MOVABLE THERMAL INSULATION FOR GREENHOUSES

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ABSTRACT

Movable curtain insulation systems can save substantial amounts of heat energy in commercial greenhouses. Work at Rutgers over the past few years has concentrated on automatically controlled mechanical systems, which draw curtains across a supporting network of polypropylene monofilaments in double-covered polyethylene greenhouses. Energy savings ranging between 22% and 58% have been obtained. It has been found that in a full-scale commercial greenhouse, the energy savings depend upon the mechanism used to pull the curtain and the material used.

It is important that the system enable all edges to be closed tightly to prevent warm air leakage past the curtain. In tightly closed systems, the energy savings depend upon the geometry of the curtain closure and the material used. The curtain area should be minimized, therefore, in gutter-connected houses; the curtain should be drawn horizontally. The completely porous materials tested provided the least heat savings but were easy to handle mechanically and had the potential to also serve as summer shade. Thermally opaque, airtight materials provided more heat savings and the best thermal insulation was provided by materials aluminized on their upper surfaces. Two such materials tested were shown capable of a 58% energy savings.

In some cases, condensation dripping from the greenhouse onto the curtain can cause mechanical problems. If the curtain geometry does not allow this moisture to drain off, a material, which allows water to pass through, should be used or the curtain should be perforated. It is desirable for a curtain to be strong and also to be capable of compacting into a small bundle for daytime storage to minimize shading.

Preliminary tests of rigid board insulation systems indicate that nighttime heat requirements can be reduced to about one half of the requirement for the best curtain material systems. Satisfactory mechanisms for the deployment of such insulation systems need to be developed.

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INTRODUCTION

Greenhouses are designed to admit light and are therefore inherently poorly insulated. During the day, the greenhouse is usually warmed directly by the sun but at night, heat must be supplied to maintain the required thermal environment. The major mechanisms for heat loss at night are conduction through the walls and roof, radiation loss and infiltration. Since the rapid escalation of fuel prices began, interest in energy conservation measures has increased dramatically. Most energy conservation measures are directed at reducing heat loss due to one or more of the three major heat loss mechanisms. The most widely recommended conservation measures are described in detail in extension publications, ‘Energy Conservation and Solar Heating of Greenhouses’, published by the Northeast Regional Agricultural Engineering Service and ‘Conserving Energy in Ohio Greenhouses’, published by the Ohio Cooperative Extension Service.

One very effective energy conservation system encloses the crop and the heating system at night to reduce heat loss. Retraction of the system in daylight hours allows light to reach the plants. Such movab1e curtain insulation systems have been given a number of names including heat blankets, thermal screens, etc. Research on the development and evaluation of these systems began at Rutgers in 1972 and the first designs were based on low-cost mechanisms developed by Roberts (1970) for pulling blackcloth shade. The results of the earliest studies were first reported by Mears et al in 1974 and a more comprehensive engineering analysis of these systems and basic data on heat transfer properties of some curtain materials were presented by Simpkins et al in 1976.

While research efforts in New Jersey were concentrating on the use of thermal blankets in polyethylene covered greenhouses, work in Pennsylvania, White et al in 1976, focused on the performance of these systems in glass houses. Considerable work on thermal blankets in greenhouses has been conducted also in Europe and Japan. One very early study on a movable insulation system using a reflective material was conducted in the 1940’s in England by Winspear (1977). There are many references on the European work and a good review can be found in the proceedings of the Symposium on More Profitable Use of Energy in Protected Cultivation edited by Kristoffersen (1978). Discussions on the Japanese systems are found in the proceedings of the Symposium on Potential Productivity in Protected Cultivation edited by Mihara and Takakura (1978). In many references, energy savings are reported on a percentage basis, for example, for glass greenhouses Von Zabeltitz (1978) reports the following savings:

Black polyethylene film	40—44%
Aluminized film on Web	48—59%
Woven polyester filter	30—35%
Shadowing systems	15%

While fuel savings based on percentages are easily understood, it is necessary to have information on the actual thermal properties of the materials since percentage savings depend upon the condition of the greenhouse before insulation, the method of curtain installation and other factors.

RESEARCH RESULTS - LABORATORY EVALUATIONS

In 1976 Simpkins et al reported on the thermal properties of a number of thin film plastic materials that could be used as insulating curtains. The thermal transmittances of these were measured in a laboratory. Then tests were conducted in an environmental control chamber and in a small prototype greenhouse. By comparing the results of these tests, it was possible to separate out the conductive and radiative heat transfer coefficients.

Since the publication of those results, efforts have been applied to determine the heat savings effected by various materials installed in full size greenhouses, to develop improved curtain materials in co-operation with industry and to improve the mechanical systems used to draw the curtains at night. With regard to the development of new materials, Stauffer Chemical Company* developed a series of materials designed specifically for greenhouse insulation and the best in that series is now being marketed under the trade name 'Ultrafilm'. * Samples of several experimental materials were sent to Holland for laboratory studies of their thermal properties. Some of the results sent to us by A.M.G. van den Kieboom (1978) are presented in Table 1. These results include four of the experimental vinyl curtain materials and a number of materials tested by van den Kieboom, which are in use in Europe. The thermal transmittance, reflectivity and emmisivity are taken between 8 and 14 µm. The location of the aluminum in the vinyl aluminized polyester laminate is between the vinyl and the polyester. Therefore, the thermal reflectance of the aluminized side is 0.33 to 0.35 as the overlying polyester layer is partially opaque to IR, even though it is only 0.01 mm thick. In contrast, the metalized PETP, which has the aluminum protected only by a thin lacquer coating, has a higher thermal reflectance of 0.71.

RESEARCH RESULTS IN PROTOTYPE GREENHOUSES

In connection with solar research, several curtain materials and deployment techniques have been evaluated and carefully monitored in a 5.2 m by 7.3 m research greenhouse over five full heating seasons. Based upon the observed results, several important considerations regarding such systems have been determined. First, it is most important that the curtain system completely close off air exchange between the crop zone and the attic (unheated) portion of the greenhouse. Second, insofar as possible, the curtain insulation system should enclose the heated crop zone with a minimum curtain area. Third, the curtain material should be aluminized for maximum heat savings in a double polyethylene house. These conclusions are borne out by the data presented in Table 2. The heat loss coefficients determined for the temperature difference between the crop area and outdoors are based upon the glazed area of the greenhouse. Comparison of the heat loss coefficient when the curtain was mechanically drawn and when the edges and corners were carefully closed manually indicates the importance of having a system that makes good air seals. Comparison of aluminized material to opaque material with all other conditions the same indicates that the

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*Reference to commercial products or trade names is made with the understanding that no discrimination and or endorsement is intended or implied.

Table 1 Thermal radiation properties of insulating curtain -- 8µm to l4µm.

Material	Side	Transmittance	Reflectance	Emmisivity
Clear Vinyl/Aluminized	Vinyl	0.07	0.08	0.85
Polyester (Stauffer)	Aluminum	0.07	0.33	0.60
Black Vinyl/Aluminized	Vinyl	0.05	0.07	0.88
Polyester (Stauffer)	Aluminum	0.05	0.35	0.60
Black Vinyl (Stauffer)		0.09	0.06	0.85
Clear Vinyl (Stauffer)		0.19	0.05	0.76
Black Polyethylene		0.23	0.06	0.61
Milkwhite Polyethylene		0.75	0.10	0.15
Woven Polyethylene Strips, milkwhite) (Nicolon		0.71	0.13	0.16
Black/White Polyethylene (Twilene)		0.50	0.08	0.42
Metalized PETP (Camtherm	Material	0.08	0.14	0.78
	Aluminized	0.08	0.71	0.21
Knitted and Metalized PETP	Material	0.28	0.06	0.66
	Aluminized	0.28	0.27	0.45
Woven PMA (W.65)		0.31	0.11	0.58
Woven PETP (Terylene)		0.10	0.07	0.83
Reemay 2016 (DuPont)		0.31	0.09	0.60
Floratex 60		0.18	0.08	0.74
Floratex 80		0.11	0.09	0.80
Floratex 100		0.10	0.08	0.82
Floratex 101		0.09	0.10	0.81

Table 2 — Insulation curtain effectiveness in 5.2m by 7.3m greenhouse

Curtain Type	Curtain Area m^2	Heat loss coefficient based on $80m^2$ glazed area (W/m^2)	
		mechanically closed	edges tucked in
No curtain		4.59	4.59
Black polyethylene	46	2.87	2.41
Black polyethylene plus air cap on side walls	46	2.58	2.12
Aluminized polyester/vinyl	46	2.47	1.95
Aluminized polyester/vinyl	63	3.44	
Rigid insulation panel, 2.5 cm	46		1.03

aluminization causes a significant fuel savings increase. Figures 1 and 2 illustrate the advantages of a curtain configuration with a minimum of surface area. In both cases, the greenhouse floor area was 38 m^2 and the greenhouse glazed area 80 m^2. In the straight installation, the curtain area was 50 m^2 and in the curved 63 m^2. The curved installation provides slightly more volume in the greenhouse for plant production as it more normally follows the greenhouse structure, but there is 35% higher heat loss associated with this geometry.

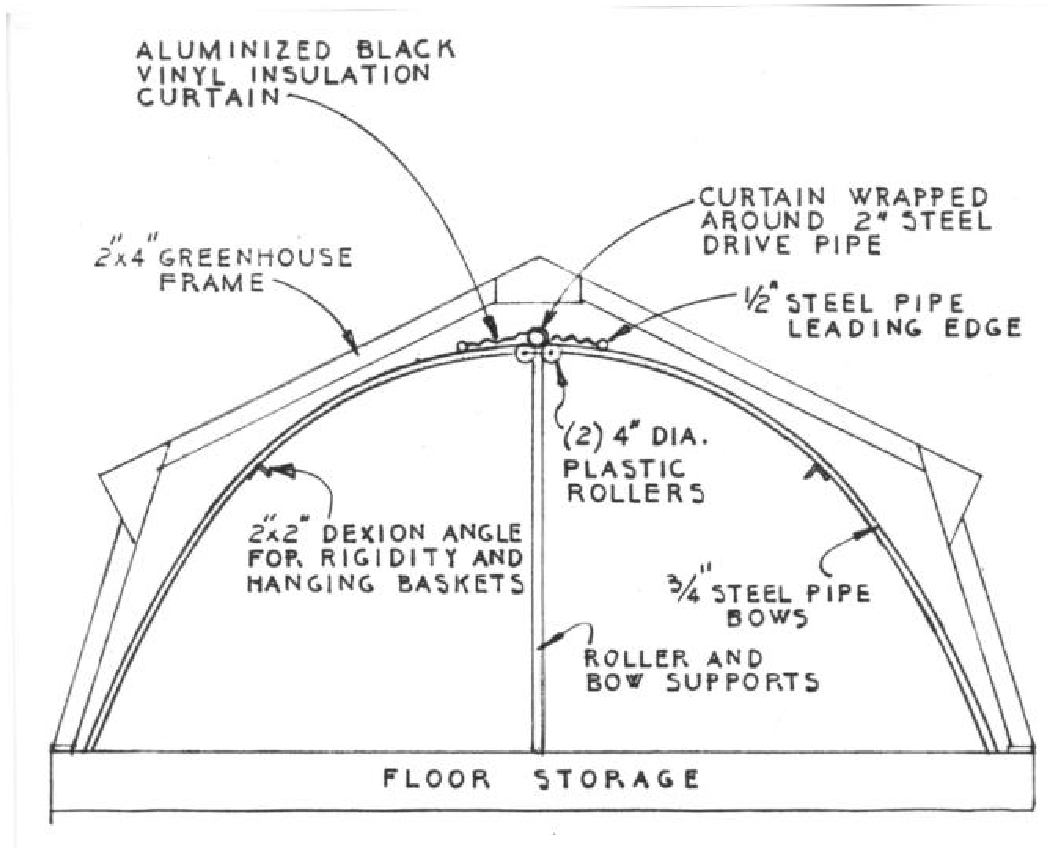

Fig. 1 Curved Curtain Insulation System for Small Prototype Greenhouse

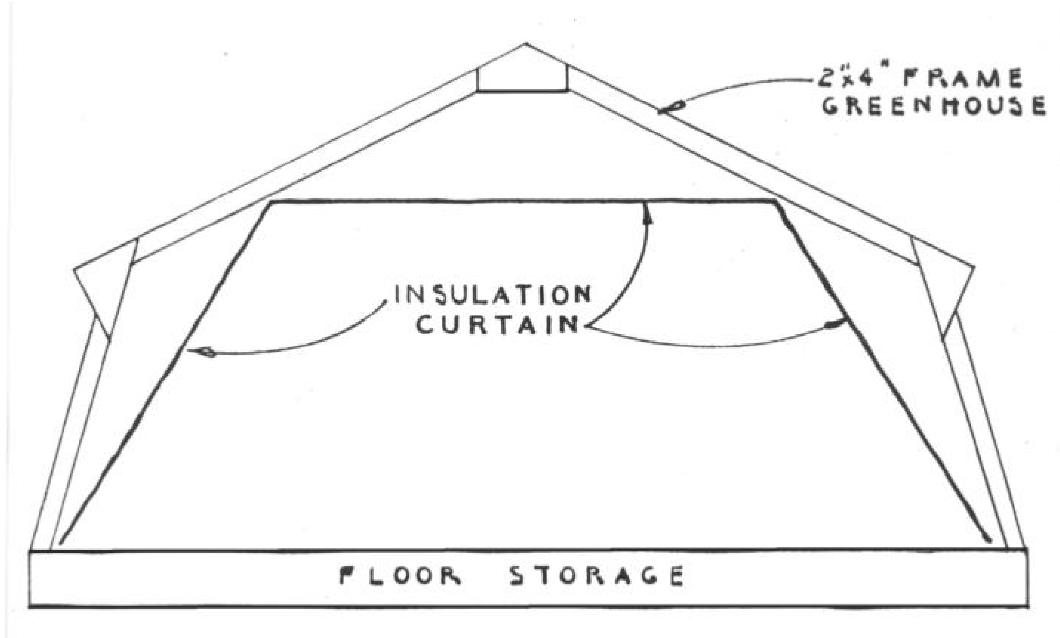

Fig. 2 Planar Insulation System for Small Prototype Greenhouse

In a larger research greenhouse used for vegetable production, an overall heat transfer coefficient of 2.58 W/m^2K was measured for three types of curtain materials tested, black polyethylene, black vinyl and clear vinyl. These results indicate that all three materials are thermally equivalent, i.e., opaque to infrared radiation. This confirms the laboratory studies indicated in Table 1. The geometry of this system is shown in Fig. 3. The excellent overall heat transfer coefficient is due to the following:

—Since the curtains move horizontally and seal off the attic, it is a bit easier to seal the edges than in the small prototype greenhouse.

—The curtain geometry is optimum, i.e., equivalent to the floor area for interior bays.

—The North wall of this greenhouse is highly insulated with a fill of Styrofoam beads between the poly layers and a clear vinyl curtain closes off the South wall and ends.

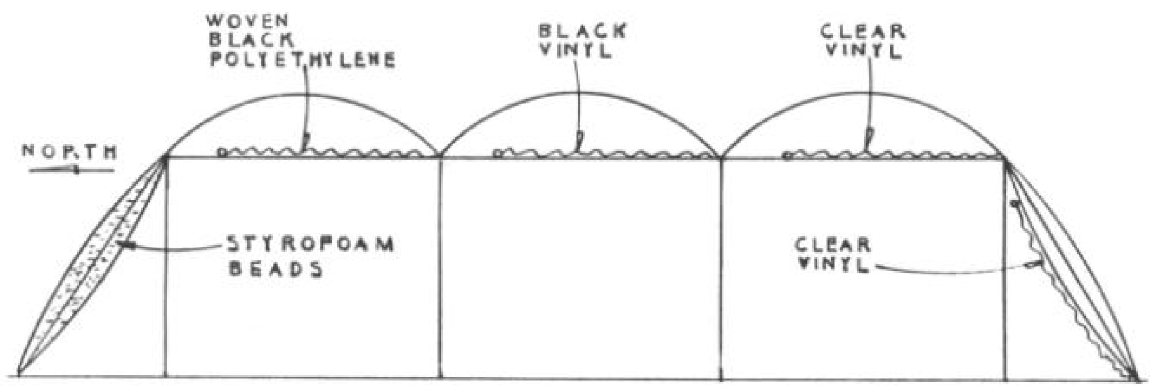

Fig. 3 Curtain Insulation System in Vegetable Production Greenhouse

During the sixth heating season, 1980, ‘81, the 5.2 m by 7.3 m research greenhouse was retrofit with a movable system of rigid board insulation of plastic foam 2.5 cm thick which completely enclosed the crop growing area. Care was taken to insure that the joints between panels were carefully sealed when the system was closed at night. Any air leaks would result in a substantial increase in heat transfer. Although the mechanical system designed for the prototype work is not fully developed for practical field application, it was adequate for determining the heat transfer parameters of the system and the effects of increased insulation effectiveness on the performance of the heating system.

It was found that this board insulation system reduced the heat transfer coefficient of the structure to 1.03 W/m^2K based on the glazed area of the greenhouse. This is about one half of the heat transfer coefficient that has been obtainable with the use of the most effective thin film materials. As the conductivity of the board itself is 0.72 W/m^2K the heat transfer due to infiltration must be 0.31 W/m^2K, a figure which is consistent with previous measures of infiltration heat transfer in polyethylene covered greenhouses. In addition to the reduction in heat requirements the major observations of the performance of the system are:

—Elimination of condensation on the underside of the insulation even though relative humidities exceeded 96%, as the inner surfaces are warm.

—All of the heat requirement of the greenhouse can be met by the floor heating system at lower floor water temperatures than are required with less effective insulation systems.

—For solar heated systems lowered floor storage temperature requirements will result in improved collector efficiency and smaller collector requirements.

—Temperatures within the growing area have been very uniform with maximum variations not exceeding 1^{o}C.

RESEARCH RESULTS IN A FULL SIZE COMMERCIAL GREENHOUSE

The operation of a 0.54-hectare solar heated demonstration project has provided an excellent opportunity to evaluate curtain insulation materials for both thermal and mechanical performance. The greenhouse has 10 bays, gutter connected, covered with double polyethylene. There are two automatic drive systems for the overhead insulation systems that pull the curtains across a network of supporting monofilaments from gutter to gutter. The performance of various materials can be compared directly under identical operating conditions. The average thermal performance of the total system can be obtained by measuring the total heat loss from the building and inside and outside temperatures. The thermal performance of individual curtains can be evaluated by measuring the attic temperature over individual curtains.

In evaluating the thermal performance of the various curtain materials, it has been found that there is a significant variation in the heat loss coefficient from hour to hour or night to night. These variations are caused by changes in cloud cover, wind velocity, precipitation, amount of condensation within the greenhouse and the mechanical performance of the pulling system, i.e., how well each curtain edge seals each night and the presence of ponds of water on top of the curtain or unrepaired tears. Therefore, it is necessary to evaluate a curtain and determine its total energy savings over an entire cropping season in order to be certain of the systems effectiveness.

The thermal performance of a number of curtain materials tested is presented in Table 3 and Fig. 4. The mean heat transfer values are presented in the table and the figure shows a bar chart depicting a range of plus and minus two standard deviations from the mean. From this chart and the table, it is clear that over varying operating conditions the thermal performance of all of the materials except for the Reemay and double knit cloth are not statistically significantly different. Variations in performance caused by changes in weather and mechanical sealing of the curtain edges dominate differences due to the curtain material. The reason that the Reemay and double knit cloth transmit more energy than the others is that these materials are very open in their construction and air moves through them quite readily.

In this greenhouse, the bay spacing is nominally 6 m and in the spring, the floor is 90% covered by the crop of annual bedding plants. Controlling the draining of the condensation, which collects on the top of the curtain during the night, is critical and a great deal of attention has been paid to solving this problem. All of the poly curtains used alone or in combination with the Reemay had 2 mm holes made by drilling the plastic while it was on the roll on either 15 cm or 30 cm spacing. The closer hole spacing allowed the water to drain through better than the wider spacing, but both techniques are judged acceptable. Drops of water on the top of the curtain tend to close the holes off but deep puddles cannot build up. The 97% shade material and the Foylon both pass water at any point on the fabric, as the material is not completely tight. In both cases, it is possible to sustain a puddle on the curtain about a cm deep. Touching the underside of a curtain starts the water flowing and in any case, water will not build up to any substantial depth before draining through.

Table 3 — Thermal performance of selected insulating curtain materials in a commercial greenhouse

Material description	Source	Heat transfer coefficient based on roof area W/m^{2}K
Reemay Spunbonded Polyester	DuPont	3.59
Double Knit Cloth	Van Wingerden	3.53
Black Polyethylene (drilled)	Monsanto	2.70
Reinforced Polyethylene	Shade Corp. of America	2.59
Black Polyethylene over Reemay		2.49
Prefabricated Aluminized Vinyl	Stauffer/Revere	2.38
Reemay over Black Polyethylene		2.21
Aluminized Vinyl – worn	Stauffer	2.18
Polypropylene Shade 97%	Shade Corp. of America	2.16
Experimental black Poly Film (drilled)	Monsanto	2.10
Foylon	Duracote	1.93

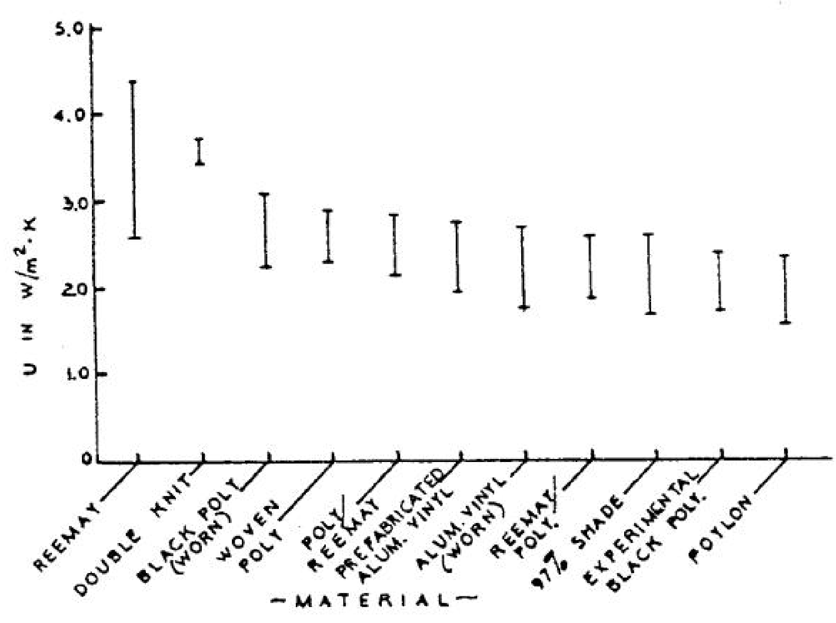

Fig. 4 Heat Transfer Coefficients for Selected Curtain Types

The aluminized polyester/vinyl laminate was installed with no provision for drainage during one growing season and the maintenance required to get the ponded condensation off the curtain created an unacceptable management problem. Later an attempt was made to fabricate this material into a curtain which had a 3 cm wide strip of woven scrim sewn into the curtain as a seam over the center walk. The plan was to allow the water collecting on the curtain to migrate to the center of the curtain when the open scrim seam was located over the center walk. This concept worked well in only a few areas on the large curtain. In sewing the seam, the stitches gathered the material so that the central drain passage was pulled tighter than the parent material on either side, thereby creating a dam preventing the water from reaching the drain.

The comparative thermal performance of various materials can best be determined in short term tests when all environmental parameters are held constant. Grouping the curtains tested into three basic categories and comparing representative materials in each class produces the results shown in Fig. *5*. With no curtain, the thermal conductivity of the uninsulated greenhouse, based on roof area, is 4.59 W/m^{2}K. Plotting heat loss vs. temperature difference under the curtains to outside produces the curves shown for the uninsulated house and three curtains. The slopes of the lines are the thermal conductivity coefficients. This graphically shows the heat savings potential of installing curtains. The porous cloth materials provide substantial energy savings while thermal performance is improved by making the material non-porous to air and by aluminizing the material.

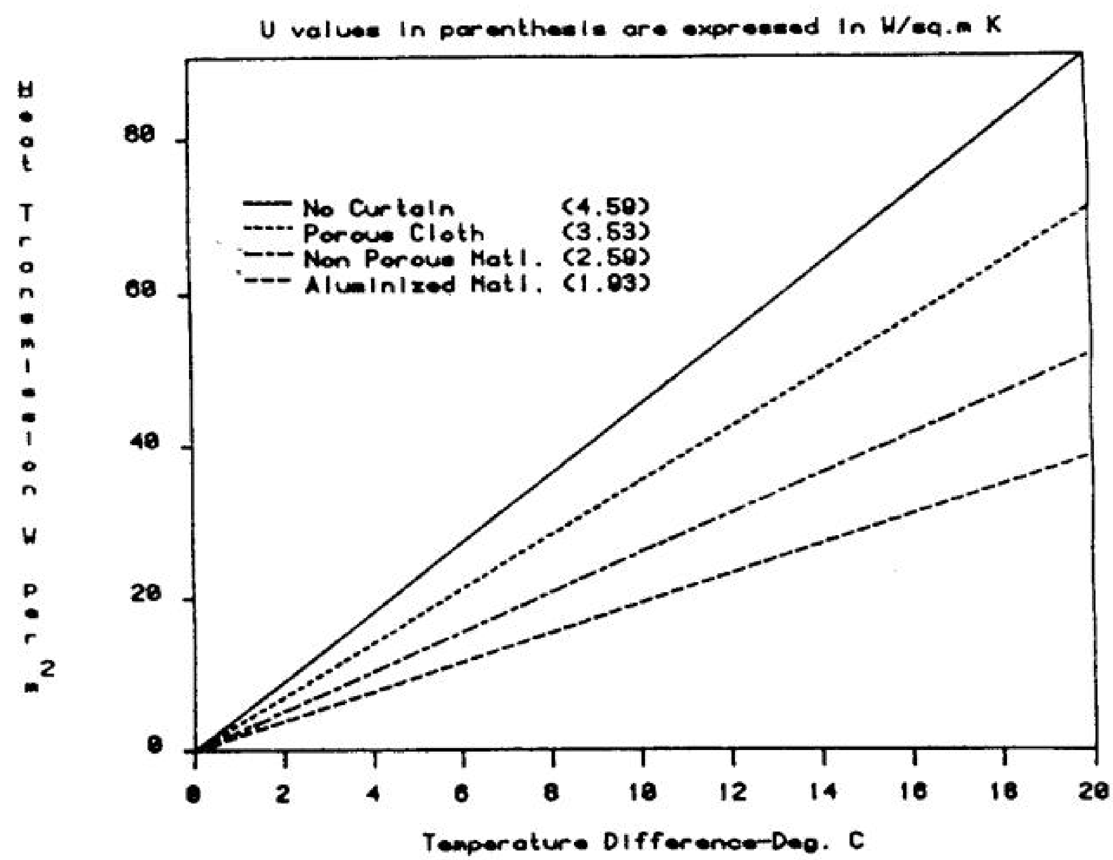

Fig. *5* Heat Transmission of Various Curtain Types

It was previously reported by Simpkins et al (1976) that an aluminized material will perform better thermally with the reflective side facing the coldest temperature (i.e., facing up in a horizontal system). This was verified in side by side testing through two cropping seasons. The heat transfer coefficient averages 5% less with the aluminized surface facing up than with the aluminized surface facing down when the edges are well sealed. If the seals are not secure, then this difference is not apparent and the heat loss is increased for both cases.

As many of the curtain materials perform similarly in regard to heat savings, it is important to consider other factors relevant to total system performance. The main problem in curtains pulled horizontally is the formation of ponds of water on the curtains. It is easy to understand the importance of avoiding this problem when one considers the size of the curtain system in a large greenhouse. Figure 6, which shows a curtain from above and below while closing, illustrates this

Fig. 6 Curtain System Viewed from Above and Below while Closing

point. This problem can be solved for row crops by suspending the supporting monofilaments over the row so that water will accumulate over the center of the walk where the curtain can be perforated to drain the water without harm to the plants. It is apparent that for a crop covering a large floor area without walks, a perforated or porous material will have a definite advantage in this regard. In order to reduce daytime shade, it is best if a curtain have a good ‘hand’ or capability to be compressed into a small space. In this regard, the Reemay, the double knit cloth and the Foylon performed the best. The aluminized vinyl and experimental poly material ranked next. The woven polyethylene and regular black polyethylene were even more bulky and the 97% shade material was the most cumbersome to fold up.

It was found that there was a strong apparent correlation between a material’s ability to drain water and its durability. Whenever large ponds of water are allowed to form, they severely load the curtain and this hastens wear of the curtain and increases the probability of tearing the curtain. In this regard, the double knit cloth, the Foylon, the 97% shade poly and the woven polyethylene were judged the most durable. The Reemay did drain well but the material is inherently weaker than the others. The experimental poly and the Reemay black polyethylene combinations were judged to be next most durable and the fabricated curtain was the least durable. It should be noted in this regard that the durability of this curtain was prejudiced by the fabrication technique, which prevented proper drainage of water and mechanical problems were all traceable to the accumulation of large ponds of water on top. In other tests, it has been found that the laminate of vinyl and aluminized polyester is quite durable if provisions are made to drain off condensing water.

It should be noted that as experience has been gained with the system, improvements have been made in the mechanical system, which enable all curtain materials to perform closer to their theoretical potential. Good mechanical seals at the edges are essential as the circulation of warm air from the crop area into the attic provides a thermal short circuit reducing the effectiveness of any material.

SUMMARY

Movable curtain insulation systems can save substantial amounts of heat energy in commercial greenhouses. Work at Rutgers over the past few years has concentrated on automatically controlled mechanical systems which draw curtains across a supporting network of polypropylene monofilaments in double-covered polyethylene greenhouses. Uninsulated greenhouses having a heat transfer coefficient of 4.59 W/m^2K can have this reduced to a value between 1.93 to 3.59 W/m^2K depending upon the type of curtain material used and the effectiveness of closure of the mechanical system. A number of materials are useful and have properties appropriate to this application. The best choice of material will depend upon the application.

The open, woven cloth materials tested offer significant energy savings, handle well mechanically, drain condensate and have a potential to double as shading materials in the summer. The thermally opaque and air tight materials tested offer significantly increased energy savings but provision must be provided to drain off condensation if the materials do not self drain. Some of these materials were found somewhat harder to handle and bulkier to store than the open woven cloth. It has also been shown that aluminizing the upper surface of a curtain can increase heat savings if the edges are well sealed. Also, some opaque and aluminized materials have a potential use for photoperiod control.

The important properties of curtain materials are: their thermal properties, their mechanical properties including strength and ability to compact easily for daytime storage and their ability to drain condensing water. This last property is not important if the curtain can be installed to that condensation does not collect on the curtain or if the curtain can be perforated. There are a variety of useful materials commercially available and careful consideration should be given to the selection of a curtain material based upon specific requirements at each installation.

Preliminary tests of rigid board insulation systems indicate that nighttime heat requirements can be reduced to about one half of the requirement for the best curtain material systems. Satisfactory mechanisms for the deployment of such insulation systems need to be developed.

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Appendix of additional figures added January 2004

A model built to demonstrate low-cost mechanism for pulling blackout curtain for photoperiod control for greenhouses is shown above. This system was installed in the Floriculture teaching greenhouse on campus and is shown open and closed below. To demonstrate the effectiveness of this system a unit heater was used to heat the space below the curtain. It was shown that fuel consumption to maintain a given temperature difference with outdoors was about half with the curtain closed as opposed to open.

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Installation of test curtain materials in 0.54-hectare greenhouse before the development of modern curtain pulling systems was a challenge. The students figured out a pulley system to draw the curtain over the galvanized trusses without tearing the material.


The curtains drawn from gutter to gutter in this installation with tails to seal at the gutters provide an insulated attic space under the double-poly roof (left). With 10 bays and 20 sections to curtain off there was the opportunity to evaluate a variety of potential materials (right). The curtain closing over an early fall poinsettia crop is shown below.
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Most of the early experimental materials tested were plastic films of various sorts, which did not drain and would therefore collect condensation. Strategic holes would drain the water but the effect on bedding plants with slow release fertilizer in the mix was undesirable, as the drips would support faster growth as shown below.

Modern material made of alternating clear and aluminized strips shown below is used for both heat retention and summer shade. Heat transfer coefficients for this type of material are needed.
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A beautiful crop such as the poinsettias shown at the right is the desired end result. In this particular installation there was a floor heating system as well as the curtain insulation and the combination of these two systems enabled this crop to be grown at slightly lower canopy air temperatures. This resulted in increased anthocyanin in the bracts resulting in a higher value crop.