INFORMATION TO USERS

This reproduction was made from a copy of a document sent to us for microfilming. While the most advanced technology has been used to photograph and reproduce this document, the quality of the reproduction is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help clarify markings or notations which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure complete continuity.

2. When an image on the film is obliterated with a round black mark, it is an indication of either blurred copy because of movement during exposure, duplicate copy, or copyrighted materials that should not have been filmed. For blurred pages, a good image of the page can be found in the adjacent frame. If copyrighted materials were deleted, a target note will appear listing the pages in the adjacent frame.

3. When a map, drawing or chart, etc., is part of the material being photographed, a definite method of "sectioning" the material has been followed. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again—beginning below the first row and continuing on until complete.

4. For illustrations that cannot be satisfactorily reproduced by xerographic means, photographic prints can be purchased at additional cost and inserted into your xerographic copy. These prints are available upon request from the Dissertations Customer Services Department.

5. Some pages in any document may have indistinct print. In all cases the best available copy has been filmed.

University Microfilms International
300 N. Zeeb Road
Ann Arbor, MI 48106

Martinez, Jaime Reynaldo

GREENHOUSE LETTUCE YIELDS AND ENERGY CONSUMPTION UNDER LIGHT SELECTIVE PLASTIC FILMS

The University of Arizona M.S. 1985

PLEASE NOTE:

In all cases this material has been filmed in the best possible way from the available copy. Problems encountered with this document have been identified here with a check mark __✓__.

1. Glossy photographs or pages __✓__
2. Colored illustrations, paper or print __✓__
3. Photographs with dark background _____
4. Illustrations are poor copy _____
5. Pages with black marks, not original copy _____
6. Print shows through as there is text on both sides of page _____
7. Indistinct, broken or small print on several pages _____
8. Print exceeds margin requirements _____
9. Tightly bound copy with print lost in spine _____
10. Computer printout pages with indistinct print _____
11. Page(s) _____ lacking when material received, and not available from school or author.
12. Page(s) _____ seem to be missing in numbering only as text follows.
13. Two pages numbered _____. Text follows.
14. Curling and wrinkled pages _____
15. Dissertation contains pages with print at a slant, filmed as received _____
16. Other _____

_____

_____

University
Microfilms
International

GREENHOUSE LETTUCE YIELDS AND ENERGY CONSUMPTION UNDER LIGHT SELECTIVE PLASTIC FILMS

by

Jaime Reynaldo Martinez

A Thesis Submitted to the Faculty of the

DEPARTMENT OF PLANT SCIENCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN HORTICULTURE

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 8 5

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at the University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his or her judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: Jamie R. Martinez

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Merle H. Jensen
Professor of Plant Sciences

Dec. 16, 1985
Date

DEDICATION

This manuscript is most affectionately dedicated to my family. Without their unwavering support and encouragement, the realization of this work and what it stands for would not have been possible.

ACKNOWLEDGEMENTS

I would like to express my most sincere gratitude to Dr. and Mrs. Merle H. Jensen; the friendship and advice they have given me have been exceptional.

Also, I would like to specially thank Drs. Paul Bessey and Norm Oebker for all the help and counseling they offered me as members of my graduate committee.

Of the E.R.L. staff, I am especially indebted to Bill Cunningham for all his help and cooperation throughout the project. My thanks also to Lisa Bates as well as the rest of the staff who have made my work at the lab very enjoyable and meaningful. A special expression of gratitude goes to my good friend Abdel Anouti.

To Mary Mashaw I am very thankful for her professional help and willingness in achieving the completion of this work.

TABLE OF CONTENTS

TABLE OF CONTENTS--Continued

LIST OF TABLES

LIST OF TABLES--Continued

LIST OF FIGURES

ABSTRACT

'Bibb' lettuce (Lactuca sativa L.) fresh weights and heating-cooling energy needs were measured in evaluating 2 light selective films and a polyester film, used as greenhouse covers. Light selectivity provided high visible light transmittance but reflected infrared radiation. The films were compared to commercial polyethylene; all treatments employed as double layers with polyethylene being the exterior layer. The test films were also compared with shade cloths of equivalent light transmission by measuring 'Bibb' lettuce fresh weights. The film-shade cloth comparison was done in a fiberglass covered greenhouse. Results indicated that average yearly yields were superior for all 3 test films. Yield increments over the control were 19% higher during cool months than during warm months. Average energy consumption for cooling was 2% higher for test films but 48% lower for heating during cold months. Light selective films had 40% higher average yields than equivalent shade cloths.

CHAPTER 1

INTRODUCTION

Perhaps what constitutes the greatest limitation for the expansion of the greenhouse industry at the present is the high cost of fuels for cooling and heating. This condition applies regardless of the geographic location in question, whether it be in the northern latitudes or in arid lands.

During the past 5 years, research teams from universities and industry worldwide have done extensive investigations to develop alternative methods for conserving and decreasing the use of fuel energy. Major research emphasis has focused on solar, geothermal and reject heat from large industrial units. Although solar energy is technically feasible, it does not appear economical because of the high collection and storage costs.

Other techniques and materials recently developed and already in use include:

(a) The use of double greenhouse plastic covers separated by air pressure;

(b) Double glass glazings with an air space in between;

(c) The utilization of new, low emissivity glass materials;

(d) The employment of heat curtains or thermal blankets, which are effective in conserving energy and in reducing the air volume to be heated; and

(e) The use of innovative plastic films which are light selective, thus effecting crop responses as well as being more energy efficient.

The objective of this study was to evaluate the performance of a new group of light selective films on greenhouse energy consumption as well as crop responses. These films are manufactured and sold under the trademark Heat Mirror, and are widely employed by the construction industry to provide house and building insulation. The insulation afforded by these films serves the ultimate purpose of reducing heating and air conditioning system capital and operating costs.

Heat Mirror films consist of a sophisticated, wavelength selective coating applied onto a weatherable polyester substrate. The transparent insulation furnished works by transmitting short wavelength solar rays, including visible rays, while blocking by reflection the longer wavelength heat rays. Heat Mirror is colorless and transparent, performing by heat reflection rather than heat absorption and reradiation.

CHAPTER 2

LITERATURE REVIEW

Energy Conservation in Greenhouses

Energy conservation is an important management practice of the greenhouse industry at the present. Approximately 70% of the total greenhouse covered area of the world is located in countries subject to long and cold winters; this area comprises nearly 30,000 hectareas which are mainly distributed in Northern Europe, the U.S.S.R., Japan, Canada and the United States (Hanan, Holley & Goldsberry, 1978).

Precisely because of their geographic location, greenhouse managers face the need to heat them, as well as to adapt new technologies which enable them to conserve energy. This constant process of adaptation becomes a must if a grower wishes to remain competitive in an already highly competitive industry. During the energy crisis of the 1970's the price of heating fuel for greenhouses doubled, tripled and even quadrupled in a matter of months; such increases, coupled with the fact that the cost for heating is approximately 8% of total operating cost, have impelled for the development and adoption of energy conservation methods and materials (Grimmer in Hanan, Holly & Goldsberry, 1978).

Maintenance and Management Practices

There are several ways by which greenhouses can be made more energy efficient and which depend on sound maintenance and planning. Stickler (1975) states that individual greenhouses are cheaper to construct; however, he also reports that a 4 sectioned ridge and furrow greenhouse requires 23% less heat than 4-single section houses of the same type, covering the same ground area. Goldsberry (1978) has indicated that during a 14-day period in late fall, 22.5% less energy was captured by a greenhouse with dirty glass in contrast to one with clean glass. It has also been reported that the use of faulty steam traps, having an 1/8 inch orifice, will use 35 pounds of steam per hour. If this consumption occurs on a 40-hour per week basis, the total energy loss will be equivalent to 7 tons of coal per year (Winspear in Hanan, Holley and Goldsberry, 1978).

Proper maintenance of the greenhouse structure will minimize infiltration heat loss. Annual potential savings ranging from 3% to 10% can be obtained if infiltration is reduced by: (a) fixing broken glass; (b) caulking foundation cracks; (c) patching torn plastic; and (d) an additional second door which forms an airlock buffer zone between doors that go directly outside and are frequently used (Badger & Poole, 1979). The same authors state that potential savings of 10% to 20% annually can be obtained by the proper maintenance of the heating and ventilating system. Specifically, the use of indicated fuel, constant monitoring of the boiler efficiency and the

provision of adequate combustion air for heaters is essential to obtain high energy efficiency.

Other factors which should be constantly verified are:

(a) The heat distribution system; it is particularly important to avoid leaky valves and pipes. A steam line having a 1/16 inch diameter hole can waste as much as 7 gallons of fuel daily.

(b) Chimney and furnace tightness.

(c) Control system: The assured precision and adequate location of thermostats will help prevent fuel wastage by indicating representative temperature readings; a 10% additional fuel is required to maintain a greenhouse at 62°F instead of 60°F, if the outside temperature is 40°F.

The adoption of sound maintenance and management practices, therefore, can help a grower considerably in conserving energy and thus reduce his operating costs.

Energy Efficient Plastic Covers

The greatest heat loss by a greenhouse occurs through its cover and structure. It has been calculated that, depending on temperature, from 30 to 210 and from 15 to 100 BTU's h^{-1} FT^{-2} of greenhouse ground area covered can be lost, respectively, from a single and double glazed polyethylene house (ASHRAE, 1974). Since it is precisely through the greenhouse structure and cover that most heat

energy is lost, the majority of the energy saving techniques recently developed are designed to reduce these specific losses.

One of the first methods devised to conserve energy in the greenhouse, by reducing losses through its cover, was the use of a double layer of polyethylene. Beseber, Axlund and Brown (1974) report that a 40% fuel savings can be obtained by using 2 polyethylene layers in contrast to 1. Their work was based upon earlier research done by Roberts (1968) who was probably the first to propose the concept of a 2 layer greenhouse. The separation of the two polyethylene layers by the application of air pressure, creates an air space which serves as insulator. It has been proven that if plastic is available, it is more economical to install a double layer cover than a single one.

A modification of the double polyethylene system is reported by Montero, Short and Bauerle (1980). These researchers devised a system by which polystyrene pellets were injected between the 2 plastic layers. The 5 inch thick pellet layer provided an insulation 90% higher than the conventional double layer polyethylene. Furthermore, it is indicated that future greenhouse coverings should be designed to be very transparent during the day and have highly insulating properties at night.

Another energy saving concept in which a double plastic layer is involved is reported by Kawamata and Ogura (1983). Their heat conserving system is composed of a vinyl plastic, doubly clad greenhouse, with a continuously circulating water film between the

2 layers. The water film serves the purpose of intercepting thermal radiation coming from the soil. An evaluation was made comparing the author's concept with a vinyl covered structure equipped with a heat saving, horizontal curtain of polyethylene. Results demonstrated that a high quality crop of potted cymbidiums was obtained in the test greenhouse; also, the winter grown crop was obtained without delay or need for any heavy oil to provide extra heating in contrast to the control house.

Wells (1978) based upon earlier work done at Arizona by Groh (1977) reports a 20% to 40% heat loss reduction by using liquid foam between 2 layers of polyethylene. This system consists in injecting soap suds between the films, at night, which serve as insulators; the soap solution is made from a 3% foam concentrate in water and has a 200:1 expansion ratio, which means that 200 FT^3 of foam can be obtained from 1 FT^3 of solution. The use of 12% ethylene glycol is reported as an antifreeze and stabilizing agent; during the day the soap is collected in a storage tank and recirculated again at night time.

More recent research has been done to evaluate the performance of newer materials versus double polyethylene covered greenhouses. Goldsberry, Wilson and Pixley (1982) evaluated 3 different materials in identical quonset style greenhouses, in contrast to a double polyethylene greenhouse of the same dimensions. The materials tested were: (a) 6 mm polycarbonate (Qualex), (b) Monsanto 603 double layer air inflated polyethylene, (c) 5-oz Tedlar coated fiberglass

reinforced plastic panels (FRP), and (d) double layer 400 XRB 162 GT Tedlar film attached to tubular steel frames (NEXGLAZE). Their results showed that the NEXGLAZE house required 8%, 9% and 42% less fuel than double poly, Qualex and single layer FRP structures, respectively. It was also proven that FRP cover transmitted 79% to 81% of the total available solar radiant energy during the winter; on the other hand, the insulation recorded under the double poly, Qualex and NEXGLAZE ranged from 65% to 73%, 59% to 61% and 62% to 72%, respectively.

In another experiment in which doubly-clad greenhouses with different materials were evaluated for energy conservation, the double coverings proved to be more energy efficient. The materials tested consisted of: (a) new double layer air inflated 4 mil Japanese P.V.C., (b) New Monsanto 603 polyethylene, (c) 2 year old double walled 4 mil P.V.F. (DuPont Tedlar), and (d) a single layer of 5-oz Tedlar coated lascolite FRP (fiberglass reinforced plastic) panels (four years old). The results obtained showed that fuel used in the double glazed structures ranged from 34% to 40% less than required for the single layer FRP treatment. An evaluation was also made concerning the average percentage of radiation transmitted during the time period September 17 to May 2. It was shown that 10% to 17% less radiation was transmitted under the double glazings than in the single FRP treatment. In terms of plant leaf temperature, results showed no significant differences between all covers (Ferrare & Goldsberry, 1984).

Further research on the influence of double layer greenhouse glazing on light transmission and fuel requirement has been done by Goldsberry, Wilson and Pixley (1982). These authors measured fuel requirements from September 1981 to March 1982 of 4 different covering materials. Results demonstrated that a greenhouse covered with double Tedlar film, required 5%, 7% and 40% less fuel than structures covered with: (a) double layer air inflated polyethylene, (b) a 6 mm thick, structure polycarbonate (Qualex), and (c) fiberglass reinforced plastic panel (FRP). Measurements of percentage solar radiation transmitted were 82%, 66%, 63% and 59% for FRP, double polyethylene, double Tedlar and Qualex respectively.

During a 5-year test period on the interaction between greenhouse covers and atmospheric conditions, Goldsberry (1982) evaluated four different materials. The experiment took place from 1976 to 1981 and the materials tested were: (a) new 5-oz corrugated fiberglass-reinforced plastic (FRP), (b) a single layer of Monsanto 6-oz polyethylene inflated by air, (c) a double layer of air inflated polyethylene, and (d) 8 year old weathered FRP panels. Cover A being the control house, results showed that fuel consumption for cover B were 5% to 6% greater than A; for cover C, fuel consumption was 33% to 36% less than A while cover D utilized from 6% to 11% more fuel than the control. It is further indicated that the double layer cladding was generally considered to be the best for lowering fuel costs.

The use of twin walled rigid plastics as energy efficient covering materials has also been recently researched. Hinton (1982) reports the use of twin walled rigid plastics as experimental materials involving commercial scale growing. In contrast to commercially available acrylic and polycarbonate, energy savings of 41% were obtained under a 22 mm section acrylic. A 34% fuel savings was obtained beneath a 10 mm polycarbonate cover. Crop yields involving early monocropped tomatoes were maintained despite considerable light reductions; it is also mentioned that fruit quality and total yield were lower under polycarbonate than under acrylic.

In one 3-season trial conducted in a commercial nursery, energy savings and crop performance were measured in 2 greenhouses. The control house was clad with a single glass layer. The test house consisted of a variglaze structure, clad with double skin panels of melinex polyester film. Air was used to inflate the air space between the two polyester layers when maximum insulation was desired. When the air was drawn out, the film behaved as a single layer, thus allowing for maximum light transmission. Results indicated that total tomato yields did not differ significantly between the two houses. Also, the variglaze system proved reliable and simple to operate without an increase in maintenance costs. Most important, the variglaze fuel consumption rate was 57% lower than that of the control house, when the film was inflated during February and March (Anonymous, 1984).

Simpkins et al. (1984) reports on the energy efficiency of a double layer, infrared radiation absorbing polyethylene film. This material was evaluated in contrast to a conventional double layer, polyethylene film. The test material is characterized as a colorless film, which diffuses light due to the addition of an infrared absorber. After a 2-year test period, results indicated that 24% heat fuel savings were obtained with the test material versus the conventional polyethylene. The authors also mention that the energy savings provided by this film are due to its ability to absorb infrared radiation. The absorbing effect reduces net radiation loss from the greenhouse, thus enabling the heating system to operate more efficiently.

Energy Efficient Glass Covers

Glass is still extensively used as a greenhouse cover throughout the world. As a matter of fact, only 6% of the total greenhouse covered area is under plastic films (Hanan, Holley and Goldsberry, 1978). Since glass covers are employed so widely in the greenhouse industry, some of the most recently developed energy saving techniques deal with this material.

One of the first methods developed was the addition of a second layer of glass to an already operating greenhouse. Energy savings of approximately 50% have been reported by Gillette (1982). This author also mentions the recent use of large, tempered glass panels. These provide a very small light reduction plus a 5 to 8 fold added strength, in contrast to double strength glass.

Another technique currently being employed is described by Badger and Poole (1979); the method consists in installing an air inflated plastic cover over a glass clad greenhouse. The added plastic cover reduces heat losses due to infiltration and conduction. Results showed that potential annual savings range between 40% to 60%.

The most recent development in greenhouse glass technology has been the use of low emissivity glass. Baille, Laury and Baille (1983) report that utilizing low emissivity glass as greenhouse covering reduced radiation losses by 70% on the average. Their analysis also showed that, over a 2-year heating period, the mean value of energy saved by this type of glass was 22%. The savings were obtained by evaluating low emissivity glass versus a conventional glass cover.

In 3-year trials in which tomatoes were grown in Venlo-type glasshouses, light and heat requirements were evaluated. Light reduction varied from 3% to 22% with the use of Hortiplus glass (tin-oxide coated) when compared to conventional hammered glass. The percentage variation depended on the time of year. These results are reported by Benoit, Ceusterans and De Boodt (1982), who also indicated that a 1% light reduction resulted in a 1.5% yield reduction. On the other hand, it was demonstrated that relative energy savings amounted to 27% to 48%, depending on rainfall and windspeed. The resulting net financial savings amounted to approximately 34%, at current prices.

Sebesta and Reinsen (1982) report the results obtained by dividing a greenhouse into 2 parts by the use of a transverse glass wall. One half was covered with 4 mm low emissivity glass (Hortiplus) and the other with double sheets of 6 mm polycarbonate (Makrolon). Results showed that, in comparison with an ordinary glasshouse in good repair, low emissivity glass reduced heat loss by about 25%. Polycarbonate sheets provided heat energy savings of approximately 30%.

Heat Curtains

One of the most recent developments in greenhouse energy conservation methods is the use of heat curtains, also known as thermal blankets. Research done at American universities and European institutions proves that thermal blankets decrease heat losses resulting from radiation, convection and infiltration. Another advantage of using heat curtains is that air stratification is reduced and volume of heating space diminishes. It has been determined that heat curtains are more effective in double layer plastic greenhouses. The reason being is because the curtain prevents an exchange of radiation that would normally occur through plastic. Heat curtains provide a potential annual energy savings of 20% to 60% (Badger & Poole, 1979).

In a study performed during the winters of 1980-81 and 1981-82, Bjerne and Amsen (1983) tested heat curtains to evaluate their energy saving potential. Their report states that the control

greenhouse consisted of a single layer glasshouse with a mobile shading curtain. Compared with the control, energy savings of 29% to 32% were achieved with double glass insulation; 39% with double acrylic insulation, and 22% to 24% with an aluminum coated thermal screen in a single layer glasshouse. Furthermore, results showed that relative humidity in the double glazed house was 80% to 86%; a 5% to 10% lower value was measured in the single layer glasshouse.

In terms of plant yields, it was determined that 3 out of 7 species of foliage plants had 5% to 10% higher weights in the double acrylic greenhouse; very similar results were obtained in the greenhouse with the thermal screen. On the other hand, 4 species showed a 10% lower yield in the double glazed treatment versus the control greenhouse.

Baille and Baille (1984) report the results of comparing 2 identical glasshouses covered with: (a) standard glass, and (b) low emissivity glass. It was determined that the use of an acryl-polypropylene thermal screen reduced convection heat loss by 50% or more. The screen, however, was less effective in reducing losses by radiation, particularly in the case of low emissivity glass. Additionally, foliage plant temperatures were similar in both houses when the screen was in position. With the screen removed, differences of up to 2°C in favor of low emissivity glass were observed. The authors state that without heating, air temperature gains induced by the screen were 1° to 2°C in both houses.

Weimann (1984), reports that inflated double plastic greenhouses with heat screens lost 65/50% (night only/total 24h) less heat than glasshouses without screens. In contrast to single layer plastic greenhouses, the heat savings observed were 51/40%. His results also showed that heat screens contributed more to the energy savings than the double plastic and there was no reduction of light transmission in the double plastic house.

Meyer (1984) evaluated 12 different heat screen materials to determine their energy savings potential. His results indicate that the greatest energy savings obtained were higher than 50%, at night; the savings were obtained using a double layer of the nonwoven polyester material FLORATEX 80. This cover was attached to an aluminum backed aircap (bubble) film, and a double layer of black polyester film.

A modified version of a heat curtain is reported by Short and Huizing (1982). These researchers employed inflatable plastic tubes connected with each other to form a screen. Results suggest a 50% night energy savings can be obtained by using this system. Additionally, it is mentioned that the inflated plastic tubes, unlike conventional sheet screens, provide a nearly complete closing of gaps. Further advantages are that deflated tubes store directly under the gutters during daytime, thus avoiding unwanted light reductions. Also, there is no condensation or icing of the upper surface, and rain water leaking through the roof cannot form into pools on the screen.

Combined Energy Saving Systems

The adoption of integrated systems will probably constitute the future trend in designing energy efficient greenhouses. A greenhouse which will conserve heat by having an insulating cover may be only part of the whole scheme. Proper maintenance procedures, well insulated floor and side walls, plus the possible storage of solar energy for night time use, are additional measures that should be considered. The ultimate objective is to minimize the amount of extra heat energy that must be used to maintain desired temperatures.

MacRoth (1984) studied the possibility of combining a number of energy saving measures during a 4-year period. His results showed a 59% energy savings in a 2,400m^2 greenhouse prototype equipped with several energy conserving devices. The greenhouse cover consisted of a triple cladding of 10 mm polycarbonate hollow plates, with a 0.08 mm plastic sheeting placed 8 cm below. The greenhouse was heated with hot water pipes and an air heater which together provided 126 W/m^2 of greenhouse area. Heat was produced by an electrically driven heat pump, and solar energy could be obtained via a heat exchanger and stored for use during the night. A propane gas fired boiler with a 230 Kw nominal capacity was employed to provide for deficit heat. In another evaluation, the same researcher mentions the use of a multi-system, energy efficient greenhouse. This structure's energy saving measures include triple polycarbonate cladding. Also employed were an EVA (acetic acid ethenyl ester polymer) film, a thermal screen,

a heat pump with heat exchangers inside and outside the structure, plus a low temperature heating system (MacRoth, 1983).

CHAPTER 3

MATERIALS AND METHODS

This study took place at the Environmental Research Laboratory, a research center of the University of Arizona. The experiment was divided in 2 parts. In Part I 2 light selective films and a polyester film were evaluated for their energy conserving efficiency and effects on 'Bibb' lettuce (Lactuca sativa L.). In Part II the light selective films were compared with non light selective shade cloths under a greenhouse cover. The objective was to evaluate 'Bibb' lettuce yields under selective and non selective covers, which could be used as possible shading materials or thermal reflection.

Part I. Two light selective films and a polyester film were evaluated versus commercially available ultraviolet resistant polyethylene. Table 1 shows the film's characteristics in terms of solar transmittance in contrast to UV-polyethylene, the control film. Polyethylene, behind glass, is the most widely used material by the greenhouse industry in the world. Its popularity derives from the fact that it is inexpensive, has good light transmitting properties and is easy to install. One of its drawbacks, however, is its relatively short useful life of 1 to 2 years. The present trend is to employ it as an inflated double layer in order to conserve heat.

Table 1. Manufacturers' Data on Transmittance of Total Solar, Visible Light and Approximate Cost of Films.

Film Type	% Total Solar Transmittance	% Visible Light Transmittance	Approximate Cost Dollars/FT^2
6 mil-UV-polyethylene	88	88	.06
3 mil-Heat Mirror 77	53	71	1.20
3 mil-Heat Mirror 88	70	82	1.20
5 mil-ICI-071-polyester	93	93	

A schematic representation of the light selective film's composition is shown in Fig. 1.

++++++++++++ = Protective Top Coat

oooooooooooo = Selective Transmission Coating

———————— = 3 or 5 mil UV-Stabilized Polyester

---------- = Antifog (Hydrophylic Coating)

Figure 1. Light Selective Film's Composition.

The schematic representation applies to the test films Heat Mirror 77 and Heat Mirror 88; the third film tested ICI-071 polyester, would consist only of the 2 interior layers. Both Heat Mirror 77 and 88 films have a thin, vacuum deposited, low emissivity coating on one side. This coating greatly reduces heat loss by radiation in the far infrared region. In addition, these films selectively transmit solar

energy, a larger percentage of photoactive light is transmitted than that of the near infrared portion.

Heat Mirror films are designed to be used as the inner glazing of 2 layer systems, placed behind a high transmission, long life outer glazing. In this experiment all 3 test materials were used as the inside layer of a doubly clad greenhouse called phytocell. The outside layer consisted of 6 mil UV-resistant polyethylene film. The control phytocell's cover was composed of 2 layers of polyethylene. The outside layer being 6 mil in thickness and the inside layer 4 mil. The films were installed during the period February 10-16, 1984.

Phytocells Description

Four small greenhouses called phytocells were used for evaluating the covering films. These phytocells were modified quonsets with a north/south orientation. The distance between each phytocell was 3 m. Each was 6 m long and 4.5 m wide, roof height was 2.6 m and curtain height was .5 m (Fig. 4). The phytocell's structure was already in place at the time the experiment began, only the film covers were additionally installed during the time period previously indicated. In order to keep the 2 film covers separated, air pressure was applied. For this purpose a "squirrel cage" blower with a 76 CFM output was employed. Once operating, the blower exerted a pressure equivalent to 1.27 cm of water and the separated films were kept approximately 13 cm apart.

Environmental Control Systems and Sensors

Each phytocell was equipped with a 2-stage evaporative cooling system having a 5500 CFM capacity. The 2-stage system consists of an initial dry cooling of air, which then flows through an evaporative cooler at a lower temperature. The result is a cooler interior temperature than would have been obtained by the use of a single stage evaporative cooler. A 4-way diffuser was installed at the end of the cooling unit's duct. Due to poor performance in cooled air distribution, this diffuser was eventually removed and a 25% greater flow was obtained.

From the time the experiment was initiated in February 1984 to May 31, 1984, the cooling system's thermostat was set at 24°C (75°F). From June 1 to October 12, the set point was 18°C (65°F); from October 13 to December 20 it was raised to 24°C. From December 13 until the end of the experiment it was set at 27°C (80°F).

The heating unit for each phytocell consisted of a natural gas operated heater with a 45,000 BTU capacity. The thermostat equipped heater was set at 12°C (55°F) during the entire period in which heating was required.

In order to monitor each film's performance relating to energy consumption and light transmission, the following sensors were employed in each phytocell: (1) dry and wet bulb temperature thermometers, (2) a globe thermometer for measuring mean radiant temperatures of objects, and (3) a quantum sensor was used for measuring PAR (phytosynthetically active radiation).

A small weather station adjacent to the phytocells recorded dry and wet bulb temperatures, PAR and total solar radiation. All sensors were connected to an IBM PC which registered all readings taken on a minute-by-minute basis. These values were taken 24 hours a day and averaged on an hourly schedule. Both gas and electricity consumption for the heating and cooling systems were recorded. Each system had its own cumulative dial which allowed for up-to-date readings.

Crop Description

The crop grown throughout this experiment was lettuce (*Lactuca sativa* L.) of the 'Bibb' type. It is the most common type used for greenhouse cultivation due to its relatively fast growout period. Two cultivars were initially employed: (1) 'Summer Bibb' (Harris Seed Co.), and (2) 'Diamant' (Enza-Zaden, Holland); the former is bolt resistant and thus has wider acceptance and use by commercial growers. A total of 11 crops were obtained during the duration of the experiment, the average growout time being 44 days.

For the first 2 crops cultivar 'Summer Bibb' was used. In crop 3 both cultivars were grown and harvested in stages at weeks 4, 5, and 6 after seeding. In crop 4 both cultivars were used again and harvested at full market size. For crops 5 through 11, only 'Summer Bibb' was grown due to excessive bolting occurring on cultivar 'Diamant'.

The seed was germinated by placing it inside "Jiffy 9", 35 mm peat pellets which allowed for germination under light conditions.

The seedlings were transplanted after 2 weeks, at which time the small rootlets had begun to outgrow the pellet. At transplant, the pellets were introduced into a previously perforated styrofoam sheet; the sheet in turn was floated upon a tank containing a hydroponic nutrient solution.[1] Each styrofoam sheet measured 3.65 m x 1.2 m and held 108 plants with a 20.3 x 20.3 cm spacing. The plants were distributed on 6 rows of 18 plants each. The polyethylene-lined nutrient tank had the same length and width as the styrofoam sheet, its depth was 30 cm.

The object of fitting the styrofoam sheet snuggly into the nutrient tank was to avoid any light penetration. By doing so, any algal growth that could occur and consume nutrients from the solution was prevented. In order to supply the roots with oxygen an aerator system was installed. A small, homesize aquarium air pump was used to supply air to each nutrient tank; their use was continuous throughout the crop's development. The oxygen concentration in the nutrient solution was kept at approximately 5 to 6 ppm and at no time were problems encountered related to oxygen shortages. The nutrient solution's temperature fluctuated between 20°C and 24°C during the entire experiment, it was not heated or cooled at any time. The type of hydroponic system used in this study is called "Raceway" and was

---

1. Nutrient solution formula on Appendix 5.

developed independently by Jensen (1980) in Arizona and Massantini (1976) in Italy (Fig. 5).

One advantage of greenhouse production over open field agriculture is the greater ease in controlling insect pests and diseases. This experiment proved to be no exception. The only pests which seemed to appear constantly were fungus gnats. As soon as this pest appeared it was quickly put under control by using insecticidal soap. Control was 100% effective although in a few crops more than one application was made to combat resurging populations. No other insect pest posed a threat at any time.

In regards to disease problems none were encountered; nevertheless, a preventive application of Ronilan (Vinclozolin 1 gr/L) was made during the cold months, when condensate from the phytocells roof fell on the plants causing a few to rot.[2] Previous experience indicated that Botrytis Spp was the probable causal organism, although in this experiment the pathogen was not identified. Once the fungicide application was made on the young plants, as a preventive treatment, no further damage was observed.

---

2. The condensate problem occurred only in the control phytocell, covered with polyethylene. This material, in contrast to the test films, does not have the "hydrophylic" coating which keeps the water from being repelled and falling on the crop.

Part II - The overall objective was to compare Heat Mirror films to equivalent[3], light reducing shade cloths, under an existing greenhouse cover. By comparing light selective versus nonselective materials, it was assumed differences in crop yields could be obtained. The differences being attributed to, perhaps, better light quality[4] or higher leaf temperatures which in turn would translate into higher fresh weights.

All three Heat Mirror films were evaluated with a corresponding shade cloth. Two additional plastic films, "Crystal" (Gila River Products-PET 3) film and ICI-071 polyester were also evaluated without corresponding shade cloths. In order to test the films and shade cloths, wooden square frames were built upon which each test material was mounted. These frames measured 2.4 m x 2.4 m and had a ground clearance of .3 m (Fig. 6). The treatments were placed inside an already existing greenhouse, adjacent to the phytocells described in Part I. This greenhouse was covered with 10 year old corrugated fiberglass panels.

---

3. By equivalent it was meant that a given Heat Mirror film and a shade cloth, both of which reduced total solar transmission (TST) by approximately the same magnitude, would be evaluated against each other. The difference being that Heat Mirror films reduce TST selectively whereas regular shade cloth does not.

4. Light quality in this context meaning light employed by plants or PAR (photosynthetically active radiation).

Table 2. Light Selective Films and Equivalent Shade Cloths Total Solar Transmission.

Film Type	Light Level[z]	Equivalent Shade Cloth	Light Level[z]
Heat Mirror 55	$.18 \times 10^4$	73%	$.12 \times 10^4$
Heat Mirror 77	$.31 \times 10^4$	39%	$.30 \times 10^4$
Heat Mirror 88	$.39 \times 10^4$	29%	$.39 \times 10^4$
"Crystal" film	____		
ICI-071-film	$.40 \times 10^4$		

[z]Values obtained with a handheld pyranometer. Units are Microeinsteins $m^{-2}s^{-1}$.

The crop grown for this second part was also 'Bibb' lettuce and the growing media was river sand. Seed was germinated in peat pellets and transplanted into the sand 2 weeks after germination. Each plantlet was placed beside an irrigation hose (4 mil twin wall Chapin) which provided the plants with the same nutrient solution employed in Part I. The irrigation frequency consisted of 3 daily waterings lasting 15 minutes each. One hundred plants having a .2 x .2 m spacing were placed under each treatment.

For the first 3 lettuce crops 2 cultivars were grown: 'Summer Bibb' and 'Diamant', the same ones used in Part I. Fifty plants of each cultivar were placed under each cover, the plants being distributed in 5 rows of 10 plants each. A diagramatic

representation of the cover-treatment's distribution inside the greenhouse is shown in Fig. 2.

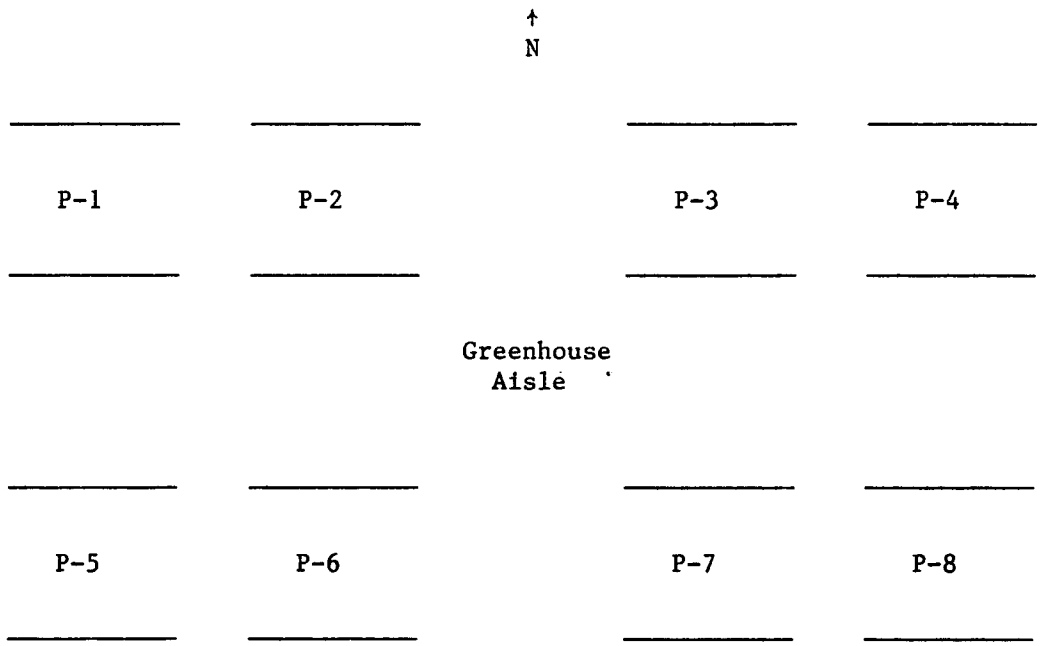

Figure 2. Frame Distribution Inside Greenhouse For Crops 1-3. (P=Position)

Table 3. Plastic Films and Shade Cloths Random Distribution Among Frames in Crops 1-3.

		Frame Position							
		1	2	3	4	5	6	7	8
Crop 1	Cover Type	73% Shade Cloth	29% Shade Cloth	ICI-071 Polyester	39% Shade Cloth	Control (no cover)	Heat Mirror 77	Heat Mirror 55	Heat Mirror 88
Crop 2	Cover Type	39% Shade Cloth	ICI-071 Polyester	29% Shade Cloth	73% Shade Cloth	Heat Mirror 88	Heat Mirror 55	Heat Mirror 77	Control (no cover)
Crop 3	Cover Type	ICI-071 Polyester	73% Shade Cloth	Heat Mirror 55	Heat Mirror 88	39% Shade Cloth	Heat Mirror 77	Control (no cover)	29% Shade Cloth

From crops 4 through 9 only the cultivar 'Summer Bibb' was grown. Each frame cover was divided in half; this done by removing one-half of the cover material and leaving the uncovered side as control (Fig. 3, 7). Twenty-four plants were used from each half to obtain yields. Also, one additional test material was added for evaluation, this material is referred to as "Crystal" film.

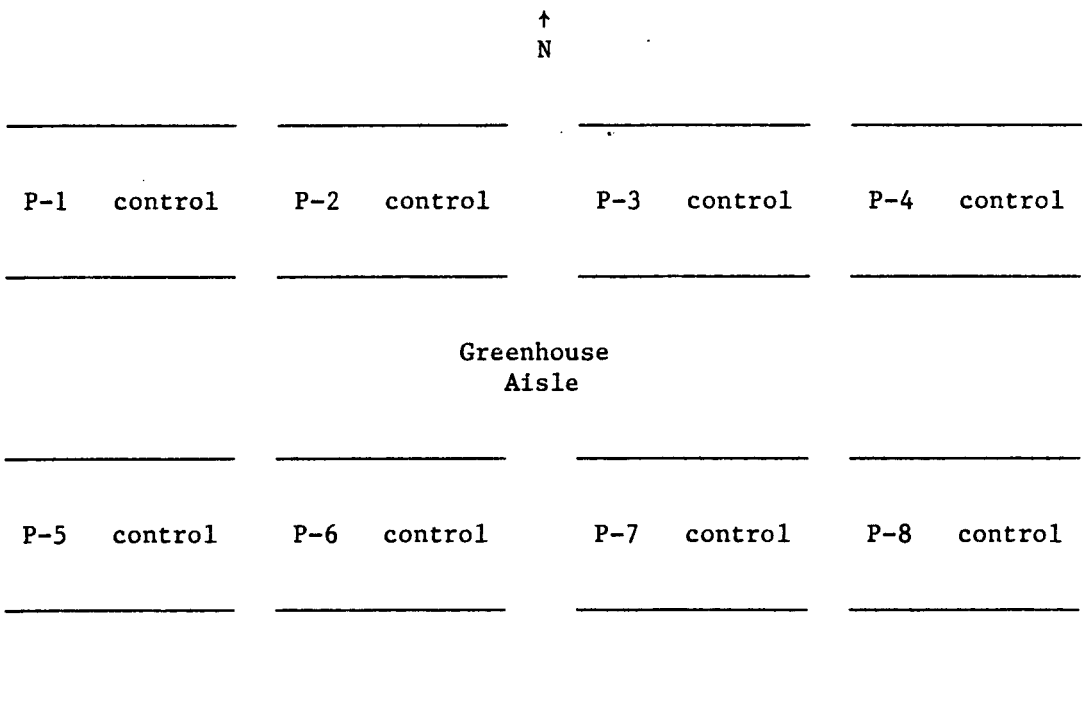

Figure 3. Frame Distribution Inside Greenhouse For Crops 4-9. (P=Position)

Table 4. Plastic Films and Shade Cloths Random Distribution Among Half Frames in Crops 4-9.

		Half Frame Position							
		1	2	3	4	5	6	7	8
Crop 4	Cover Type	73% Shade Cloth	ICI-071 Polyester	39% Shade Cloth	29% Shade Cloth	Crystal Film	Heat Mirror 88	Heat Mirror 55	Heat Mirror 77
Crop 5	Cover Type	Heat Mirror 77	Crystal Film	Heat Mirror 88	29% Shade Cloth	73% Shade Cloth	39% Shade Cloth	Heat Mirror 55	ICI-071 Polyester
Crop 6	Cover Type	73% Shade Cloth	39% Shade Cloth	29% Shade Cloth	Heat Mirror 88	Heat Mirror 55	Heat Mirror 77	ICI-071 Polyester	Crystal Film
Crop 7	Cover Type	Crystal Film	39% Shade Cloth	Heat Mirror 88	ICI-071 Polyester	29% Shade Cloth	Heat Mirror 55	73% Shade Cloth	Heat Mirror 77
Crop 8	Cover Type	Heat Mirror 88	73% Shade Cloth	29% Shade Cloth	Heat Mirror 77	39% Shade Cloth	ICI-071 Polyester	Crystal Film	Heat Mirror 55
Crop 9	Cover Type	Heat Mirror 77	Heat Mirror 55	39% Shade Cloth	Crystal Film	ICI-071 Polyester	73% Shade Cloth	Heat Mirror 88	29% Shade Cloth

Crop Data

For both Part I and Part II of the experiment, lettuce fresh weights were recorded. In Part I, each lettuce head was weighed individually and the sum total divided by the number of heads to obtain average weights in every crop. All plants were included in the average. In Part II each row excluding edge rows (buffers) was weighed individually; the sum totals of all the row in 1 treatment were added and divided by the total number of plants to obtain average weights. Water consumption was also measured under all phytocells.

The criteria used for harvesting was a visual determination of a marketable lettuce headsize. Tip burn and bolting were recorded as part of the crop's performance, in both Part I and II. No dry weights were obtained in this experiment; the reasoning supporting the use of fresh weights only was that lettuce growers sell fresh produce which includes water content in its entirety.

Energy Data

For Part I of the experiment, the following parameters were recorded and analyzed for each phytocell individually: (a) light transmission, specifically PAR (photosynthetically active radiation), (b) electrical energy consumption for cooling, and (c) natural gas consumption for heating. In Part II light or energy data was not obtained. Initial light transmission readings for each treatment were, however, taken with a handheld pyranometer sensor (Tab. 2).

Figure 4. Exterior View of Phytocells.

Figure 5. Front View of "Raceway" Hydroponic Culture System.

Figure 6. Overview of Test Films and Shade Cloth Covered Frames Inside Fiberglass Greenhouse.

Figure 7. Overview of Test Films and Shade Cloth Half-Covered Frames Inside Fiberglass Greenhouse.

CHAPTER 4

RESULTS AND DISCUSSION

Cooling Energy Requirements

Energy expenditure for cooling is summarized in Tab. 12. Although Heat Mirrors 77 and 88 transmit 26% and 19% less PAR than the control film, their cooling requirements were just as high. Heat Mirror 77 requiring 5.1% more energy overall. The explanation might be that Heat Mirror films reflect near and far infrared radiation and are less transparent to far infrared than polyethylene. By doing so, energy which might otherwise dissipate from the phytocell was retained, thus needing an extra amount of cooling to maintain the desired temperature. This assumption may be supported also by the fact that leaf temperatures were higher under both Heat Mirror treatments than the control film (Appendix 7).

Heating Energy Requirements

Natural gas consumption for heating is shown in Tab. 13. Both Heat Mirror films proved to be much more heat energy efficient than either the control film or the ICI-071 polyester. It is again the infrared properties of these films which allow for explaining the high energy savings during the cold months. If the infrared wavelengths are reflected and kept inside the phytocell, overall temperatures should be higher and heat energy requirements should be lower.

In other words, what was an apparent disadvantage during the warm months, became an advantage during the cool season.

Fresh Weight Yields Part I

In Part I fresh weight yields showed that all 3 test films performed better than the double-polyethylene control film (Tab. 5). The best performing cover in terms of lettuce fresh weight was the ICI-071 polyester. Although this film showed an 8% less PAR transmission than double poly, overall yields on the average were 20.1% higher than the control (Tab. 7). This might be explained by the fact that total solar transmission was 5% higher in the ICI-071 film. Another factor which might help to explain ICI-071 better yields, are the higher leaf temperatures registered under this film (Appendix 7).

Tab. 7 indicates that on a yearly basis, all test films yielded higher fresh weights than the control film. If crops are separated into seasons, however, each film's performance is more accurately evaluated. For the spring and summer crops (Tab. 8, 9) Heat Mirror films had little positive increments over the control, or even showed negative increments. The ICI-071 film did show, notwithstanding, considerable improvement over the control in the same time period. For the fall and winter seasons, Heat Mirror films showed large yield increments over the control film. Heat Mirror 88 even outperforming ICI-071 for the winter crops (Tab. 10, 11).

Crop 3 which was harvested in stages (Tab. 6), showed similar tendencies in terms of fresh weight yields. For both cultivars and for all 3 harvest dates, ICI-071 film yielded best, the other

3 films showing very similar results. Bolting became an apparent problem in this crop for cultivar 'Diamant'. As mentioned earlier, this cultivar is not bolt resistant and the negative effects were not long in showing. In crop 4 cultivar 'Diamant' was again grown (Appendix 6). Yields were similar to crop 3 in that the ICI-071 film showed highest results; Heat Mirror films showed better yields than the control film. The damage caused by tip burn and bolting was also very high as Appendix 6 shows.

Tip Burn and Bolting Damage Part I

Overall, yearly averages demonstrated that Heat Mirror 77 and ICI-071 were the two films under which tip burn was most apparent. Bolting was simply not a problem for cultivar 'Summer Bibb' (Appendix 1). Tip burn was much more apparent during the warm month crops, as Appendix 1 shows. This is also verified in Appendix 3 which shows dates for each crop.

A possible explanation for the high tip burn incidence under Heat Mirror 77 might be the film's properties. Under this film, cooling energy consumption and leaf temperatures were highest among all treatments. Since tip burn is individually associated to transpiration rates, plants subject to higher temperatures will transpire more, and a possible outcome might be tip burn damage. Therefore, even though Heat Mirror 77 had a 24% less PAR transmission than the control film, its heat conserving properties might have promoted the high tip burn damage observed.

Fresh Weight Yields Part II

The first 3 crops in Part II must be discussed separately from crops 4 through 9. In crops 1-3, 2 cultivars were grown and the growing conditions were different than in crops 4 through 9. Tab. 15, 16 and 17 show a very similar tendency in terms of fresh weight yields. Heat Mirror films had higher average weights than their equivalent shade cloths for both cultivars. The ICI-071 film showed the highest yields of all treatments, and its average weights were quite close to the control plots which had no cover. Average fresh weights for both cultivars were very close, the major difference being that cultivar 'Diamant' was again badly affected by bolting.

For crops 4 through 9 where only cultivar 'Summer Bibb' was grown, definite tendencies were again observed. Heat Mirror films in all crops yielded higher fresh weights than their equivalent shade cloths (Tab. 18). Average percentual increases of Heat Mirror films over shade clothes are reported on Tab. 20. It is possible that yields were higher under Heat Mirror films due to their light selective properties. Tab. 2 shows that total solar transmission is roughly similar in the 3 Heat Mirror films and the 3 shade cloths compared. However, PAR transmission and infrared radiation are selectively transmitted or rejected by Heat Mirror films. Shade cloths do not have these properties. A growth enhancement effect may be assumed due to the films' properties, but not verified. Tab. 19 shows the average percentage yields of all treatments compared to the control plots for crops 4 through 9. The ICI-071 film

shows very close yields to the control plots, a similar trend to the one observed in crops 1 through 3.

Tip Burn and Bolting Damage Part II

In crops 4 through 9 bolting was not present at all, this due to the fact that only cultivar 'Summer Bibb' was grown. Tip burn, as Appendix 2 shows, was negligible. The only appearance of significance was in crop 5 under Heat Mirror 77. This may be related to Part I where it was also Heat Mirror 77 which had very high tip burn incidence in contrast to the other films. If leaf temperatures had been measured in Part II, a possible explanation could have arisen to justify the higher yields obtained under Heat Mirror films as well as tip burn damage.

Table 5. Average Plant Weights in Double Polyethylene, H. Mirror 77, H. Mirror 88 and ICI-071-Polyester Films For Crops 1-11.[z]

Crop Number	COVER TYPE			
	Double Polyethylene	Heat Mirror 77	Heat Mirror 88	ICI-071 Polyester
1	197.3	199.8	195.6	196.2
2	164.6	166.0	161.3	177.8
4	164.1	172.0	181.5	214.3
5	136.4	148.6	105.0	160.1
6	169.0	155.0	150.8	196.2
7	162.7	165.7	163.6	196.7
8	146.8	158.2	177.3	177.6
9	72.9	92.8	112.6	104.1
10	110.6	124.7	141.3	129.9
11	105.0	119.0	124.5	133.7
$\bar{x}$	142.9	150.2	151.3	168.6

[z]Weights in grams, cultivar evaluated: 'Summer Bibb'.

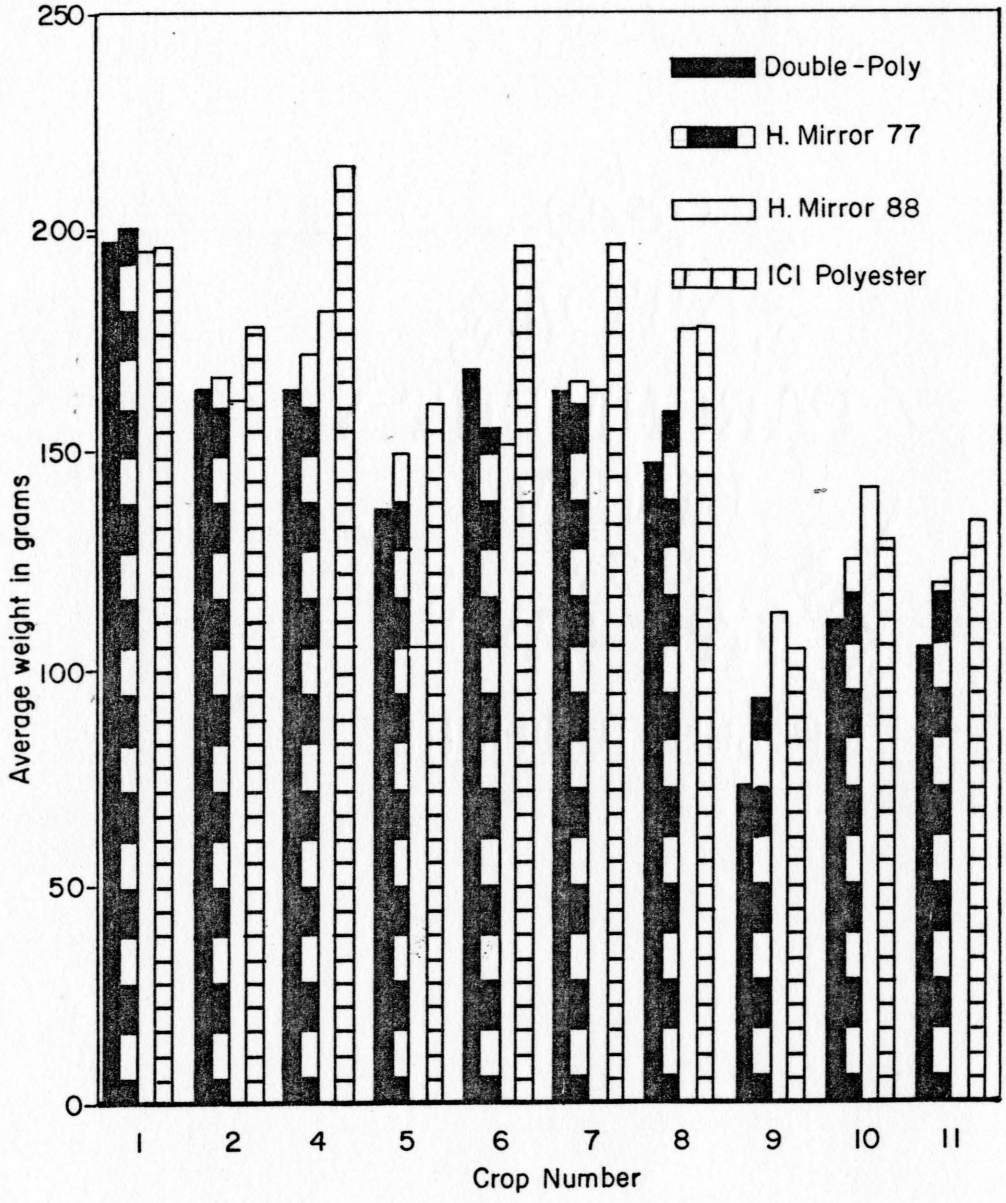

Figure 8. Average Plant Weight in Phytocells for Crops 1-11.

Table 6. Results of Crop 3 for 2 Cultivars Harvested in 3 Stages[z] in Double Polyethylene, H. Mirror 77, H. Mirror 88 and ICI-071 Polyester Films.

	'SUMMER BIBB'											
	Avg. Weight/Plant (grs)			% Weight Increase Over Control			% Bolting			% Tip Burn		
Cover Type	Week 4	Week 5	Week 6	Week 4	Week 5	Week 6	Week 4	Week 5	Week 6	Week 4	Week 5	Week 6
Double Poly	55.9	235.1	376.6	0.0	0.0	0.0	0	0	27	0	0	38
Heat Mirror 77	55.4	219.7	344.6	-.8	0.7	-9.2	0	0	100	38	55	88
Heat Mirror 88	57.1	229.8	370.6	2.1	-2.3	-1.6	0	0	77	27	28	44
ICI-071 Polyester	68.8	270.9	415.3	18.7	15.2	10.3	0	0	94	38	33	55

Table 6, Continued.

'DIAMANT'

Cover Type	Avg. Weight/Plant (grs) Week 4	Week 5	Week 6	% Weight Increase Over Control Week 4	Week 5	Week 6	% Bolting Week 4	Week 5	Week 6	% Tip Burn Week 4	Week 5	Week 6
Double Poly	59.1	234.4	313.3	0.0	0.0	0.0	0	0	94	17	94	100
Heat Mirror 77	67.4	231.9	314.6	12.3	-1.0	0.4	0	0	100	50	100	100
Heat Mirror 88	63.5	235.2	318.7	7.4	0.3	1.7	0	0	94	38	100	100
ICI-071 Polyester	72	250.3	350.6	21.8	6.7	12.0	0	6	100	22	100	100

[z]Harvests done at 4, 5 and 6 weeks after seeding.

Harvest Week 4 = 6-2-84
Harvest Week 5 = 6-10-84
Harvest Week 6 = 6-17-84

Table 7. Average Percent Annual Increase in Plant Weight for H. Mirror 77, H. Mirror 88, and ICI-071-Polyester vs. Double Polyethylene.

Crop	Harvest Date	Double Polyethylene	Heat Mirror 77	Heat Mirror 88	ICI-071 Polyester	Season
1	04-10-84	0	1.2	-.8	-.5	Spring
2	05-13-84	0	0.8	-2.1	9.2	Spring
4	07-15-84	0	4.8	10.6	30.5	Summer
5	08-08-84	0	8.9	-23.0	17.3	Summer
6	09-07-84	0	-9.0	-12.0	16.1	Summer
7	10-12-84	0	1.8	0.5	20.8	Fall
8	11-23-84	0	7.7	20.7	20.5	Fall
9	12-30-84	0	27.4	54.4	42.7	Fall
10	02-11-85	0	12.7	27.7	17.4	Winter
11	03-17-85	0	13.3	18.5	27.3	Winter
	Total	0	69.6	94.5	201.3	
	$\bar{x}$ Percent Increase	0	6.9	9.4	20.1	

Table 8. Average Percent Increase in Plant Weight Per Crop for Double Polyethylene, H. Mirror 77, H. Mirror 88 and ICI-071 Polyester During Spring Crops.

Crop	Harvest Date	Double Polyethylene	Heat Mirror 77	Heat Mirror 88	ICI-071-Polyester	Season
1	4-10-84	0	1.2	-.8	-.5	Spring
2	5-13-84	0	0.8	-2.1	9.2	Spring
	Total	0	2.0	-2.9	8.7	
	$\bar{x}$ Percent Increase	0	1	1.45	4.3	

Table 9. Average Percent Increase in Plant Weight Per Crop for Double Polyethylene, H. Mirror 77, H. Mirror 88 and ICI-071 Polyester During Summer Crops.

Crop	Harvest Date	Double Polyethylene	Heat Mirror 77	Heat Mirror 88	ICI-071 Polyester	Season
4	07-15-84	0	4.8	10.6	30.5	Summer
5	08-08-84	0	8.9	-23.5	17.3	Summer
6	09-07-84	0	-9.0	-12.0	16.1	Summer
	Total	0	4.7	-24.9	64.0	
	$\bar{x}$ Percent Increase	0	1.6	8.3	21.3	

Table 10. Average Percent Increase in Plant Weight Per Crop for Double Polyethylene, H. Mirror 77, H. Mirror 88 and ICI-071 Polyester During Fall Crops.

Crop	Harvest Date	Double Polyethylene	Heat Mirror 77	Heat Mirror 88	ICI-071 Polyester	Season
7	10-12-84	0	1.8	0.5	20.8	Fall
8	11-23-84	0	7.7	20.7	20.5	Fall
9	12-30-84	0	27.4	54.4	42.5	Fall
	Total	0	36.9	75.6	83.3	
	$\bar{x}$ Percent Increase	0	12.3	25.2	27.7	

Table 11. Average Percent Increase in Plant Weight Per Crop for Double Polyethylene, H. Mirror 77, H. Mirror 88 and ICI-071 Polyester During Winter Crops.

Crop	Harvest Date	Double Polyethylene	Heat Mirror 77	Heat Mirror 88	ICI-071 Polyester	Season
10	2-11-85	0	12.7	27.7	17.4	Winter
11	3-17-85	0	13.3	18.5	27.3	Winter
	Total	0	26.0	46.2	44.7	
	$\bar{x}$ Percent Increase	0	13	23.1	22.4	

Table 12. Energy Use For Cooling in Phytocells For Period March 1984 - March 1985.

	ANNUAL TOTALS			
Cover Type	Blower Hours	% Increment vs. Double Poly	KWH	% Increment vs. Double Poly
Double Polyethylene	3778.8	0.0	4825.3	0.0
Heat Mirror 77	3990.5	5.6	5072.2	5.1
Heat Mirror 88	4042.4	7.0	4810.2	-0.3
ICI-071 Polyester	3846.0	1.8	4870.9	0.9

Table 13. Natural Gas Consumption For Heating in Phytocells for Period March 1984 - March 1985.

	ANNUAL TOTALS			
Cover Type	Ft^3 of Gas	% Increment vs. Double Poly	Heat Hours	% Increment vs. Double Poly
Double Polyethylene	7250	0.0	145.6	0.0
Heat Mirror 77	3400	-53.1	72.3	-50.3
Heat Mirror 88	4150	-42.8	92.8	-37.0
ICI-071-Polyester	7750	6.9	159.5	9.5

Table 14. Accumulated[z] Average Weight, Water Use Per Plant and Ratio of Water Use to Fresh Weight for Double Polyethylene, ICI-071 Polyester, H. Mirror 77 and H. Mirror 88 Films.

Cover Type	$\bar{x}$ Weight/ Plant[y]	$\bar{x}$ Water Use/Plant[x]	Water Use/ Fresh Weight Ratio
Double Polyethylene	140.0	1.5	10:1
ICI-071 Polyester	165.6	1.8	11:1
H. Mirror 77	149.6	1.8	12:1
H. Mirror 88	151.4	1.8	12:1

[z]Accumulated average for crops 1-11, excluding crops 3 and 6. Individual crop values reported on Appendix 9 and Appendix 10.

[y]Weight in grams.

[x]Water use in liters.

Table 15. Results Crop 1 in Plastic Film-Shade Cloth Evaluation[z].

Cover Type	$\bar{x}$ Weight/ Plant 'Summer Bibb'	% Tip Burn	% Bolting	$\bar{x}$ Weight/ Plant 'Diamant'	% Tip Burn	% Bolting
29% Shade Cloth	138.7	0	0	138.2	0	0
39% Shade Cloth	102.2	0	0	115.5	0	0
73% Shade Cloth	64.6	0	0	70.2	0	0
Heat Mirror 55	102.8	0	0	122.6	0	0
Heat Mirror 77	140.6	0	0	137.0	0	0
Heat Mirror 88	139.8	0	0	144.2	0	0
ICI-071 Polyester	150.2	0	0	166.6	4	1
Control	160.6	0	0	169.1	5	0

[z]Two cultivars evaluated: 'Summer Bibb' and 'Diamant', average weight in grams, 32 plants per cultivar used to obtain averages.

Table 16. Results Crop 2 in Plastic Film-Shade Cloth Evaluation[z].

Cover Type	$\bar{x}$ Weight/ Plant 'Summer Bibb'	% Tip Burn	% Bolting	$\bar{x}$ Weight/ Plant 'Diamant'	% Tip Burn	% Bolting
29% Shade Cloth	172.18	0	0	171.7	21	56
39% Shade Cloth	129.14	0	0	137.4	3	46
73% Shade Cloth	79.0	0	0	95.9	0	96
Heat Mirror 55	134.8	0	0	125.9	6	25
Heat Mirror 77	178.3	3	0	152.9	21	44
Heat Mirror 88	160.8	0	0	165.8	12	44
ICI-071 Polyester	199.4	3	0	207.8	12	71
Control	201.9	9.4	0	198.4	53	65

[z]Two cultivars evaluated: 'Summer Bibb' and 'Diamant', average weights in grams, 32 plants per cultivar used to obtain averages.

Table 17. Results Crop 3 in Plastic Film-Shade Cloth Evaluation[z].

Cover Type	$\bar{x}$ Weight/ Plant 'Summer Bibb'	% Tip Burn	% Bolting	$\bar{x}$ Weight/ Plant 'Diamant'	% Tip Burn	% Bolting
29% Shade Cloth	86.8	0	0	107.2	1	19
39% Shade Cloth	62.9	0	0	81.5	1	12
73% Shade Cloth	31.9	0	0	46.9	0	0
Heat Mirror 55	80.6	0	0	93.0	0	5
Heat Mirror 77	106.3	0	0	109.6	3	11
Heat Mirror 88	93.0	12	0	122.3	11	20
ICI-071 Polyester	102.7	3	0	124.0	9	14
Control	113.4	0	0	122.6	0	12

[z]Two cultivars evaluated: 'Summer Bibb' and 'Diamant', average weights in grams, 32 plants per cultivar used to obtain averages.

Table 18. Average Plant Weights in Plastic Films-Shade Cloth Evaluation Crops 4-9[z].

Crop No.	29% Shade Cloth	39% Shade Cloth	73% Shade Cloth	Heat Mirror 55	Heat Mirror 77	Heat Mirror 88	ICI Polyester	Crystal Film	Control[y]
4	88.2	78.9	45.9	75.4	89.7	96.9	110.6	98.7	101.2
5	105.1	93.2	48.3	90.8	109.7	120.5	119.3	100.4	126.4
6	125.2	82.6	41.3	92.0	135.9	139.4	142.9	112.1	159.0
7	80.3	59.1	40.2	63.7	80.3	87.3	115.8	96.9	117.4
8	76.8	60.2	30.6	54.0	73.1	80.3	103.9	92.0	109.2
9	80.3	78.0	40.1	70.7	92.2	113.5	134.7	92.2	127.7

[z]Weight in grams.

[y]Average of all control plots.

Table 19. Plastic Film and Shade Cloth Total Average Yields[z].

Treatment	$\bar{x}$ Yields in gr.	% Yield As Compared To Control
29% Shade Cloth	92.6	75%
39% Shade Cloth	75.3	61%
73% Shade Cloth	41.0	33%
Heat Mirror 88	106.3	86%
Heat Mirror 77	96.8	78%
Heat Mirror 55	74.4	60%
ICI-071	121.2	98%
Crystal Film	98.7	80%
Control	123.5	100%

[z]Fresh weight averages for crops 4-9. Cultivar: 'Summer Bibb'.

Table 20. Percentual Yield Differences Between Equivalent Treatments.

Treatment	$\bar{x}$ Yield In Grams		% Differences
73% Shade Cloth	41.0		
Heat Mirror 55	74.4	----------→	+ 80%
39% Shade Cloth	75.3		
Heat Mirror 77	96.8	----------→	+ 29%
29% Shade Cloth	92.6		
Heat Mirror 88	106.3	----------→	+ 15%

CHAPTER 5

SUMMARY AND CONCLUSIONS

Two light selective films and a polyester film were used as greenhouse covers and evaluated versus polyethylene. Their performance was studied by measuring 'Bibb' lettuce yields as well as the energy consumed in cooling and heating the greenhouses. Each film was clad on a small greenhouse called phytocell; all phytocells had a double plastic layer, the test films being the inside layer and polyethylene the outside layer. Polyethylene composing both layers of the control phytocell. The same films were also compared with shade cloths of equivalent light transmission to evaluate 'Bibb' lettuce fresh weight yields. The plastic film-shade cloth comparison was done inside a large fiberglass covered greenhouse.

Results obtained seem to indicate that:

(a) 'Bibb' lettuce fresh weights were superior in all 3 test films to those obtained under the control film on a yearly basis. Fall and winter fresh weight increments were considerably larger than the yield increments of spring and summer crops.

(b) The test films were not more energy efficient than the control film in regards to energy consumption for cooling. During the cold months, however, Heat Mirror 88

and 77 films consumed 43% and 53% less heating energy, respectively, than the polyethylene film.

(c) The higher fresh weight yields obtained during the winter months seem to be related to higher leaf temperatures recorded under the Heat Mirror test films.

(d) Heat Mirror films proved to yield higher fresh weights than equivalent shade cloth covers. The superiority might be based on the test film's light selective properties. Such selectivity could have provided for more PAR to reach plants grown under Heat Mirror films than the ones growing under shade cloth covers.

(e) Based on their performance, Heat Mirror films would probably be more efficient in northern climates. If used in cooler environments, the films' cooling energy requirements would decrease. Concomitantly, the energy required for heating would also be less than that required by typical greenhouse covers such as polyethylene. In short, Heat Mirror films have better applications where summers are milder and winters cooler than in Tucson. As it is, more northerly latitudes is where the bulk of the greenhouse industry is located; be it the northern United States, Canada, Western or Eastern Europe as well as Japan.

APPENDIX 1

PERCENTAGE TIP BURN AND BOLT DAMAGE OF LETTUCE[z] FOR ALL COVER FILMS IN PHYTOCELLS

Crop No.	Double Polethylene Tip Burn	Bolting	Heat Mirror 77 Tip Burn	Bolting	Heat Mirror 88 Tip Burn	Bolting	ICI-071 Polyester Tip Burn	Bolting
1	8	0	25	0	22	0	34	0
2	11	0	28	0	19	0	41	0
4	31	0	59	0	37	0	31	0
5	5	0	45	0	6	0	55	0
6	1	0	6	0	0	0	5	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	0	0	0	0	4	0	0	0
$\bar{x}$	6	0	16	0	9	0	17	0

[z]Cultivar evaluated: 'Summer Bibb'. Crop 3 not included in this table.

APPENDIX 2

PERCENTAGE TIP BURN AND BOLT DAMAGE FOR CROPS 4-9 IN PLASTIC FILM-SHADE CLOTH EVALUATION[z].

Crop No.	29% S.Cloth Tip Burn	29% S.Cloth Bolting	39% S.Cloth Tip Burn	39% S.Cloth Bolting	73% S.Cloth Tip Burn	73% S.Cloth Bolting	H.Mirror 55 Tip Burn	H.Mirror 55 Bolting	H.Mirror 77 Tip Burn	H.Mirror 77 Bolting	H.Mirror 88 Tip Burn	H.Mirror 88 Bolting	ICI-Polyester Tip Burn	ICI-Polyester Bolting	Crystal Film Tip Burn	Crystal Film Bolting
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	3	0	14	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$\bar{x}$	0	0	0	0	0	0	0.3	0	2	0	0	0	0	0	0	0

[z]Cultivar evaluated: 'Summer Bibb'. Crops 1-3 reported individually.

APPENDIX 3

CHRONOLOGICAL DEVELOPMENT FOR LETTUCE CROPS IN PHYTOCELLS

Crop No.	Date Seeded	Date Transplanted	Date Harvested	Crop[z] Duration
1	02-22-84	03-10-84	04-10-84	47
2	03-31-84	04-15-84	05-13-84	42
4	06-10-84	06-24-84	07-15-84	35
5	07-03-84	07-18-84	08-08-84	35
6	07-31-84	08-15-84	09-07-84	35
7	08-31-84	09-16-84	10-12-84	42
8	10-05-84	10-20-84	11-23-84	49
9	11-05-84	11-24-84	12-30-84	56
10	12-18-84	01-07-85	02-11-85	56
11	01-25-85	02-16-85	03-17-85	49

[z]In number of days.

APPENDIX 4

CHRONOLOGICAL DEVELOPMENT FOR LETTUCE CROPS
IN PLASTIC FILM-SHADE CLOTH EVALUATION

Crop No.	Date Seeded	Date Transplanted	Date Harvested	Crop[z] Duration
1	04-11-84	05-02-84	05-23-84	42
2	05-14-84	06-03-84	06-22-84	35
3	06-18-84	07-04-84	07-23-84	35
4	07-11-84	07-26-84	08-15-84	35
5	08-07-84	08-22-84	09-14-84	37
6	09-08-84	09-23-84	10-22-84	42
7	10-15-84	11-05-84	12-07-84	51
8	11-25-84	12-16-84	01-26-85	60
9	01-14-85	02-05-85	03-11-85	56

[z]In number of days.

APPENDIX 5

ELEMENT CONCENTRATION OF HYDROPONIC SOLUTION

Macronutrients

N	= 197
P	= 62
K	= 232
Mg	= 50
Ca	= 202

Micronutrients

Fe	= 5.0
B	= 0.5
Mn	= 0.62
Cu	= 0.10
Mo	= 0.03
Zn	= 0.27
Cl	= 0.86

APPENDIX 6

RESULTS CROP 4 FOR CULTIVAR 'DIAMANT'[z]

Cover Type	$\bar{x}$ Weight/ Plant (grs)	% Tip Burn	% Bolting	% Weight Increase Over Control
Double Polyethylene	146.3	85.0	59.0	0.0
Heat Mirror 77	165.2	85.0	40.7	12.9
Heat Mirror 88	173.3	81.0	40.7	18.4
ICI-071 Polyester	186.3	83.0	48.0	27.3

[z]Averages obtained from three rows of eighteen plants each.

APPENDIX 7

LEAF TEMPERATURES RECORDED FOR DOUBLE POLYETHYLENE, H. MIRROR 77, H. MIRROR 88 AND ICI-071 POLYESTER FILMS (°C)[z]

Date of Readings	Double Polyethylene	Heat Mirror 77	Heat Mirror 88	ICI-071 Polyester
12-22-84	10.2	12.0	12.2	11.5
12-23-84	10.2	11.8	12.0	11.2
12-24-84	11.5	13.2	13.8	12.5
12-25-84	12.5	14.0	15.0	12.8
12-26-84	10.2	14.5	15.2	13.2
12-27-84	14.2	15.0	15.8	14.2
12-28-84	14.0	14.8	15.8	14.0
12-29-84	13.2	14.5	16.0	14.0
12-30-84	13.2	14.5	15.8	12.8
12-31-84	13.0	14.0	15.5	12.0
01-01-85	12.0	13.2	14.8	11.5
01-02-85	11.0	12.2	14.0	10.0
01-03-85	9.8	11.5	13.2	9.5
01-04-85	10.0	12.2	13.5	10.0
01-05-85	11.2	13.2	15.0	11.2
01-06-85	12.0	13.8	15.5	13.2
01-07-85	11.5	13.0	14.0	12.0
01-08-85	11.8	12.8	14.2	12.2
$\bar{x}$	11.8	13.3	14.5	12.1
% Increment	0.0	12.7	22.9	2.6

[z]Readings taken from 12-22-84 to 01-08-85 using a 30 gage thermocouple sensor.

APPENDIX 8

PAR[z] VALUES RECORDED FOR DOUBLE POLYETHYLENE, H. MIRROR 77, H. MIRROR 88 AND ICI-071 POLYESTER FILMS

Month	Double Polyethylene	Heat Mirror 77	Heat Mirror 88	ICI-071 Polyester
May	13510	10663	11714	13137
June	13024	10096	11138	12511
July	11793	9189	9980	11324
August	12737	9575	10165	11957
September	10612	8080	8491	9624
October	8417	6240	6464	7409
November	6308	4343	4448	4993
December	5381	4094	4307	4958
January	8927	6772	6899	7932
February	6352	4659	4939	5504
$\bar{x}$	9706	7371	7854	8934

[z]PAR or phytosynthetically active radiation values reported in Microeinsteins $M^{-2}S^{-1}$ recorded under clear sky conditions from May 1984 to February 1985.

APPENDIX 9

AVERAGE WEIGHT, WATER USE PER PLANT AND RATIO OF WATER USE TO FRESH WEIGHT UNDER DOUBLE POLYETHYLENE AND ICI-071 POLYESTER FILMS FOR CROPS 1-11[z]

	DOUBLE POLYETHYLENE			ICI-071 POLYESTER		
Crop	$\bar{x}$ Weight/ Plant[y]	$\bar{x}$ Water Use/ Plant[x]	Water Use/ Fresh Weight Ratio	$\bar{x}$ Weight/ Plant	$\bar{x}$ Water Use/ Plant	Water Use/ Fresh Weight Ratio
1	197.3	2.4	12:1	196.2	2.8	14:1
2	164.6	1.3	8:1	177.8	2.8	15:1
4	164.1	2.3	14:1	214.3	2.6	12:1
5	136.4	1.9	14:1	160.1	2.2	14:1
7	162.7	1.8	11:1	196.7	2.0	10:1
8	146.8	1.5	10:1	177.6	1.6	9:1
9	72.9	0.4	5:1	104.1	0.8	8:1
10	110.6	0.9	8:1	129.9	1.1	9:1
11	105.0	1.3	12:1	133.7	1.5	11:1
$\bar{x}$	140.0	1.5	10:1	165.6	1.8	11:1

[z]Values for crops 3 and 6 were not taken.

[y]Average weights in Grams.

[x]Water use values in liters.

APPENDIX 10

AVERAGE WEIGHT, WATER USE PER PLANT AND RATIO OF WATER USE TO FRESH WEIGHT UNDER H. MIRROR 77 AND H. MIRROR 88 FILMS. FOR CROPS 1-11[z].

	HEAT MIRROR 77			HEAT MIRROR 88		
Crop	$\bar{x}$ Weight/ Plant[y]	$\bar{x}$ Water Use/ Plant[x]	Water Use/ Fresh Weight Ratio	$\bar{x}$ Weight/ Plant	$\bar{x}$ Water Use/ Plant	Water Use/ Fresh Weight Ratio
1	199.8	2.8	14:1	195.6	3.0	15:1
2	166.0	2.4	15:1	161.3	1.4	9:1
4	172.0	2.2	13:1	181.5	2.4	13:1
5	148.6	2.2	15:1	105.0	1.6	15:1
7	165.7	1.7	10:1	163.6	1.8	11:1
8	158.2	1.7	11:1	177.3	1.8	10:1
9	92.8	0.6	7:1	112.6	1.0	9:1
10	124.7	0.9	8:1	141.3	1.4	10:1
11	119.0	1.6	13:1	124.5	1.9	15:1
$\bar{x}$	149.6	1.8	12:1	151.4	1.8	12:1

[z]Values for crops 3 and 6 were not taken.

[y]Average weights in grams.

[x]Water use values in liters.

LITERATURE CITED

Anonymous. 1984. High Performance. An interim report on the comparison of the Variglaze double glazing system to a standard house. United Kingdom Department of Energy. GC and HTJ 196 (19):33.

Ashrae. (Am. Soc. Heating, Refrigeration, Air-Conditioning Engineers). 1974. Handbook and Product Directory, Applications.

Badger, P. C. and H. A. Poole. 1979. Conserving Energy in Ohio Greenhouses. The Ohio State University, Ohio Cooperative Extension Service.

Baille, M., J. C. Laury, and A. Baille. 1983. Influence of the covering material on the energy balance of a glasshouse: comparison of ordinary glass with low emissivity glass. Agronomie 3 (3):197-202.

Baille, M., J. C. Laury, and A. Baille. 1984. Influence of a thermal screen on the nocturnal energy balance and microclimate of a glasshouse. Agronomie 4 (4):327-332.

Benoit, F. N. Ceustermans, and E. De Boodt. 1982. The effect of Hortiplus glass on light reduction, energy saving and tomato production. Boer en de Tuinder 88 (30):13-15.

Besemer, S. T., D. S. Axlund, and A. Brown, Jr. 1974. Greenhouse Insulation Experiment. San Diego Gas and Electric Co.

Bjerre, H. and M. G. Amsen, 1983. Pot plant production environmental conditions and energy consumption in insulated greenhouses. Tidss Krift for Planteavl 87 (6):581-595.

Ferare, J. and K. L. Goldsberry. 1984. Environmental conditions created by plastic greenhouse covers. Acta Horticulturae 148 (2):675-682.

Goldsberry, K. L. 1978. Unpublished data.

Goldsberry, K. L. 1982. Greenhouse heat conservation: covers vs. atmospheric conditions during a five-year period. Research Bulletin, Colorado Greenhouse Growers Association 381:1-4.

Goldsberry, K. L., D. D. Wilson, and W. C. Pixley. 1982. Influence of double layer plastic greenhouse glazing on fuel requirements and light transmission. Research Bulletin, Colorado Greenhouse Growers Association 389:1-3.

Hanan, J. J., W. D. Holley, and K. L. Goldsberry. 1978. Greenhouse Management. Springer-Verlag, Berlin. pp. 170-175.

Hinton-Mead, T. M. 1982. Energy saving with protected crops in the UK using twin-walled rigid plastic glazing materials. Abstracts, XXIst International Horticultural Congress. Hamburg, German Federal Republic.

Kawamata, T. and Y. Ogura. 1983. Structure and Cost-Efficiency of a double-roofed greenhouse. Bulletin, College of Agriculture, Utsonomiya University 12 (1):23-28.

Mackroth, K. 1982. Greenhouse with triple shelters; heat pump and six additional steps to decrease heat costs. Abstracts, XXIst International Horticultural Congress. Hamburg, German Federal Republic.

Meyer, J. 1984. The influence of thermal screens on energy consumption of greenhouses. Gartenbauwissenschaft 49 (2):74-76.

Montero, J., T. H. Short., and W. L. Bauerle. 1980. An evaluation of new greenhouse sheeting materials for a poly-pellet insulation system. Proceedings, 15th National Agricultural Plastics Congress. April 13-17, Tucson, Arizona.

Sebesta, Z. and D. Reiersen. 1982. The effect of low emissivity glass and double ploy-carbonate (MAKROLON) on heat loss from greenhouses. Gartenbauwissenschaft 47 (5):228-232.

Short, T. H. and J. Huizing. 1982. An inflated tube night screen for greenhouses. Ohio Report on Research and Development 67 (5):87.

Simpkins, J. C., D. R. Mears., W. J. Roberts, and H. Janes. 1984. Testing of infrared radiation barrier greenhouse films. New Jersey Agricultural Experiment Station.

Stickler, M. P. 1975. The use of plastics for heat insulation in greenhouses. Plasticulture 25:41-53.

Weimann, G. 1984. Energy saving measures in plastic greenhouses. Deutscher Gartenbau 38 (37):1569-1571.

Wells, O. S. 1978. Conserving energy in plastic greenhouses with liquid foam insulation. Proceedings, 15th National Agricultural Plastics Congress. April 13-17, Tucson Arizona.