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EVALUATION OF AN EXPERIMENTAL GREENHOUSE FILM  
WITH IMPROVED ENERGY PERFORMANCE

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**SUMMARY:**

Four 8.5m x 14.6m frame greenhouses were used to test an experimental plastic film glazing material and compare it with conventional plastic film glazing. Heat savings and crop responses have been measured and evaluated. Significant energy savings have been obtained and suggestions for possible changes in growing practices, which save additional energy, are offered.



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## Evaluation of an Experimental Greenhouse Film with Improved Energy Performance

Joel C. Simpkins\*, David Mears\*, William Roberts\*, Harry Janes\*\*

### Introduction

A testing program was begun in the spring of 1982 to compare the performance of infrared radiation (IR) absorbing polyethylene greenhouse glazing films to that of a conventional film. The objectives were to evaluate the new material from the standpoints of ability to save energy, light transmission and crop response for some representative crops. The first test film formulation was evaluated in spring and fall 1982 and spring 1983. This material will be referred to as infrared test material 1 (M1) in this report. The second material, referred to as infrared test material 2 (M2) was evaluated in the fall of 1983 and spring of 1984. The test material was provided by Monsanto and is characterized as a colorless film, which diffuses light due to the addition of the IR absorber. IR test material 2 (M2) is being marketed under the trade name, "Cloud Nine". Monsanto 602 film was used for comparison on all tests.

The major objective of this study is the evaluation of the effect of the IR absorber on the energy balance of the greenhouse and seasonal energy requirement. Four new greenhouses were constructed and fully instrumented for this program. Typical fall and spring greenhouse crops were produced and crop response to the glazing system was evaluated. In depth discussion of plant response as affected by the IR absorber in the glazing is being presented independently.

### Testing System Description

Four separate 8.5m wide (28 ft) by 14.6m (48 ft) long [Benbow greenhouses](#) were erected for this project by the supplier during the winter of 1981-82. The houses are identical and have 2.1m (7 ft) high vertical sidewalls with an arch-shaped roof. The floor area is 125m<sup>2</sup> (1350 sq ft) and the roof and wall heat loss area totals 125m<sup>2</sup> (2700 sq ft). The houses are all oriented with the 14.6m dimension running east to west and are positioned in a straight line as shown in Fig. 1. The 3.7m (12 ft) by 6.4m (21 ft) boiler/computer shed shown in this figure houses a 168.5 kW (575,000 Btu/h) central boiler that supplies hot water to all four test greenhouses and the central components of the computer based data acquisition system.

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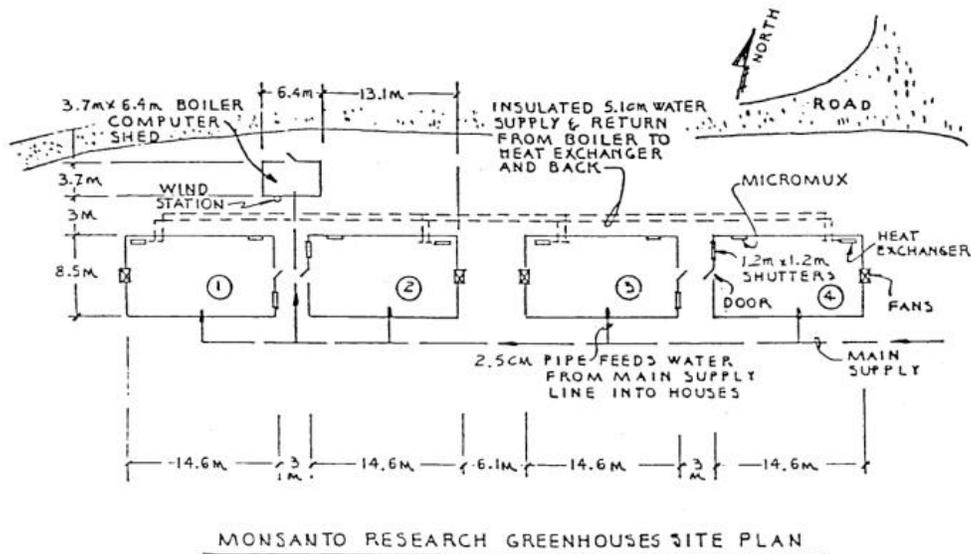
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Reference to commercial products or trade names is made with the understanding that no discrimination or endorsement is intended or implied.

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Testing facility in the fall of 1983. House 2, the second from the right, has 602 on the outside  
[Return to Testing System Description](#)



**Fig. 1.** Testing Facility Site Plan

All greenhouses are identical internally as shown in Fig 2. Crops are grown on benches and air is continuously circulated through perforated 0.6m (24 in.) diameter polyethylene air distribution tubes installed under the benches. The tubes are connected to a 0.76m (30 in.) diameter polyethylene header duct that is attached to the [heat exchanger](#). When heat is required, the circulator pump is turned on and the heat input continuously monitored by the data acquisition system, which measures the temperature of the water entering and leaving the heat exchanger and the water flow rate. Each greenhouse has its own water to air heat exchanger with a 40.75 kW (139,000 Btu/h) nominal rating. The individual 125 W (1/6 horsepower) circulator pumps are controlled by a single stage thermostat housed in an aspirated [control box](#) located in the center of the greenhouse 0.3m (one ft) above crop height. The box also contains a two-stage thermostat that activates a two-speed fan for ventilation and an emergency alarm temperature sensor. The 1.1m (42 inch) two-speed ventilation fan is powered by a 375 W (1/2 horsepower) motor and the ventilation air inlet is a 1.44m<sup>2</sup> (16 ft<sup>2</sup>) motorized shutter.

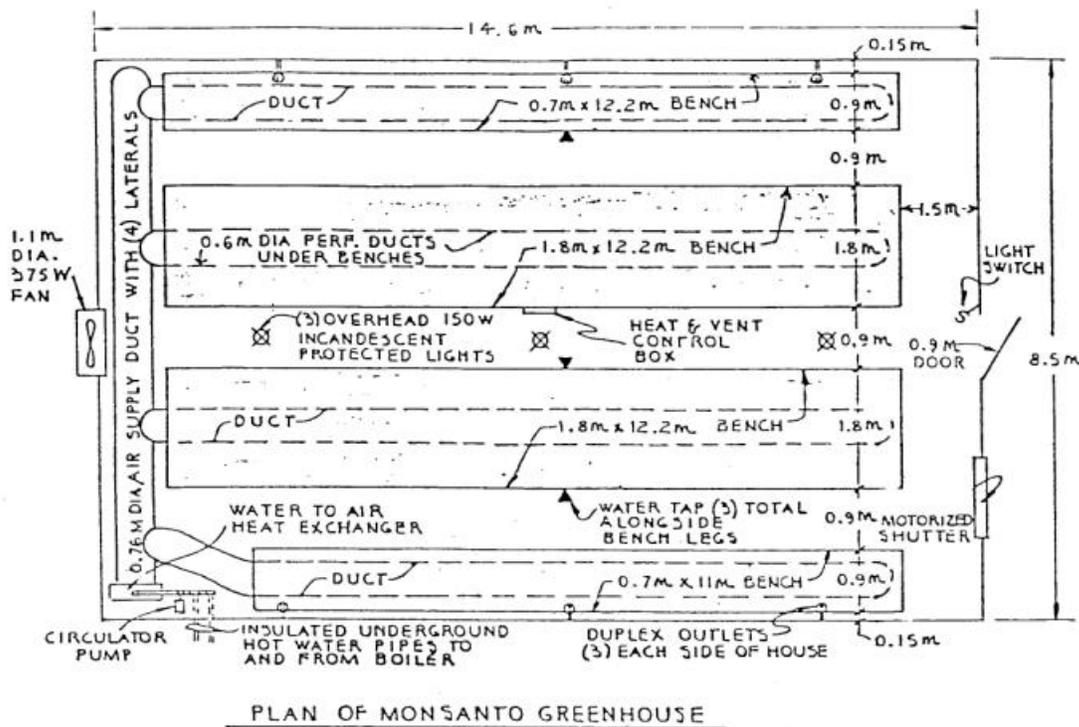
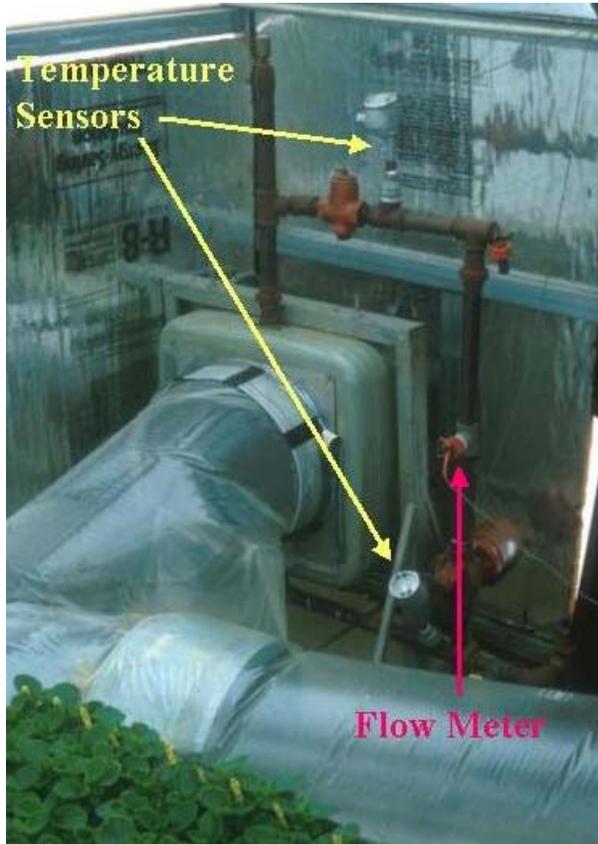
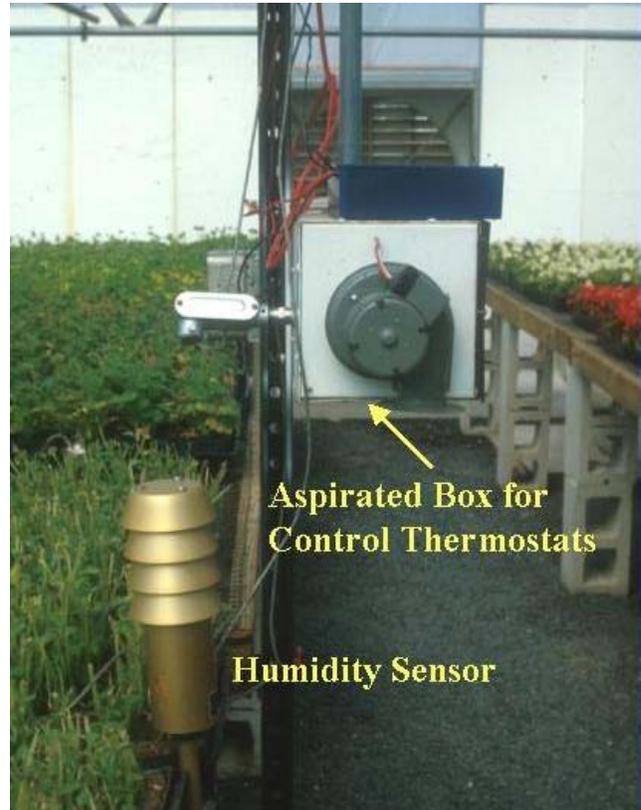


Fig. 2. Test Greenhouse Layout



Heat exchanger, inlet/outlet temperature sensors and flow meter to determine energy input by the heat exchanger.

[Return to heat exchanger text](#)



Aspirated control box for thermostats and temperature sensor behind suction fan and humidity sensor.

[Return to control discussion](#)

Instrumentation and sensors were installed in each greenhouse and out of doors to enable energy balances to be determined for each house on a continuous basis and to monitor a number of important environmental parameters. Inside each greenhouse the following [sensors](#) were mounted horizontally 1.2m (4 ft) above the benches:

- a photosynthetically active radiation (PAR) sensor; Licor LI-1905B Quantum Sensor
- a Micromet Instruments, Fritschen type, miniature net radiometer
- a Dodge Products Model SS-100 solar sensor for the total solar Spectrum

The PAR sensor measures radiation in the 0.4 to 0.7 micron waveband. The net radiometer measures radiation in the 0.3 to 60 micron waveband and the solar sensor's spectral response is between 0.4 and 1.1 microns.



Radiation sensor array inside the greenhouse that measure: Total solar spectrum, PAR and net thermal radiation from crop canopy  
[Return to sensor description](#)

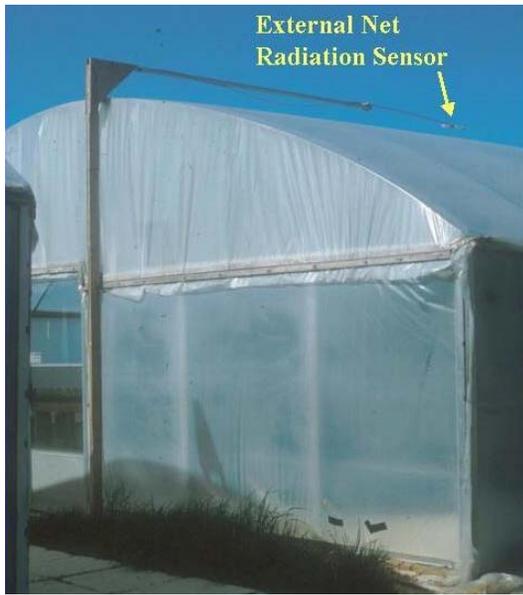
Infrared thermometer  
[Return to text IR thermometer](#)

Other sensors installed in the greenhouses included:

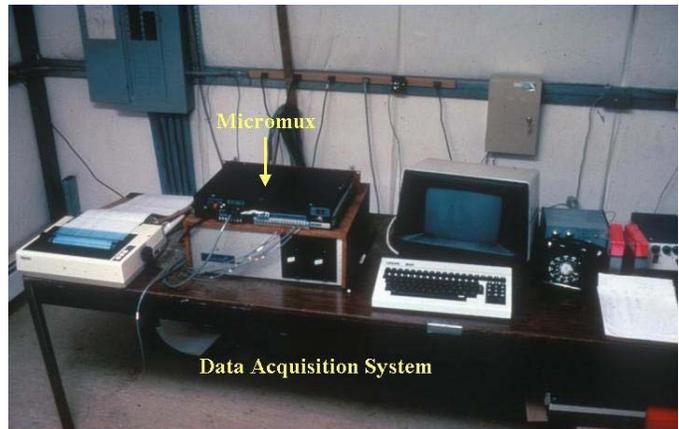
- A Texas Electronics Model TH—2013 [relative humidity](#) sensor was located at bench height.
- Greenhouse ambient air temperature was measured in the aspirated control box and in the attic 15 cm (6 in.) below the roof of the greenhouse using 100 ohm platinum RTD's in conjunction with Action Instruments 100 ohm platinum Thermopaks having a 4-20 mA output.
- Similar RTD's were installed in the water inlet to and exit from the [heat exchanger](#).
- A Signet Scientific 14K 315 paddle wheel flow sensor connected to a 4-20 mA MK 314 signal conditioner was installed in the heat exchanger exit water line for measuring water flow.
- Another RTD was used to measure soil temperature in the spring of 1984 only.
- In the fall of 1983 and spring 1984 an Everest Interscience Model 112 noncontact [infrared thermometer](#) was installed in each greenhouse to measure plant leaf temperature.

External environmental conditions that were monitored were:

- Outside ambient air temperature using an RTD [installed in a louvered shelter 1.5 m (5 ft) above ground located well away from all buildings].
- Relative humidity using a Texas Electronics sensor.
- Wind velocity and direction using a Gill microvane and three cup anemometer system located atop a 10.7 m (35 ft) high pole next to the shed.
- PAR using a Licor sensor and total solar radiation using a Dodge sensor both mounted horizontally above the plane of the top of the greenhouse roofs.
- [Net radiation sensors](#) were installed outside over the roof of each greenhouse in the fall of 1983. Each unit was mounted approximately 30 cm (one ft) above the glazing, 4.6 m (15 ft) from the end of the greenhouse on the end opposite the heat exchanger and 0.9 m (3 ft) north of the greenhouse ridgeline.



External net radiation sensor added in second year of testing to refine the radiation component of the greenhouse heat loss.  
[Return to text on external sensor](#)



Data acquisition system in the headhouse with Micromux unit on the Northstar computer  
[Return to DA system description](#)

A Burr Brown Micromux MM 6403 enclosed 16 channel two wire transmitter was located in each greenhouse. Each could accept a total of eight millivolt and eight milliamp inputs for transmission to a Burr Brown MM 6164-AA [Micromux](#) receiver, which interfaces with a Northstar Horizon microcomputer. The computer periodically interrogates the data inputs through the interface. The programs that are used to operate the system and record data were written by Tom Manning (1983). The sequence of data points to be read, processing of the data and appropriate time intervals are all set by the system user. Typically, each data point was read every ten seconds and two hour averages and/or totals recorded for subsequent analysis. In some tests the averages were recorded over intervals as small as two minutes. Some summary data were periodically printed out while other data were stored by the computer for subsequent analysis. Data on PAR received and the amount of heat input to each greenhouse could be totaled on an hourly and/or daily basis.

### Experimental Procedure

The testing was done over five separate cropping periods. There was an initial bedding plant crop (spring 1982) followed by poinsettias (fall/winter 1982) then bedding plants (spring 83), then poinsettias (fall/winter 1984) and ending with bedding plants (spring 1984). There were also two sets of greenhouse glazing schemes over the duration of the testing. The first sequence of tests conducted in the spring of 1982 compared the first test material (M1) to Monsanto 602 and this testing continued through the spring of 1983. The glazing combinations for the four test houses are presented in Table 1.

TABLE 1  
First Glazing Scheme

<u>Greenhouse</u>	<u>outer layer</u>	<u>inner layer</u>
greenhouse #1	test material 1 (M1)	test material 1 (M1)
greenhouse #2	test material 1 (M1)	602
greenhouse #3	602	test material 1 (M1)
greenhouse #4	602	602

The second sequence of tests commenced in the fall of 1983 and compared a new formulation, referred to as test material 2 (M2) to Monsanto 602. The glazing combinations for the four test houses are presented in Table 2.

TABLE 2  
Second Glazing Scheme

<u>Greenhouse</u>	<u>outer layer</u>	<u>inner layer</u>
	test material 2 (M2)	602
greenhouse #1	602	602
greenhouse #2	test material 2 (M2)	test material 2 (M2)
greenhouse #3	test material 2 (M2)	test material 2 (M2)

This second glazing scheme enabled one of the greenhouses double covered with the test material (greenhouse #4) to be operated at a lower minimum nighttime air temperature than the other (greenhouse #3). The trial of 602 over test material was eliminated to enable this to be done. All of the above glazings were 150 micron (6 mil) thick material.

Samples of the two test materials and the Monsanto 602 film being used as a control were taken when the greenhouses were being glazed and from both the outer and inner glazings at the end of the first test sequence. (The second glazing system is still on the greenhouses as of the writing of this paper.) These samples were sent to the IMAG, Wageningen, The Netherlands, for measurement of perpendicular beam and diffuse transmission of PAR. The tests were done by Mr. Adrie Van den Kieboom according to procedures described by him in 1982.

In order to evaluate gross energy savings, the total energy input for each greenhouse for each cropping season was calculated. While all parameters, except glazing system, that could be kept constant between houses were, it was not possible to eliminate the effect of position of the greenhouses. The two inner units (#2 and #3) are sheltered by the end units (#1 and #4) and have both end walls radiating to another heated greenhouse. Units #1 and #4 have one end completely exposed to wind and radiation loss, and prevailing winds affect house #4 at the east end, the most. In order to determine the effect of position on energy requirement, the glazing system of house #1 and #4 were switched to houses #3 and #2 for the second series of tests that began in the fall of 1983.

A number of energy balance studies were undertaken on the data collected in an effort to gain insight into the heat loss mechanisms and the effect of the IR absorber on these mechanisms. Instantaneous overall and seasonal average heat transfer coefficients for the several glazing

systems were established. These heat transfer coefficients were correlated with environmental factors for each glazing system to determine which factors had the most significant effects on heat loss and their relative importance.

The effect of the glazing system on the internal environmental parameters was also investigated and the indirect effect of glazing on plant leaf temperature and soil temperature are discussed. Some of the major horticultural evaluations of the plants grown in the test houses are also presented.

## Results and Discussion

### Light Transmission:

Laboratory measurements of direct perpendicular beam and diffuse PAR light transmission of single layers of glazing material were made for us by Mr. Adrie Van den Kieboom of the IMAG, Wageningen, The Netherlands for new materials and for some of the materials at the end of the initial testing program. The transmission values for a single layer of unused material, as a percent of available PAR, are presented in Table 3.

TABLE 3  
Single Layer Percent PAR Transmission of Unused Material

Year and Material	Perpendicular beam	diffuse
1982 - test material1 (M1)	86	75
1982 - Monsanto 602	87	78
1983 - test material2 (M2)	88	74
1983 - Monsanto 602	89	79

Table 3 shows that in 1983 for a single layer of each material the perpendicular beam transmission was about the same (88 and 89 percent) while the 602 had an initial diffuse transmission value five percentage points better than M1.

When all the units were reglazed (late summer of 1983), glazing material samples of the old coverings were taken and analyzed both before and after cleaning. The results for perpendicular beam and diffuse PAR transmission of both inner and outer layers before and after cleaning are presented in Table 4.

TABLE 4  
Single Layer Percent PAR Transmission of Glazings  
When New and After 18 Months on the Greenhouses

greenhouse #, film location & material	Glazing Condition					
	new		used (before cleaning)		used (after cleaning)	
	perpen- dicular	diffuse	perpen- dicular	diffuse	perpen- dicular	diffuse
1, inner layer, M1	0.86	0.75	0.86	0.76	0.87	0.76
1, outer layer, M1	0.86	0.75	0.82	0.70	0.85	0.74
2, inner layer, 602	0.87	0.78	0.84	0.74	0.86	0.75
2, outer layer, M1	0.86	0.75	0.82	0.71	0.84	0.74
3, inner layer, M1	0.86	0.75	0.86	0.75	0.86	0.76
3, outer layer, 602	0.87	0.78	0.80	0.69	0.83	0.74
4, inner layer, 602	0.87	0.78	0.85	0.73	0.85	0.74
4, outer layer, 602	0.87	0.78	0.80	0.69	0.83	0.74

Table 4 indicates the relative effects of aging and dirt accumulation (which may be site specific) on PAR light transmission.

In addition to the laboratory tests, the field measurements were summed up to determine the total percent of available PAR transmitted to the crop over each entire growing season. The values represent the daily average percent PAR transmission through two glazing layers and whatever dirt and condensation that was present on them during the test period. The results for four complete growing seasons are shown in Table 5 and Fig. 3.

TABLE 5  
Double Layer Percent PAR Transmission, Field Measurements

Greenhouse Number	First Glazing Scheme	Spring '82	Fall '83	Spring '83	Fall '83	Second Glazing Scheme
1	M1/M1	62.4	60.6	60.6	66.0	M2/602
2	M1/602	63.0	59.0	60.9	70.8	602/602
3	602/M1	62.4	59.3	56.9	66.2	M2/M2
4	602/602	64.1	57.3	57.1	66.3	M2/M2

The field measurements total the PAR received at the plant canopy over all hours of the day under all weather conditions for an entire growing season. The spring '82 and fall '83 tests indicate that when all materials are new the 602 has higher PAR transmittance than the test material with the IR absorber additive. However, as time goes on, light transmission reduction due to dirt accumulation and material darkening is less with the IR absorbing material and it subsequently had higher PAR transmittance than 602. Table 5 clearly indicates that the major reduction in light transmission for 602 occurs over the summer. Tables 4 and 5 indicate that the IR absorber in the outer layer tends to protect the inner layer of 602 in test house #2.

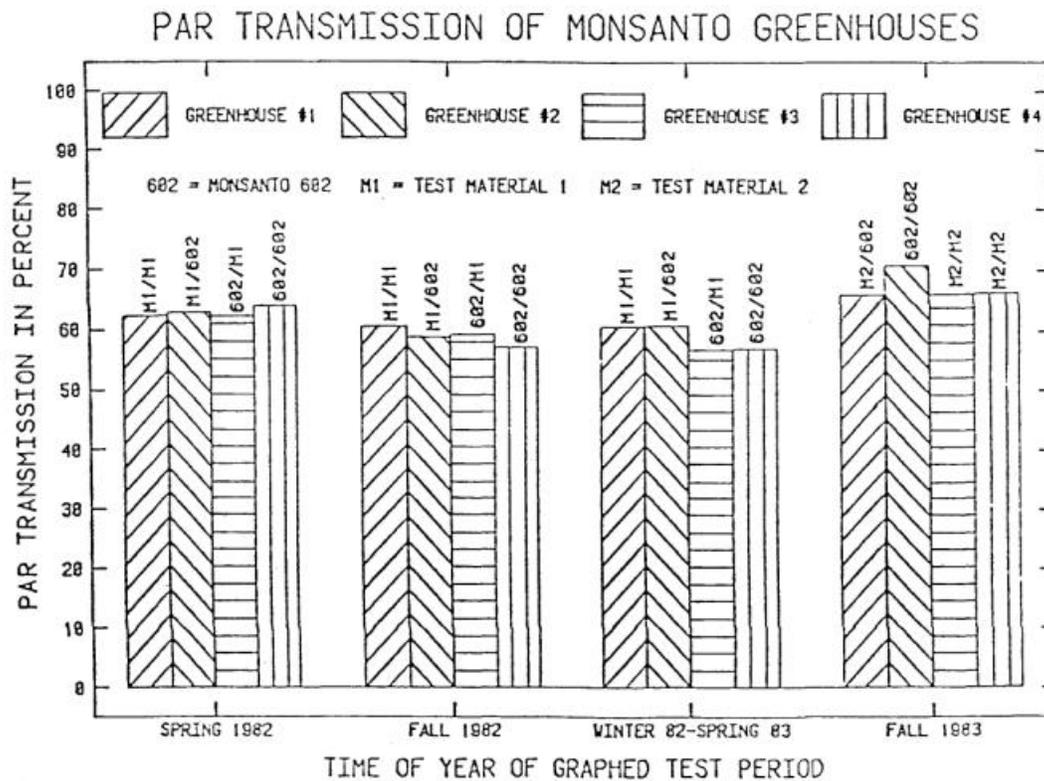


Fig. 3. PAR Transmission of all Test Houses in all Test Periods

#### Energy Savings:

A major objective of the testing program has been the determination of the total heat saving potential of the new film and a detailed study of the heat transfer properties of the glazing systems so that the energy savings being documented can also be understood. The instrumentation systems installed provided information on the relationship between total heat loss, heat loss due to radiation, various environmental factors and the glazing system. The most important data obtained in this part of the program is the total energy requirement for each of the test houses during each of the cropping seasons for which complete records were kept.

Table 6 outlines the total energy requirements for the test houses. The first three time periods are for the first test material (M1) with the glazing systems for the various houses as indicated in the second column. The fourth period is for the second test material (M2) and the glazing systems are indicated in the seventh column. All greenhouse nighttime minimum ambient air temperature and daytime ventilation thermostat settings were set as close to identical as possible in all greenhouses during all testing periods. The one exception was in greenhouse #4 (M2/M2) during the fall '83 and spring '84 testing period when the minimum nighttime ambient air temperature setting was approximately 1°C (2°F) lower than that in the other three greenhouses.

TABLE 6  
Energy Use for Four Test Seasons

Greenhouse Number	First Glazing Scheme	Energy Use in Gigajoules				
		Fall '82	Winter '82/ Spring '83	Late Spring '83	Fall '83	Second Glazing Scheme
1	M1/M1	30.7	50.7	606	35.0	M2/602
2	M1/602	30.6	50.6	6.0	44.1	602/602
3	602/M1	29.2	49.1	6.3	32.5	M2/M2
4	602/602	45.0	84.5	10.6	34.4	M2/M2

The data in the above table are also presented graphically In Fig. 4. The percentage of savings is based on the 602/602 glazed greenhouse heat use. It is important to note that the data clearly indicate that in addition to the energy saving that can be attributed to the use of one or two layers of IR absorbing film; there is also a significant effect of greenhouse location on energy use.

The first set of tests on the first material (M1) had each house glazed differently and one objective was to determine the effect of using one layer of IR absorbing film instead of two and if a single layer were to be used whether it should be the outer or inner layer. When the second test material (M2) was installed, the location of the several glazing schemes used was changed to enable the effect of greenhouse location to be separated from the effect of the glazing system. Also, greenhouse #4 was operated with a slightly lower nighttime heating thermostat setting than the other greenhouses in the fall 1983 tests. Both greenhouses #3 and #4 were glazed with two layers of test material. Earlier tests indicate that plant leaf temperatures are slightly higher in houses glazed with test material, particularly on clear nights when radiation heat loss is highest. By lowering air temperature slightly, additional energy savings can be achieved.

Detailed analysis of the data over all heating seasons indicates that on a percentage basis, using the 602/602 houses as the control, there is a 7 to 8 percentage point location penalty for greenhouse #4, and 4 to 5 percentage point location penalty for greenhouse #1.

## HEAT USE OF MONSANTO GREENHOUSES

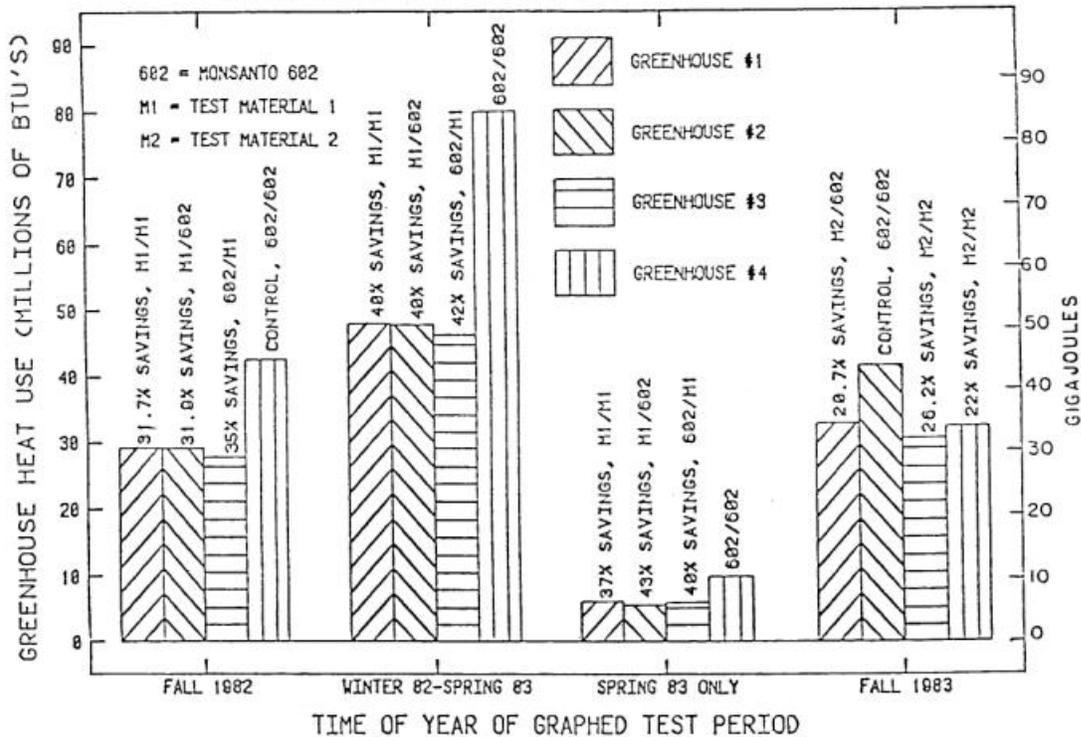


Fig. 4. Total Energy Consumption for Four Test Periods

Note that for the evaluation of the first test material (M1) the control house was in the most exposed location and the house with two layers of test material was the second most exposed location. For the second material (M2), the house with the double layer test material and the lowered air temperature was in the most exposed location.

The raw percentage savings based on the 602/602 glazed house as the control are presented for each of four summary time frames over the bars in Fig. 4. Table 7 presents estimated percent savings for these four seasonal totals after correcting for an average locational penalty of 8 percentage points for greenhouse #4 and 5 percentage points for greenhouse #1. It should be understood that these factors are very weather dependent for any given growing season. Note also that there is some decrease in heat use in greenhouse #4 in the fall of 1983 due to the 1.1°C (2°F) thermostat setback relative to similarly glazed greenhouse #3.

TABLE 7  
Calculated Percent Energy Savings Corrected for Position

Greenhouse Number	First Glazing Scheme	Energy Savings %					Second Glazing Scheme
		Fall '82	Winter '82/ Spring '83	Late Spring '83	Fall '83		
1	M1/M1	29	37	34	24	M2/602	
2	M1/602	24	32	35	Control	602/602	
3	602/M1	27	34	32	30	M2/M2	
4	602/602	Control	Control	Control	34.4	M2/M2	

The energy savings provided by the new IR film is due to the ability of the film to absorb infrared radiation, thereby reducing net radiation loss from the greenhouse, and the interaction of this savings with the heating system to provide additional savings. The heating system is controlled by an air temperature sensor set to maintain desired air temperature at the plant canopy. With the forced air heating system being used, there is a tendency for the attic to heat up faster than the air at the crop level. As a result, the control house, which does not have the energy conserving property of the IR absorbing film, operates with a significantly higher average attic air temperature than the houses with one or two layers of test material. This is shown dramatically in the details of the dynamics of the temperatures in the attic and the aspirated control box where the ambient air temperatures for a single typical night are shown in Figs. 5-8. The more energy conservative the glazing system the less the attic overheating and the less dramatic the cycling of both attic and air temperature. For greenhouses #1, #2 and #3, the average attic temperature is approximately equal to the average ambient air temperature, but for greenhouse #4 (the 602/602 combination) it is approximately 1.7°C (3°F) higher. The average outside ambient temperature was -1.4°C (29.5°F) during this time period. This higher attic temperature is due to the much higher heat demand of the 602/602 combination covering greenhouse #4. The heat is on longer, so on the average, the attic air is warmer and the conduction/convection and infiltration heat losses are greater than in the other three greenhouses.

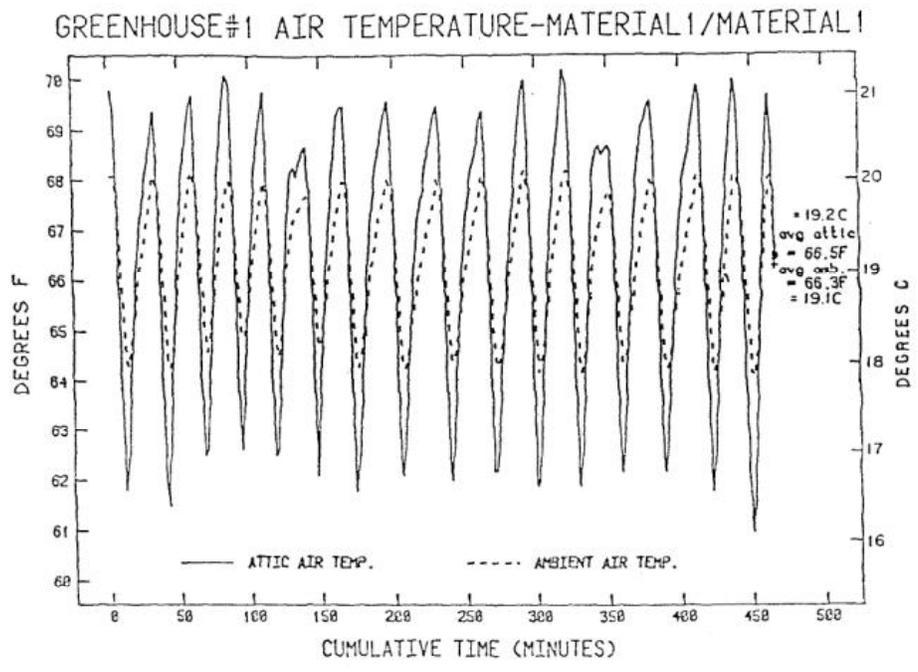


Fig. 5. Detailed Temperature Data Showing Heater Cycling Greenhouse 1

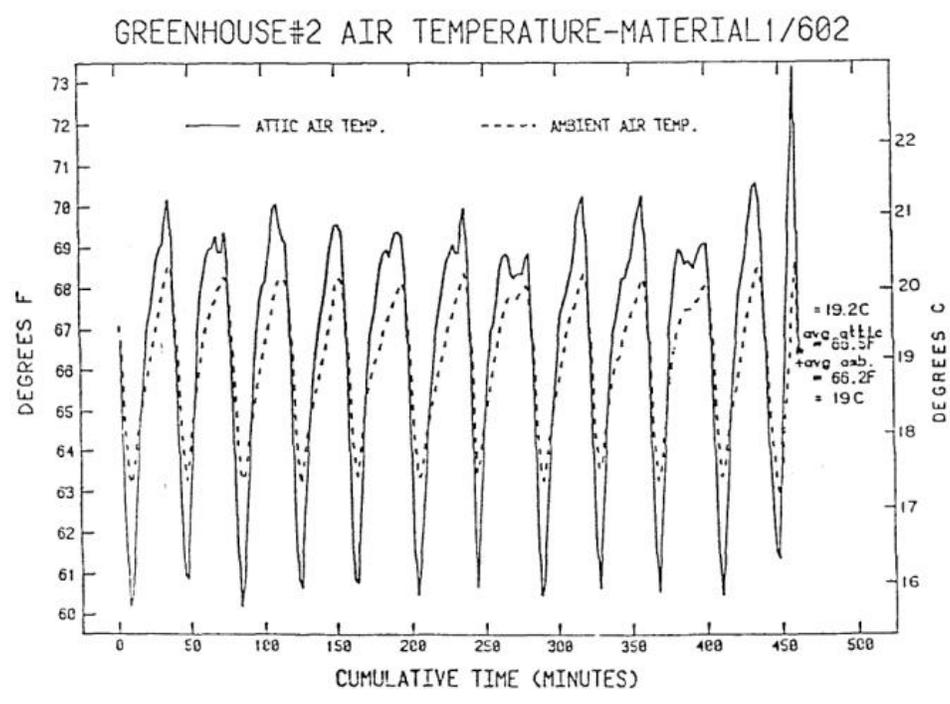


Fig. 6. Detailed Temperature Data Showing Heater Cycling Greenhouse 2

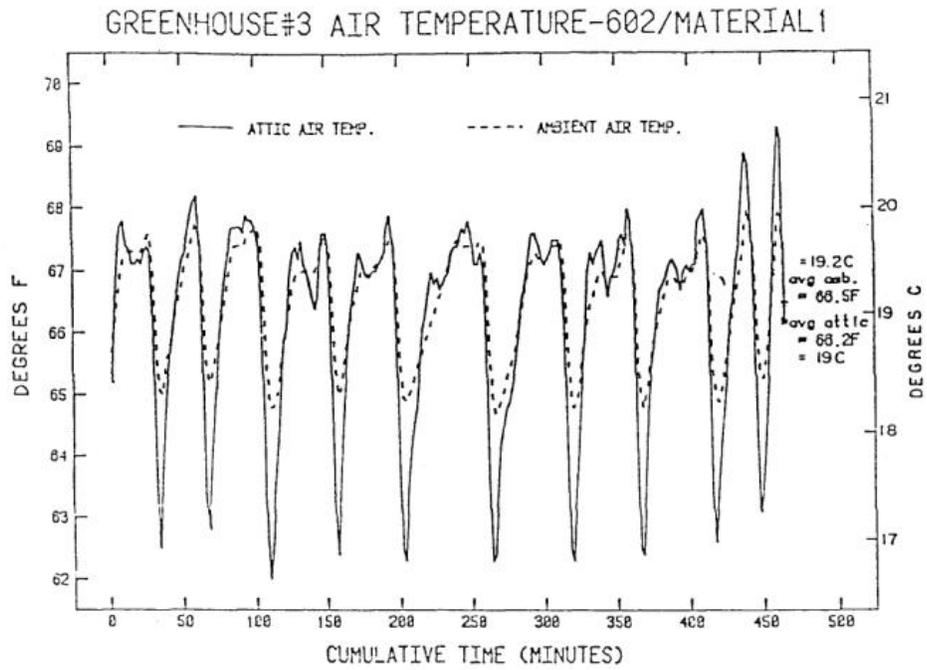


Fig. 7. Detailed Temperature Data Showing Heater Cycling Greenhouse 3

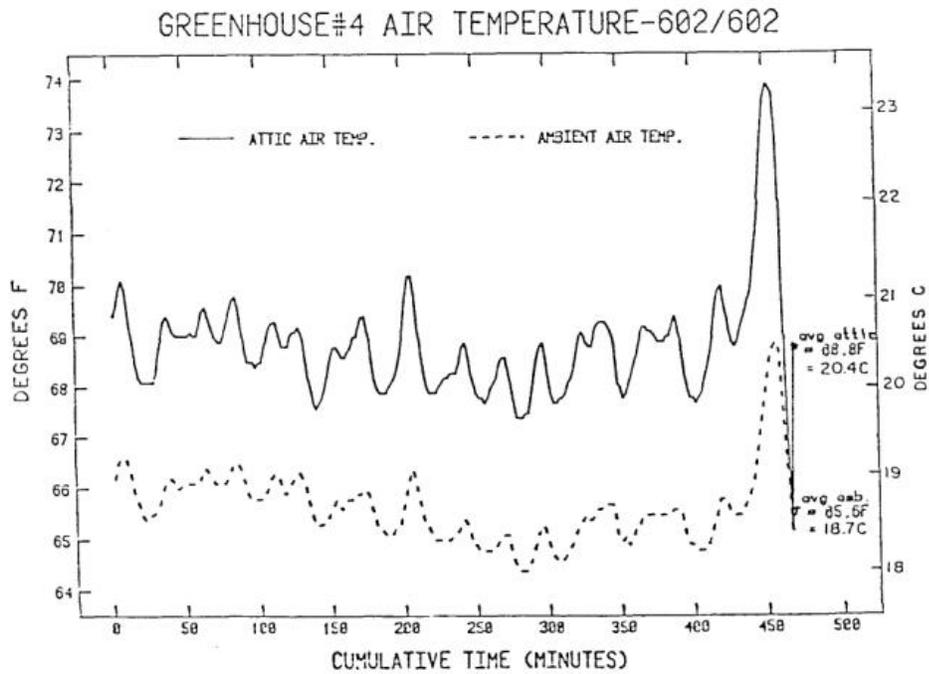


Fig. 8. Detailed Temperature Data Showing Heater Cycling Greenhouse 4

These figures also illustrate the inherent inefficiency of a forced air heating system controlled by a thermostat. A heating system with a modulating control system would be subject to far less dynamic cycling. Modulating hot water heating systems and greenhouses receiving a portion of their heat from a floor heating system also experience lower attic, relative to ambient, air temperatures (Roberts and Mears, 1980).

Typical nighttime outside net radiation loss from the greenhouses on a clear cold night is presented in Fig. 9. Greenhouse #3 (M2/M2) which is in a sheltered location, exhibits the lowest radiation heat loss. Greenhouse #4 (M2/M2) in an end location has higher radiation heat loss than #3 even though both are glazed identically. Greenhouse #4 is very similar to greenhouse #1 (M2/602), which is also an end greenhouse. The end greenhouses have a greater heat demand than the sheltered one and therefore higher heat fluxes, which is reflected in the data. Greenhouse #2 (602/602) has the greatest radiation heat loss due to its glazing not being an infrared radiation absorber.

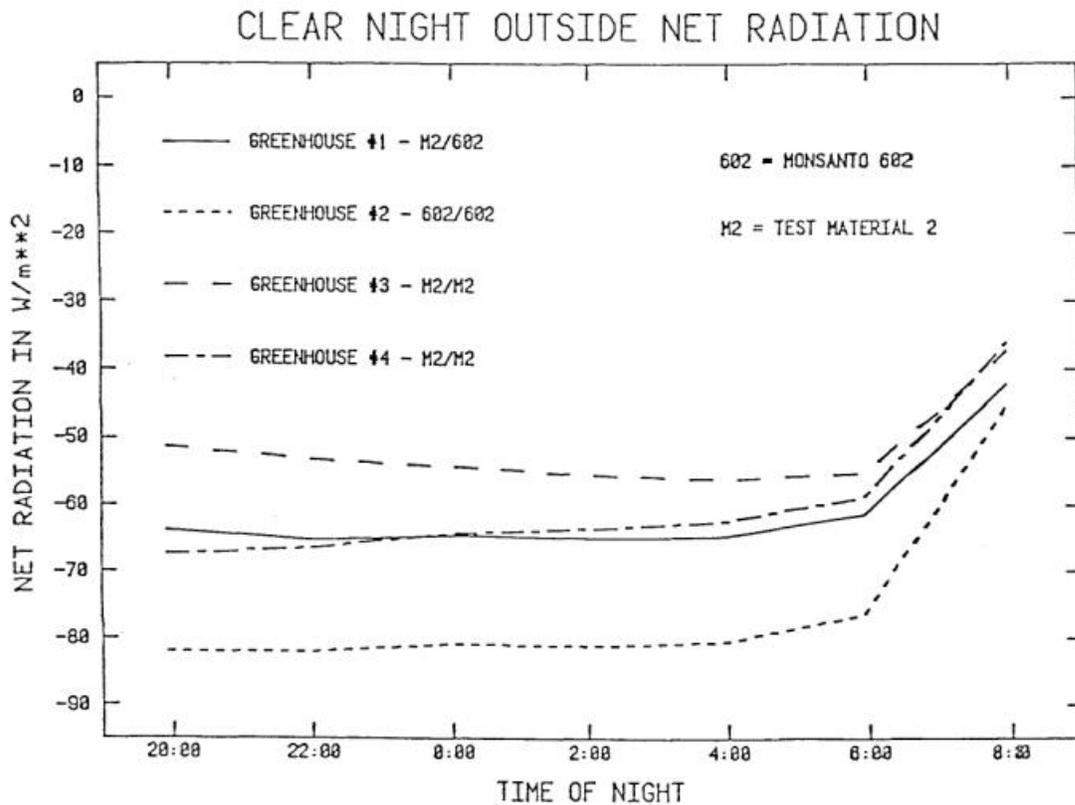


Fig. 9.

Overall Heat Loss Coefficient (“U” Value):

The overall heat loss coefficient (“U” value) is calculated for each greenhouse, each night, using the equation:

$$U = (A\Delta T)/Q$$

where:

$U$  = nighttime overall heat loss coefficient in  $W/m^2K$  ( $Btu/hft^2\text{ }^\circ F$ )

$A$  = heat loss area of the greenhouse in  $m^2$  ( $ft^2$ )

$\Delta T$  = average nighttime inside ambient air temperature minus average nighttime outside ambient air temperature in  $K$  ( $^\circ F$ )

$Q$  = average hourly nighttime heat requirement of the greenhouse in  $Wh$  ( $Btu$ )

The nighttime overall heat loss coefficient of a greenhouse will vary from night to night depending on the environmental conditions inside and outside the greenhouse. The value obtained varies mainly with:

1. ambient air temperature difference from inside to outside of the greenhouse
2. heat radiation exchange between inside and outside the greenhouse
3. outside wind velocity and greenhouse exposure

When the temperature difference (or  $\Delta T$ ) variation from inside the greenhouse to outdoors is relatively small [ $8.3^\circ C$  ( $15^\circ F$ ) or less], the heat stored in the greenhouse interior mass makes a significant contribution to the nighttime heat requirement of the greenhouse. When the average temperature values over the night and the heat input to the greenhouse by the heating system are used to calculate the “ $U$ ” value for the greenhouse for that night, the value obtained is often very low. Also, when “ $U$ ” values and total heat use is small there is great variation in empirical data. To minimize this effect on the regression analysis of the “ $U$ ” value as a function of environmental and system parameters, only data from nights when the average  $\Delta T$  was  $11^\circ C$  ( $20^\circ F$ ) or greater were used. This helped to eliminate a large portion of the variability that resulted from daytime heat storage and resulted in better correlation values for the equations.

A number of preliminary studies of the data determined that only two environmental parameters are needed to determine “ $U$ ” value by multilinear regression. They are:

1. A sky index value (spring 1983) that accounts for cloud cover and altitude, or the outside net radiation (fall 1983) measured with the net radiometers installed outside above the greenhouses.
2. Wind velocity measured 10.7m (35 ft) above ground level.

No outside net radiation sensors were installed over the greenhouses prior to the fall 1983 test period, so an artificial indicator of sky radiation conditions, called a sky index value, was established.

The sky index value, used to analyze the spring 1983 data, is the sum of a number indicating the percent of the sky covered with clouds and an adjusted cloud temperature number based on cloud altitude. An index value of 0 indicates a 100% cloud filled sky with the clouds near ground, level. An index of 22.6 is for a completely cloudless sky. Index values between 0 and 22.6 are a

combination of cloud cover and altitude. The clear sky number would be 10 if there were no clouds and 0 for 100% cloudy. Cloud cover at 0m (0 ft) altitude has a value of 0, at 305m (1000 ft) it is 3.6 and at 10,670m (35,000 ft), 12.6. As an example then, a 35% clear sky has a value of 3.5 and if the cloud altitude is 6100m (20,000 ft), the altitude value is  $2.0 \times 3.6 = 7.3$  (the altitude value increases 3.6 per 3,050m (10,000 ft)). The sum of the two values then is  $3.5 + 7.3 = 10.8$ , which is the sky index value. The altitude value never exceeds 12.6 because clouds above 10,670m (35,000 ft) are always the same temperature regardless of their altitude. The maximum 12.6 value is also used for a completely clear sky. The sky index value is not a true measure of radiation exchange between the greenhouse and the atmosphere. However, it does provide an indication of an increasing or decreasing radiation heat loss situation.

The effect of the temperature difference factor ( $\Delta T$ ) was found to be very small when analyzing only nights with a minimum  $11^\circ\text{C}$  ( $20^\circ\text{F}$ )  $\Delta T$ . This essentially eliminated any effect on the data of the daytime solar heat that was stored in the mass inside of the greenhouses. In cases where the  $\Delta T$  was between  $2.8^\circ\text{C}$  ( $5^\circ\text{F}$ ) and  $11^\circ\text{C}$  ( $20^\circ\text{F}$ ) the effect of the heat stored during the day was dramatic and dependent on the amount of solar energy that had been available that day and the mass within the greenhouse. For all conditions when it is cold outside,  $\Delta T > 11^\circ\text{C}$  ( $20^\circ\text{F}$ ), a linear relationship was assumed for the “U” value regression equations:

$$U \text{ value} = a_0 + a_1 * (\text{sky index or } |\text{outside net radiation}|) + a_2 * (\text{wind velocity})$$

where:

$a_0$  = constant with units of  $\text{W/m}^2\text{K}$  ( $\text{Btu/hft}^2\text{ }^\circ\text{F}$ )

$a_1$  = sky index coefficient with units of  $\text{W/m}^2\text{K}$  ( $\text{Btu/hft}^2\text{ }^\circ\text{F}$ ) for the spring of 1983.

or

outside net radiation coefficient with units of  $1/\text{K}$  ( $1/\text{h } ^\circ\text{F}$ ) for the fall of 1983.

$a_2$  = wind velocity coefficient with units of  $\text{Wh/m}^2\text{K km}$  ( $\text{Btu/ft}^2\text{ }^\circ\text{F mile}$ )

Note: Because outside net radiation is a negative value, its absolute value will be used in the “U” value equation so it will not be necessary to multiply  $a_1$  by a minus sign.

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TABLE 8

Spring 1983 Multilinear Regression “U” Value Coefficients

covering combination	greenhouse #	$a_0$	$a_1$ multiply by $10^{-3}$	$a_2$ multiply by $10^{-3}$
M1/M1	1	2.3	43.7	54
M1/602	2	2.0	53.9	47
602/M1	3	1.5	78.4	46
602/602	4	2.6	133	83

The sky index and wind velocity parameters are both independent variables. Therefore, the coefficients  $a_0$ ,  $a_1$ , and  $a_2$  can be compared directly between greenhouses. Table 8 shows that for greenhouse #3 (602/M1) the  $a_0$  term is significantly lower than the other three greenhouses. The reason for this is unknown, but this also occurs during the fall of 1983, so it may be position related.

The range of sky index values was between 0 and 22.6 while the wind velocity was in the 2.5 km/h (1.6 mph) to 20 km/h (12.5 mph) range for the spring 1983 test period. The maximum wind velocity value is approximately equal to the maximum sky index value, so under the worst condition situation, [sky index = 22.6, wind velocity = 20 km/h (12.5 mph)] it is the magnitude of the  $a_1$  and  $a_2$  coefficients that determine to what extent the sky index and wind velocity terms affect the calculated U value.

The coefficients for greenhouses #1 (M1/M1) and #2 (M1/602) indicate that the effect of sky index and wind velocity would be about equal. Greenhouse #3 (602/M1) would be more affected by the sky index as would greenhouse #4 (602/602). This indicates high radiation loss for greenhouse #4 in particular since its  $a_1$  and  $a_2$  coefficients are the largest of all greenhouses.

The best condition situation [assume sky index = 2 and wind velocity = 2.5 km/h (1.6 mph)] would yield similar results to the worst condition situation. In fact, under any circumstances where the sky index value and wind velocity are of similar magnitude, the results would be about the same.

In summary:

1. in the regression equations minimum and maximum numerical values for sky index and wind velocity are equivalent.
2. under low sky index and wind conditions the  $a_0$  term is the most important - but this seldom if ever occurs.
3.  $a_1$  coefficients show M1/M1 least affected by the radiation condition, M1/602 next least, 602/M1 more affected and 602/602 most affected. This is the list of order of radiation savings.
4.  $a_2$  coefficients show house #4 most susceptible (exposed) to wind, house #1 next most and houses #2 and #3 protected by #1 and #4.

TABLE 9  
Fall 1983 Multilinear Regression "U" Value Coefficients

covering combination	greenhouse #	$a_0$	$a_1$ multiply by $10^{-3}$	$a_2$ multiply by $10^{-3}$
M2/602	1	2.3	10	27
602/602	2	2.7	14	15
M2/M2	3	2.1	11.5	45
M2/M2	4	2.4	10.5	30

In analyzing the fall 1983 (Table 9) data, it is important to recognize that the outside net radiometer readings themselves are a function of the glazing system. The net radiometer values that could be substituted into the regression equations are unique for each greenhouse and are not independent values as the sky index was. The fact that net radiation values are not independent affects the wind coefficient ( $a_2$ ) calculation for each equation, so comparisons between greenhouses can not be made directly as was the case with the spring 1983 data. The range of average nighttime net radiation values during cold weather for each greenhouse over the fall 1983 test period was:

TABLE 10  
Range of Outside Net Radiation Loss Values  
and Wind Velocity: Fall 1983

covering combination	W/ m <sup>2</sup>	(Btu/hrft <sup>2</sup> )
Greenhouse #1	- 18.3 to - 74.1	(- 5.8 to - 23.5)
Greenhouse #2	- 18.9 to - 83.6	(- 6.0 to - 26.5)
Greenhouse #3	- 17.4 to - 58.4	(- 5.5 to - 18.5)
Greenhouse #4	- 16.7 to - 63.1	(- 5.3 to - 20.0)

The average nighttime wind velocity ranged from 2.7 km/h (1.7 mph) to 23 km/h (14.3 mph).

As with the spring 1983 equations, these equations are only applicable to normal environmental conditions. They do not apply to very mild weather, continuous rain situations or times when there is snow and ice accumulated on the greenhouses.

The coefficients from Table 9 and range values from Table 10 can be used to calculate the extreme condition “U” values for each greenhouse that are predicted by the regression equations. The results can then be used to identify the relative effects of the net radiation loss and wind velocity on the calculated “U” value of each greenhouse. The absolute value of the net radiation readings is used so that a negative  $a_1$  coefficient isn’t required.

TABLE 11  
High Net Radiation Loss and Wind Velocity “U” Value Calculations  
(Worst Conditions)

greenhouse number (glazing combination)	$a_0$ term + constant W/m <sup>2</sup> K	$a_1$ term + net radiation W/m <sup>2</sup> K	$a_2$ term = wind velocity W/m <sup>2</sup> K	“U” value overall heat loss coefficient W/M <sup>2</sup> K
1 (M2/602)	<u>2.3 +</u>	(0.01)(  -74.1  ) = <u>0.74 +</u>	(0.027)(23) = <u>0.62</u>	= <u>3.66</u>
2 (602/602)	<u>2.7 +</u>	(0.014)(  -83.6  ) = <u>1.2 +</u>	(0.015)(23) = <u>0.35</u>	= <u>4.25</u>
3 (M2/M2)	<u>2.1 +</u>	(0.0115)(  -58.4  ) = <u>0.67 +</u>	(0.045)(23) = <u>1.0</u>	= <u>3.77</u>
4 (M2/M2)	<u>2.4 +</u>	(0.0105)(  -63 1  ) = <u>0.66 +</u>	(0.030)(23) = <u>0.69</u>	= <u>3.75</u>

TABLE 12  
Low Net Radiation Loss and Wind Velocity “U” Value Calculations  
(Best Conditions)

greenhouse number (glazing combination)	a <sub>0</sub> term + constant W/m <sup>2</sup> K	a <sub>1</sub> term + net radiation W/m <sup>2</sup> K	a <sub>2</sub> term = wind velocity W/m <sup>2</sup> K	“U” value overall heat loss coefficient W/M <sup>2</sup> K
1 (M2/602)	<u>2.3 +</u>	(0.01)( -18.3 ) = <u>0.18 +</u>	(0.027)(2.7) = <u>0.07</u>	= <u>2.55</u>
2 (602/602)	<u>2.7 +</u>	(0.014)( -18.9 ) = <u>0.26 +</u>	(0.015)(2.7) = <u>0.04</u>	= <u>3.00</u>
3 (M2/M2)	<u>2.1 +</u>	(0.0115)( -17.4 ) = <u>0.20 +</u>	(0.045)(2.7) = <u>0.12</u>	= <u>2.42</u>
4 (M2/M2)	<u>2.4 +</u>	(0.0105)( -16.7 ) = <u>0.18 +</u>	(0.030)(2.7) = <u>0.08</u>	= <u>2.66</u>

If both the worst condition (highest radiation loss and highest wind velocity) and best condition (lowest radiation and lowest wind velocity) calculations are done using the “U” value equations the relative affect of the wind and net radiation loss factors on “U” value for the extreme conditions can be calculated. The worst condition (Table 11) results are that net radiation loss and wind velocity have an approximately equal effect on “U” value for greenhouses #1, #3 and #4. The net radiation loss factor is four times the wind factor for greenhouse #2 (602/602). The reason for this large effect is a combination of the 602/602 greenhouse losing more heat by net radiation and the fact that it is in one of the sheltered locations, so wind isn’t as significant.

The best condition (Table 12) calculation indicates that net radiation loss has an approximately 2 to 2.5 times as large an effect on “U” value as wind velocity for greenhouse #1, #3 and #4. For greenhouse #2 (602/602) the net radiation effect is seven times larger than the wind effect for the same reasons cited previously. The two extremes indicate that for the greenhouses as they were glazed for these tests and in these locations, the net radiation loss has an equal or greater effect on “U” value than wind velocity for greenhouses #1, #3 and #4. Net radiation loss is four to seven times more important for greenhouse #2 (602/602) due to the higher infrared radiation transmission of the 602.

Comparing the fall 1983 results to those from the spring of 1983 for similar glazing schemes yields some information on the effect of greenhouse location on “U” value. Reviewing the equations for the 602/602 glazed structures (greenhouse #4 for spring 1983 and #2 for fall 1983) shows that for the worst condition scenario in the spring equation; the radiation effect on “U” value is approximately double the wind effect, while in the fall 1983 it is four times. Under the best conditions situation it is about two times (in the spring) and seven times (in the fall) the wind effect. This demonstrates the effect that end versus sheltered location has on the relative importance of wind velocity and greenhouse radiation heat loss. Similar comparisons can be made for the other greenhouses.

#### Interaction of Radiation Heat Loss and Energy Savings:

Data are presented in Tables 13-17 that verify the basic energy saving properties of the IR test material (M2) and give an indication of the amount of energy saving that can be credited directly to the reduction in radiation loss and that which is saved due to more efficient heating system operation as a result of the radiation loss reduction.

The data for a typical cold night with average radiation heat loss is presented in Table 13. Note that the nighttime minimum ambient air temperature in greenhouse #4 is set approximately 1°C (2°F) lower than the other greenhouses.

TABLE 13  
Monsanto Greenhouses: Data for an Average Cold Night; 12/18/83

greenhouse number	glazing	total heat use kJ	amb. temp. °C	attic air temp. °C	T <sub>outside</sub> °C	“U” W/m <sup>2</sup> K	% savings	outside net rad. W/m <sup>2</sup>
1	M2/602	571,430	15.9	15.3	-0.2	2.6	23	-32.5
2	602/602	759,900	16.4	17.1	-0.2	3.4		-38.2
3	M2/M2	548,900	15.6	15.7	-0.2	2.5	27	-26.8
4	M2/M2	543,700	14.6	14.7	-0.2	2.7	20	-27.4

Length of night = 902 minutes  
Wind = 4.5 km/h from the east

The total heat use column is affected by the greenhouse ambient temperature column and for this reason the “U” value (based on greenhouse heat loss area) is needed to properly compare the data. The percent savings column is based on the “U” values and not total heat use (as it was in Fig. 3) so that the different greenhouse ambient air temperature can be accounted for. Adding the location penalty to these savings would make them all very similar in percent savings, as would be expected. The order of outside net radiation values is also as expected and similar to those in Fig. 9. The greenhouse attic air temperature column, when compared to the greenhouse ambient air temperature column also yields the expected results for the greenhouses as was shown in Figs. 5, 6 and 8.

On nights when it rains heavily and continuously all night, it was observed that the heat requirement of all the greenhouses was essentially the same. Table 14 presents the data for one such night.

TABLE 14  
Monsanto Greenhouses: Data for a Night When it Rained Continuously; 4/15/84

greenhouse number	glazing	total heat use kJ	amb. temp. °C	T <sub>outside</sub> °C	inside net rad. W/m <sup>2</sup>	“U” W/m <sup>2</sup> K	% savings	outside net rad. W/m <sup>2</sup>
1	M2/602	242,900	16.7	8.1	-7.9	3.0	6	-3.8
2	602/602	255,000	16.6	8.1	-7.6	3.2		-6.9
3	M2/M2	248,000	16.7	8.1	-8.5	3.1	5	-3.8
4	M2/M2	240,600	15.6	8.1	-6.9	3.4	-5	-3.2

Length of night = 765 minutes  
Wind = 12.9 km/h from the northeast

The rainy night data indicates that there still is some heat savings for greenhouses glazed with at least one layer of M2, but it is small. The wind speed and direction indicates that greenhouse #1 was the most sheltered and #4 the least sheltered on this windy night. This is the reason for the

“U” value use of greenhouse #4 being the greatest. The outside net radiation readings are all low, with the 602/602 glazed greenhouse being the largest by a small amount. This indicates that when it is raining, and there is a film of water running continuously over the exterior glazing layer of the greenhouses, the radiation losses from all the greenhouses are close to being equal, and consequently heat savings is small. This case then represents the situation when there is almost no difference in radiation loss between greenhouses, and as a result no conduction/convection savings being provided by the IR material. It also indicates that when there is heavy condensation on the inside of the inner glazing layer that a layer of both 602 and M2 are similar in performance from the standpoint of infrared radiation absorption and transmission. This case most dramatically shows that when the radiation savings is eliminated that the conduction/convection savings is lost as well because it is dependent on the former.

Tables 15 and 16 present the data for two different, very cold nights when the circulators in all the greenhouses were operating continuously.

TABLE 15

Monsanto Greenhouses: Data for a Night When the Heat Input to the Greenhouse was Continuous; 12/19/83

greenhouse number	glazing	total heat use kJ	amb. temp. °C	attic air temp. °C	T <sub>outside</sub> °C	“U” W/m <sup>2</sup> K	% savings	outside net rad. W/m <sup>2</sup>
1	M2/602	605,000	16.2	16.7	-7.5	3.3	5	-46.4
2	602/602	612,900	15.1	15.8	-7.5	3.5		-45.7
3	M2/M2	579,400	16	15.8	-7.5	3.2	8	-40.7
4	M2/M2	584,200	15.2	15.6	-7.5	3.3	5	-39.4

Length of night = 518 minutes  
Wind = 11.9 km/h from the east

TABLE 16

Monsanto Greenhouses: Data for an Average Cold Night; 12/18/83

greenhouse number	glazing	total heat use kJ	amb. temp. °C	attic air temp. °C	T <sub>outside</sub> °C	“U” W/m <sup>2</sup> K	% savings	outside net rad. W/m <sup>2</sup>
1	M2/602	1,388,200	15.2	14.7	-14.7	3.5	8	-71.0
2	602/602	1,325,800	11.5	12.2	-14.7	3.8		-63.1
3	M2/M2	1,286,200	14.3	14.2	-14.7	3.3	13	-58.4
4	M2/M2	1,284,400	12.2	12.8	-14.7	3.55	6	-63.1

Length of night = 892 minutes  
Wind = 17.1 km/h from the east

As the circulators in all the greenhouses were operating continuously, the effect of longer heater running times increasing relative attic air temperatures disappeared, thus eliminating the conduction/convection portion of the heat savings provided by the IR material. This savings is

eliminated because the average attic air temperature/ambient air temperature difference advantage usually present in the greenhouses glazed with at least one layer of IR material has been greatly reduced. It was lost because there was no cycling of the circulator pump. This is indicated by comparing the greenhouse attic air temperature column to the greenhouse ambient air temperature column. In both tables they are quite close to being equal (within approximately 0.5°C (1°F)), which varies from the normal condition where the 602/602 greenhouse attic air temperature is about 2°C (3°F) higher than the ambient air. The “U” value based percent savings in Table 15 are lower than those of Table 16 because it was not as clear a night, as is indicated by the values in the outside net radiation column. If the savings from Table 16 are adjusted for greenhouse position they become:

greenhouse #1	(M2/602)	12%
greenhouse #2	(602/602)	control
greenhouse #3	(M2/M2)	13%
greenhouse #4	(M2/M2)	13%

This indicates that on a very clear, cold night the savings provided by the IR material (due to radiation savings only) is on the order of 13%. This represents about half of the average percent savings (25%) for the sheltered M2/M2 glazed greenhouse over the year. On the average, half of the total savings provided by the IR material is directly due to its radiation saving property and the other half due to the interaction of the heating system (conduction/convection savings) with this primary energy saving feature.

Very cloudy weather also has a direct effect on the energy savings. Data for a very cloudy night is presented in Table 17.

TABLE 17

Monsanto Greenhouses: Data for a Very Cloudy Night; 12/21/83

greenhouse number	glazing	total heat use kJ	amb. temp. °C	attic air temp. °C	T <sub>outside</sub> °C	“U” W/m <sup>2</sup> K	% savings	outside net rad. W/m <sup>2</sup>
1	M2/602	580,100	16.2	15.7	1.3	2.6	8	-11.0
2	602/602	611,300	15.9	16.6	1.3	2.8		-12.6
3	M2/M2	552,800	16.2	16.1	1.3	2.5	12	-6.3
4	M2/M2	535,700	15.1	15.5	1.3	2.6	8	-6.3

Length of night = 984 minutes  
Wind = 11.7 km/h from the north

The unadjusted percent energy savings are small, again due to the low values of outside net radiation loss. On cold, cloudy nights the percent energy savings is low, whereas on clear, cold nights, as long as it isn't extremely cold, the energy savings is greater. The high wind velocity and end wall effects are also noticeable when greenhouses #3 and #4 are compared. They have the same glazings, but #4 is four percentage points lower in savings (based on “U” value) than #3. This is due to the combination of wind and colder end wall radiation environment for one of the end walls in greenhouse #4.

## Plant Leaf Temperature:

Multilinear regression and ANOVA statistical analysis was done on the leaf temperature data and it indicates that the average plant leaf temperatures in the 602/602 greenhouse were approximately equal to, and in the M2/602 greenhouse slightly lower than, those in the M2/M2 greenhouse that was operated at the same minimum nighttime temperature. The M2/M2 greenhouse that was operated at a 1°C (2°F) lower nighttime minimum air temperature setting was also slightly lower than the other M2/M2 greenhouse. It appears that due to the longer run time of the heat exchanger in the 602/602 greenhouse, the inside layer is warmer than the other greenhouses and this compensates for some of the increased radiation heat loss from that greenhouse.

The inside net radiation values were found to be the best indicator of plant leaf temperature in all of the greenhouses. The greater the radiation loss from the plants to the environment above them, the colder the leaf temperature. An approximation of the relationship, which applies to all of the greenhouses, was:

$$\begin{aligned} \text{inside ambient air temperature minus leaf temperature} = \\ 0.6^{\circ}\text{C} + 0.04 * |\text{inside net radiation}| \\ (1^{\circ}\text{F} + 0.4 * |\text{inside net radiation}|) \end{aligned}$$

The absolute value of the inside net radiation term is used in this case to change it from negative to positive and make the form of the equation simpler. The equation calculates the difference in temperature between the greenhouse inside ambient air temperature and the plant leaf temperature. The constant term indicates a minimum 0.6°C (1°F) leaf temperature depression with a 0.04m<sup>2</sup>K/W (0.40°F ft<sup>2</sup>h/Btu) coefficient for the inside net radiation. This should be independent of the greenhouse the plant is in, so if the net radiation a plant is experiencing in its environment is known, then the plant leaf temperature can be calculated. The equation is for nighttime only. The daytime relationship would be greatly affected by ventilation, solar radiation, transpiration and other factors. Again it should be emphasized that the internal net radiation readings relative to external environment depend on the glazing system.

## Growing Media Temperature:

Preliminary data obtained on the average nighttime growing media temperature of the bedding plant flats in the greenhouses indicate that in cold weather, growing media temperature is probably more a function of heating system than greenhouse radiation, if a full plant canopy exists. The heating system used, where the heating tubes are under the bench, will cause the soil or mix to be warmest in the greenhouse where the heat is on the most. The growing media in the 602/602 greenhouse was slightly warmer than in the other greenhouses on very cold nights because the heat was on much longer. This difference became less and less apparent as the weather became milder because the heat wasn't on as often and the variation of the growing media temperature became less pronounced. Mild weather reverses the trend and the average growing media temperature is highest in the M2/M2 greenhouse because it loses heat at the slowest rate. The mix cools slower, so on the average, the growing media temperature is warmer. The variation is seldom more than 0.6°C (1°F) in favor of either greenhouse.

## Crop Response:

Poinsettias were grown in the four houses in the fall of 1982 and again in the fall of 1983. The houses were covered as noted earlier. Rooted poinsettia (both red and white) cuttings were purchased from a local supplier. The plants were placed in the greenhouses on 9/7/82 and 9/14/83. Plants were pinched two weeks after receipt and received a Cycocel spray (750 ppm) approximately two weeks after pinching. Fertilization consisted of Osmocote and 15-15-15 at 200 ppm Nitrogen when watered. Plants were randomly sampled during the growing season and data on growth and earliness collected.

Figure 10(A & B) shows that in both 1982 and 1983 the poinsettias were more advanced in the house covered with the double IR material when compared to the house covered with double 602. In Fig. 10(A) the anthocyanin content on 11/2/82 clearly depicts this enhancement in either floral initiation or rate of development. The data in Fig. 10(B) taken on 12/14/83 again supports this conclusion. The plants grown in 1982 were about 10-14 days earlier and 3-7 days earlier in 1983. This difference in earliness between the 2 years may be due to the different relative light intensities. That is, in 1982 the double IR material had a 3 percentage point higher PAR transmission compared to the double 602 while in 1983 this situation was reversed.

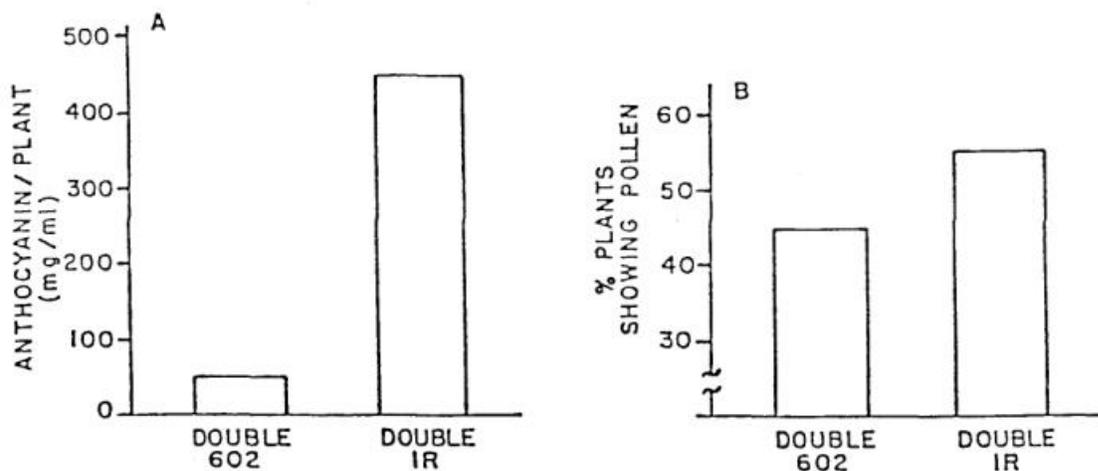


Fig. 10. Comparison of earliness in Dark Red Annette Hegg poinsettias grown in greenhouses covered with a double layer of 602 or a double layer of new IR material. (A) Anthocyanin development was measured on 11/2/82, (B) Percentage of plants reaching anthesis as of 12/14/83.

The data in Table 18 indicate that in each year the flower/leaf ratios (fresh weight) are very comparable regardless of the greenhouse covering. This shows that while plants in the double IR house are somewhat earlier, they are proportionally similar to those in the double 602 greenhouse by the time they are ready for sale. In none of the covering schemes studied did the IR material result in a deleterious growth response.

TABLE 18

Flower:Leaf ratio calculated on a gram fresh weight basis for white and red poinsettias (12/6/82 and 12/8/83)

	RED		WHITE	
	double IR	double 602	double IR	double 602
1982	1.38	1.25	1.02	.87
1983	.85	.88	.75	.70

In 1983 the air temperature was lowered by 1°C (2°F) in one of the double IR covered greenhouses. This was done in an effort to capitalize on the earliness noted the year before. On 12/12/83 there was a higher anthocyanin content in the bracts of the poinsettias grown in the “cool” double IR house in comparison to plants grown in the “warm” double IR house. Therefore, besides being able to conserve fuel, slightly lowering air temperatures intensified bract coloration even further.

In the spring of 1983 and again in 1984, six species (two varieties each) of bedding plants were distributed throughout the four houses. These included geraniums, begonias, impatiens, petunias, marigolds, and tomatoes. These were obtained as young seedlings and were set in the greenhouses between March 10 and 24. In general, the bedding plants in each house were of comparable quality by early May when they would be in greatest demand. Some earliness to flower (a few days) was noted for impatiens, begonia, and petunia. However, we do not believe the differences were significant enough to warrant any change in cultural practices. In no case did we note a delay in flowering of plants in the double IR house.

Rooted chrysanthemum cuttings (Yellow Knob Hill) were placed in the greenhouses in early February in both 1983 and 1984. In 1983 the average flower diameter in the double IR house on 5/10/83 was 14 cm while in the 602 covered house it was 9 cm. Similarly by May 1, 1984, about 90% of the chrysanthemums in the double IR house had reached a diameter of 16 cm, but only 40% of the flowers in the double 602 covered house had reached the same diameter.

It is consistently clear that the double IR material has a somewhat promotive effect on the photoperiodically sensitive plants that we have studied. The exact cause of this effect is at present unknown. It is also clear that the growth of the bedding plants is somewhat less altered, but in several cases responds favorably to the double IR film. These positive flowering responses may allow the grower, based on his experience, to change growing practices by starting later or lowering air temperatures. In most experiments environmental conditions were maintained as consistent as possible among the various treatments and at no time did this result in an unsaleable crop at the proper time of the year.

## Conclusions

### PAR Transmission:

When initially installed on the greenhouses, the 602/602 glazing combination had the highest PAR transmission of all the glazing combinations and the M1/M1 combination was the lowest. The initial difference was approximately 2 percentage points (64% vs 62%). After the greenhouses had gone through a single summer the M1/M1 combination had the greatest PAR transmission, due to the reduced transmission of the 602 on the other greenhouses. Installing M1 over 602 helps to protect the 602 from darkening and would be the recommended combination for a two-material glazing scheme for that reason.

The same comparisons with M2 installed in place of M1 has yielded similar results to this point. The 602/602 combination had the greatest PAR transmission in the fall of 1983. Contrary to the previous results, where by the second crop the 602/602 combination had dropped to the lowest PAR transmission, that probably will not occur as soon in this group of tests because the greenhouses have not gone through a summer period yet. It appears that it is during the summer (especially the first summer a layer of 602 is exposed) that the majority of the darkening due to UV exposure occurs. That won't be occurring until after the second crop, so the 602/602 combination should still have the greatest PAR transmission this spring (1984).

### Heat Savings:

The percent heat savings should be evaluated considering the respective locations of the greenhouses and adjusting the numbers accordingly. The greenhouse's location can have a dramatic effect on its heat requirement. The location advantage of a sheltered over an exposed greenhouse in these tests could affect the calculated heat saving by as much as 8 percentage points. A double layer of either M1 or M2 provided the greatest adjusted savings in all test periods. The combinations of M1/602, 602/M1 and M2/602 provided slightly less adjusted saving than the double test material combinations. The new film, M2, will reduce greenhouse heat requirement if used in either a double layer or single layer with 602 combination.

### Crop Response:

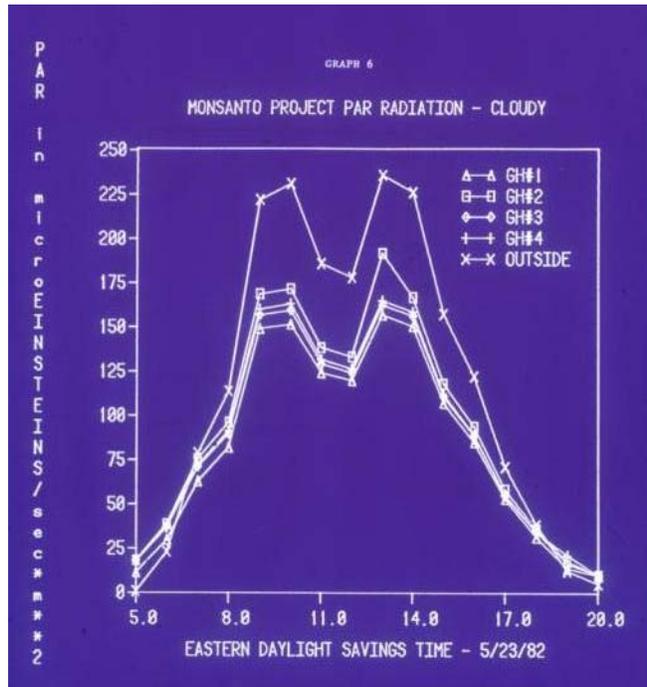
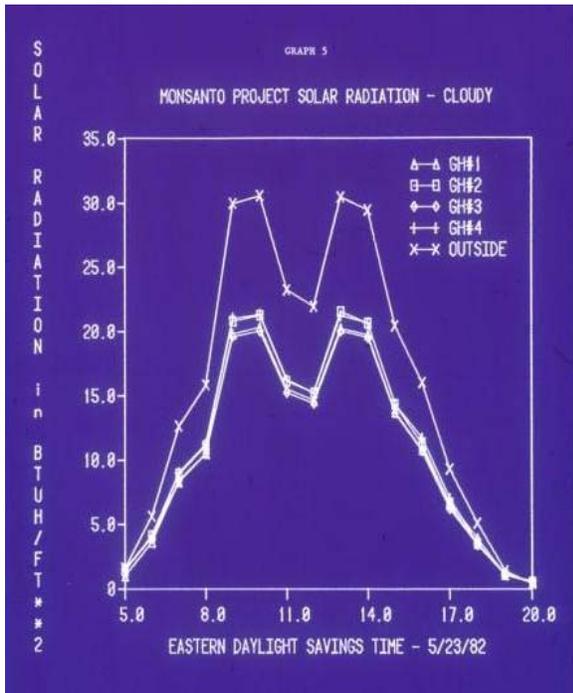
The infrared absorbing glazing materials, M1 and M2, have a promotive effect on photoperiodically sensitive plants. The cause of this effect is not known at this time.

The effect of the IR materials on the growth of bedding plants and those non-photoperiodically sensitive plants tested, is less pronounced. Some of these crops did respond favorably to the test glazings. A saleable crop was produced at the proper time of year in all test periods with no adverse effects.

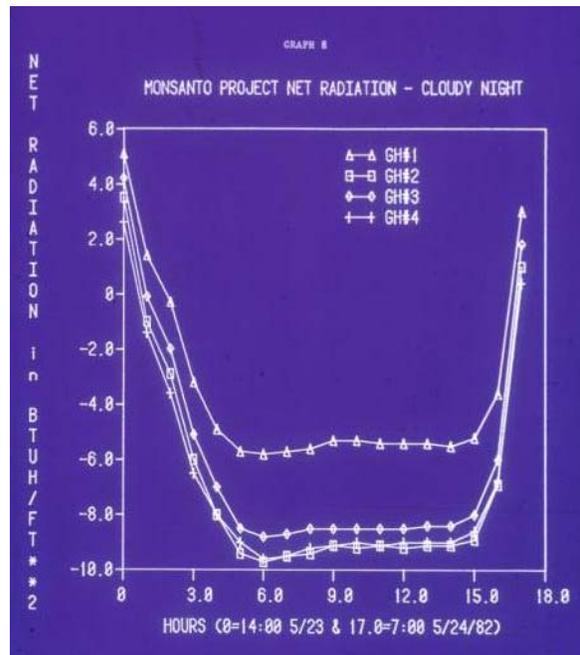
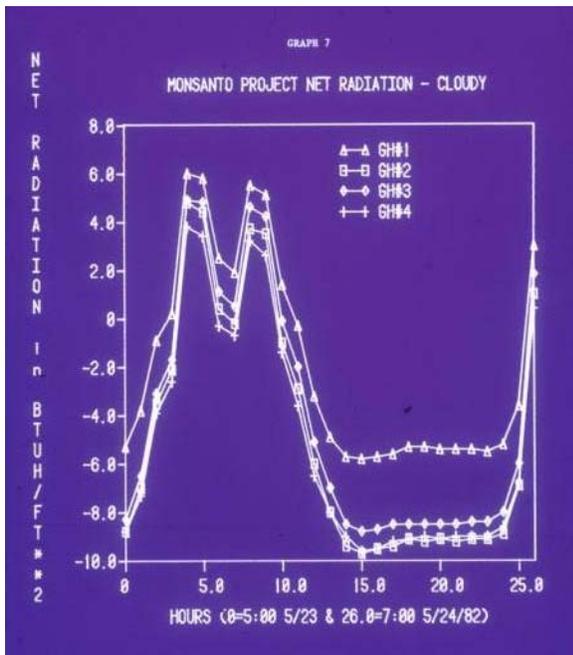
## References

1. Kieboom, A. M. G. van den. 1982. Radiation properties of greenhouse covering materials and greenhouses. IMAG. Wageningen, Netherlands. 48 pgs.
2. Manning, T. O. 1983. Logger. Copyright 1982.
3. Roberts, W. J. and D. R. Mears. 1980. Floor heating of greenhouses. ASAE Paper No. 80 - 4027, ASAE, St. Joseph, MI 49085.

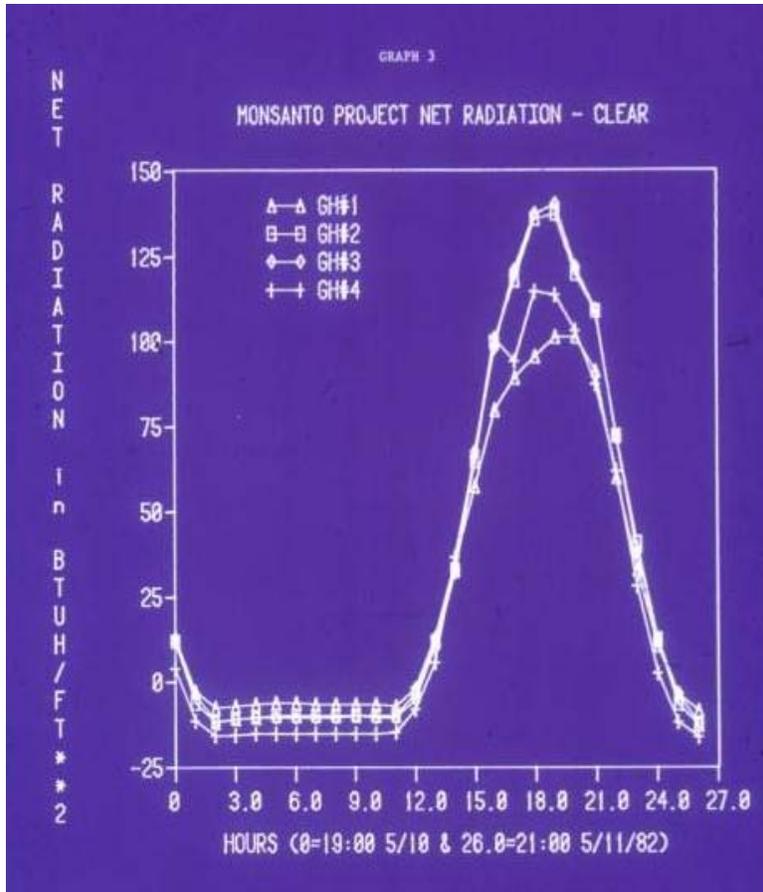
## Illustrations and Additional Figures



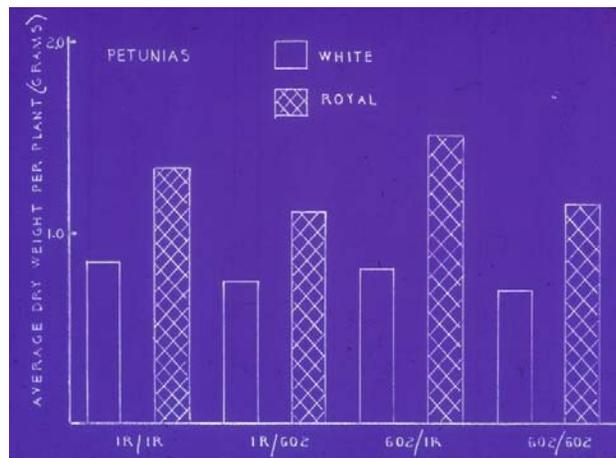
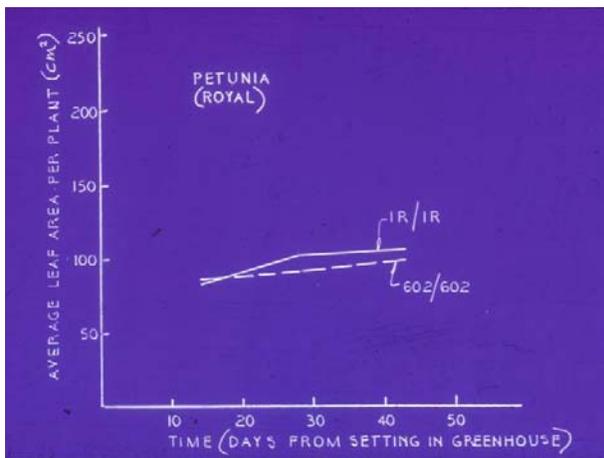
Representative total solar radiation and PAR radiation outside and inside each greenhouse for a partially cloudy day



Representative net radiation for the test houses day and night on the left and expanded night scale on the right



Representative net radiation on a clear night and day



Growth data for Petunias comparing double IR film to double non-IR with regard to leaf index for one variety and dry weights for two varieties grown in each of the four test greenhouses



Illustrations of crops grown in the test greenhouses