
    IF(SCREEN.EQ.0.0) GO TO 199
    IF(TOUR.LT.SCROPEN.OR.TOUR.GT.SCRDRAW) GO TO 198
    GO TO 199
198 SUNSOIL(K)=0.0
    PHOTRAB(K)=0.0
```

Having calculated the coefficients, it is now possible to calculate the amount of radiation transmitted and absorbed by the various components. TRARAD3(K) is the amount of radiation transmitted through the upper roof layer which is equal to the incident radiation multiplied by the transmission coefficient. The calculated values are then increased by a factor of 1.0/V(42) in order to convert the value so that it represents the amount absorbed by the roof per square metre of floor. V(42) is the cosine of the difference in angle between the roof slope and the floor slope and is usually equal to the cosine of the roof slope angle as the floor slope is usually 0.0°. This also applies to the calculation of ABSRAD7 later. The amount absorbed, shown in the next line, is slightly more complicated and the equation will be expanded to help describe the situation. The expression can be split into three parts, the first of which is:

SUNRAD(K)*ABSCO3(K)

This is the amount absorbed by the glass due to the incident solar radiation. The second part is:

SUNRAD(K)*ABSCO3(K)*TRANCO3(K)*REFCO7(K)

The amount of radiation transmitted through the glass is SUNRAD(K)*TRANCO3(K) and part of this is reflected from the second glass layer, if one is present. This flux can be calculated by multiplying by REFCO7(K). By multiplying by ABSCO3(K) the second contribution to the absorbed radiation is calculated. The final part of the expression is:

SUNSOIL(K)*V(9)*COEFF(1)*COEFF(11)

The first two terms of this expression represent the amount of radiation reflected by the floor surface. This radiation is assumed to be diffuse and to strike the underside of the roof at an angle, V(39) set by the user. This is convenient because it allows the absorption reflection and transmission coefficients to be calculated once in one of the initialising subroutines, thus saving computer time. The last two expressions in this line are COEFF(1)*COEFF(11), the transmission coefficient for the diffuse radiation passing through the lower roof and the absorption coefficient for the upper roof respectively. When only a single roof is present then COEFF(1) is set at 1.0 and the lower layer absorption and reflection coefficients are both set at 0.0 A full description of the calculation of the diffuse, reflected radiation routines can be found in the description of the initialisation subroutines.

Returning to the program listing, with a single roof there is of course no need to calculate any second roof absorption or transmission so control of the program jumps to label 405. With a second roof present, then the amounts of radiation absorbed and transmitted are calculated in much the same way as described above with COEFF(5) being the absorption coefficient for the lower roof layer for the diffuse radiation. PHOTRAB(K) is the amount of radiation which is available for the plant to use and has been termed 'photosynthetically active' radiation. It is calculated here as a fraction of the downward flux inside the glasshouse and more will be said about this variable later. Finally, if there is no screen, then control jumps to label 199 in the ventilation section but if there is a screen then a check must be made to see if it is present above the crop or drawn back to the sides of the glasshouse. If it is closed then PHOTRAB(K) and SUNSOIL(K) are both 0.0 W/m^2 as no radiation is allowed through the screen in this model. This is not a bad assumption as the screen is opened and closed very near to sunrise and sunset so any solar radiation will be of a low intensity anyway. With the screen open, control jumps to 199.

SECTION 9 VENTILATOR CONTROL

```
199 IF(TOUR.LT.SUNRISE.OR.TOUR.GT.SUNSET) GO TO 200
    VDELTA=(V(8)-V(7))/C(14)
    VTOPEN(K)=(TEMP15-V(11))/V(12)
    IF(VTOPEN(K).LT.C(13)) VTOPEN(K)=C(13)
    IF(VTOPEN(K).GT.C(14)) VTOPEN(K)=C(14)
    VENT(K)=V(7)+VTOPEN(K)*VDELTA
    GO TO 220
200 VENT(K)=V(7)
    VTOPEN(K)=C(13)
220 CONTINUE
```

Direct heat exchange between the inside and outside air takes place via passive and active ventilation. Passive ventilation can be described as the leakage of air through cracked or broken windows or through gaps between the glass and its glazing bars. With the ventilators open active ventilation occurs. Before sunrise and after sunset the ventilators are kept closed to retain heat so the ventilation rate. VENT(K), is kept at the passive rate, V(7) and the percentage opening of the vents VTOPEN(K), is set at 0.0. During the day the vents open at a temperature set by the user from 0.0 to 100.0 percent over a temperature range dependent upon V(12). In order for the vents to open by an amount equivalent to 1.0 percent the temperature must have increased by V(12) K until VTOPEN(K) has reached 100.0%. If the temperature of the inside air, TEMP15, is less than V(11) the vents stay closed, but if it is greater, then the difference between the two is divided by the temperature increment to give VTOPEN(K). From this set up the range over which ventilation occurs can be calculated. For example, with V(12) = 0.04, to achieve 100 0% opening of the vents the inside air temperature must be 100.0 * 0.04 = 4.0 K above the ventilator opening setting of V(11). V(7) and V(8) are the passive and active ventilation rates respectively, with units of m^3/m^2s and the difference between them divided by 100.0 is called VDELTA. The final rate is calculated as the sum of the passive rate, V(7), and the active component, VTOPEN(K) * VDELTA.

```
SECTION 10 LW RADIATION
RLW1(K)=EMLR(1)*(C(10)*TEMP1**4)*(C(23)+C(24)*SQRT(C(25)*HAO(K)))/V(42)
RLW1(K)=RLW1(K)*(C(6)+V(42))/C(1)
RLW31(K)=EMLR(3)*TEMP3**4*C(10)/V(42)
RLW37(K)=C(10)*(TEMP7**4-TEMP3**4)/(C(6)/EMLR(4)+C(6)/EMLR(7)-C(6))/V(42)
RLW1117(K)=C(10)*(TEMP17**4-TEMP11**4)/(C(6)/0.95+C(6)/EMLR(17)-C(6))
RLW711(K)=C(10)*(TEMP11**4-TEMP7**4)/((C(6)-EMLR(7))/EMLR(7)+
*C(1)/(C(6)+V(42))+((C(6)-EMLR(11))*V(42)/EMLR(11)))
RLW717(K)=C(10)*(TEMP17**4-TEMP7**4)/((C(6)-EMLR(8)/EMLR(8))+
*(C(1)/C(6)+V(42))+(C(6)-EMLR(17))*V(42)/EMLR(17))
RLW311(K)=C(10)*(TEMP11**4-TEMP3**4)/((C(6)-EMLR(4))/EMLR(4)+
*(C(1)/C(6)+V(42))+(C(6)-EMLR(11))*V(42)/EMLR(11))
```

```
      RLW317(K)=C(10)*(TEMP17**4-TEMP3**4)/((C(6)-EMLR(4))/EMLR(4)+
     *(C(1)/(C(6)+V(42)))+(C(6)-EMLR(17))*V(42)/EMLR(17))
```

Long-wave or thermal radiation is emitted from all surfaces of the structure as well as from the sky. This section calculates all of the interactions between the surfaces for such radiation. The systems of equations are different depending on whether or not a thermal screen is present at night. RLW1(K) is radiation from the sky directed downward towards the roof.

RLW31(K) is the radiation from the upper roof surface directed upwards towards the sky. All of the other radiation variables use a standard nomenclature the first number in the variable name indicates the radiation destination and the second shows from which component it originates. This can be confusing in the equations which indicate an overall exchange of radiation between glasshouse surfaces such as RLW711(K). For example the net flux of radiation may be from component 11 to 7 if all the conditions are correct for this but a negative value of RLW711(K) means that the net flow is actually from component 7 to 11. The equations used here for the interaction between the parallel roof surfaces and between the screen and the glasshouse floor can be found in any heat transfer text (e.g. Duffie and Beckman, 1980). The exchanges between the sloping roof and the horizontal floor or screen are described in a different way and a view factor is incorporated. This is defined as the fraction of radiation which leaves one surface and arrives at the second surface and has a value between 0 and 1.

```
      IF(ROOF.EQ.1.0.AND.SCREEN.EQ.0.0) GO TO 412
      IF(ROOF.EQ.2.0.AND.SCREEN.EQ.0.0) GO TO 414
      IF(ROOF.EQ.1.0.AND.SCREEN.EQ.1.0) GO TO 416
      IF(ROOF.EQ.2.0.AND.SCREEN.EQ.1.0) GO TO 417
  412 RLW37(K)=0.0
      RLW311(K)=0.0
      RLW711(K)=0.0
      RLW717(K)=0.0
      RLW1117(K)=0.0
```

```
      GO TO 418
  414 RLW711(K)=0.0
      RLW311(K)=0.0
      RLW317(K)=0.0
      RLW1117(K)=0.0
      GO TO 418
  416 IF(TOUR.GT.SCROPEN.AND.TOUR.LT.SCRDRAW) GO TO 412
      RLW37(K)=0.0
      RLW317(K)=RLW317(K)*V(34)
      RLW711(K)=0.0
      RLW717(K)=0.0
      GO TO 418
  417 IF(TOUR.GT.SCROPEN.AND.TOUR.LT.SCRDRAW) GO TO 414
      RLW311(K)=0.0
      RLW317(K)=0.0
      RLW717(K)=RLW717(K)*V(34)
  418 CONTINUE
```

There are several different combinations of screen and roof which can be used in the model and each of these will give a different set of long-wave radiation equations. The four tests on SCREEN and ROOF decide what combination is present and then set the appropriate long-wave interactions to 0.0. For example, without a screen during the day, there will be no long-wave interaction between a screen and the floor so RLW1117(K)=0.0. If the thermal screen is present at night there may be some longwave exchange through it if its transmissivity, V(34), to such radiation is non-zero. Because of this, there are alterations in both of the screened sections which make allowance for this.

```
      HMSAT15(K)=C(26)*EXP(C(27)*(TEMP15-C(15))/(TEMP15-C(28)))/TEMP15
      IF(PHOTRAB(K).LE.V(21)) RES=V(18)
      IF(PHOTRAB(K).GT.V(21).AND.PHOTRAB(K).LT.C(14)) RES=V(18)-
     *V(20)*(PHOTRAB(K)-V(21))
      IF(PHOTRAB(K).GE.C(14)) RES=V(19)
      TLEAF=TEMP15+V(37)
```

```
      HMSATLF=C(26)*EXP(C(27)*(TLEAF-C(15))/(TLEAF-C(28)))/TLEAF
      R(K)=RES(K)+V(25)
      HUMDIF=HMSATLF-HAI
      IF(HUMDIF LT C(13)) HUMDIF=C(13)
      EVAPHT(K)=(C(33)-C(34)*(TEMP15-C(15)))*(HMSAT15(K)-
     *HAI)/R(K)*V(43)
      IF(EVAPHT(K).LT.0.0) EVAPHT(K)=0.0
```

The last part of this section deals with the evaporation of water from the leaves in the crop. HMSAT15(K) is the humidity of saturation of the inside air at its temperature of TEMP15 and RES is a part of the resistance to water flow from the leaf to the air. The resistance varies with the opening and closing of the stomata which, in turn, depends upon the amount of photosynthetically active radiation present. In this example Van Bavel's (1979) values are used and under low radiation conditions RES becomes V(18), 5000.0 s/m. Between radiation values of 10.0 and 100.0 W/m^2 the resistance is calculated from the expression:

RES=V(18)-V(20)*(PHOTRAB(K)-V(21))

At radiation levels above C(14), 100.0 W/m^2, the stomata are assumed to be fully open and the resistance is at a minimum, V(19) s/m. The leaf temperature, TLEAF, is assumed to follow the same curve as the inside air temperature but its actual value with respect to TEMP15 depends on V(37), the temperature difference set by the user. HMSATLF is the humidity of saturation at the leaf temperature and R(K) is the leaf's resistance to water flow across its surface comprising RES plus a constant value of 333.0 s/m. EVAPHT(K) is the amount of energy lost from the leaf or inside air due to latent heat flow. This is dependent upon the air temperature, the humidity of the air with respect to the humidity of saturation of the air and the resistance to flow. The final line ensures that EVAPHT(K) never falls below 0.0

SECTION 11 THERMAL SCREEN EQUATIONS

```
      IF(SCREEN.EQ.0.0) GO TO 500
      IF(TOUR.GT.SCROPEN.AND.TOUR.LT.SCRDRAW) GO TO 440
  420 HV9=V(38)*(TEMP9-TEMP1)*HEATCAP(9)*VENT(K)*V(5)
      BAL9(K)=-HV9
      TEMP5=(TEMP3+TEMP7)/C(1)
      IF(ROOF.EQ.1.0) GO TO 425
      RAD17(K)=SUNSOIL(K)-RLW1117(K)-RLW717(K)*V(34)
      RAD3(K)=RLW1(K)*EMLR(3)-RLW31(K)+RLW37(K)
      RAD7(K)=RLW711(K)-RLW37(K)+RLW717(K)*V(34)
      RAD11(K)=RLW1117(K)-RLW711(K)
      TEMP3T=TRI(3)*(CHT(2)*(TEMP1-TEMP3)-CHT(4)*(TEMP3-TEMP5)+
     *RAD3(K))
      TEMP7T=TRI(7)*(CHT(6)*(TEMP5-TEMP7)-CHT(8)*(TEMP7-TEMP9)+
     *RAD7(K))
      TEMP9T=TRI(9)*(CHT(8)*(TEMP7-TEMP9)-CHT(10)*(TEMP9-TEMP11)+
     *BAL9(K))
      GO TO 445
  425 RAD3(K)=RLW1(K)*EMLR(3)-RLW31(K)+RLW311(K)+RLW317(K)*V(34)
      RAD17(K)=SUNSOIL(K)-RLW1117(K)-RLW317(K)*V(34)
      RAD11(K)=RLW1117(K)-RLW311(K)
      TEMP5=0.0
      TEMP7=0.0
      TEMP9T=TRI(9)*(CHT(9)*(TEMP3-TEMP9)-CHT(10)*(TEMP9-TEMP11)+
     *BAL9(K))
      TEMP3T=TRI(3)*(CHT(2)*(TEMP1-TEMP3)-CHT(9)*(TEMP3-TEMP9)+
     *RAD(3))
      RAD7(K)=0.0
  445 CONTINUE
```

Previous sections have calculated and set variables required by FORSIM and UPDATE in the integration stages. This section is the first of the integration stages and deals with the times when a thermal screen is present. The first line of this section is a check on the presence or absence of a screen, if no screen is present there is no need to execute this section and the program jumps to label 990. HV9 is the heat lost from the upper, inside air layer by ventilation and the storage array for this is BAL9(K) (note the sign change with " - " indicating a loss from the inside air to the outside). TEMP5 is the temperature of the air gap between the upper and lower roof layers and is taken to be the average temperature of the two roof layers. This was done for the sake of efficiency because in practice, this air gap is small (1 cm) and so calculations that FORSIM tries to carry out over reasonably long time steps may produce results for this air gap temperature which fall outside the error limits. That stage would have to be repeated again and again until the value of TEMP5 was acceptable. This, in itself, would probably not be too wasteful were it not for the fact that all the other variables and temperatures would have to be recalculated as well, even though they may well have been acceptable the first time around.

After this the program branches into two paths, one which deals with a double glazed roof and the other which handles a single glazed roof. If there is double glazing, the program continues by calculating the RAD variables which are radiation balances on the components. For example, RAD11 is the long wave radiation balance on the thermal screen which undergoes exchange with the roof above it and with the floor beneath it. RAD17(K) is the radiation balance on the floor surface and includes SUNSOIL(K) even though no solar radiation is allowed through the screen when it is over the crop. It is included so that the calculation could be changed in the future to allow some radiation through the screen to simulate shaded structures for example. The next line is the first of the derivative equations and it will be described in some detail to serve as an example of the other derivatives which have the same form.

The change in TEMP3 can be considered by looking at the energy exchanges between component 3 and the component above (the outside air), and the one below (the air gap in a double glazed structure). The CHT variables are coefficients of heat transfer between components, for example CHT(2) is the coefficient of heat transfer between components 1 and 3 and is a convective transfer coefficient in this case. These coefficients are set by the user in the initialisation subroutines before integration begins and have units of W/m^2K. When these are multiplied by the temperature difference between components the result is a power exchange per square metre. In the TEMP3T equation there are two of these terms which represent exchanges between the roof and the outside air, and between the roof and the air gap as shown below:

CHT(2) * (TEMP1-TEMP3)

CHT(4) * (TEMP3-TEMP5)

When TEMP1 is less than TEMP3 we get a loss from the roof to the outside air and when TEMP5 is greater than TEMP3 the roof gains energy from the air gap. The net gain depends upon the values of the CHT coefficients and upon the temperature differences between the components. RAD3 the longwave radiation balance for 3 is added to this net gain (it also has units of W/m^2). This sum is then multiplied by the temperature rise index, TRI(3), which has units of $K/(W/m^2)FS$ and this variable requires explanation. As TEMP3T is the derivative of TEMP3 it represents the temperature change in component 3 with time. This is calculated by considering the temperature change per unit of energy available to the component. The power is in W/m^2 and can be re-written as J/sm^2 with seconds being real time. However, FORSIM works in FS and there needs to be some correction factor to change FORSIM time to real time. This correction is contained within the TRI coefficient and is:

8640 0 * DAYS s/FS

thus, if DAYS = 1.0 then 1 FS corresponds to 8640.0 real seconds and if DAYS = 2.0 then 1 FS represents 17280.0 real seconds. TEMP3T is calculated as the change in temperature due to the energy flow per FORSIM SECOND which is a multiple of 8640.0 real seconds depending on the number of days being simulated. For example, if TEMP3T has a value of 86.4 at a given time during a run of one day, this means that the temperature would rise by 86.4 K during one FS but the temperature rise in one real second would be:

86.4 / 8640.0 = 0.01 K.

TEMP7T and TEMP9T are calculated in a similar way except that TEMP9T does not have a radiation balance component since it is an air layer although it does have a ventilation heat exchange one, BAL(9). The program then jumps to label 445. The single glazing routine is very like the double glazing one and begins at label 425, but the absence of the lower roof and air gap means that heat exchange takes place between different components. For convenience the temperatures of components 5 and 7 are set to 0.0 K and RAD7(K) is set at 0.0 W/m^2 if this pathway is followed.

```
      TEMP11T=TRI(11)*(CHT(10)*(TEMP9-TEMP11)-CHT(12)*(TEMP11-TEMP13)+RAD11(K))
      HV13=V(38)*(TEMP13-TEMP1)*HEATCAP(13)*VENT(K)*V(6)
      HV(K)=HV9+HV13
      IF(TEMP13.GT.V(22)+V(41)) GO TO 447
      IF(HEATER.EQ.0.0) GO TO 447
      HTPWR(K)=CHT(12)*(TEMP13-TEMP11)+CHT(14)*(TEMP13-TEMP17)+
     *HV13+(V(22)-TEMP13)*THICK(13)*HEATCAP(13)*DENSITY(13)/V(23)+EVAPHT(K)
      IF(HTPWR(K).LT.0.0) GO TO 447
      GO TO 448
  447 HTPWR(K)=0.0
  448 BAL13(K)=-HV13
      TEMP13T=TRI(13)*(CHT(12)*(TEMP11-TEMP13)-CHT(14)*
     *(TEMP13-TEMP17)+BAL13(K)+HTPWR(K)-EVAPHT(K))
      BAL17(K)=RAD17(K)
      TEMP17T=TRI(17)*(CHT(14)*(TEMP13-TEMP17)-CHT(18)*
     *(TEMP17-TEMP19)+BAL17(K))
      HAIT=C(2)*DAYS*(((HUMDIF*V(43))/R(K))-V(38)*(HAI
     *-HAO(K))*VENT(K)*V(6))/THICK(9)
      TEMP15T=0.0
      TEMP15=TEMP13
      HV15=0.0
      BAL15(K)=0.0
      GO TO 460
```

TEMP11T is the change in temperature of the thermal screen and this is handled in the same way as the roof temperatures by considering the temperature difference between the screen and the air components above and below it, including the net long-wave radiation incident upon it. HV13 is the heat exchange due to ventilation between the lower air layer and the outside air. More ventilative exchange occurs between the upper air layer and the outside air than between the lower air layer and the outside air and the fractions of each can be set using the V(5) and V(6) variables. HV(K) is the storage array name for the total heat exchange due to ventilation.

Heat can be provided to the inside air by a system designed to give exactly that amount of heat needed to maintain the given heating set-point temperatures. If the inside air temperature is above the set point temperature (plus a small increment) then the heater is switched off and the heater power calculations are not carried out. The amount of heat added is calculated so that it has a value equal to the losses from the lower air layer plus any extra heat needed to ensure that the blueprint temperature is adhered to BAL13(K) is a variable similar to BAL9(K) acting as a store for HV13. Having completed these calculations, TEMP13T can now be calculated in the same way as TEMP9T including the heating. TEMP17T is the temperature change for the top floor layer and heat exchange is by convection to the air, by radiation to whichever surface is above it and by conduction to the soil beneath it.

HAIT is the rate of change of inside air humidity and is calculated for the lower air layer when the screen is over the crop. The amount of moisture in the air is measured in kg/m^3 and so the rate of change of this must be kg/m^3s As before the rate must be per FORSIM SECOND and the conversion occurs after multiplying by 86400 * DAYS. The amount of water evaporated into the air depends upon the difference between the humidity of saturation at the leaf temperature and the inside air humidity divided by the resistance to water evaporation. This gives units of:

$$kg/m^3 * m/s = kg/m^2s$$

There is also exchange between the inside and outside air via ventilation which gives rise to a change in humidity. The exchange depends upon the difference in humidities between the inside and outside air and the ventilation rate. This ventilation rate is in m^3/m^2s which gives us the same units as above when multiplied by the humidity difference. At this point the evaporation is per square metre and to change it to a volume measure it must be divided by the thickness of the air layer. In other words, all the water which is evaporated from the square metre is evenly distributed in the volume directly above.

When there is no screen present during daylight hours for example, the inside air is component 15 which replaces both component 9 and 13 and although it has no meaning when a screen is present, TEMP15T must be assigned a value to satisfy FORSIM. Here it is merely set to 0.0 and TEMP15 is given a value equal to the value of the lower air layer temperature. HV15 and BAL15(K) are set equal to 0.0 as they too have no meaning when the screen is in position but must be given values for storage reasons.

SECTION 12 MIXING OF THE AIR LAYERS

```
 440 IF(SCREEN.EQ.0.0) GO TO 500
     RAD11(K)=0.0
     DELTAC=(TEMP13-TEMP9)
     TIMERSC=SUNRI10-TOUR
     IF(TOUR.GT.SUNRI10) GO TO 500
     DELTEMT=DELTAC*(SIN((C(6)-(C(31)/V(16)*(SUNRI10-TOUR)
    */TDAY))*PI/C(1)+PI)+C(6))
     TEMINCR=DELTEMT/C(1)*V(24)*DAYS
```

At such times when a thermal screen is in position over the crop, there are two separate layers of air inside the glasshouse. These are components 9 and 13 in the model and have different temperatures. Upon the removal of the screen these two air layers undergo mixing and the result is a single air layer, component 15, of uniform temperature. This section handles the mixing of the two air layers in a fixed time.

With the removal of the thermal screen component 11 RAD11 is set at 0.0 W/m^2. DELTAC is the temperature difference between the upper and lower air layers and TIMERSC is the length of time between TOUR, the present time, and SUNRI10, the time at which mixing must be complete. The IF test checks on the current time and if the screen is still in place, or, if mixing is now complete. then there is no need to execute this section and the program jumps to label 500. If the time is such that the model is still in the mixing section, then the next stage is to calculate the temperature changes of each layer due to the mixing. The mixing takes place over a number of minutes set by the user ten in this example, and this has to be converted to FORSIM time. The mixing occurs over a section of a sine curve, between Pi and 3Pi / 2 with most of the mixing occurring at the beginning of the time period when the temperature difference is greatest. It does not matter if the actual mixing pathway is sinusoidal or exponential because the only reason for including it and not allowing the program merely to average the two temperatures is that FORSIM handles smooth changes more efficiently than sharp ones. DELTAC is multiplied by a number between 1 and 0, 1 at the beginning of the period and 0 at the end. As an example of this with TDAY = 10.0 SUNRISE = 2.5 and given that the screen is opened at SUNRISE, if TOUR is also 2.5 (FS) we get -

```
DELTEMT = DELTAC * (SIN((1-(1440/10*(2.5+10/1440-2.5)/10))*Pi/2+Pi)+1)
        = DELTAC * (SIN((1-(144*(1/144))*Pi/2+Pi)+1)
        = DELTAC * (SIN((1-1)*Pi/2+Pi)+1)
        = DELTAC * (SIN(Pi)+1)
        = DELTAC
```

At the end of the mixing time TOUR = SUNRI10 (SUNRISE + V(16) in FS) and the result becomes -

```
DELTEMT = DELTAC * (SIN((1-(1440/10*(0)/10))*Pi/2+Pi)+1)
        = DELTAC * (SIN((1-0)*PI/2+PI)+1)
        = DELTAC * (SIN(3PI/2)+1)
        = 0
```

This temperature change has to be handled by the derivative equation so the number passed on must represent the rate of temperature change per FORSIM second.

```
HV9=V(38)*(TEMP9-TEMP1)*HEATCAP(9)*VENT(K)*V(5)
BAL9(K)=-HV9
HV13=V(38)*(TEMP13-TEMP1)*HEATCAP(13)*VENT(K)*V(6)
BAL13(K)=-HV13
```

```
HV(K)=HV9+HV13
```

As in the previous section, whilst there are two distinct air layers at different temperatures, the heat lost from each one due to ventilation is calculated separately. HV9 is the heat lost from the upper layer, component 9, and HV13 is the heat lost from the lower layer, 13.

```
IF(ROOF.EQ.1.0) GO TO 450
RAD3=RLW1(K)*EMLR(3)-RLW31(K)+RLW37(K)+ABSRAD3(K)
RAD7(K)=RLW717(K)-RLW37(K)+ABSRAD7(K)
RAD17(K)=SUNSOIL(K)-RLW717(K)
TEMP5=(TEMP3+TEMP7)/C(1)
TEMP3T=TRI(3)*(CHT(2)*(TEMP1-TEMP3)-CHT(4)*(TEMP3-TEMP5)+
*RAD3(K))
TEMP7T=TRI(7)*(CHT(6)*(TEMP5-TEMP7)-CHT(8)*(TEMP7-TEMP9)+
*RAD7(K))
TEMP9T=TRI(9)*(CHT(8)*(TEMP7-TEMP9)+BAL9(K)+TEMINCR
GO TO 455
```

These equations handle the temperature changes in the roof and air layers when the roof is double glazed. If it is single glazed the program jumps to label 450. RAD3(K) is the net radiation which contributes to the heating of layer 3 and, as before, it contains the net long-wave radiation exchanges between the upper roof surface and the sky and between the two roofs themselves. The solar gain is in the form of absorbed solar radiation. ABSRAD3(K) RAD7(K) represents the same thing except for the lower roof layer. Again, there is a contribution from absorbed solar radiation RAD17(K) comprises the absorbed solar shortwave radiation SUNSOIL(K) and the exchange between the floor and the roof. Once again TEMP5 is set as the average temperature between the two roofs and as before, TEMP3T and TEMP7T describe the change in temperature (in one FORSIM second) due to the energy flows TEMP9T is, as expected different in this case. Part of the temperature change depends upon the flow of heat between the lower roof layer component 7, and the upper air and the flux due to ventilation. The remainder is due to TEMINCR the gain arising from the mixing of the air layers. Upon completion of these routines the program jumps to label 455.

```
 450 RAD3(K)=RLW1(K)*EMLR(3)-RLW31(K)+RLW317(K)+ABSRAD3(K)
     RAD7(K)=0.0
     RAD17(K)=SUNSOIL(K)-RLW317(K)
     TEMP5=0.0
     TEMP7T=0.0
     TEMP9T=TRI(9)*(CHT(9)*(TEMP3-TEMP9)+BAL9(K)+TEMINCR
     TEMP3T=TRI(3)*(CHT(2)*(TEMP1-TEMP3)-CHT(9)*
    *(TEMP3-TEMP9)+RAD3(K))
     JM=JM+1
 455 CONTINUE
```

For the single glazed roof the equations are slightly different as there is no lower roof layer or air gap present. The equations are similar to those found in the preceding sections, with TEMP9T gaining heat due to the mixing of the air layers, TEMINCR JM is a counter used to see how many times this section is executed.

```
     IF(TEMP13.GT.V(22)+V(41)) GO TO 457
     IF(HEATER.EQ.0.0) GO TO 457
     HTPWR(K)=CHT(14)*(TEMP13-TEMP17)+HV13+TEMINCR/TRI(13)+(V(22)-
    *TEMP13)*THICK(13)*HEATCAP(13)*DENSITY(13)/V(23)+EVAPHT(K)
     IF(HTPWR(K).LT.0.0) GO TO 457
     GO TO 456
 457 HTPWR(K)=0.0
```

The heater power is calculated as before by summing the heat losses from the inside air and considering the difference between the actual temperature and the required temperature.

```
 456 TEMP13T=TRI(13)*(-CHT(14)*(TEMP13-TEMP17)+BAL13(K)+HTPWR(K)-
    *EVAPHT(K)-TEMINCR
```

```
      TEMP11T=0.0
      BAL17(K)=RAD17(K)
      TEMP17T=TRI(17)*(CHT(14)*(TEMP13-TEMP17)-CHT(18)*
     *(TEMP17-TEMP19)+BAL17(K))
      TEMP11=TEMP13
      HAIT=C(2)*DAYS*(((HUMDIF*V(43))-V(38)*(HAI-HAO(K))*VENT(K))
      TEMP15T=0.0
      TEMP15=TEMP13
      HV15(K)=V(38)*(TEMP15-TEMP1)*HEATCAP(15)*VENT(K)
      BAL15(K)=0.0
      GO TO 460
```

TEMP13T is calculated as before, except the exchange with the upper air is passed to the equation as -TEMINCR. TEMP17T is calculated as the exchange with the air and the lower soil layer and HAIT the inside air humidity, is calculated as before. TEMP15T is set at 0.0 and TEMP15 is set equal to TEMP13 so that when TEMP15 does have to be calculated at later times, then FORSIM will not have too much difficulty in bringing it up to its correct value from some arbitrary level.

SECTION 13 EQUATIONS FOR SYSTEM WITHOUT SCREEN (DAYTIME)

```
  500 CONTINUE
      BAL13(K)=0.0
      HV15=V(38)*(TEMP15-TEMP1)*HEATCAP(15)*VENT(K)
      BAL15(K)=-HV15-EVAPHT(K)
      IF(ROOF.EQ.1.0) GO TO 471
      C3Y=CHT(7)
      TEMPY=TEMP7
      GO TO 472
  471 C3Y=CHT(5)
      TEMPY=TEMP3
  472 IF(TEMP15.GT.V(22)+V(41)) GO TO 481
      IF(HEATER.EQ.0.0) GO TO 481
      HTPWR(K)=C3Y*(TEMP15-TEMPY)+CHT(16)*(TEMP15-TEMP17)+HV15
```

```
      *+(V(22)-TEMP13)*THICK(13)*HEATCAP(15)*DENSITY(15)/V(23)+EVAPHT(K)
      IF(HTPWR(K) LT 0 0) GO TO 481
      GO TO 482
  481 HTPWR(K)=0.0
```

During daylight hours the thermal screen is removed from its position over the crop and rolled up at the side of the glasshouse. This section deals with the equations for the structure during the day and here the inside air is considered to be one whole component of uniform temperature. Any loss due to ventilation now occurs from component 15. BAL13(K) is set to 0.0 and BAL15(K) is the storage array for this loss as well as the loss due to evaporation and transpiration from the plants. Once again, the program can follow two pathways depending upon the number of roofs present. C3Y is a variable that takes the value of CHT(7) when there are two roofs, and CHT(5) when there is only one. Similarly TEMPY takes on the value of either TEMP7 or TEMP3. The value of HTPWR(K) as before and the use of the variables C3Y and TEMPY in this section saves computer time and space as only one expression of HTPWR(K) is required. If the inside air temperature is above the set point temperature, then the heating is cut to 0.0 W/m^2. If the temperature becomes too high, the ventilators open and heat is lost via ventilation. The heating system cannot be used as a cooling system in this example of the model, although it could be altered to be used as such.

```
  482 HV(K)=HV15
      RAD11(K)=0.0
      BAL9(K)=0.0
      TEMP9T=0.0
      TEMP11T=0.0
      TEMP13T=0.0
      IF(ROOF.EQ.1.0) GO TO 480
      RAD3(K)=RLW1(K)*EMLR(3)-RLW31(K)+ABSRAD3(K)+RLW37(K)
      RAD7(K)=RLW717(K)-RLW37(K)+ABSRAD7(K)
      RAD17(K)=SUNSOIL(K)-RLW717(K)
      TEMP5=(TEMP3+TEMP7)/C(1)
      TEMP3T=TRI(3)*(CHT(2)*(TEMP1-TEMP3)-CHT(4)*(TEMP3-TEMP5)+RAD3(K))
```

```
      TEMP7T=TRI(7)*(CHT(6)*(TEMP5-TEMP7)-CHT(7)*(TEMP7-TEMP15)+RAD7(K))
      TEMP15T=TRI(15)*(CHT(7)*(TEMP7-TEMP15)-CHT(16)*
     *(TEMP15-TEMP17)+BAL15(K)+HTPWR(K))
      GO TO 485
  480 RAD3(K)=RLW1(K)*EMLR(3)-RLW31(K)+RLW317(K)+ABSRAD3(K)
      RAD17(K)=SUNSOIL(K)-RLW317(K)
      RAD7(K)=0.0
      TEMP3T=TRI(3)*(CHT(2)*(TEMP1-TEMP3)-CHT(5)*(TEMP3-TEMP15)+RAD3(K))
      TEMP5=0.0
      TEMP7T=0.0
      TEMP15T=TRI(15)*(CHT(5)*(TEMP3-TEMP15)-CHT(16)*
     *(TEMP15-TEMP17)+BAL15(K)+HTPWR(K))
  485 CONTINUE
      BAL17(K)=RAD17(K)
      TEMP17T=TRI(17)*(CHT(16)*(TEMP15-TEMP17)-CHT(18)*
     *(TEMP17-TEMP19)+BAL17(K))
      TEMP9=TEMP15
      TEMP11=TEMP15
      TEMP13=TEMP15
      HAIT=C(2)*DAYS*((HUMDIF*V(43))/R(K))-V(38)*(HAI-HAO(K))*VENT(K))
  460 CONTINUE
```

With the screen withdrawn several of the components play no active part in the thermal 'picture' and have to be assigned values. RAD11(K), the net radiation flux on the thermal screen, is set to 0.0 as is BAL9(K) the heat lost from the upper air layer due to ventilation. The DERIVT variables TEMP9T, TEMP11T and TEMP13T are all set to 0.0 as there is now no upper and lower air layer but a single one, component 15. Once again there are two similar sections which follow, one dealing with the double glazed case and the other dealing with the single glazed case. These two sets of routines are in fact the same as those found in section 12, the air mixing section and will not be described again here.

Finally in this section, TEMP17T and HAIT, the rates of change of floor temperature and inside air humidity respectively, are calculated and the now redundant components are assigned the same temperature as the inside air.

SECTION 14 EQUATIONS FOR LOWER SOIL LAYERS

```
HEATINT=C(2)*DAYS*HTPWR(K)/V(27)
TEMP19T=TRI(19)*(CHT(18)*(TEMP17-TEMP19)-CHT(20)*(TEMP19-TEMP21))
TEMP21T=TRI(21)*(CHT(20)*(TEMP19-TEMP21)-CHT(22)*(TEMP21-TEMP23))
TEMP23T=TRI(23)*(CHT(22)*(TEMP21-TEMP23)-CHT(24)*(TEMP23-TEMP25))
TEMP25T=TRI(25)*(CHT(24)*(TEMP23-TEMP25)-CHT(26)*(TEMP25-TEMP27))
TEMP27T=TRI(27)*(CHT(26)*(TEMP25-TEMP27)-CHT(28)*(TEMP27-V(10)))
```

The lower soil layers exchange heat with each other in the same way no matter what time of the day it happens to be and consequently these equations remain the same throughout the run. The soil beneath the bottom soil layer, component 27, is assumed to have a constant temperature which can be set by the user as V(10). In order to measure the amount of heating supplied by the heater to the inside air, another variable HEATINT, is defined. FORSIM handles this in the same way as the temperature change variables by setting the change in the heater input equal to the current heater power divided by a large number, V(27), to scale down the large steps which might occur in HTPWR(K). In practice, V(27) is 10^6 which converts the heating values to mega-Joules.

SECTION 15 ...ECONOMY PACKAGE

```
TEMP5T=0.0
NUMBERA=NUMBER(1)+1.0
NUMBER(1)=NUMBERA
TTOTA=TTOT(1)+DT
TTOT(1)=TTOTA
DERIV(2)=TEMP3T
DERIV(3)=TEMP5T
DERIV(4)=TEMP7T
DERIV(5)=TEMP9T
DERIV(6)=TEMP11T
```

```
      DERIV(7)=TEMP13T
      DERIV(8)=TEMP15T
      DERIV(9)=TEMP17T
      DERIV(10)=TEMP19T
      DERIV(11)=TEMP21T
      DERIV(12)=TEMP23T
      DERIV(13)=TEMP25T
      DERIV(14)=TEMP27T
      DERIV(15)=HAIT
      DERIV(16)=HEATINT
      DO 735 JTEST=2,16
      IF(ABS(DERIV(JTEST)).GT.ABS(DERVAL(JTEST,1))) GO TO 805
      IF(ABS(DERIV(JTEST)).LT.ABS(DERVAL(JTEST,2))) GO TO 815
      GO TO 735
  805 DERVAL(JTEST,1)=DERIV(JTEST)
      TM(JTEST,1)=T
      DTM(JTEST,1)=DT
      GO TO 745
  815 DERVAL(JTEST,2)=DERIV(JTEST)
      TM(JTEST,2)=T
      DTM(JTEST,2)=DT
  735 CONTINUE
```

In the development of the program it was important to keep some check on the efficiency with which it was running. This economy package records when the maximum and minimum values of the derivatives occur and their values at those times, and by printing out this record it can be seen which derivatives are causing FORSIM to work hardest. The lines involving NUMBERA and NUMBER(1) record how many times FORSIM has called UPDATE (anything up to about 100,000 times). Each time this section is executed the DERIV variables are equated to the derivatives and then tests are performed on each to see if the new value is greater than the previous maximum value or less than the previous minimum value. If either of these conditions is satisfied then the new value replaces the stored one and the time, T, and step length, DT, are recorded also. A very large positive or negative value of a derivative, coupled with a small value of DT, would indicate that FORSIM had difficulty with the equation in question, possibly due to a sharp change in the parameters affecting that component. It is at such times that the program uses more computer time and any "smoothing out" of problem areas which can be done improves the efficiency.

SECTION 16 INSTANTANEOUS HEAT STORAGE

```
      HSTOR1(K)=(HEATCAP(1)*DENSITY(1)*(TEMP1-C(15))+(C(33)-C(34)*
     *(TEMP1-C(15)))*HAO(K))/C(3)
      HSTOR3(K)=DENSITY(3)*THICK(3)*HEATCAP(3)*(TEMP3-C(15))/C(3)
      IF(ROOF.EQ.1.0) GO TO 515
      HSTOR7(K)=DENSITY(7)*THICK(7)*HEATCAP(7)*(TEMP7-C(15))/C(3)
      HSTOR5(K)=(HEATCAP(5)*THICK(5)*(TEMP5-C(15))+
     *(C(33)-C(34)*(TEMP5-C(15)))*HAO(K))/C(3)
      GO TO 516
  515 HSTOR7(K)=0.0
      HSTOR5(K)=0.0
```

Each component of the glasshouse acts as a heat store but the amount of energy stored depends upon the physical characteristics and dimensions of the component. The amount of energy stored in each component by virtue of its temperature is calculated with respect to 273.16 K. In other words, the energy stored in component 3 is calculated as the energy stored due to TEMP3 less the energy stored at 273 16 K for the same component. Slight amendment to this would allow the values to be printed out as kJ/°C or whatever units would suit the user.

HSTOR1(K) is the energy stored in the outside air and is calculated as the heat capacity of component 1, HEATCAP(1), multiplied by the temperature difference TEMP1 - C(15) where C(15) = 273.16 K. The second part of the expression is concerned with the amount of latent heat present in the air and is dependent upon the outside air humidity. The expression C(33) - C(35) * (TEMP1 - C(15)) is the latent heat of vaporisation of water at temperature (TEMP1 - 273.16) K. This result is in units of J/kg and when multiplied by the outside air humidity, in kg/m^3, gives the latent heat stored in units of J/m^3. The final division by C(3) merely changes the units from Joules to kilo-Joules. The heat stored in the roof is calculated by multiplying the density, thickness, heat capacity and the temperature of the roof. The units of this are:

$$kg/m^3 * m * J/kgK * K = J/m^2$$

In fact the thickness measure can be taken as a volume because we are always considering a representative square metre in the middle of a glasshouse array. Taking this into account gives the heat stored in Joules. If the roof is single glazed then there is no energy stored in either an air gap or in a second roof layer but if there is double glazing, then the heat stored in the second layer is calculated in exactly the same way, using the appropriate values.

```
516 IF(TOUR.LE.SCROPEN.OR.TOUR.GE.SCRDRAW) GO TO 520
    GO TO 540
520 IF(SCREEN.EQ.0.0) GO TO 540
    HSTOR9(K)=(HEATCAP(9)*DENSITY(9)*THICK(9)*(TEMP9-C(15))+
   *(C(33)-C(34)*(TEMP9-C(15)))*HAI)/C(3)
    HSTOR13(K)=(HEATCAP(13)*THICK(13)*(TEMP13-C(15))+
   *(C(33)-C(34)*(TEMP13-C(15)))*HAI)/C(3)
    HSTOR15(K)=0.0
    GO TO 560
540 HSTOR15(K)=(HEATCAP(15)*THICK(15)*(TEMP15-C(15))+
   *(C(33)-C(34)*(TEMP15-C(15)))*HAI)/C(3)
    HSTOR9(K)=0.0
    HSTOR13(K)=0.0
560 HSTAIR(K)=HSTOR9(K)+HSTOR13(K)+HSTOR15(K)
```

With a screen present there are two distinct air layers, 9 and 13 but without the screen there is only one layer, 15. The heat stored in the inside air is calculated depending upon the presence of the screen and a total inside air heat storage variable, HSTAIR(K), is set as the sum of HSTOR9(K), HSTOR13(K) and HSTOR15(K). In practice this is always either HSTOR9(K) + HSTOR13(K) or HSTOR15(K) alone.

```
      HSTOR11(K)=DENSITY(11)*THICK(11)*HEATCAP(11)*
     *(TEMP11-C(15))/C(3)
      IF(SCREEN.EQ.0.0) HSTOR11(K)=0.0
      HSTOR17(K)=HEATCAP(17)*THICK(17)*(TEMP17-C(15))*DENSITY(17)/C(3)
      HSTOR19(K)=HEATCAP(19)*THICK(19)*(TEMP19-C(15))*DENSITY(19)/C(3)
      HSTOR21(K)=HEATCAP(21)*THICK(21)*(TEMP21-C(15))*DENSITY(21)/C(3)
      HSTOR23(K)=HEATCAP(23)*THICK(23)*(TEMP23-C(15))*DENSITY(23)/C(3)
      HSTOR25(K)=HEATCAP(25)*THICK(25)*(TEMP25-C(15))*DENSITY(25)/C(3)
      HSTOR27(K)=HEATCAP(27)*THICK(27)*(TEMP27-C(15))*DENSITY(27)/C(3)
      HSTORE(K)=HSTORE3(K)+HSTOR5(K)+HSTOR7(K)++HSTOR11(K)+HSTOR17(K)+
     *HSTOR19(K)+HSTOR21(K)+HSTOR23(K)+HSTOR25(K)+HSTOR27(K)+HSTAIR(K)
```

The screen heat storage is calculated throughout the day since it is still in the glasshouse even if it is not over the crop and it still has a temperature heat capacity and thickness etc. In the complete absence of a screen HSTOR11(K)is set to 0.0 although another way to accomplish this without including this extra line would be to set the screen thickness to 0.0 in the initialisation routine. The next lines calculate the heat stored in the soil layers and the equations are of the same form as the roof layer ones. Finally, a total heat storage variable is calculated, containing all the variables within the glasshouse structure.

SECTION 17 RELATIVE HUMIDITY CALCULATIONS

```
      IF(SCREEN EQ.0.0) GO TO 593
      IF(TOUR.LT.SCROPEN.OR.TOUR.GT.SCRDRAW) GO TO 590
  593 HMSAT11(K)=0.0
      RELHU11(K)=0.0
      GO TO 595
  590 HMSAT11(K)=C(26)*EXP(C(27)*(TEMP11-C(15))/(TEMP11-C(28)))/TEMP11
      RELHU11(K)=HAI/HMSAT11(K)*C(14)
```

```
595 IF(ROOF.EQ.1.0) GO TO 600
    HMSAT7(K)=C(26)*EXP(C(27)*(TEMP7-C(15))/(TEMP7-C(28)))/TEMP7
    IF(SCREEN.EQ.0.0) GO TO 598
    IF(TOUR.GT.SCROPEN.AND.TOUR.LT.SCRDRAW) GO TO 598
    HUMROOF(K)=HAI/HMSAT7(K)*C(14)/V(28)
    GO TO 599
598 HUMROOF(K)=HAI/HMSAT7(K)*C(14)
599 HMSAT3(K)=0.0
    GO TO 610
600 HMSAT7(K)=0.0
    HMSAT3(K)=C(26)*EXP(C(27)*(TEMP3-C(15))/(TEMP3-C(28)))/TEMP3
    IF(SCREEN.EQ.0.0) GO TO 605
    IF(TOUR.GT.SCROPEN.AND.TOUR.LT.SCRDRAW) GO TO 605
    HUMROOF(K)=HAI/HMSAT3(K)*C(14)/V(28)
    GO TO 610
605 HUMROOF(K)=HAI/HMSAT3(K)*C(14)
610 RELHU15(K)=HAI/HMSAT15(K)*C(14)
```

This section is designed to detect the presence of condensation on any of the component surfaces. The first line checks on the status of the screen and if there is no screen, then the humidity of saturation at the screen temperature and the corresponding relative humidity are both set to 0.0. For the doubled glazed roof the humidity of saturation at the lower roof temperature is calculated and the relative humidity at this temperature, HUMROOF(K) is calculated. If the inside air humidity is greater than the humidity of saturation then condensation will occur on the surface which in this case would be the underside of the lower roof. So if HUMROOF(K) is greater than 100.0% then condensation will be present. With the double glazed roof HMSAT3(K) the humidity of condensation at TEMP3 is set to 0.0. With a single glazed roof HMSAT7(K) is set at 0.0 and the relative humidity at the roof temperature is calculated depending upon TEMP3. With the screen present, HMSAT11(K) is calculated along with the relative humidity at TEMP11, and the humidity in the upper air layer is reduced by multiplying by a fraction, V(28), set in one of the initialisation routines.

SECTION 18 HEAT LOSS

```
DELT151=TEMP15-TEMP1
CHLS(K)=CHT(28)*(TEMP27-V(10))
RHLR(K)=RLW31(K)-RLW1(K)*EMLR3(K)
CHLR(K)=CHT(2)*(TEMP3-TEMP1)
VHLR(K)=HV(K)
HLS(K)=CHLS(K)
HLR(K)=RHLR(K)+VHLR(K)+CHLR(K)+EVAPHT(K)
SUNGAIN(K)=SUNSOIL(K)+ABSRAD3(K)+ABSRAD7(K)
HFLUX(K)=HTPWR(K)-HLS(K)-HLR(K)+SUNGAIN(K)
```

Heat loss from and heat gain to the system occurs in a variety of ways and this section calculates the rates of loss at given instants. DELT151 is the temperature difference between the inside and outside air and CHLS(K) is the storage array for conductive heat loss through the soil beneath the structure. Through the roof, heat loss occurs via three different paths, radiation, conduction and ventilation. RHLR(K) is the net radiative heat loss and a negative value would indicate a net gain from the sky to the roof. CHLR(K) is the conductive heat loss occurring from the upper roof to the outside air and VHLR(K) is the ventilative loss from the structure due to leakage or active ventilation. HLS(K) and HLR(K) are storage arrays for the total losses through the soil and through the roof and SUNGAIN(K) is the total gain to the system due to the solar radiation. HFLUX(K) is the net gain to the system and is the sum of SUNGAIN(K) and HTPWR(K), less HLR(K) and HLS(K). A negative value of HFLUX(K) will indicate that the glasshouse is losing more energy than it is gaining.

SECTION 19 ARRAY ASSIGNMENT

```
HEATOT(K)=HEATIN*C(3)
ZTEMP1(K)=TEMP1-C(15)
ZTEMP3(K)=TEMP3-C(15)
ZTEMP5(K)=TEMP5-C(15)
ZTEMP7(K)=TEMP7-C(15)
```

```
      ZTEMP9(K)=TEMP9-C(15)
      ZTEMP11(K)=TEMP11-C(15)
      ZTEMP13(K)=TEMP13-C(15)
      ZTEMP15(K)=TEMP15-C(15)
      ZTEMP17(K)=TEMP17-C(15)
      ZTEMP19(K)=TEMP19-C(15)
      ZTEMP21(K)=TEMP21-C(15)
      ZTEMP23(K)=TEMP23-C(15)
      ZTEMP25(K)=TEMP25-C(15)
      ZTEMP27(K)=TEMP27-C(15)
      ZHAI(K)=HAI
```

FORSIM does not allow the user to store values in arrays of the same name as those variables listed in the INTEGT and DERIVT blocks and so, this section stores the component temperatures in arrays such as ZTEMP5. The program handles temperatures in °K and the subtraction of C(15) in this section stores the values in the Z arrays in °C. Note that these arrays contain the values of component temperature at instants in time just before K is incremented to the next value. When the print subroutines are called the contents of these arrays can be printed out.

```
      IF(T.GE.TFIN) K=KMAX
      IF(INOUT.NE.1) GO TO 631
      IF(K.EQ.KMAX) GO TO 632
      GO TO 631
  632 HEATDAY(N(KMAX))=HEATOT(KMAX)-FLUXTOT(5)
      FLUXTOT(5)=HEATOT(KMAX)
      DN(5)=DN(5)+V(33)
      NKM=N(KMAX)-1
      IF(NKM.EQ.3.OR.NKM.EQ.5.OR.NKM.EQ.7) GO TO 633
      IF(T GT 9.99) GO TO 633
      N(KMAX)=N(KMAX)+1
  631 RETURN
  633 CONTINUE
```

The program uses FORSIM to calculate how much heat has been used since the run began at 0.00 h on the first day but because it is useful to know how much heat is applied each day, and this section calculates this figure for each day of the run. When INOUT is given a value of 1 by FORSIM it means that conditions are suitable for the remainder of this section to be checked. However, if K is not equal to KMAX (if we are not at the end of a day) then the program will return control to FORSIM for another sweep of UPDATE. When the program is satisfied that conditions are correct for continuing and that we are at the end of a day, it carries out the heat measurement routines. The amount of heat used since the run began is stored in an array called HEATDAY and the final daily value is in HEATDAY(N(KMAX)). DN(5) is the daynumber being simulated (taking Jan. 1st = 1) and this is incremented by V(33) in this section in preparation for the next day. V(33) is usually assigned a value of 1.0 but it may also take a value of 0.0 if the same day is to be simulated over and over again, to try to find an equilibrium perhaps. N(KMAX) is a measure of how many days of the run have been completed and is distinct form V(33).

The three checks on the value of NKM are used here to provide a means of producing printouts for some days in the middle of the run in this example these days are 3, 5 and 7. Next, if we are at the end of the last day of the run then conditions are correct for the final printout routines and control jumps to statement 633, but if T is less than 9.99 then the program increments N(KMAX) by one and returns for another simulated day.

```
SECTION 20---PRINT OUTPUT

CALL STATE(DAYS KMAX SCREEN ROOF)
CALL DAYHEAT(DAYS,KMAX)
CALL TEMPS(KMAX)
CALL RLW(KMAX)
CALL RADBAL(KMAX)
CALL RADIAT(KMAX)
CALL HEATHUM(KMAX)
CALL HTSTORE(KMAX)
```

```
CALL HTLOSS(KMAX)
CALL STRUCT
CALL INTDER
CALL MISC
N(KMAX)=N(KMAX)+1
RETURN
END
```

This routine handles the final stage of the program, the printing of the results. If the printing conditions are met, then printout can proceed and the print subroutines are called. STATE prints out information about the system being simulated, the presence of a thermal screen for example. DAYHEAT prints out the amount of heat required from the heating system for each day of the run and TEMPS prints out the component temperatures at intervals throughout the final day RLW, RADBAL and RADIAT print out the long- wave radiation exchange, the energy balance variables and the solar radiation variables respectively.

HEATHUM controls the printing of the values of the humidity variables, HTSTORE prints the values of the heat storage for the components and HTLOSS prints information about the flow of heat into and out of the system. STRUCT prints out the economy package values and INTDER prints out the final values of the INTEGT and DERIVT variables which would be of use to the user who wishes to continue the simulation over a further period of time. Finally MISC is included and can be used to print out any particular variables which the user requires. In this example it is set up to print some of the variables which control the outside air temperature interpolation routine.

This calling section and the print subroutines are designed to allow the user to include or exclude any of the reoutines in whatever order he requires. Thus, if he is interested solely in the temperatures of the components, then he need call TEMPS alone and leave out the other routines. The initialisation and print subroutines are described in detail in the next chapter

UPDATE is a subroutine of the main calling program FORSIM which contains all of the routines which describe the thermal behaviour of a glasshouse.

It may be called many thousands of times and in order to save computer time and make the program function more efficiently, many of the variables and constants are set at the start of the run by means of subroutine calls. In other words, these subroutines are called once only at the beginning of a run and the values of constants are then stored in the memory for future use. In this way the values are not read in each time UPDATE is called by FORSIM. Two other types of subroutine are also used and these handle the reading in of data and the printing out of results.

```
SUBROUTINE ASSIGN(DAYS.ROOF.RAD)

COMMON/INIT2/C(40),CHT(28),DENSITY(27),EMLR(17),FLUXTOT(98),
*HAO(98),HEATCAP(27),LHEAT(98),N(98),RI(7),THICK(27),TRI(27),
*V(45),COEFF(10)
```

In this subroutine the user can define the system that he wishes to simulate. Each variable or array will be defined in the order in which it is listed. The first four lines define the name of the subroutine (ASSIGN) and the names of those variables and constants which will be common to both this subroutine and UPDATE, the main simulation program. DAYS ROOF and RAD are variables named along with the subroutine and are not stored between calls to UPDATE but those variables listed in the common block called INIT2 are defined in this routine once only during a program run.

The C array contains constants which are commonly used throughout UPDATE and whilst the program would be easier to understand if numbers were used in the equations, the use of a named array constant makes the computing more efficient. Some of the numbers have fairly obvious uses in this type of program and the array will be listed here with a brief explanation of some of the values.

C(1) = 2.0
C(2) = 8640.0 Number of seconds in 2.4 hours
C(3) = 1000.0
C(4) = 10.0

C(5) = 24.0 Number of hours in one day

C(6) = 1.0

C(7) = 2.4

C(8) = 60.0 Number of minutes in one hour

C(9) = 180.0 Pi radians = 180 degrees

C(10) = 5.67E-08 Sigma the Stefan-Boltzmann constant

C(11) = 0.6

C(12) = 3600.0 Number of seconds in one hour

C(13) = 0.0

C(14) = 100.0

C(15) = 273.16 0 degrees Celsius in degrees Kelvin

C(16) = 23.45 Used in declination calculation

C(17) = 284.0 Used in declination calculation

C(18) = 365.0 Number of days in one year

C(19) = 360.0 Number of degrees in 2 * Pi radians

C(20) = 15.00 Degrees of arc in one solar hour

C(21) = 0.5

C(22) = 90.0

C(23) = 0.605

C(24) = 0.0408

C(25) = 1370.0

C(26) = 1.323 Used in relative humidity calculations

C(27) = 17.27 Used in relative humidity calculations

C(28) = 35.86 Used in relative humidity calculations

C(29) = DAYS* C(2) Used in the TRI calculations

C(30) = 3.1415927 The value of Pi

C(31) = 1440.0

C(32) = 4.0

C(33) = 2494630.0 Used in latent heat calculations

C(34) = 2247.0 Used in latent heat calculations

Other values can be added to this if the program were to be extended but the dimension of the array would have to be increased if more than 40 values were to be included.

The following parameter values can all be altered by a user with an editing package before running the main program. The numbers shown below may be taken as representative values and some have been discussed in earlier chapters.

The DENSITY array contains the values of the density of the components. The numbering system in this section is entirely consistent with the component numbering system so that DENSITY(7) is the density of component 7.

ARRAY MEMBER	VALUE	DESCRIPTION	
DENSITY(1) =	1.293	Density of air	kg/m^3
DENSITY(3) =	2600.0	Density of glass	
DENSITY(5) =	1.293	Density of air	
DENSITY(7) =	2600.0	Density of glass	
DENSITY(9) =	1.293	Density of air	
DENSITY(11) =	920.0	Density of thermal screen plastic	
DENSITY(13) =	1.293	Density of air	
DENSITY(15) =	1.293	Density of air	
DENSITY(17) =	1500.0	Density of soil	
DENSITY(19) =	1500.0	Density of soil	
DENSITY(21) =	1500.0	Density of soil	
DENSITY(23) =	1500.0	Density of soil	
DENSITY(25) =	1500.0	Density of soil	
DENSITY(27) =	1500.0	Density of soil	

The EMLR array contains the emissivities to long-wave radiation for the various components. Once again, the numbering system is not as straightforward for this array as it is for others. The emissivity is a property of a surface so that the thermal screen for example, has to be given two values of emissivity, one for the upper surface and one for the lower.

ARRAY MEMBER	VALUE	DESCRIPTION
EMLR(1) =	1.0	Sky
EMLR(3) =	0.94	Upper roof, upper surface
EMLR(4) =	0.94	Upper roof lower surface
EMLR(7) =	0.94	Lower roof, upper surface
EMLR(8) =	0.94	Lower roof lower surface
EMLR(11) =	0.96	Screen, upper surface
EMLR(12) =	0.96	Screen lower surface
EMLR(17) =	1.0	Floor

The HEATCAP array contains the values of the heat capacity of the components in units of J/kgK.

ARRAY MEMBER	VALUE	HEAT CAPACITY OF:
HEATCAP(1) =	1008.0	Air
HEATCAP(3) =	840.0	Glass
HEATCAP(5) =	1008.0	Air
HEATCAP(7) =	840.0	Glass
HEATCAP(9) =	1008.0	Air
HEATCAP(11) =	2300.0	Polyethylene
HEATCAP(13) =	1008.0	Air
HEATCAP(15) =	1008.0	Air
HEATCAP(17) =	1500.0	Soil
HEATCAP(19) =	1500.0	Soil
HEATCAP(21) =	1500.0	Soil
HEATCAP(23) =	1500.0	Soil
HEATCAP(25) =	1500.0	Soil
HEATCAP(27) =	1500.0	Soil

RI is the variable name for the refractive index of the components. It is only used in this model in the components corresponding to the roof layers and the immediately adjacent air (or gas) layers. In this case the numbers refer to the components themselves.

ARRAY MEMBER	VALUE	REFRACTIVE INDEX OF:
RI(1) =	1.0	Air
RI(3) =	1.526	Glass
RI(5) =	1.0	Air
RI(7) =	1.526	Glass

The THICK array contains the values of the thickness of the components in metres.

ARRAY MEMBER	VALUE	THICKNESS OF:
THICK(3) =	0.003	Upper roof
THICK(5) =	0.02	Air gap
THICK(7) =	0.003	Lower roof
THICK(9) =	1.5	Upper air layer
THICK(11) =	0.001	Thermal screen
THICK(13) =	2.5	Lower air layer
THICK(15) =	4.0	All inside air
THICK(17) =	0.01	Top soil layer
THICK(19) =	0.02	Soil layer
THICK(21) =	0.04	Soil layer
THICK(23) =	0.08	Soil layer
THICK(25) =	0.16	Soil layer
THICK(27) =	0.32	Soil layer

When all the previous arrays have been assigned values the TRI array can be set. TRI stands for temperature rise index and is calculated in the following way:

```
      DO 7000 J=3,27,2
      TRI(J)=C(29)/(HEATCAP(J)*DENSITY(J)*THICK(J))
 7000 CONTINUE
```

TRI is easily calculated using a DO loop which increments J from 3 to 27 in steps of 2. In other words, J will take on the value corresponding to each component number. TRI is then calculated for each component. C(29) is DAYS * 8640.0 and represents the number of real seconds simulated by one second of FORSIM time. Looking at the equation in dimensional terms we get:

$$TRI = \frac{s}{FS} * \frac{kgK}{J} * \frac{m^3}{kg} * \frac{1}{m} = \frac{m^2K}{WFS} = \frac{K}{(W/m^2)FS}$$

This is a temperature rise per W/m^2 for each FORSIM SECOND.

The V array contains those frequently used variables which can be set by the user to define either some physical factor affecting the structure or the model, or some factor that controls the flow of the program. The array will be listed here and a description of each variable will be included along with a sample value.

Variable Value	Description	UNITS
V(1) = 26.5*RAD	Slope of roof from the horizontal	Radians
V(2) = 0.0*RAD	Roof azimuth angle measured in degrees from the South	Radians
V(3) = 16.1	Glass extinction coefficient used in the calculation of the roof layer absorption coefficient	
V(4) = 0.9	Solar radiation reduction coefficient used to reduce the solar radiation intensity due to dust etc	
V(5) = 0.8	Upper air ventilation fraction represents the fraction of the total ventilation which occurs from the upper air layer	
V(6) = 0.2	Lower air ventilation fraction, as above but for the lower air layer	
V(7) = 0.002	Passive ventilation rate, ventilation rate due to leakage etc	m^3/m^2s
V(8) = 0.04	Active ventilation rate, rate when vents are fully open.	m^3/m^2s

Variable Value	Description	UNITS
V(9) = 0.2	Albedo or reflection coefficient of the floor surface	
V(10) = 288.0	Temperature of the soil beneath the deepest soil layer modelled by the program	K
V(11) = 297.0	Temperature at which active ventilation starts	K
V(12) = 0.04	Temperature increment which corresponds to a 1% opening in the ventilators above the temperature set in V(11)	K
V(13) = 12.0	Time when special data begins	Hr.mins
V(14) = 13.0	Time when special data ends. These variables may be used to define when minute by minute data is available, for example	Hr mins
V(15) = 52.0	Geographical latitude of the glasshouse being simulated	Degrees
V(16) = 10.0	Length of time during which the air layers are mixed after removal of the thermal screen	Minutes
V(17) = 0.57	Fraction of radiation which is photosynthetically active	
V(18) = 5000.0	Component of leaf resistance during periods of zero or low radiation flux	s/m
V(19) = 50.0	Component of leaf resistance during high radiation flux	s/m
V(20) = 55.0	Used to calculate leaf resistance during periods of intermediate radiation intensity	s/m
V(21) = 10.0	As above, low solar radiation level	W/m^2
V(22) = 289.0	Heater setpoint. Although assigned a value here, this variable takes on the value of the heater setpoint defined in the data	K

Variable	Value	Description	UNITS
V(23)	= 45.0	Heating time coefficient	s
V(24)	= 43.2	Air mixing time variable used in the calculation of temperature changes in the air layers after the removal of the thermal screen	
V(25)	= 333.0	Boundary layer resistance	s/m
V(26)		Unused	
V(27)	= 1.0E6	Variable used in the calculation of the amount of heat supplied to the system	
V(28)	= 2.0	Factor used in the calculation of the loss of heat due to latent heat loss via ventilation	
V(29)	= 0.0*RAD	Floor slope angle from the horizontal	Radians
V(30)	= 0.0*RAD	Floor azimuth angle in degrees from the South If V(29) is 0.0 then the azimuth angle is meaningless	Radians
V(31)	= 1.0	Time interval between special data points. With minute by minute data this value is 1.0	Minutes
V(32)	= 82.0	Daynumber of run (Jan 1st.=1)	
V(33)	= 0.0	Increment in daynumber	Days
V(34)	= 0.1	Long-wave transmissivity of screen	
V(35)	= 45.0	Time after sunrise when screen opens	Minutes
V(36)	= 15.0	Time after sunset when screen closes	Minutes
V(37)	= 2.0	Leaf temperature increment above air temperature	K
V(38)	= 1.5	Air mixing factor	
V(39)	= 60.0*RAD	Angle of incidence of diffuse radiation on the glasshouse roof	Radians
V(40)	= 5.0	Maximum value of time step	Minutes
V(41)	= 0.02	Heating setpoint increment	K
V(42)	= COS(V(1)	Cosine of roof slope angle	
V(43)	= 0.0	Leaf area per floor area	m^2/m^2
V(44)	= 26.5*RAD	Lower roof slope angle	Radians

Angles need only be specified by the user in degrees because the multiplication by RAD in the routine converts these to radians.

The CHT array contains the coefficients of convective and conductive heat transfer for the components. The numbering system is slightly different in this array because these forms of heat transfer usually operate between consecutive components. For example, transfer between components 1 and 3, the outside air and the upper roof layer is represented by CHT(2) and exchange between components 3 and 5 is represented by CHT(4). This system is used throughout this array wherever possible, but in some cases this is impossible to maintain. When the thermal screen is not present, heat exchange occurs between component 7 if there is a double glazed roof, and component 15, the inside air, and this is denoted by CHT(7). The units of these are W/m^2K. V(42) is a member of the V array and has the value of the cosine of the roof slope angle. The increase in value of the heat transfer coefficients by V(42) allows the real roof heat loss per square metre of floor area to be calculated.

Array Member	Value	Heat exchange coefficient between
CHT(2) =	25.0/V(42)	1 and 3
CHT(4) =	7.0/V(42)	3 and 5
CHT(5) =	7.0/V(42)	3 and 15
CHT(6) =	7.0/V(42)	5 and 7
CHT(7) =	7.0/V(42)	7 and 15
CHT(8) =	7.0/V(42)	7 and 9
CHT(9) =	7.0/V(42)	3 and 9
CHT(10) =	7.0	9 and 11
CHT(12) =	7.0	11 and 13
CHT(14) =	7.0	13 and 17
CHT(16) =	7.0	15 and 17
CHT(18) =	67.0	17 and 19
CHT(20) =	33.0	19 and 21
CHT(22) =	16.0	21 and 23
CHT(24) =	8.0	23 and 25
CHT(26) =	4.0	25 and 27
CHT(28) =	2.0	27 and 29

Component 29 is used here to denote the soil beneath the system. The soil CHT values are all calculated using a thermal conductivity of 1.0 W/mK but it is possible to use different values for each layer if simulation of some heat storage system is being attempted.

The remainder of this subroutine is used to calculate the solar radiation coefficients for diffuse radiation reflected from the glasshouse floor up to the roof layers.

```
      THETA5R=V(39)
      IF(ROOF.EQ.1.0) GO TO 321
      SINTHE6=RI(1)*SIN(THETA5R)/RI(7)
      THETA6R=ASIN(SINTHE6)
      DELTHET=THETA6R-THETA5R
      DELTHET=ABS(DELTHET)
      SUMTHET=THETA6R+THETA5R
      REFPERP=SIN(DELTHET)**2/SIN(SUMTHET)**2
      REFPAR=TAN(DELTHET)**2/TAN(SUMTHET)**2
      TAUALF1=EXP(-V(3)*THICK(7)/COS(THETA6R))
      TRPAR=TAUALF1*((C(6)-REFPAR)/(C(6)+REFPAR)*(C(6)-REFPAR**2)
     */(C(6)-REFPAR**2*TAUALF1**2))
      TRPERP=TAUALF1*((C(6-REFPERP)/(C(6)+REFPERP)*
     *(C(6)-REFPERP**2)/(C(6)-REFPERP**2*TAUALF1**2))
      TRANCO6=C(21)*(TRPAR+TRPERP)
      REFCO6=C(21)*(REFPAR*(C(6)+TAUALF1*TRPAR)+REFPERP*
     *(C(6)+TAUALF1*TRPERP))
      ABSCO6=C(6)-REFCO6-TRANCO6
      GO TO 317
```

In the description of the solar radiation section of the model the radiation reflected from the floor of the structure is assumed to be totally diffuse and is then either absorbed by the roof, or transmitted through, leaving the system entirely. A further simplifying assumption is made here and that is that the reflected, diffuse radiation strikes the underside of the roof at a fixed angle of 60.0 degrees. Once again this removes the requirement for integration over a hemisphere and if the 60.0 degrees is assumed to be a good enough approximation, then only one set of calculations need be carried out to calculate all the transmission and absorption coefficients at that angle for each run of the model. It would be possible merely to calculate these coefficients and use them in the appropriate routines without further calculation being required, but including a section of the program which actually does work out these values allows the user to change this angle if he so chooses. The results are automatically passed on to the main program.

The first half of this routine calculates the absorption, reflection and transmission coefficients for the lower roof layer at the fixed angle of 60.0 degrees. The lower roof coefficients are calculated first because the radiation reflected from the floor is coming up from underneath the roof. The method for doing this is exactly the same as that used in the main program and will not be described here.

```
321 TRANCO6=1.0
    REFCO6=0.0
    ABSCO6=0.0
    SINTHE8=RI(1)*SIN(THETA5R)/RI(3)
    THETA7R=THETA5R
    GO TO 319
317 SINTHE7=RI(7)*SIN(THETA6R)/RI(5)
    THETA7R=ASIN(SINTHE7)
    SINTHE8=RI(5)*SINTHE7/RI(3)
319 THETA8R=ASIN(SINTHE8)
    DELTHE8=ABS(THETA8R-THETA7R)
    SUMTHE8=THETA8R+THETA7R
    REFPER8=SIN(DELTHE8)**2/SIN(SUMTHE8)**2
    REFPAR8=TAN(DELTHE8)**2/TAN(SUMTHE8)**2
    TAUALF2=EXP(-V(3)*THICK(3)/COS(THETA8R))
    TRPAR2=TAUALF2*((C(6)-REFPAR8)/(C(6)+REFPAR8)*
   *(C(6)-REFPAR8**2)/(C(6)-REFPAR8**2*TAUALF2**2)
    TRPERP2=TAUALF2*((C(6)-REFPER8)/(C(6)+REFPER8)*
   *(C(6)-REFPER8**2)/(C(6)-REFPER8**2*TAUALF2**2))
    TRANCO8=C(21)*(TRPAR2+TRPERP2)
    REFCO8=C(21)*(REFPAR8*(C(6)+TAUALF2*TRPAR2)+REFPER8*
```

```
     *(C(6)+TAUALF2*TRPERP2))
      ABSCO8=C(6)-REFCO8-TRANCO8
      COEFF(1)=TRANCO6
      COEFF(3)=REFCO6
      COEFF(5)=ABSCO6
      COEFF(7)=TRANCO8
      COEFF(9)=REFCO8
      COEFF(11)=ABSCO8
      RETURN
      END
```

The second half of the routine calculates the coefficients for the upper roof layer in the same way. Finally, the results are stored in an array called COEFF and are used in the absorption routines in the main program.

The INITIAL subroutine assigns values to the INTEGT and DERIVT variables and sets the values of some of the arrays used in UPDATE.

```
      SUBROUTINE INITIAL(TEMP1,ROOF,KMAX,DAYS)
      COMMON/INTEGT/TEMP3,TEMP7,TEMP9,TEMP11,TEMP13,TEMP15,
     *TEMP17,TEMP19,TEMP21,TEMP23,TEMP25,TEMP27,HAI,HEATIN
      COMMON/DERIVT/TEMP3T,TEMP7T,TEMP9T,TEMP11T,TEMP13T,
     *TEMP15T,TEMP17T,TEMP19T,TEMP21T,TEMP23T,TEMP25T,TEMP27T,
     *HAIT,HEATINT
      COMMON/INIT1/DERIV(16),DERVAL(16,2),NUMBER(98),TM(16,2),
     *TTOT(98),DTM(16,2)
      COMMON/INIT2/C(40),CHT(28),DENSITY(27),EMLR(17),FLUXTOT(98),
     *HAO(98),HEATCAP(27),LHEAT(98),N(98),RI(7),THICK(27),TRI(27),
     *V(45),COEFF(10)
      COMMON/EM1/DN(98),HEATOT(98),HTPWR(98),TIMDEC(98),TIME(98),
     *VENT(98),VTOPEN(98)
```

The first line names the subroutine (INITIAL) and lists certain non-array variables which are common to both INITIAL and UPDATE. The remaining lines at the beginning list the common blocks and variables which are required by UPDATE and are initialised in this subroutine.

```
      NUMBER(1)=0
      DO 185 L=1,16
      DERIV(L)=0.0
      DERVAL(L,1)=0.0
      TM(L,1)=0.0
      DTM(L,1)=0.0
      DERVAL(L,2)=10000
      TM(L,2)=0.0
      DTM(L,2)=0.0
  185 CONTINUE
      TTOT(1)=0.0
      N(KMAX)=1
      FLUXTOT(5)=0.0
```

NUMBER is the variable which is incremented by one each time a sweep through UPDATE is carried out and therefore, by printing it out at the end of the run, the user can see how many times UPDATE was called by FORSIM. Here it is set at 0. The DERIV, DERVAL, DTM and TM arrays are initialised within a DO loop and are all set at 0.0 with the exception of DERVAL(L,2) which is set at 10000. All the (L,1) variables are used to find the maximum absolute values of the DERIVT variables and the time (TM) and step length (DTM) when they occured. The (L,2) variables find the smallest absolute values of these variables with their corresponding times and time steps. DERVAL(L,2) must be set to a value greater than any value it is likely to be set to by UPDATE itself. In other words. because DERVAL(L,1) is looking for a maximum, it will be increased by UPDATE and needs to be small initially, and because DERVAL(L,2) is looking for a minimum, it will be decreased by UPDATE and needs to be large to start with. N(KMAX) is used in the printout to indicate which day of the simulation is currently indicated and here it is set at 1. FLUXTOT(5) is used in the calculation of the heating input and is set at 0.0.

```
      TEMP1 = 10.0+C(15)
      TEMP3 = 10.0+C(15)
      TEMP7 = 15.0+C(15)
      TEMP9 = 19.0+C(15)
```

```
      TEMP11  =  19.0+C(15)
      TEMP13  =  19.0+C(15)
      TEMP15  =  19.0+C(15)
      TEMP17  =  19.329+C(15)
      TEMP19  =  19.975+C(15)
      TEMP21  =  21.137+C(15)
      TEMP23  =  22.785+C(15)
      TEMP25  =  22.890+C(15)
      TEMP27  =  19.819+C(15)
      TEMP3T = -1.706
      TEMP7T = 0.0
      IF(ROOF.EQ.1.0) GO TO 184
      GO TO 186
  184 TEMP7T = 0.0
      TEMP7 = 0.0
  186 CONTINUE
      TEMP9T = 0.0
      TEMP11T = 0.0
      TEMP13T = 0.0
      TEMP15T = -1.238
      TEMP17T = -16.522
      TEMP19T = -19.105
      TEMP21T = -22.955
      TEMP23T = -24.508
      TEMP25T = -6.301
      TEMP27T = 0.588
      HAI = 0.009
      HAIT = 0.0
      HEATIN = 0.0
      HEATINT = 0.0
      VENT(1) = V(7)
      DN(4) = 1.0
      DN(5) = V(32)
      DN(6) = DN(5)+DAYS
      RETURN
      END
```

At the start of the run FORSIM must know the temperature of each component and also the rate of change of this temperature. This part of the subroutine assigns these initial temperatures and rates of change. For example TEMP15, the inside air temperature, might be set at 289.0 K and TEMP15T, the rate of change of TEMP15, might be set at 0.0. This would indicate to FORSIM that at midnight on the first day to be simulated, the inside air temperature was 289.0 K and was not changing. The model user can set the initial temperatures in °C and the addition of C(15) to these values by the model increases them by 273.16 to convert them to values of K. There is a test carried out in the middle of this section to see if the roof is single or double glazed. If it is single glazed then TEMP7 and TEMP7T are both set to 0.0 as component 7 is non-existent.

```
      SUBROUTINE PARAOUT

      COMMON/INT2/C(35),CHT(28),DENSITY(27),EMLR(17),
     *FLUXTOT(98),HAO(98),HEATCAP(27),HEATIME(98),LHEAT(98)
     *N(98),RI(7),THICK(27),TRI(27),V(35),COEFF(10)
      V1=V(1)/RAD
      V2=V(2)/RAD
      V29=V(29)/RAD
      V30=V(30)/RAD
      V39=V(39)/RAD
      V44=V(44)/RAD
      WRITE(6 5101)V1 V2
 5101 FORMAT(/.1X."V(1) ROOF SLOPE ANGLE (DEGREES)".8X,F10.2,2X,
     *"V(2) ROOF AZIMUTH ANGLE (DEGS FROM S)",2X,F10.2)
      WRITE(6,5102)V(3),V(4)
 5102 FORMAT(/,1X,"V(3) GLASS EXTINCTION COEFFICIENT",6X,F10.2,2X,
     *"V(4) RADIATION REDUCTION FACTOR",8X,F10.2)
      WRITE(6,5103)V(5),V(6)
 5103 FORMAT(/ 1X,"V(5) UPPER AIR VENTILATION FRACTION".4X,F10.2,2X.
     *"V(6) LOWER AIR VENTILATION FRACTION",4X,F10.2)
```

```
      WRITE(6,5104)V(7),V(8)
 5104 FORMAT(/,1X,"V(7) PASSIVE VENTILATION RATE (M3/M2S)",1X,F10.6,
     *2X,"V(8) ACTIVE VENTILATION RATE (M3/M2S)",2X,F10.3)
      WRITE(6,5105)V(9),V(10)
 5105 FORMAT(/ 1X,"V(9) ALBEDO OF FLOOR",19X,F10.2,
     *2X,"V(10) TEMPERATURE OF SOIL BENEATH (K)",3X,F10.3)
      WRITE(6,5106)V(11),V(12)
 5106 FORMAT(/,1X,"V(11) VENTING TEMPERATURE (K)",11X,F10.3,
     *2X "V(12) VENTING TEMPERATURE RANGE (K)"5X,F10.3)
      WRITE(6,5107)V(13),V(14)
 5107 FORMAT(/,1X,"V(13) DATA START TIME (HOURS)",11X,F10.2
     *2X,"V(14) DATA END TIME (HOURS)",13X,F10.2)
      WRITE(6,5108)V(15),V(16)
 5108 FORMAT(/ 1X,"V(15) LATITUDE (DEGREES) ",F10 2
     *2X "V(16) AIR MIXING TIME (MINUTES) ",F10.2)
      WRITE(6 5109)V(17) V(18)
 5109 FORMAT(/,1X "V(17) PHOTRAB FRACTION ",F10.2,
     *2X,"V(18) LEAF RESISTANCE (S/M) ",F10.2)
      WRITE(6,5110)V(19),V(20)
 5110 FORMAT(/ 1X,"V(19) LEAF RESISTANCE (S/M) ",F10 2,
     *2X,"V(20) RESISTANCE SLOPE ",F10.2)
      WRITE(6 5111)V(21) V(22)
 5111 FORMAT(/,1X,"V(21) RESISTANCE SLOPE ",F10.2,
     *2X,"V(22) HEATING SET POINT (K) ",F10.2)
      WRITE(6,5112)V(23),V(24)
 5112 FORMAT(/,1X,"V(23) HEATING TIME COEFFICIENT ",F10.2,
     *2X,"V(24) AIR MIXING TIME COEFFICIENT ",F10.2)
      WRITE(6,5113)V(25),V(26)
 5113 FORMAT(/,1X,"V(25) BOUNDARY LAYER RESISTANCE (S/M) ",F10.2,
     *2X,"V(26) UNUSED ",F10 2)
      WRITE(6,5114)V(27),V(28)
 5114 FORMAT(/,1X,"V(27) HEATING COEFFICIENT (J/MJ) ",F10.2,
     *2X,"V(28) HUMIDITY HEAT LOSS FACTOR ",F10.2)
      WRITE(6,5115)V29,V30
 5115 FORMAT(/,1X,"V(29) FLOOR SLOPE ANGLE (DEGREES) ",F10.2
     *2X,"V(30) FLOOR AZIMUTH ANGLE (DEGREES) ",F10.2)
```

```
      WRITE(6,5116)V(31),V(32)
 5116 FORMAT(/,1X,"V(31) TIME INTERVAL BETWEEN DATA (MINS) ",F10.2,
     *2X,"V(32) DAYNUMBER OF RUN (JAN 1ST = 1 0) ",F10.2)
      WRITE(6,5117)V(33),V(34)
 5117 FORMAT(/,1X,"V(33) INCREMENT IN DAYNUMBER (DAYS) ",F10.2,
     *2X,"V(34) LW TRANSMISSIVITY OF SCREEN ",F10.2)
      WRITE(6,5118)V(35),V(36)
 5118 FORMAT(/,1X,"V(35) SCREEN OPEN (MINS AFTER SUNRISE) ",F10.2,
     *2X,"V(36) SCREEN CLOSE (MINS AFTER SUNSET) ",F10 2)
      WRITE(6,5119)V(37),V(38)
 5119 FORMAT(/,1X,"V(37) LEAF TEMPERATURE (K ABOVE AIR T) ",F10.2,
     *2X,"V(38) ANGLE OF INC OF DIFFUSE RAD. ",F10.2)
      WRITE(6,5120)V39,V(40)
 5120 FORMAT(/,1X,"V(39) ANGLE OF INCIDENCE OF DIFFUSE RADN",F10.2,
     *2X "V(40) MAX. VALUE OF TIME STEP (MINUTES) ",F10.2)
      WRITE(6,5121)V(41),V(42)
 5121 FORMAT(/,1X,"HEATING STE POINT INCREMENT (K) ",F10.3,
     *2X "V(42) COSINE OF ROOF SLOPE ANGLE ",F10 4)
      WRITE(5122)V(43),V(44)
 5122 FORMAT(/,1X "V(43) LEAF AREA PER FLOOR AREA (M2/M2) ",F10.2,
     *2X "V(44) LOWER ROOF SLOPE ANGLE (DEGREES) ",F10.3)
      RETURN
      END
```

This subroutine is called in the initialisation section of the program and prints out the values of the V array which describe the system being modelled. This gives the user a quick reference list at the beginning of each run so that he can see which values are being used. Included is a brief description of each variable but because of a lack of space when printing out results, the user should refer to the text for a more detailed description of the function of each V array member.

The print subroutines are called at the end of a run when all the simulation has been completed. The storage arrays only contain the values of the variables for the final day of the run too much computer memory would be required to save any more, and groups of related variables are printed out together, in blocks. Only the first print routine will be described in any detail as the subsequent ones are practically identical, except that they control the printing of different variables.

```
      SUBROUTINE TEMPS(KMAX)

      COMMON/EM1/DN(98),HEATOT(98),HTPWR(98),TIMDEC(98),TIME(98),
     *VENT(98),VTOPEN(98)
      COMMON/TEMP/ZTEMP1(98),ZTEMP3(98),ZTEMP5(98),ZTEMP7(98),
     *ZTEMP9(98),ZTEMP11(98),ZTEMP13(98),ZTEMP15(98),ZTEMP17(98),
     *ZTEMP19(98),ZTEMP21(98),ZTEMP23(98),ZTEMP25(98),ZTEMP27(98)
      WRITE(6,2000)
 2000 FORMAT(/,2X,4HTIME,4X,5HTEMP1,5X,5HTEMP3,5X,5HTEMP5 4X,5HTEMP7,
     *4X,5HTEMP9,4X,6HTEMP11,4X,6HTEMP13,4X,6HTEMP15,5X,5HHTPWR,5X,
     *6HVTOPEN)
      WRITE(6,2100)
 2100 FORMAT(12X,1HC,7(9X,1HC),5X,4HW/M2,7X,2HPC)
      DO 5 K=1,KMAX
      WRITE(6,2200)TIME(K),ZTEMP1(K),ZTEMP3(K),ZTEMP5(K),ZTEMP7(K),
     *ZTEMP9(K),ZTEMP11(K),ZTEMP13(K),ZTEMP15(K),HTPWR(K),VTOPEN(K)
 2200 FORMAT(F6.2,10F10.3)
    5 CONTINUE
```

The first line gives the name of this subroutine, TEMPS, and also passes on the name of a variable, KMAX, which will be common to both UPDATE and this subroutine. The following four lines name the common blocks and variables which will also be common to both sections of the program. The WRITE(6 2000) and the accompanying FORMAT statement instruct the program to print the variables' names across the top of the table, in this case these are the temperatures of the upper components of the glasshouse. Underneath these names the units appropriate to each variable are printed and this is controlled by the WRITE(6,2100) and FORMAT statements. For example, all of these units will be "C" indicating degrees Celsius except the HTPWR (heater power) variable and the VTOPEN (percentage opening of the vents) which will be W/m^2 and % respectively. The next section of the routine is contained within a DO loop.

An integer variable K is made to take values between 1 and KMAX inclusive. K is incremented and the values stored in storage location K are printed. When K becomes greater than KMAX, the process stops as all the values required have been printed out, and control passes on to the next stage of the program.

```
      WRITE(6,2400)
 2400 FORMAT(/ 2X,"TIME" 2X,"TEMP17" 3X,"TEMP19" 3X,"TEMP21",3X,
     *"TEMP23" 3X,"TEMP25",3X,"TEMP27")
      WRITE(6,2500)
 2500 FORMAT(11X 1HC,5(8X,1HC))
      DO 10 J=1,KMAX
      WRITE(6,2500)TIME(J),TEMP17(J),TEMP19(J),TEMP21(J),
     *TEMP23(J),TEMP25(J),TEMP27(J)
 2600 FORMAT(F6.2,7F9.3)
   10 CONTINUE
      RETURN
      END
```

The floor and soil temperatures are also printed out in this section and the above program lines handle this. Once again the headings and units are printed out, and then the values are printed out using a DO loop as before The RETURN statement then returns control of the program to UPDATE.

The next listings are the remaining print subroutines.

```
      SUBROUTINE RLW(KMAX)

      COMMON/EM1/DN(98),HEATOT(98),HTPWR(98),TIMDEC(98),TIME(98),
     *VENT(98),VTOPEN(98)
      COMMON/LWRAD/RLW1(98),RLW31(98),RLW37(98),RLW311(98),
     *RLW317(98),RLW711(98),RLW717(98),RLW1117(98)
      WRITE(6,2700)
 2700 FORMAT(/,2X"TIME",5X,"RLW1",5X,"RLW31",5X,"RLW37",4X,
     *"RLW311",4X,"RLW317",4X,"RLW711",4X,"RLW717",4X,"RLW1117")
```

```
      WRITE(6,2800)
 2800 FORMAT(10X,"W/M**2",7(4X,"W/M**2"))
      DO 15 L=1,KMAX
      WRITE(6,2900)TIME(L),RLW1(L) RLW31(L),RLW37(L) RLW311(L),
     *RLW317(L),RLW711(L),RLW717(L),RLW1117(L)
 2900 FORMAT(F6.2,8F10.3)
   15 CONTINUE
      RETURN
      END

      SUBROUTINE RADBAL(KMAX)

      COMMON/EM1/DN(98),HEATOT(98),HTPWR(98),TIMDEC(98),TIME(98),
     *VENT(98),VTOPEN(98)
      COMMON/BALRAD/BAL9(98),BAL13(98),BAL15(98),BAL17(98),
     *EVAPHT(98),HV(98),RAD3(98),RAD7(98),RAD11(98),RAD17(98)
      WRITE(6,2950)
 2950 FORMAT(/,2X,"TIME",5X,"BAL9",5X,"BAL13",5X,"BAL15",5X,
     *"BAL17",6X,"RAD3",6X,"RAD7",5X,"RAD11",5X,"RAD17",5X,"EVAPHT",6X,"HV")
      WRITE(6,2955)
 2955 FORMAT(10X "W/M**2",9(4X,"W/M**2))
      DO 17 K=1,KMAX
      WRITE(6,2960)TIME(K),BAL9(K),BAL13(K),BAL15(K),BAL17(K),
     *RAD3(K),RAD7(K),RAD11(K),RAD17(K),EVAPHT(K),HV(K)
 2960 FORMAT(F6.2,10F10 3)
   17 CONTINUE
      RETURN
      END


      SUBROUTINE HTSTORE(KMAX)

      COMMON/EM1/DN(98),HEATOT(98),HTPWR(98),TIMDEC(98),TIME(98),
     *VENT(98),VTOPEN(98)
      COMMON/STOREHT/HSTAIR(98),HSTORE(98),HSTOR1(98),HSTOR3(98),
     *HSTOR5(98),HSTOR7(98),HSTOR9(98),HSTOR11(98),HSTOR13(98)
```

```
     *HSTOR15(98),HSTOR17(98),HSTOR19(98),HSTOR21(98),HSTOR23(98),
     *HSTOR25(98),HSTOR27(98)
      WRITE(6,3000)
3000  FORMAT(/,2X,"TIME" 4X,"HSTOR1",4X,"HSTOR3",4X "HSTOR5",4X,
     *"HSTOR7",4X,"HSTOR9",4X,"HSTOR11",3X,"HSTOR13",3X,"HSTOR15")
      WRITE(6,3100)
3100  FORMAT(12X,"KJ",7(8X,"KJ"))
      DO 20 L=1,KMAX
      WRITE(6,3200)TIME(L),HSTOR1(L),HSTOR3(L),HSTOR5(L),HSTOR7(L)
     *,HSTOR9(L),HSTOR11(L),HSTOR13(L),HSTOR15(L)
3200  FORMAT(F6.2,8F10.3)
   20 CONTINUE
      WRITE(6,3250)
3250  FORMAT(/,2X,"TIME",4X,"HSTOR17",3X,"HSTOR19",3X,"HSTOR21",
     *3X,"HSTOR23",3X,"HSTOR25",3X,"HSTOR27",4X,"HSTAIR",4X,"HSTORE")
      WRITE(6,3252)
3252  FORMAT(12X,"KJ" 7(8X,"KJ"))
      DO 23 L=1,KMAX
      WRITE(6 3255)TIME(L),HSTOR17(L),HSTOR19(L),HSTOR21(L),HSTOR23(L),
     *HSTOR23(L),HSTOR25(L),HSTOR27(L),HSTAIR(L),HSTORE(L)
3255  FORMAT(F6.2,8F10.3)
   23 CONTINUE
      RETURN
      END


      SUBROUTINE RADIAT(KMAX)

      COMMON/EM1/DN(98),HEATOT(98),HTPWR(98),TIMDEC(98),TIME(98),
     *VENT(98) VTOPEN(98)
      COMMON/RADIATE/ABSCO3(98),ABSCO7(98),ABSRAD3(98),ABSRAD7(98),
     *PHOTRAB(98),R(98),REFCO3(98),REFCO7(98),SUNRAD(98),
     *SUNSOIL(98),THETA1(98),THETA2(98),THETA4(98),TRANCO3(98),
     *TRANCO7(98),TRARAD3(98),TRARAD7(98)
      WRITE(6,3600)
```

```
3600 FORMAT(/,2X,"TIME",2X,"ABSCO3",4X,"ABSCO7",4X,"REFCO3",
    *"REFCO7", 4X ,"TRANCO3",3X ,"TRANCO7",4X ,"THETA1",4X ,"THETA2",
    *3X,"THETA4")
     WRITE(6,3700)
3700 FORMAT(70X,"DEGS",2(6X,"DEGS"))
     DO 30 L=1 KMAX
     WRITE(6,3800)TIME(L),ABSCO3(L),ABSCO7(L),REFCO3(L),
    *REFCO7(L),TRANCO3(L),TRANCO7(L),THETA1(L),THETA2(L),THETA4(L)
3800 FORMAT(F6.2,6(3X,F5.3,2X),3(3X,F5.2,2X))
  30 CONTINUE
     WRITE(6,3850)
3850 FORMAT(/,2X,"TIME",4X,"SUNRAD",4X,"ABSRAD3",3X,"ABSRAD7",
    *3X ,"TRARAD3",3X,"TRARAD7",3X ,"SUNSOIL",2X ,"PHOTRAB",6X ,"R")
     WRITE(6,3855)
3855 FORMAT(6X 8(4X,"W/M**2"))
     DO 32 L=1,KMAX
     WRITE(6,3857)TIME(L),SUNRAD(L),ABSRAD3(L),ABSRAD7(L),
    *TRARAD3(L),TRARAD7(L),SUNSOIL(L),PHOTRAB(L),R(L)
3857 FORMAT(F6.2,8F10.3)
  32 CONTINUE
     RETURN
     END


     SUBROUTINE HEATHUM(KMAX)

     COMMON/INIT2/C(35),CHT(28),DENSITY(27),EMLR(17),FLUXTOT(98),
    *HAO(98),HEATCAP(27),HEATIME(98),LHEAT(98),N(98),RI(7),
    *THICK(27),TRI(27),V(35),COEFF(10)
     COMMON/EM1/DN(98),HEATOT(98),HTPWR(98),TIMDEC(98),TIME(98),
    *VENT(98),VTOPEN(98)
     COMMON/HUMHEAT/HMSAT3(98),HMSAT7(98),HMSAT11(98),HMSAT15(98),
    *HUMROOF(98),RELHU11(98),RELHU15(98),ZHAI(98)
     WRITE(6,3300)
3300 FORMAT(/,2X "TIME",7X,"HAO",7X "HAI",7X,"HS",6X,"HMSAT7",
    *4X,"HMSAT11",3X ,"HUMROOF",3X ,"RELHU11",3X ,"RELHU15",5X,
```

```
     *"VENT",5X,"VTOPEN")
      WRITE(6,3400)
3400 FORMAT(9X,5(1X,"KG/M**2",2X),3(2X,"PERCENT",1X),"M**3/M**2S",
     * 2X,"PERCENT")
      DO 25 L=1,KMAX
      WRITE(6,3500)TIME(L),HAO(L),ZHAI(L),HMSAT15(L),HMSAT7(L),
     *HMSAT11(L),HUMROOF(L),RELHU11(L),RELHU15(L),VENT(L),VTOPEN(L)
3500 FORMAT(F6.2,8F10.3,F10.5,F10.2)
   25 CONTINUE
      RETURN
      END


      SUBROUTINE HTLOSS(KMAX)

      COMMON/EM1/DN(98),HEATOT(98),HTPWR(98),TIMDEC(98),TIME(98),
     *VENT(98),VTOPEN(98)
      COMMON/BALRAD/BAL9(98),BAL13(98),BAL15(98),BAL17(98),EVAPHT(98),
     *HV(98),RAD3(98),RAD7(98),RAD11(98),RAD17(98)
      COMMON/LWRAD/RLW1(98),RLW31(98),RLW37(98),RLW311(98),RLW317(98),
     *RLW711(98),RLW717(98),RLW1117(98)
      COMMON/EM2/CHLR(98),CHLS(98),DELT151(98),SUNGAIN(98),HFLUX(98),
     *HLR(98),HLS(98),RHLR(98),VHLR(98)
      WRITE(6,5200)
5200 FORMAT(/ 2X,"TIME",4X,"RLW1",5X,"SUNGAIN",4X "HTPWR",5X,
     *"RLW31",6X,"VHLR",6X,"CHLR",7X,"RHLR",5X,"CHLS",5X,"EVAPHT",
     *5X,"HFLUX")
      WRITE(6,5210)
5210 FORMAT(10X,"W/M**2",9(5X,"W/M**2"))
      DO 37 L=1,KMAX
      WRITE(6,5220)TIME(L),RLW1(L),SUNGAIN(L),HTPWR(L),RLW31(L),
     *VHLR(L),CHLR(L),RHLR(L),CHLS(L),EVAPHT(L),HFLUX(L)
5220 FORMAT(F6.2,10F10.3)
   37 CONTINUE
      RETURN
      END
```

The following subroutine is used to print results of any variables which the user wishes. The common blocks containing these variables have to be declared first and then the changes have to be made to the headings and print commands. In this example the routine prints out information on the outside air temperature variables.

```
      SUBROUTINE MISC

      COMMON/EM1/DN(98),HEATOT(98),HTPWR(98),TIMDEC(98),TIME(98),
     *VENT(98),VTOPEN(98)
      COMMON/MISCEL/TEMDEL(98),TINCR(98),TMINSAR(98),TMP1DAT(98)
      WRITE(6,1300)
 1300 FORMAT(/ 4X,"TIME" 3X "TINCR",4X,"TEMDEL",4X "TMINSAR",3X,
     *"TMP1DAT")
      WRITE(6,1400)
 1400 FORMAT(13X,"K",7X,"K" 9X "MIN",8X,"K")
      DO 16 L=1,KMAX
      WRITE(6,1500)TIME(L),TINCR(L),TEMDEL(L),TMINSAR(L),
     *TMP1DAT(L)
 1500 FORMAT(F6.2,4F10.3)
   16 CONTINUE
      RETURN
      END
```

The next subroutine prints out the daynumber of the run an the amount of heat used for each day of the simulation so far completed.

```
      SUBROUTINE DAYHEAT(DAYS,KMAX)

      COMMON/DAYHT/HEATDAY(98)
      COMMON/EM1/DN(98),HEATOT(98),HTPWR(98),TIMDEC(98),TIME(98),
     *VENT(98),VTOPEN(98)
      COMMON/INIT2/C(40),CHT(28),DENSITY(27),EMLR(17),FLUXTOT(98),
```

```
     *HAO(98),HEATCAP(27),LHEAT(98),N(98),RI(7),
     *THICK(27),TRI(27),V(45),COEFF(10)
      WRITE(6,1000)
1000 FORMAT(//,"*****************")
      WRITE(6 1100) N(KMAX)
1100 FORMAT(5X,"*",4X,"DAY ",I4,4X,"*")
      WRITE(6 1200)
1200 FORMAT(/,"*****************")
      IDAY=IFIX(DAYS)
      WRITE(6,6800)
6800 FORMAT(/,2X "DAYNUMBER".10X,"HEATINPUT /KJ")
      DO 33 I=1 IDAY
      DAYNUM=DN(6)-DAYS+FLOAT(I)
      WRITE(6 6850) DAYNUM,HEATDAY(I)
6850 FORMAT(5X,F4.0,18X,F15.3)
   33 CONTINUE
      RETURN
      END
```

Subroutine STRUCT prints out the economy package information.

```
      SUBROUTINE STRUCT
      COMMON/INIT1/DERIV(16),DERVAL(16,2),NUMBER(98),TM(16,2),
     *TTOT(98),DTM(16 2)
      WRITE(6,6300)
6300 FORMAT(/.2X,"COMPONENT",10X,"DERIVT MAX",10X,"TIME",
     *10X,"DT",10X,"DERIVT MIN",10X,"TIME",10X,"DT")
      DO 40 L=1,16
      J=L*2-1
      WRITE(6,6400)J,DERVAL(L,1),TM(L,1),DTM(L,1),DERVAL(L,2),
     *TM(L 2),DTM(L 2)
6400 FORMAT(4X,I4,13X,F10.2,10X,F5.3,6X,F8.6,7X,F10.2,10X,F5.3,
     *6X,F8.6)
   40 CONTINUE
      WRITE(6,6600)NUMBER(1),TTOT(1)
```

```
 6600 FORMAT(//,2X,"NUMBER OF CALLS TO UPDATE  ",I10,
     *" SUM OF DT'S: ",F20 15)
      RETURN
      END
```

The following subroutine prints out information about the state of the glasshouse system before each set of results. For example, it will print whether or not a thermal screen is present at night or if the glasshouse is double or single glazed.

```
      SUBROUTINE STATE(DAYS,KMAX,SCREEN,ROOF)

      WRITE(6,6700) DAYS,KMAX
 6700 FORMAT(/,2X,F4.0," DAY RUN. OUTPUT FOR LAST DAY, ",I4,
     *" VALUES")
      IF(SCREEN.EQ.0.0) GO TO 42
      GO TO 43
   42 WRITE(6,6710)
 6710 FORMAT(/,2X,"THERMAL SCREEN PRESENT AT NIGHT")
      GO TO 44
   43 WRITE(6,6720 FORMAT(/,2X,"NO SCREEN PRESENT")
   44 IF(ROOF.EQ.1.0) GO TO 46
      GO TO 47
   46 WRITE(6,6730)
 6730 FORMAT(/,2X,"SINGLE GLAZED ROOF")
      GO TO 48
   47 WRITE(6,6740)
 6740 FORMAT(/,2X,"DOUBLE GLAZED ROOF")
   48 RETURN
      END
```

Some data is required by this model and this subroutine handles the input and printing out of such data. The printout is called before the main results are printed so that the user can check and ensure that the correct data has been used by the program.

```
      SUBROUTINE DATREAD

      COMMON/READAT/TEMPONE(98),SUNREAD(98),OUTHUM(98),TEMCHEK(98)
      COMMON/RADIATE/ABSCO3(98) ABSCO7(98).ABSRAD3(98),ABSRAD7(98),
     *PHOTRAB(98),R(98),REFCO3(98),REFCO7(98),SUNRAD(98),SUNSOIL(98),
     *THETA1(98),THETA2(98),THETA4(98),TRANCO3(98),TRANCO7(98),
     *TRARAD3(98),TRARAD7(98)
      J=26
      DO 2 L=1,J
      READ(5,*)TEMPONE(L),SUNREAD(L),OUTHUM(L),TEMCHEK(L)
    2 CONTINUE
      WRITE(6,1600)
 1600 FORMAT(/,2X,"DATA CHECK: POINT TEMP1 SUNREAD
     * OUTHUM HEATER SETPT ")
      DO 3 L=1,J
      WRITE(6,1700)L,TEMPONE(L),SUNREAD(L),OUTHUM(L),TEMCHEK(L)
 1700 FORMAT(15X,I4,F10.3,8X,F6.2,8X,F10.8,5X,F10.3)
    3 CONTINUE
      RETURN
      END
```

This subroutine is called DATREAD and the common blocks listed below the name contain the variables common to both DATREAD and UPDATE. J is a variable used in the DO loop and is set to 26. Inside the DO 2 loop L is incremented between 1 and J and the data values are read in (READ(5,*)). The WRITE(6,1600) and subsequent lines print out the data so that it can be checked.

```
      SUBROUTINE INTDER

      COMMON/INTEGT/TEMP3,TEMP7,TEMP9,TEMP11,TEMP13,TEMP15,TEMP17,
     *TEMP19,TERMP21,TEMP23,TEMP25,TEMP27,HAI,HEATIN
```

```
      COMMON/DERIVT/TEMP3T,TEMP7T,TEMP9T,TEMP11T,TEMP13T,TEMP15T,
     *TEMP17T,TEMP19T,TEMP21T,TEMP23T,TEMP25T,TEMP27T,HAIT,HEATINT
      WRITE(6,5100)
 5100 FORMAT(/ 2X "TEMP: 3,7,9,11,
     * 13, 15,17")
      WRITE(6,5110)TEMP3,TEMP7,TEMP9,TEMP11,TEMP13,TEMP15,TEMP17
 5110 FORMAT(2X,7F10.3)
      WRITE(6,5120)
 5120 FORMAT(/,2X,"TEMPT: 3T 7T 9T 11T
     * 13T 15T 17T")
      WRITE(6,5130)TEMP3T,TEMP7T,TEMP9T,TEMP11T,TEMP13T,TEMP15T,
     *TEMP17T
 5130 FORMAT(2X,7F10.3)
      WRITE(6,5140)
 5140 FORMAT(/,2X,"TEMP: 19 21 23 25
     * 27 HAI HEATIN")
      WRITE(6,5150)TEMP19,TEMP21,TEMP23,TEMP25,TEMP27,HAI,HEATIN
 5150 FORMAT(2X,7F10.3)
      WRITE(6,5160)
 5160 FORMAT(/,2X,"TEMPT: 19T 21T 23T 25T
     * 27T HAIT HEATINT")
      WRITE(6,5170)TEMP19T,TEMP21T,TEMP23T,TEMP25T,TEMP27T,HAIT,
     *HEATINT
 5170 FORMAT(2X,7F10.3)
      RETURN
      END
```

Subroutine INTDER prints out the final values of all the INTEGT and DERIVT variables. This is useful if the user wishes to continue the run for a further number of days because he can then just use these final values in the initialisation routine as the starting values for the new run. The section starts by listing the common blocks which are to be available to both UPDATE and this subroutine, and then headings for the various variables are printed out. In the TEMP: line, the numbers refer to the components and underneath these the final temperatures of these are printed out. The remaining lines do the same for the other components and for the DERIVT variables.

Appendix II

List of Variables

NAME	DESCRIPTION	UNITS
ABSCO3	Absorption coefficient of component 3	
ABSCO6	Absorption coefficient for diffuse radiation on the lower roof	
ABSCO7	Absorption coefficient of component 7	
ABSCO8	Absorption coefficient for diffuse radiation on upper roof	
ABSRAD3	Radiation absorbed by component 3	W/m^2
ABSRAD7	Radiation absorbed by component 7	W/m^2
BAL9	Heat lost by ventilation from component 9	W/m^2
BAL13	Heat lost by ventilation from component 13	W/m^2
BAL15	Heat lost by ventilation from component 15	W/m^2
BAL17	Long wave radiation and latent heat balance for component 17	W/m^2
C	Array name for constants used in the program	
CHLR	Convective/conductive heat loss from the roof	W/m^2
CHLS	Conductive heat loss through the soil	W/m^2
CHT(X)	Coefficients of heat transfer for component X	W/m^2K
COEFF	Array for storage of diffuse radiation transmission absorption and reflection coefficients	
COSTHE1	Cosine of THETA1	
COSTH17	Cosine of angle of incidence of solar radiation with the floor	
COSTHOR	Cosine of angle of incidence of solar radiation with a horizontal surface	
COST1	Cosine of angle of incidence of solar radiation on other roof surface (azimuth = 1st roof azimuth +180°) see text	
COSZEN	Cosine of ZENITH angle	

NAME	DESCRIPTION	UNITS
C3Y	Working variable which takes on the value of a heat transfer coefficient	W/m^2K
DATAIN	Indicates presence or absence of data	
DAYS	Number of days program will run	
DEC	Solar declination	RADIANS
DECLIN	Solar declination	DEGREES
DELTAC	Temperature difference between components 9 and 13	K
DELTEMT	Temperature difference between data points	K
DELTHET	Difference between THETA1R and THETA2R or between THETA6R and THETA5R	RADIANS
DELTHE4	Difference between THETA3R and THETA4R	RADIANS
DELTHE8	Difference between THETA8R and THETA7R, used in the diffuse radiation routine	RADIANS
DELT151	Temperature diference between components 15 and 1	K
DENSITY	Component density	kg/m^3
DERIV	Array used in the economy section takes on value of the derivatives	K/FS
DERVAL	Array used in the economy section, used to store maximum and minimum derivative values	K/FS
DL	Number of daylight hours	HOURS
DN	Daynumber (Jan 1st = 1)	
DT	Time step FORSIM is using	FS
DTM	Time step when a derivative minimum or maximum value occured	FS
DTMAX	Maximum time step FORSIM may use	FS
DTOUR	Value of DT in real seconds	s
DTOUT	Time interval at which results will be recorded for final printout	FS
EMAX	Maximum error allowed by FORSIM	
EMLR(X)	Long-wave emmissivity for component X	

NAME	DESCRIPTION	UNITS
EVAPHT	Energy used to evaporate water latent heat	W/m^2
FLUXTOT	Array used for storage of heat input	W/m^2
HA	Solar hour angle	RADIANS
HAI	Humidity of the inside air	kg/m^3
HAIT	Rate of change of humidity of inside air	kg/m^3FS
HAO	Humidity of the outside air	kg/m^3
HEATCAP	Heat capacity of components	J/kgK
HEATDAY	Energy used to heat glasshouse for the day	kJ
HEATER	Switch for heating system, 1 0 = heater will be used, 0.0 = heater switched off	
HEATIN	Heat input from heater	kJ
HEATINT	Rate of heat input from heater	kJ/FS
HEATOT	Running total of heat input since beginning of run	kJ
HFLUX	Net heat flow into the glasshouse	W/m^2
HLR	Heat lost via the roof	W/m^2
HLS	Heat lost via the soil	W/m^2
HMSATLF	Humidity of saturation at leaf temperature	kg/m^3
HMSAT3	Humidity of saturation at temperature of component 3	kg/m^3
HMSAT7	Humidity of saturation at temperature of component 7	kg/m^3
HMSAT11	Humidity of saturation at temperature of component 11	kg/m^3
HMSAT15	Humidity of saturation at temperature of component 15	kg/m^3
HOUR	Length of time in FORSIM seconds of one hour	FS
HSTAIR	Heat stored in the air inside, relative to 273.16K	kJ
HSTORE	Heat stored in the system relative to 273.16K	kJ

NAME	DESCRIPTION	UNITS
HSTOR1-HSTOR27	Heat stored in components 1-27	kJ
HTDEL	Temperature difference between most recent heater data point and the next data point	K
HTINCR	Increment in temperature applied to most recent heater data point after interpolation	K
HTPWR	Heater output	W/m^2
HUMDEL	Humidity difference between most recent humidity data point and the next data point	kg/m^3
HUMDIF	Humidity difference between inside and outside air	kg/m^3
HUMINCR	Increment in humidity applied to most recent humidity data point after interpolation	kg/m^3
HUMROOF	Relative humidity at roof temperature	%
HV	Heat lost by ventilation	W/m^2
HV9	Heat lost by ventilation from upper air	W/m^2
HV13	Heat lost by ventilation from the lower air	W/m^2
HV15	Heat lost by ventilation from the inside air when screen is absent	W/m^2
I	Integer	
IDAY	Integer variable, whole number of FORSIM seconds in TDAY or integer value of DAYS	FS
IHOUR	Present time in whole number of hours	HOURS
INOUT	FORSIM control variable	
J	Integer	
JM	Integer flag	
JN	Integer flag	
JTEST	Integer	
K	Integer variable dependent upon time, used to allocate array variables	
KMAX	Integer maximum value of K	

NAME	DESCRIPTION	UNITS
LHEAT	Integer	
LK	Integer flag	
LM	Integer flag	
METHOD	FORSIM variable controlling method of integration	
N	Integer	
NKM	Value of N(KMAX) used in print time checks	
NUMBER	Integer array which stores the number of calls FORSIM has made to UPDATE	
NUMBERA	Integer variable used to set NUMBER	
OUTHUM	Storage array for outside air humidity data	kg/m^3
PHI	Latitude of system	DEGREES
PHOTRAB	Amount of photosynthetically active radiation	W/m^2
PI	Pi	
R	Stomatal resistance to latent heat exchange	s/m
RAD	Degrees to radians conversion factor	RADS/DEG
RAD3	Radiation balance on component 3	W/m^2
RAD7	Radiation balance on component 7	W/m^2
RAD11	Radiation balance on component 11	W/m^2
RAD17	Radiation balance on component 17	W/m^2
RAD90	90 degrees expressed in radians	RADIANS
RAD180	180 degrees expressed in radians	RADIANS
REFC03	Reflection coefficient for component 3	
REFC06	Reflection coefficient for lower roof layer diffuse radiation calculation	
REFC07	Reflection coefficient for component 7	

NAME	DESCRIPTION	UNITS
REFC08	Reflection coefficient for upper roof layer diffuse radiation calculation	
REFPAR	Parallel component of reflection coefficient	
REFPAR4	Parallel component of reflection coefficient for lower roof	
REFPAR8	Parallel component of reflection coefficient for upper roof diffuse radiation calculation	
REFPERP	Perpendicular component of reflection coefficient	
REFPER4	Perpendicular component of reflection coefficient for lower roof	
REFPER8	Perpendicular component of reflection coefficient for upper roof diffuse radiation calculation	
RELHU11	Relative humidity at temperature 11	%
RELHU15	Relative humidity at temperature 15 (inside air)	%
RES	Component of stomatal resistance dependent on amount of photosynthetically active radiation	s/m
RHLR	Radiative heat loss from the roof	W/m^2
RI(X)	Refractive index of X	
RLW1	Long-wave radiation from sky	
RLW31	Long-wave interaction between 3 and 1	W/m^2
RLW37	Long-wave interaction between 3 and 7	W/m^2
RLW311	Long-wave interaction between 3 and 11	W/m^2
RLW317	Long wave interaction between 3 and 17	W/m^2
RLW711	Long-wave interaction between 7 and 11	W/m^2
RLW717	Long wave interaction between 7 and 17	W/m^2
RLW1117	Long-wave interaction between 11 and 17	W/m^2
ROOF	Flag to indicate presence of single or double glazing. 1.0 = single, 2.0 = double glazing	
SCRDRAW	Screen closing time	FS
SCREEN	Flag to indicate presence of a thermal screen at night, 1.0 = screen present 0.0 = screen absent	

NAME	DESCRIPTION	UNITS
SCROPEN	Screen opening time	FS
SINSNAZ	Sine of solar azimuthal angle	
SINTHE2	Sine of THETA2	
SINTHE3	Sine of THETA3	
SINTHE4	Sine of THETA4	
SINTHE6	Sine of THETA6 used in diffuse radiation routine	
SINTHE7	Sine of THETA7 used in diffuse radiation routine	
SINTHE8	Sine of THETA8 used in diffuse radiation routine	
SUMTHET	Sum of THETA1R and THETA2R or of THETA5R and THETA6R	RADIANS
SUMTHE4	Sum of THETA3R and THETA4R	RADIANS
SUNAZ	Solar azimuth angle	DEGREES
SUNDEL	Radiation intensity difference between most recent solar data point and the next data point	W/m^2
SUNGAIN	Net solar radiation gain to the glasshouse	W/m^2
SUNINCR	Radiation increment to most recent data point after interpolation	W/m^2
SUNRAD	Solar radiation	W/m^2
SUNREAD	Storage array for solar radiation data	W/m^2
SUNRISE	Time of sunrise	FS
SUNRI10	Sunrise time + V(22) minutes of air mixing time	FS
SUNSET	Time of sunset	FS
SUNSOIL	Solar radiation absorbed by the soil	W/m^2
T	FORSIM time variable	FS
TAUALF1	Transmission coefficient for upper roof medium considering absorption losses only	
TAUALF2	Transmission coefficient for lower roof medium considering absorption losses only	
TDAY	Length of one day in FORSIM seconds	FS
TDAY1	Variable used in K calculation routine	FS

NAME	DESCRIPTION	UNITS
TDL	Daylight length in FORSIM seconds	FS
TDLM	Length of morning/afternoon (ie sunrise to noon)	FS
TEMCHEK	Storage array for heater setpoint temperature data	K
TEMDEL	Temperature difference between most recent outside temperature data point and the next point	K
TEMINCR	Temperature increment applied to upper air temperature during air mixing after removal of screen	FS
TEMPONE	Storage array for outside air temperature data points	K
TEMPY	Working variable, takes on the value of a roof layer temperature depending on single or double glazing	K
TEMP1- TEMP29	Component temperatures	K
TEMP2T TEMP27T	Temperature change for each component	K/FS
TFIN	Simulation finishing time	FS
THETA1	Angle of incidence of solar radiation on upper roof surface	DEGREES
THETA1R	THETA1 expressed in radians	RADIANS
THETA2	Angle of refraction in upper roof layer	DEGREES
THETA2R	THETA2 expressed in radians	RADIANS
THETA3R	Angle of incidence of solar radiation on lower roof, if present	RADIANS
THETA4	Angle of refraction in lower roof, if present	DEGREES
THETA4R	THETA4 expressed in radians	RADIANS
THETA5R	Angle of incidence of diffuse radiation on underside of lower roof	RADIANS
THETA6R	Angle of refraction of diffuse radiation in the lower roof medium	RADIANS
THETA7R	Angle of incidence of diffuse radiation on underside of upper roof	RADIANS

NAME	DESCRIPTION	UNITS
THETA8R	Angle of refraction of diffuse radiation in the upper roof medium	RADIANS
THICK(X)	Thickness of component X	m
TIM	Time of day	Hrs.mins
TIMDE	Time of day in decimal hours since mid-night	HOURS
TIMDEC	Storage array for TIMDE	HOURS
TIME	Storage array for TIM	Hrs.mins
TIMERSC	Time variable use din air mixing routine	FS
TINCR	Temperature increment applied to most recent outside air temperature data point after interpolation	K
TLEAF	Leaf temperature	K
TM	Time at which a derivative minimum or maximum occured	FS
TMIDAY	Time of mid-day	FS
TMINS	Number of minutes after the hour	FS
TMINSAR	Array storage for TMINS	FS
TMINVAL	Total number of minutes represented by TIMDEC	MINUTES
TMINVAR	Time variable used in air temperature interploation	FS
TMP1DAT	Most recent outside air temperature data point	K
TOUR	Time of current day in FORSIM seconds. If the run is for two days, at mid-day on second day, T will be 7.5 and tour will be 2.5. See text.	FS
TRANC03	Transmission coefficient for component 3	
TRANC07	Transmission coefficient for component 7	
TRARAD3	Radiation transmitted by component 3	
TRARAD7	Radiation transmitted by component 7	W/m^2
TRI	Temperature rise index. This is the temperature rise per W/m^2 in one FORSIM SECOND. See text.	$K/(W/m^2)FS$
TRPAR	Parallel component of transmission coefficient for upper roof	

NAME	DESCRIPTION	UNITS
TRPAR2	Parallel component of transmission coefficient for lower roof	
TRPERP	Perpendicular component of transmission coefficient for upper roof	
TRPERP2	Perpendicular component of transmission coefficient for lower roof	
TTOT	Storage name for sum of FORSIM time steps	FS
TTOTA	Variable used to calculate TTOT	FS
V	Array name for variables set by user to describe system	
VDELTA	Difference between active and passive ventilation rates divided by 100	m^3/m^2s
VENT	Actual ventilation rate	m^3/m^2s
VHLR	Heat loss through ventilation	W/m^2
VTOPEN	Percentage opening of the vents	%
ZENITHA	Solar zenith angle	DEGREES
ZHAI	Array name for inside air humidity	kg/m^3
ZTEMP1-ZTEMP27	Array names for component temperatures. These are used for storage and print-out	°C

Appendix III

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