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# PROCEEDINGS OF A CONFERENCE ON SOLAR ENERGY FOR HEATING GREENHOUSE AND GREENHOUSE-RESIDENTIAL COMBINATIONS

## Solar, Long Wavelength, and Photosynthetic Energy Transmission of Greenhouse Cover Materials; March 20–23, 1977

By
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November 1977
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MASTER

Ohio Agricultural Research and Development Center
Wooster, Ohio

and

Energy Research and Development Administration
Washington, D. C.



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Solar Energy

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# PROCEEDINGS

# A CONFERENCE ON

# SOLAR ENERGY FOR HEATING GREENHOUSES AND

# GREENHOUSE-RESIDENTIAL COMBINATIONS

March 20-23, 1977

MARRIOTT INN
Jct. I-71 and 150th Street
Cleveland, Ohio 44135

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Edited By

Ted H. Short

Co-Sponsored By

The Ohio Agricultural Research and Development Center
and
The Energy Research and Development Administration

In Cooperation With The

Cleveland Greenhouse Vegetable Growers Association
Cleveland Greenhouse Flower Growers Association
Agricultural Research Service, USDA
Ohio Cooperative Extension Service
American Society of Agricultural Engineers
Greenhouse Vegetable Day Committee

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# FOREWORD

Greenhouse grown vegetables and ornamentals continue to be important to the economy and quality of life for all people. Greenhouse grown products are of the highest quality and have consistently been competitive in the open market. Through energy intensiveness, greenhouse growers produce yields from 5 to 15 times normal field yield.

Greenhouse structures are heated almost entirely by solar energy by day and fossil fuel by night. It is the fossil fuel requirement at night that is becoming or has become prohibitively costly. Yet the greenhouse remains one of man's most practical solar collectors with possible applications for heating residences as well as the greenhouse itself.

A research and development program to evaluate the feasibility of heating and cooling greenhouses and greenhouse-residential combinations was initiated in 1975 by the Energy Research and Development Administration (ERDA). Since most greenhouse research is applied to agriculture, ERDA funds were administered through the United States Department of Agriculture/Agricultural Research Service (USDA/ARS). Results from nine projects funded in 1975-76 were presented at a solar greenhouse workshop on April 5-6, 1976, at the University of Arizona, Tucson. A total of eleven projects listed in Appendix A were funded through ERDA-USDA/ARS in 1976-77 with most being continued from the previous year. Results from the eleven were presented at a solar greenhouse conference in Cleveland, Ohio, and the Ohio Agricultural Research and Development Center, Wooster, Ohio, on March 20-23, 1977. It is the detailed results of the 1977 greenhouse conference that are reported in these proceedings.

The 1977 Solar Greenhouse Conference was designed to inform the general public, greenhouse growers, and related greenhouse and solar industries of the current state of the art. The conference was attended and supported by greenhouse and solar industry exhibitors (Appendix B) and by growers from all regions of the United States and Canada (Appendix C). Most conference participants were highly interested in the commercial greenhouses toured on March 22, 1977 (Appendix D) since the Cleveland area has one of the oldest and largest concentrations of greenhouses in the U.S.

The third day of the conference was combined with the Annual Greenhouse Vegetable Day program at the Ohio Agricultural Research and Development Center at Wooster, Ohio (Appendix E). The OARDC has traditionally supported multidisciplinary research on production problems related to greenhouse crops. Except for a solar pond project, research that was

presented or demonstrated at OARDC is not included in the proceedings. Information on any one of the topics listed in Appendix E may be obtained from OARDC or the individual researchers.

The conference was supported financially by ERDA and the OARDC. Special thanks go to Mr. William Auer, ERDA Project Coordinator; Dr. Landy Altman, USDA-ARS Energy Research Coordinator; Dr. Ted Bond, Project Leader, for helping to plan and coordinate the technical portion of the conference program. Further thanks go to the Cleveland Greenhouse Vegetable and Flower Growers Associations and the Greenhouse Vegetable Day Committee for helping to plan tours and to help with registrations. Special thanks and appreciation goes to Ms. Sherrie Lindsco for managing and efficiently executing registration and the final preparation of these proceedings.

Appreciation is extended to all the speakers who have presented their research results in these proceedings. Special appreciation goes to Mr. Richard Pretzer who presented the energy perspectives of a greenhouse grower; Dr. Warren Roller, Associate Chairman, Department of Agricultural Engineering who challenged everyone with his banquet speech on Energy and the Food Chain; Dr. Roy M. Kottman, Director, OARDC, for enlarging our prospectus of world food production, and to Dr. Clive Donoho, Associate Director, OARDC, for opening the conference.

Ted H. Short
Conference Coordinator

CONTENTS


| | PAGE |
|---|---|
| Foreword | i |
| ERDA-USDA/ARS PROJECTS ON SOLAR HEATING AND COOLING OF GREENHOUSES AND RURAL RESIDENCES, T. E. Bond | 1 |
| ENERGY MANAGEMENT AND ENERGY TOOLS THAT CAN BE USED BY THE GREENHOUSE GROWER, Richard Pretzer | 8 |
| A GREENHOUSE-RESIDENCE UTILIZING A "CLEARVIEW" SOLAR COLLECTOR AND TWO-STAGE EVAPORATIVE COOLING, John F. Peck, Carl N. Hodges, Merle H. Jensen and T. Lewis Thompson | 14 |
| CONSTRUCTION AND OPERATION OF A SOLAR HEATED RESIDENCE/ GREENHOUSE COMBINATION, Charles C. Smith | 53 |
| DYNAMIC VERSUS STEADY-STATE THERMAL ANALYSIS OF SOLAR RESIDENCE/GREENHOUSE COMBINATION, H. F. Zornig, R. C. Fowler, and L. C. Godbey | 79 |
| DYNAMIC THERMAL SIMULATION OF A PROTOTYPE SOLAR HEATING AND COOLING SYSTEM, R. C. Fowler and V. P. Martelli | 96 |
| ROCK COLLECTOR AND STORAGE SYSTEM FOR GREENHOUSE AND RESIDENT HEATING, James M. Akridge | 122 |
| PERFORMANCE OF THE NEW JERSEY SOLAR SYSTEM FOR HEATING GREENHOUSES, David R. Mears, William J. Roberts and Joel C. Simpkins | 135 |
| SOIL AND GROUNDWATER FOR SOLAR HEAT STORAGE IN HEATING AND COOLING GREENHOUSES, Alvin C. Dale, Larry W. Turner, and P. Allen Hammer | 149 |
| CROP RESPONSE IN SOLAR HEATED GREENHOUSES VENTILATED WITH DEEP COAL MINE AIR, Jack W. Buxton, John N. Walker, Larry Collins, Dean Knavel and John Hartman | 166 |
| ENERGY CONSERVATION SYSTEMS FOR GREENHOUSES, J. W. White, R. A. Aldrich, J. L. Duda, S. M. Rebuck, J. Tesca, A. Rotz and A. Merbaum | 186 |
| COMPUTER SIMULATION OF SOLAR GREENHOUSE HEATING SYSTEMS FOR ECONOMIC OPTIMIZATION, Paul O. McCormick | 205 |

PAGE

A SOLAR POND FOR HEATING GREENHOUSES AND RURAL RESIDENCES, Ted H. Short, Phillip C. Badger and W. L. Roller 220

SOLAR, LONG WAVELENGTH, AND PHOTOSYNTHETIC ENERGY TRANSMISSION OF GREENHOUSE COVER MATERIALS, T. E. Bond, L. C. Godbey and H. F. Zornig 234

EXPERIMENTAL RESULTS OF A GREENHOUSE SOLAR COLLECTION AND MODULAR GRAVEL STORAGE SYSTEM, G. E. Wilson, D. R. Price, L. D. Albright, N. R. Scott, R. W. Langhans and Pitam Chandra 256

ENERGY AND THE FOOD CHAIN, Warren L. Roller 287

FUTURE PROSPECTS FOR WORLD FOOD PRODUCTION, Roy M. Kottman 306

APPENDICES:

A. Summary of 2nd Year Research Programs for Solar Heating and Cooling of Greenhouses and Rural Residences 319

B. Conference Exhibitors 328

C. Conference Attendance List 329

D. Greenhouse Industry Tour 342

E. Tour of Greenhouse Energy Research 343

# ERDA-USDA/ARS PROJECTS ON SOLAR HEATING AND COOLING OF GREENHOUSES AND RURAL RESIDENCES

T. E. Bond[1]

In June 1975, nine projects were funded at various State Agricultural Experiment Stations, Universities, industrial laboratories, and at laboratories of the Agricultural Research Service of USDA. Funding was supplied by the Energy Research and Development Administration and management of the research program was provided by the Agricultural Research Service of USDA. I serve as the Principal Investigator for the project on behalf of the Agricultural Research Service.

In April 1976, a workshop was held at Tucson, Arizona, to present the first nine months of progress from these nine projects. Now, nearly a year later, we are again meeting to review progress. Additional projects were added in June 1976, so we currently have eleven active projects -- and you will hear about these today.

As with our 1976 meeting, we have invited those interested in greenhouse energy problems to meet with us and to share in any new knowledge and ideas that have developed.

My purpose at this time is to make you aware of the eleven current ERDA-funded projects related to solar heating and cooling of greenhouses and rural residences, and to let you know where they are located and who the Project Manager is at each location.

Following is a list of the projects and the Project Managers, each of whom, or his representative, is here and will report to you. I hope that during the next few days you will meet these project representatives and discuss some of your problems with them.

I shall do no more than mention the location, the Project Manager, and the objectives of each of the eleven projects. The research progress of each project will be covered during the meeting.

---

[1] T. E. Bond, Research Leader, ARS Rural Housing Research Unit, and Principal Investigator for the ERDA-USDA/ARS project, Solar Heating and Cooling of Greenhouses and Rural Residences, Clemson, South Carolina 29631.

1. LOCATION: University of Arizona, Tucson (Continuing Project)

TITLE: Residential Environmental Control Utilizing a Combined Solar Collector Greenhouse

PROJECT MANAGER: Dr. Carl N. Hodges, Director
Environmental Research Laboratory
Tucson International Airport
Tucson, Arizona 85706
(602) 834-2931

OBJECTIVES: Extend systems of operation of the greenhouse-residential combination from the completion of Phase I through the summer and winter of 1976-77 to compile a full year's data on solar heating and storage, evaporative cooling and storage, and to confirm seasonal variations of crop production in the greenhouse chamber.

Integrate improvements into the system, particularly in regard to the ERL-type solar collector and techniques of foam insulations for greenhouse roofs and develop appropriate greenhouse/rural residence designs for the U.S. Southwest desert.

2. LOCATION: ARS-USDA Rural Housing Research Unit, Clemson, South Carolina (Continuing Project)

TITLE: Solar Energy and Waste Heat Utilization with Greenhouse/Residence Combo

PROJECT MANAGER: Dr. T. E. Bond, Research Leader
Rural Housing Research Unit, ARS-USDA
P. O. Box 792
Clemson, South Carolina 29631
(803) 654-3646

OBJECTIVES: Construct prototype greenhouse-residence combination developed in Phase I and test and evaluate the prototype for cost-benefit of added greenhouse and equipment in terms of food and fossil fuel costs saved.

Determine greenhouse area required per family member for year-around food growth, and develop and test cropping programs for maximum family utilization of the greenhouse area.

Analyze all prototype cost and performance data and determine or predict economic feasibility and acceptability in each of the major geographical and climatological areas.

3. LOCATION: Solar Energy Applications Laboratory, Colorado State University, Fort Collins, Colorado (New Project)

TITLE: Solar Heating of Greenhouses Combined with Space Heated Buildings

PROJECT MANAGER: Dr. C. C. Smith
Solar Applications Laboratory
Colorado State University
Fort Collins, Colorado
(303) 491-1101

OBJECTIVES: Design, construct, and test an optimized solar heated greenhouse/space heated building combination that will provide solar heating to meet 50 to 70 percent of the heating requirements of the combination.

Operate the greenhouse under actual plant growing conditions through a heating season, and monitor both thermal and plant growth performance.

4. LOCATION: Cornell University, Ithaca, New York (Continuing Project)

TITLE: Heating Greenhouses and Rural Residences with Solar Energy

PROJECT MANAGER: Dr. D. R. Price, Associate Professor
Dept. of Agricultural Engineering
Cornell University
Ithaca, New York 14853
(607) 256-4548

OBJECTIVES: Optimize the design of greenhouse solar system for the northeast by computer simulation of various systems of solar collection, transport and heat storage.

Test and evaluate alternative designs of greenhouse structures and components including:
(a) type of collection by the greenhouse itself

or in conjunction with external collectors; (b) heat storage systems utilizing earth, stones, or buried pipe; (c) heat transport systems including both water and air; and (d) insulation techniques.

5. LOCATION: Georgia Institute of Technology, Atlanta, Georgia (New Project)

TITLE: Design of Solar Collector and Energy Storage for Heating Greenhouses and Rural Residences

PROJECT MANAGER: N. E. Poulos
Georgia Tech Research Institute
Georgia Institute of Technology
Atlanta, Georgia 30332
(404) 894-3656

OBJECTIVES: To design, fabricate, test and furnish plans for a solar collector and storage system suitable for heating farm buildings, and rural residences with possible secondary use as an agricultural dryer.

6. LOCATION: University of Kentucky, Lexington, Kentucky (Continuing Project)

TITLE: Solar Heated Greenhouses Ventilated with Deep Mine Air

PROJECT MANAGER: Dr. J. N. Walker, Chairman
Dept. of Agricultural Engineering
University of Kentucky
Lexington, Kentucky 40506
(606) 258-5657

OBJECTIVES: To determine if deep mine air can be economically used to improve the solar energy utilization of greenhouses.

7. LOCATION: Lockheed Missiles & Space Company, Huntsville, Alabama (Continuing Project)

TITLE: Greenhouse Heating and Cooling

PROJECT MANAGER: P. O. McCormick, Research Engineer
Lockheed Missiles & Space Co., Inc.
4800 Bradford Drive, N.W.
Huntsville, Alabama 35807
(205) 837-1800

OBJECTIVES: To acquire data on a non-integral greenhouse/ solar heating system and compare the data with computer model results. Modify analytic models as necessary so as to provide an accurate analytical model.

8. LOCATION: Ohio State University, Wooster
(Continuing Project)

TITLE: Continuation of Experimental Studies on a Solar Pond for Heating and Cooling Greenhouse and Residences

PROJECT MANAGER: Dr. T. H. Short, Assistant Professor
Dept. of Agricultural Engineering
Ohio Agricultural Research and Development Center
Wooster, Ohio 44691
(216) 264-1021

OBJECTIVES: Determine the feasibility and efficiency of a "bubble" covered solar pond (sized for a single family residence) as an integrated solar collector and heat storage unit for greenhouses and homes.

Devise methods of moving heat into or out of the solar pond directly or via a heat pump for use in a greenhouse and study alternatives and develop a closed-cycle gradient maintenance system for the pond.

9. LOCATION: Pennsylvania State University, University Park
(Continuing Project)

TITLE: Energy Conservation Systems for Greenhouses

PROJECT MANAGER: Dr. J. H. White, Associate Professor
Horticulture Department
Pennsylvania State University
University Park, Pennsylvania 16802
(814) 865-6595

OBJECTIVES: Develop a greenhouse structure and control systems that will make efficient use of solar energy.

Develop a solar heat storage and recovery system using the greenhouse as a collector.

10. LOCATION: Purdue University, West Lafayette, Indiana (New Project)

TITLE: Solar Energy for Heating and Cooling Greenhouses and Rural Residences

PROJECT MANAGER: Dr. Alvin C. Dale, Professor
Dept. of Agricultural Engineering
Purdue University
West Pafayette, Indiana 47907
(317) 749-2971

OBJECTIVES: Develop an improved solar energy collection method utilizing a system of reflectors to concentrate solar energy entering an insulated air collector, devise a system for the transfer of the collected energy to a soil and groundwater storage, and determine the rates of energy gains and losses of the insulated storage field of soil with a high groundwater table.

Determine the feasibility of using direct air flow from the energy storage through a greenhouse to serve as its energy source for heating, and determine the possibility of using the cool air in the later winter and early spring to cool the soil and groundwater and then using this cooled mass as a supplement for cooling greenhouses.

11. LOCATION: Rutgers University, New Brunswick, New Jersey (Continuing Project)

TITLE: Heating Greenhouses with Solar Energy

PROJECT MANAGER: Dr. D. R. Mears
Dept. Biological and Agricultural Engineering
Rutgers University
New Brunswick, New Jersey 08903
(201) 932-9752

OBJECTIVES: Develop and evaluate practical systems for heating greenhouses with warm water obtained from low cost collectors.

Study conduction heat loss, radiation heat loss, and heat exchange from the floor and beds, and develop and test techniques which utilize the floor, wall, and roof areas as heat exchange surfaces.

Investigate and evaluate various dye concentrations to reduce insolation during summer months.

# ENERGY MANAGEMENT AND ENERGY TOOLS THAT CAN BE USED BY THE GREENHOUSE GROWER

A Talk by Richard Pretzer
Pretzer Farms, Cleveland, Ohio

I will try to relate a few of the problems that I believe growers have in relationship to energy. We have been trying to conserve energy for years from the force of economics. Coal was very expensive to us years ago; gas is expensive, labor is expensive and equipment can be very expensive. So, in going through a brief outline, I was given the subject of energy management and energy tools that can be used by the greenhouse grower.

We have several things in the management of energy. First of all are concepts in breaking away from the normal thought that people usually relate to energy. In this concept of management of a greenhouse or management of a farm or the management of anything I would like to break away from the normal routine of crop production. Instead of relating production to pounds per acre, baskets per acre, units per acre, think along the lines of energy per unit produced. This is a kind of mental trick, but when you make management decisions that relate energy to units produced, it gives you a whole new concept in your thinking. Along with this type of thought, I would like to relate what we have found when we take this kind of approach. A growth chamber is diametrically opposite to using the direct sun to grow a crop. When we take all of the energy and all of the related things and concentrate the energy, and conserve the energy, and transform the energy, the growth chamber does not consume any more energy per unit produced than a greenhouse. This has a lot of related factors, of course. From the standpoint of using all the energy, on-site generation is a must. Using all the waste heat, using everything all the way down the line including hot water in an absorption chiller, it is all part of the picture.

The second thing in the management of energy is the ability to store it. As all of you who have been working on solar collectors know, storage is the big problem. What do we do when the sun isn't there? One of the easiest ways to store energy is in the soil. Since people are hauling in rocks and hauling in other things, if we just use the greenhouse soil as a medium of collecting energy by the proper ventilation of the greenhouse and so forth, we find that we can raise soil temperature by itself. By raising the soil temperature, by closing the greenhouse down early in the evening, and so forth, we can build up our temperature and use less heat. The time of sterilizing is also important. When we have to sterilize by using fuels, sterilizing during the summertime when we already have big heat problems should be avoided. If we manage our production and change our timing a little bit, we find

that we can steam sterilize the soil in the late fall of the year and use the so-called waste heat from the sterilization to heat the crop for several months afterwards.

There are several methods of storing energy in such things as water solutions, and chemicals. This is one idea that I think has not been looked into too much yet, but I think it has a great potential for the future. We talked to some people recently who were talking about storing wind energy from a wind generator in sodium hydroxide solution. Sodium hydroxide has the capability of going up to 700 or 800°F. This gives a capability of getting energy from a higher source and it is more amenable or compatible to a conventional greenhouse heating system. One of the big pitfalls of most solar energy systems is that, at this point in time, all of our heat exchangers and all of our distribution systems or heating systems would have to be greatly modified. To modify these would be extremely costly.

Another idea I have often thought about is a change in state of chemicals. If we would play the game a little bit with calcium chloride for instance, we could use a greenhouse as an evaporator, use a wind generator as a concentrator, and store energy in calcium chloride. When you reactivate the calcium chloride into solution, it liberates heat that you can control for useful purposes and the unwetted calcium chloride remains a storable heat source.

One of the other things that I think we have to look at is total energy from electrical generation. It is really kind of unique the way Mother Nature designed everything, but in a growth chamber, from the standpoint of a growth chamber, if we take fossil fuel, put it into an engine, the engine generates about 60% of energy from the standpoint of mechanical energy (40% we have a problem with). So, by taking the heat from the water of the engine and then taking the waste heat from the exhaust of the engine we can pretty well use the rest of that energy since it is on site. The growth chamber is unique from the standpoint that about the time the temperature reaches 60°F outside on the rise, we need to start to cool inside. We take heat from the engine and use it in an absorption chiller to make cold water to keep the chamber under control. One of the reasons why (going back to the first comment that I made on energy per unit produced) the growth chamber becomes efficient is that it is in an insulated building. It never needs any heat, the lights produce all the heat you need. By using all of the waste heat, we come up with a very economical situation.

The other thing that we get into then is energy tools. The tools that we need to work with energy. One of them is structures. I will just briefly show you a few of the things that a redesign of a structure can do. In Figure 1 is the inside of a conventional glass greenhouse as you all know. Look up on top and see all the bars, all the glass, all of the stuff that is cutting out the light. I think that Dr. Short and Dr. Bauerle have found out that when you start double layering over

this, you are fighting yourself. This puts a big challenge on an operator to completely eliminate the capital investment that he has. We know we have to go to something else, to make growing economical. I think the transition is going to be a very difficult one. The latest building that we have had is shown in Figure 2 and 3. Look at the difference in what is overhead here. It is a double layer so the greenhouse in essence becomes a solar collector. It also has two layers so that you can heat the air between the two layers and make it into a much more efficient operation. In addition, we have to remember that people are energy also and we have to make it so that we can do it with less people. The open span and the clearness of the film are very important.

One of the things that we found out, and we are getting to the third subject that I would like to touch on a little bit, is the fact that we need suppliers. We need suppliers and we need materials. This is a part that hasn't been touched on at all yet and it is a big void.

Then we have another way of managing energy and that is to put up something that is so cheap that you can care less whether or not it runs. I am speaking of a particular air inflated tunnel greenhouse that we built last year (Figure 4). It can be erected for approximately 30 to 40¢ per sq. ft.; it has no concrete, the sides are buried in the ground; and it is absolutely as cheap as you can get. If the gas company tells you that you can't have any fuel, you can pull the cork and let it down on the ground and wait until next March to put it up again. That is what we did this year. This particular unit was 350 feet long and 22 feet wide. It is a single layer cover, but we can make it with a double layer and still keep it cheap.

Another part of the energy thing that I think we have to worry about is people. We have been on our hands and knees transplanting lettuce and tomatoes for years and we feel that we have an energy problem in people. The next step is to adapt present field machines to the open structured greenhouse as shown in Figure 5. The transplanter requires a little bit less energy from the people and is a little bigger than most greenhouse machinery. Full transplanting automation is shown with the lettuce transplanter in Figure 6 that we developed. These developments seemingly are very simple and should take very little time. However, we have been working on them for over six years. This particular planter has been modified for planting trees automatically, which goes back to energy again. The Canadian Forest Service has a terrific problem in producing tree seedlings to get trees for pulpwood and also trees are an excellent source of storage for energy from solar source.

In relationship to these problems, I would like to close in saying that I think probably the biggest problems that are holding us up right now in making progress are the development of products, films, suppliers, fabricators and people of this sort. I don't think anybody here can really understand or can really appreciate how long it is going to take to develop a new technology and then put it into hardware that someone else can operate until you actually try to do it.

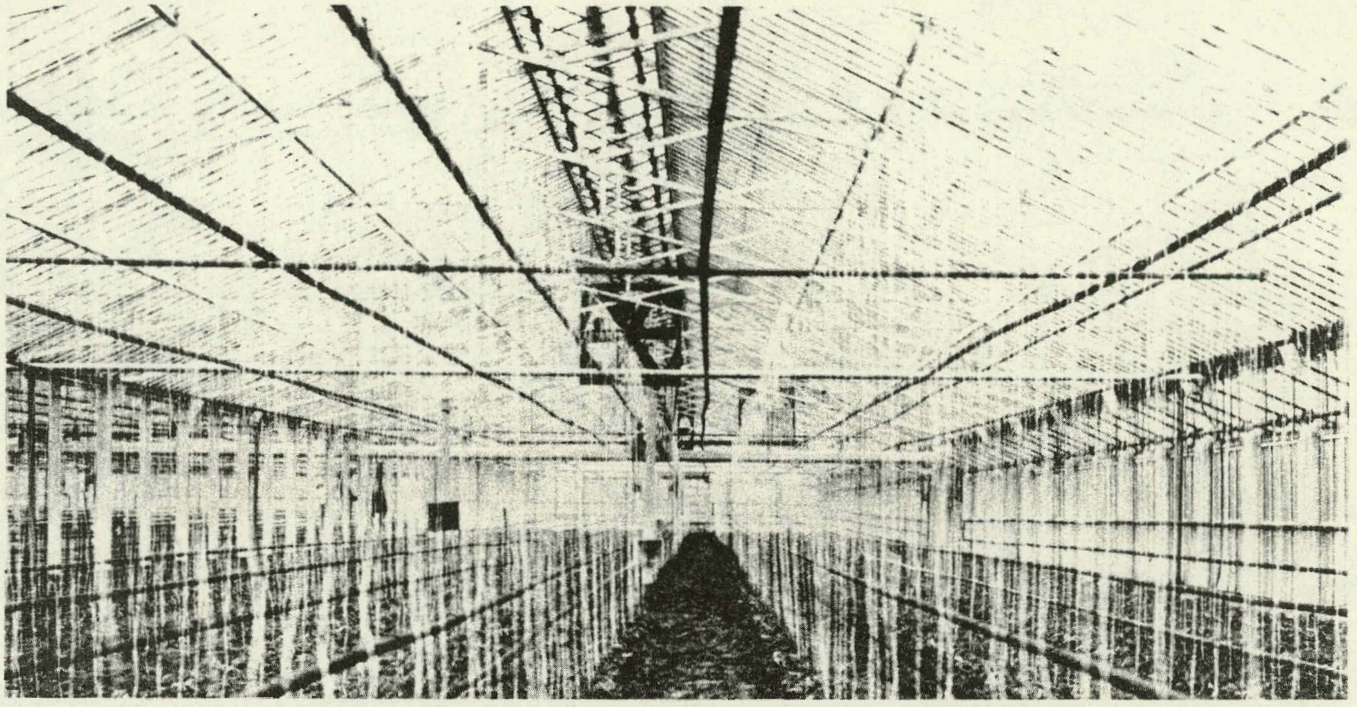


FIGURE 1. An inside view of a conventional glass greenhouse used to grow tomatoes and lettuce. Note all the framing and structural members interferring with light transmission and mechanical systems.

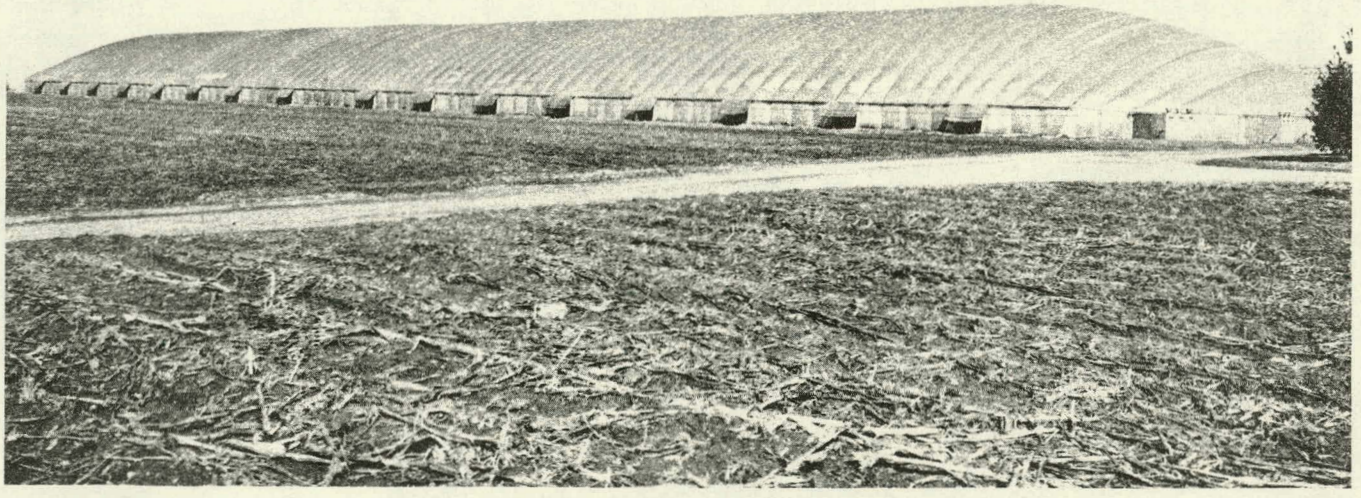


FIGURE 2. An acre-size (100' x 450') air-supported greenhouse at Pretzer Farms, Wooster, Ohio.

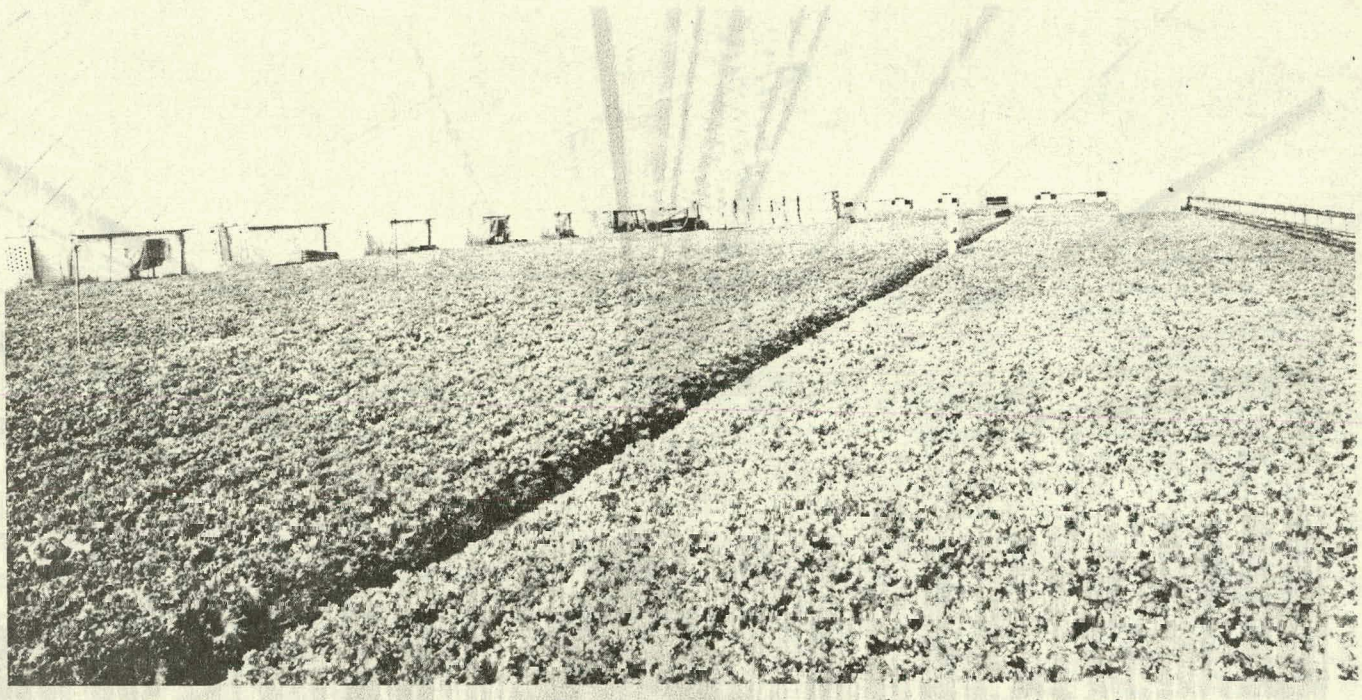


FIGURE 3. An inside view of a lettuce crop in the acre-size air-supported greenhouse. Note the elimination of all overhead structural support.

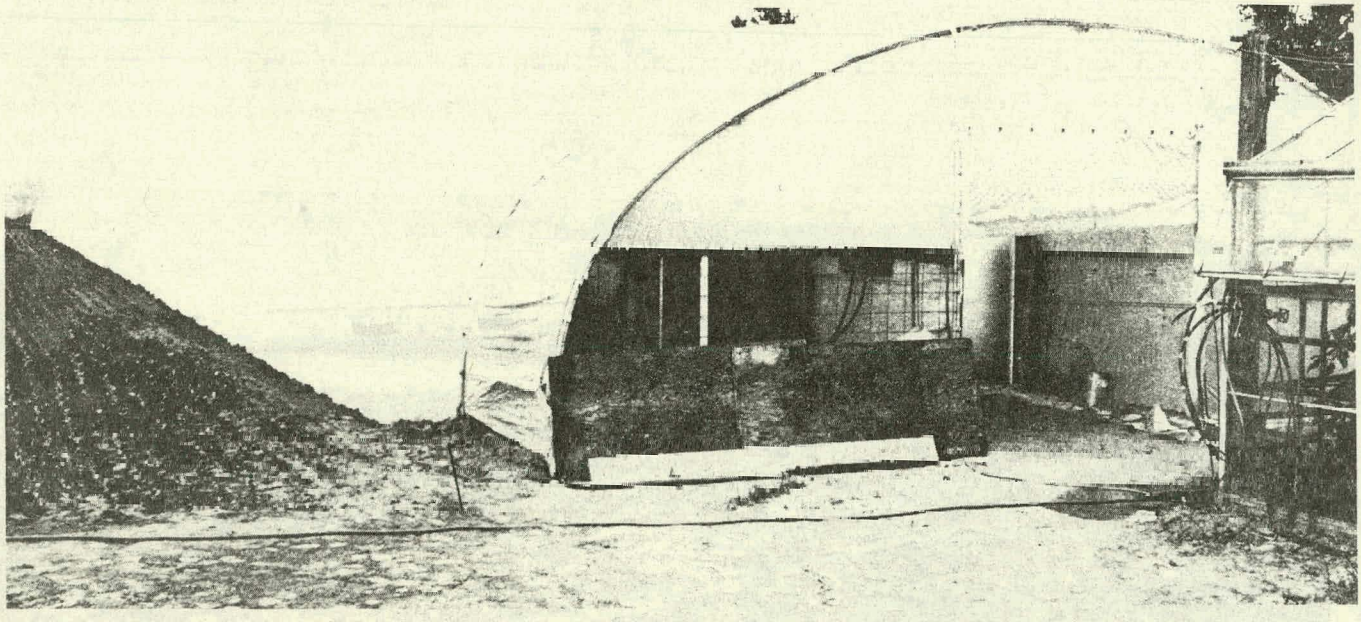


FIGURE 4. An air-supported tunnel greenhouse (22' x 350') at Pretzer Farms, Cleveland, Ohio.

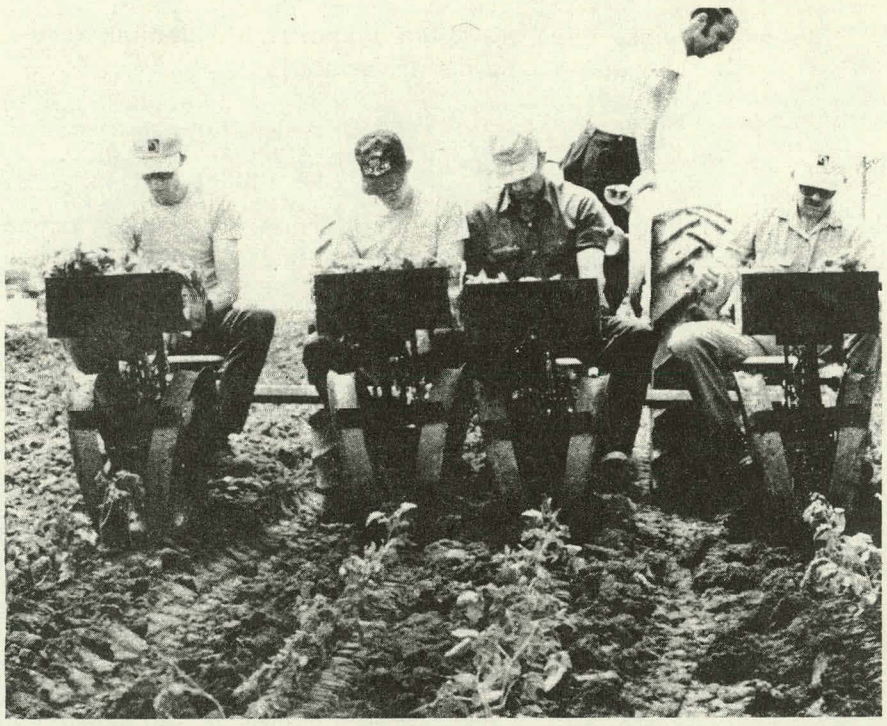


FIGURE 5. A four row tomato transplanter being used in the one-acre air-supported greenhouse.

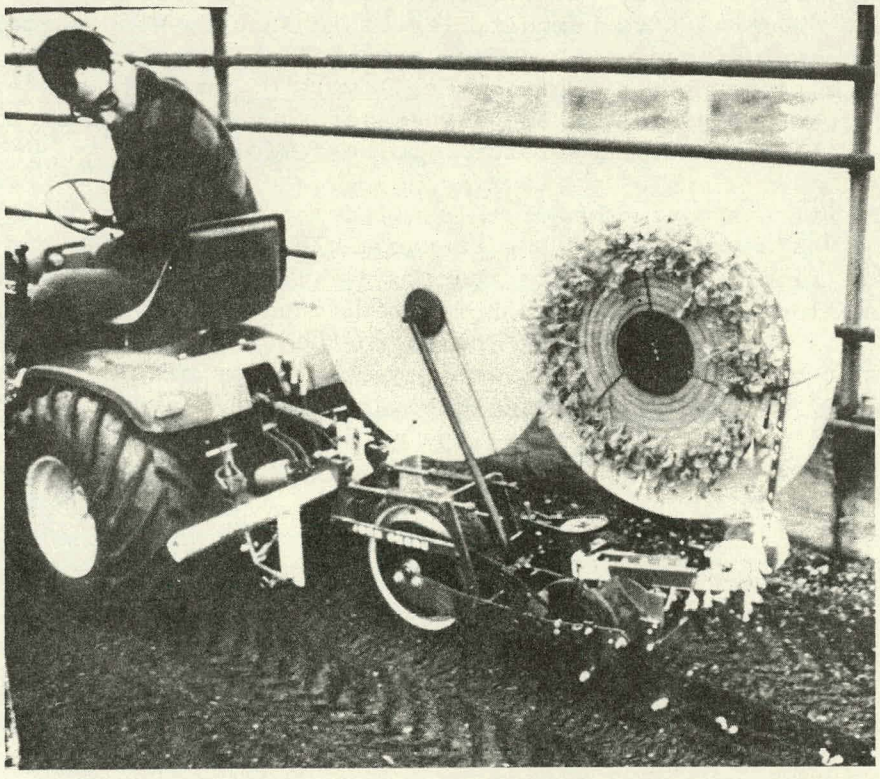


FIGURE 6. A fully automated tape transplanter being used to transplant lettuce. A similar version has been developed to transplant forest seedlings.

# A GREENHOUSE-RESIDENCE UTILIZING A "CLEARVIEW" SOLAR COLLECTOR AND TWO-STAGE EVAPORATIVE COOLING

John F. Peck, Carl N. Hodges, Merle H. Jensen
and T. Lewis Thompson[1]

## INTRODUCTION

The finite limits of non-renewable energy sources have been emphasized by fuel shortages and price increases. Simultaneously, public concern about the environmental effects of large scale usage of fossil fuels has increased greatly. These factors have shifted the national objectives toward the development of natural energy systems and renewable resources. A project at the Environmental Research Laboratory (ERL) of the University of Arizona demonstrates the heating of a residential unit through the use of a combined solar collector-greenhouse, as well as producing vegetables for home use (Fig. 1). Integrated into the demonstration unit is the ClearView solar collector and rockbed, which are used to collect and store heat for nocturnal use. Also included in the facility is one or two-stage evaporative cooling for summer use. The integration and performance of these concepts are reported in this paper.

## HEATING

### The Attached Residential Greenhouse as a Heat Source.

The attached greenhouse furnished adequate heat for the office during all but extremely cloudy days. Ventilation was commonly used from 12:00 noon to 4:00 p.m. The relative humidity levels in January were normally 80-90%; however, these high levels would drop somewhat if this size greenhouse were attached to a larger home. While these levels of humidity are excessive, they do counter the usual extreme dryness of the air in heated homes, as well as permitting lower temperatures to be comfortable.

The outside walls and windows of this office have a combined heat loss of approximately 370 Btu/°F hr. Due to the angle of the winter sun at mid-day, the concrete floor of the office itself was illuminated by direct sunlight, and light reflected from the floor was reflected onto the surrounding walls, reminiscent of many passive solar homes in the Santa Fe, New Mexico, area. Since 60° nocturnal temperatures are acceptable for plants, the thermostat was set at 60° at night for the active part of the system. Heat from the rockbed was seldom required, since the minimum temperature in the greenhouse at 7:00 a.m. only reached 56°F (at a 26.5°F outside temperature), with no heat supplied from the rockbed (Fig. 2).

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[1]Peck, Project Engineer; Hodges, Director; Jensen, Research Horticulturist; and Thompson, Chemical Engineer, Environmental Research Laboratory, University of Arizona, Tucson International Airport, Tucson, Arizona 85706.

This study was supported in part by the Energy Research and Development Administration and the USDA Agricultural Research Service.

[2]"ClearView" is being trademarked in connection with venetian blind collectors as described here.



Fig. 1. Vegetables and herbs are planted in the solar collector-greenhouse. Note the ClearView venetian blind collector in the wall of the greenhouse.

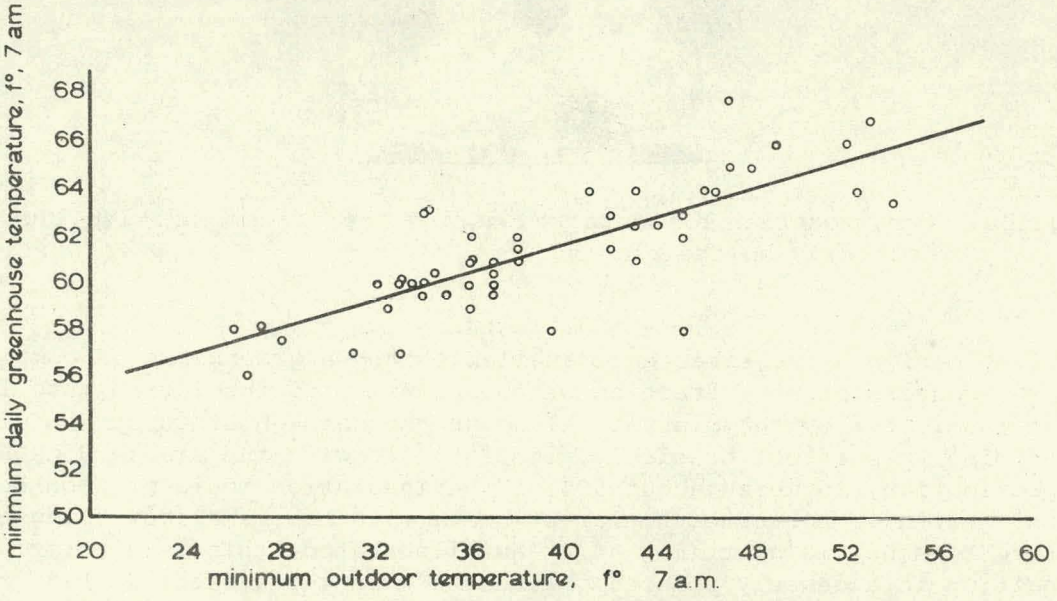



Fig. 2. Relation of minimum interior temperature to minimum outdoor temperature with no heating during night, December 1976-January 1977, Tucson, Arizona.

This implies that a passive system can be quite effective, especially in mild climates. Such a system might involve clay pots for horticultural plants, a concrete floor, a double-glazed patio door between the house and the greenhouse, and dark colored, grouted block walls between the rest of the greenhouse and the home. Additionally, a venetian blind could be used in the south wall to increase the quantity of heat available in the early morning (Fig. 3), if an active ClearView collector is not used. This blind would be raised at mid-morning on clear days.

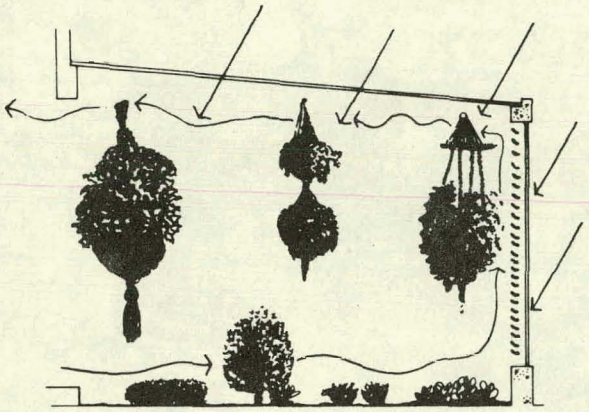


Fig. 3a. Dark venetian blind lowered in the early morning to maximize heat output of the greenhouse.

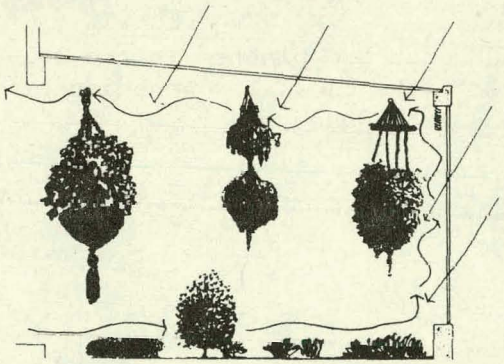


Fig. 3b. Dark venetian blind raised during the day to maximize light intensity on the plants.

The estimation of sensible heat available from a greenhouse is complicated by the conversion of a fraction of the transmitted insolation into latent heat (humidity) by the plants. Although the data obtained at ERL did not determine this effect precisely, it did agree with the standard ASHRAE approximation, in which about 50% of the insolation incident upon dense plant growth is converted to latent heat, with the remainder being converted to sensible heat (Fig. 4). As illustrated, this is a normal summer condition in a densely planted greenhouse. In the winter, if half the transmitted insolation strikes plant surfaces, approximately 70% of the transmitted insolation is converted to sensible heat (Fig. 5). These values require confirmation and depend on the location of plants, but

should be useful in estimating the thermal performance of small greenhouses.

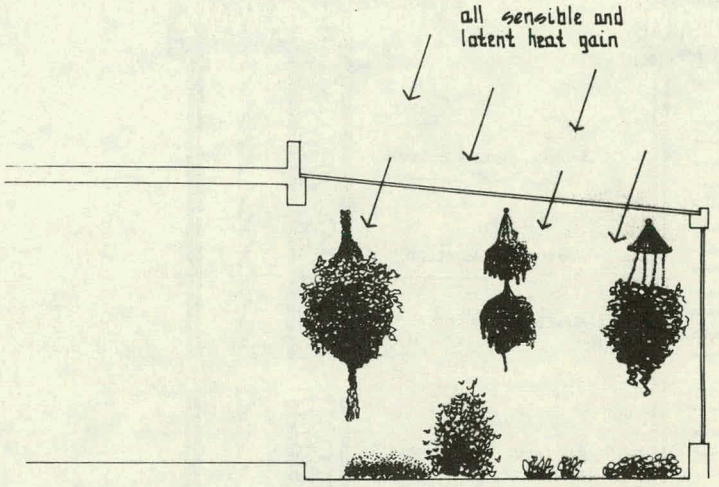



Fig. 4. Summer heat gain ($\frac{\text{sensible heat gain}}{\text{total heat gain}} = .5$).

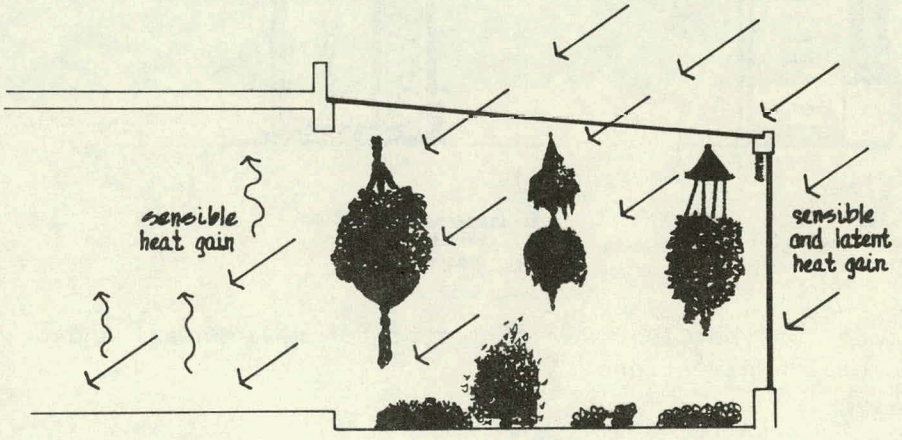



Fig. 5. Winter heat gain ($\frac{\text{sensible heat gain}}{\text{total heat gain}} = .70$).

The Active ClearView Collector and Rockbed.

An active model of the ClearView collector designed at the Environmental Research Laboratory for residential and light commercial applications is illustrated in Figure 6. This version is used in integrated residential greenhouse applications, and is only one model of the ClearView collector system. Of course, a greenhouse has a clear roof, as opposed to the illustration, which is for the wall of the home.

Air is heated as it flows horizontally across the solar heated dark slats

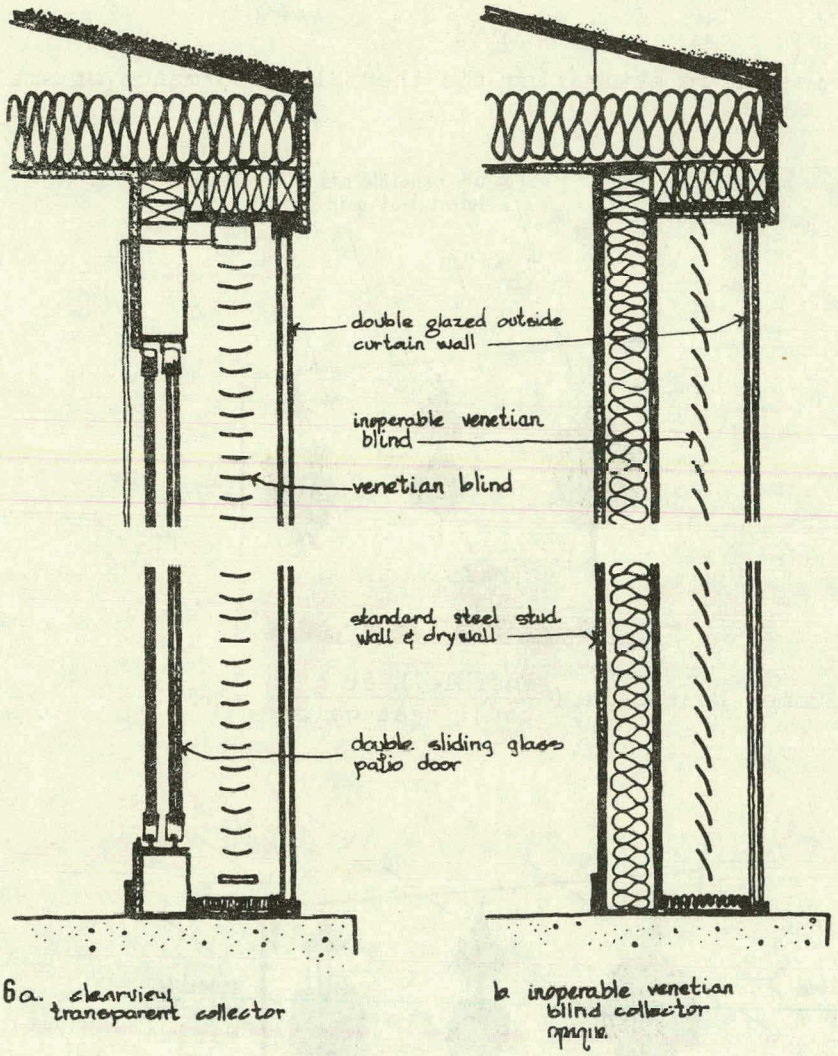



Fig. 6. An active model of the ClearView collector for residential and light commercial applications.

of the venetian blind. Vertical airflow designs are also under test. This hot air subsequently heats rocks in the rockbed. The exterior glazing is a curtain wall of patio door glass (water white or low iron glass is preferred, if available), while the interior wall is a double sliding patio door in a suitable framework, which allows complete access for cleaning glass surfaces and blind maintenance. The blinds are completely operable from inside the greenhouse or the house, and while the tilt of the slats can be adjusted as often as desired, a monthly adjustment will suffice. The collector may be closed at night for privacy in the room (Fig. 7). This collector is very attractive, completely removes the restrictions on windows that most solar collectors impose when used on south walls, and is simple to install.

The performance of the active ClearView collector closely parallels the theoretical analysis presented in Appendix 1. On clear January days in



Fig. 7. The "ClearView" solar collector closed at night for privacy in the room and to reduce heat loss out of the greenhouse.

Tucson, Arizona, using standard patio door glass, the output of the ClearView solar collector was 650-700 Btu/ft$^2$/day with the blinds allowing vision outside, while intercepting all direct sunlight, and was approximately 850 Btu/ft$^2$/day with the blind closed. The latter increase in performance is due to the interception of diffuse and reflected ground radiation when the blinds are closed. When the house and collector are considered as a system, this unintercepted radiation is not a loss, unless the house is being ventilated during the day to prevent overheating. The use of water white glass will increase the amount of heat collected by approximately 20%. Further significant increases in performance are expected if low reflectance glass is used.

Relatively high airflow rates are used through the solar reflector to minimize temperature gain in the solar collector, and thus increase the efficiency of both the collector and the storage facility. A useful airflow rate is 4 ft$^3$ air/min/ft$^2$ of glass area, providing a temperature change from the input to the output of approximately 25°F in Tucson. The input temperatures to the collector are commonly in the low 70° range, due to the reversal of airflow direction from day to night. During space heating (Fig. 8), the room temperature return air from the office cools one end of the rockbed to room temperature. During subsequent solar collection (Fig. 9), the airflow is reversed and air at room temperature from the

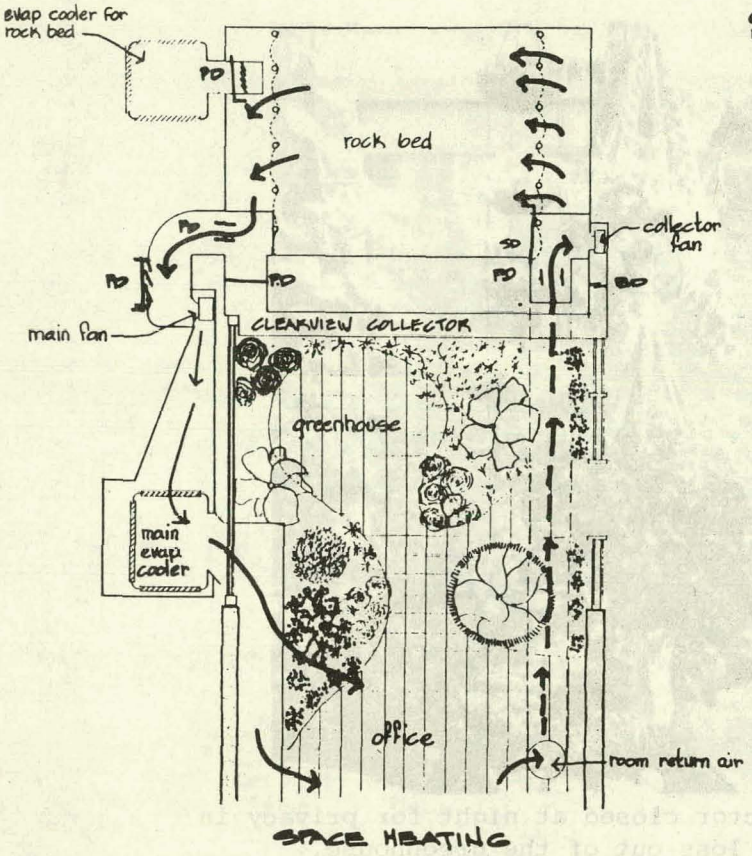



Fig. 8. Space heating of greenhouse-office or residential unit.

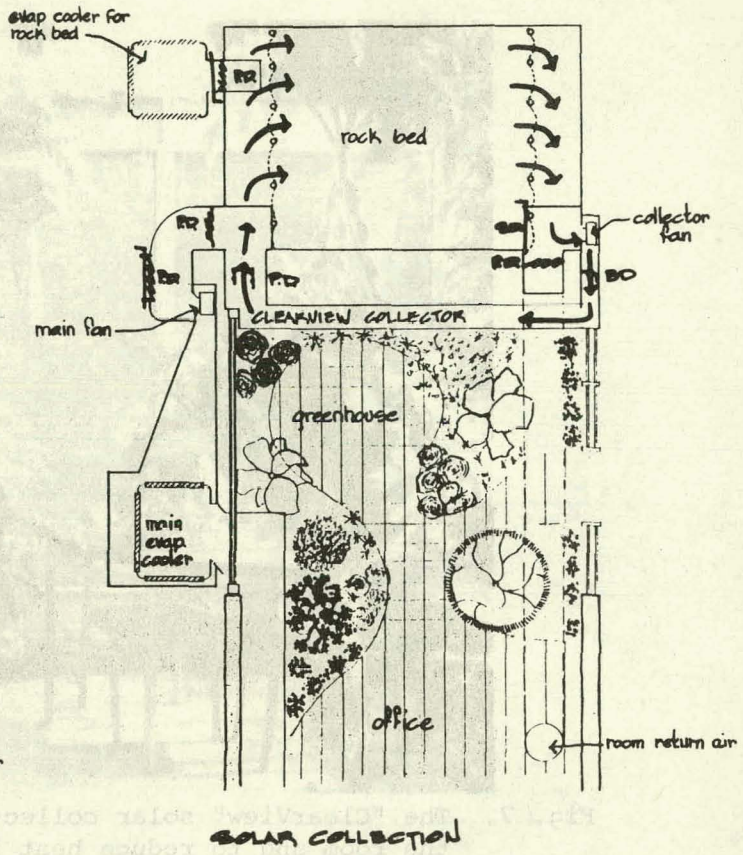



Fig. 9. Solar collection during winter time daylight hours.

cool end of the rockbed enters the solar collector. This lowers the average air temperature in the collector, thus increasing its efficiency.

While the preferred rockbed location is under the house, the rockbed and major ducts at ERL were located outside the building. This tended to increase losses of heat in the winter and the effect of small air leaks in the ducts. The rockbed volume of 300 $ft^3$ of nominal 3-6 inch rock was adequate to heat the office on cloudy days, as well as in the morning. The rockbed output temperature was commonly 100°F, decreasing to 80° during cloudy periods. The airflow path length is approximately 16 feet.

During winter months, the air-inflated, double polyethylene roof of the greenhouse may be filled with a liquid-based foam for nighttime insulation, a technique still in development at ERL. The small bubbles of the foam reduce heat transfer through the greenhouse roof (Fig. 10). During daylight hours, the foam material is reconstituted into liquid to facilitate storage and reuse.

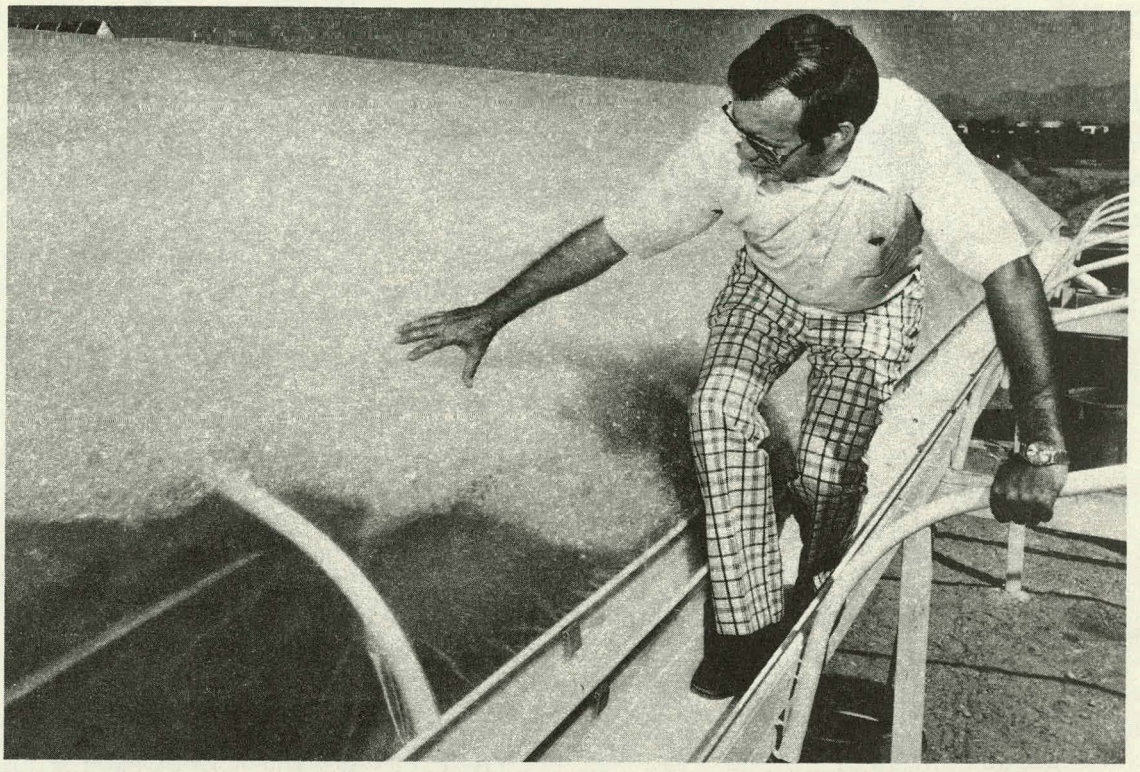


Fig. 10. Roof of greenhouse filled with foam for nighttime insulation.

COOLING

One and Two-Stage Evaporative Cooling.

Refrigeration-type air conditioning has become very popular in the desert Southwest, but increasing power costs are causing many people to return to evaporative cooling, since operational costs can be about one-fifth of those of air conditioning. Ordinary one-stage evaporative cooling, where outside air is cooled by humidification prior to entering the house, can be quite effective in low humidities (Fig. 11). The maximum output temperature of the cooler on the day illustrated in Figure 11 was about 73°F. In a well designed house, the interior temperatures on this day could be held at about 73-77°. Another advantage of evaporative cooling is that a residential greenhouse attached to an evaporatively-cooled home costs almost nothing to cool, since the evaporatively-cooled air is exhausted through the greenhouse instead of out the window. Additionally, some evaporatively-cooled air is exhausted through the active ClearView collector as well, effectively removing the small quantity of heat collected in the summertime.

During July and August, more humid times, the evaporative cooler output temperatures can be in the 76-78° range, and the house interior space can vary from 76-82°, or more in poorly insulated houses. These conditions are not optimum, due to the humidity, although the air velocities associated

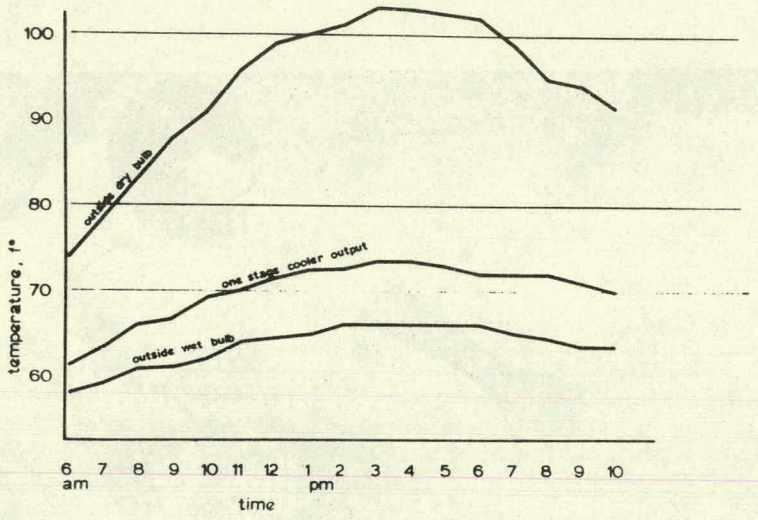



Fig. 11. One-stage evaporative cooling performance, Tucson, Arizona, July 4, 1976.

with evaporative cooling tend to mitigate these conditions somewhat. If the rockbed is evaporatively-cooled at night, outside air can be drawn through it during the day, and subsequently cooled without additional humidification. This precooled outside air can then be evaporatively-cooled further in a second stage of evaporative cooling, producing significantly lower output temperatures than a standard one-stage cooler. From psychometric charts, the cooler output temperature is reduced approximately 3° for every 10° of precooling, which was confirmed in our work.

Since the air was precooled in the rockbed by 15-27° on most days last summer, the output cooler temperature was dropped from 4.5 to 8°. The maximum output temperatures last summer were 77° for one-stage evaporative cooling and 72° for two-stage evaporative cooling. Figure 12 illustrates a day in which the system was switched between one and two-stage evaporative cooling. Although the day was fairly humid, the two-stage cooler output temperature was never over 70-71°F, while the one-stage evaporative cooler reached 76°F. While the difference is not great, it means that the house will be at a comfortable 70-74° with two-stage evaporative cooling, instead of a relatively uncomfortable 76-80° range with one-stage evaporative cooling. Figure 13 shows two consecutive days in which one and two-stage evaporative cooling were directly comparable. If the output of the two-stage evaporative cooler is too cool, it is also possible to cool the house without humidification for periods of seven hours or more, when the output temperatures of the rockbed will be 75° or less, at low air velocities in the rockbed. Subsequently, as the temperatures in the rockbed begin to rise in the afternoon, the pump on the evaporative cooler is turned on, and true two-stage evaporative cooling is used.

The rockbed at ERL had a 16-foot airflow part length and a 60 ft/min airflow velocity. In normal designs, airflow velocities are approximately 25 ft/min. This velocity, with an airflow path length of 16 feet, will give an approximate 12-hour two-stage evaporative capacity. If shorter

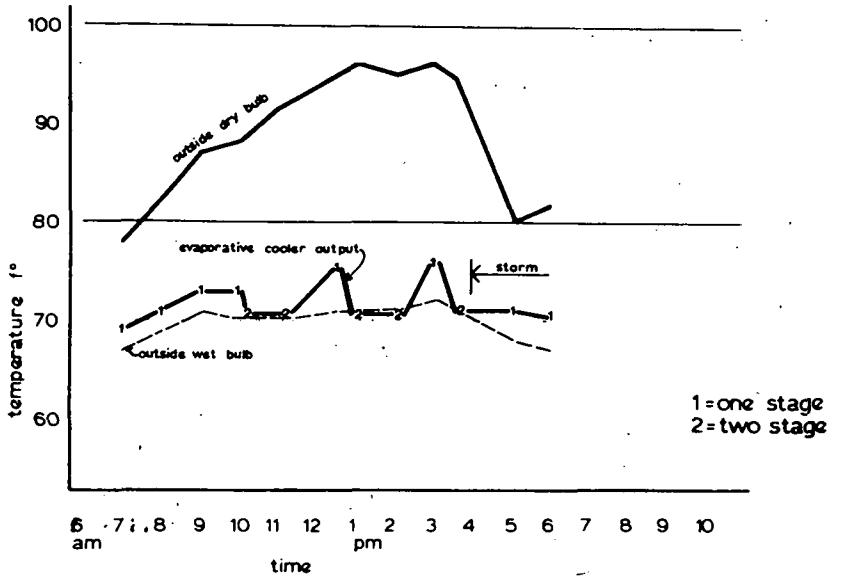



Fig. 12. Comparison of one and two-stage evaporative cooling, used alternately on the same day, August 10, 1976.

two-stage evaporative cooling periods are desired, the rockbed airflow path length is proportionally shortened. The face area may also be reduced slightly. For comparison, the time scale in Figures 12 and 13 would be lengthened by approximately two and a half times in a normal installation. Figure 14 illustrates the absorption of heat during daytime two-stage evaporative cooling and heat rejection during the night. The arrows on the left point to the cooling of the air as it passes through the cool rockbed during the day, and the arrows on the right point to the heating of the air as it passes through the rockbed and exhausts heat from it during the night. Many people prefer to cool a structure by recirculating house air through a nocturnally-cooled rockbed. While this method has its advantages, it does not allow cooled air from the house to be exhausted in various simple ways to reduce heat gain into the house during the day.

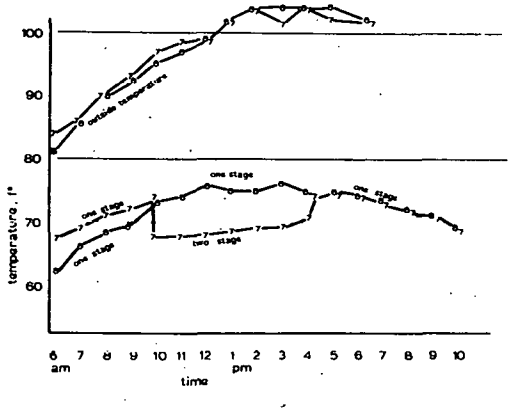



Fig. 13. Comparison of two-stage evaporative cooling on July 7, 1976, with one-stage evaporative cooling on July 8, 1976, Tucson, Arizona.

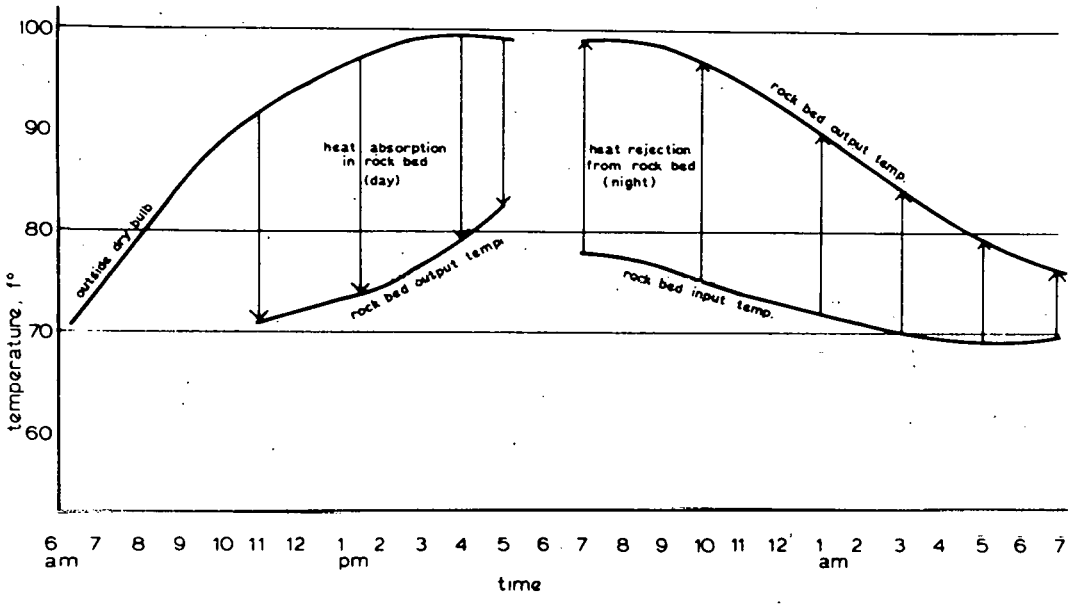



Fig. 14. Typical heat absorption and rejection cycle in rockbed.

The seasonal power costs for two-stage evaporative cooling can be only slightly greater than the cost of one-stage evaporative cooling as normally practiced, since one-stage cooling can be used whenever the weather conditions permit. This is not recommended if mechanical refrigeration is used.

The additional cost of the very large rockbed required for two-stage evaporative cooling, above that of a normal size rockbed, need not exceed the $2,700 cost of a commercial absorption solar air conditioning unit, without the required cooling tower, whose lifetime is much less than that of a rockbed. Also, the large rockbed has several advantages in the winter, such as lower collector operating temperatures, greater collector efficiency, and a long-term energy storage capacity that is almost seasonal in nature.

Attached Greenhouse Design Considerations.

The design of an integrated home-greenhouse involves three factors: the area of the greenhouse that the owner wants to properly care for, the cooling of the greenhouse with available evaporatively-cooled air, and the daytime excess heat available from the greenhouse to heat the associated home. We feel that most homeowners would not want to take care of an integrated greenhouse larger than approximately 200 square feet. The 1.5 to 2 lbs/day of vegetable production in the 187 $ft^2$ greenhouse at the Environmental Research Laboratory is quite adequate for a family. In climates similar to Tucson, the typical 4,000 $ft^3$/min airflow of evaporatively-cooled air in a well-insulated 2,000 $ft^2$ house should produce an acceptable temperature rise of 3-4.5°F in a 200 $ft^2$ greenhouse, projected from the results at the ERL installation. In homes with lower evaporative cooling airflow rates, the greenhouse should be proportionally smaller, or the evaporative cooler size increased, at greater cost. In many cases

these factors, not winter heat production, will determine the size of the greenhouse.

## HORTICULTURE

### Horticultural Practices in Attached Home Greenhouses.

Homes of the future may have their own year-round vegetable gardens in greenhouses that double as solar energy collectors. To produce a predictable and continuing supply of fresh table vegetables for the family, plus the aesthetic pleasure of such cultivation inside the home, presents an opportunity to enhance the quality of life while reducing the dependence upon energy derived from fossil fuels.

Selection of vegetable cultivars. Cultivars have been selected for least sensitivity to exact growing temperatures, particularly day-night changes in temperature. Also taken into consideration is their adaptability to growing in containers holding approximately one-half cubic foot of growing medium. Plants, cultivars and sources are listed in Table 1.

Location of cultivars in greenhouse. Reduced amounts of light are received at ground level in the greenhouse since the north side is attached to the office and the south wall contains the venetian blind "ClearView" solar collector. Plants that require only lower levels of light, such as lettuce and herbs, are planted at ground level in areas that receive no direct sunlight. Ground areas that receive approximately two to four hours of direct sunlight can be planted to peppers, cabbage, Chinese cabbage, broccoli, radish, lettuce and herbs. Such fruit-bearing plants as cucumber, eggplant and tomato, need approximately six hours of direct sunlight to produce suitable yields. These are placed in hanging pots near the roof of the chamber, where amounts of incoming radiation are maximized (Fig. 1). If macrame hangers are used to support the plant containers, care must be taken not to wet the hangers with drainage water, as this will cause the hemp, jute or sisal to quickly rot, especially when the water contains fertilizer. Drainage is necessary, but it must be channeled away from the hanger.

Fertilizers and growing medium. Plants are grown in a peat moss-vermiculite medium, such as Jiffy Mix, Redi Earth or Pro-Mix. Such mixtures are important due to their water holding capacity. Mixed into the growing medium are such slow-release fertilizers as Mag Amp (3 oz/ft$^3$) and Osmocote[1] (6 oz/ft$^3$). The latter should be the 8-9 month Osmocote (18-6-12), where the nutrients are released at a comparatively low rate for the first 30 to 45 days and thereafter at about double the initial rate until the nutrients are virtually depleted in 8 to 9 months (at 70°F average soil temperature). Since the soil temperatures are usually higher than 70°, the nutrients seem to be depleted in a shorter period of time, which is not a disadvantage since most vegetable plants are not cropped in one particular container for more than 5 to 6 months at most. If a plant is grown for a longer period and additional fertilizer is needed, a soluble fertilizer (20-20-20 mixed at 3 lb/100 gal water) may be added every 8 to 10 days at a rate of one quart per plant.

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[1]E. C. Geiger, Box 285, Rt. 63, Harleysville, PA 19438.

Table 1. Selected cultivars

| Vegetables | Cultivar | Plant or seed source |
|---|---|---|
| Pepper | Christmas Pepper | George Ball Pacific, Inc.[1] |
| | New Ace | Takii and Co., Ltd.[2] |
| | Bell Boy | van der Ploeg[7] |
| Lettuce | Dutch type | Rijk Zwaan[3] |
| | Summer Bibb | Joseph Harris Co.[4] |
| | Salad Bowl | Joseph Harris Co. |
| Chinese cabbage | Tropicana | Takii and Co., Ltd. |
| | WR-55 | Takii and Co., Ltd. |
| Tomato | Patio | George Ball Pacific, Inc. |
| | Tiny Tim | George Ball Pacific, Inc. |
| | Small Fry | George Ball Pacific, Inc. |
| Eggplant | Beauty Hybrid | George Ball Pacific, Inc. |
| | Black Prince | Takii and Co., Ltd. |
| | Dusky | Peto Seed Co.[8] |
| Cucumber | Patio Pik | George Ball Pacific, Inc. |
| | Femfrance | van der Ploeg |
| Spinach | Malabar | Burpee Seed Growers Co.[5] |
| Snap Bean | Green Crop | Northrup, King & Co.[9] |
| Radish | Champion or Red Prince | Joseph Harris Co. |
| Cabbage | Express Cross 60 | Takii and Co., Ltd. |
| | K-K Cross | Takii and Co., Ltd. |
| Fruit | | |
| Strawberry | Fresno | California Strawberry Foundation[6] |
| Banana | Dwarf | Environmental Research Laboratory |
| Herbs | | |
| Annuals and Perennials | Assorted | George Ball Pacific, Inc. |

[1]Box 9055, Sunnyvale, California 94088.
[2]Umekoji-Inokuma, P. O. Box 3091 (Kyoto Central), Kyoto, Japan.
[3]Rijk Zwaan's Zaadteelt en Zaadhandel B.V., Burgem. Crezeelaan 40 De Lier, Holland.
[4]Moreton Farm, 3670 Buffalo Road, Rochester, New York 14624.
[5]P. O. Box 6929, Philadelphia, Pennsylvania 19132.
[6]Plants Nursery, 3570 Old Alturas Road, Redding, California 90001.
[7]D. van der Ploeg's Elite Zaden N.V., P. O. Box 19, Barendrecht, Holland.
[8]P. O. Box 4206, Saticoy, California 93003.
[9]1500 Jackson St., N.E., Minneapolis, Minnesota 55413.

Growing of transplants. A number of transplant containers, such as Jiffy 7 peat pellets, BR-8 blocks or Kys-Kubes, may be used. If peat, plastic or clay pots are used, they may be filled with a peat moss-vermiculite growing medium. The seeds are planted directly into these containers and the plants later transplanted to the large containers or beds.

Watering systems. A trickle irrigation system operated on a time clock is used to water all the crops growing in the greenhouse (Fig. 15). In watering the plants in the hanging containers, three-quarter inch polyethylene pipes are run from the ground beds, up the side wall, and attached to the overhead members of the greenhouse. From the overhead lines, small polyethylene tubes, .076 inch inside diameter, are loosely woven in the hanger and lead to the container. Such watering tubes are also used to water the plants in the ground beds. They are called "on-off tubes" and can be purchased from Chapin Watermatics, Inc., P. O. Box 298, Watertown, New York 13601. Depending on the time of year and the location, the water system may be regulated to turn on for approximately two minutes two to three times daily.

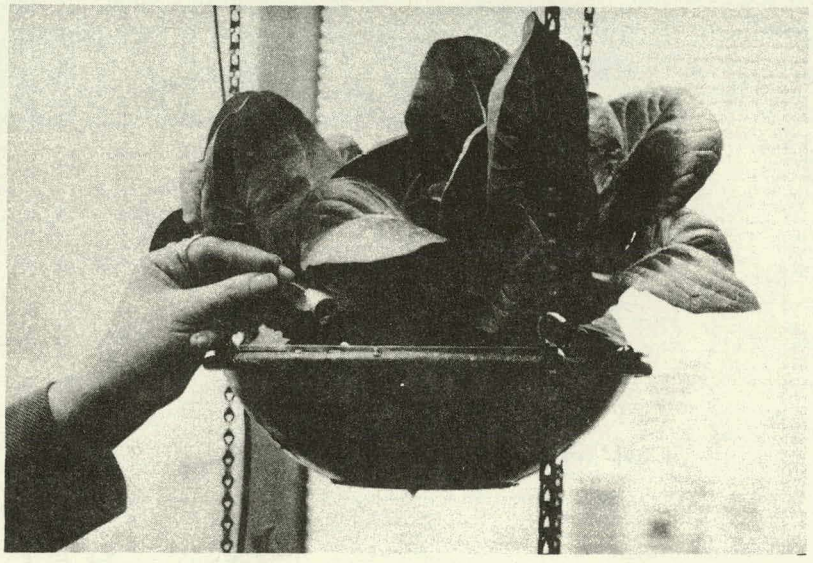


Fig. 15. A trickle irrigation system is used to water all of the crops in the greenhouse.

Vegetable and herb yields. The estimated and actual yields from the crops grown in the greenhouse unit for one year (March 15, 1976 to March 15, 1977) are listed in Table 2. The total actual yield was far greater than estimated. The major vegetables, such as tomatoes, cucumbers, eggplant, peppers and lettuce, produced a continuous supply since each vegetable was planted on a staggered timetable. It is not recommended that banana plants be grown, as their large leaves tend to shade other plants. Strawberries are very seasonal and therefore were replaced with snap beans. While radishes easily could be grown, it was decided to use that growing space for Swiss chard, broccoli and cabbage. It is important to use those cultivars listed

Table 2. Estimated and actual vegetable and herb yields (lbs)

| Month | Pepper | | Lettuce | | Tomato | | Eggplant | | Cucumber | | Spinach | | Snap Bean | | Herbs | | Misc. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Est. | Act. | Est. | Act. | Est. | Act. | Est. | Act. | Est. | Act. | Est. | Act. | Est. | Act. | Est. | Act. | Est.[1] | Act.[2] |
| Mar 15-30 | 0.8 | -- | 4.5 | 8.8 | 3.0 | 17.6 | 0.5 | -- | 1.0 | -- | -- | -- | -- | -- | -- | 7.9 | .5 | -- |
| Apr | 1.5 | 0.8 | 9.0 | 10.2 | 8.0 | 21.1 | 2.0 | 1.9 | 2.0 | 10.3 | -- | 1.0 | -- | -- | -- | 18.7 | 5.0 | -- |
| May | 2.0 | 1.2 | 10.0 | 7.7 | 10.0 | 16.8 | 2.0 | 12.1 | 2.0 | 15.6 | 1.0 | 2.5 | -- | -- | -- | -- | 15.0 | -- |
| June | 3.0 | 1.7 | 12.0 | 3.9 | 10.0 | 31.7 | 2.0 | 13.1 | 3.0 | 18.1 | 1.0 | 1.8 | -- | 0.6 | -- | 11.1 | 2.0 | -- |
| July | 3.0 | 6.9 | 12.0 | 4.2 | 10.0 | 15.5 | 3.0 | 12.2 | 4.0 | 6.5 | 1.0 | 6.4 | -- | 2.4 | -- | 5.4 | 2.0 | 1.9 |
| Aug | 3.0 | 5.4 | 12.0 | -- | 10.0 | 17.2 | 3.0 | 10.8 | 4.0 | 24.9 | 1.0 | 2.2 | -- | 2.1 | -- | 4.2 | 2.0 | 1.8 |
| Sep | 3.0 | 3.4 | 10.0 | -- | 10.0 | 6.7 | 3.0 | 4.2 | 4.0 | 14.8 | 1.0 | 1.1 | -- | 1.8 | -- | 11.9 | 2.0 | 2.3 |
| Oct | 2.5 | 5.1 | 10.0 | 1.3 | 8.0 | 4.8 | 2.0 | -- | 3.0 | 10.0 | -- | 4.5 | -- | .4 | -- | -- | 2.0 | -- |
| Nov | 1.5 | 1.0 | 9.0 | -- | 8.0 | 16.9 | 2.0 | 1.6 | 2.0 | 12.7 | -- | -- | -- | 2.7 | -- | -- | 12.0 | -- |
| Dec | 1.0 | -- | 9.0 | 2.7 | 8.0 | 26.6 | 2.0 | 0.3 | 1.0 | 1.2 | -- | -- | -- | 3.1 | -- | 2.4 | 1.0 | 5.4 |
| Jan | 1.0 | 3.6 | 7.0 | -- | 6.0 | 20.9 | 1.0 | 1.0 | 1.0 | 0.8 | -- | -- | -- | 2.0 | -- | -- | 1.0 | 2.1 |
| Feb | 1.0 | 1.8 | 7.0 | 2.0 | 6.0 | 13.5 | 1.0 | 1.9 | 1.0 | -- | -- | -- | -- | 1.4 | -- | -- | 1.0 | 0.6 |
| Mar 1-15 | 0.7 | 5.0 | 4.5 | 2.6 | 3.0 | 4.2 | 0.5 | 1.2 | 1.0 | 5.7 | -- | -- | -- | .4 | -- | 2.2 | .5 | 1.4 |
| Total | 24.0 | 35.9 | 116.0 | 43.4 | 100.0 | 213.5 | 24.0 | 60.3 | 29.0 | 120.6 | 5.0 | 19.5 | 0 | 16.9 | 0 | 63.8 | 46.0 | 19.0 |

Estimated yield for one year = 356.0 lbs

Actual yield for one year = 593.1 lbs

[1]Radish, strawberry, banana

[2]Cabbage, Swiss chard, broccoli

in Table 1 as they are best suited for containers and/or the temperatures maintained within a home.

Pest control. Plant diseases have not been a problem due to the sterile growing medium used. Such insects as mites, white fly and aphids have caused problems, but they have been kept under control by using standard insecticides recommended for greenhouse vegetables. Pesticides in a greenhouse-residential unit must be used with extreme caution and applied as on foliage plants. Increasing attention will be given in this program to the use of organic and biological control procedures.

Growing costs versus returns. Such initial costs as the growing containers, macrame or chain hangers, watering system, and the time clock and solenoid valve total approximately $250 to $300. The growing or operational costs, which include the growing medium, fertilizers, pesticides and seeds, average $8.41 per month (Fig. 16). If one values the harvested vegetables at $0.35

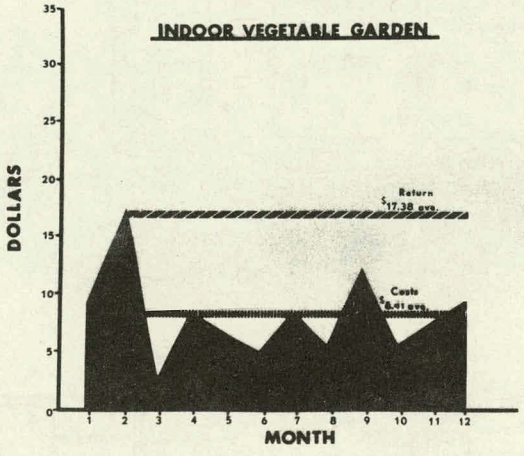



Fig. 16. Average monthly costs and returns for growing vegetables in a greenhouse-residential unit.

per pound, the return on vegetables would average $17.38 per month, excluding labor. The average monthly labor input is 13.95 hours (Fig. 17).

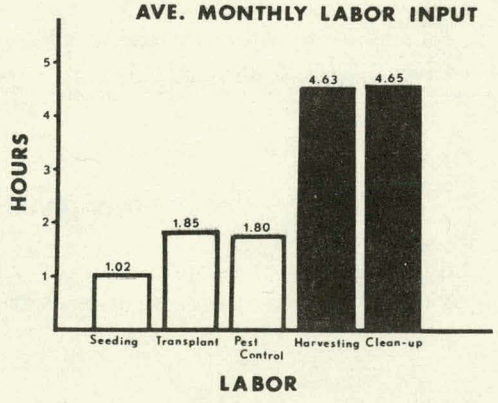



Fig. 17. Average monthly labor input for various cultural requirements.

TWO SCHEMATIC STUDIES OF HOME DESIGNS USING THE ATTACHED GREENHOUSE FOR HOME HEATING[1]

An oblique view and floor plan of a home using the complete attached greenhouse, active ClearView collector, rockbed, and one/two-stage evaporative cooling capability are shown in Figure 18, and Figure 19 illustrates another similar home which also can be adapted to one/two-stage evaporative cooling.

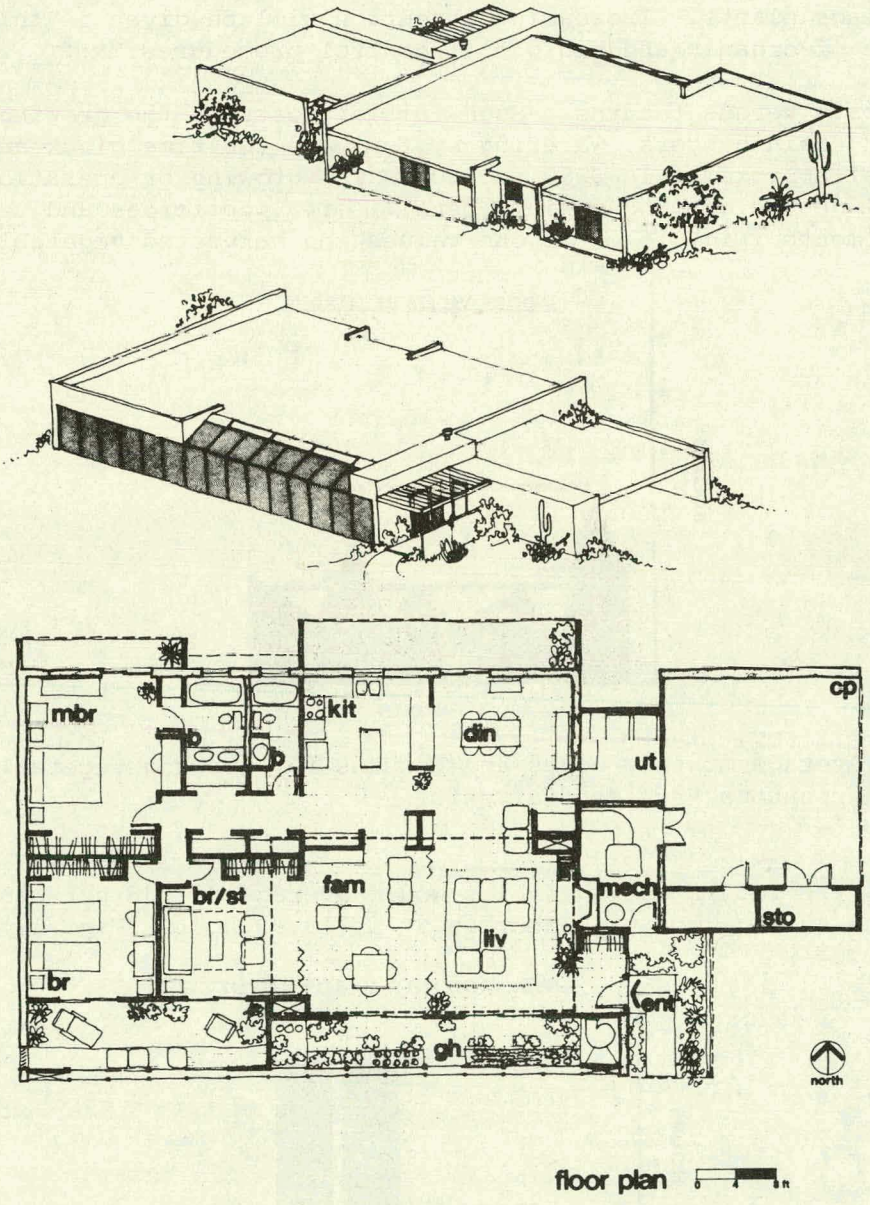



Fig. 18. Home using the attached greenhouse with an active ClearView collector, rockbed and one/two-stage evaporative cooling.

[1]Designs by Leslie Medlin, AIA, Tucson, Arizona.

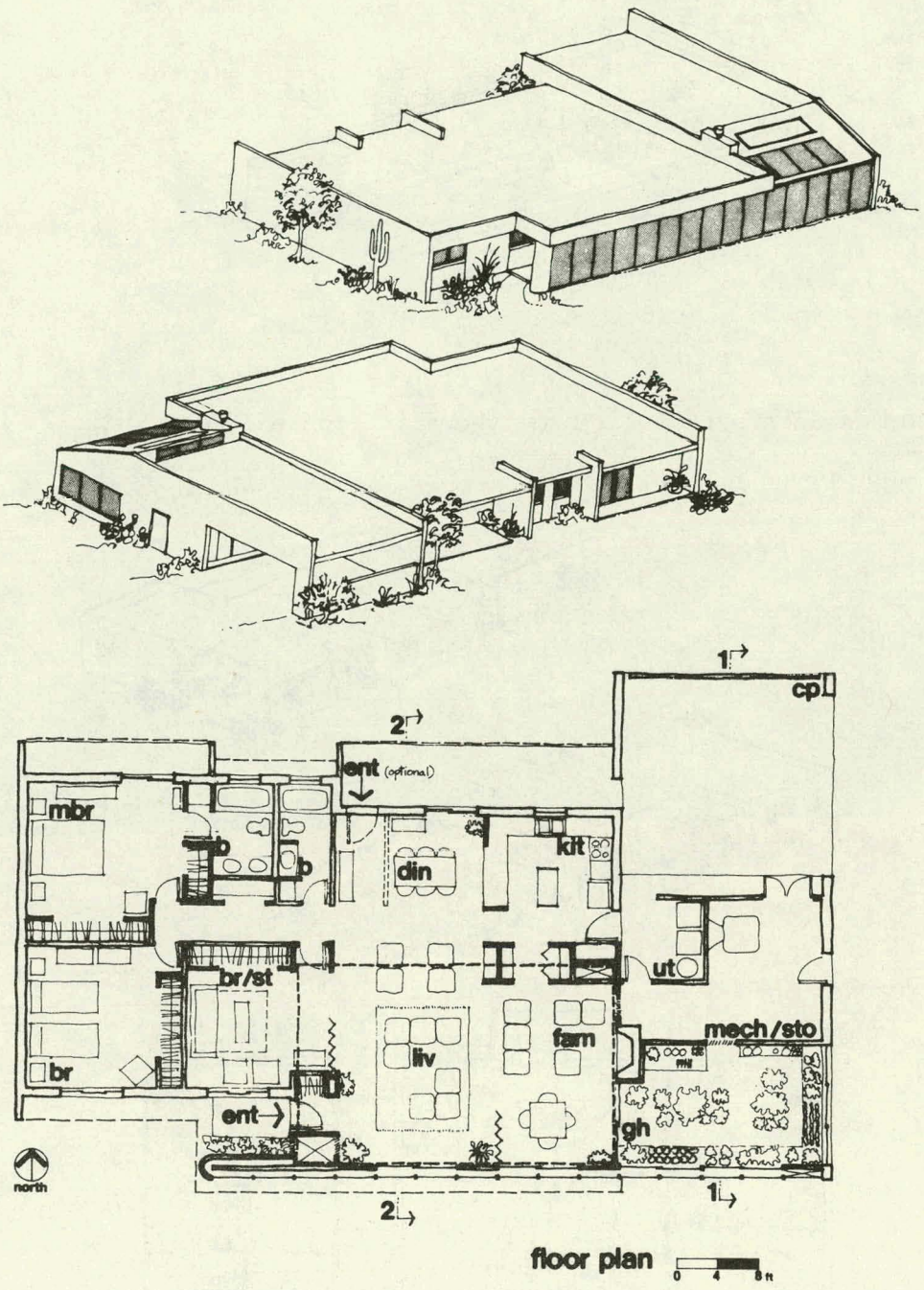



Fig. 19. A similar home using the attached greenhouse with an active ClearView collector and rockbed, which can be adapted to one/two-stage evaporative cooling.

The relatively simple duct system for this home is shown in Figure 20.

An oblique view and floor plan of a home using an attached greenhouse and windows for daytime heating, and external insulation of masonry walls to increase early morning minimum temperatures, is shown in Figure 21.

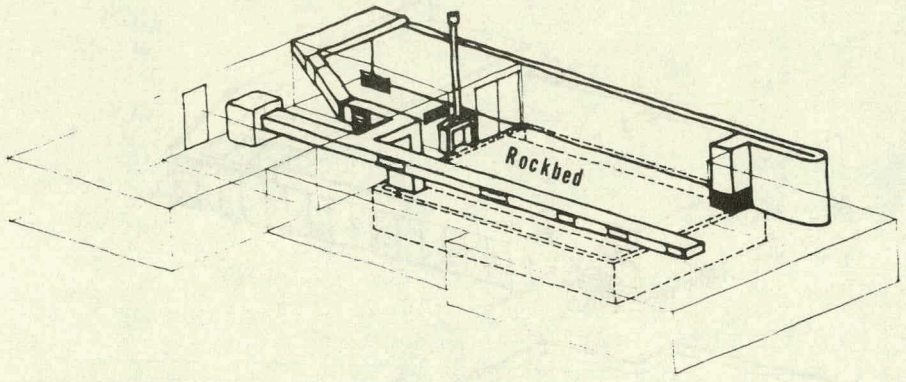



Fig. 20. A duct system for home shown in Figure 19.

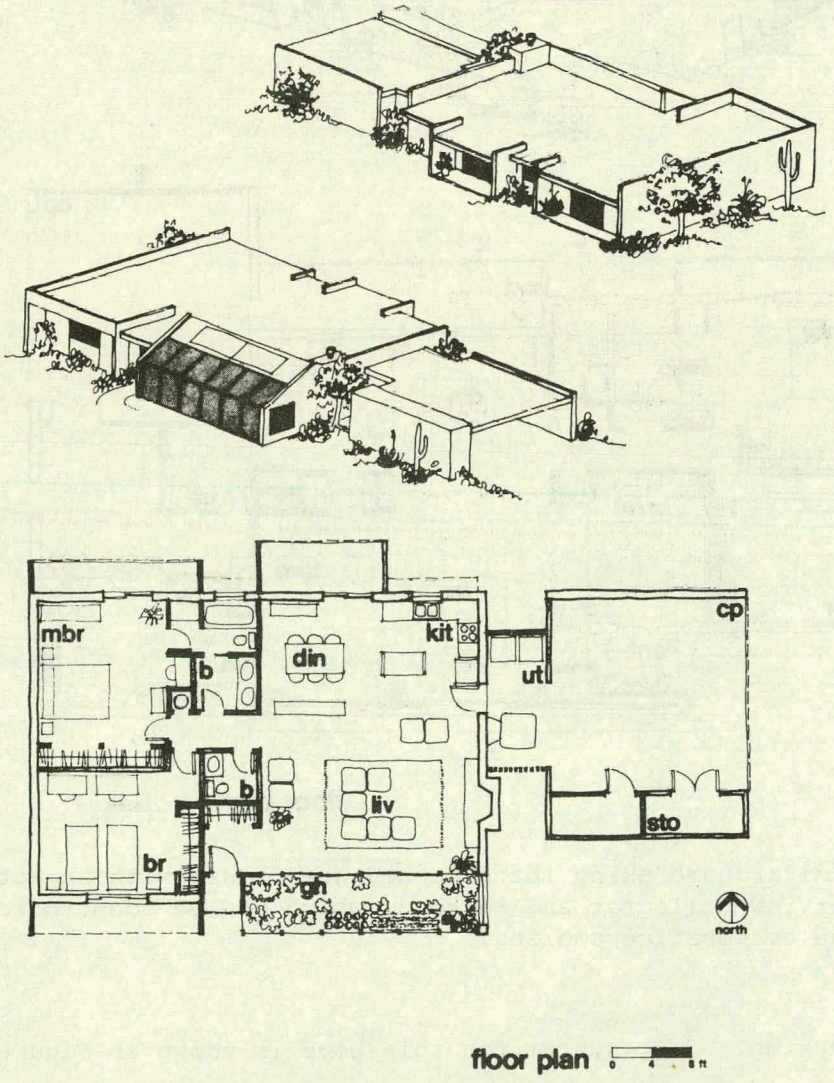



Fig. 21. Home using an attached greenhouse and windows for daytime heating and external insulation of masonry walls to increase early morning temperatures.

# APPENDIX I

## ANALYSIS AND PERFORMANCE OF THE CLEARVIEW COLLECTOR

### Derivation of Collector Equations

Methods for determining the equations which describe the performance of conventional flat-plate collectors and air heaters are presented in detail in the literature.[1,2,3] The equation describing the performance of the Clear-View collector is similar to those derived for other collectors, but has an additional term to account for heat transfer into the building:

$$q_a = F'F''[\alpha q_s - U_{Lo}(\bar{t}_a - t_o) - U_{Li}(\bar{t}_a - t_i)] \quad (1)$$

where $q_a$ is the energy gain by the airstream as it passes through the collector, Btu/(hr)(sq ft); F' is the collector efficiency factor, dimensionless; F" is the collector flow factor, dimensionless; $\alpha$ is the fraction of solar radiation incident on the outside of the collector, which is absorbed by the blade surfaces and includes allowance for reflection and absorption by the glass and reflection from the blades, dimensionless; $q_s$ is the solar radiation flux on the outside of the collector, Btu/(sq ft)(hr); $U_{Lo}$ and $U_{Li}$ are the overall heat loss coefficients to the outside and inside of the building, respectively, Btu/(sq ft)(hr)(°F); $\bar{t}_a$ is the mean air temperature in the collector, °F; and $t_o$ and $t_i$ are the outside and inside air temperatures, °F.

The terms in equation 1 are evaluated by writing energy balances around the various components of the collector and solving the resulting equations simultaneously. Figure 22 is a cut-away drawing of the collector showing the various surfaces and temperature designations.

In this analysis, the airflow will be considered parallel to the blades (horizontal), although the same analysis can also be used for flow upward or downward across the blades with only obvious modification.

An energy balance around the blade surface is given by:

Solar radiation absorbed by blade =

convection to airstream + radiation to glass surfaces

$$\alpha q_s = 2\frac{x_b}{y} h_{cb}(t_b - t_a) + 2\frac{x_b}{y}(Eh_r)_{b1}(t_b - t_1) + 2\frac{x_b}{y}(Eh_r)_{b2}(t_b - t_2) \quad (2)$$

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[1] Hottel, H. C. and A. Whillier, 1955, Evaluation of flat-plate solar collector performance, Trans. Conf. on Use of Solar Energy, 3, Tucson, Ariz., p 74-104.

[2] Bliss, R. W., 1959, The derivations of several "plate-efficiency factors" useful in the design of flat-plate solar heat collectors, *Solar Energy*, Vol. III, No. 4, p 55-64.

[3] Whillier, A., 1964, Performance of black-painted solar air heaters of conventional design, *Solar Energy*, Vol. VIII, No. 1, p 31-37.

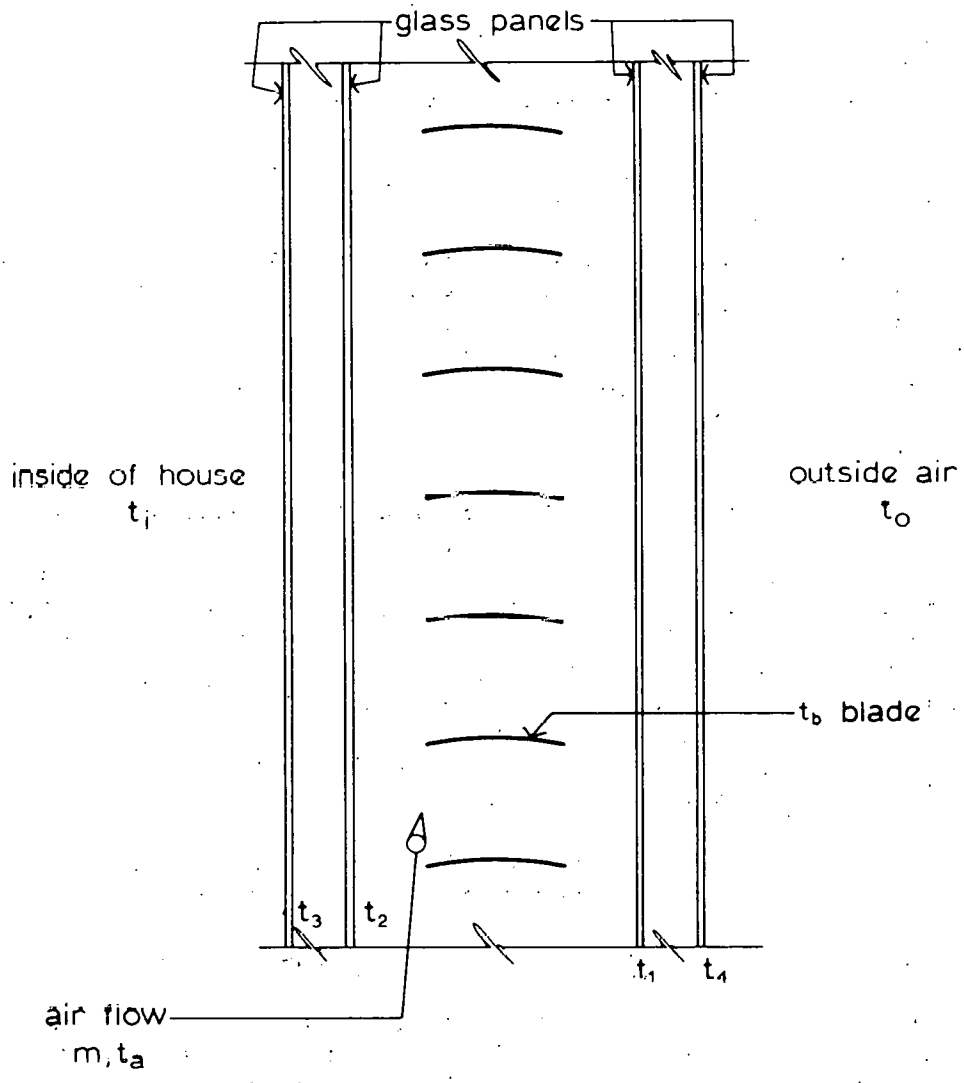



Fig. 22. Section of ClearView collector showing temperature locations.

Equation 2 is written for a differential element of length of the collector "dL" for which the various temperatures and coefficients can be considered constant. In this analysis, heat transfer by radiation will be treated using an equivalent heat transfer coefficient for radiation "$h_r$"[1], Btu/(sq ft)(hr)(°F). Under these conditions:

$$h_r = 4\sigma(\bar{T})^3$$

where $\bar{T}$ is the average of the absolute temperatures of the surfaces considered, °R; and $\sigma$ is the Stefan-Boltzmann Constant, Btu/(sq ft)(hr)(°R)$^4$. The term $Eh_r$ is the product of the overall radiation interchange factor and the radiation coefficient. E is a function of the emissivity and geometry of the various surfaces involved. Equation 2 is written for the

[1]McAdams, W.H., 1954, *Heat Transmission*, 3rd Ed., McGraw-Hill Book Co., Inc., New York, New York.

case where the emissivity of the blade bottom and top are equal. The blade temperatures are also assumed to be equal, so that no net blade-to-blade exchange occurs. Also, in equation 2, $\alpha q_s$ is the solar radiation transmitted by the glass and absorbed by the blades, but is referenced to a vertical surface for ease of computation. Hence each of the terms on the R.H.S. of 2 contains the term $2x_b/y$, which is the ratio of the blade surface area to that of a vertical plane.

For the airstream adjacent to the blade surface for the same element dL:

Temperature increase of the air =

convective gain from the blades - convective loss to the glass panes

$$m\, C_p\, dt_a = \left[2\frac{x_b}{y} h_{cb}(t_b - t_a) - h_{cg}(t_a - t_1) - h_{cg}(t_a - t_2)\right](HdL) \qquad (3)$$

where m is the flow rate of air through the collector, lb/hr; $C_p$ is the heat capacity of air, Btu/lb °F; $x_b$ is the blade width, ft; y is the distance between blades, ft; $h_{cb}$ is the convective heat transfer coefficient from the blade surfaces to the airstream, and $h_{cg}$ is the convective coefficient between the airstream and innermost glass panes, Btu/(sq ft)(hr)(°F); and H is the collector height, ft.

Similarly, balances around the innermost glass panes are:

Radiation from blade to glass + radiation from glass-to-glass + convection from air-to-glass = Radiation and convection through adjacent glass panes to inside (or outside) of house

$$2\frac{x_b}{y}(Eh_r)_{b1}(t_b - t_1) + (Eh_r)_{21}(t_2 - t_1) + h_{cg}(t_a - t_1) = U_{1o}(t_1 - t_o) \qquad (4)$$

$$2\frac{x_b}{y}(Eh_r)_{b_2}(t_b - t_2) + (Eh_r)_{21}(t_1 - t_2) + h_{cg}(t_a - t_2) = U_{2i}(t_2 - t_i) \qquad (5)$$

Equations 4 and 5 utilize combined heat loss coefficients, $U_{1o}$ and $U_{2i}$, for determining heat transfer from the glass surface through succeeding panes to the outside air (or that inside the building).

$$U_{1o} = \frac{1}{\frac{1}{(Eh_r)_{14} + h_{c14}} + \frac{1}{(Eh_r)_o + h_{co}}} \qquad (6)$$

$$U_{2i} = \frac{1}{\frac{1}{(Eh_r)_{23} + h_{c23}} \quad \frac{1}{(Eh_r)_i + h_{ci}}} \qquad (7)$$

These terms allow the analysis to be easily extended to any number of glass panes, as, for $U_{lo}$:

one pane: $$U_{lo} = (Eh_r)_o + h_{co} \tag{8}$$

two panes: See equation 6.

"n" panes: $$U_{lo} = \frac{1}{\sum_{j=1}^{n-1}\left[\frac{1}{(Eh_r) + h_c}\right]_j + \frac{1}{(Eh_r)_o + h_{co}}} \tag{9}$$

The term $(Eh_r)_{21}(t_2 - t_1)$ in equations 4 and 5 represents radiation transferred between the two innermost glass panes of the collector, across the blades. Such exchange occurs primarily because of the difference between the temperatures inside and outside the building. The term has little effect on overall collector performance and will be ignored in determining collector efficiency.

Equations 2 - 5 can be combined to yield the expression:

$$\frac{m\,C_p}{H}\frac{dt_a}{dL} = F'[\alpha q_s - U_{Lo}(t_a - t_o) - U_{Li}(t_a - t_i)] \tag{10}$$

The equations for the overall loss coefficients are

$$U_{Lo} = \frac{1 + \dfrac{h_{cg}}{\dfrac{x_b}{2\frac{}{y}(Eh_r)_{b1}F'}}}{\dfrac{1}{U_{lo}} + \left[\dfrac{1}{\dfrac{x_b}{2\frac{}{y}(Eh_r)_{b1}}}\right]\left[1 + \dfrac{h_{cg}}{U_{lo}}\right]} \tag{11}$$

$$U_{Li} = \frac{1 + \dfrac{h_{cg}}{\dfrac{x_b}{2\frac{}{y}(Eh_r)_{b2}F'}}}{\dfrac{1}{U_{2i}} + \left[\dfrac{1}{\dfrac{x_b}{2\frac{}{y}(Eh_r)_{b2}}}\right]\left[1 + \dfrac{h_{cg}}{U_{2i}}\right]} \tag{12}$$

while the collector efficiency factor is:

$$F' = \left\{ 1 + \left[ \frac{\dfrac{1}{\dfrac{1}{U_{lo}} + \left[\dfrac{1}{2\frac{x_b}{y}(Eh_r)_{b1}}\right]\left[1 + \dfrac{h_{cg}}{U_{lo}}\right]} + \dfrac{1}{\dfrac{1}{U_{2i}} + \left[\dfrac{1}{2\frac{x_b}{y}(Eh_r)_{b2}}\right]\left[1 + \dfrac{h_{cg}}{U_{2i}}\right]}}{2\frac{x_b}{y} h_{cb} + \dfrac{\left(\frac{h_{cg}}{U_{lo}}\right)}{\dfrac{1}{U_{lo}} + \left[\dfrac{1}{2\frac{x_b}{y}(Eh_r)_{b1}}\right]\left[1 + \dfrac{h_{cg}}{U_{lo}}\right]} + \dfrac{\left(\frac{h_{cg}}{U_{2i}}\right)}{\dfrac{1}{U_{2i}} + \left[\dfrac{1}{2\frac{x_b}{y}(Eh_r)_{b2}}\right]\left[1 + \dfrac{h_{cg}}{U_{2i}}\right]}} \right] \right\}^{-1} \tag{13}$$

These expressions are rather onerous to apply, as the free convection coefficients, $h_{c14}$ and $h_{c23}$, and the radiative coefficient ($h_r$), are functions of temperature. Hence, for a given set of conditions, it is necessary to iteratively solve equations 2 - 5, adjusting the various coefficients after each iteration, until a stable solution results.

The collector flow factor in equation 1, F", results from the integration of equation 10. Defining:

$$G = \frac{m}{HL} \tag{14}$$

and

$$N_t = \frac{F'(U_{Lo} + U_{Li})}{GC_p} \tag{15}$$

$N_t$ is analogous to the "number of transfer units" used in heat exchanger design.

By integrating equation 10 and rearranging:

$$F'' = \frac{2}{N_t}\left[\frac{(1 - e^{-N_t})}{(1 + e^{-N_t})}\right] \tag{16}$$

where $\bar{t}_a$ is the arithmetic mean air temperature in the collector $\frac{1}{2}(t_{a1} + t_{a2})$ for use in equation 1.

For computation, it is often more convenient to express equation 1 in terms of the initial air temperature, $t_{a1}$, in which case:

$$F''_{a1} = \left(\frac{1}{N_t}\right)(1 - e^{-N_t}) \tag{17}$$

In general, it is more correct to evaluate the coefficients at the true, $\bar{t}_{a,t}$, rather than arithmetic, mean air temperature in the collector. If

$$\bar{t}_{a,t} = t_{a1} + C_a \Delta t_a \tag{18}$$

then $C_a$ is given by

$$C_a = [1/(1 - e^{-N_t})] - (1/N_t) \tag{19}$$

When $\bar{t}_{a,t}$ is used in equation 1, then F" = 1.

Figure 23 shows how F", $F''_{a1}$ and $C_a$ vary with the number of transfer units. At high airflows, and consequently low values of $N_t$, $C_a \simeq \frac{1}{2}$, and $\bar{t}_{a,t}$ becomes the arithmetic mean temperature, and F" approaches 1.0.

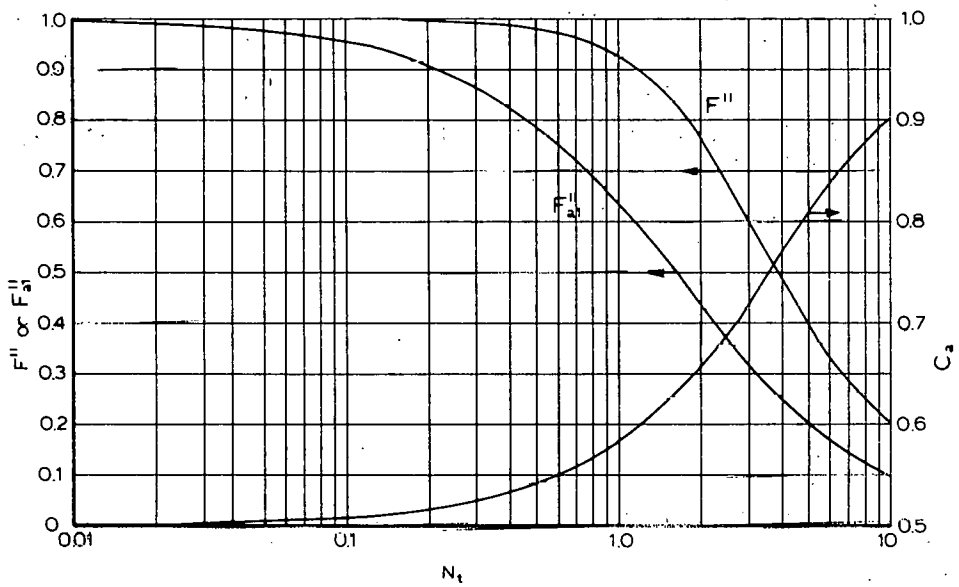



Fig. 23. Collector flow factors.

Evaluation of Terms in the Equations

The convective coefficient at the outmost glass can be calculated for smooth surfaces[1] as:

$$h_{co} = 0.9 + 0.3V_w \tag{20}$$

where $V_w$ is the wind velocity, mph.

[1]Hutchinson, F. W., 1962, *Heating and Humidifying Load Analysis*, Ronald Press, New York, New York, p 109.

Under most conditions, the convective coefficients between the blades and airstream and inner glass panes (1 and 2) can be assumed equal and calculated using an equivalent diameter and the Dittus-Boelter equation[1]; that is,

$$D_e = \frac{2x_g}{1 + (\frac{x_b}{y})} \tag{21}$$

then for air at 100°F:

$$h_{cb} = h_{cg} = 0.0103\left[\frac{1 + (\frac{x_b}{y})}{x_g}\right]^{0.2} V_a^{0.8} \tag{22}$$

where $V_a$ is the air velocity, ft/min and $x_g$ is the distance between panes 1 and 2, ft.

At low airflows, free convection from the blinds may increase the coefficient at the blind surface above that predicted by equation 22. In general, it is recommended that the Reynold's number[1] be calculated using the equivalent diameter, $D_e$, from equation 21. If the flow is turbulent, equation 22 can be applied; if laminar or transitional, other relationships given in the literature can be applied.[1] If the flow is not turbulent, it is further recommended that the free convection coefficient be calculated; as recommended by McAdams[1], the higher value should be used.

Heat transfer into the building from the innermost pane can be assumed to occur by free convection and radiation from the pane. The free convection coefficient for a tall vertical plate is taken from McAdams[1], page 173, as:

$$h_{ci} = 0.19\Delta t^{1/3} \tag{23}$$

Free convection heat transfer coefficients, $h_{c14}$ and $h_{c23}$, between panes may be calculated by an equation from the literature[2] for heat flow across an air gap between vertical plates as:

$$h_c = 0.126\Delta t^{1/4} \tag{24}$$

With regard to long wave radiation heat transfer, the interchange factors at the inside and outside glass panes, $E_i$ and $E_o$, may be taken as the emissivity of glass, $\varepsilon_g$. This is equivalent to assuming that the indoors and outdoors are black bodies at $t_i$ and $t_o$, respectively. No allowance has been made for the fact that the effective radiative sky temperature

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[1] *Op. cit.*, McAdams.

[2] Hottel, H. C. and B. B. Woertz, 1942, Performance of flat-plate solar heat collectors, Trans. ASME 64, p 91-104.

is below that of the air at ground level;[1] this is offset by the fact that the soil in front of the collector absorbs solar radiation, and its temperature exceeds the air temperature.

The interchange factors between the two innermost and outermost pairs of glass panes, $E_{14}$ and $E_{23}$, may be calculated using the equation[2] for infinite parallel plates:

$$E_{14} = E_{13} = \frac{1}{(\frac{2}{\varepsilon_g}) - 1} \tag{25}$$

Infrared radiation between the blades and inner glass panes is treated using techniques given in the literature.[2] A view factor, "F", can be calculated for blade-to-blade transfer using Hottel's "string" technique for areas of infinite extent in one direction. While no net blade-to-blade exchange occurs in this case, the blade-to-blade view factor is still required for the analysis. If the angle of the blades with the horizontal is $\beta$, then:

$$F_{bb} = \tfrac{1}{2}[\sqrt{1 - (2\ y/x_b)\mathrm{Sin}\beta + (y/x_b)^2} + \sqrt{1 + (2\ y/x_b)\mathrm{Sin}\beta + (y/x_b)^2}\ ] - (y/x_b) \tag{26}$$

Blade-to-wall and wall-to-wall factors are then calculated with simple area relationships and considerations of symmetry:

$$F_{bb} + F_{b1} + F_{b2} = 1$$

$$F_{b1} = F_{b2} = \tfrac{1}{2}(1 - F_{bb}) \tag{27}$$

and $A_b F_{b1} = A_g F_{1b} = A_g F_{2b}$

where $A_b$ is the blade area and $A_g$ is the glass area, sq ft.

$$F_{1b} = (x_b/y)F_{b1}$$

$$F_{1b} + F_{1b} + F_{12} = 1;\ F_{12} = 1 - 2F_{1b} = 1 - 2(x_b/y)F_{b1} \tag{28}$$

For standard venetian blinds, $x_b/y = 1.185$ and $F_{bb} = 0.465$, $F_{b1} = F_{b2} = 0.268$ and $F_{12} = 0.366$.

The overall radiation interchange factors (E) can be calculated using

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[1] Bliss, R. W. 1961, Atmospheric radiation near the surface of the ground: a summary for engineers, *Solar Energy*, Vol. V, No. 3, p 103-120.

[2] *Op. cit.*, McAdams.

values for the various emissivities (and consequently reflectances) by Hottel's technique.[1] For standard venetian blinds, if the emissivities of the blind surfaces and glass are taken as 0.95, then $E_{bb} = 0.428$, $E_{b_1} = E_{b_2} = 0.252$, and $E_{12} = 0.338$. If the blade surfaces were coated with a selective coating[2] with $\varepsilon_b = 0.11$, then $E_{bb} = 0.007$, $E_{b_1} = E_{b_2} = 0.050$, and $E_{12} = 0.578$. The effect of such a coating on overall collector performance will be described in a later section.

To calculate $\alpha q_s$, the total solar radiation incident on the collector should be separated into its diffuse, $q_{s\delta}$, and direct, $q_{sd}$, components.[3] The angle of incidence for direct radiation striking the collector can be calculated[3] given the solar time, latitude, and declination. The transmission of direct radiation through glass can be determined from curves, such as Figure 24, for the patio door glass used in these studies, or

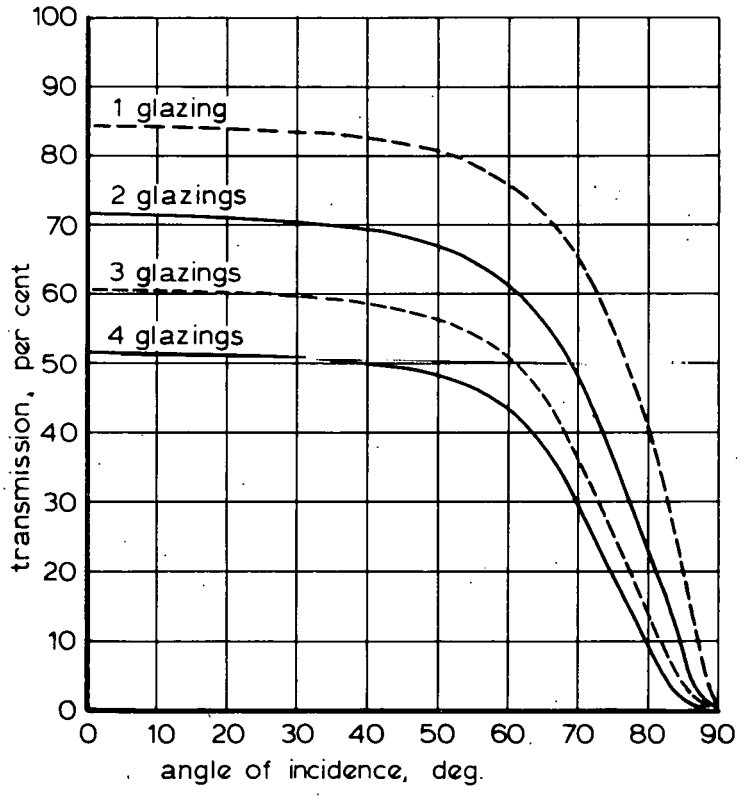



Fig. 24. Transmittance of 3/16-inch thick patio door glass.

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[1] *Op. cit.*, McAdams.

[2] Tabor, H., *et al*, 1964, Further studies on selective black coatings, Proceedings, U.N. Conference on New Sources of Energy, 4, p 618.

[3] Duffie, J. A. and W. A. Beckmann, 1974, *Solar Energy Thermal Processes*, John Wiley & Sons, New York, New York.

Figure 25 for low-iron or water white glass. These curves were calculated using Stokes'[1] equation, with extinction coefficients of 0.45/in, experimentally determined for the patio door glass, and 0.1/in for water white glass.[2] The transmission of diffuse radiation, including diffusely

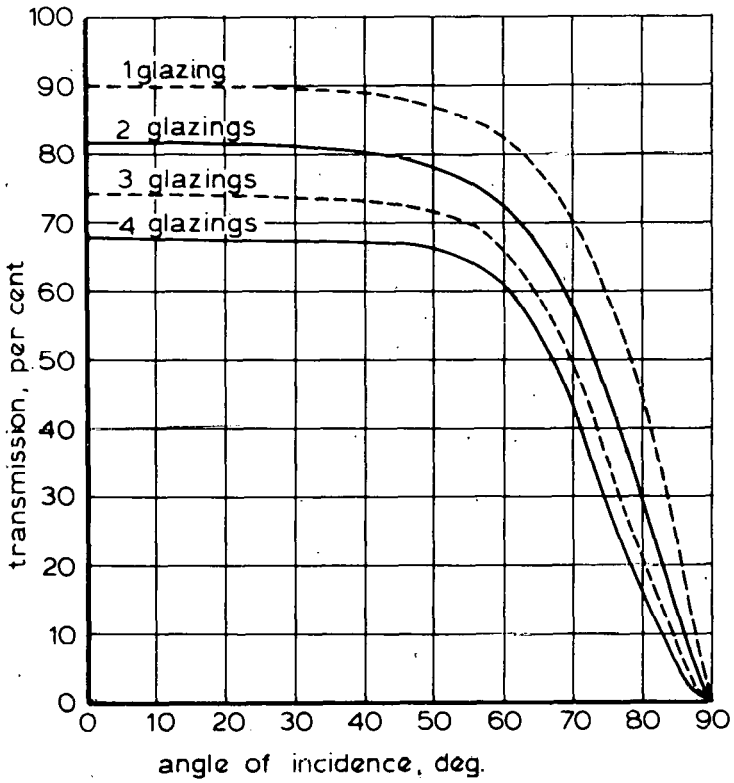



Fig. 25. Transmittance of 3/16-inch thick water white glass.

reflected solar radiation from the surroundings in front of the collector, is calculated from Figure 24 or 25 by assuming that the radiation strikes the glass at an effective angle of incidence of 58°.[3] The radiation striking the blind surface which is absorbed is determined by the coating on the blind surface, and is usually a function of the angle of incidence. In these studies, a dark brown paint was used[4] which had a slightly lower absorptivity than black, 0.94 at 50° and 0.96 at 10° angle of incidence, but had a more aesthetic appearance. For direct radiation, the angle can be determined when the tilt of the blade is specified and the absorptivity

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[1]Stokes, G. G., 1860-1862, On the intensity of the light reflected from or transmitted through a pile of plates, Proc. Royal Soc., London, 11, 545-556.

[2]*Op. cit.*, Duffie and Beckman.

[3]Zarem, A. M. and D. D. Erway, 1963, *Introduction to the Utilization of Solar Energy*, McGraw-Hill Book Co., Inc., New York, New York, p 94.

[4]Aqua-paque®, mustang brown, product of Pioneer Paint & Varnish, Co., 438 W. Congress. Tucson, Arizona.

determined. Absorption of diffuse radiation is estimated by using the absorptivity of the surface at 58° and multiplying this value by $2F_{1b}$ from equation 28 to allow for the fact that a large component of the diffuse radiation passes through the blinds without striking the blades. Shading from the structural members supporting the glass and blinds can be appreciable and may be readily calculated as explained in the literature.[1] Shading may be assumed to block the direct radiation, but not the diffuse.

To summarize the solar absorption calculations:

$$\alpha q_s = \alpha_p \tau_{gd} f_u q_{sd} + \alpha_p \tau_{g\delta} (2F_{1b}) q_{s\delta} \tag{29}$$

where $\alpha_p$ is the absorptivity of the paint, $\tau_g$ is the overall transmission of the glass panes, $\tau_{gd}$ for direct and $\tau_{g\delta}$ for diffuse radiation, and $f_u$ is the fraction of the collector unshaded.

Application of the Equations

Best results will be obtained using equation 1, if the coefficients are determined rigorously for the case at hand. However, for estimating purposes, the following approximations may be used:

Ranges of variables for equations 30-32:

$$100° < \bar{t}_a < 150°F$$
$$0 < t_o < 50°F$$
$$t_i = 72°F$$
$$0 < V_w < 20 \text{ mph}$$

$$U_{Lo} \cong \left[(0.365\, V_w + 2.09)^{-1} - 0.54(\bar{t}_{ao}/100) + 1.62\right]^{-1} \tag{30}$$

$$U_{Li} \cong 0.416 + 0.155(\bar{t}_{ao}/100) + 0.059(\Delta t_{ao}/100) \tag{31}$$

$$F' \cong 0.911 - 0.049(\bar{t}_{ao}/100) \tag{32}$$

where $\bar{t}_{ao} = 0.5(\bar{t}_a + t_o)$ and $\Delta t_{ao} = \bar{t}_a - t_o$.

These expressions approximate the exact solutions to within ±3% in the specified temperature-wind velocity regime. However, their use outside of those limits may lead to serious errors.

Equations 30-32 are based on standard venetian blinds ($x_b/y = 1.185$) placed between glass panes 3 inches apart. The air velocity was taken as 214 fpm, the upper limit used experimentally.

Values for $\alpha q_s$ for use in equation 1 should be determined for each specific

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[1] *Op. cit.*, Hottel and Woertz.

location under consideration. Since solar radiation values for different locations throughout the world are usually given in terms of horizontal radiation, it is generally necessary to convert the data to values for a vertical, south-facing surface.[1,2] This operation requires some knowledge of the ground reflectance in front of the collector; Liu and Jordan[1,2] suggest values of 0.2 when there is no snow and 0.7 when there is snow cover. In the case of the prototype tested here, the reflectance was in the range of 0.4 to 0.5. Convenient tabulated data[3] are also available in the literature for the case of zero ground reflectance.

Typical clear day values of $\alpha q_s$ for Tucson, Arizona, for a ground reflectance of 0.2, are given in Figure 26 for the usual heating season, while

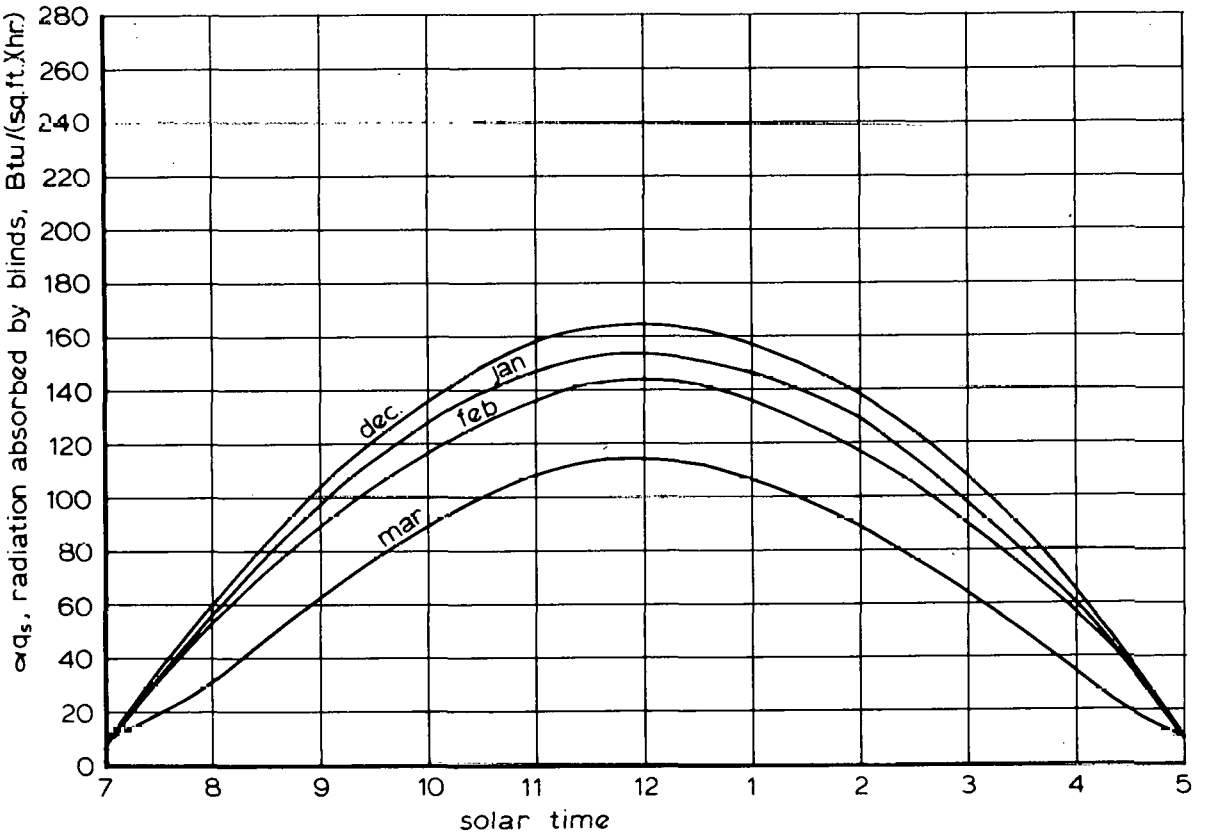



Fig. 26. Hourly values of solar radiation absorbed by the blinds; clear day data for Tucson, Arizona; ground reflectance of 20%.

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[1]Liu, B. Y. H. and R. C. Jordan, 1960, The interrelationship and characteristic distribution of direct, diffuse and total solar radiation, *Solar Energy*, 4, No. 3.

[2]Liu, B. Y. H. and R. C. Jordan, 1963, The long-term average performance of flat-plate solar energy collectors, *Solar Energy*, 7, 53.

[3]Hill, J. E. and T. Kusuda, 1974, Method of testing for rating solar collectors based on thermal performance, National Science Foundation Interim Rpt. NBSIR-74-635, 59 pp.

Figure 27 gives integrated daily values for the year. The shading factor, $f_u$, was calculated based on standard panels of patio door glass 46" x 92" (unframed), with the blinds 2¼" from the edge of the shading member.

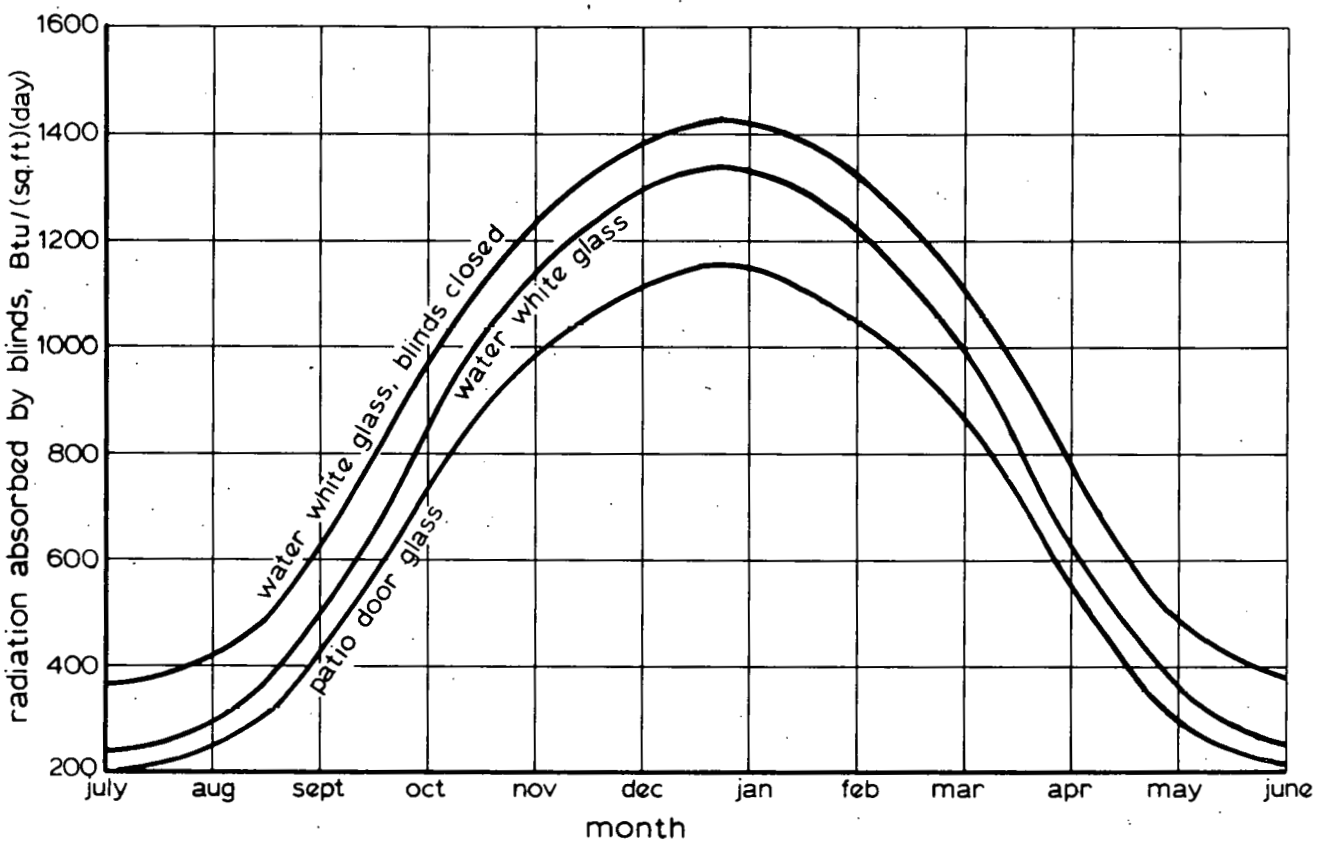



Fig. 27. Daily solar radiation absorbed by blinds; clear-day data for Tucson, Arizona; ground reflectance of 20%.

The following example illustrates the use of equations 30-32 in conjunction with Figure 26.

Example: Estimate the temperature rise in the airstream of a ClearView collector at noon in December if the inlet temperature is 100°F, the room temperature 72°F, the outdoor temperature 32°F, the wind velocity 10 mph, and the airflow rate through the collector 20 lb/(hr)(sq ft of collector).

Solution: From Figure 26, $\alpha q_s$ = 165 Btu/(sq ft)(hr). For a first approximation, take $\bar{t}_a$ = 100°F, $\Delta t_{ao}$ = 100 - 32 = 68, $\bar{t}_{ao}$ = 66. Then:

$U_{Lo} \cong 0.695$ (from equation 30)

$U_{Li} \cong 0.558$ (from equation 31)

$F' \cong 0.879$ (from equation 32)

The number of transfer units is then, from equation 15 with $C_p$ = 0.24 Btu/lb °F:

$$N_t = (0.879)(0.695 + 0.558)/(0.24)(20) = 0.229$$

From Figure 23, or equation 17, $F''_{a1}$ = 0.894 and, using the form of equation 1 employing the inlet air temperature ($t_{a1}$) instead of the average temperature:

$$q_a = F'F''_{a1}[\alpha q_s - U_{Lo}(t_{a1} - t_o) - U_{Li}(t_{a1} - t_i)]$$

$$= (0.879)(0.894)[165 - (0.695)(100 - 32) - (0.558)(100 - 72)]$$

$$= 80.2 \text{ Btu/(sq ft)(hr)}$$

Since $q_a = G\, C_p \Delta t_a$, then $\Delta t_a$ = 16.7; from Figure 23 or equation 19, $C_a$ = 0.519 and $\bar{t}_{a,t}$ = 108.7°F, then $\Delta t_{ao}$ = 76.7, $\bar{t}_{ao}$ = 70.3°F.

For the next iteration: $U_{Lo} \cong 0.707$

$U_{Li} \cong 0.570$

$F' \cong 0.877$

From equation 1:

$$q_a = (0.877)(1.0)[165 - (0.707)(108.7 - 32) - (0.570)(108.7 - 72)]$$

$$= 78.8 \text{ Btu/(sq ft)(hr)}$$

$$\Delta t_a = (78.8)/(20)(0.24) = 16.4$$

or the collector outlet temperature will be approximately 116°F. A more rigorous approach using equations 1-16 gives $t_{a2}$ = 116.3°F.

Experimental Results

Figure 28 shows a comparison of experimental with calculated values for the air temperature leaving the solar collector on December 21, 1976. The airflow rate through the collector was 413 CFM and the collector area 94.6 sq ft. The calculated values are slightly higher in the morning and lower in the afternoon; however, the results are sufficiently accurate for most purposes. The calculated energy gain during the operating period was 681 Btu/sq ft, while the actual gain was 685 Btu/sq ft. Had the operating period been extended as shown by the dashed lines for a longer period of heat collection, the energy gain could have been increased to 731 Btu/sq ft or by approximately 7%. Note that the inlet air temperature increases during the day, due to heating of the rockbed.

Table 3 shows the experimental performance of the collector during the winter of 1976-77. The outdoor temperatures are averages based on the period of operation only, while the solar radiation is the total for the day

Table 3. Collector Performance

| Date | Air-flow (CFM) | Operating period (hrs) | Energy collected (Btu/sq ft) | Solar radiation (Btu/sq ft) | Temperature, °F | | Wind velocity (mph) |
|---|---|---|---|---|---|---|---|
| | | | | | Outdoor | Collector | |
| 12-20-76 | 413 | 7 | 639 | 1874 | 58.3 | 89.4 | 10.1 |
| 21 | | 7 | 685 | 1943 | 57.3 | 88.9 | 11.0 |
| 24 | | 6½ | 690 | 1990 | 59.7 | 92.5 | 8.1 |
| 25 | ↓ | 5 | 589 | 2030 | 56.9 | 94.6 | 6.6 |
| 1- 9-77 | | 6 | 687 | 2048 | 46.1 | 85 | 6.2 |
| 10 | | 7 | 722 | 2026 | 49.8 | 85.5 | 4.8 |
| 11 | | 6½ | 689 | 2038 | 53.1 | 86.7 | 5.7 |
| 12 | 413 | 6½ | 676 | 1957 | 58.4 | 87.6 | 7.6 |
| 15 | 323 | 7 | 708 | 2031 | 55.4 | 80.2 | 6.2 |
| 16 | ↓ | 5 | 542 | 2043 | 64.3 | 87.9 | 7.4 |
| 31 | 323 | 6½ | 641 | 2014 | 61.3 | 82.7 | 7.0 |
| 2- 2-77 | 254 | 7 | 668 | 1891 | 56.6 | 90.0 | 6.7 |
| 5 | ↓ | 7½ | 661 | 1974 | 66.0 | 94.0 | 8.7 |
| 7 | 254 | 7 | 613 | 1947 | 64.7 | 93.3 | 5.7 |
| 13 | 164 | 6½ | 597 | 1974 | 67.8 | 95.8 | 7.7 |
| 14 | ↓ | 8 | 669 | 1975 | 67.6 | 94.1 | 7.3 |
| 16 | | 6½ | 590 | 1981 | 75.5 | 96.6 | 7.0 |
| 17 | 164 | 8 | 639 | 2007 | 78.5 | 98.8 | 7.9 |

measured on the plane of the collector. The wind velocity data were obtained from the Tucson International Airport, very near the test site, and the values are 24-hour averages. The energy collected is that delivered to the rockbed, and not the total energy delivered to the system, which would also include that transferred into the room behind the collector. The solar radiation shown in Table 3 is higher than one would expect from tabulated values for this latitude (32°) given in the literature[1] for a south-facing, vertical surface:

| | |
|---|---|
| December 21 | 1794 Btu/sq ft |
| January 21 | 1779 Btu/sq ft |
| February 21 | 1644 Btu/sq ft |

The higher experimental solar radiation values are due to the relatively high reflectance of the surroundings in front of the collector. However, this reflected contribution is predominantly diffuse radiation, which is not well utilized by this collector with the blind blades in the open position.

Figure 29 shows additional data collected on January 12, 1977, when the blind

[1] *Op. cit.*, Hill and Kusuda.

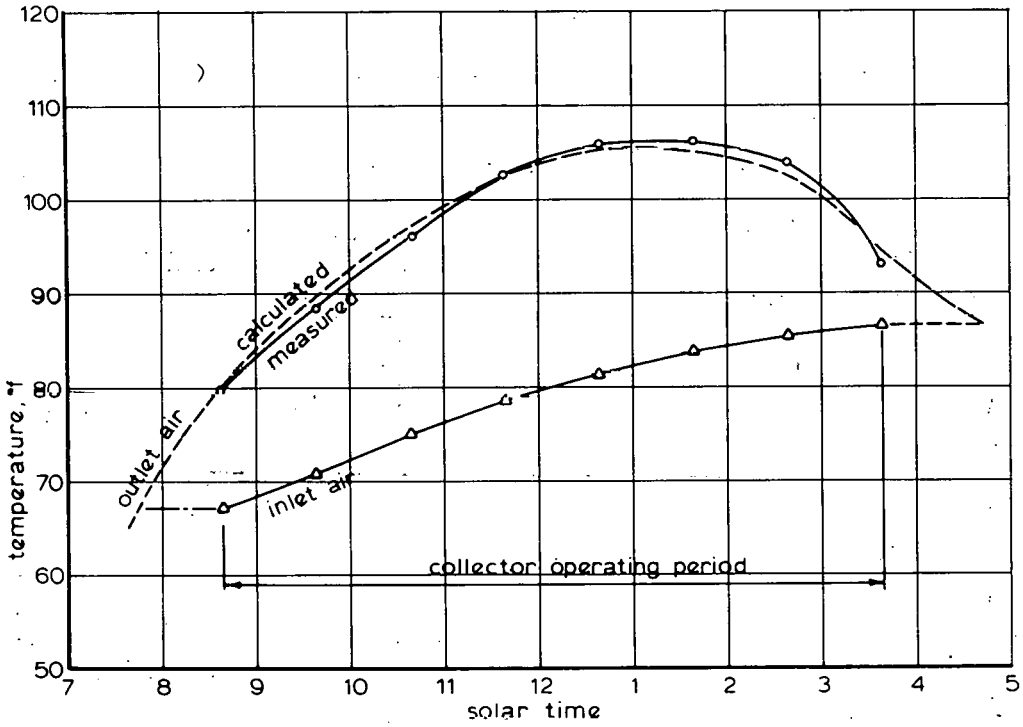



Fig. 28. Comparison of calculated and experimental results; 12-21-76, solar radiation = 1943 Btu/(sq ft)(day), mean wind velocity = 14.7 mph, mean outdoor temperature = 57.3°F, mean indoor air temperature = 72.6°F, collector airflow = 4.37 cu ft/sq ft of collector.

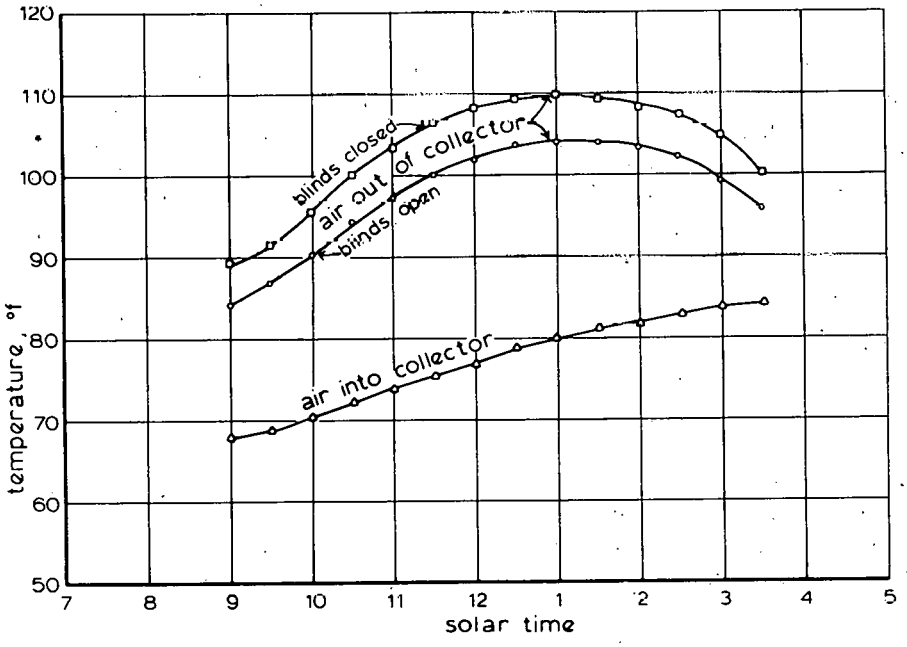



Fig. 29. Effect of blind closure on collector performance; 1-12-77, solar radiation = 1957 Btu/(sq ft)(day), mean wind velocity = 6.2 mph, mean outdoor temperature = 58.4°F, mean indoor temperature = 75.8°F, collector airflow = 4.37 cu ft/sq ft of collector.

blades were alternatively opened and closed, with sufficient time allowed for stabilization in each case. This gives a direct comparison of the efficiency of the collector with the blinds open and closed. With the blinds open, the energy collected was 676 Btu/sq ft; in the closed configuration, the amount was 852 Btu/sq ft or an increase of 26% to the rockbed. In effect, the occupant of the room can control, to a limited extent, the partition of energy between the room and the rockbed.

Improving Collector Efficiency

In the example of Figure 28, only around 56% of the solar energy striking the outside of the collector was absorbed by the blind surface. This figure can be improved by using "water white" or low-iron glass for the two outermost panes of glass. Figure 30 shows the calculated performance of collectors having patio door glass and water white glass under the same circumstances, for December 21 conditions. The water white glass collector gains approximately 18% more energy. Figure 27 shows the effect on solar absorption for the entire year, with a 20% ground reflectance, and also presents the case of a collector using water white glass with the blinds closed. The latter case would probably be the maximum collection attainable.

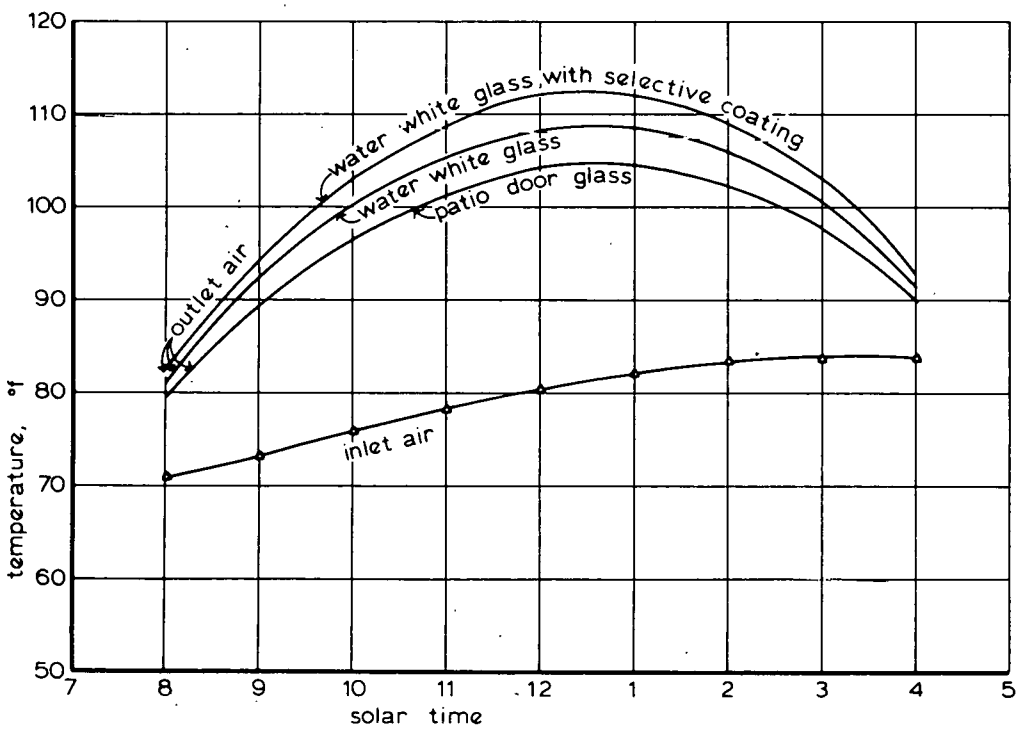



Fig. 30. Calculated effect on collector performance of water white glass and selective coating on the blade; $t_i$ = 72°F, $t_o$ = 55°F, $V_w$ = 7.2 mph (constant during operation); inlet temperatures from 2-7-77 data; solar radiation for Dec. 21, 32° latitude, zero ground reflectance; collector airflow = 4.37 cu ft/sq ft of collector.

Low reflectance coatings[1] on the glass could appreciably reduce reflection losses and improve collector efficiency; however, low reflective glass is not commercially available in large sheets, and is likely to be prohibitively expensive when available.

A further possibility for increased efficiency would be the use of a selective coating on the venetian blind blades. The top curve of Figure 30 would result if the blades were coated with a material having a solar absorptivity of 0.94 and a long wave emissivity of 0.11, mentioned earlier. Approximately 13% more energy would be gained by the airstream if the selective coating were used, relative to the case with water white glass alone. The selective coating is not as effective for increasing the efficiency in this collector as it would be for one operating at higher temperatures.[2]

Tilting the collector to a more favorable angle for solar energy absorption could also increase the energy gain; however, the cost of the unit would be greatly increased.

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[1] Thomsen, S. M., 1951, Low reflection films produced on glass in a liquid fluosilicic acid bath, *RCA Review*, March, p 143-149.

[2] *Op. cit.*, Zarem and Erway, p 85.

# APPENDIX 2

## ECONOMIC CONSIDERATIONS

### The Attached Greenhouse

The estimation of cost and potential savings is fraught with pitfalls. On new construction, the extra cost of glazed greenhouse walls and roofs (replacing standard walls and roof) can be approximately $2.00/sq ft installed for a wood frame, double-glazed, tempered patio door glass (with sealed dead air space containing a dessicant) installation. The associated extra ducts and fans to distribute heat, as well as louvers, etc., could cost approximately $500. Thus, the added cost on a new house of an 8 x 20-foot attached greenhouse could reach $1,500. Lower cost methods are available, but have the hidden cost of increased maintenance and replacement of glazing material. If evaporatively-cooled air from the home is used to cool the greenhouse, and a passive design is used to heat the greenhouse in mild climates, the cost of cooling and heating can be extremely low.

It is difficult to give a meaningful general description of the value of the heat delivered by the greenhouse to the main house. This depends on the usability of the heat by the house (that is, are the other windows of the house ample to heat it?), and the amount of heat absorbed by the walls and floor of the greenhouse itself, which depends on its design. Basically, if the homeowner likes to grow fresh vegetables of high quality, or likes the greenhouse for other reasons, he would be well advised to incorporate the greenhouse into the home heating system. A person who does not really like to grow plants should use some other type of daytime hot air collector, if his windows do not supply adequate heat on most winter days.

The prior cost for attached greenhouses on new homes could also be applied to retrofit applications, if the greenhouse is considered added usable area. In this case, the extra cost of glazed construction is balanced by the advantage of heat production, vegetable production, and intangibles such as, whether or not the homeowner likes greenhouses.

### ClearView Collector and Rockbed

Estimated costs of the ClearView collector system with two-stage evaporative cooling, from an analysis of a 2,000 sq ft typical Tucson dwelling of conservative design, with a very large rockbed (2,250 cu ft), a 468 sq ft (glass area) ClearView collector, and a 12+ hour two-stage evaporative cooling capacity are:

| | |
|---|---|
| collector | $ 3,000 |
| rockbed | 4,500 |
| ducts, dampers, controls | 2,500 |
| | $10,000 |

At 8% interest over 30 years, the additional monthly payment is $73.38 ($880/year). Compared to a resistance-heated, air-conditioned home, the utility savings are approximately $400 per year at present costs.

Additional cost reductions are realized from the standard 1976 Federal Income Tax deduction for interest paid. Initially, approximately $800 of the yearly $880 additional payment will be interest. In the lowest tax bracket (32%) at $20,000 per year, $256 of the $880 is not paid as income tax and hence is deducted from the $880. Since this comparison is against an air-conditioned home, a payment for the $1,500 installed cost of the air conditioner (not including ducts) over its average 12-year life (8%) is $194.88 and is deducted from the $880. Also, according to local repairmen, air conditioners require a new $500 compressor every six years, on the average, at $105.24 (@8%) per year in payments. Thus, the approximate costs and savings are:

| Debit | Credit | | | | Net |
|---|---|---|---|---|---|
| -$880 | +$400 | +$256 | +$195 | +$105 | +$124 |

Thus this system may at least break even at present costs and will save increasing amounts of money as power costs increase. Of course, the proportion of interest payments will decrease with time, partially negating the effect of increased fuel prices.

# CONSTRUCTION AND OPERATION OF A SOLAR-HEATED RESIDENCE/GREENHOUSE COMBINATION

Charles C. Smith[1]

## ABSTRACT

A solar heated residence/greenhouse combination structure has been developed and operated during the 1976-1977 heating season by the Solar Energy Applications Laboratory at Colorado State University. The greenhouse is situated on the south side of the structure with a solid wall separating it from the residence area. Each area comprises 640 square feet (59.5 square meters) with 450 square feet (42 square meters) of growing area in raised benches.

Solar heat is collected by forced air through the greenhouse and flat-plate solar collectors and stored as sensible heat in a rock bed for nighttime or cloudy day use. The solar system was started up on December 10, 1976, and has operated without interruption since that date. Performance data have been obtained and are reported. Operational and construction characteristics of this solar project are also documented.

## INTRODUCTION

The objective of the solar greenhouse and residence project at Colorado State University is to determine the compatibility of residential and garden greenhouse spaces combined in the same structure. In addition, solar energy is utilized as the primary heating source for the combination building.

Architects, realizing the appeal of plants in or near living quarters, often design some form of greenhouse area incorporated into residential buildings. The requirement for such greenhouse space is quite simple -- transparent walls and roof which are exposed to the southern direction for winter sunlight. The difficulty lies in maintaining the greenhouse within acceptable temperature limits. Greenhouses will overheat during a cold but sunny afternoon. At night the heating requirements become very high for the greenhouse, due to the obvious lack of insulation, demanding perhaps five or more times the heat for a house of the same size.

Depending upon how a person or family considers the value of their time, home greenhouse gardening can produce high quality produce at a savings. Such savings can be lost, however, due to fuel costs necessary to heat

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[1]Research Associate, Solar Energy Applications Laboratory, Colorado State University

the greenhouse. A solution to heat savings lies in reducing the heat loss by "tight" greenhouse construction and, secondly, by utilizing any excess solar heat generated in the greenhouse during the day to be applied to heating at night. Heat loss can be cut to one-half or less of that for conventional greenhouse structures without excessive cost or elaborate methods. With such construction, the greenhouse becomes a solar collector with substantial excess heat during sunny periods. This heat may then be transferred to a rock box and stored for night time heating of the greenhouse or house. Flat-plate solar collectors are optional, but may be applied to achieve 70 percent or more of heating demand supplied by solar energy.

## PRINCIPLE OF THE SOLAR HEATED GREENHOUSE/RESIDENCE COMBINATION

A combined residence/greenhouse solar heating system can be constructed which will enhance the overall performance of the solar system when compared with solar heating of the residence or greenhouse alone. This is due to two factors. First, the heating demands of the greenhouse and residence are not on the same diurnal or seasonal schedule. Therefore, "excess" solar heat, with respect to one, may be supplied to the other, an obvious advantage. Secondly, the greenhouse can tolerate greater temperature excursions than are acceptable in the residence. The greenhouse may be warmer during the day and cooler at night than the home and in fact, many plants benefit from this diurnal temperature cycle. The advantage of this greenhouse temperature cycle relative to the home derives from two fundamental conditions, that of increased solar heat recovery at lowered temperature and thermal stratification in the solar heat storage. A solar air heating system with a pebble-bed storage unit will sustain a large temperature gradient (thermal stratification) in the direction of air flow through the bed, as indicated in Figure 1, from actual measurement. This thermal stratification is developed by flowing the solar heated air in one direction (i.e., from the top to the bottom) and reversing the flow of air for heat removal (i.e., from bottom to top). Liquid storage tanks, by contrast, are quite difficult to stratify, and also liquid must be passed through a duct coil unit to effect space heating.

Thermal stratification assists both solar collection and space heating of the house-greenhouse combination. Air at the lowest useful temperature (i.e., the greenhouse at night) is delivered to the solar collector. In addition, air is delivered to the house or greenhouse from the pebble-bed at the highest collector operating temperature. The highest collector operating temperature will be dependent upon the collection conditions (radiation levels, outdoor temperature, wind, etc.) and the air flow rate.

## APPLICATION TO LARGE GREENHOUSES

The commercial greenhouse operator would normally have a much larger greenhouse than his own house. It would then be advisable to combine

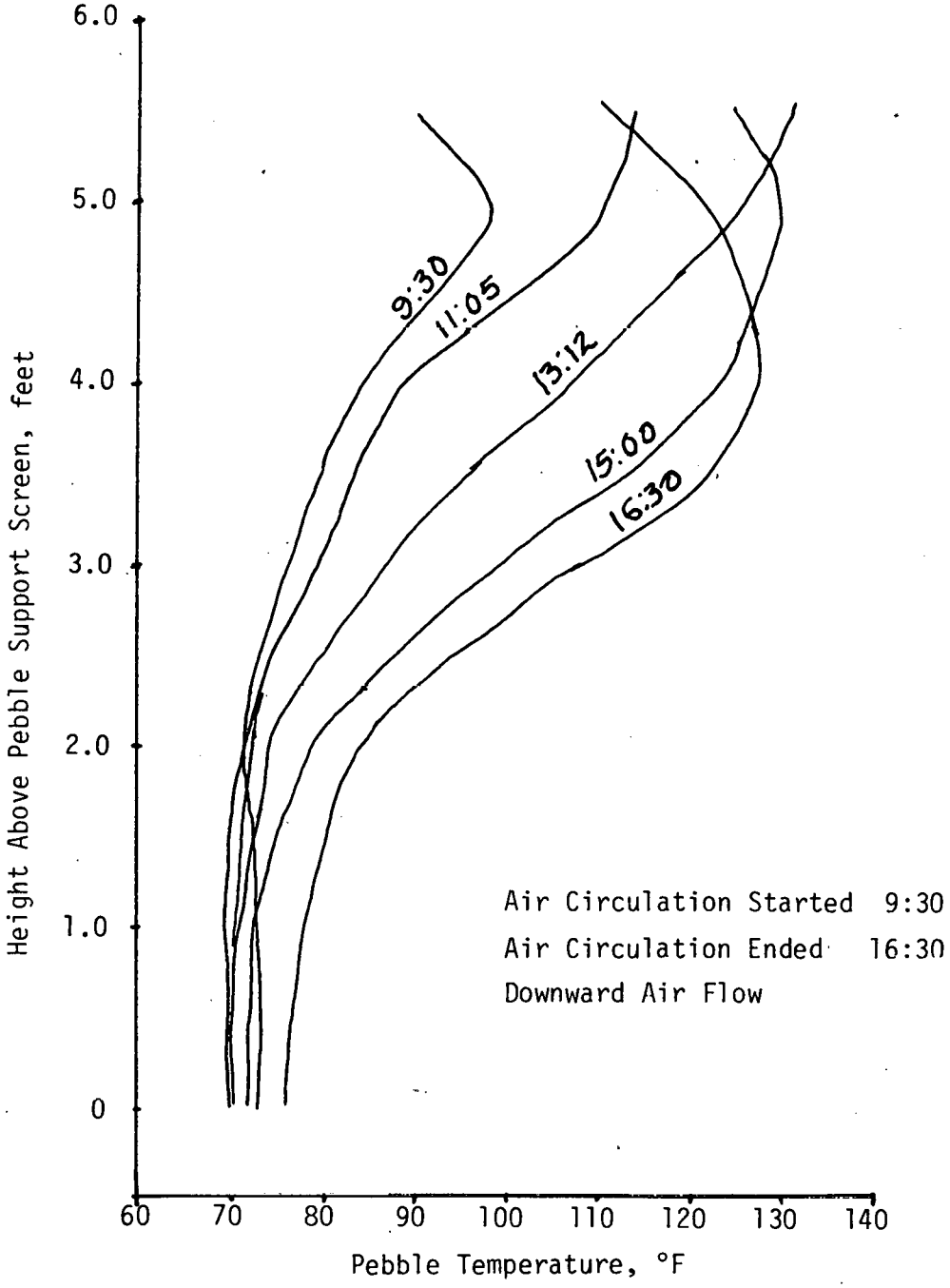



Figure 1. Pebble-Bed Thermal Stratification Variations

the greenhouse with a larger commercial or institutional building. If such buildings are unoccupied at night, they would compliment the greenhouse better than a residence, because more of the stored solar heat for night time heating may be applied to the greenhouse. The building could be any building which requires space heating, but would likely be functionally related to the greenhouse, such as a horticulture building or a vegetable processing plant.

## APPLICATION TO COOL, DRY CLIMATE

The cool dry climate is characterized by large diurnal temperature change and cool temperatures combined with clear skies. While heating requirements are high (often 6000 to 10,000 degree-days), the solar conditions are extremely favorable (refer to Figures 2 and 3).

In this climate a well-constructed greenhouse receives excess solar heat during solar hours, even in midwinter. At night, however, the heat load is high due to low surface temperatures and radiation to clear skies. A definite advantage is seen by coupling the greenhouse to a residence with heat storage. The diurnal extremes of the greenhouse are buffered by this arrangement and maximum advantage is taken of all available solar insolation.

## GREENHOUSE CONSTRUCTION

Greenhouse construction methods were employed at the Colorado State University solar greenhouse, which have reduced the heating requirements to less than one-half that of a conventional greenhouse. These include double glazing, caulking, and perimeter insulation in the ground. Combining the greenhouse with the house also reduces the heat loss because the north wall of the greenhouse is shared with the house and, consequently, heat is not lost through that wall.

The greenhouse roof consists of 3 by 6.5 foot (.9 by 2 meter) double glass units which are supported on redwood 4 by 4 inch (10 by 10 cm) rafters on 3 foot (.9 meter) spacing and a pitch of 10 in 12, or approximately 40 degrees from the horizontal. The greenhouse glass roof and solar collectors are depicted in the photographs of Figures 4 and 5. The glass units are hermetically sealed to prevent the entrance of moisture or other foreign material, with a sealed air space of .75 inch (1.5 cm) thick.

The end walls and three foot (one meter) high south wall are made of double thickness corrugated fiberglass. Glass was not used on the walls because of the irregular shape, which required cutting and fitting of the fiberglass and also because of the breakage hazard of glass close to the ground. Five-ounce Tedlar coated fiberglass was selected with spacing and weather seal between fiberglass sheets provided by .5 inch (1 cm) diameter butyl rubber strips. The inner layer of fiberglass was installed,

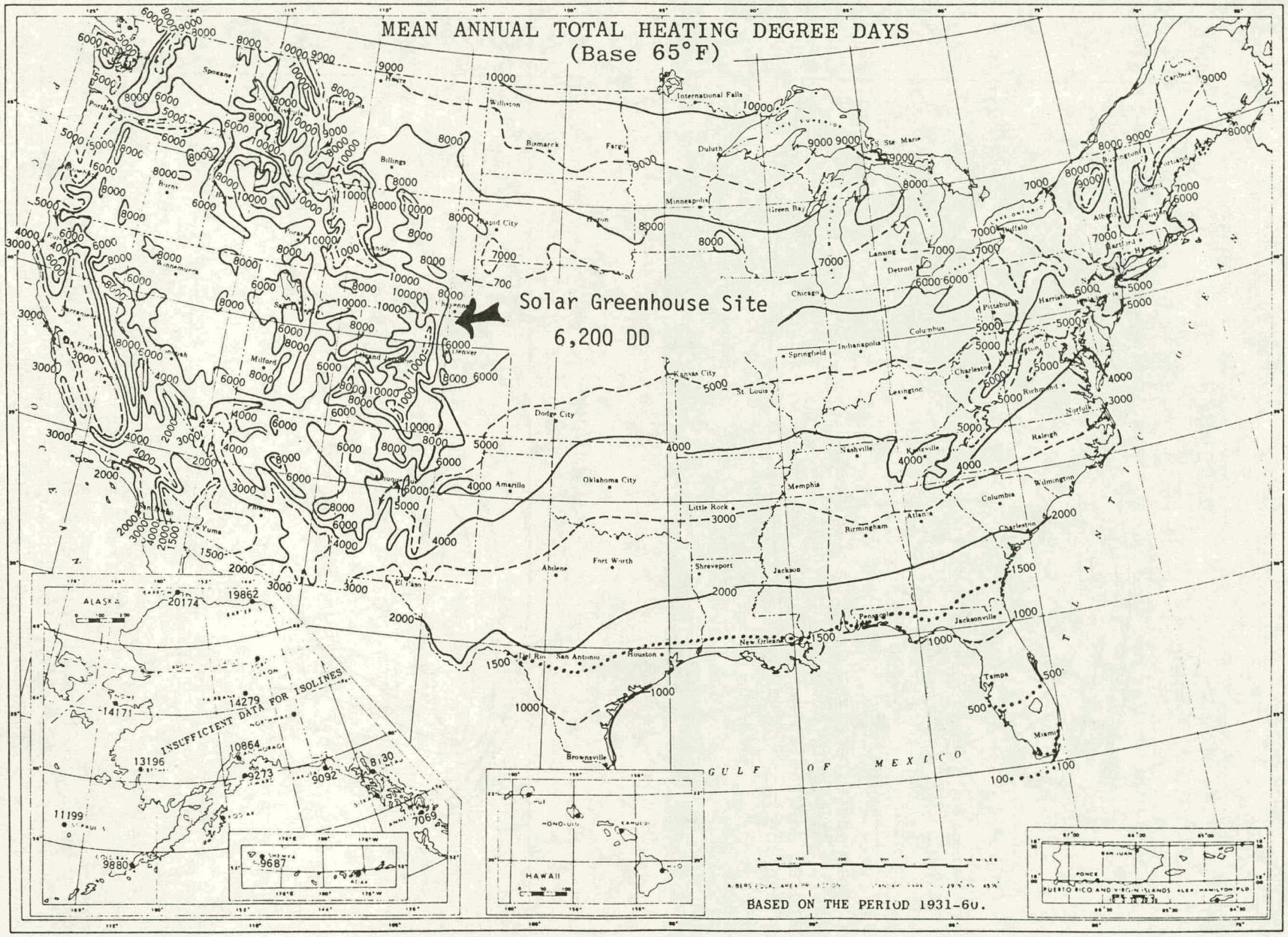

MEAN ANNUAL TOTAL HEATING DEGREE DAYS
(Base 65°F)
Solar Greenhouse Site
6,200 DD
INSUFFICIENT DATA FOR ISOLINES
ALASKA
HAWAII
PUERTO RICO AND VIRGIN ISLANDS
GULF OF MEXICO
BASED ON THE PERIOD 1931-60.

Figure 2

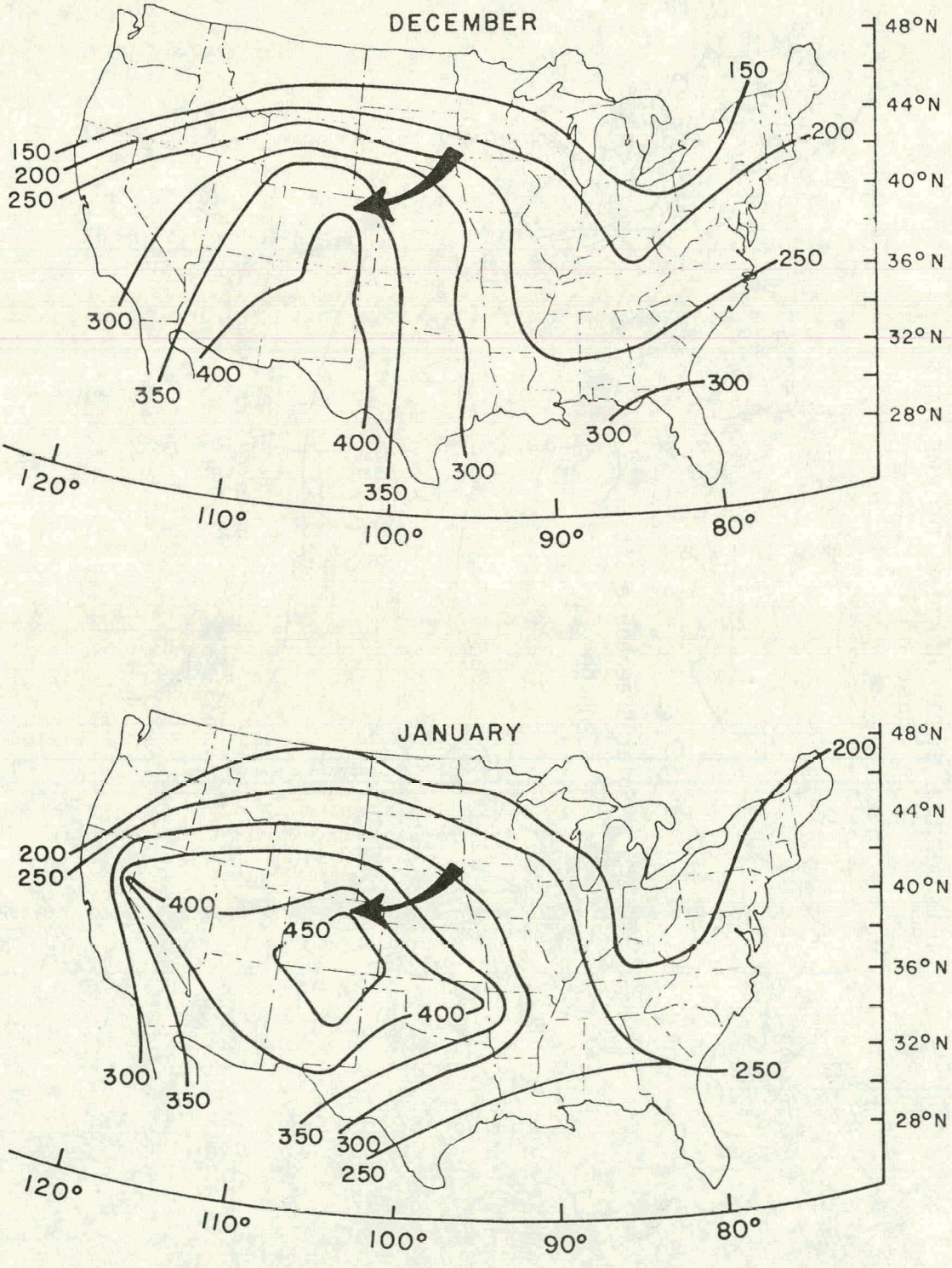



Fig. 3. Estimated average solar and sky radiation in gram calories/ ($cm^2$)(day) incident upon a south - facing vertical surface (Figures 12 and 13 on page 119 of the December, 1953, issue of Heating, Piping, and Air Conditioning).

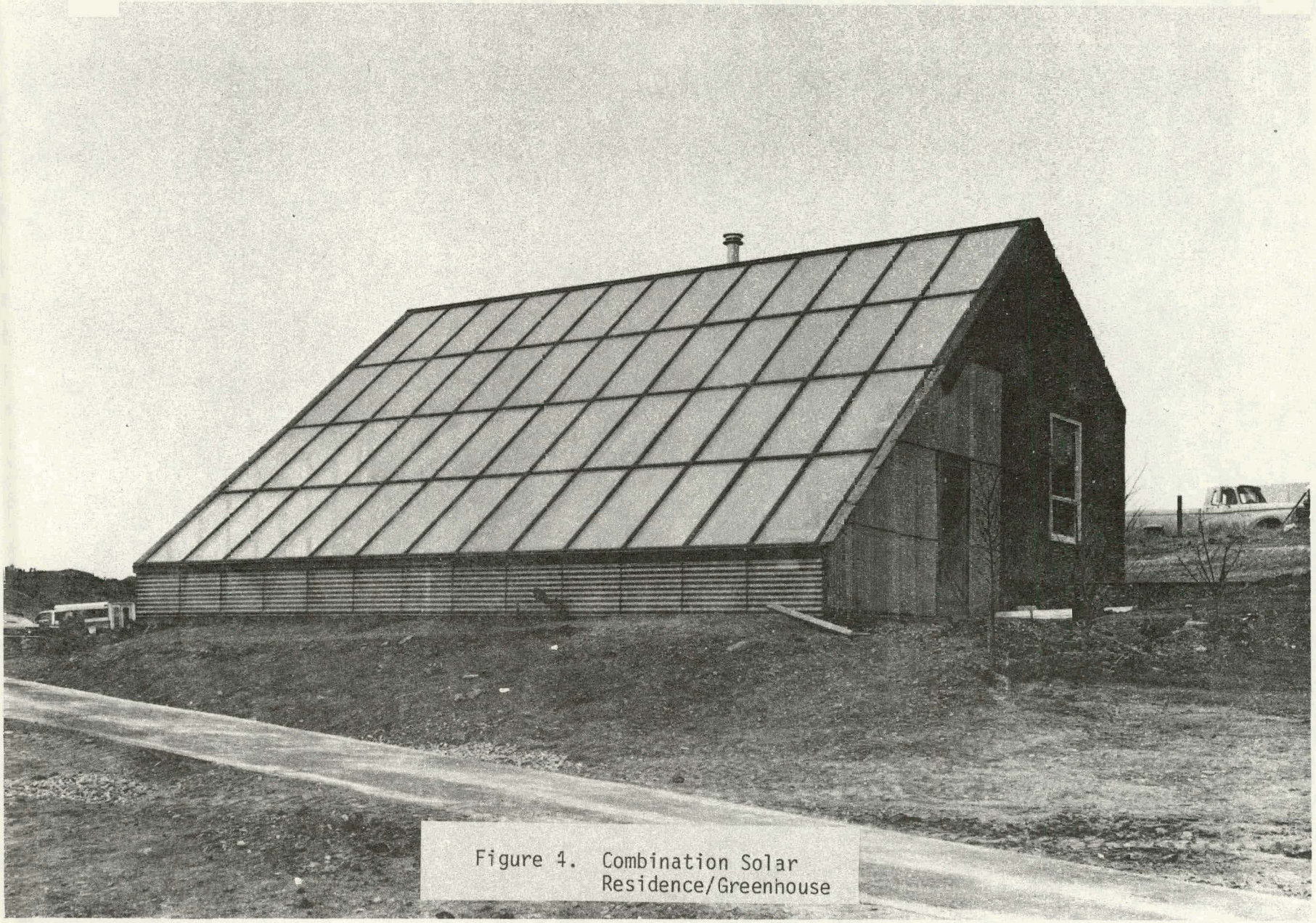


Figure 4. Combination Solar Residence/Greenhouse

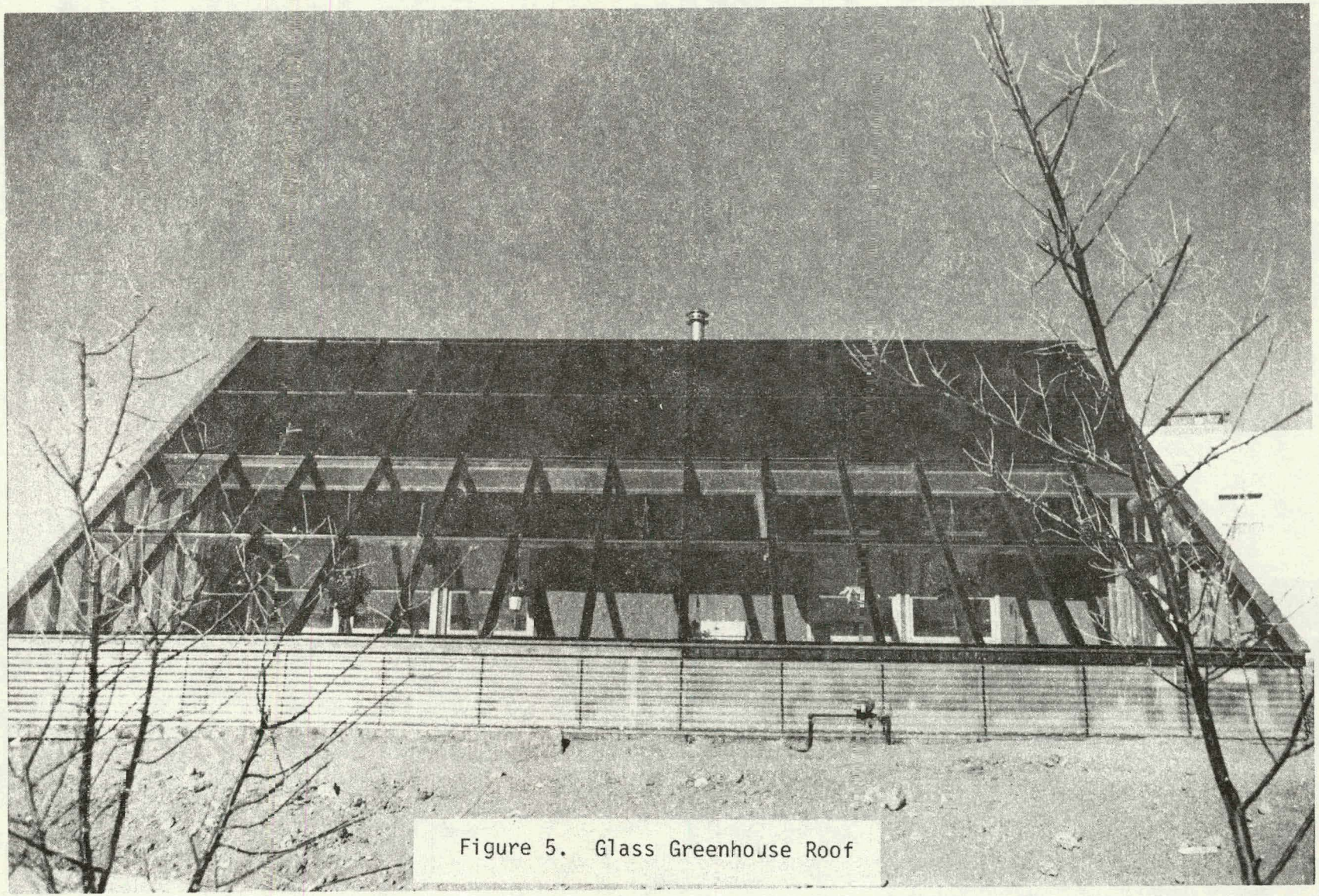


Figure 5. Glass Greenhouse Roof

followed by the butyl rubber strips, and finally the outer fiberglass layer was applied. The dual fiberglass walls could also be preassembled before installation if dimensions are not too intricate. It is critical in either case that the perimeter of the fiberglass be completely sealed against the intrusion of water or dirt. The corrugated ends were sealed with neoprene rubber fill strips, which are supplied with the fiberglass. All cracks and holes in the wall which could allow air infiltration were filled afterward with silicone caulking.

Perimeter insulation was placed on the ground below the greenhouse walls to reduce ground heat loss. The insulation consisted of 1.5 inch (5 cm) of styrofoam board, sandwiched between two pieces of .5 inch (1 cm) inch asphalt impregnated sheathing. The insulation reached 16 to 22 inches (40 to 56 cm) below grade.

These energy conserving features, in addition to the elimination of heat loss from the north wall of the greenhouse (this is the house wall), reduced the heating demand substantially. Also, outdoor air was never brought into the greenhouse when it was being heated. The calculated heat loss (which was verified by the heat load data), is 20,930 Btu per degree-day (3.4 kWh/°C·day), or 32.7 Btu/DD per square foot of greenhouse. This compares with 60 Btu/DD·ft$^2$ or higher for typical commercial greenhouses.

## GREENHOUSE OPERATION

Vegetable and foliage plants are grown in raised benches totaling 450 square feet (42 square meters) of actual growing area. Growing is done by the hydroponics method in #2 chip gravel, with water and nutrients applied every four hours by trickle irrigation. See Figure 6.

A two-stage thermostat is set at 58°F (14.5°C) and 54°F (12.2°C) for heating. The solar heat from the rock box is applied at the 58 degree point. If the greenhouse temperature should fall to 54°F (14.5°C), a natural gas burner comes on to supplement the solar heat.

Cooling of the greenhouse is accomplished by ventilation with or without evaporation pads. A two-stage cooling thermostat is set at 80°F (26.7°C) and 90°F (32.2°C). At 80°F the fans come on to ventilate the greenhouse with outdoor air. At 90°F, water is admitted to evaporation pads which cover the air intakes. With the double glazed greenhouse, cooling is necessary during warm sunny days in the winter as well as summer.

## ENERGY RELATED FACTORS

Several factors affect the heating requirement of any structure, however, there are some unique aspects which have been identified on this particular structure. Winds in the region create a very high heat load on any structure, and particularly on a greenhouse. A 40 mph (64.36 km/hr)

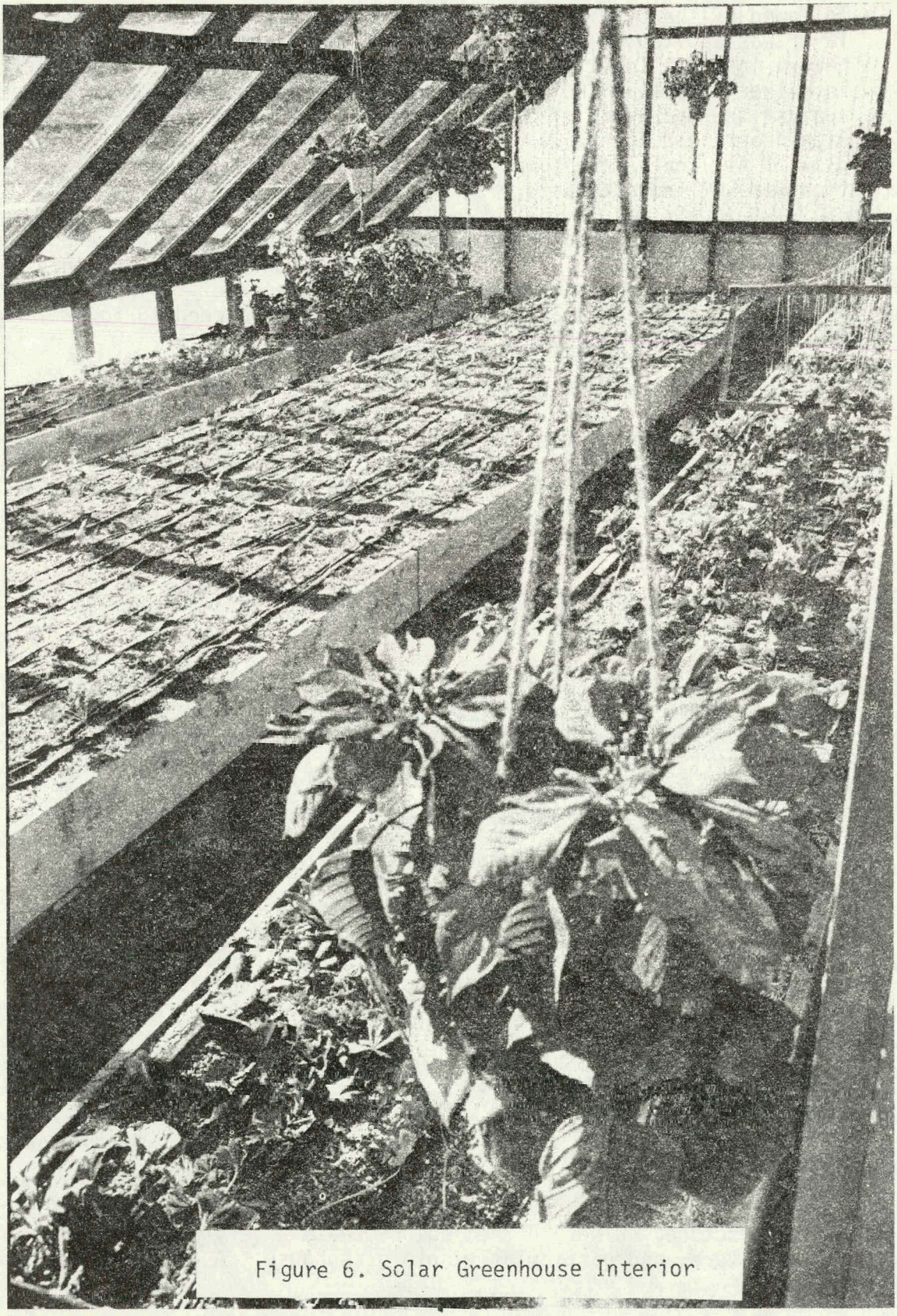


Figure 6. Solar Greenhouse Interior

wind blowing at 40°F (4.5°C), which is not unusual at the project site, results in the same heating load for the greenhouse as the design temperature of -10°F (-23.3°C) with no wind. The greenhouse receives no protection from the wind because there are no adjacent trees, fences, or other structures to resist wind. The residence on the north side does, however, spare the greenhouse from exposure to wind on that side.

Humidity levels in the greenhouse are another important heat load factor. The moisture condenses on the greenhouse roof and walls at night, giving off the latent heat to the walls, which in turn convect and radiate the heat to the outside. A layer of moisture adheres to the surface, but most of it drips or runs to the floor of the greenhouse. The trickle irrigation system and gravel growing benches reduce the amount of atmospheric humidity in the greenhouse. Therefore less moisture is condensed on the greenhouse walls and less heat is lost by this mechanism. The lowered humidity is also useful in maintaining the desirable humidity in the residence.

Eighty gallons (300 liters) per day of water are used for watering the greenhouse plants. This water is brought in at 50°F (10°C) and is heated to 65°F (18.3°C) in the gravel beds. Consequently, 10,000 Btu (2093 kWh) are consumed as water heating in the greenhouse.

## GREENHOUSE PRODUCTION

Vegetables were brought into the greenhouse during the first week in December. Some were transplanted as two- to four-week old plants, and others were seeded at that time. Flowering plants were also grown in hanging pots suspended from the greenhouse rafters. Table 1 is a summary of the greenhouse plant production.

## RESIDENCE CONSTRUCTION

The residence space is constructed to current Federal Housing Administration (FHA) insulation standards for residential buildings in the northern Colorado region. This consists of R = 11 $ft^2 \cdot °F \cdot hr/Btu$ for the frame walls and foundation walls, and R = 19 $ft^2 \cdot °F \cdot hr/Btu$ in the ceiling. Two windows (40 square feet) are exposed to the outside and five windows (100 square feet) are exposed to the greenhouse. All windows are wood frame double glazed. The 640 square foot (59.4 square meter) ground level and the open attic area are both heated with a heating load of 8,540 Btu per degree-day (1.4 kWh/°C·day).

The rock box is built into the residence and is supported on a 6 inch (15 cm) concrete slab located two feet below grade. The rock box requires 8 feet by 6 feet (2.4 by 1.8 meters) of floor space, however, the top of the rock box is used as the mechanical equipment area and is easily accessible through a door from inside the building.

Table 1

Solar Greenhouse Production

| Variety | Days since transplant (T) or seed (S) to present or harvest (H) | Total fresh weight, grams | Square feet | Quantities | Comments |
|---|---|---|---|---|---|
| Blue Bantam Peas | 116 (T) | 385 | 52.5 | | Nutrient deficiencies due to fertilizer problems. Yellowing and reduced growth. Presently returning to production |
| Tenderpod Peas | 114 (T) | 552 | 52.5 | | Same as above |
| Broccoli - Green Comet Hybrid | 80 (T) | 647 | 99.0 | | Nutrient deficiencies resulted in reduced growth |
| Cauliflower Snow King | 100 (T) | 3343<br>4877 | 99.0 | 37 - split heads<br>21 - good heads | Same as above. Heat as high as 85°F has resulted in split heads |
| Lettuce - Salad Bowl | 84 (T) (H) | 4513 | 16.5 | 34 heads | |
| Radishes - Comet | 86 (S) (H) | 2860 | 9 | 17.5 dozen | |
| Black Zucchini Squash | 73 (S) | 320 | 18 | 1 head | |

## RESIDENCE OPERATION

The residence portion of the building functions as a visitor center and a laboratory space rather than living quarters. This arrangement allows exposure to the public and facilitates the data and operational requirements of the project, while still representing a structure of residential construction for heat load considerations. Lighting, door openings, and human occupancy are typical of a residence during the daytime.

## SOLAR SYSTEM OPERATION

When the solar collectors are sufficiently warmer than the rock box, a differential temperature control turns on the collector blower and also opens the collector damper. Air is then forced through the greenhouse and collectors to gather solar heat. The air is passed through the rock box if the house is not calling for heat (Figure 7, Mode 1). This solar storage process continues until the rock box temperature approaches the collector temperature. The differential temperature range is adjustable so that a proper compromise can be reached between solar heat collection and the blower power consumption. If the house thermostat calls for heat while solar heat is being collected, the hot air is directed to the house instead of the rock box (Figure 7, Mode 2).

Space heating is provided to the greenhouse and house as separate zones. Each zone has a two-stage thermostat. At 70°F or 21.1°C (first stage), the house thermostat turns on the house blower and opens the house damper. This directs air from the rock box to the house utilizing the stored solar heat (Figure 7, Mode 3H). If the temperature falls to 68°F or 20°C, the second stage thermostat turns on a gas burner to supplement the solar heat.

The greenhouse is heated by the same process as the house, except that the thermostats are set lower (Figure 7, Mode 3G). Solar heat is applied to the greenhouse at 58°F (14.4°C) and fuel is used at 54°F (12.2°C).

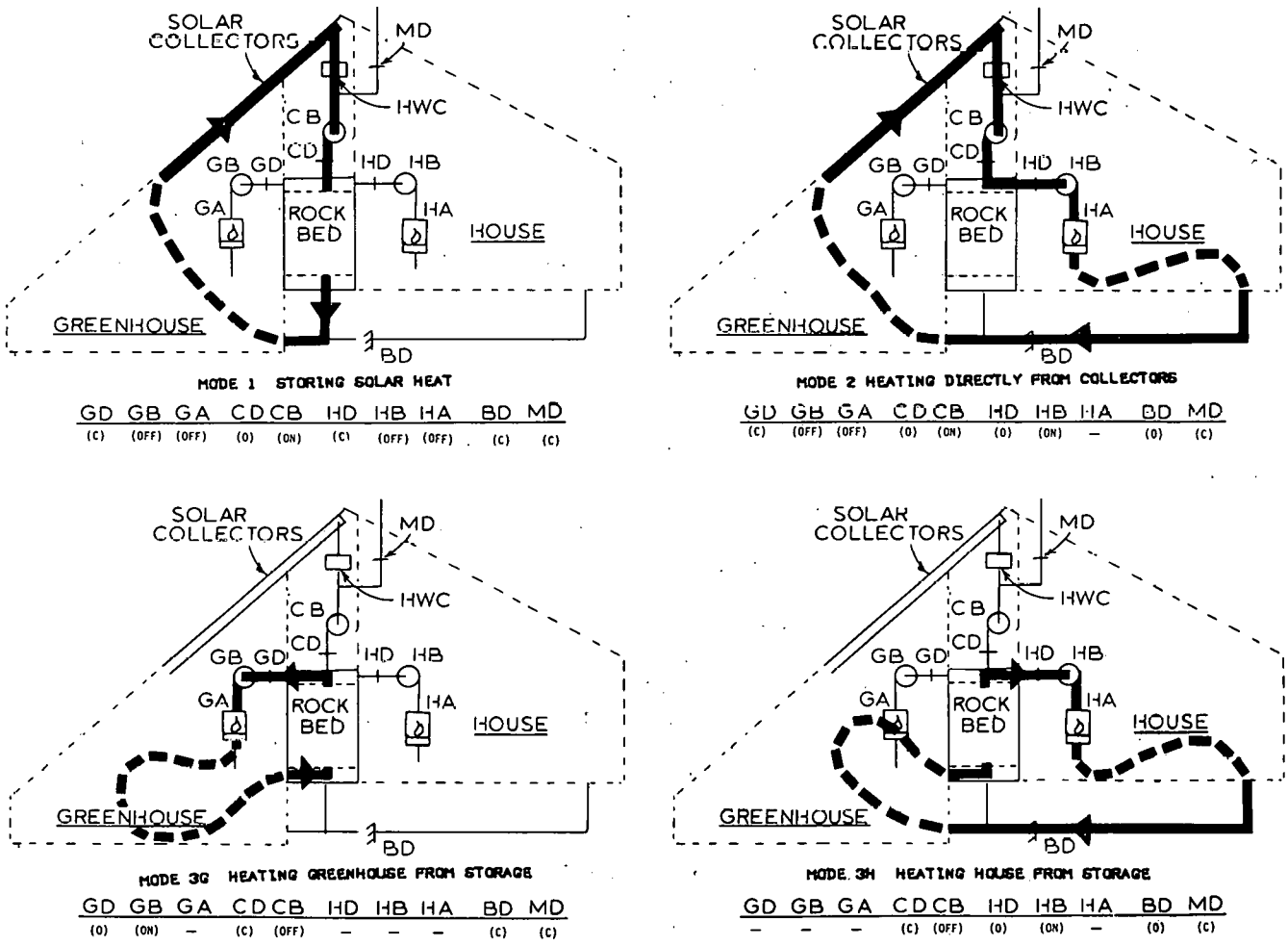
The solar heat delivered from the rock box is lower in temperature than from a fuel heater. Consequently, the blower must run longer to satisfy the heating demand. Electrical energy is somewhat higher for the solar heat as a result.

During the cooling season the collectors may be employed to help cool the greenhouse. By opening the collector outlet to the outdoors, air is drawn out of the greenhouse by convective flow. A manual damper is provided for this purpose, which will be left open during summer months.

## SOLAR SYSTEM CONSTRUCTION

Solar collectors were purchased which were preassembled and ready to be placed on the roof. A standard roof with 2 by 8 rafters and .5 inch plywood was provided upon which to mount the collectors. The collectors

CSU SOLAR HOUSE/GREENHOUSE
System Schematic




BD - BACK DRAFT DAMPER
CD - COLLECTOR DAMPER
CB - COLLECTOR BLOWER
GD - GREENHOUSE DAMPER
GB - GREENHOUSE BLOWER
GA - GREENHOUSE AUXILIARY FUEL HEATER
HD - HOUSE DAMPER
HB - HOUSE BLOWER
HA - HOUSE AUXILIARY FUEL HEATER
HWC - HOT WATER HEATING COIL
MD - MANUAL DAMPER FOR SUMMER VENT
VB - VENTILATION BLOWER

Figure 7. Modes of Operation

were installed by three workmen in two days. The finished collector installation includes cap strips and gaskets which prevent water leakage, and thus constitutes the weatherproof roof for the building. As shown in Figure 4, the greenhouse roof was integrated into the same plane as the collectors to save building cost and add to the appearance of the overall structure. The pitch of the collector and greenhouse roof is 10 in 12, or approximately 40 degrees from the horizontal, which is just equal to the latitude of the project site. The ideal angle for winter solar collection is approximately latitude plus 15 degrees, as shown in Figure 8, however the steeper angle would create an excessive elevation of the roof for this design. The slight sacrifice in performance (estimated at five percent) was considered tolerable. Snow accumulates to a maximum of one inch before it slides off the collectors and greenhouse to the ground.

The collectors are internally manifolded with four duct penetrations through the building subroof to bring air out of the collectors. Air enters the collectors from the greenhouse through four backdraft dampers which permit air to flow up into the collectors but prevent air from flowing in the reverse direction. This is done to avoid cold air in the collectors at night from draining down into the greenhouse.

The collectors are double glazed with sealed glass units, 3 feet by 6.5 feet, or .9 by 2 meters (the same as the greenhouse roof). A non-selective black coating with absorptivity of .97 is applied on 22 gauge steel as the solar radiation absorber. Air is forced beneath the absorber plate in a .5 inch (1.3 cm) deep duct to be heated. Air flow is 2 cfm per square foot (10 liters per second per square meter) of collector or 625 feet per minute (3.17 meters per second) velocity. The resulting Reynolds number at 120°F (49°C) air temperature based on the duct depth is 2100 in the collectors.

The collectors are insulated on the back and around the perimeter to minimize heat loss from these surfaces. There are 26 collector units with outside dimensions of 3 feet by 6.5 feet (.9 by 2 meters), for a total area of 507 square feet (47.1 square meters). The actual absorber area exposed to the sun rays is about 450 square feet (42 square meters) or 89 percent of the total area.

The collectors were allowed to reach stagnation temperature (probably 300°F (150°C) or higher) for three weeks prior to system start-up. The glass, coating, and other materials showed no sign of deterioration from this experience, however, summer ventilation will be employed to lessen the potential for deterioration under such high temperature conditions (see Solar System Operation).

Dirt, moisture, and wind have not affected the integrity or functioning of the collectors. Winds have gusted to 78 miles per hour (125 km/hr) without glass breakage. Blowing dust has also occurred with no perceptible penetration into the collector.

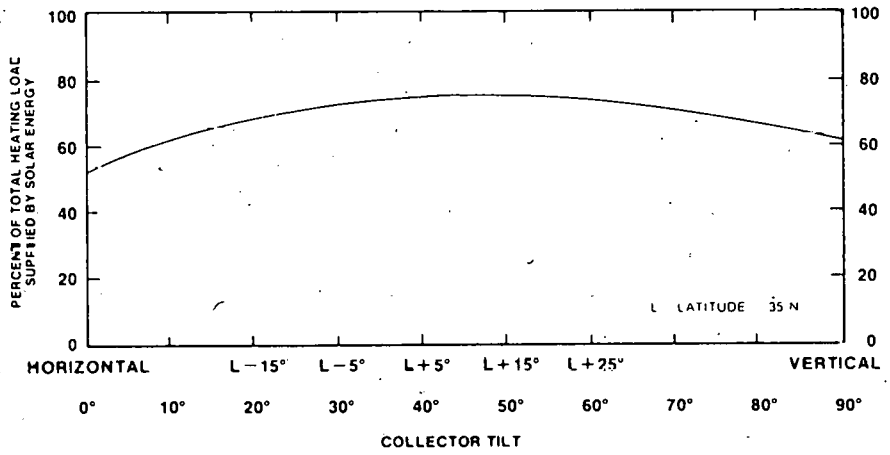



Figure 8. Effect of Collector Tilt on Total System Performance for a Typical Installation at 35°N Latitude

(J.D. Balcomb, J.C. Hedstrom, B.T. Rogers, "Design Considerations of Air Cooled Collector/Rock-Bin Storage Solar Heating Systems", presented at 1975 International Solar Energy Society Meeting, August 1975)

## ROCK BOX

Solar heat is stored as sensible heat in rocks for delivery to the building during non-solar periods. The rock is screened between .75 and 1.5 inch (2 to 4 cm) in diameter. It is hard rounded stone which is sold locally as concrete aggregate. The heat capacity of the rock is .2 Btu per pound, degree F (.2 cal/gram·°C), and has a fill density of 100 pounds per cubic foot (1608 KG per cubic meter), or 20 Btu per cubic foot, degree F.

The rock box for the CSU solar greenhouse/residence contains 336 cubic feet (9.5 cubic meters) of 16.8 tons of rock. This quantity of rock is designed to store the maximum solar energy collected during a clear day, which is about 500,000 Btu (147 kWh) from both the greenhouse and solar collectors.

The duration of solar heating from storage is influenced by many factors, however, when the rock box is charged from a full day of solar collection, it will normally carry the heating load for 24 hours of winter weather without additional collection. Cloudy periods exceeding 24 hours are too infrequent at the site to justify the cost and space of a larger rock box for solar heating storage.

## ROCK BOX DESIGN

The rock box is designed so that air will flow vertically through the rock. Hot air from the collectors enters the top of the box and flows downward. Greenhouse or house air enters the bottom and flows upward. The resulting temperature profile in the vertical direction is complex (see Figure 9), however it is always hotter near the top than at the bottom. The hot end is preferred at the top rather than the bottom because it is easier to insulate the top, and also because the equipment layout is simpler for this application. The disadvantage of the hot end at the top is that dampers and blowers are operating in the hot air streams, whereas they could be in the cold air streams with a reversed rock box.

A wood frame rock box 8 feet deep, 8 feet long, and 6 feet wide (2.44 by 2.44 by 1.83 meters) is used to contain the rocks. The back walls are constructed of 2 by 4 inch (5 by 10 cm) vertical studs at one foot spacing, which are covered on the inside with .75 inch (2 cm) plywood. The walls are tied together at the middle (four feet from the bottom) with steel crating bands which are spaced two feet (tied to alternate studs). The 3.5 inch (9 cm) thick space between studs is filled with bonded fiberglass insulation. The top of the box is insulated with one-inch high density fiberglass board with an aluminum scrimcoat facing the rock. Three-quarter inch plywood was placed over the fiberglass board, which is supported on 2 by 4 inch (5 by 10 cm) wood at two foot spacing. The top forms a platform upon which all of the mechanical equipment is mounted.

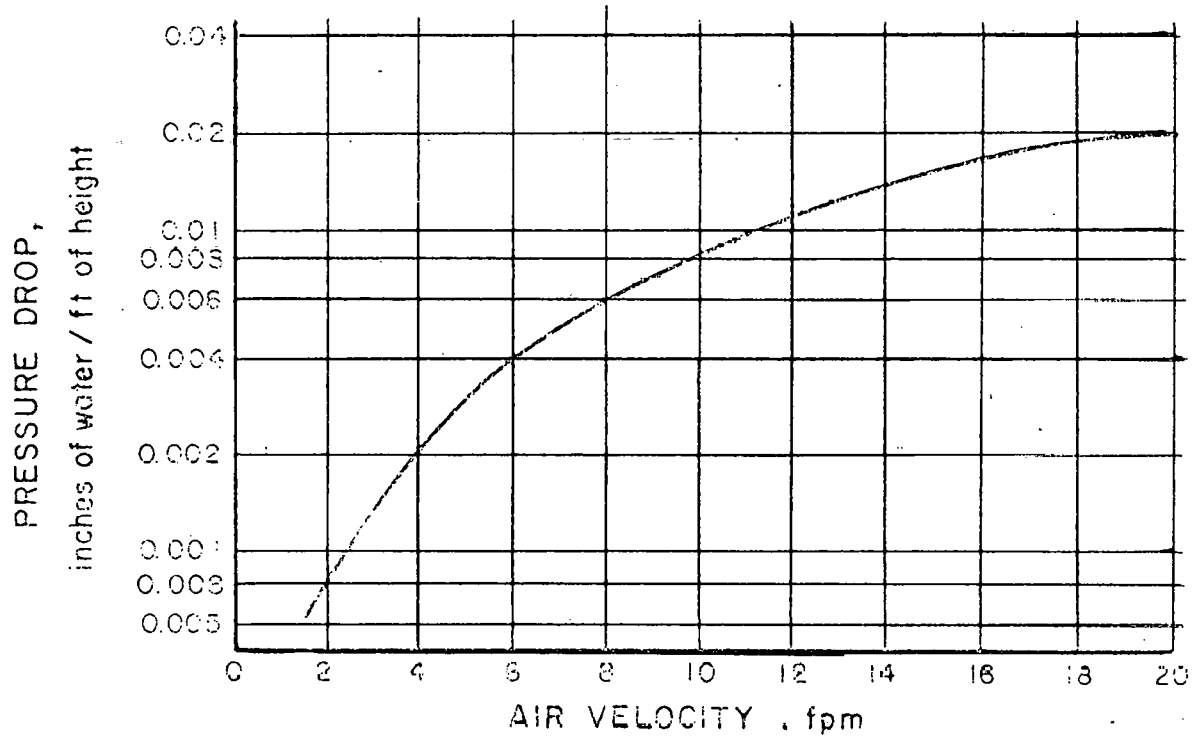



Figure 9. Pressure Drop Through a Rock Bin with .75 to 1.5 Inch Rocks

The floor of the rock box is a six-inch (15.2 cm) thick concrete slab with reinforcing steel mesh, capable of supporting the rock load without cracking. An air plenum must be provided at the bottom to allow proper air flow. This was accomplished by an array of concrete bond beam blocks on the floor with the webs pointing upward. An expanded metal screen with .75 inch (2 cm) hole size was placed over the blocks which support the rock while allowing proper air distribution at the bottom of the rock box.

The rock depth is important with respect to air pressure and the associated blower power. To determine the static air pressure in the rock box, it is first necessary to know the air flow rate for the system. This air flow is entered into the pressure drop curve of Figure 8. The design procedure is actually trial and error or computer solved because the depth and cross-section area can be varied while maintaining the same rock volume. The cross-section area for the CSU project is 48 square feet (4.46 square meters) and the air flow rate is 1000 cfm (471 liters per second). The pressure drop through the seven feet of rock depth, using Figure 8, is .14 inches (3.5 mm). This is in close agreement with the actual static pressure shown in Table 2.

## SOLAR SYSTEM DESIGN

Sizing of the solar system was based on two factors; the portion of heating requirement to be provided by solar and the physical space available on the roof of the building upon which to place the solar collectors. The solution is actually then a compromise between what is the best economic size and what is acceptable in terms of space available or aesthetics. The optimum economic sizing of the solar system for this project was performed by a sizing procedure developed for solar space heating [1] The procedure is not a topic of this paper, but may be obtained from the reference. From this procedure a solar heating capability corresponding to 70 percent of the annual heating demand for the combined structure was determined to be appropriate. The required collector area to accomplish this portion of the heating demand was computed from the climatic conditions of Fort Collins, Colorado and the estimated heat load for the residence and greenhouse. A solar collection area of approximately 500 square feet (46.5 square meters) was selected. The solar heat recovery from the greenhouse was less well defined, but was expected to contribute an additional 10 or 15 percent to the heat supply. The extent to which solar energy can be extracted from the greenhouse depends upon the upper temperature limit in the greenhouse. This is an operational or plant response limitation rather than a system limitation. Consequently, the greenhouse contribution could only be found by an operational or experimental determination.

Sizing of the rock box was discussed previously. It must be capable of storing the maximum solar collection during a full day of clear sky solar radiation. For the collectors this would require one-half cubic foot of rock per square foot of collector, or 250 cubic feet (7.06 cubic meters). The rock bed volume of 336 cubic feet (9.4 cubic meters) was provided

Table 2

System Static Air Pressure

Solar Collection

Air flow: 1000 cfm
Blower power: 370 watt
Static air pressure (in W.G.):

| | |
|---|---|
| Collectors and backdraft damper | .45 |
| Rock box and air filter | .34 |
| Total | .78 |

Greenhouse Heat

Air flow: 1400 cfm
Blower power: 550 watts
Static air pressure (in W.G.)

| | |
|---|---|
| Rock box and filter distribution: | .29 |
| Distribution | .16 |
| Total (external to furnace) | .45 |

Residence Heat

Air flow: 800 cfm
Blower power: 340 watts
Static air pressure (in W.G.)

| | |
|---|---|
| Rock box and filter | .13 |
| Distribution | .21 |
| Total (external to furnace) | .34 |

with 86 cubic feet (2.4 cubic meters) of excess. This was added to accommodate the storage of greenhouse solar radiation.

## AIR DUCT DESIGN

Solar air systems depend heavily upon good quality ducts and dampers to assure that most of the collected heat reaches the heated space when required. From the thermal standpoint, ducts must be sealed against leakage and must be insulated where hot air is conveyed. This is accomplished by taping all duct seams so that air cannot leak in or out. This is not a difficult or costly task, but is simply not done on conventional residential ductwork. The insulation should be one inch thick or have an R value of at least 4 $ft^2 \cdot °F \cdot hr/Btu$. This can be applied as a duct lining or by using high density fiberglass duct board.

The fiberglass duct board was selected for use in the CSU project. It is less expensive than lined sheet metal and requires fewer mechanical skills and tools. Duct board is not as strong as metal duct, and thus should not be employed where heavy traffic or other factors might cause it to be damaged. Duct sizing is done using conventional methods for good duct design. The ducts are large enough to minimize pressure loss and noise, but not oversized, which would increase the cost unreasonably and consume excess space. The ducts were sized for a maximum of 700 feet per minute (3.55 meters per second) air velocity. Also, turning vanes were used in all ducts greater than 12 inches (30.5 cm).

Dampers were used which have compressive rubber seals. They are specified to have five percent leakage at two inches of static pressure. The dampers are operated by conventional 24 volt electric damper motors. An important consideration is to provide access openings next to the dampers. This is to make adjustments and to inspect the dampers for leakage or any mechanical problems.

Blowers are standard commercial products, sized for the system by conventional engineering practice for cfm, static pressure, speed, and power considerations. Belt-driven blowers are preferred over direct drivers because fine speed changes can be made by simple pulley adjustments. Blower speeds above 1000 rpm should be avoided because of noise considerations.

The blowers for space heating of both the residence and greenhouse were provided in the auxiliary forced air furnace. This was convenient because the blowers were preassembled and installed.

## SYSTEM OPERATION

The solar system went into operation on December 10, 1976. The month of December was devoted to system testing and balancing. The data measurement system was installed during December and the first two weeks of January. A few days were required to verify measurements by making an

energy balance of the storage unit. This was simply to confirm that the energy delivered to the rock box equaled that removed from the box over a period of four or more days. When this was accomplished, the official data monitoring period began, which was January 23, 1977.

Data have been processed for January and February for entry into this report. Results for this period are presented as bar charts in Figures 10 through 12. For the period January 23 to February 20, 1977, 84 percent of the heating requirement of the combined residence and greenhouse was met by solar energy. Of this solar heat recovery, 87 percent was derived from solar collectors and 13 percent was obtained from the greenhouse.

It is important to note that, on several days, the greenhouse reached 90°F (32°C) while solar heat was being collected. At that point, the greenhouse was ventilated to avoid high temperature stress to the plants. Available solar heat was thus lost because the air flow was insufficient to collect the heat below 90°F. Also, there is warm air returning from the rock box to the greenhouse on days when large quantities of heat are collected. This indicates that more energy could be stored from the greenhouse if the air flow was increased or if the rock box were deeper. The penalty, however, is in additional blower power.

Electrical power was measured during the February operation and compared with solar heat delivered to the building. This is the electrical power required to operate the collector blower plus the portion of the greenhouse and house heating blower power to deliver solar heat. That quantity of power was 4.8 percent of the delivered solar heat.

Blower power is a function of the volumetric air flow rate and the static pressure of the system. Table 2 lists the static air pressure distribution for the three air circuits.

## CONCLUSION

Solar heating can be applied effectively to supply a major fraction of the heating demand for a greenhouse or greenhouse/residence combination. A well-constructed greenhouse is considered basic to such a solar application. This is because economics do not favor a large solar system to meet the demands of a high heat loss structure. Also, the tightly constructed greenhouse becomes a low temperature solar collector to be employed with or without additional solar collectors for the capture of solar heat. The degree to which the greenhouse can contribute useful solar heat depends upon climatic conditions and the upper temperature limit in the greenhouse.

The Colorado State University Solar greenhouse/residence project has demonstrated that a solar heating capability of 87 percent is obtainable during a winter heating period using commercially available equipment and conventional (or easily developed) construction methods. Combining a greenhouse with a solid wall space heated structure offers some heating advantage. This results from heat loss reduction and overall solar

Figure 10.

# HEAT SUPPLY AND DEMAND
## JAN. 23 - 31, 1977

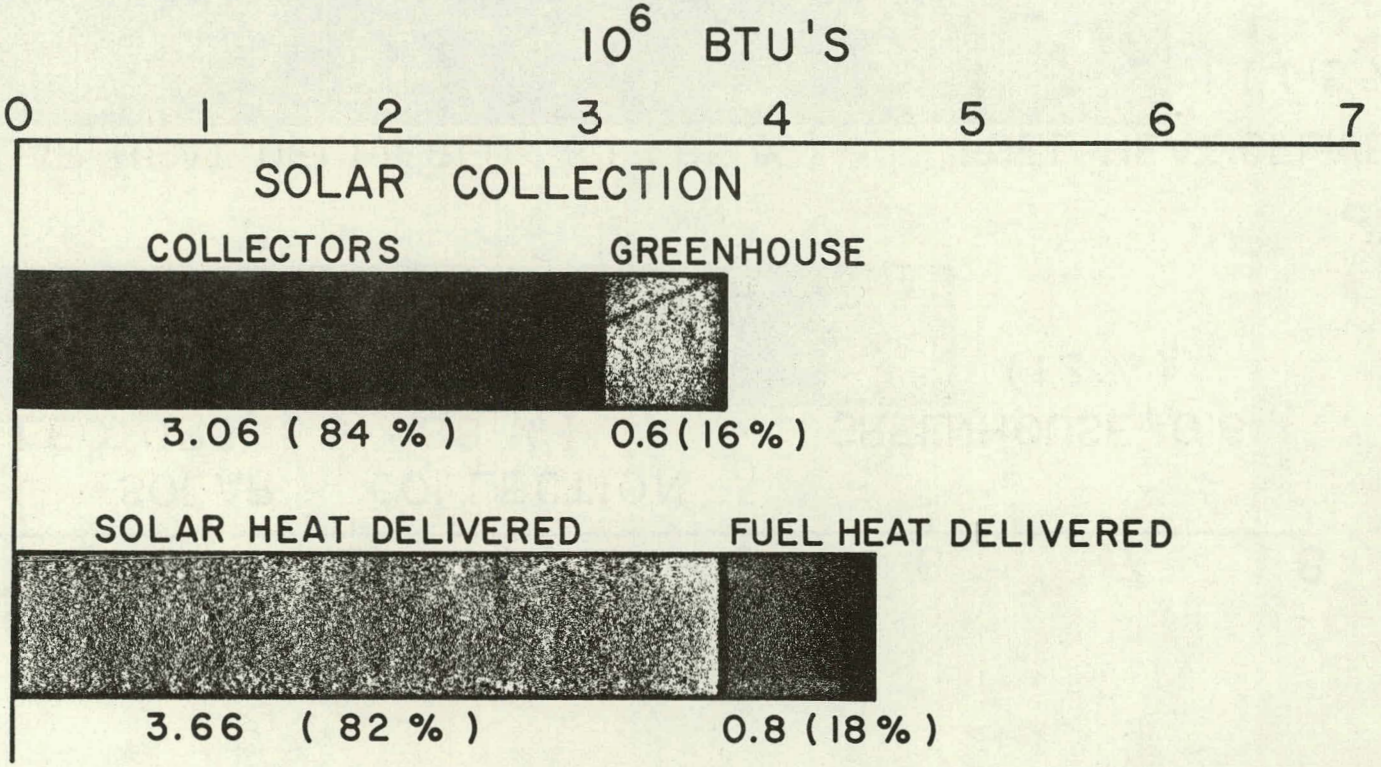


Figure 11.

# HEAT SUPPLY AND DEMAND

## FEB. 1-20, 1977

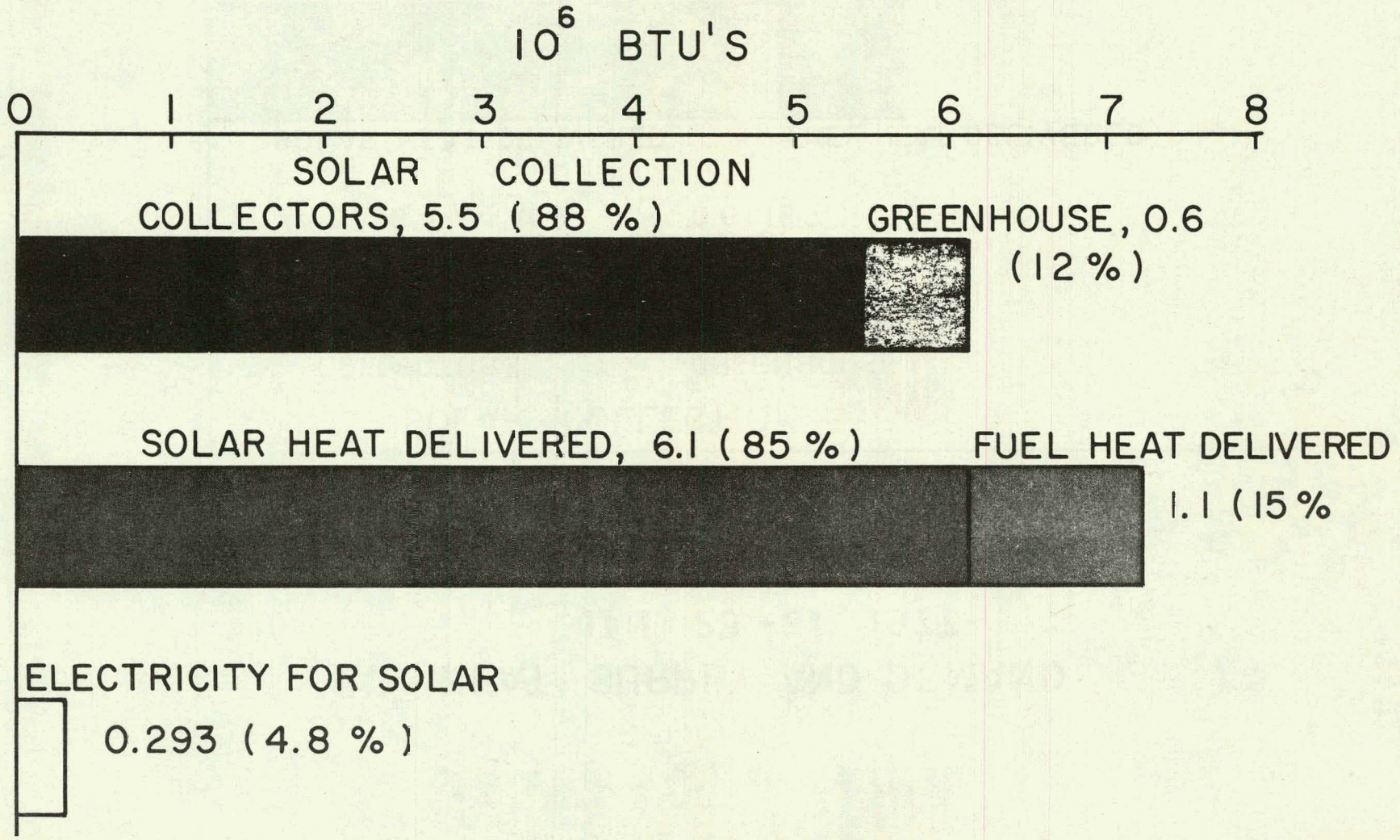
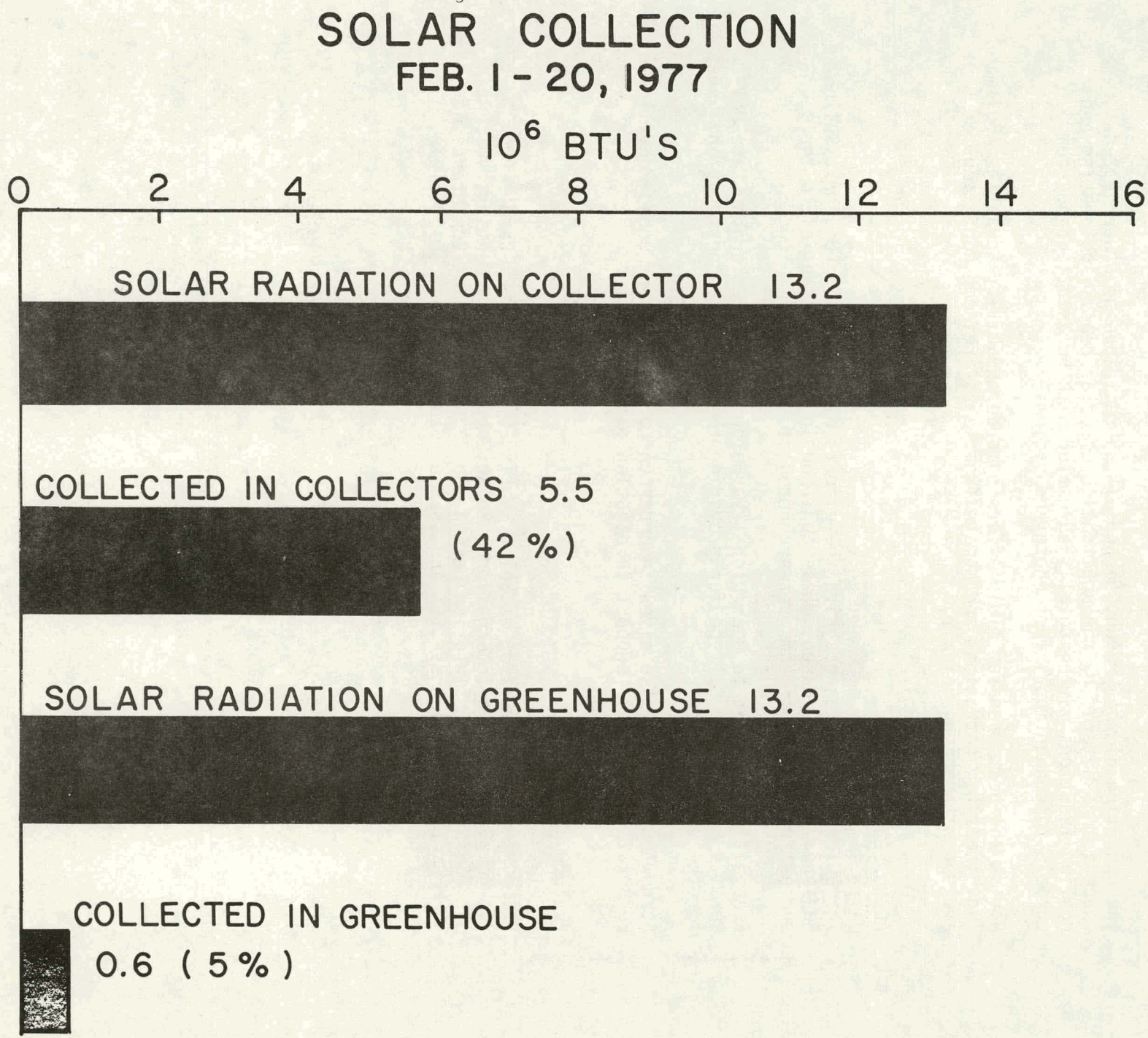


Figure 12.


SOLAR COLLECTION
FEB. 1 - 20, 1977
$10^6$ BTU'S
0
2
4
6
8
10
12
14
16
SOLAR RADIATION ON COLLECTOR 13.2
COLLECTED IN COLLECTORS 5.5
(42 %)
SOLAR RADIATION ON GREENHOUSE 13.2
COLLECTED IN GREENHOUSE
0.6 ( 5 % )

system performance. This influence of combined structures is not seen to be size dependent, and should be valid for larger scale installations.

The operation of the greenhouse and of the residence or other heated space is not altered by the application of solar heat. The heating and cooling functions may be totally automated with human attendance comparable to conventional fuel energized systems.

Air as the heat transfer fluid offers some dependability advantage. Boiling, freezing, corrosion, and damage from leaks are some conditions avoided with the use of air.

## ACKNOWLEDGEMENT

The author wishes to recognize the efforts of Dr. G.O.G. Löf, Mrs. Shilon Bedford, and Dr. J. Hanan, whose contributions were essential to the successful conduct of this research project.

Recognition is given to Dean Lionel V. Baldwin of the Colorado State University Engineering College for providing the necessary construction funds for the visitor center.

Acknowledgement is also given to Andersen Corporation and Johns-Manville Corporation for their support in donating materials.

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# DYNAMIC VERSUS STEADY-STATE THERMAL ANALYSIS OF SOLAR RESIDENCE/GREENHOUSE COMBINATION

H. F. Zornig[1], R. C. Fowler[2], and L. C. Godbey[1]

This report covers the second phase of a research project directed at developing practical residence/greenhouse combinations. Two prototypes were designed during phase one by the ARS Rural Housing Research Unit in cooperation with Clemson University. These prototypes were designed to provide home food production and solar energy utilization and are described in figures 1-9. During the past year, construction plans and specifications were developed for both prototypes and this required a complete thermal analysis of each so that the solar collector, rock heat storage and mechanical equipment could be sized. Initially, a modified steady-state thermal analysis was used to develop design criteria (7). However, a dynamic thermal analysis was also needed to check various design parameters. This, obviously, required digital computer simulation. Changing temperatures and insolation outside and inside a greenhouse and a solar collector, and the changing temperature and thermal lag of a rock storage system, made the steady-state method of thermal analysis difficult to use even when it was modified to take into account the average insolation rate, air temperature, and actual test data provided by related research (8).

During phase I, a dynamic thermal analysis was attempted by use of the National Bureau of Standards' Heating and Cooling Loads Simulation Program (NBSLD) (6). This attempt failed after nearly one year of effort because of difficulties in modifying the NBLSD program. The task was later contracted to Mechanics Research, Inc. (MRI) of Santa Monica, California. I will briefly report on what that firm accomplished for us during about 6 months of effort. Following my report, Mr. Fowler of MRI will report on how the required dynamic analysis was accomplished[3].

---

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[2] R. C. Fowler, Engineer, Mechanics Research, Inc., Los Angeles, California.

[3] Mention of a trademark or proprietary product does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture, and does not imply its approval to the exclusion of other products that may also be suitable.

## USE OF DYNAMIC ANALYSIS

We planned to use the results of the dynamic analysis to check the design before construction, and because construction of one prototype was scheduled to take place during the current phase of this research, time was critical. Some of the results were available from MRI only days before construction started in January 1977. However, there was still time to make several important changes in the design.

Many of the researchers at this meeting have probably performed similar dynamic thermal analyses for which they considered hourly weather data and thermal lag. Except for simulating heat flow in the rock storage and earth under the rock thermal storage, the programming methodology required has been developed and reported by Buffington (3), Albright and Scott (1), and Duncan, et al (4). However, the analysis reported here is somewhat unusual because of the design and operating parameters that were considered along with changing climatic conditions. Many of the parameters needed were not readily available, and some of them had to be developed by the Rural Housing Research Unit (RHRU) by building and testing a section of the solar collector and rock thermal storage. Other parameters such as rate of plant transpiration and the rate of heat diffusion in different soils were found by searching the literature. Not all the parameters needed were developed or discovered in the literature. One parameter still missing is the change in rate of infiltration as a function of wind velocity in both houses and greenhouse. Other parameters that were used need to be checked against actual operating data.

The dynamic thermal effect of structural mass and earth of sufficient depth under the thermal storage, all energy inputs from occupants, mechanical equipment, lights, and latent heat, and changing infiltration and insulation values as affected by wind direction and velocity should be considered in a dynamic simulation program. In addition, all the operating modes of heating and cooling equipment should be programmed for optimum energy conservation. Nearly all of these parameters were adequately considered in the program developed by MRI.

Although MRI has identified certain program modifications which should in the future reduce computer simulation time, it is nevertheless too costly at the present time to use the program for the parametric studies needed to check the design parameters over long simulation runs of several months.

An example of the useful data obtained from the analysis is given in Table 1. The table provides a summary of total operating time in each of the modes of operation described in figure 6 for the first prototype.

TABLE 1.--Distribution of Modes, Heating and Cooling[1]

| Percent Operating Time in Each Heating Mode[2] | | | | | |
|---|---|---|---|---|---|
| Number | 1 | 2 | 3 | 4 | 9 |
| December 1958 | 2.8 | 18.0 | 4.9 | 13.1 | 61.3 |
| January 1959 | 2.7 | 12.7 | 3.7 | 10.4 | 70.5 |
| February 1959 | 1.9 | 14.5 | 2.2 | 9.1 | 72.3 |

| Percent Operating Time in Each Cooling Mode[3] | | | | | |
|---|---|---|---|---|---|
| Number | 5 | 6 | 7 | 8 | 9 |
| June 1959 | 1.5 | 21.3 | 19.3 | 8.7 | 49.3 |
| July 1959 | 0.7 | 21.3 | 35.6 | 5.2 | 37.1 |
| August 1959 | 0.1 | 16.0 | 41.6 | 2.7 | 39.6 |

[1] Thermal analysis based on Nashville, Tennessee, average year hourly weather data and the prototype design shown in Figures 1-6.

[2] Heating Modes:

1. Solar collector to house
2. Solar collector to rock storage
3. Rock storage to house
4. Auxiliary heater to house
9. Idle

[3] Cooling Modes;

5. Outside air to house
6. Rock storage to house
7. Auxiliary cooling to house
8. Outside air to rock storage
9. Idle

Data given in Table 1 were used to evaluate total fan operating time to optimize system performance. For instance, the low percentage of fan operating time in mode 8 (cooling-outside air to rock) indicated an operational problem. We expected this mode to require just as much operating time as mode 6 (cooling-rock storage to house), however, it was much less. When the results were checked, we learned that the system had not operated for optimum cooling efficiency. During many cool nights the collection was idle, even when outside air was 4 or 5°C cooler than the inlet temperature of the rock storage. Evidently, the temperature difference selected to control the cooling mode was too small.

Another apparent problem in the program for cooling involved collector temperatures. The printed results were searched for maximum solar collector output temperature, and according to the dynamic simulation, this temperature reached 120°C (248°F) in August 1959 with free convection flow (vents open and collector not in use). Actual tests showed that temperature should not exceed 66°C (150°F) with free convection flow through the vented collector in the summer. We discovered that the computer program ignored the predicted convection air flow of about 1700 $ft^3$/min through the collector, and this allowed the collector to overheat.

Although the details of the cooling analysis described above were not very helpful in design, because of discrepancies noted, the heating analysis helped in checking the size of fans, auxiliary heater, and rock storage, and both analyses were helpful in determining requirements for system operation.

One potential problem brought to light by the dynamic analyses during the heating period, was that the greenhouse got too hot. Because of this, the design collection fan capacity was increased and an automatic auxiliary cooling method was added in the greenhouse. It may also be necessary to bypass the greenhouse with return air from the rock whenever this return air is too warm for the greenhouse.

Some comparisons of the results from the dynamic analysis and the modified steady-state analysis are given in Table 2. As with the results of the cooling analysis, we found some of these results difficult to explain or compare with results from the modified steady-state analysis, particularly the difference in greenhouse heating load.

Table 2 was prepared primarily to show how much the results differ with the two different methods of thermal analysis. One of the most significant differences was in the greenhouse heating load, PGHL. This difference might be partially accounted for because the greenhouse temperature was allowed to float, reaching a low of 5.7°C (41°F) for a few hours during the period when data was being collected for the dynamic analysis, whereas, for the steady-state analysis, the minimum temperature was held at 13°C (55°F). In addition, it should be noted that

TABLE 2.--Total Monthly Heat Gains and Losses (kJ x $10^6$)[1]

| Parameters[2] | December 1958 (873 DD)[3] | | January 1959 (837 DD)[3] | | February 1959 (685 DD)[4] | |
|---|---|---|---|---|---|---|
| | Dynamic | Steady-State | Dynamic | Steady-State | Dynamic | Steady-State |
| QHT | 0.6 | 6.6 | 0.1 | 5.6 | 0.4 | 2.6 |
| QSPH | 0.6 | --- | 0.6 | --- | 0.3 | --- |
| QSPR | 3.8 | 11.6 | 2.8 | 11.6 | 3.0 | 10.8 |
| QRS | 5.2 | 9.7 | 5.4 | 9.7 | 3.6 | 9.0 |
| QRE | 1.2 | 1.9 | 1.9 | 1.9 | 1.9 | 1.8 |
| QHL | -4.9 | -6.7 | -4.7 | -6.4 | -3.6 | -5.2 |
| QGHL | -1.3 | -9.6 | -1.7 | -8.9 | -1.2 | -6.4 |

[1] One kilojoule (kJ) equals 0.95 British thermal units (Btu) and is 1000 joules.

[2] QHT = auxiliary heat
QSPH = solar panel to house
QSPR = solar panel to rock
QRS = rocks to house and greenhouse
QRE = rocks to environment
QHL = house heating load
QGHL = greenhouse heating load

[3] Degree days based on 700 hours in January and December

[4] Degree days based on 685 hours in February.

The energy balance equation of the December 1958 results given in Table 2 for the dynamic analysis in kilojoules is

$$Q_{SPH} + Q_{HT} + Q_{RS} = Q_{HL} + Q_{GHL}$$

$$\text{or } 0.6 \times 10^6 \times 0.6 \times 10^6 + 5.2 \times 10^6 = 4.9 \times 10^6 + 1.3 \times 10^6$$

$$6.4 \times 10^6 = 6.2 \times 10^6$$

and considering the results of the steady-state analysis, the balance would be

$$Q_{HT} + Q_{RS} = Q_{HL} + Q_{GHL}$$

$$6.6 \times 10^6 + 9.7 \times 10^6 = 6.7 \times 10^6 + 9.6 \times 10^6$$

$$16.3 \times 10^6 = 16.3 \times 10^6$$

The theoretical percent of heating load provided by solar heat in each analysis is given in Table 3.

TABLE 3.--Percent Residence/Greenhouse Heating Load Provided by Solar Heat.

| | December 1958 | January 1959 | February 1959 |
|---|---|---|---|
| Dynamic | 90 | 90 | 92 |
| Steady-State | 60 | 63 | 78 |

the weather data from somewhat different climatic areas were considered in both analyses. The dynamic analysis was done for Nashville, Tennessee, and the steady-state analysis for Greenville, South Carolina. Although average monthly temperatures were nearly the same, the available insolation may have differed more.

Relative humidity in the residence was also simulated by considering outside relative humidity, changing temperatures, plant transpiration in the greenhouse and normal household moisture input. The only apparent problem was that the relative humidity might get down to 17% in the house during heating, and this is too low. However, it is unlikely that this would be a serious problem because moisture vapor can be easily added to the air during normal greenhouse operation.

Two additional computer runs for a period of 14 days were performed with rock storage volume reduced by 25% and 50% to check the amount of thermal storage needed. This analysis showed that a 25% reduction in storage would only reduce energy savings by one percent. Halving the amount of storage would reduce savings by 8%. It was decided that it would not be economical to reduce the volume of rock, because any extra rock storage volume should improve efficiency during the summer cooling cycle.

## CONCLUSIONS

Results of the dynamic thermal analysis described in this paper were useful in providing improved design insight. The results indicated that several changes were necessary in the prototype changes that would save time and money. However, the computer programming method used in this analysis was costly to run and proved to be difficult to modify. Only a few of the prototype design parameters were checked during this analysis. Although the original intent was to vary size of greenhouse, solar collector and rock storage to develop design criteria, only the effect of changing the volume of rock storage was checked because of programming difficulties and related cost over-runs.

The next step planned involves modifying the dynamic thermal simulation program to lessen the computer time needed to check the remaining design parameters. The computer simulation program will also be checked against actual field test data. This will be done during the third phase of this project. Hourly weather data and prototype performance for at least 1 year will be monitored and checked against the simulated performance.

It is important that designer and programmer closely coordinate and fully understand each other's problem to obtain full benefits from computer simulation as a design tool. Preferably, they should work together during the initial development of the program.

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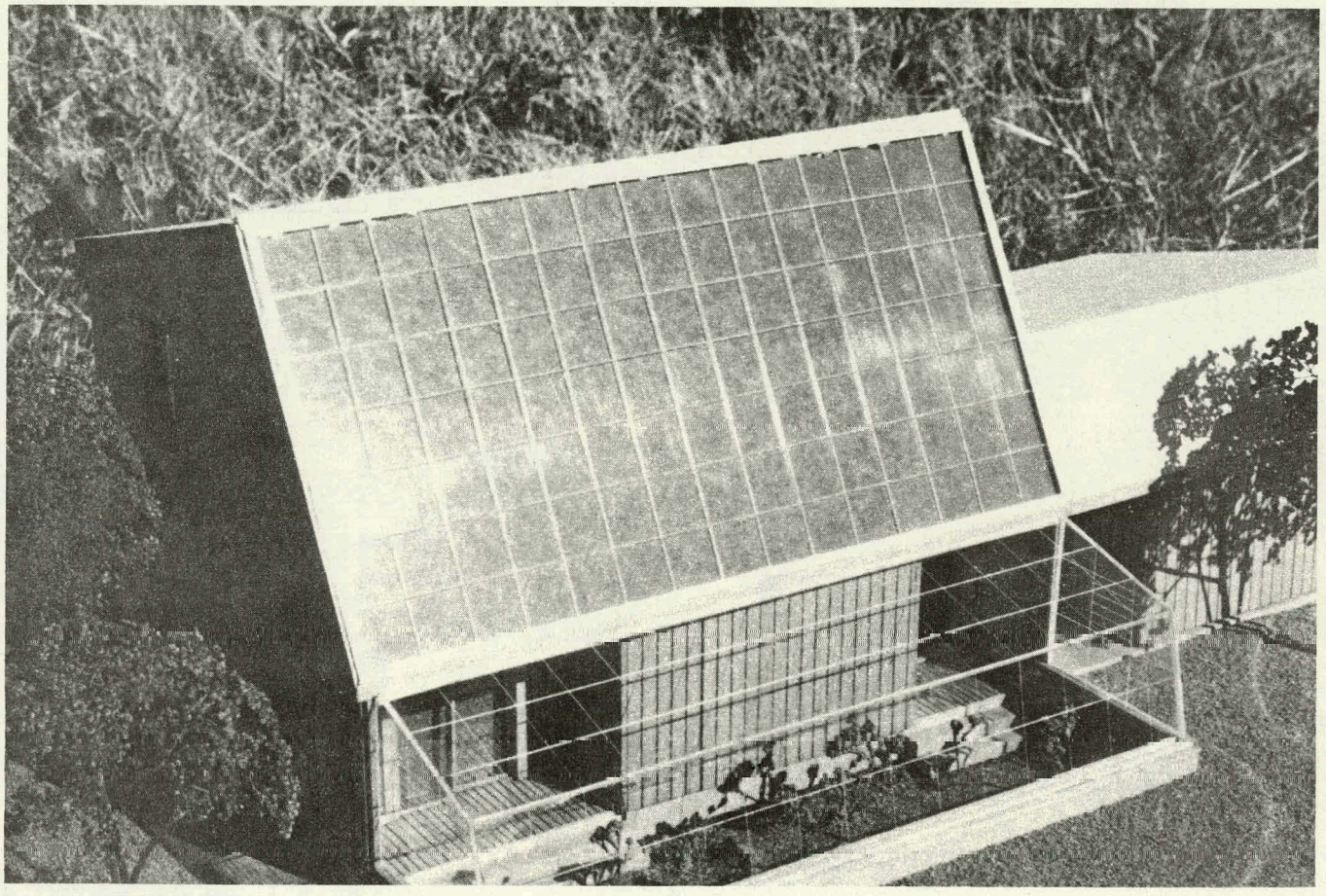


Figure 1.--Model of first solar residence/greenhouse combination.

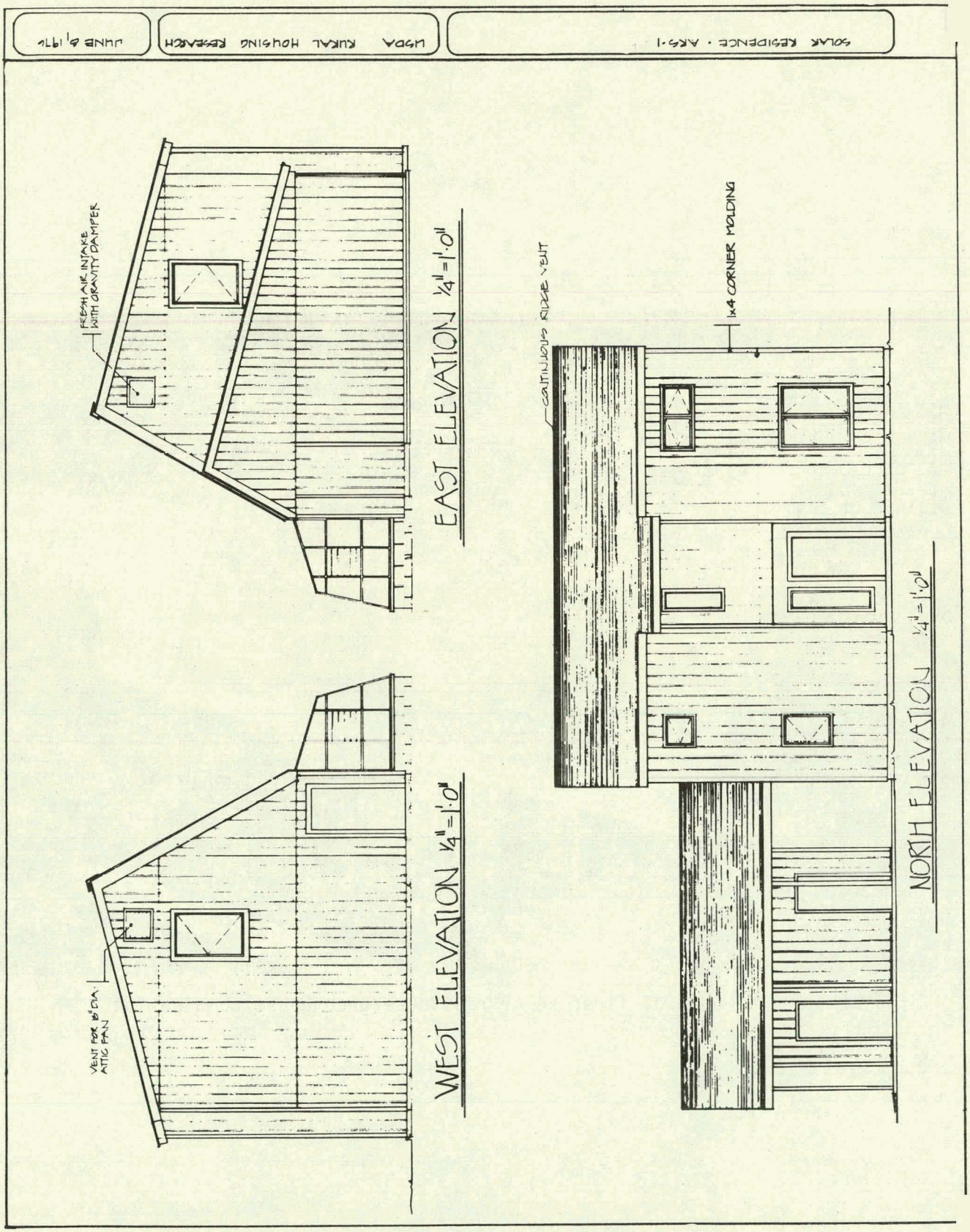



Figure 2.--Elevations from construction plans of first solar residence/greenhouse combination.

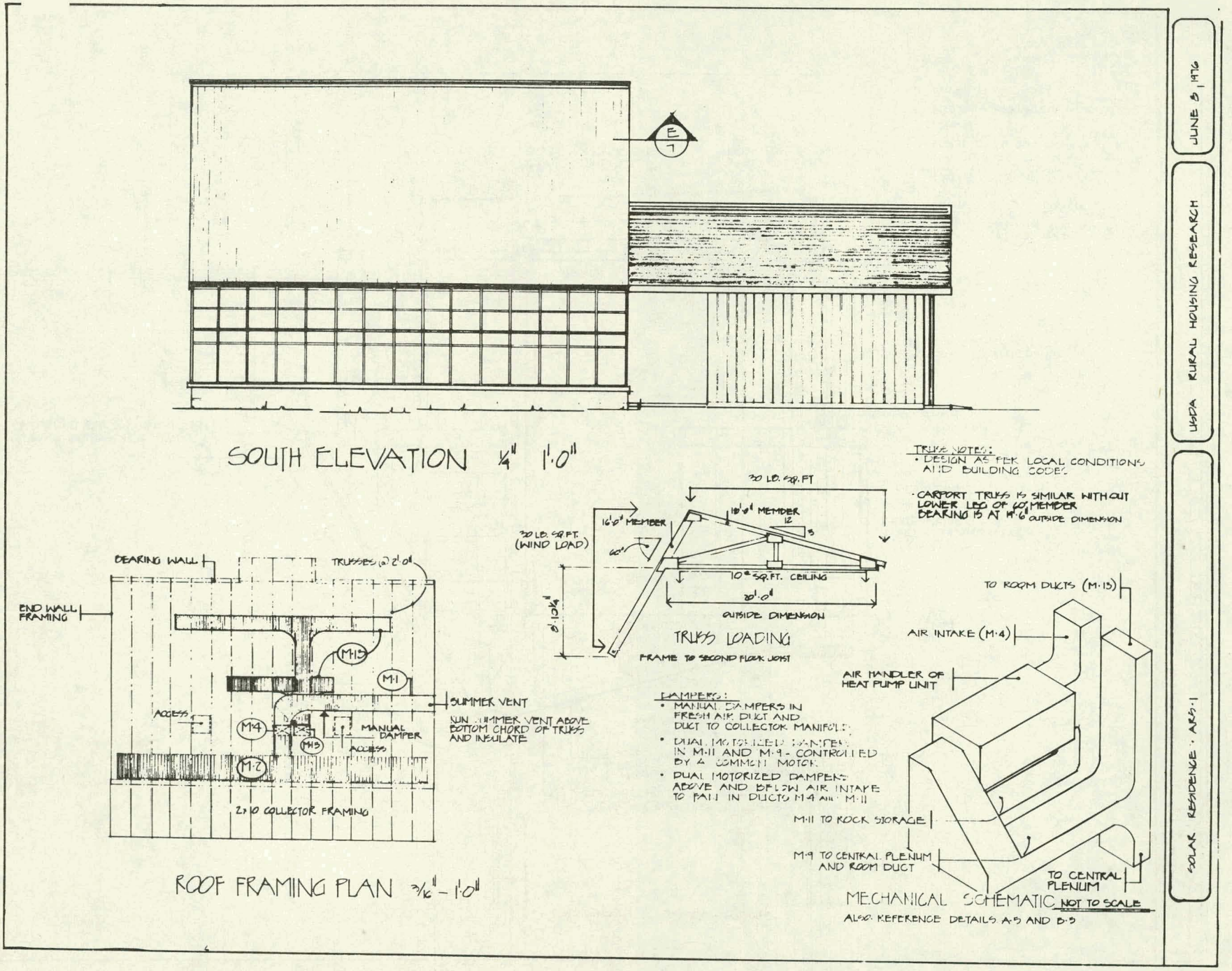



Figure 3.--Elevation and details from construction plans of first solar residence/greenhouse combination.

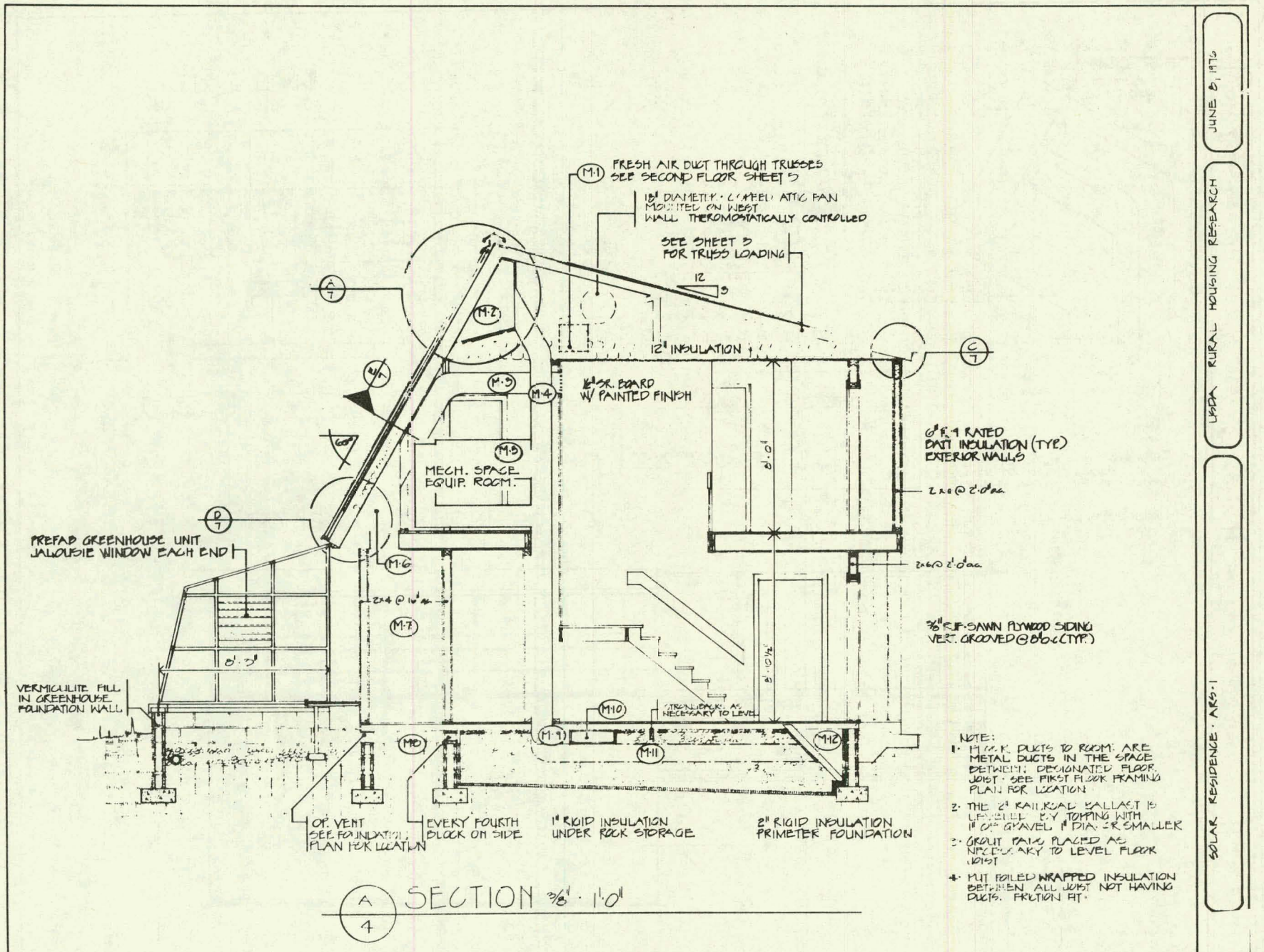



Figure 4.--Structural section from construction plans for first solar residence/greenhouse combination.

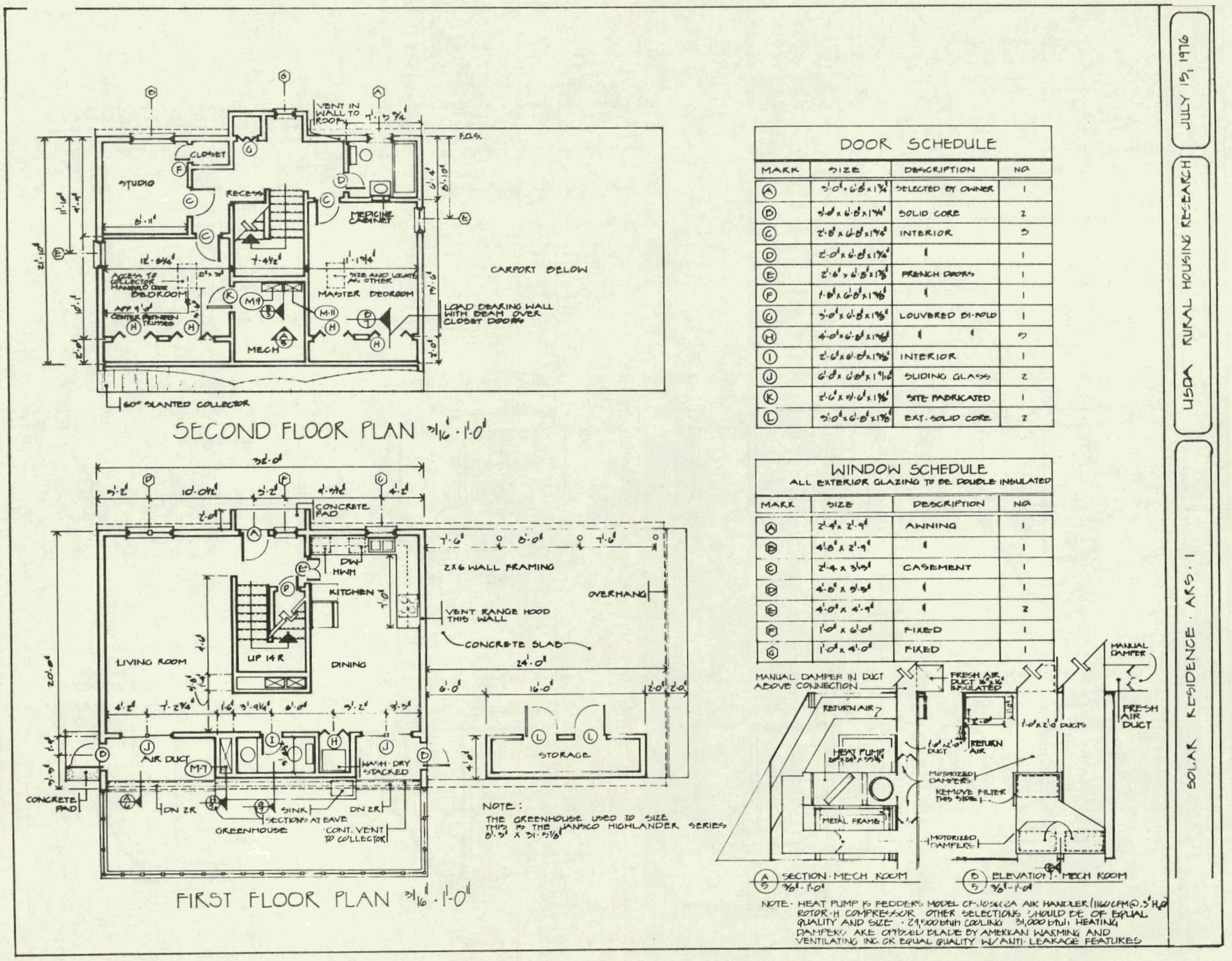



Figure 5.--Floor plans from construction plans for first solar residence/greenhouse combination.

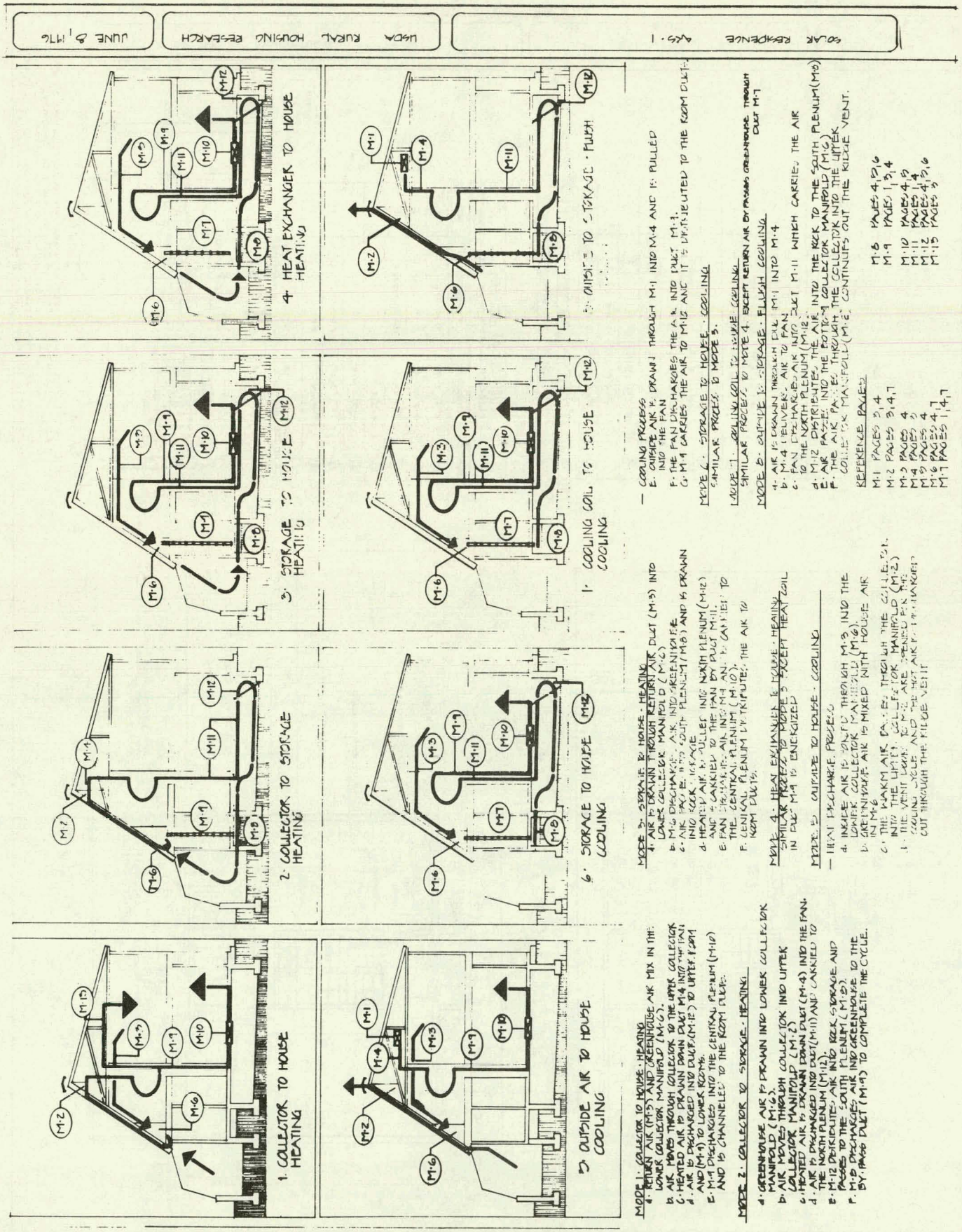



Figure 6.--Operating modes from construction plans for first solar residence/greenhouse combination.

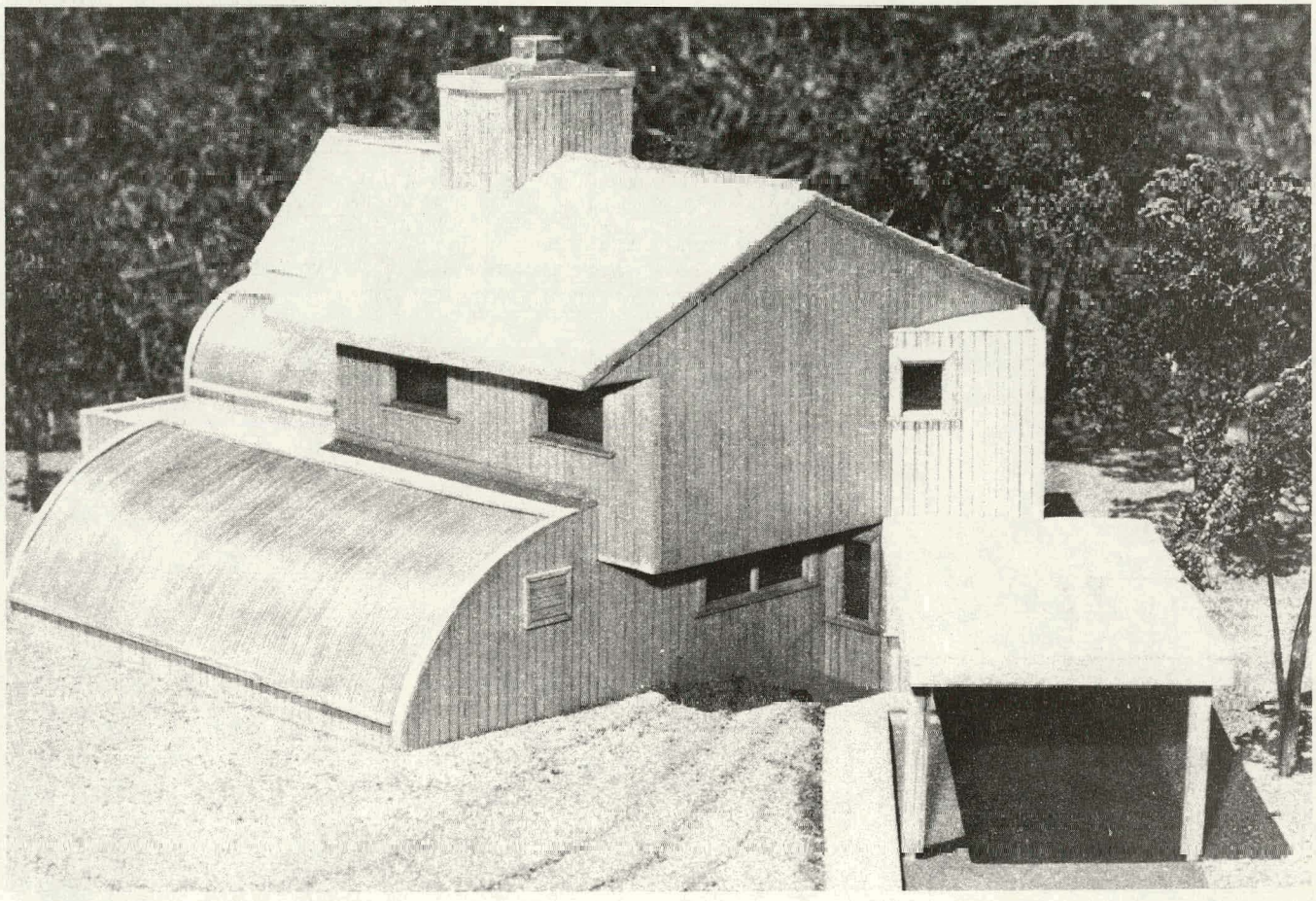


Figure 7.--Model of second solar residence/greenhouse combination.

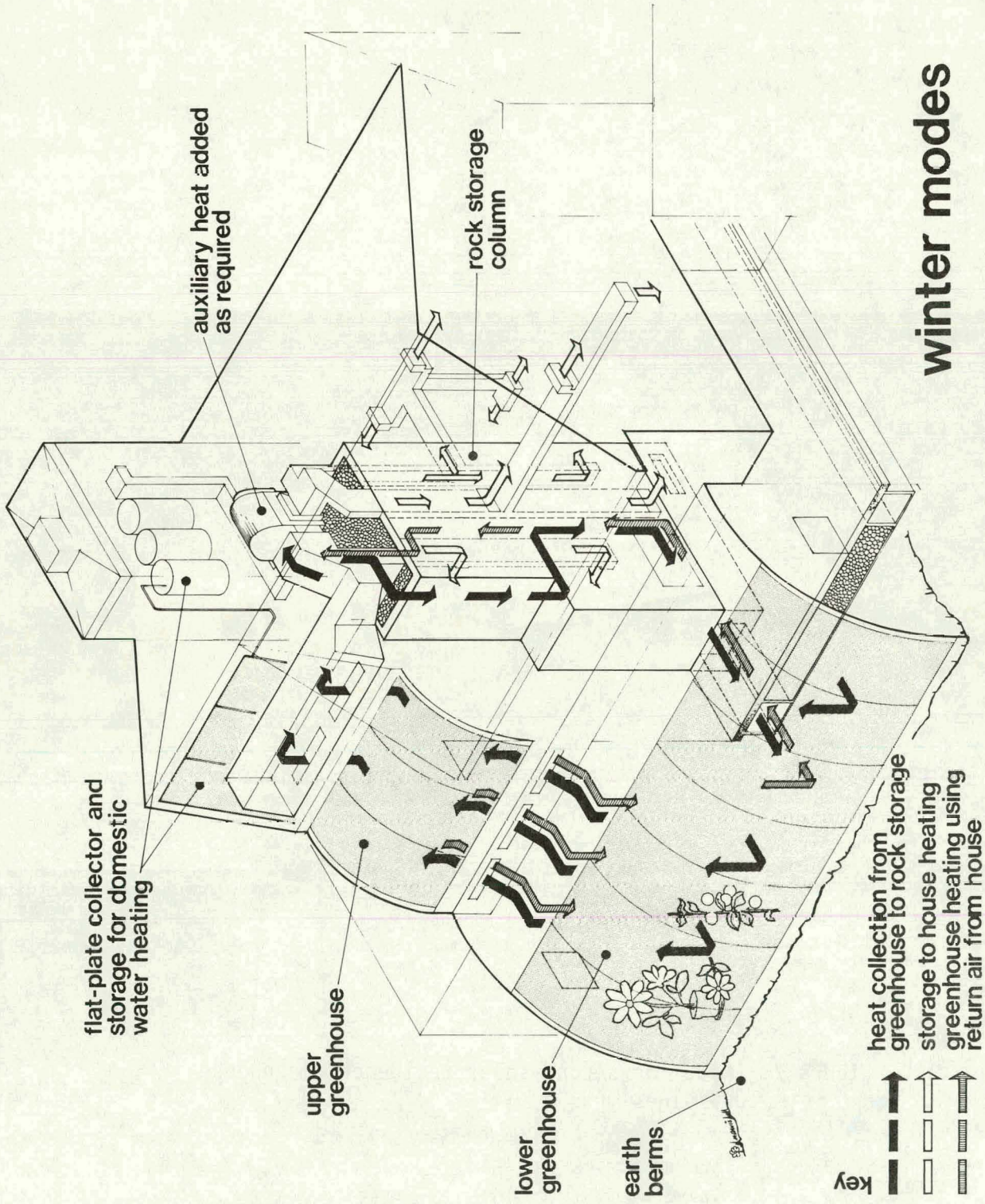



Figure 8.--Winter operating modes for second solar residence/ greenhouse combination.

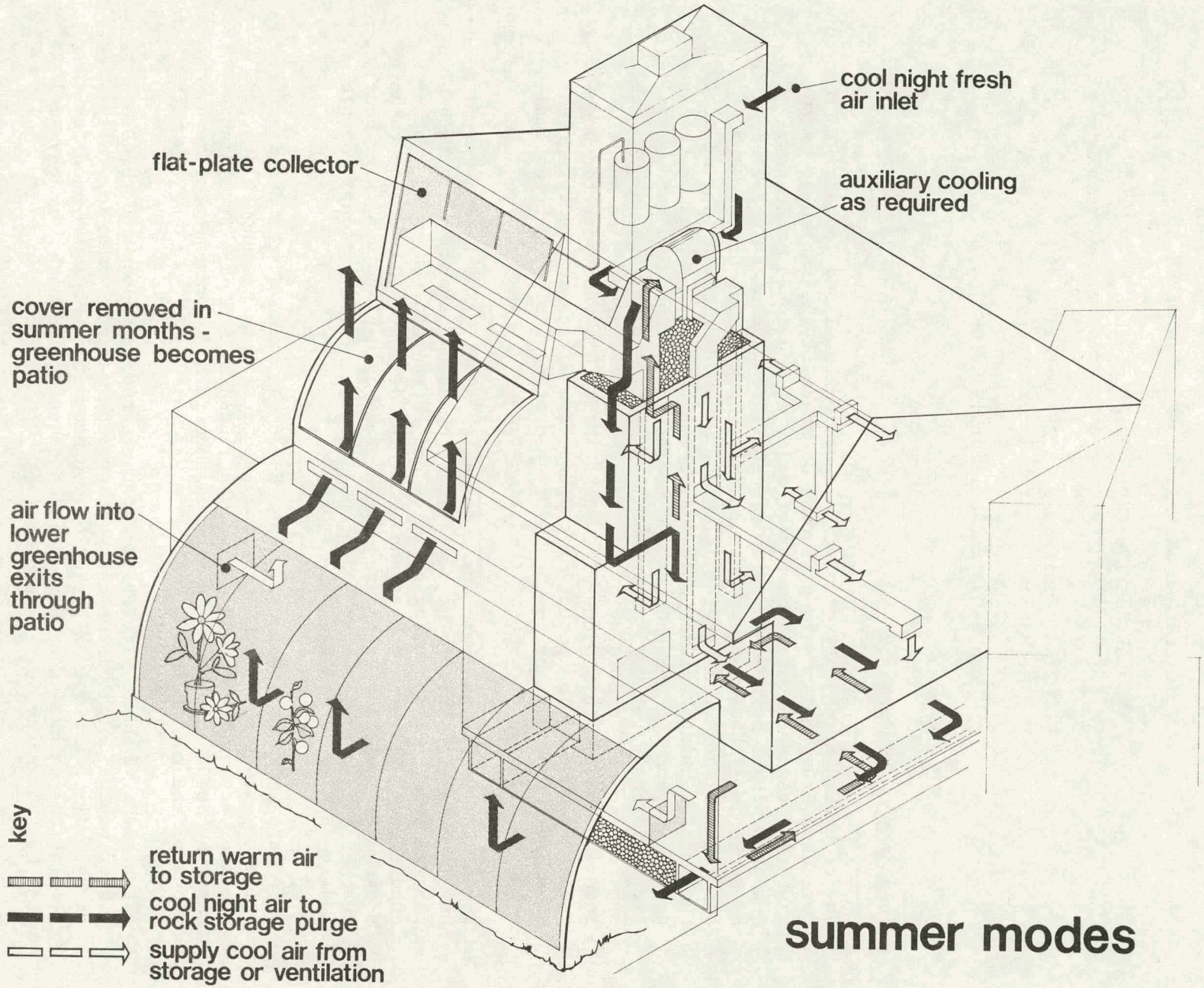



Figure 9.--Summer operating modes for second solar residence/ greenhouse combination.

# DYNAMIC THERMAL SIMULATION OF A PROTOTYPE SOLAR HEATING AND COOLING SYSTEM

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## INTRODUCTION AND SUMMARY

One of the major objectives of ERDA's Agricultural and Industrial Process Heat Program is the application of state-of-the-art solar components and technology to a number of major agricultural processes. Research within one such program element, greenhouses and residences, is being accomplished by the USDA Rural Housing Research Unit (RHRU), Agricultural Research Service, Clemson, S. C. During the spring of 1975 the Rural Housing Research Unit and Clemson University began a research project to combine greenhouses and residences so that low income families living in the rural U.S. could obtain significant savings on both fuel and food costs. According to (1), a family of four with an annual income of $8,000 to $10,000 will spend about $935 each year for vegetables and fuel. The potential savings from living in a solar greenhouse-residence similar to the RHRU's prototype designs were estimated to be at least 75 percent of this amount.

The prototype designs were based on analyses performed by the Rural Housing Research Unit. These analyses included a steady-state type of thermal load analysis using averages and extremes of observed weather conditions. To verify the adequacy of the design, RHRU decided to have a dynamic simulation of the residence-greenhouse prototype using hourly weather data recorded near the proposed sites by the National Oceanic and Atmospheric Administration (NOAA).

This paper presents the results and the description of the dynamic thermal analysis of one of the two prototype residence-greenhouse designs. The adequacy of the second design was judged by MRI on a preliminary basis by comparison of the design parameters and environmental condtions of the two designs.

A transient, dynamic simulation for three summer months and three winter months using historical weather data was performed for this study. Also, a two week period of winter weather data was used for two simulations to evaluate the effect of reducing the rock load physical size by 25% and by 50%, respectively.

The method of analysis and the technique of utilizing actual hourly weather data are described below along with the results. The quantities calculated and printed consist of the important temperatures, the quantities of heat (+ or −) flowing from one element to another during the simulation period, the mode of operation at any given time, and the cumulative effects including the total time spent in each mode of operation. The results show that the greenhouse-residence system will operate as designed to maintain the residence temperature within the limits of 65°F to 70°F.

During the winter the solar collector in combination with the rock storage provided 14.2 million kilojoules of heat while the heater provided an additional 1.1 million kilojoules for a net saving of about 93% for the three month period.

The house temperature always remained about 18°C (64°F); however, the greenhouse experienced minimum temperatures of 5°C (41°F) for short periods of time during the cold winter nights. This problem can be prevented by limiting the heat loss from the greenhouse during cold nights (e.g., an insulating cover over the greenhouse glass). The greenhouse temperature reached a maximum of 47°C (120°F) during the time of operation when heat passes from the collector to rocks. This problem can be prevented by redirecting the air flow to bypass the greenhouse when its temperature exceeds the desired upper limits.

The summer months simulation reveals no major problems. The rock storage absorbed 2.2 million kilojoules of energy while the heating unit provided 5.6 million kilojoules of refrigeration for a net saving of about 28%. This saving is slightly high because during the first and third week of June the temperature dropped into the 60's and 50's during the night, providing additional help in cooling the house during that period. A 20% saving was achieved during most of the simulation of the summer months.

An attempt to reduce the rock storage shows that it may be reduced by 25% without any efficiency loss during the winter. However, it is felt that such reduction may reduce the summer energy savings which are already low (simulation with a reduction in rock bed size was only done for the winter).

Therefore, it may be stated that the system design is slightly conservative being based on the original steady-state design calculations. Only minor modifications have been recommended involving shielding the greenhouse from heat loss or high temperatures.

## PROBLEM DEFINITION

The USDA greenhouse/residence design consists of a greenhouse having a roof, three exterior walls, and an interior wall common with the residence; a residence having a roof, attic and three exterior walls, solar panels located on south-facing portion of the residence roof; and

a rock storage bed located under the residence. A fan provides air circulation through the ducts leading to the rooms, the solar panel, and the rock storage. Auxiliary heating and cooling are provided by a heat pump. The walls, roofs, and ceilings all have conductances, heat transfer areas, and capacitances; while the interior of the building has capacitance. The orientation of the exterior surface determines the solar radiation received from the sun and must be calculated to consider the changing position of the sun.

All of the parametric values were provided by USDA or taken from their drawings except for capacitances, which were determined by MRI. From the architectural drawings of the Solar Residence Greenhouse and thermal characteristics provided by USDA, MRI had to develop a model of the complete building including walls, roof, attic, solar collector, greenhouse, growing plants (including evapotransmission effects), heat pump, occupants, lighting, rock thermal storage bed, soil beneath the rocks, solar infiltration, single glazing, double glazing, and air flow patterns. The interactions among all of these factors and the hourly varying weather data had to be simulated to provide a realistic simulation as shown in Figure 1.

Weather input data was extracted from two NOAA magnetic tapes containing the hourly weather data for Nashville, Tennessee during the winter and summer of 1959 (three months each). The tapes had considerable amount of data superfluous to the analysis and occasionally some missing data. From these source tapes, a final weather input data tape for the analysis was created by extracting the required temperatures, solar radiations, wind speeds, and humidity data.

The building can be operated in any one of nine modes (four heating, four cooling, and idle). The analysis had to determine the most economical mode of operation that is feasible at each point in time and divert the flow of air (hot or cold) as necessary to achieve simulation of that operational mode. The analysis also had to account for a three-foot portion of the soil under the rock storage to determine its effect on system performance. Its performance was simulated for two weeks to indicate the adequacy of the thermal storage capability.

## GREENHOUSE/RESIDENCE SYSTEM DESCRIPTION

Exterior views of the design of the residence-greenhouse combination are shown in Figure 2. The 464 $ft^2$ roof-top solar collector is attached to the south facing roof of the residence at an angle of 60°. The working medium is air which, during the winter, is preheated by available sunshine in the greenhouse to a temperature $T_G$, before passing into the roof-top solar collector.

A two-story frame house with full insulation between 2 by 6 studs, and a 12 in. thick ceiling insulation and small windows (double glazed)

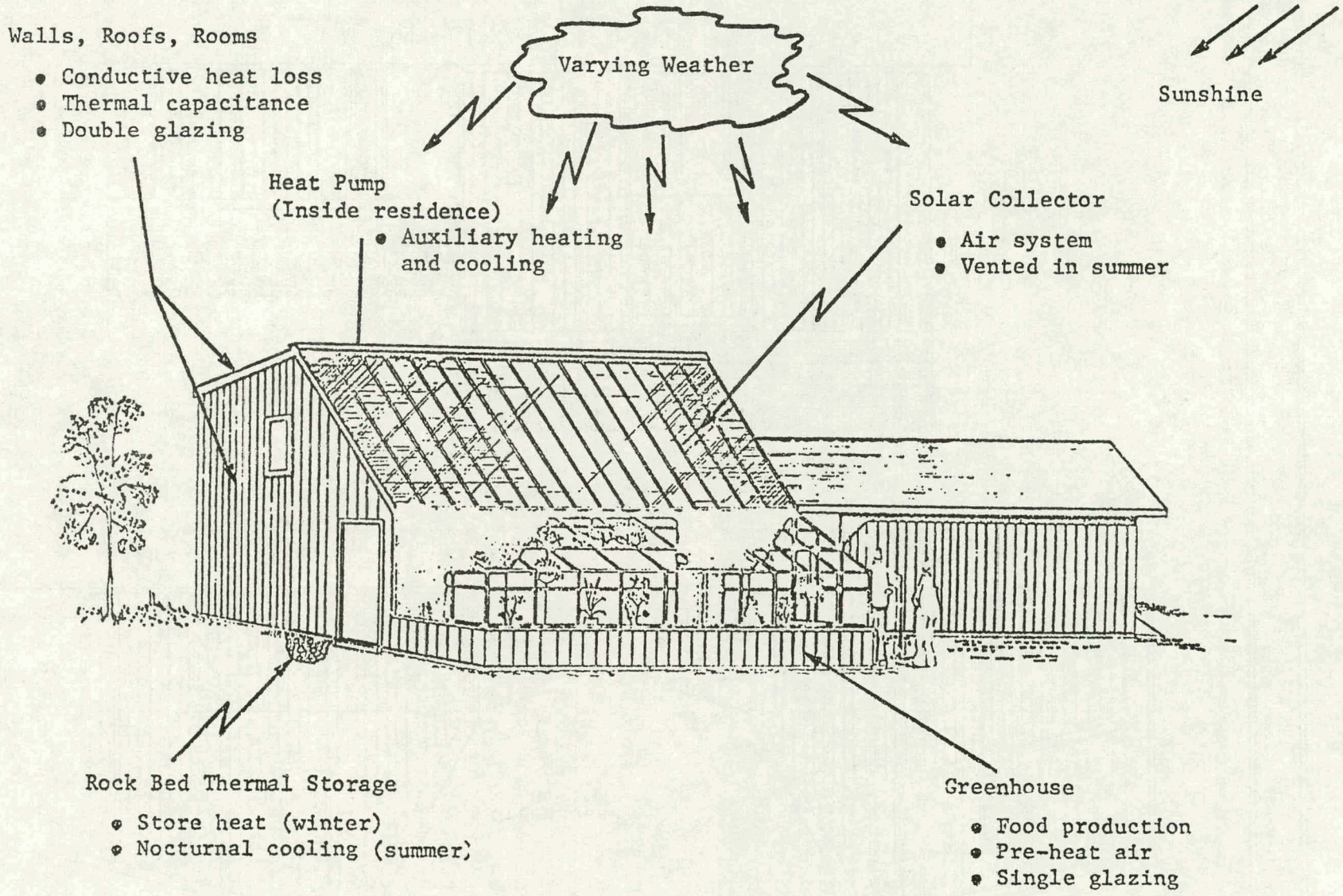



Figure 1. Solar Collector - Greenhouse - Residence.

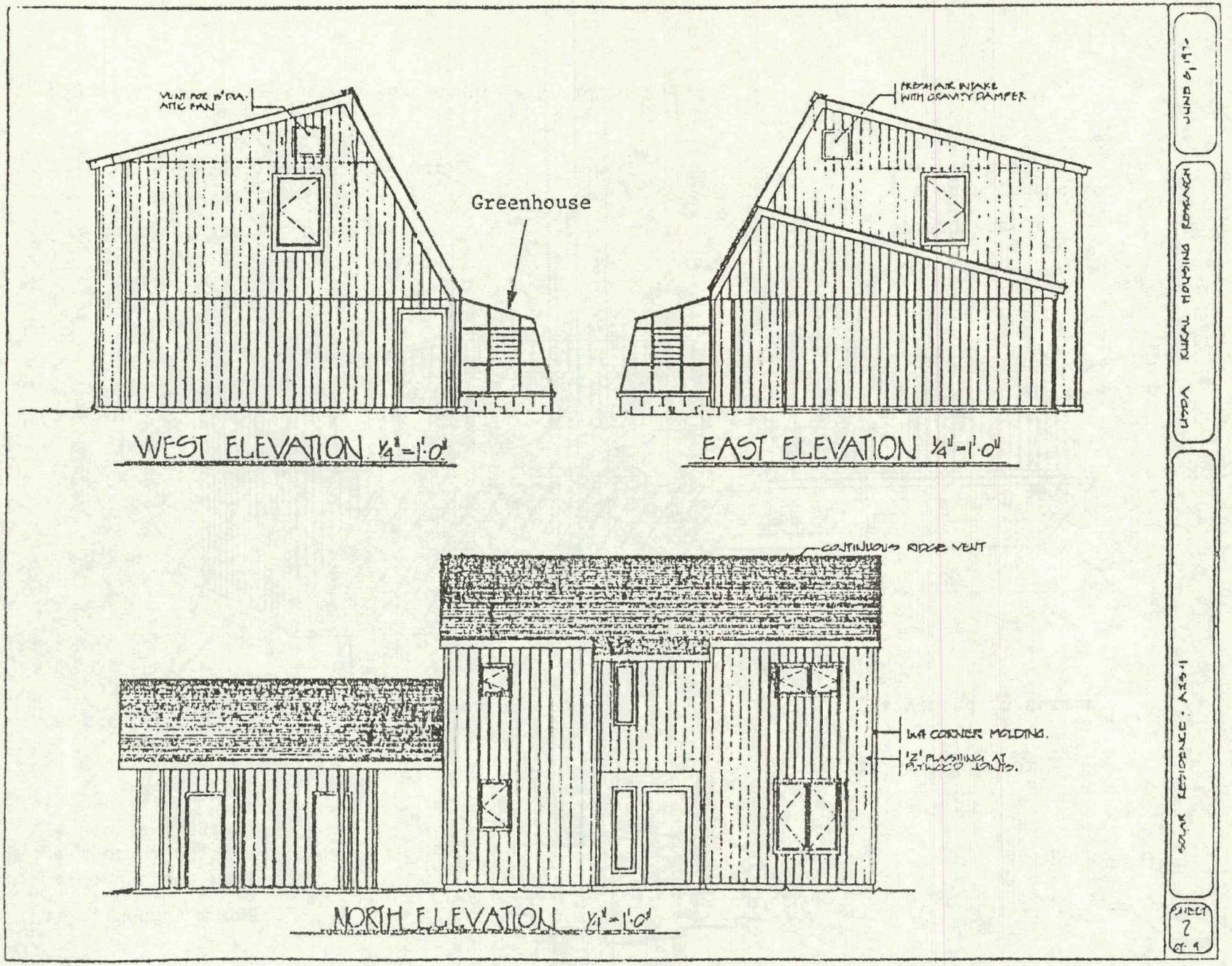



Figure 2

Architectural Drawing of a Prototype Residence/Greenhouse

were used to minimize heat loss. The house has 1600 $ft^2$ of living space and is occupied by four people 50% of the time. A 1200 btu constant heat input is used to represent all inhouse mechanical equipment heat output. The house air infiltration is assumed to be 1/2 air change per hour.

The greenhouse is constructed of prefabricated single glass layers for both walls and roof. It has a soil area of 286 $ft^2$ and is assumed to be 75% planted. The air infiltration in the greenhouse is assumed to be 1 air change per hour in the winter and 30 per hour during the summer.

The rock storage is placed under the house and is 17 ft. long with 82.2 $ft^2$ of cross sectional area. The bed is filled with crushed granite with a density of 94 $lb./ft^3$. The sides of the rock bed are fully insulated whereas the bottom sits directly on heavy clay soil.

The system has a total of nine modes of operation, one for idle, four for heating, and four for cooling. Briefly, the four heating modes are: (1) air heated in the collector passes into the house to directly raise the room temperature of the residence, (2) air passes from the collector into the rock bed for thermal storage, (3) air is heated in the rock bed and passes into the house for heating, and (4) air heated by the heat pump passes directly into the house. The four cooling modes (5 through 8) are: (5) outside air is brought into the house for cooling, (8) outside air passes through and cools the rock storage bed, (6) the cool rock storage bed air passes into the house, and (7) the heat pump cools the residence directly. In the ninth mode, (9) all components are in an idle mode. See Figure 3 for air flow patterns of each of the modes.

Both in the physical system and in the analysis to be discussed later, a control system which activates each of the operational modes is necessary. As the building model is "exposed" to historical transient weather conditions, the control system attempts to keep the residence within preset temperature limits by the most economical mode of operation while all other temperatures are allowed to "float". The greenhouse temperature, the rock bed temperatures, the temperature of the air at the collector exit, as well as the house temperature and ambient conditions must be monitored. When the residence temperature approaches either limit of the design boundary prescribed the control system will activate a heating or cooling mode as necessary. The eight operational modes are shown in Figure 3 and are activated in accordance with the requirements placed on residence temperatures (heating is required at 18°C and heating stops at 20°C, cooling is required at 25°C and stops at 23°C). The selected mode continues to operate until the residence temperature reaches the opposite extreme of the "comfort zone" which is specified as a design parameter.

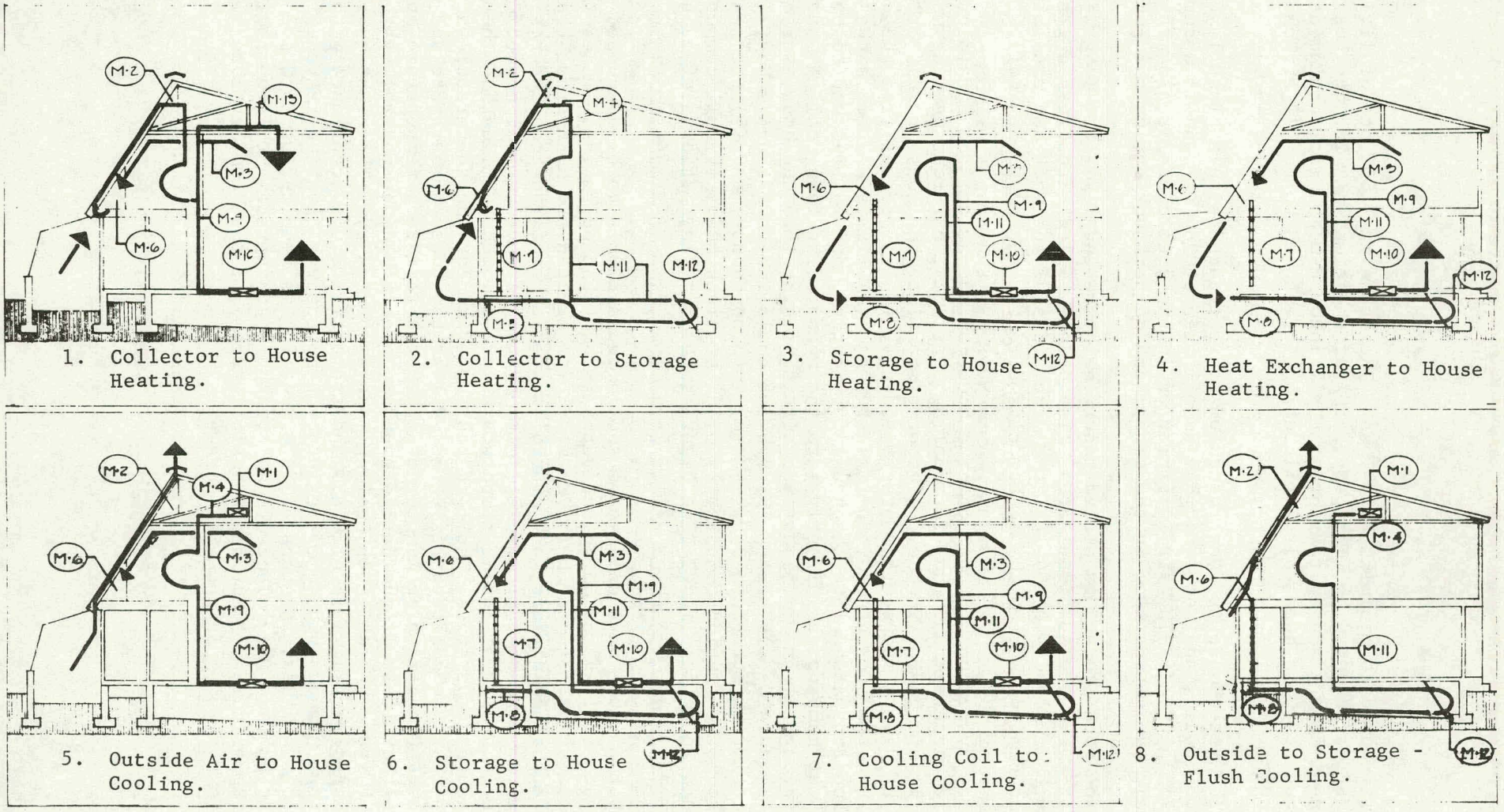



Figure 3. Modes of Operation.

## TECHNICAL APPROACH

The analysis code SOLSTAB (Solar Simulation for Thermal Analysis of Buildings) developed by MRI is based on the TRNSYS (transient simulation) code developed by the University of Wisconsin (2). Major modifications and additions to TRNSYS were necessary to account for the control system governing the operation of each of the components of the system, to account for humidity increases resulting from evapotranspiration, to include the characteristics of performance for the selected heat pump, to calculate the sum the degree days of heating/cooling, and to integrate the time of operation in each of the allowable modes.

The modular simulation technique of SOLSTAB greatly reduces the complexity of system simulation because it essentially reduces a large problem into a number of smaller problems, each of which can be more easily solved independently. In addition, many components are common to different systems and, provided that the performance of these components is described in a general form, they can then be used in many different systems with little or no modification. This feature makes modular simulation most attractive.

Insofar as this dynamic analysis of the heating and cooling system is concerned, the system is defined to be a set of interconnecting components, a solar collector, a rock bed thermal storage unit, an auxiliary heater (heat pump), a fan, walls and roofs, windows, soil under the rock bed, and several temperature sensing controllers. Because the system consists of components, it is possible to simulate the performance of the system by collectively simulating the performance of the interconnected components. The performance of a system component will normally depend upon characteristic fixed parameters, the performance (or output) of other components, and time-dependent forcing functions. For this solar heating and cooling system, information on the weather (i.e., solar radiation, ambient temperature, etc.) and the thermal load demand as a function of time is necessary in order to determine the transient system performance. It is important to realize that time dependent forcing functions can be thought of as outputs of specialized system components and they can thus be treated in the same manner as any other component.

With a program such as the one used in this analysis, the problem of system simulation reduces to a problem of identifying all of the components, formulating a general mathematical description of each, and interconnecting them properly. The example of Figure 4 indicates how the modular system components interact during the mode 2 operation (heat from solar collector to rock storage mode). The solar radiation and weather interact with the solar panel, greenhouse walls, and the other elements so indicated by arrows in the figure. In turn, those elements interact with the components shown in the lower row of modules in the way indicated. This example is greatly simplified insofar as the flow of information and control logic is concerned, but serves to illustrate the usefulness of the modular approach.

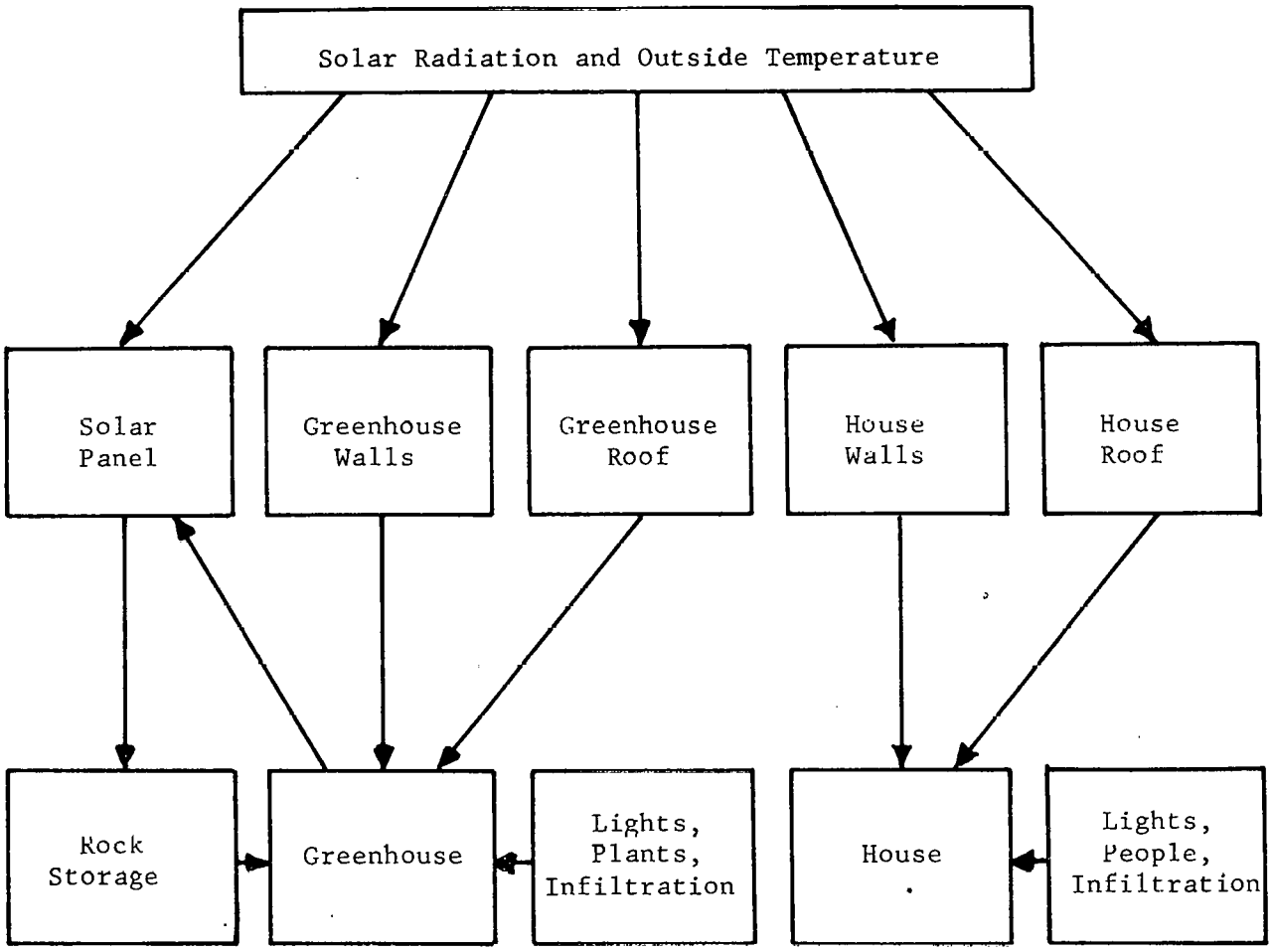



FIGURE 4. Example - Components Interaction. Solar Greenhouse Residence. Simplified Block Diagram for Solar to Rock Storage Heating Mode.

Figure 5 shows the components of the system. Each component must first be described in terms of the mathematical description which best simulates its performance and considers all the thermal characteristics needed to determine its thermal behavior.

Once all of the components of a system have been identified and a mathematical description of each component has been formulated, it is necessary to construct an information flow diagram for the system. An information flow diagram is a schematic representation of the flow of information into and out of each of the system components. In the diagram, each component is represented as a box. Each piece of information required to completely describe the component is listed next to the box. Each piece of information calculated by equations describing the component can be independently directed out of the box into any other component. Four types of information flow may exist in the information flow diagram, INPUTS, OUTPUTS, PARAMETERS, and TIME.

Figure 6 indicates the manner in which components can be independently connected. INPUTS are those parameters whose values may vary with time during the simulation period but come into that component (subroutine) at that particular time as inputs from the output of another component (they were dependent variables in the component from which they came but are independent variables in the component of interest for that time period). In other words, INPUTS have specific values when used to solve the differential equations for the component of interest but may have varied during the solution of the equations governing the previous component behavior, and so must be "updated" at each time interval. OUTPUTS are the new values of those parameters which govern the behavior of the component of interest after solution to the differential equations governing that behavior has been accomplished. PARAMETERS are those pieces of information that are always constants in the differential equations to be solved. TIME is the independent variable in the equations. In some cases, DERIVATIVES may be identified in the information flow chart and are those dependent variables whose initial values must be specified in order that the derivative of those parameters with respect to time can be estimated for solution of a set or sets of algebraic equations consistent with a Modified-Euler method of numerical integration. The derivatives are re-estimated until convergence of the solution to the algebraic equations is achieved.

An executive program combines all the components into a set of algebraic and first order differential equations. For a dynamic analysis, the performance of the system is analyzed at each (pre-set) time interval. A small enough time step is selected so that instabilities in the analysis do not occur. The executive routine cycles the program through each time step so that the performance of each unit can be calculated. The direction of flow and positions of flow diverters are determined by the control unit based on the temperatures of the house, ambient conditions, rocks and solar panel.

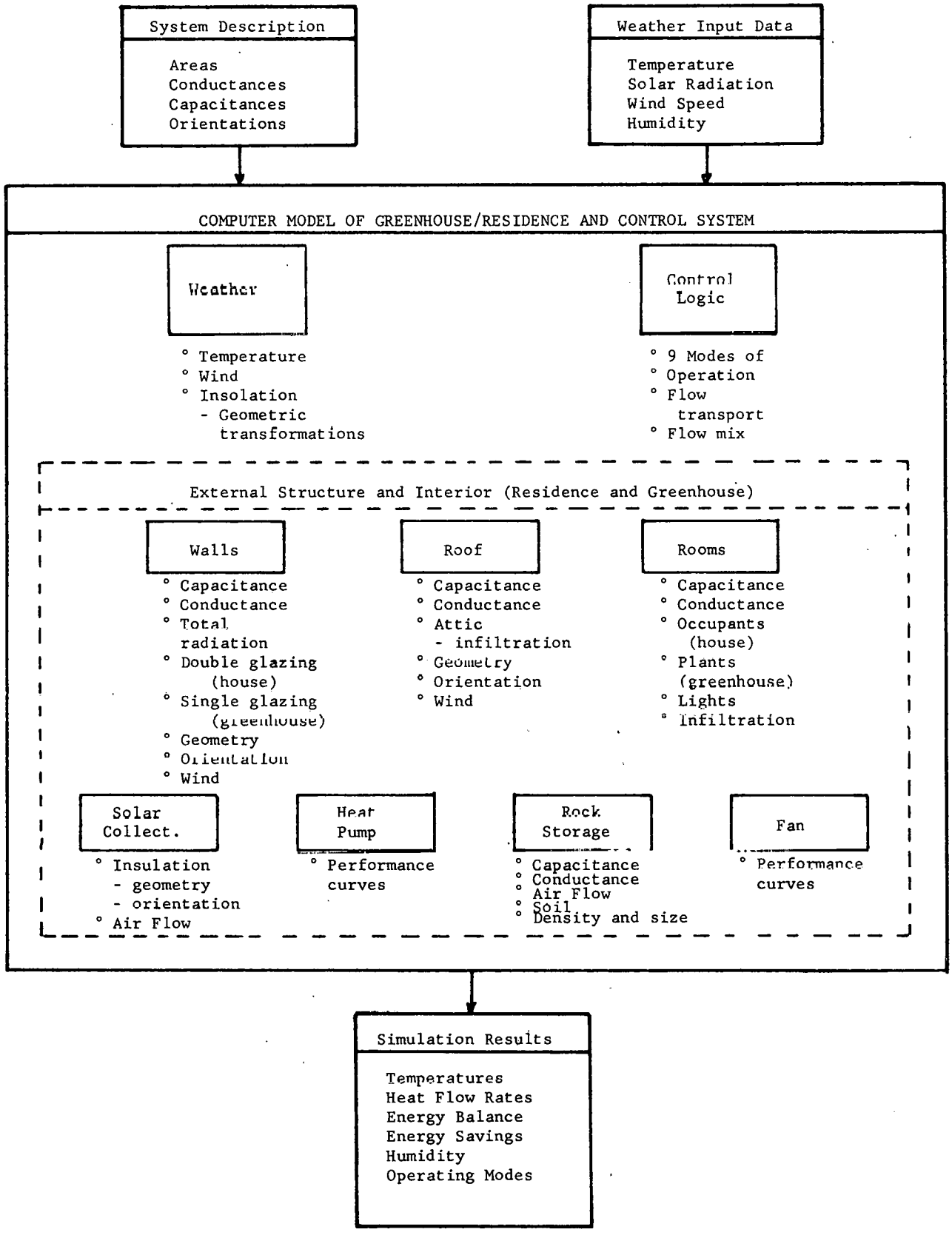



FIGURE 5. Solar Greenhouse/Residence Analysis Requirements.

Table 1 summarizes the steps to be taken in this analysis method.

## WEATHER DATA

As indicated in Figure 7, the weather data used in the analysis and solar radiation, dry bulb temperature, wet bulb temperature, relative humidity, and wind speed. These, plus other data, are available from the National Oceanic and Atmospheric Administration (NOAA) on magnetic tapes. Tape Numbers 144 and 280 (Nashville, Tennessee) were used for the analysis as representing the nearest location to Clemson, S. C. for which there are hourly data from 1958 through 1966. The data from the NOAA tapes for the coldest three winter months (December 1958, January and February 1959) and the hottest three summer months (June, July and August 1959) were extracted to form two new tapes; one for each of the three month periods. The hourly data on the tapes are read into the computer program which interpolates for weather values at times between the hours recorded.

## DEGREE DAYS

An indicator of the climate in an area, which is generally accepted by the "solar community", is the number of degree days for heating and for cooling. Heating degree days is the integral with respect to time of the difference between 65°F and the ambient temperature, when the temperature is below 65°F. Cooling degree days is the similar integral of the temperature above 75°F. The totals of each are computed and output at each integration time step.

## INCLINED SURFACES

The flat-plate solar collector, the walls, and the roofs are at an incline with respect to horizontal. The solar radiation data contained on the NOAA tapes, however, were taken by instrumentation on horizontal surfaces. Therefore, it was necessary to estimate the radiation impinging on a tilted surface from the radiation measurements on a horizontal surface. Although the estimate is based primarily on the geometrical relationships, which depend on latitude and time of day, it is not entirely straightforward because of the difficulty in treating diffuse radiation on tilted surfaces. The relationship used for this component (3) appears to be the most reasonable available.

## MODE LOGIC

The nine modes of operation of the residence (four heating, four cooling, and idle) were specified by the RHRU. The mode used at any point in time depends on the various temperatures in the system. The mode is

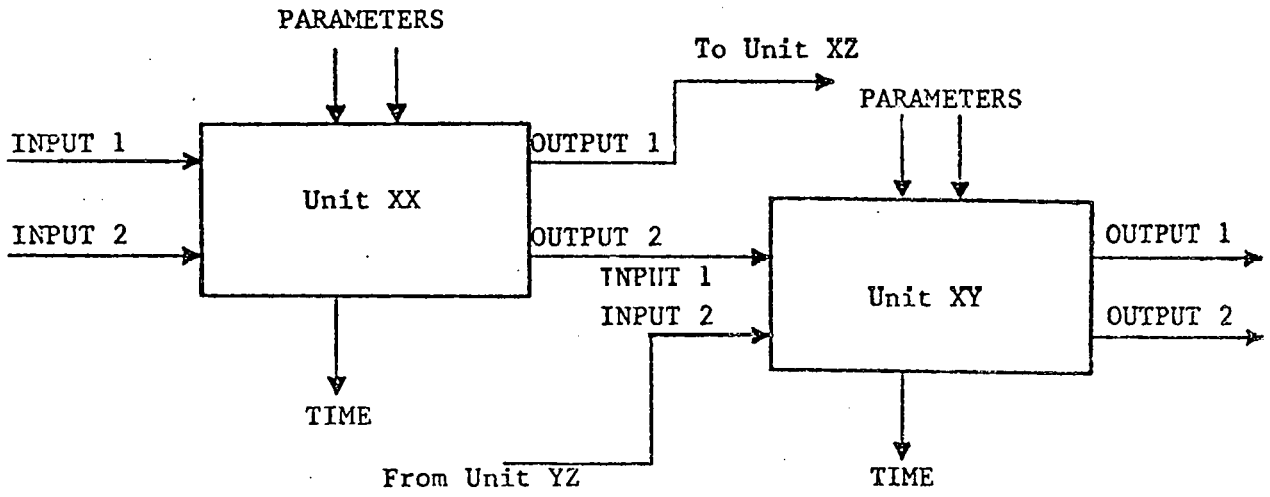



FIGURE 6. Flow diagram for computer analysis.

TABLE 1. Required Steps for Analysis Method.

- Identify System Components
- Construct Information Flow Diagram
- Associate TYPE Numbers With the System Components
- Assign UNIT Numbers to the System Components
- Identify and Sequence Component INPUTS, OUTPUTS, and PARAMETERS
- Identify and Initialize Time-Dependent Variables
- Construction Logic Diagram Connecting the Outputs and Inputs of Components Which Interact
- Specify Starting and Stopping Time for Simulation and the Integration Time Step
- Activate Executive Routine Having Proper Access to Logic Subroutines and Component Subroutines

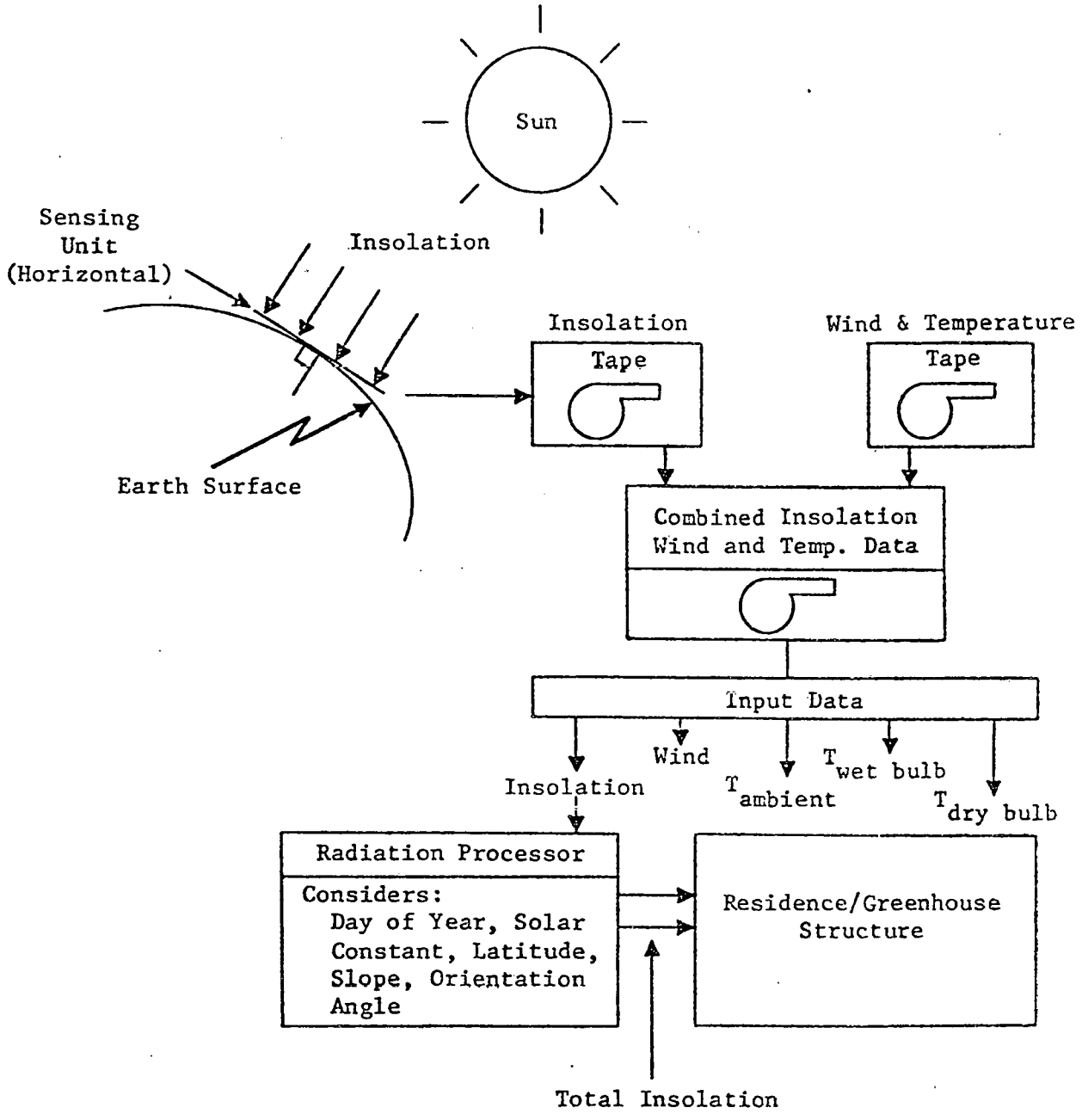



Figure 7. Weather Data

then selected based on a) a comparison of the temperatures of the residence and the preset heating and cooling threshold temperatures, and b) heat requirements (see Table 2). The selected mode dictates the heat flow patterns through the building. A controller subroutine performs all of the logical decision-making and sets the variables that control the flow at each integration time interval.

## FLOW TRANSPORT AND MIXING

To simulate the air flow patterns in the various modes of operation, it is necessary to "switch" the air flow. This is done by means of diverters and mixers. The diverter proportions a flow between two paths (usually all to one or all to the other). The mixer combines part of one flow with part of another to form a single flow (usually all of one or all of the other). Proper combinations of diverters and mixers simulate flow reversal, bypassing parts of the house, etc.

## COMPONENT ANALYSES

The performance of each of the various components of the residence/greenhouse was separately modeled and described mathematically to simulate the salient features affecting system performance.

As indicated previously, one of the first steps in the dynamic simulation was to formulate mathematical models of the components of the system. For use in this simulation, the models must be programmed in accordance with the previously discussed procedure so that the executive routine can perform the component interconnections as directed by the user.

## SOLAR COLLECTOR

Several different models of the thermal performance of flatplate solar collectors with forced fluid circulation have been investigated (4). The HWB model which was described by Hottel (5), Whillier (6), and Bliss (7) appears to be best suited for simulations because of its computational simplicity and its excellent agreement with more elaborate models.

## FAN

A fan is modeled by specifying the maximum flow rate which the fan is capable of delivering. The output flow rate of the fan is determined by the input flow rate and can be between 0 and 1 times the maximum flow rate. For the present system, there is no continuous modulation and the control function is either 0 or 1. The temperature of the outlet stream is the same as the inlet stream.

| Control System Logic | | |
|---|---|---|
| Mode | Temperature Requirements | Heat Requirements |
| 1 - Collector to house heating | TOUT > TH < THMIN | None |
| 2 - Collector to storage heating | THMIN < TH < THMAX AND WINTER TOUT > TSTOR | None |
| 3 - Storage to house heating | TSTOR > TH > TOUT AND TH < THMIN | ΣQH > 0 |
| 4 - Heater to house heating | TSTOR < TH > TOUT AND TH < THMIN | None |
| 5 - Outside air to house cooling | TA < TH > THMAX | None |
| 6 - Storage to house cooling | TA > TH > STOR AND TH > THMAX | ΣQH < 0 |
| 7 - A/C to house cooling | TA ≥ TH ≤ TSTOR AND TH > THMAX | None |
| 8 - Outside to storage flush cooling | THMIN < TH < THMAX AND SUMMER TA < TSTOR | None |
| 9 - Idle | THMIN < TH < THMAX WINTER TOUT < TSTOR SUMMER TA > TSTOR | None |

TA = Ambient temperature
TH = House temperature
THMAX = Maximum house temperature
THMIN = Minimum house temperature
TOUT = Solar panel output temperature
TSTOR = Rock storage temperature
ΣQH = Summation of house heat (gain or lose) conduction through the walls and roof and air flow through rock storage. (This condition is met as long as the residence is obtaining some net advantage from the rocks.)

Table 2

EVAPOTRANSPIRATION (8), (9)

The effect of evapotranspiration of the greenhouse plants on the house humidity was analyzed by

Potential ET = .0004396 (I - .746)
ET = (.5) (Potential ET)
where: ET = Evapotranspiration rate in lb./hr.
I = Solar radiation on plants in Langleys/hr.

After conversion of the relative humidity of the incoming air into the ratio of moisture weight to air volume, the additional moisture added to the air by evapotranspiration can be included and a new dew point and relative humidity can be calculated. That calculation requires a relationship between the final ratio of air volume to moisture weight at saturation, V, and the temperature, T. That relationship (from standard steam tables) can be expressed as $V = 325.54/T^{1.28} - 545.3$ with less than 5% error between 32 and 100°F (where V = $ft.^3/lb.$ and T = °F).

WALLS

A multinode, thermal capacitance wall model has been used to represent all wall constructions. Each exterior wall of a structure is treated as a separate unit, thereby allowing for different wall area, window area, window shading area, orientation, construction details, etc.

Successive energy balances are done on each node to determine all node temperatures. Node S is assumed to be an algebraic node, i.e., no thermal capacitance, while nodes 1 through N are capacitive thermal nodes (see figure below). The wall subroutine is used to describe all external residence and greenhouse walls plus the greenhouse roof, since the wall subroutine best describes the glass plate greenhouse roof (no attic). It is also used to simulate the soil under the rock storage, since the soil can be represented as series of layers each of which is similar to a wall insofar as its composition is a series of conductances and capacitances.

## ROCK BED THERMAL STORAGE

Rock bed thermal storage can be described by the relations governing heat transfer for fluid flow in packed beds. Temperature gradients within the rocks are neglected, and a uniform flow distribution of air through the bed is assumed. Two partial differential equations describing the air and rock temperatures as a function of the distance along the bed length and time were used. These equations are solved by finite difference methods. However, small time steps (.083333 hours was used) and many nodes are required to maintain accuracy. As a result the use of this model in simulations for extended periods (e.g., a heating season or a year) becomes expensive in terms of computing costs.

## SOIL

The soil under the rock bed may provide additional thermal storage depending upon the moisture conditions. Measurements by USDA have shown the first three feet to be effective, so this much of the soil was modeled as three one-foot layers. Since the soil is essentially a series of conductances and capacitances, the wall model was suitable for representing the soil, using appropriate values. The soil was specified as type M2 in Reference (10) and is saturated with moisture at the bottom and dry at the top. Conductivity and capacitance are given for dry and damp soil in Reference (7) and are used for the upper and middle layers respectively. Conductivity and capacitance are given at saturation in Reference (11) for several soils. They did not vary greatly; so an average value was used for the lower layer.

The soil properties are

| Soil Condition | Conductivity $\frac{BTU}{m\text{-}ft\text{-}^\circ F}$ | Capacitance $\frac{BTU}{ft^3\ ^\circ F}$ |
|---|---|---|
| Dry | .2 | 25 |
| Damp | .9 | 30 |
| Saturated | 1.3 | 67 |

## HEAT PUMP

Manufacturer specified performance curves (12) were stored in the computer in tabular form to simulate its performance. This component received its input conditions from other subroutines as did the previously described components and the performance (heat output or refrigeration) was determined from the manufacturer specified specifications and performance curves.

ROOM

A one node room model has been used with the wall and roof models for calculation of space heating or cooling load. Energy flow rates into (or out of) the room are accepted from its walls and the roof. An arbitrary number of other heat gains (or losses) may be input from sources such as rock storage or cyclical light fixture loads. The model calculates the energy flows through the baseline (or slab floor), infiltration losses, and internal generation from occupants, lights, appliances, etc. After summing all of the energy flows, the room temperature is calculated from the user-specified value of room thermal capacitance, net energy flow, and the room temperature at the previous timestep ($T^-$).

This model is used for the residence and the greenhouse.

ROOF

A "standard" pitched roof model, as shown in Figure 8, was used to represent the roof of the residence. The analysis is similar to that for the walls insofar as the capacitance and conductance of thermal energy is concerned.

RESULTS

The results are based on a 6 months simulation equally divided between winter and summer seasons. An average energy saving of about 90% during the winter and 20% during the summer has been shown by the simulation. Reduction of the rock storage size to 75% and 50% of its design value (for two weeks of winter simulation only) results in 1% and 10% (i.e., rather than 90%) less savings.

HEAT GAINS AND LOSSES

The analysis during three winter months of simulation has resulted in the following heat gains and losses:

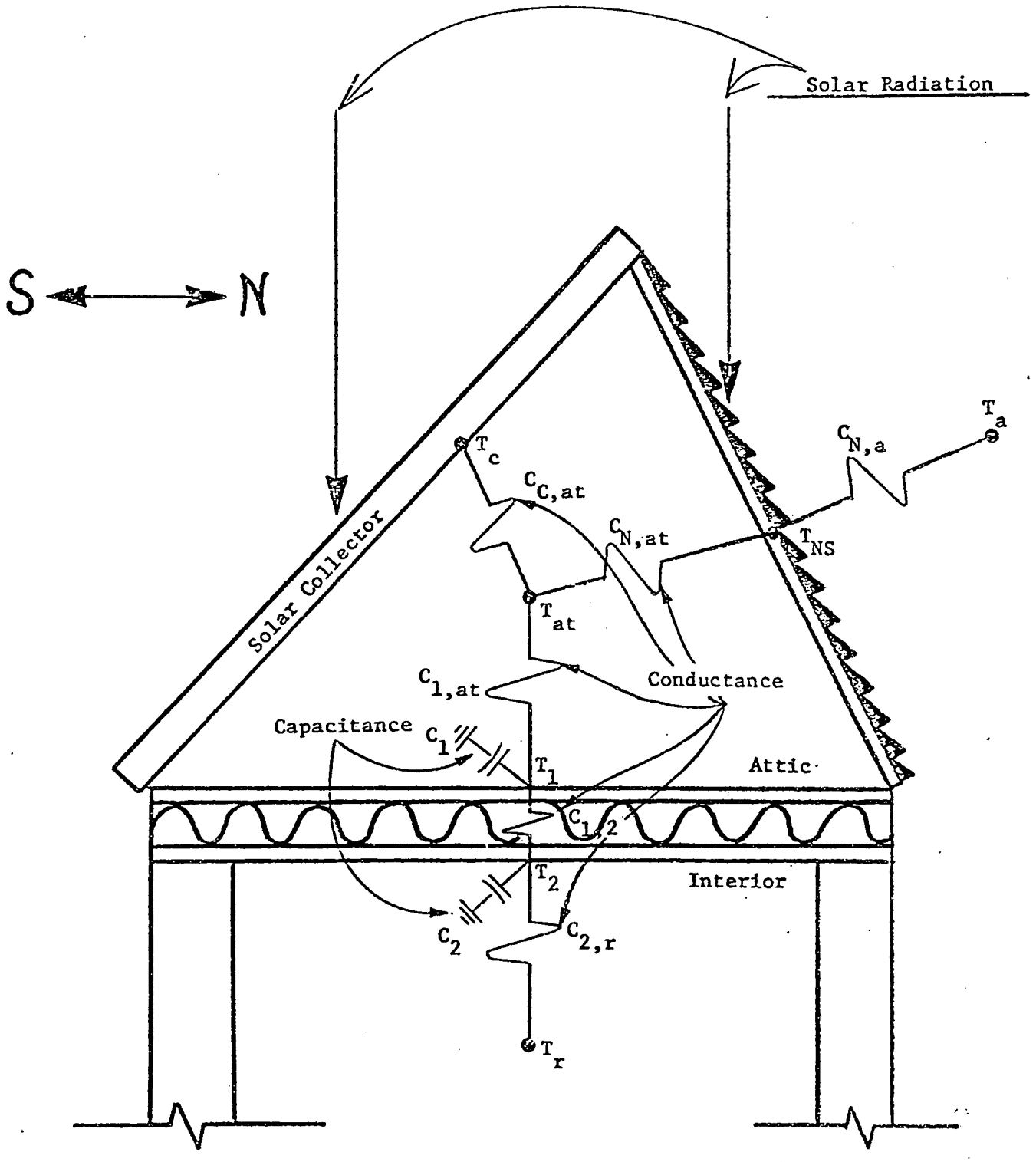



Figure 8

Pitched Roof Model

| Month | Heat Gains (KJ) | Heat Losses (KJ) |
|---|---|---|
| Dec. 58 | Heater = $5.8 \times 10^5$ | House = $4.9 \times 10^6$ |
| | Solar Panel | Greenhouse = $1.3 \times 10^6$ |
| | to Rocks = $3.0 \times 10^6$ | |
| | to House = $5.5 \times 10^5$ | |
| | Storage to System = $5.2 \times 10^6$ | |
| Jan. 59 | Heater = $.85 \times 10^5$ | House = $4.7 \times 10^6$ |
| | Solar Panel | Greenhouse = $1.7 \times 10^6$ |
| | to Rocks = $2.8 \times 10^6$ | |
| | to House = $.60 \times 10^6$ | |
| | Storage to System = $5.4 \times 10^6$ | |
| Feb. 59 | Heater = $3.9 \times 10^5$ | House = $3.6 \times 10^6$ |
| | Solar Panel | Greenhouse = $1.2 \times 10^5$ |
| | to Rocks = $3.0 \times 10^6$ | |
| | to House = $3.0 \times 10^5$ | |
| | Storage to System = $3.57 \times 10^6$ | |

DISTRIBUTION OF MODES

The percentage of time that the system operated in each of the four heating modes (see 3.3.3) and idle is as follows:

| | | 1 | 2 | 3 | 4 | 9 |
|---|---|---|---|---|---|---|
| (Dec. 58) | % | 2.78 | 17.97 | 4.89 | 13.09 | 61.27 |
| (Jan. 59) | % | 2.69 | 12.68 | 3.72 | 10.43 | 70.48 |
| (Feb. 59) | % | 1.91 | 14.46 | 2.23 | 9.07 | 72.33 |

ENERGY BALANCE

In order to check the simulation for possible unstable conditions, energy balances at the end of each month were performed. If the system is in balance then the heat output of heater plus rocks and solar panel heat input to house/greenhouse should be equal to the heat losses of the house/greenhouse.

$$Q_{\text{solar panel - house}} + Q_{\text{heater}} + Q_{\text{rocks - house}} = Q_{\text{loss house}} + Q_{\text{loss greenhouse}}$$

A lack of balance is generally caused by program manipulation errors, integration round off errors, transients, etc. Another source of error peculiar to this specific system is that when mode 1 is in operation the house/greenhouse system will not receive the total amount of heat obtained from the solar panel. This is due to an additional amount of outside air which enters the greenhouse when the system is heated via the solar panel. For comparison purposes, it is assumed

that 90% of the solar panel output goes in the house/greenhouse energy balance.

The energy balances for the three winter months are tabulated below:

| Month | Heat Gain (KJ) | Heat loss (KJ) | Error |
|---|---|---|---|
| Dec. 58 | $6.31 \times 10^6$ | $6.22 \times 10^6$ | 1.4% |
| Jan. 59 | $5.954 \times 10^6$ | $6.46 \times 10^6$ | 7.8% |
| Feb. 59 | $4.26 \times 10^6$ | $3.71 \times 10^6$ | 13.0% |
| Cumulative | $1.657 \times 10^7$ | $1.637 \times 10^7$ | 10.6% |

HEATING DEGREE DAYS

The heating degree days, based on a heating temperature of 65°F, are:

| | | |
|---|---|---|
| Dec. 58 | 873 (based on 700 hrs) | $\overline{T} = 35°F$ |
| Jan. 59 | 837 (based on 700 hrs) | $\overline{T} = 36°F$ |
| Feb. 59 | 680 (based on 685 hrs) | $\overline{T} = 41°F$ |
| Total | 2390 (based on 2085 hrs) | $\overline{T} = 37.5°F$ |

ENERGY SAVINGS

The energy savings were calculated by:

$$(Q_{save})\% = \frac{Q_{rocks - house}}{Q_{rocks - house} + Q_{heater}} \times 100$$

Results for three winter months simulation yield:

Dec. 58 - 90%
Jan. 59 - 98%
Feb. 59 - 90%
Cumulative - 90.9%

A similar analysis for the months of June to August inclusive has yielded the following information:

| Month | Heat Gains (KJ) | Heat Losses (KJ) |
|---|---|---|
| June 59 | Heater (A/C) = $.11 \times 10^7$ | House = $.25 \times 10^7$ |
| | Rocks-to-house = $.12 \times 10^7$ | |
| July 59 | Heater (A/C) = $.23 \times 10^7$ | House = $.29 \times 10^7$ |
| | Rocks-to-house = $.59 \times 10^6$ | |
| Aug. 59 | Heater (A/C) = $.22 \times 10^7$ | House = $.26 \times 10^7$ |
| | Rocks-to-house = $.37 \times 10^6$ | |

DISTRIBUTION OF MODES

| Month | Modes 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|
| (June 59)% | 1.46 | 21.30 | 19.28 | 8.69 | 49.27 |
| (July 59)% | .73 | 21.31 | 35.58 | 5.24 | 37.14 |
| (Aug. 59)% | .12 | 16.00 | 41.64 | 2.69 | 39.55 |

ENERGY BALANCE

The energy balance for the summer months will take the following form:

$$Q_{\text{heater (A/C)}} + Q_{\text{rocks - house}} = Q_{\text{house - loss}}$$

Then the balance for each month of the summer simulation are:

| Month | Heat Gain | Heat Loss | Error |
|---|---|---|---|
| June 59 | $.24 \times 10^7$ | $.22 \times 10^7$ | 7.0% |
| July 59 | $.28 \times 10^7$ | $.29 \times 10^7$ | 2.4% |
| Aug. 59 | $.26 \times 10^7$ | $.26 \times 10^7$ | 1.0% |
| Cumulative | $.78 \times 10^7$ | $.80 \times 10^7$ | 2.5% |

COOLING DEGREE DAYS

The cooling degree days are based on a cooling temperature of 75°F. The results are:

| | | |
|---|---|---|
| June 59 | 93 (based on 700 hrs) | $\overline{T}$ = 78°F |
| July 59 | 130 (based on 700 hrs) | $\overline{T}$ = 79.5°F |
| Aug. 59 | 147 (based on 685 hrs) | $\overline{T}$ = 80°F |

ENERGY SAVINGS

The energy savings for the summer are:

| | |
|---|---|
| June 59 | 53% |
| July 59 | 21% |
| August 59 | 14% |
| Cumulative | 28%* |

*During the 1st and 3rd week of June there were a few days where the temperature dropped into the 50's relieving the cooling probelm somewhat. A 20% saving occurred most of the time in the absence of such a low ambient temperature.

SIZE REDUCTION OF ROCK STORAGE

Two additional computer runs with the rock storage depth reduced by 25% and 50% were also performed. These simulations were performed for a period of 14 days. Results from these runs are tabulated below.

| Parameters \ Rock Storage Size | Full | 75% | 50% |
|---|---|---|---|
| Heat Gains (KJ) | $.41 \times 10^6$ | $.42 \times 10^6$ | $.59 \times 10^6$ |
| Heater | $.41 \times 10^6$ | $.42 \times 10^6$ | $.59 \times 10^6$ |
| Solar Panel | | | |
| to Rocks | $1.5 \times 10^6$ | $1.49 \times 10^6$ | $1.43 \times 10^6$ |
| to House | $.36 \times 10^6$ | $.33 \times 10^6$ | $.36 \times 10^6$ |
| Rocks to House | $2.8 \times 10^6$ | $2.8 \times 10^6$ | $2.5 \times 10^6$ |
| Heat Losses (KJ) | | | |
| House | $2.5 \times 10^6$ | $2.5 \times 10^6$ | $2.5 \times 10^6$ |
| Greenhouse | $1.1 \times 10^6$ | $1.1 \times 10^6$ | $1.0 \times 10^6$ |
| Energy Savings (%) | 80.2 | 79.4 | 73.9 |

CONCLUSIONS AND RECOMMENDATIONS

Based on the six months of analysis it may be concluded from dynamic simulation for the first prototype residence/greenhouse system that the design is quite adequate and furthermore may be slightly overdesigned based on conservative, steady-state design calculations.

The heat pump and rock storage are capable of supplying the required energy to heat the system during the 3 coldest months of the 1958-59 winter season. The rock storage and solar collector are capable of supplying more than 90% of the heat required. During the summer season the rock storage is capable of supplying about 20% of the cooling required by the house.

The greenhouse will experience temperatures as low as 5°C (41°F) during a cold night, and a maximum of 47°C (117°F) during the collector to rocks heating mode. The summer greenhouse temperature has been observed to reach 43°C (110°F) in the middle of the day.

During the winter months, the rock storage temperatures ranged from a minimum of 9°C (55°F) at the cold end to a maximum of 59°C (138°F) at the hot side. The average rock temperatures ranged from 18°C (64°F) to 48°C (118°F). The ability to contain the heat loss to a minimum has enabled the system to obtain the very high energy savings indicated.

During the summer months, the rock temperature rarely dropped below 20°C (68°F), therefore minimizing its contribution to the refrigeration

load. The analyses with a 25% reduction in rock size has not shown any loss in heating capability, however, such a reduction may reduce the summer energy savings below the 20% average savings observed in the simulation.

Based on the simulation, the following recommendations are suggested:

- Supply shades in the greenhouse in order to reduce heat loss during the cold winter nights and reduce heat gain during the summer hot days.
- Monitor the greenhouse during the collector to rocks heating mode and, if the temperature gets too hot, bypass the greenhouse with the air flow.
- Construct the second prototype design according to the current design specifications since it, like the first prototype, is based on steady-state calculations that appear only slightly conservative.
- Monitor the working prototypes with sufficient detail to determine the accuracy of the simulation and modify the computer module (if necessary).
- Use of the simulation as a design tool for future construction.

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# ROCK COLLECTOR AND STORAGE SYSTEM FOR GREENHOUSE AND RESIDENT HEATING

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## ABSTRACT

An experimental solar collector and energy storage system which combines the collection and storage functions into one unit has been constructed and is being tested. The system uses a bed of rock painted flat black and is simply glazed - as with conventional flat-plate collectors. The rock serves as the collector, as the storage media, and as the heat exchanger. Although not fully optimized, the system performance has been very promising. Operational data are presented.

## INTRODUCTION

The world is currently faced with what is called an "Energy Crisis," i.e., the demand for energy has increased more rapidly than the supply of fossil fuels. This crisis has become particularly severe in the eastern half of the United States this winter. Unfortunately, this "Energy Crisis" directly affects the nation's ability to produce food, which may lead to a far more serious crisis.

Lagging the "Energy Crisis" only slightly and only felt to a very limited extent in the United States is a far more serious "Food Crisis" which both directly and indirectly interacts with the "Energy Crisis." One method of meeting the "Food Crisis" is to increase productivity. Increased productivity of food can be met to a limited extent by increasing the land committed to food production. The most effective increases are more likely to come from higher utilization of fertilizers and greater use of greenhouses. Use of fertilizers has always been high in the United States and has been increasing in recent years. Not common in the United States is the use of greenhouses. It is estimated that the U. S. has only 12 percent as many greenhouses as Europe. Due to more than sufficient land available for food production, the U. S. has not been forced to move to high use of greenhouses. As worldwide demand for food continues to increase and the U. S. continues to be a major producer of food, it is likely that the usage of greenhouses will increase significantly.

That greenhouses offer a significant potential for increased production of many food products is well recognized. Some crops respond better to greenhouse production than do others. Those with better performance have shown yields 4 to 12 times above field grown products. This

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increased productivity can no longer be ignored. The world demand for food will require our developing all sources for increased production.

Unfortunately, the use of fertilizers and greenhouses interact with the "Energy Crisis." Most fertilizers come directly from fossil fuels or require substantial energy in their production. Research has shown that most greenhouse plants grow more effectively at temperatures approaching $27^{o}$ C ($80^{o}$ F). This requires an energy input of approximately 284 Kw-hrs/$m^2$/yr (90 x $10^3$ Btu/$ft^2$/yr). This energy input interacts with the "Energy Crisis" because fossil fuels are presently the source of this energy.

Currently the costs to heat commercial greenhouses range from 20 to 50 percent of the operating expenses of such structures. As explained above, most commercial greenhouses are heated with fossil fuels and many are dependent upon natural or LP gas, both of which are becoming more expensive and in some cases unavailable. Switching to oil heating will increase heating cost by at least 50 percent and will be only a temporary solution to the problem.

Fortunately greenhouses do not require high grade energy as do solar power plants, industrial processes, and fertilizer plants. With a temperature requirement of only $27^{o}$ C ($80^{o}$ F), solar heated greenhouses appear not only desirable but practical. Greenhouses are inherrent solar collectors when the sun is shining, with excess energy being a problem sometimes during warm days with high insolation levels. Unfortunately, they have proven to have high thermal losses at night. While greenhouses are relatively good solar collectors, few have any storage capability, and therefore require substantial energy input at night. Reports indicate that over 75 percent of all greenhouse energy is used at night.

Homes also do not require high grade energy and, with temperature requirements of $21^{o}$ C ($70^{o}$ F) or less, appear to be as promising as the greenhouse as an economically practical user of solar energy. Many, if not most, rural residences use LPG as an energy source. LPG is in such high demand its use as a home heating fuel has become prohibitively expensive. Fortunately, most rural residences lend themselves well to ground based inexpensive solar collectors.

Flat-plate collectors have been and are currently being extensively developed for home and building heating and cooling systems. Most commercially available flat-plate collectors have become extremely expensive due to attempts to combine high efficiency with delivery temperatures high enough to drive absorption refrigeration. Even simple water heaters are much more expensive than is desirable because manufacturers are attempting central assembly by skilled high priced labor rather than on-the-site construction by locally available less expensive labor. An economic analysis will quickly show that $\$108/m^2$ ($\$10/ft^2$) collectors are too expensive for greenhouses and probably for rural residences and related buildings.

Fortunately, rural residences and greenhouses are not usually restrictive regarding the size of the collector as are most city or industrial buildings. This raises the question of whether one can trade efficiency for lower costs. Fortunately one can make this trade, i.e., one can design collectors which, although being less efficient, are much less expensive per $ft^2$ of collector. Analysis of several collector configurations specifically designed for rural use, where collector size is not severely limited, indicated that one design appeared especially promising. This collector-storage system appeared capable of supplying energy at a cost more than competitive with fossil fuels. This system, called the "Solar Rock Collector," is the basis for the work reported here.

## DESIGN CONCEPT

The original concept for the solar rock collector came from an attempt to obtain the energy collection and storage capability of the south facing glazed wall, Balcomb (1), Trombe (2), with a less expensive and simplier construction. It soon became apparent that horizontal construction would reduce the cost and may not penalize the performance severely, particularly at lower latitudes. Since concrete construction is expensive, loose rock soon replaced the concrete. In other words, the solar rock collector is a horizontal glazed "wall" fabricated from loose rock. In many areas rock is available at a cost as low as $2.50 per ton. This results in a collector-storage system whose components are very inexpensive.

It was felt that the success of solar heating systems for rural residences and farm buildings and probably for greenhouses may depend on whether the system can be fabricated on site with locally available materials and readily available labor rather than be factory fabricated and shipped in. Local fabrication makes possible the utilization of less expensive labor and locally available materials and minimizes shipping costs. Figure 1 shows the basic rock collector concept. This system can be completely built by local labor using inexpensive locally available materials.

Figure 2 shows one way the solar rock collector can be used with greenhouses. It is important to point out here that the system can be adapted to existing greenhouses or buildings, or be designed as an integral part of more efficient greenhouses and buildings. One could build a number of variations of this basic design to meet specific site or load requirements.

## EXPERIMENTAL SYSTEM

Although considerable work has been done on rock storage concepts and on flat-plate collectors, no prior work on combination collector-storage systems, other than the south facing glazed wall, could be found. Since the concept showed promise of being capable of collecting and storing

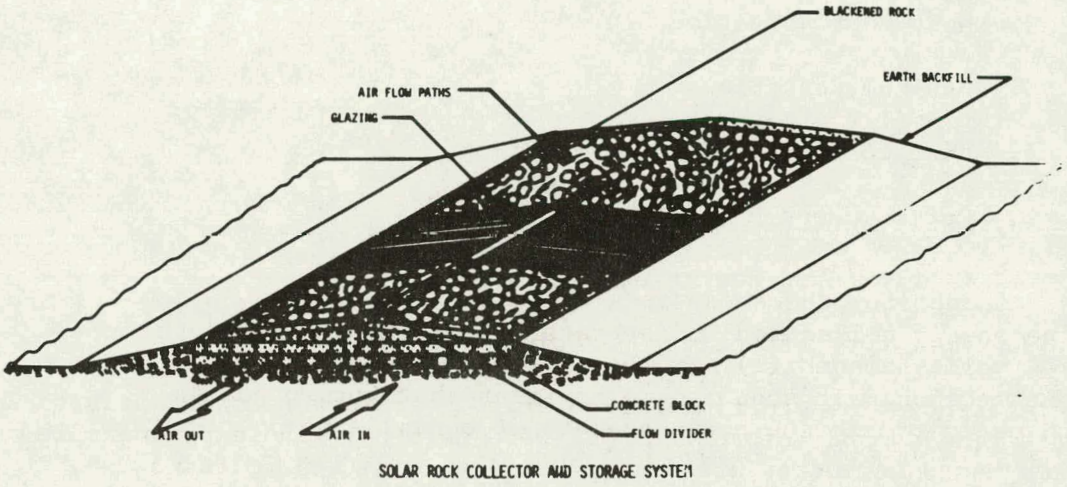



Figure 1. Basic Rock Collector Concept.

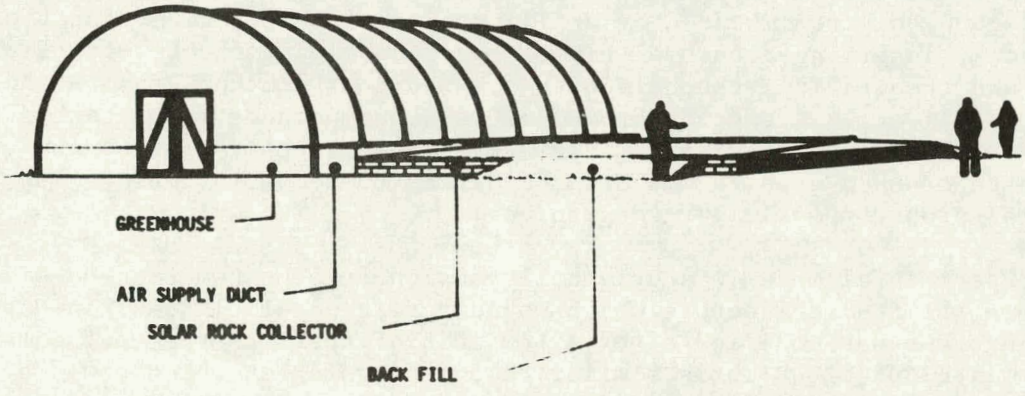



Figure 2. Rock Collector with Greenhouse.

solar energy at a fraction of the cost of most competitive systems, an experimental collector was constructed to investigate the concept and to determine:

1. Best Fabrication Techniques
2. Most Cost Effective Glazing
3. Optimum Rock Size
4. Most Cost Effective Rock Coatings
5. Optimum Rock Depths
6. Continuous Circulation Needed
7. Most Cost Effective Operating Technique

Figure 3 shows the experimental solar rock collector loaded with rock before glazing and before the rock were painted. The experimental system has a collector area of 5.76 $m^2$ (62 $ft^2$) and contains 2495 Kg (5500 lbs) of granite giving a collector to storage ratio of 433 $Kg/m^2$ (89 $lb/ft^2$). The granite is approximately 0.3 m (12 inches) deep and is sprayed flat black on the upper surface as shown in Figure 4. Figure 5 shows the system with a single layer of 0.74 mm (0.029 inch) regular grade Kalwall glazing. Figure 6 shows the system after glazing with Filon tedlar coated corrugated fiberglass. Figure 7 gives a cutaway view of the experimental system showing the small fan used for continuous recirculation and the larger fan used to extract heat from the collector. Figure 7 also shows the baffling used to cause the air to move the energy from the upper rock to the lower rock. Figure 8 shows the 76 mm-102 mm (3-4 inch), granite used in the initial tests beside the 203 mm-305 mm (8-12 inches) granite presently being tested. The rock have been painted flat black. Figure 8 also shows the thermocouples used to measure the rock thermal gradient. The thermal gradient was determined by imbedding thermocouples in the rock. The thermocouples were imbedded by drilling a small hole to the center of the rock, inserting a chromel-alumel thermocouple to the bottom of the hole and then filling the hole with a mixture of crushed granite and sodium silicate. A second chromel-alumel thermocouple was attached to the rock surface with either sodium silicate or epoxy. The sodium silicate crushed granite mixture solidifies to become a cement with thermal properties similar to granite.

The experimental model was originally designed to be two side-by-side 2.88 $m^2$ (31 $ft^2$) collectors which would permit parallel simultaneous testing, but was modified after a few initial tests to the configuration shown in Figure 7 which is similar to a configuration which could be used with a greenhouse or rural residence.

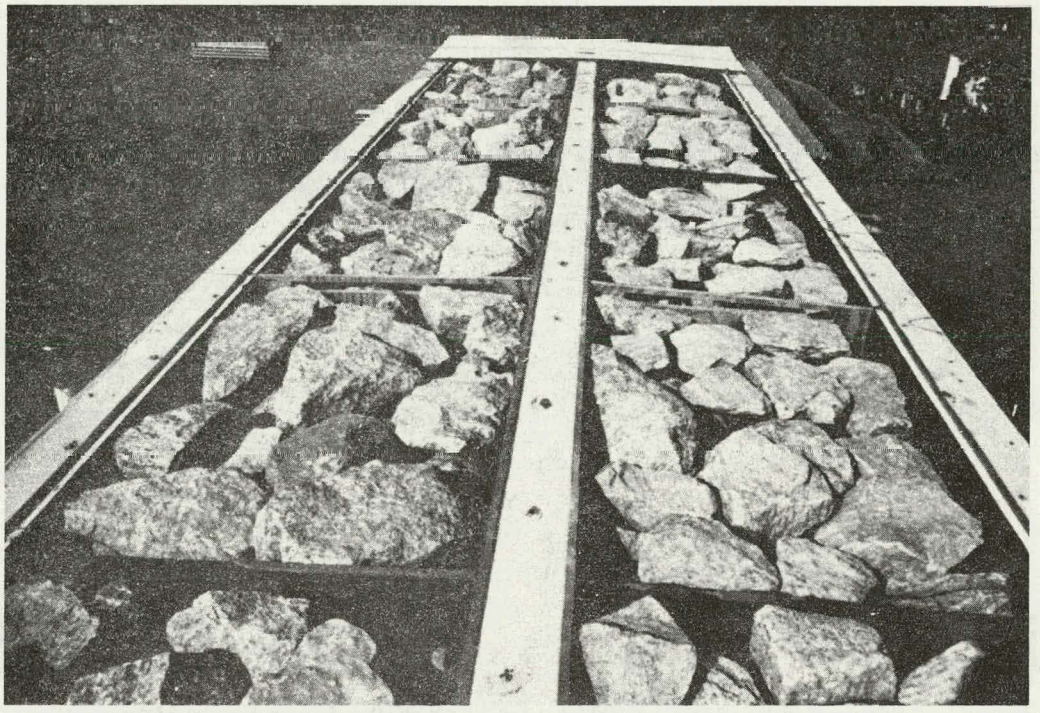


Figure 3. Experimental Collector Filled with Rock.

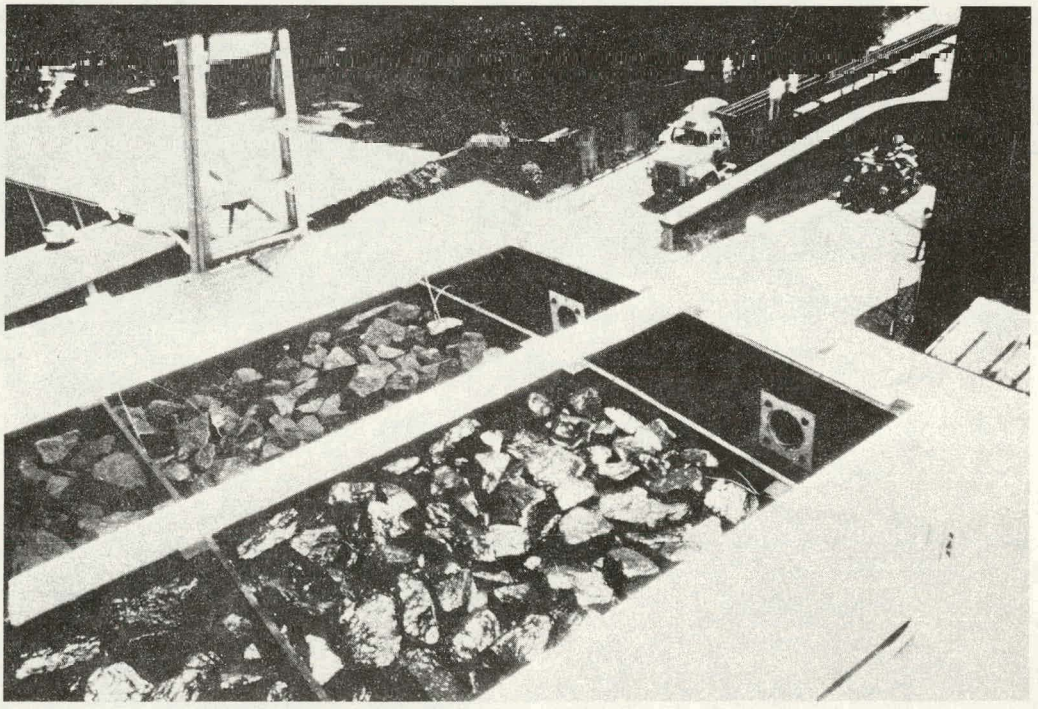


Figure 4. Experimental Collector with Painted Rock.

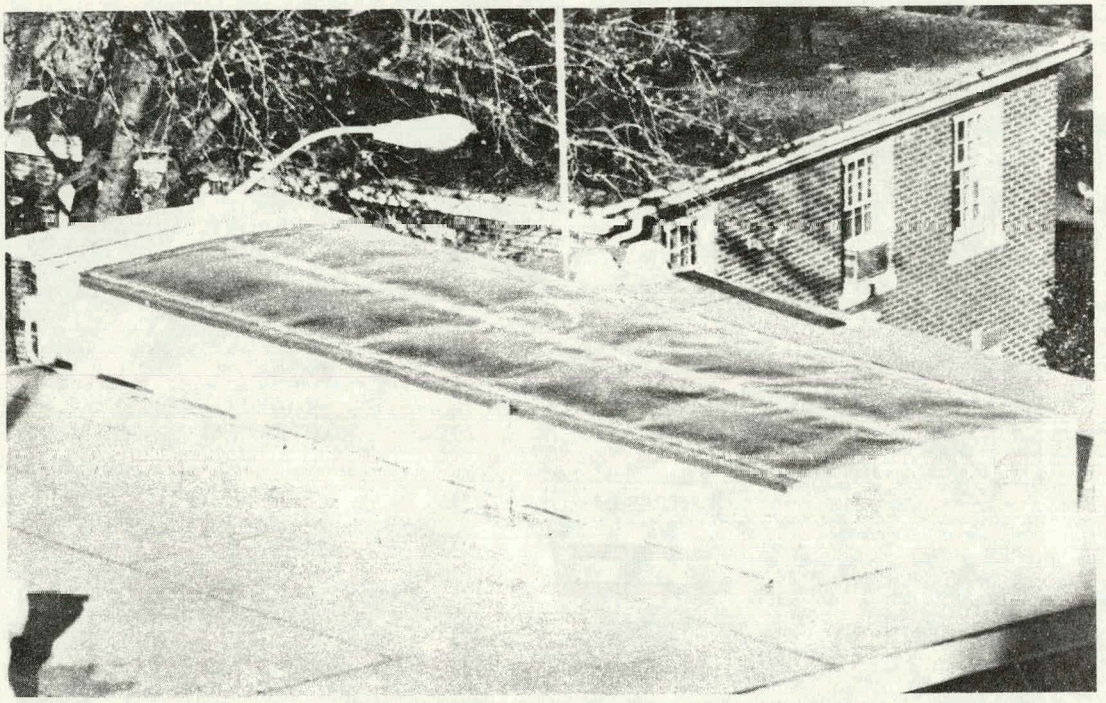


Figure 5. Single Glazed Experimental Rock Collector.

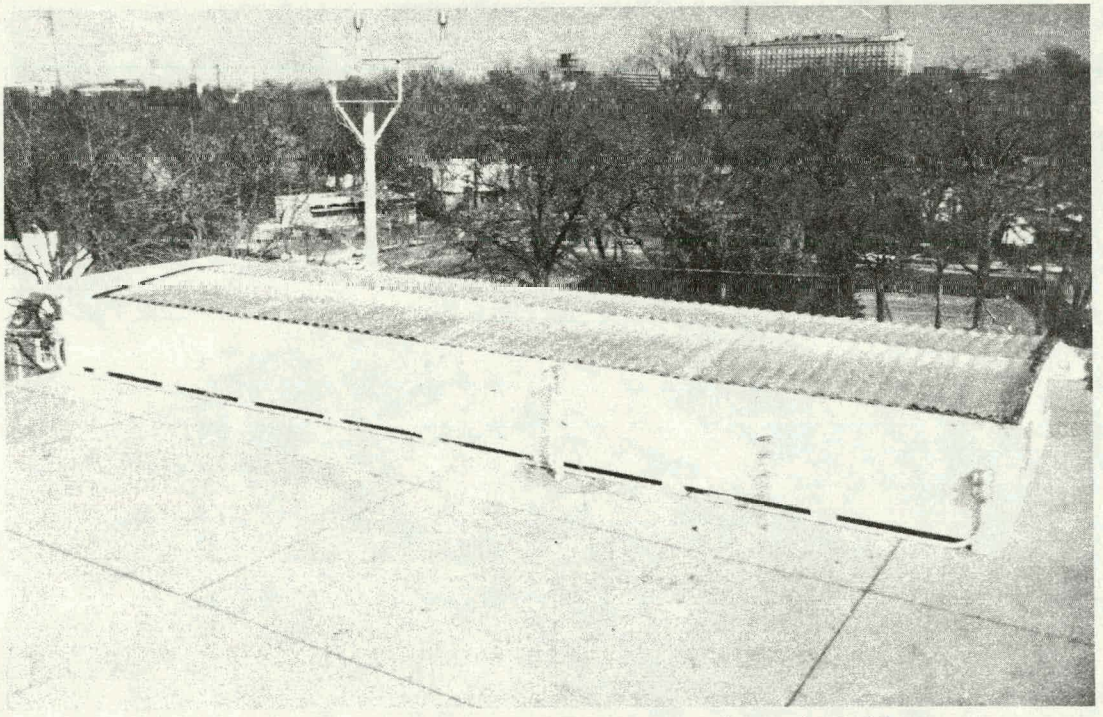


Figure 6. Double Glazed Experimental Rock Collector.

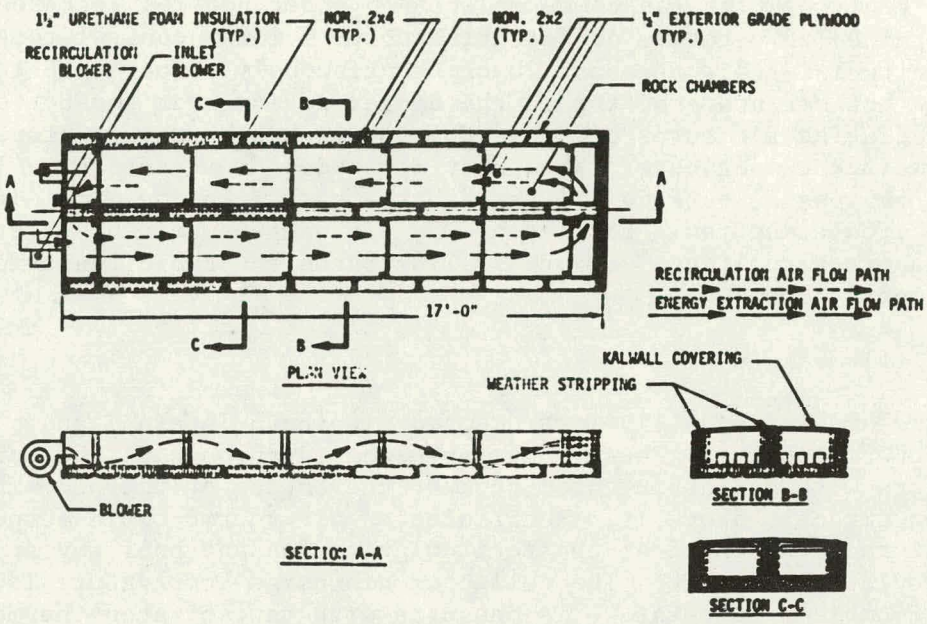



Figure 7. Cutaway View of Experimental Rock Collector.

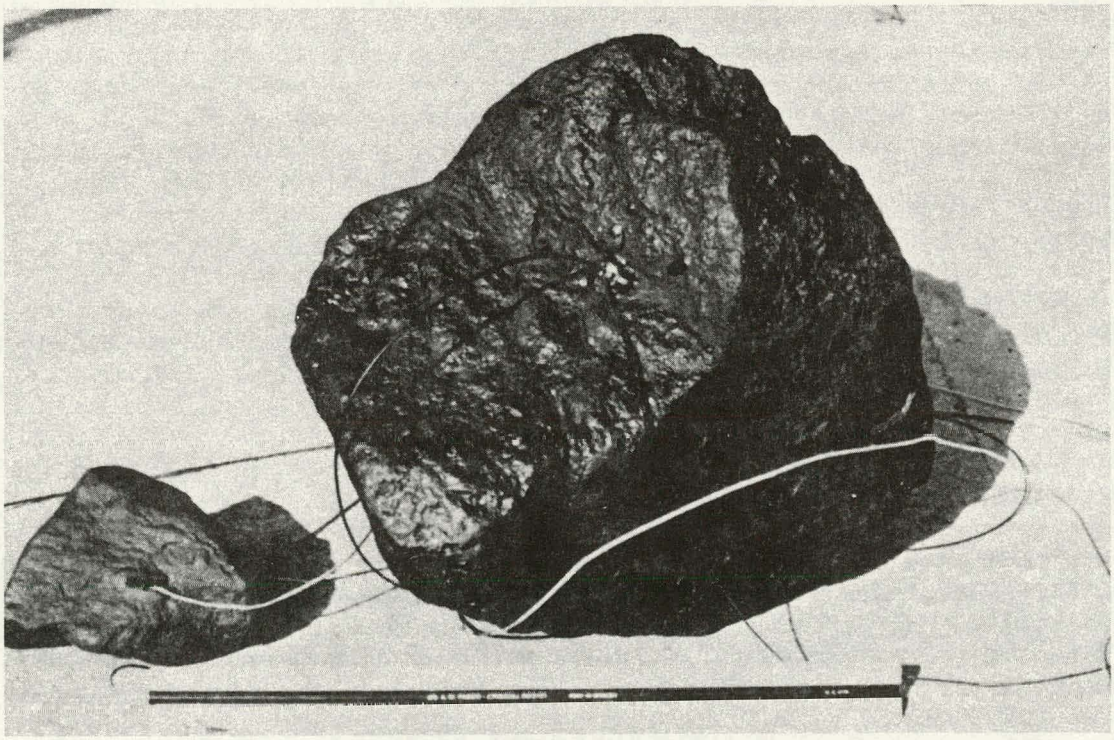


Figure 8. Instrumented Rock Used in Experimental Collector.

The small recirculating fan comes on when an upper control rock reaches a predetermined temperature differential above a lower control rock. This fan circulates air at about 20 cfm continuously through the rock, moving the hot air near the top to the cooler region near the bottom. The recirculating fan turns off when the top rock temperature drops near the bottom rock temperature. When heat is needed from storage, a larger (100 cfm) fan pushes outside air through the system in the same direction as the recirculating fan. Simple one way air dampers prevent reverse flow and short circuiting. Figure 7 illustrates the two circulation modes of operation.

## INSTRUMENTATION

Eight rocks are individually instrumented with both internal and external thermocouples. These rocks are located throughout the collector in pairs with an instrumented rock at the bottom of the bed with one at the top directly above it. Recirculation air thermocouple temperature monitors are located at the recirculating fan and half way around the recirculation circuit. The collector discharge temperature is also measured. Ambient temperature is measured with an aspirated thermocouple.

Figure 9 shows the instrumentation used with this program plus the weather and solar instrumentation also located at the site. Total insolation is measured with an Eppley Model 8-48 black and white pyranometer. Direct insolation is measured with an Eppley Model NIP normal incidence pyrheliometer. The total and direct insolation are recorded continuously on a dual pen strip chart recorder calibrated to read 100 watts/meter$^2$/mv. The insolation signals also go to 0-5v amplifiers and voltage to frequency converters which are calibrated to give one pulse per 0.1 watt-hour. The pulses from the voltage to frequency converters are accumulated on electromechanical counters connected to a stepping relay. This permits seven days of integrated data to be accumulated before the system must be read and reset.

The collector performance is printed out on either a 30 channel Fluke data logger or a 20 channel Digitec data logger. The data loggers can be programmed to read any or all channels and to sample the sensors at a number of different time rates.

## EXPERIMENTAL RESULTS

The experimental system was initially designed to permit parallel testing. The first few tests were conducted using the parallel testing capability to determine whether selective paints such as Solarsorb C-1077-3 offered any advantage over flat black paints such as Glidden number 908. Comparative tests using 120 cfm air flow through each side, and single 24 mm (0.029 inch) Kalwall regular grade glazing showed the Glidden flat black to be slightly better overall, with rock surface temperature reaching about 3° C (5.4° F) higher than the selective paint.

It was also determined during these initial tests that the collector needed to have a small continuous air flow to assist in moving the energy from the upper rock to the lower rock. Thermal gradients within the rock also proved to be much lower than expected reaching a maximum of less than 3° C (5.4° F) from the surface to the middle of the rock. This differential is too low to provide a significant thermal resistance to energy loss at night.

Since the merit of direct testing had become questionable, the collector was modified to the configuration shown in Figure 7. The 76 mm-102 mm (3-4 inches) filter gravel was removed and replaced with 203 mm-305 mm (8-12 inches) granite rip rap.

Transmissivity measurements made on the 0.74 mm (0.029 inch) regular grade Kalwall used to cover the collector revealed that the transmissivity was only 77-79 percent at noon on days when the total energy was high and the direct energy was low. The same material transmitted 86-88 percent when both the total and direct radiation was high. This loss in transmission apparently comes from the inability of glazings which scatter light to transmit at low angles of incidence. This suggests that ASTM E424-71 may not be totally adequate for determining the potential of glazing materials.

As ambient temperatures dropped, it was determined that 4-7° C (40-45° F) minimum daily temperature was about the limit at which a single glazed solar rock collector system would perform efficiently. The collector was double glazed using Filon tedlar coated corruaged glass-reinforced polyester as a second glaze above the Kalwall glaze. The crown of the collector was increased another 38 mm (1½ inches) resulting in the center of the collector being 64 mm (2½ inches) above the edges. This eliminated water accumulation on the top of the collector as experienced with the single glazed collector. Figure 6 shows the collector in the double glazed configuration.

Double glazing resulted in a substantial improvement in the collector performance. Figure 10 shows a top and bottom rock temperature profile in relation to the ambient temperature and total insolation over a 72 hour period. The data in Figure 10 follows several days of cloudy weather with little or no solar total insolation. Although the rock collector was not designed for storage over several days, Figure 10 shows the storage temperature to be approximately 11° C (20° F) above ambient. The first day plotted, March 6, was also cloudy as shown by the insolation plot. Although storage temperature had dropped to 13° C (56° F) by 8 a.m., March 7, it maintained a temperature 11° C (20° F) above ambient. The weather was clear on the 7th and 8th, resulting in a substantial increase in storage temperature. Storage was 23° C (73° F), 18° C (32° F) above ambient at 8 a.m. on March 8, and 28° C (82° F), 22° C (40° F) above ambient at 8 a.m. on March 9.

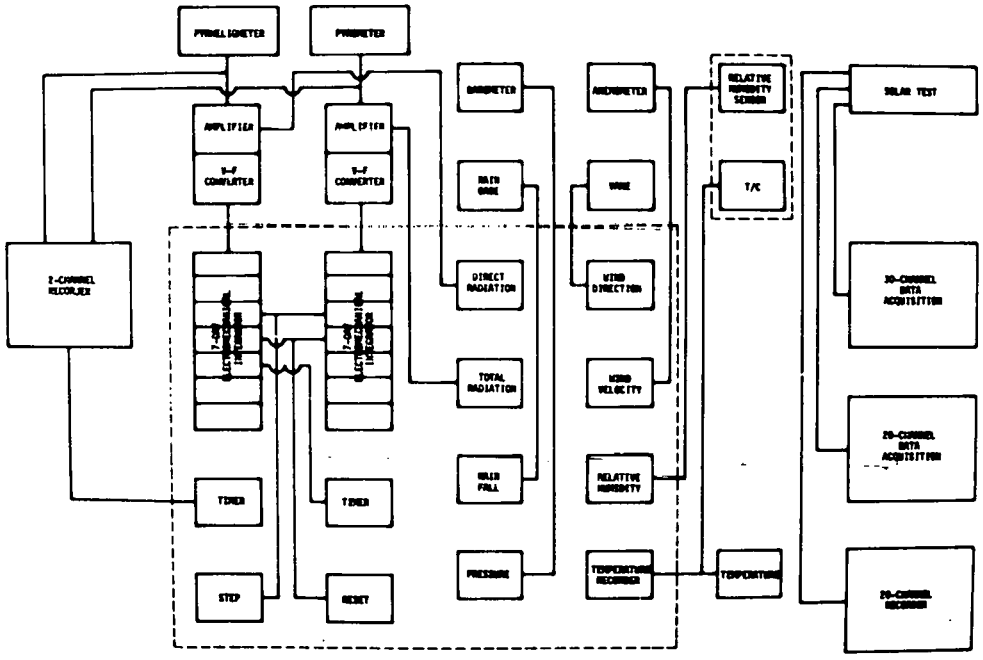


Figure 9. Instrumentation Diagram.

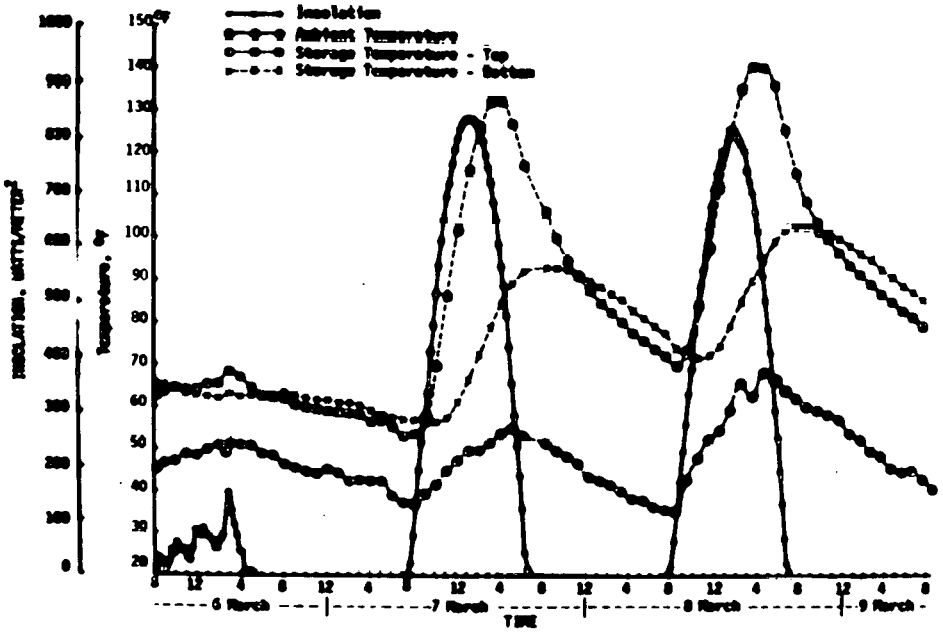



Figure 10. Rock Collector Performance Curves.

Higher storage temperatures could be obtained by decreasing the storage mass to collector area ratio from the present 433 Kg/$m^2$ (89 lb/$ft^2$). The present storage to collector area ratio is approximately correct for separate collectors and storage, but appears to be high for the combination collector storage system.

## SUMMARY AND CONCLUSIONS

The experimental Rock Solar Collector and Energy Storage System has demonstrated the capability of collecting and storing solar energy at useful temperatures. It has demonstrated the ability to retain a significant percentage of this energy overnight. The system uses no expensive materials and can be fabricated from readily available materials by local unskilled labor.

The system can be built in varying degrees of sophistication from simple passive systems located on hillsides and costing under \$10/$m^2$ (\$1/$ft^2$) of collector to more complicated automatically controlled designs costing well under \$21/$m^2$ (\$2/$ft^2$). The system can be retrofitted to existing greenhouses and rural residences or be integrated into the design of new structures.

The system performs best when located on a south facing hill, but as demonstrated by the experimental system will perform well when mounted horizontally. Performance of horizontal units can be improved significantly in the winter months through the use of a vertical or near vertical reflector located on the north side.

Single glazed collectors perform satisfactorily until the minimum daily temperature drops to approximately 7° C (45° F). Although there is obviously a minimum daily temperature at which the performance of double glazed systems become marginal, it is well below freezing. A modified version of the double glazed system probably will perform satisfactorily at minimum daily temperatures below -18° C (0° F).

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# PERFORMANCE OF THE NEW JERSEY SOLAR SYSTEM FOR HEATING GREENHOUSES

David R. Mears, William J. Roberts and Joel C. Simpkins[1]

## INTRODUCTION

Research on solar heating of greenhouses at Rutgers has been geared to applications with commercial, double-covered polyethylene structures. Emphasis has been placed on the development of relatively low-cost systems in order to have an economically feasible alternative to fossil fuel for greenhouse heating as soon as possible. The materials and construction techniques being utilized are currently available in the greenhouse industry. The performance of the system from September 1976 through February 1977 is presented. Based upon experience to date, some estimates are made regarding the economic potential of the entire system based on current prices.

The Rutgers integrated solar assisted heating system was first presented by Roberts et al in 1976 (2). This system consists of four major elements, all of which are necessary for maximum conservation of fossil fuel. One element is the movable curtain insulation system first reported in 1974 (1) and later described in more detail by Simpkins et al (3). Double-covered polyethylene greenhouses require two-thirds the heat of similar size and shape single glazed structures, but further heat loss reduction is needed if solar heating is to become practical. Curtain insulation systems to reduce heat loss are now being utilized with conventional heating systems.

The next element is the composite floor which serves a dual role of heat storage and exchange. The floor is constructed of four layers, the bottom being polystyrene board insulation, the next a vinyl swimming pool liner, the third, gravel,

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which will be flooded with water and the top is a cap of porous concrete. The porous concrete forms a firm floor, a heat exchange surface and allows excess irrigation water to drain. The layer of gravel with the voids filled with water serves as the thermal storage and the vinyl liner contains the water. The insulation also serves as mechanical protection for the liner during construction.

To provide additional heat transfer between the stored warm water and the greenhouse, vertical curtain heat exchangers have been developed. A trickle irrigation hose is tied to a horizontal support and a plastic film draped over the support. This support is attached to the curtain insulation system so the vertical curtain can be dropped to the floor when not in use. Warm water is pumped from the floor storage into the trickle hose, flows between the two sheets of plastic releasing heat to the greenhouse and returns to storage through the porous concrete.

The fourth element is the solar collector which consists basically of a frame covered with five layers of plastic film. The middle layer is a black, light absorbing layer and the outer two layers are clear greenhouse grade polyethylene. The spaces between the bottom two layers and the top two layers are inflated and the black layer is pressed between the two inflated sections. The collector is tipped to the south and water introduced through a pipe manifold at the top. The water is warmed as it flows over the black layer, is collected in a return gutter at the bottom and returns by gravity flow to floor storage.

An oil-fired burner is used to supply supplemental heat to the greenhouse when sufficient solar energy is not available. Heat is delivered to the floor storage through a pipe loop buried in the gravel layer of the floor. In this way all heat is delivered to the greenhouse through the combination of the warm floor and vertical curtain heat exchanger. Heat is added to the floor by the furnace if the floor temperature falls below a set level as determined by a thermostat in the floor. Another thermostat turns on the circulator pump for the curtain heat exchangers when the greenhouse ambient air temperature falls. A differential thermostat controls the collector pump, circulating water when the collector is 5.6$^{o}$C warmer than the floor. The curtain insulation system is closed and opened by a time clock.

## SYSTEM OPERATION AND PERFORMANCE

The test greenhouse and solar collector are shown in Fig. 1. The pattern of water flow from the greenhouse floor storage through the solar collector and back is shown in the schematic of Fig. 2. The greenhouse is nominally 5.2 m by 7.3 m (17 ft by 24 ft). The useful floor area in the greenhouse is 33.4 $m^2$ (360 $ft^2$) and the exposed roof and wall area is 79.9 $m^2$ (860 $ft^2$). The face area of the collector is 33.8 $m^2$ (364 $ft^2$). The exposed heat transfer area of the vertical curtain heat exchangers is 37.2 $m^2$ (400 $ft^2$). The system has been run continuously on automatic control since August 1976 and the performance of each component has been monitored.

The growing area has been maintained throughout the heating season at a minimum of 15.6°C (60°F) by holding the temperature of the water in the floor at 22.2°C (72°F) or more. When the floor storage temperature falls to this level, heat is added from the fossil fuel backup. Typically, when the outside air temperature is above 5°C, enough heat is delivered passively by the floor to maintain the set temperature. Under the coldest conditions the heat exchangers run continuously. There were a number of nights when outside temperatures fell below 0°F (the lower limit of the temperature recorder). Under these conditions the system maintained 14.4°C (58°F) in the growing area while temperatures inside the greenhouse, but above the black polyethylene insulating curtain, fell to freezing.

The heat transfer rates from the floor and the vertical curtain heat exchangers have been determined over a wide range of operating conditions. When the floor alone is providing the heat, the heat transfer rate from the floor storage to the greenhouse averages 8.23 $W/m^2K$ (1.45 $BTUh/ft^2\,°F$). This value varies with the temperature difference between the water in the storage and the greenhouse. When the vertical curtain heat exchangers are running constantly, the weighted average heat transfer rate from floor storage to the greenhouse through both the floor surface and the vertical curtain exchangers is 8.69 $W/m^2K$ (1.53 $BTUh/ft^2\,°F$). Some improvement in the heat transfer rate from the vertical curtains is anticipated.

The insulating curtain of black polyethylene has proven effective in reducing heat loss from the greenhouse. The heat loss coefficient from the entire building has averaged 2.55 $W/m^2K$ (0.45 $BTUh/ft^2\ ^oF$) based on the total exposed roof and wall area. Without the curtain the heat loss rate from this building is 4.54 $W/m^2K$ (0.80 $BTUh/ft^2\ ^oF$). A fringe benefit of the entire system is its capability to carry a crop safely through a component failure during cold weather. One night the fuel oil line to the burner froze and the outside temperature fell below $0^oF$. The floor storage fell to $17.2^oC$ ($63^oF$) and the greenhouse temperature dropped to $11.1^oC$ ($52^oF$), but there was no damage to the tomato crop. For two nights there was no fossil fuel backup due to a fault in the oil burner. The outside temperatures were $-14.4^oC$ ($6^oF$) the first night and $-12.8^oC$ ($20^oF$) the second. This time the system ran on solar energy alone and again the crop was maintained safely at $9^oC$ ($49^oF$). The insulating curtain and the large thermal mass of the floor provide a significant carrying capacity in the event of power outage or other temporary component failure.

The energy budget of the entire system as operated during the heating season is presented in Table 1 and Fig. 3. The data is presented for each week through the end of February 1977. Solar energy has provided all of the needed heat in the first two weeks of March.

The weekly totals on degree days indicate the unusual severity of the past winter. In Table 1 energy used has been converted to the equivalent in gallons of fuel oil for the entire greenhouse at the rate of 1 gallon for each 100,000 BTU. There was no fossil fuel requirement through October and the solar energy noted is only that required to provide the needed heat. Excess solar energy was collected during this period and will be again in the spring. Over the entire period solar energy provided 48% of the total energy required. This percentage will be significantly increased when the spring season data is added.

For economic evaluation it is important to know the total fuel requirement per unit floor area of each of several greenhouse systems. The data collected thus far has been used to produce the calculated results shown in Table 2 and Fig. 4. The projections are based on the actual performance of the solar system this past winter in which the degree

days accumulated through February are about equal to the total for a normal winter. The first column of Table 2 shows the predicted weekly fuel oil use in the greenhouse if it were single glazed with a heat transfer coefficient of 6.81 $W/m^2K$ (1.2 $BTUh/ft^2\ ^oF$). The total of 857 gallons of fuel works out to 2.38 gallons per square foot of floor. The second column gives the fuel requirement for the same size house with double polyethylene cover but no insulation or solar heat input. The total of 572 gallons is 1.59 gallons per square foot of floor. Table 1 showed that the insulation reduced the total requirement to 321 gallons or 0.89 gallons per square foot of floor. The solar system provided 0.43 gallons and the fossil fuel system 0.46 gallons per square foot. These figures indicate a 1.13 gallon/$ft^2$ savings for the Rutgers system over a conventional double-polyethylene-covered greenhouse.

Size of the greenhouse is very important and a multibay gutter-connected greenhouse of an acre or more would have one-half the exposed roof and wall area compared to floor area of the small test greenhouse. The data in the last two columns of Table 2 are based on an equivalent floor area as the test unit which is included in a large, multibay gutter-connected greenhouse. The total heat requirement per unit area is half that actually achieved in the test facility and is 0.45 gallons per square foot of floor. If the same floor and storage system were used and the ratio of solar collector area to floor area were kept at 1 to 1, the solar contribution could be expected to remain the same. The resulting predicted fossil fuel requirement in the last column of Table 2 totals 0.09 gallons per square foot of floor area.

Actual operation of the small test house has indicated that increased storage is desirable. The floor storage of additional units now under construction have had the gravel depth increased 50 percent in a 36 ft by 48 ft greenhouse and 100 percent in a 36 ft by 100 ft greenhouse. Substantial storage increases can be obtained at relatively low cost as the only added cost of storage is the incremental cost of the extra stone being used. Due to the concrete cap this cannot be added later.

The contribution of the solar collector to the system is given in the fourth column of Table 1. The instantaneous efficiency characteristics of the collector have been presented (2). The efficiency at any time depends upon insola-

tion and the relative temperatures of the water and the outdoor ambient air. Analysis of data collected thus far indicates that with the temperatures usually encountered, collector efficiency ranges between 40% and 60% on clear days with the higher efficiencies occurring on warmer days. On the coldest days efficiency was about 35%. Low storage temperatures is the most important factor in keeping collection efficiency up and this is another reason for increasing storage capacity.

A crop of trough culture tomatoes was planted in the fall and floor temperatures were deliberately elevated to determine the effects of the warm floor heating system on plants. No adverse effects on the tomatoes were noted for temporary floor temperature as high as 47.8°C (118°F) and soil temperatures of 42.2°C (108°F). The soil mix of 50% peat moss/ 50% vermiculite has a 90% voids ratio. It is presumed that good root aeration overcame any deleterious effects of high soil temperature. In spite of some rough horticultural treatment, the yield was 2.7 kg (6 lb) of fruit per plant and larger than normal individual fruit size was noted. A spring tomato crop and several varieties of bedding plants are being grown directly on the floor at present. Also, crops of tomatoes and cucumbers are being planted in trough culture in a 36 ft by 100 ft house. The beds in this house are set directly on the gravel and only the walks are paved with porous concrete.

## ECONOMIC PROJECTIONS

Predictions of economic feasibility of the complete system are difficult to make objectively and are very sensitive to assumptions. Of particular importance is the initial heat requirement of the greenhouse to be solarized. Dramatic fuel savings are predicted when an energy inefficient greenhouse is selected for comparison. In this discussion the standard reference is a gutter-connected, double-covered polyethylene greenhouse of at least one acre in size. This is a very energy-efficient structure by current standards and should require about 0.8 gallons of fuel oil per square foot for a heating season resembling that profiled in Table 2.

Construction of a floor system with 23 cm (9in.) of storage and a collector area equal to floor area should result in a

reduction of fossil fuel heating requirement to 0.1 gallons of fuel per square foot for the same heating season. At 50¢ per gallon for fuel oil, this would be a savings of 35¢ per square foot per year. The material costs per square foot of floor for building the complete system have been estimated as follows: for the insulation, liner, rock, heat transfer loop and concrete in the floor, 95¢; for the heat conserving curtain system, 20¢; for the vertical curtain heat exchangers, 5¢; for the solar collector, 50¢, and for pumps, piping and controls 10¢: for a total of $1.80. The annual cost of recovering the collector would be 5¢.

Based upon the above the complete system would save 30¢ per year to be applied to the amortization of the initial cost which would be $3.60 if labor were equal to materials. Labor is the most difficult cost to estimate as such a system has not been installed on a large scale. There would be one or two important items to consider that would reduce the relative cost of the solar heating system for new construction. First would be a credit for the cost of the conventional heating system. If an overhead pipe system with hot water were being replaced, the overhead pipe which costs about $1.00 per square foot for materials would be saved. The oil burner for the backup in the solar heating system would be smaller than that in a conventional system so the costs of these units would at least cancel. The extra cost for the materials for the solar heating system would be reduced to 80¢ per square foot in this case and the economic comparison is much more favorable. An additional 25¢ per square foot in the differential cost would be eliminated if a concrete floor were to be installed in either case. The use of a warm concrete floor could allow crops to be grown on the floor in some cases, thereby saving the cost of benches.

A complete retrofit, where conventional heating system, benches and other items are in place is not economical based on current fuel prices. However, if savings on floor or benches and on conventional heating systems can be applied to construction of the solar heating system, then the economic feasibility of the system is greatly enhanced. The entire system can be amortized in a few years under the most favorable circumstances. The reduction in total heat requirement due to the curtain insulation system is the most significant factor in the cost effectiveness of the system.

The comparison is more favorable on a relatively less energy efficient greenhouse, such as the unit actually tested. The actual total fuel savings due to the insulation and solar heating system amounted to 1.13 gallons of fuel per square foot of greenhouse for a savings of 56¢ per year; 51¢ after subtracting the collector recovering cost.

## FURTHER WORK

The system needs to be tested on a larger scale under commercial operating conditions to determine crop response and to get more data on operating performance. No serious crop response problems are anticipated, but demonstration of compatibility of the heating system with various cultural practices is needed. System modifications will be required for crops that require different growing environments. Two existing greenhouses on the Rutgers campus are being retrofit for these studies and plans have been developed for a 670 $m^2$ commercial demonstration project which could be operating next winter if all goes on schedule.

## ACKNOWLEDGEMENTS

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TABLE 1

Actual Energy Use in Test Greenhouse
in Equivalent Gallons of Fuel Oil

| Week Beginning | Degree Days | Total Energy Use | Energy from Solar | Energy from Fuel Oil |
|---|---|---|---|---|
| Sept. 1 | 16 | 1.46 | 1.46 | |
| 8 | 8 | 0.52 | 0.52 | |
| 15 | 0 | 0.17 | 0.17 | |
| 22 | 39 | 1.78 | 1.78 | |
| 29 | 54 | 2.22 | 2.22 | |
| Oct. 6 | 53 | 1.98 | 1.98 | |
| 13 | 109 | 5.77 | 5.77 | |
| 20 | 123 | 10.42 | 10.42 | |
| 27 | 164 | 9.15 | 8.99 | .16 |
| Nov. 3 | 157 | 12.55 | 7.93 | 4.62 |
| 10 | 197 | 14.21 | 8.54 | 5.67 |
| 17 | 177 | 12.16 | 8.12 | 4.04 |
| 24 | 181 | 13.45 | 6.30 | 7.15 |
| Dec. 1 | 274 | 19.18 | 6.22 | 12.96 |
| 8 | 235 | 17.62 | 5.83 | 11.79 |
| 15 | 214 | 16.32 | 3.84 | 12.48 |
| 22 | 270 | 18.64 | 9.02 | 9.62 |
| 29 | 312 | 19.53 | 8.66 | 10.87 |
| Jan. 5 | 276 | 19.89 | 3.27 | 16.62 |
| 12 | 354 | 22.28 | 5.99 | 16.29 |
| 19 | 325 | 19.09 | 8.88 | 10.21 |
| 26 | 320 | 18.76 | 10.35 | 8.41 |
| Feb. 2 | 284 | 19.60 | 6.96 | 12.64 |
| 9 | 208 | 15.43 | 4.58 | 10.85 |
| 16 | 269 | 16.80 | 7.33 | 9.47 |
| 23 | (NA) | 12.49 | 8.66 | 3.83 |
| TOTALS | 4619 | 321.47 | 153.79 | 167.68 |

TABLE 2

Predicted Energy Use for Equal Floor Areas
in Equivalent Gallons of Fuel Oil

| Week Begin. | No Insul. Sing. Glaze | No Insul. Dbl. Poly | Total Use in Large House | Fossil Fuel Use in Large House |
|---|---|---|---|---|
| Sept. 1 | 3.90 | 2.60 | 0.73 | |
| 8 | 1.38 | 0.92 | 0.26 | |
| 15 | 0.45 | 0.30 | 0.09 | |
| 22 | 4.76 | 3.17 | 0.89 | |
| 29 | 5.92 | 3.94 | 1.11 | |
| Oct. 6 | 5.28 | 3.52 | 0.99 | |
| 13 | 15.40 | 10.27 | 2.88 | |
| 20 | 27.78 | 18.52 | 5.21 | |
| 27 | 24.41 | 16.27 | 4.58 | |
| Nov. 3 | 33.47 | 22.32 | 6.28 | |
| 10 | 37.91 | 25.27 | 7.10 | |
| 17 | 32.42 | 21.61 | 6.08 | |
| 24 | 35.88 | 23.92 | 6.72 | 0.42 |
| Dec. 1 | 51.16 | 34.11 | 9.59 | 3.37 |
| 8 | 46.98 | 31.32 | 8.81 | 2.98 |
| 15 | 43.54 | 29.02 | 8.16 | 4.32 |
| 22 | 49.73 | 33.15 | 9.32 | 0.30 |
| 29 | 52.09 | 34.73 | 9.76 | 1.11 |
| Jan 5 | 53.04 | 35.36 | 9.94 | 6.68 |
| 12 | 59.42 | 39.61 | 11.14 | 5.15 |
| 19 | 50.92 | 33.95 | 9.54 | 0.66 |
| 26 | 50.02 | 33.35 | 9.38 | |
| Feb. 2 | 52.26 | 34.84 | 9.80 | 2.84 |
| 9 | 41.16 | 27.44 | 7.72 | 3.14 |
| 16 | 44.80 | 29.86 | 8.40 | 1.07 |
| 23 | 33.30 | 22.20 | 6.24 | |
| TOTALS | 857.38 | 571.57 | 160.72 | 32.04 |

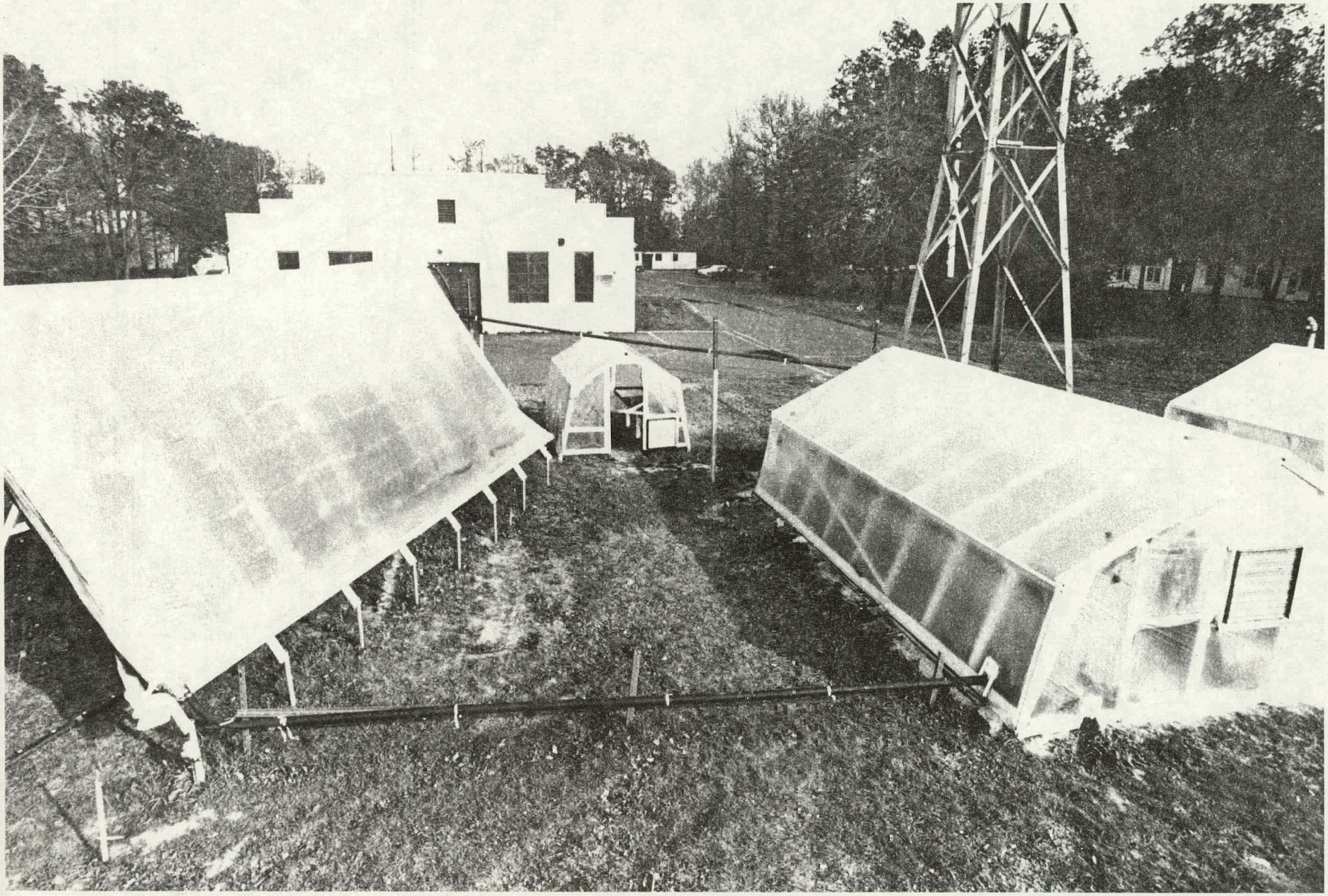


FIGURE 1. RUTGERS TEST GREENHOUSE AND SOLAR COLLECTOR.

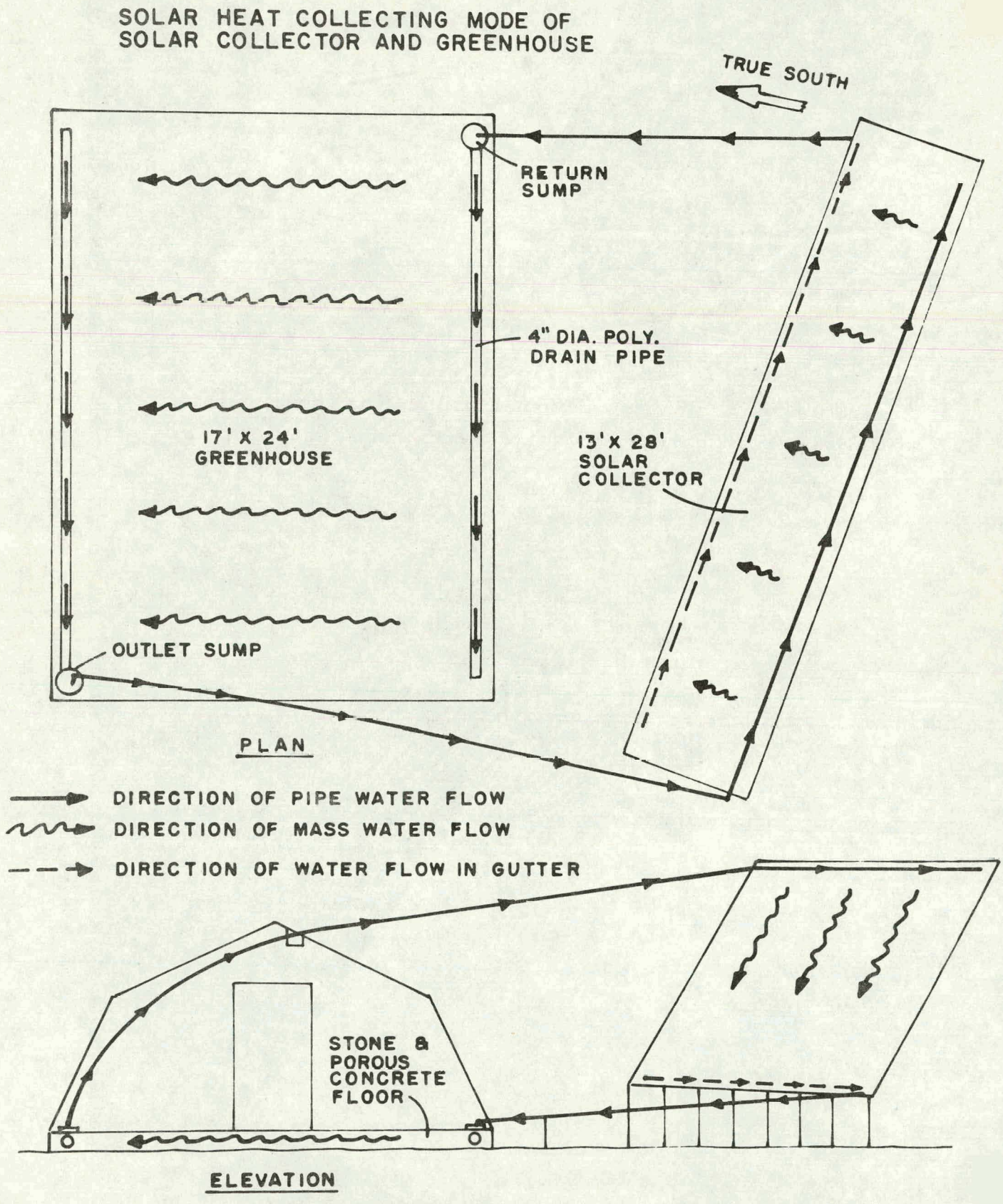



FIGURE 2. SYSTEM WATER FLOW IN COLLECTING MODE.

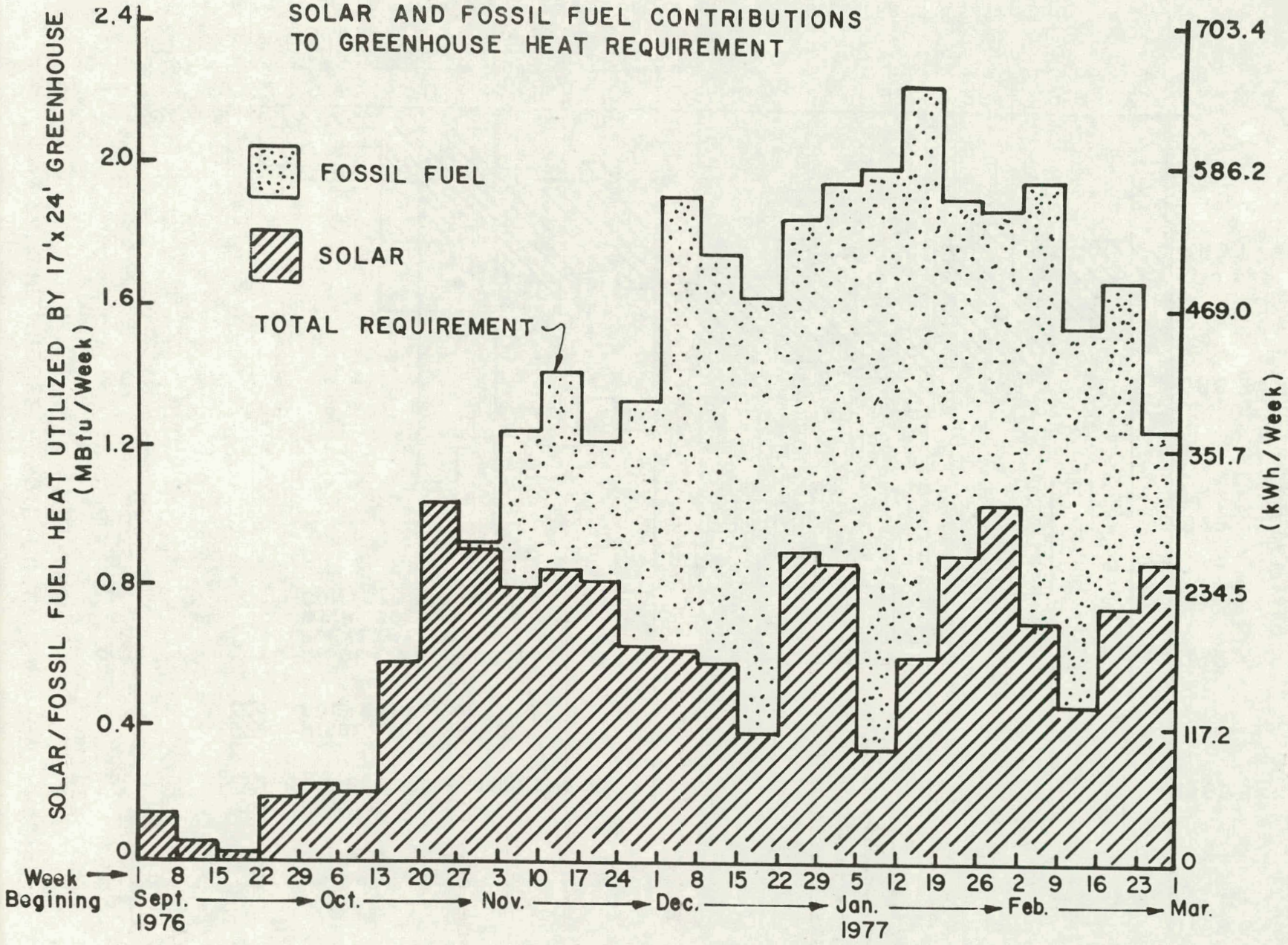
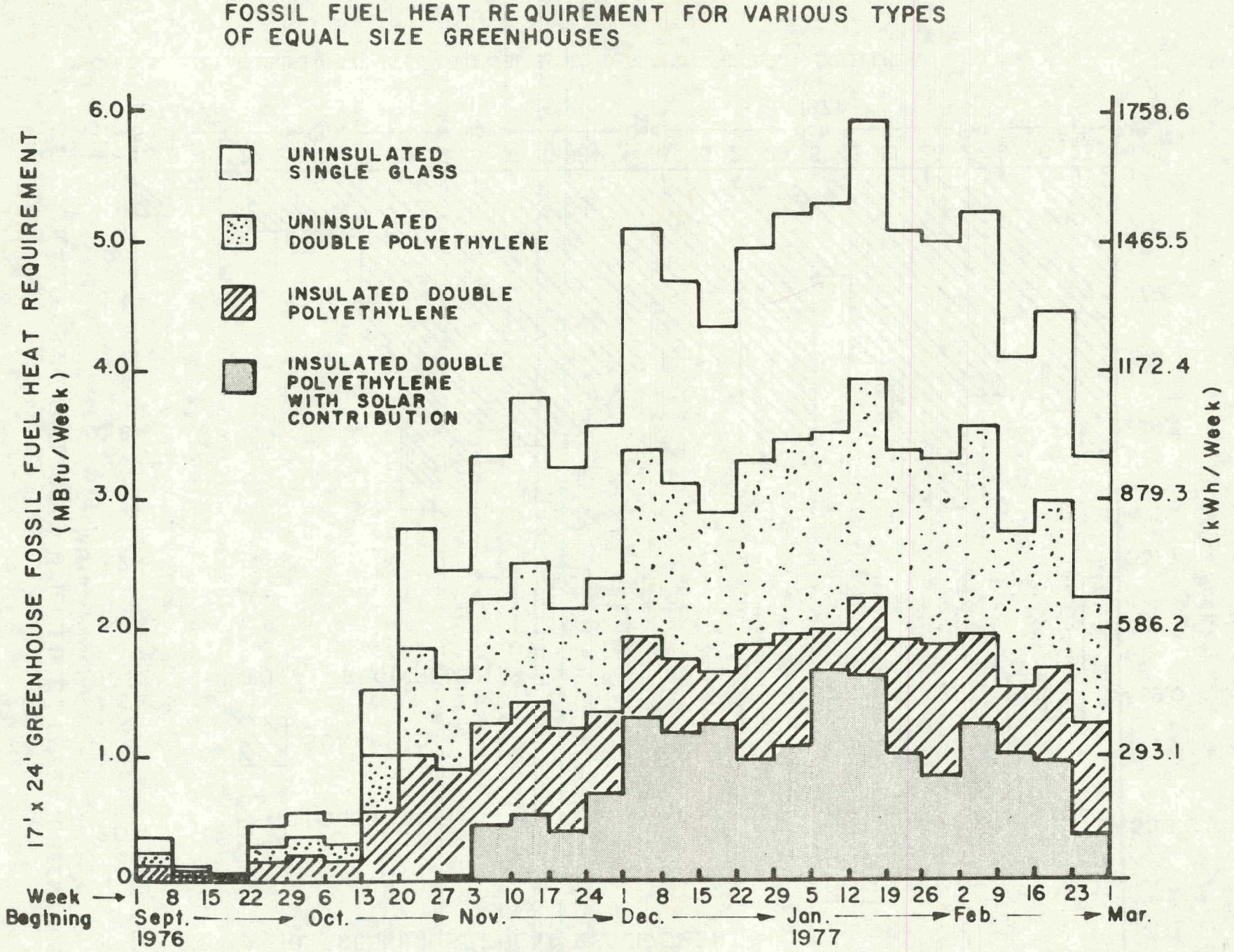



FIGURE 3. SOLAR AND FOSSIL FUEL CONTRIBUTIONS TO GREENHOUSE HEAT REQUIREMENT.




URE 4. FOSSIL FUEL REQUIREMENT FOR VARICUS TYPES OF EQUAL SIZE GREENHOUSES.

# SOIL AND GROUNDWATER FOR SOLAR HEAT STORAGE IN HEATING AND COOLING GREENHOUSES

Alvin C. Dale, Larry W. Turner and P. Allen Hammer[1]

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## INTRODUCTION

For solar energy to become one of the main sources of energy, the problem of storage of this energy must be solved. During the periods of the greatest need for energy, solar energy is available in limited quantities only about 15 to 20 percent of the time. Thus, regardless of collector efficiency and performance characteristics, solar energy storage is a must. All requirements of a solar energy storage are not evident but many of them are. Solar energy storages should be:

1. Moderate in cost.
2. High in thermal capacity.
3. Easy from which to reclaim energy.
4. Slow to lose energy to surroundings.

It is evident that keeping solar energy stored, from a time of plenty to the time of need, with subsequent release at that time is a desirable goal. This project is an attempt to reach that goal while meeting the above requirements.

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Acknowledgements: The authors are indebted to David A. Fouts, Student in Agricultural Engineering, Purdue University, for his contributions in the programming and operation of the computer models. We also wish to thank Martin R. Okos, Assistant Professor, and Steven R. Eckhoff, Graduate instructor, Agricultural Engineering Department, Purdue University for advice and consultations concerning the modeling of the storage system.

## GOALS AND OBJECTIVES

The goal of this research is to develop a system for the collection, storage, and utilization of solar energy for heating and cooling greenhouses or rural houses, or both that will reduce the requirements of energy derived from fossil fuels. In addition, the system to be developed could be applied to drying grain, to heating water, and to the heating and cooling of other buildings such as farm machine shops and animal shelters. Specific objectives are as follows:

1. To develop an improved solar energy collection method utilizing a system of reflectors to concentrate the solar energy entering an insulated air collector.

2. To devise a system for the transfer of the collected energy to a soil and groundwater storage.

3. To determine the rates of energy gains and losses of the insulated storage field of soil with a high groundwater table.

4. To determine the feasibility of using direct air flow from the energy storage through a greenhouse to serve as its energy source for heating.

5. To determine the possibility of using the cool air in the late winter and early spring to cool the soil and groundwater and then using this cooled mass as a supplement for cooling greenhouses.

6. To maximize solar energy as the heat source while minimizing the greenhouse heat requirements at night with the use of an insulating system.

## BRIEF DESCRIPTION OF SYSTEM

An insulated solar energy collector has been fabricated with two reflectors to concentrate the solar energy. The reflectors are placed at the top and bottom of the collector at such an angle so as to reflect additional solar energy into the collector, thus increasing efficiency. Air serves as the energy exchange medium between the collector and storage field. The solar heated air is being blown through an insulated energy storage field of soil and groundwater at a depth of seven and nine feet for transfer of the heat to these materials. Figure 1 shows a plot plan of the setup and Figure 2 shows a cross section through the system.

Starting in August or early September, the collector is to be placed in operation to build up the stored energy for the winter. In the late winter or early spring (about the first of March), the solar

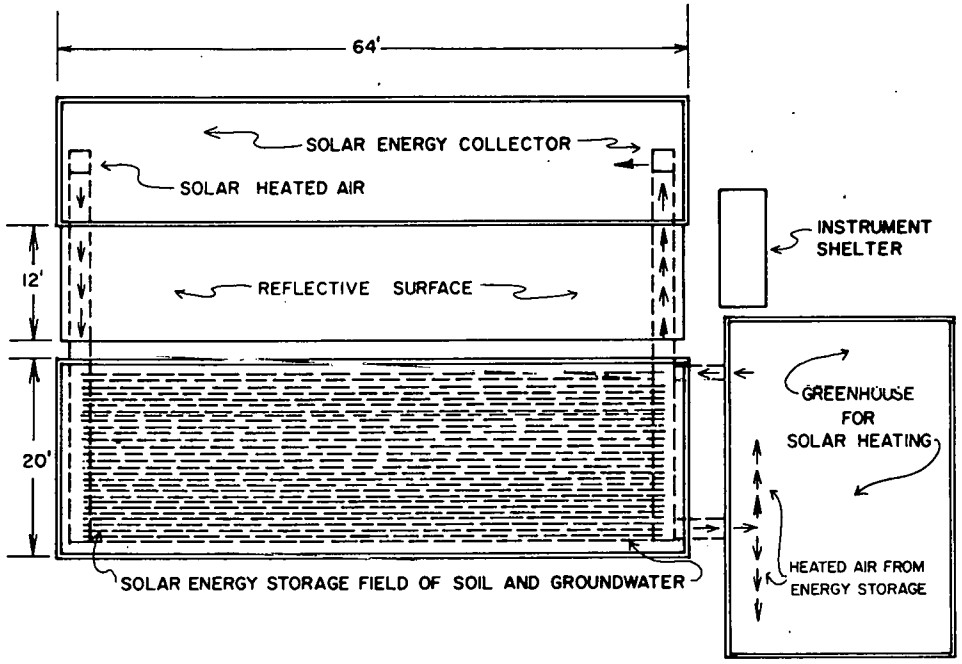



FIGURE 1 PLOT PLAN OF SOLAR ENERGY COLLECTION, STORAGE, AND UTILIZATION SYSTEM.

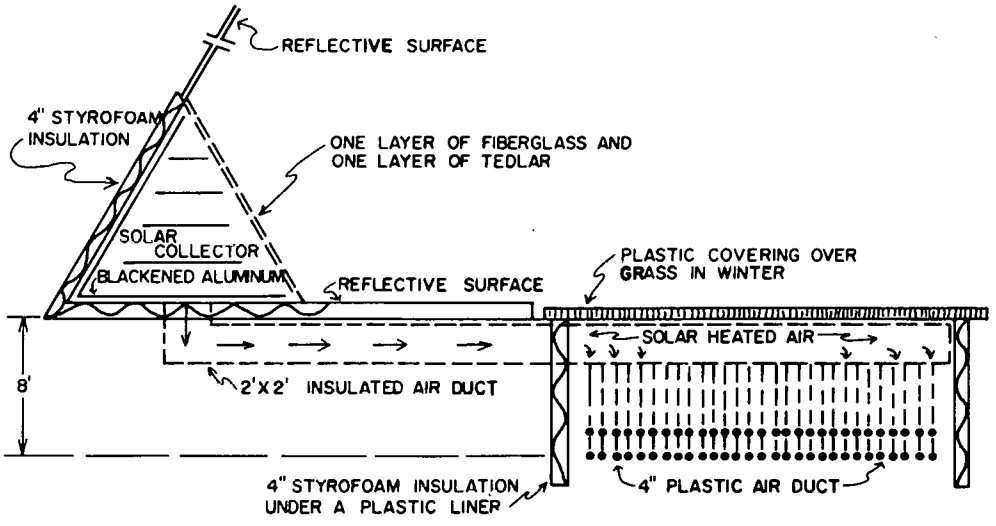



FIGURE 2 CROSS SECTION THROUGH THE SOLAR COLLECTOR AND ENERGY STORAGE FIELD

energy collector is to be covered with white plastic and the cool air circulated through the field to cool the storage. During the summer, air is to be circulated through the storage field to provide cool air for ventilation and cooling of greenhouses and houses.

RATIONALE OF A SOIL AND GROUNDWATER SOLAR ENERGY STORAGE

The question may well be asked, why consider the use of soil and groundwater for solar energy storage? Some of the reasons are as follows:

1. Soil is available everywhere in almost unlimited quantities.
2. Soil and groundwater are low in cost.
3. Soil and groundwater requires no maintenance.
4. Soil furnishes insulation above and around system if permitted to dry out.
5. Saturated soil has good thermal capacity.
6. The storage is safe requiring no fencing or protection.
7. A soil and groundwater storage can be adapted to a solar collector at moderate cost.
8. Warming of the soil and groundwater can start long before the heating season starts when a larger supply of solar energy is available.
9. The greenhouse may be built over a soil and groundwater solar energy storage.

Some requirements of a soil and groundwater energy storage are as follows:

1. Water is necessary to aid in heat transmission as the conductivity of dry soil is low.
2. Water must be retained in the system with an impermeable membrane placed on the bottom and sidewalls.
3. Energy must be conveyed and transferred to soil by a system of small tubes or air ducts to facilitate the transfer of energy.
4. Storage should be relatively close to facility where energy is to be used.
5. An open area is needed.
6. A thin impermeable cover may be needed near top to prevent evaporation.

Possible uses of soil and groundwater solar energy storage are as follows:

1. Source for the direct reclamation of energy for heating any building.
2. Preheating water for any use - heat exchanger pipe required.
3. As a solar energy storage for a solar assisted heat pump system.

Some points worthy of consideration are the following:

1. Since soil and groundwater are readily available in large

quantities, the storage should probably be made larger than normally considered.
2. Soil and groundwater storage may be covered with one or two layers of clear plastic to make its surface a collector and to assist in warming the storage.
3. Greenhouses may be built over the storage.

DESIGN OF THE SOIL AND GROUNDWATER STORAGE

Saturated soil has almost as much thermal capacity per unit volume as water. Thus on a volumetric basis, it can store almost as much energy as a solar pond. However, it does require a solar collector and an energy transfer system.

The volume weight of most subsoils is about 1.5 to 1.6 times that of water. The sandy clay in this case weighs about 100 lbs/cu. ft. The specific gravity for the same material is about 2.65. The pore space is computed as follows:

$$\text{Percent Pore Space} = 100\% - \left(\frac{1.6}{2.65} * 100\right)$$

$$= 100 - 60.4 = 39.6\%$$

With the soil saturated, this pore space is occupied by water. The combined weight of the soil and water is the following:

wt. of soil/cu. ft. + wt. of water/cu. ft. =

wt. of mixture/cu. ft.

100 lbs. cu. ft. + .396 * 62.42 = 125 lbs. cu. ft.

The energy or heat required to raise one cu. ft. one degree Fahrenheit would be

$$0.2 * 100 + 1 * 25 = 45 \text{ Btus/cu. ft.}$$

$$c = 45 \div 125 = 0.360 \text{ Btu/°F - lb of mixture}$$

Thus, compared to water, the possible energy storage per unit of volume is not much different. Soil and groundwater combined store about 72% as much energy as water per unit volume.

The size of the storage was determined on the basis of the desired energy storage and the average thermal capacity of the soil and groundwater. By the selection of the greenhouse to be heated and the storage time required, the size of the storage pit may be computed. However, the greenhouse's heating requirements in this project are more than might be expected daily from a reasonably sized solar collector. Thus, a storage volume was selected to store about 40 million Btus of energy with a temperature rise of 60°F.

$$M * C\rho * \Delta t = Q$$

$$M = \frac{Q}{C\rho * \Delta t} = \frac{50,000,000}{0.360 * 60} = 1,850,000 \text{ lbs.}$$

$$\text{Volume} = \frac{1,850,000}{125} = 14,800 \text{ cu. ft.}$$

A storage 36' x 72' x 11' deep with a one to one side slope was selected. These dimensions provide a volume of 14,500 cu. ft. The physical construction of the eleven foot deep soil and groundwater solar energy storage as shown in Figures 3 and 4 consisted of the following steps:

1. Soil was removed and stored closeby.
2. Four inches of polyurethane insulation was placed on sides of pit.
3. A 22 ml plastic liner was placed in the hole over the soil bottom and insulation.
4. Two feet of soil was placed back in the excavation and compacted.
5. A row of 28, 4" plastic ducts were placed on the two feet of fill and fixed in position with soil and cement.
6. Two more feet of soil were compacted into position over these ducts.
7. A second row of 28, 4" plastic ducts was positioned in place on top of the second two-foot layer of soil.
8. The excavation was refilled with the stored soil to within 18" of the top.
9. A second plastic film was placed over the storage and lapped with the edges of the bottom liner.
10. The final fill of soil was returned to the pit.
11. Water was added to saturate the storage.

DESIGN OF AIR DUCTS

Original plans were to install only one row of about 8 - 4" plastic ducts at about the 8 ft. depth. However, a more rigorous computation showed that this number of 4" ducts was not sufficient to transfer the energy to the storage. By the use of Nusselt's equation from Brown (1942) it was established that 15 ducts 60' in length were required to transfer the maximum energy (192,000 Btu/hr) collected hourly by the solar collector to the soil and groundwater. Nusselt's equation, simplified for this application is as follows:

$$hc = 0.0202 \frac{k}{D} \frac{(DV\rho)^{0.8}}{(\mu)}$$

which reduces to

$$\frac{C^{G^{0.8}}}{D^{0.2}}$$

where hc is the heat conduct coefficient, k is a constant for air,

D is the diameter of the pipe in feet

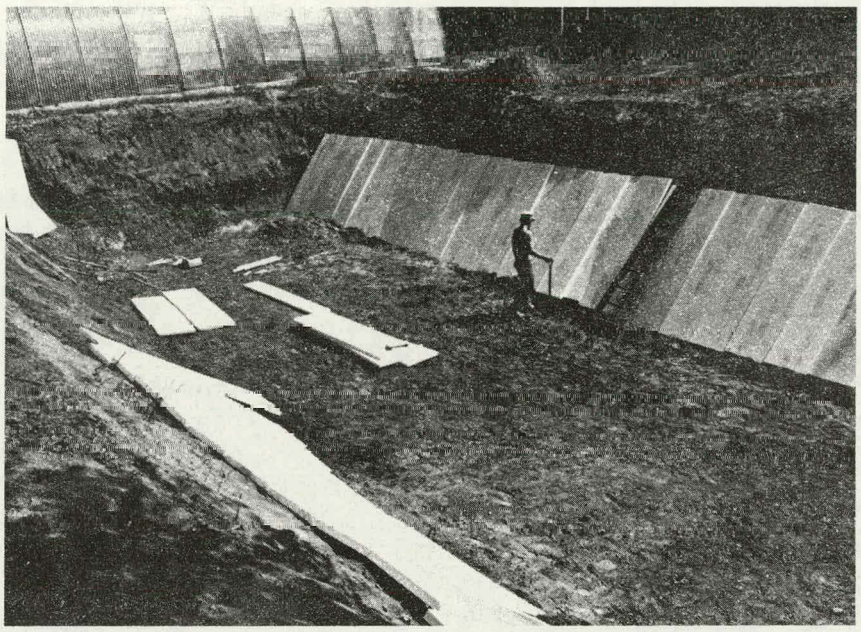


Figure 3. Installation of Insulation in the Eleven-foot Deep Excavation for the Soil and Groundwater Solar Energy Storage.

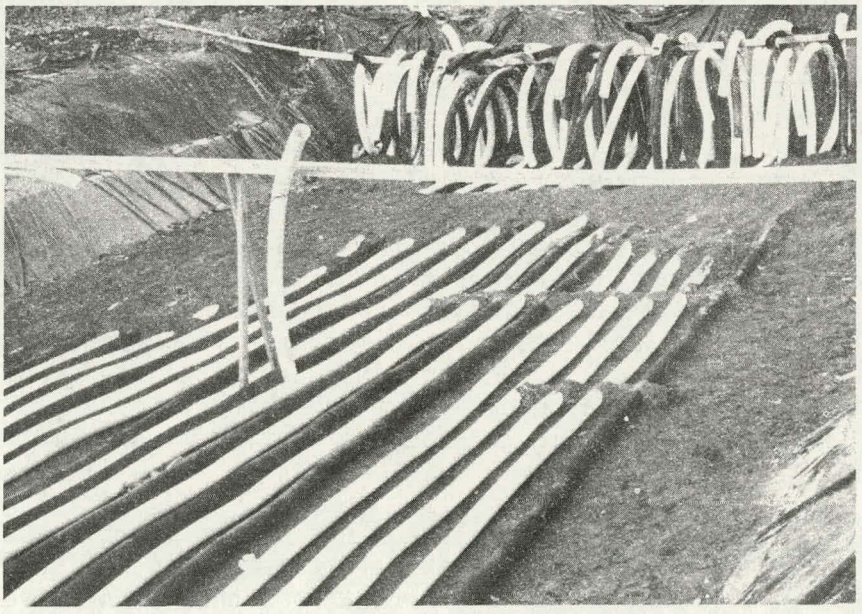


Figure 4. The Second Row of Four-Inch Air Ducts Were Installed Seven Feet Below the Surface.

V is the mass velocity, lbs/sq. ft. - hr

$\mu$ is the viscosity of the fluid

C = 0.00336 for air

$G = \rho V$

with substitutions in the equation, based on a volume flow of 1800 cfm and varying the number of ducts, $h_c$ was found to be approximately 4.0 Btu/ft$^2$-hr-°F. This led to the selection of 15 - 60' ducts to transfer the required energy at a 50°F temperature differential.

SOLAR COLLECTOR BEING USED

The solar collector is designed with several criteria in mind. It must be adaptable to many different situations. A freestanding collector was chosen since it can be adapted to both greenhouses and houses. Also, it is not integrated into the building, so it does not limit building orientation. A freestanding collector is more applicable for retrofitting existing systems - it is not limited to new installations. The collector also needs to be constructed of materials which are readily available - no exotic materials were used.

A primary criterion is cost. The materials and construction methods must be as low in cost as possible without sacrificing efficiency. The overall goal then, was a collector with the lowest cost per Btu of heat collected which met the heating needs of a greenhouse in a variety of situations.

The configuration of the design chosen is shown in Figure 5. The frame is constructed of wood, 2" x 6" material with 2" x 4" members for framing. The cover consists of an outer layer of clear superior grade greenhouse-type corrugated Filon fiberglass with an inner layer of Tedlar. The absorber plate is made from aluminum roofing panels painted with Slip-Plate graphite based black paint to absorb the greatest amount of energy. Four inches of Styrofoam insulation separate the absorber plate from the plywood back which is exposed to the ambient air. Air is passed through the collector by a blower and then transferred to the storage system. The flat reflecting wings are fabricated from reflective aluminum roofing on a wooden frame. The front cover of the collector is 12' wide and 64' long. Each reflecting wing is 12' wide also.

The A-frame or Vee-type solar collector has proven to be one of the more efficient configurations for an air system. Close (1963) found an increase in efficiency for Vee-corrugations due to increased plate area and better spectral-reflectance characteristics. Black and Schoenhals (1968) investigated the effects of a vee-cavity on absorption of radiation and found a marked increase in performance. The reflecting wings also serve to increase the performance of the col-

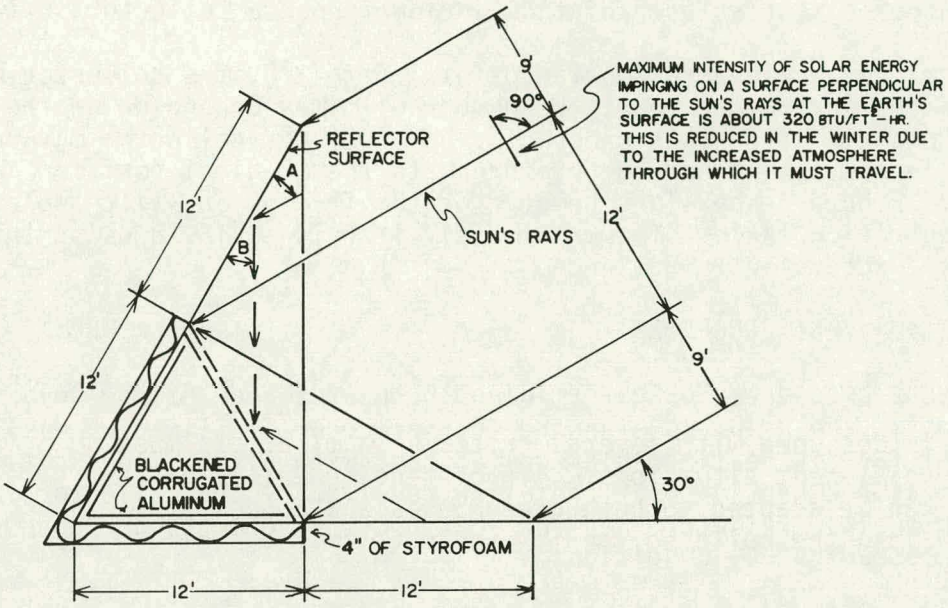



FIGURE 5 CROSS SECTION THROUGH COLLECTOR

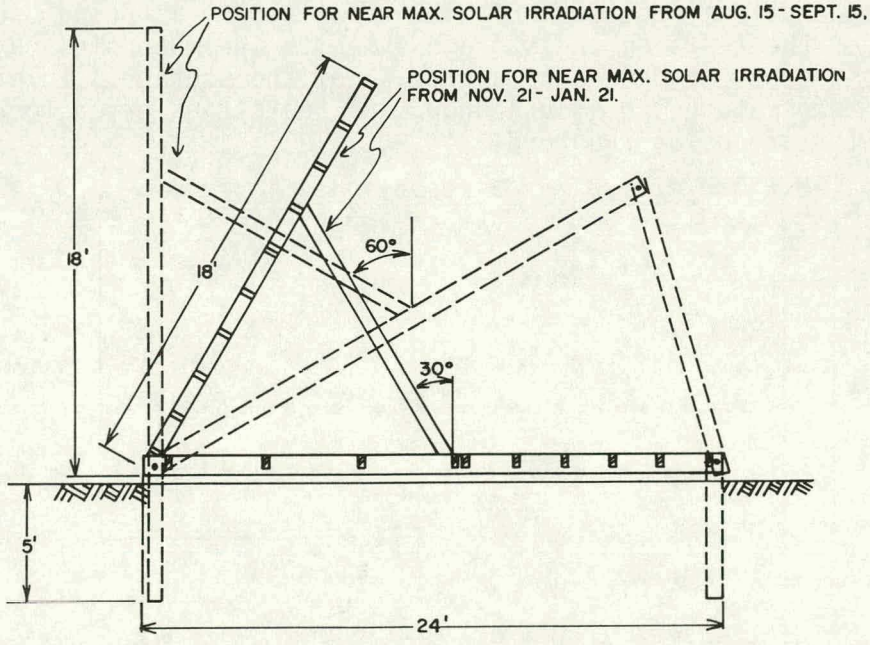



FIGURE 6 SCHEMATIC OF FRAMING AND POSITIONS FOR MAXIMUM SOLAR IRRADIATION

lector. Hollands (1970) studied the use of reflecting wings analytically and found concentration factors of from 1.5 to 2.5 times the amount of direct solar radiation incident upon a collector surface.

To achieve a concentration factor of 1.5 to 2.5, the collector must be tilted during the year, the number of times depending on the angle $\theta$. An angle of 60° was chosen for $\theta = 60°$, the collector may be tilted once in the spring and then returned to the original position in the fall. Figure 6 shows a schematic of the framing and tilt angle. A concentration factor of approximately 1.75 is achieved using this procedure, according to Hollands.

## COLLECTOR TEST PROCEDURE

The test procedure for determining the performance of the solar collector is the proposed standard test procedure outlined by Hill et al. (1976) for air heating solar collectors, with slight modifications. For measured hourly solar radiation received by the collector, average efficiencies are determined for that hour. The tests are conducted under steady state conditions.

Temperature measurements are being made with thermopiles at the inlet and outlet of the solar collector. Additional measurements are being made of ambient temperature, plate temperature, cover temperature of each cover, and the temperature of the plywood back with radiation shields used when necessary to obtain true readings. Figure 7 shows a schematic of the thermopile layout.

The standard test procedure of Hill et al (1976) is being used as a guide for the tests on the storage system. Thermocouples have been placed in order to determine a profile of the storage. Inlet and outlet temperatures, pressure drop, and heat transferred to and from the system are being recorded.

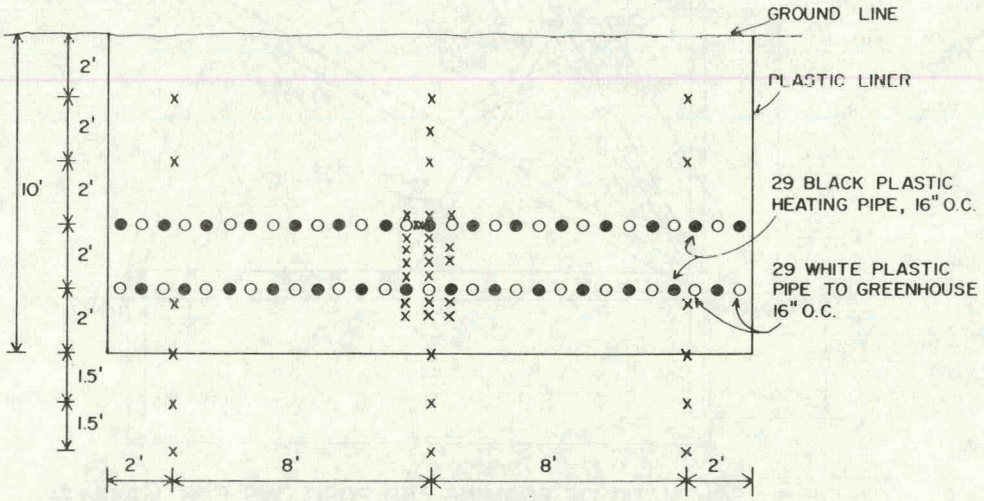



FIGURE 7 PROFILE OF SOIL AND GROUNDWATER STORAGE WITH THERMOCOUPLE GRID. (x's INDICATE THERMOCOUPLE POSITION)

Data are monitored by a Doric Digitrend 220 microprocessor data logger and transferred using an analog to digital converter, serialize and telephone line interface. Periodic readings are then transmitted over a telephone line to a remote computer in the Agricultural Engineering Building for permanent storage. The collected data are then available for subsequent display and analysis.

The Agricultural Experiment Station operates a unique data acquisition system called MIRACLE. The MIRACLE system acquires and processes large amounts of data on-line. In connection with the MIRACLE system, the NOAA Agricultural Weather Service collects hourly weather data at the Agronomy Farm, only about eight miles from the greenhouse location. Dry bulb and dew-point temperatures, wind speed, and total short-wave radiation incident on a horizontal surface are measured and integrated over a one-hour period with 15-second time steps.

Air flow measurements through the collector are made with a flow nozzle installed in accordance with the standard. Pressure drop across the collector is also measured with a manomenter. The collected data are then analyzed to determine hourly efficiencies and collected energy.

COMPUTER MODEL OF STORAGE

In addition to field tests of the storage system a computer model of the system is being used to predict performance with respect to heat transfer to the storage bed and temperature profiles of bed cross sections.

The assumptions used as a basis for the model are as follows:

i) CONSTANT PROPERTIES

1. for the air - $\rho$ = 0.667 lb/ft$^3$

   $Cp^2$ + 0.24 Btu/lb - °F

   K = 0.0157 Btu/hr - ft - °F

   $\mu^2$ = 0.0459 lb/ft - hr

2. for the soil - $\rho Cp$ = 40.0 Btu/ft$^3$ - °F

   K = 0.8 Btu/hr - ft - °F

ii) FLOW RATE = 85 cfm/pipe

iii) TEMPERATURE

1. Air temperature in = 115°F

2. Initial soil temperature = 50°F

iv) Nusselt's equation applies for turbulent flow in the tubes

Since modeling the complete storage bed would result in a large and unwieldy model, a typical section of the bed was chosen. Numerical methods are used to analyze the section. Nodes in the X-Y plane (cross section of bed) were established with Dx-Dy = 2.0 inches. In the Z direction (length of bed) the bed was broken up into eight sections. The procedure for analysis is to calculate the heat transferred between nodes over a specified time period with a time increment Dt of 0.05 hours.

Figure 8 shows the predicted temperature profile of an 8' - 0" deep by 4' - 6" wide section (dimensions of figure are not to scale) of the storage bed immediately after six days of operation (six heating periods). The operating conditions are assumed to be eight hours of solar heat at 115°F with 16 hours off. The bed temperature was initially 50°F throughout and has been heated to the temperature shown. There is localized heating around the six pipes included in the model, with the soil groundwater temperature near the surface only being raised 5°F. After sixteen hours of equilibration, the bed temperature becomes more uniform as shown in Figure 9. The total heat added to the 8' - 0" x 8' - 0" x 4' - 6" section of storage during the six day period is $1.72 \times 10^6$ Btu. The boundaries of the section are assumed to be perfectly insulated.

Additional runs were made cooling the bed for four days with the initial soil temperature at 115°F and the air temperature at 50°F. The heat is removed on a 16 hours on - 8 hours off schedule. The total heat removed during this time is $1.99 \times 10^6$ Btu from the section.

Further refinements of the model are being made with the objectives of modeling over a longer time period, heating and cooling simultaneously, and providing a varying solar heat input. Results up to this point indicate that the system will perform well as a heat storage medium.

ANALYTICAL COLLECTOR PERFORMANCE MODEL

A computer model of the collector is being used to predict its performance under a variety of conditions of flow rate, ambient temperature, and insulation rate. The model of the collector may then be used in conjunction with the storage model to predict the behavior of the system under various conditions. The field tests will assist in determining the validity of the model.

The collector model assumes steady-state, one-dimensional fluid flow. An energy balance was made on a differential length of the collector to find how the air temperature varies with distance along the collector. The resulting equation is as follows:

$$\frac{dT_a}{dx} = \frac{4}{mC_p} \left(3\, q''_s - 5\, q_{l_b} - 3\, q''_{l_c}\right)$$

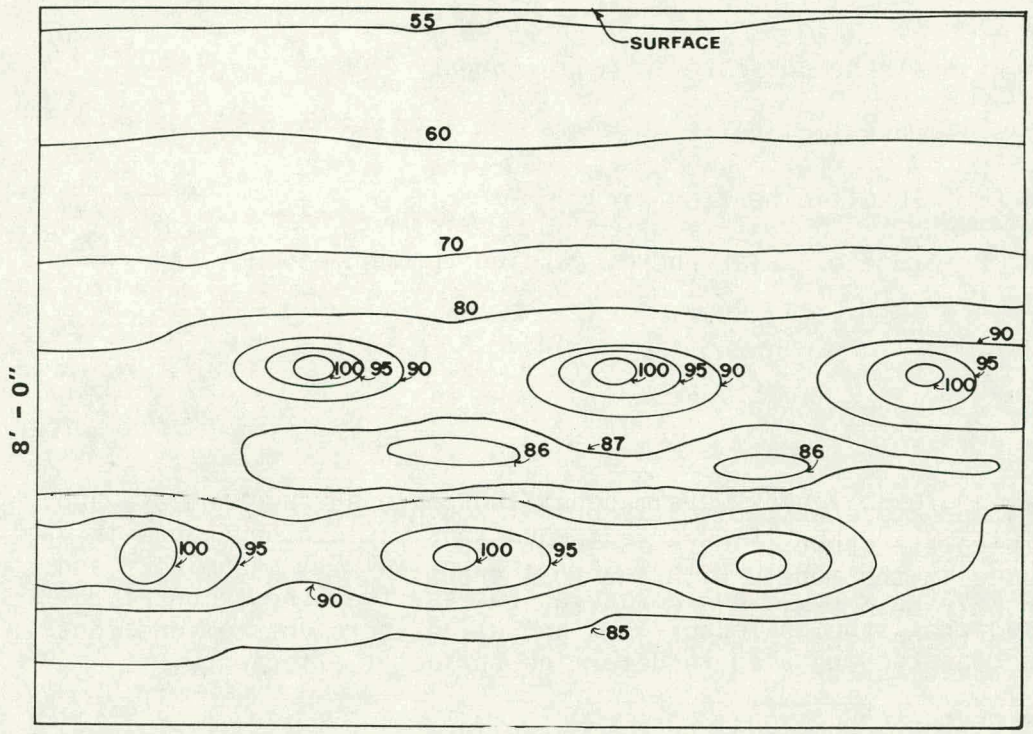



Figure 8. Predicted temperature profile of an 8' - 0" deep by 4' - 6" wide section of the storage bed immediately after the sixth heating period.

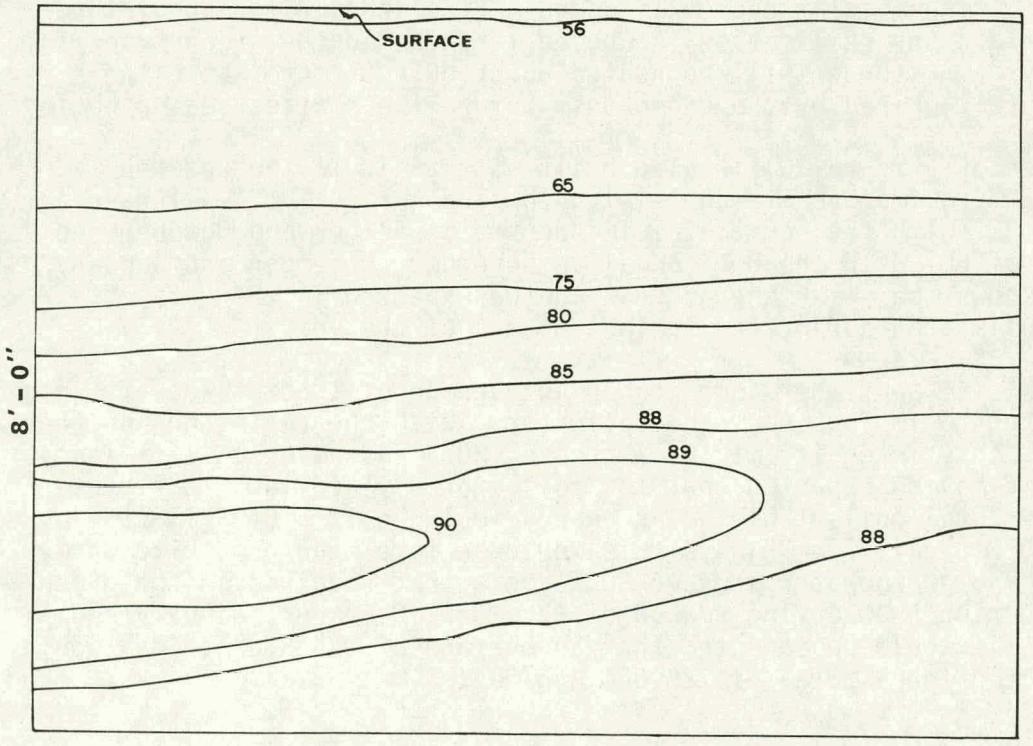



Figure 9. Predicted temperature profile of the section of storage sixteen hours after the sixth heating period.

where: $t_a$ = air temperature in collector

$m$ = mass flow rate

$C_p$ = specific heat or air

$q''_s$ = rate of solar energy passing through cover system

$q''_{l_b}$ = back losses

$q''_{l_c}$ = cover losses

Additional energy balances were made at the plate surface and at each cover. Solving the resulting set of equations yields the change in temperature for a given increment of X and initial $T_a$, assuming m and Cp are constant. Through an iterative process, then the temperature difference across the collector is found using increments of one foot. This value can then be used to determine collector efficiency.

OPERATION OF THE COLLECTOR

Since the soil and groundwater storage is large in relation to the solar collector, and since far more solar energy is available during the late summer and early fall than during the winter, the transfer of collected solar energy to the storage is to be started about the first of August. Thus, solar energy is added to the storage for about three months before any reclamation is needed for heating the greenhouse. Hopefully, the storage will be heated about 60°F or more above the temperature required by the greenhouse before the heating season begins.

The collector (Figure 10) is also built so that it may be rotated through 30° to improve its angle with the sun's rays. It will have an angle of 30° with the horizontal in August, September and October and an angle of 60° with the horizontal in November, December and January. Table I shows the solar energy that can be expected in the Lafayette - Indianapolis area during the various months of the year.

During August, September and October an average of 1850 Btu/day-ft$^2$ can be expected to impinge upon the collector. With the reflectors on the collector this intensity may be increased 50%. Assuming an efficiency of 50%, it may be expected that the collector will collect 1387.5 Btu/ft$^2$ day. Total collectable solar energy would be 12 * 64 * 1387.5 = 1,065,000 Btu/day. In 90 days this would be more than enough to warm the soil and groundwater storage 60°F above that required in the greenhouse. During the heating season of November, December, January and February, it would be expected that an average of 945 Btu/ft$^2$-day would be collected for a total of 725,000 Btu/Day.

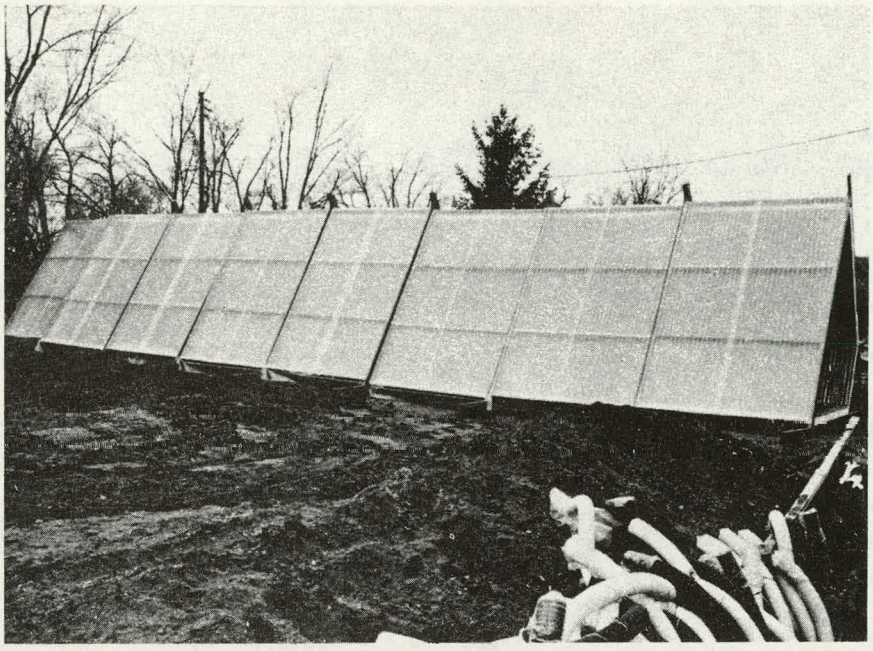


Figure 10. Solar Collector Units Being Lined Up on the North Side of the Soil and Groundwater Storage.

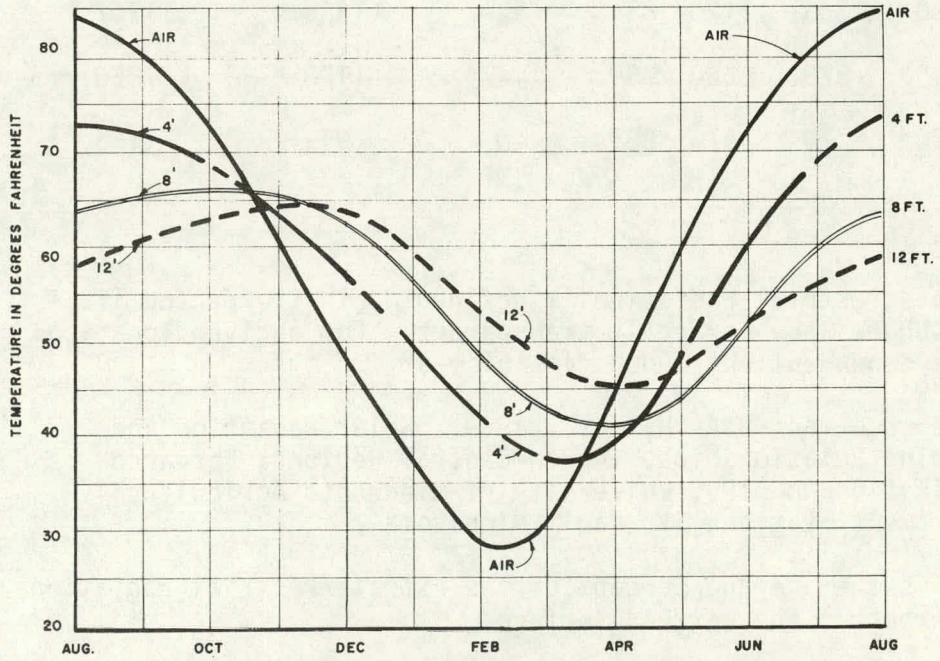



FIGURE 11. SEASONAL TEMPERATURE VARIATIONS OF AIR AND SOIL AT 4', 8', AND 12' DEPTHS- LAFAYETTE

TABLE I. AVERAGE SOLAR RADIATION ON SURFACES AT INDIANAPOLIS, INDIANA & at 40° N. LATITUDE (Btu per sq. ft. per day.)

| Mo. | Extra-terrestrial[1] | Measured[2] High | Ave | Low | Ave. %[3] Trans-mission | Ave. Quantity of Radiation Incident on Surface at Tilt Given 30° | 60° |
|---|---|---|---|---|---|---|---|
| JAN | 1415 | 851 | 610 | 402 | 43% | 1049 | 1220 |
| FEB | 1870 | 1183 | 845 | 660 | 45 | 1234 | 1317 |
| MAR | 2540 | 1397 | 1155 | 822 | 45 | 1420 | 1374 |
| APR | 3165 | 1758 | 1540 | 575 | 49 | 1632 | 1364 |
| MAY | 3585 | 2263 | 1890 | 1433 | 53 | 1796 | 1390 |
| JUN | 3750 | 2325 | 2080 | 1780 | 56 | 1914 | 1413 |
| JUL | 3645 | 2229 | 2025 | 1644 | 56 | 1923 | 1488 |
| AUG | 3300 | 1935 | 1840 | 1492 | 56 | 1950 | 1630 |
| SEP | 2760 | 1820 | 1550 | 1286 | 56 | 1966 | 1844 |
| OCT | 2100 | 1363 | 1120 | 884 | 53 | 1635 | 1747 |
| NOV | 1345 | 870 | 680 | 369 | 44 | 1170 | 1360 |
| DEC | 1270 | 770 | 510 | 361 | 40 | 959 | 1148 |

References & Notes:

1. Extraterrestrial radiation is defined as that expected if atmosphere were perfectly transparent. For a given location it is dependent only upon time of year.

2. Baker, D.G. and D.A. Haines. 1969. Solar Radiation and Sunshine Relationships. North Central Regional Research Publication No. 195, University of Minnesota Agricultural Experiment Station, St. Paul, Minnesota.

3. This is the average percent of the extraterrestrial radiation that reaches the earth's surface.

GREENHOUSE DESCRIPTION

The greenhouse being used in this study is a Lord and Burnham Grow-Mor greenhouse of the quonset type, 32' x 48' in dimensions. The outside surface is corrugated greenhouse fiberglass. The inside has been lined with clear plastic to decrease the heat loss. It has an approximate heat loss rate of 46,000 Btu/degree day. The solar heat is to be supplemented by propane fueled unit heaters.

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# CROP RESPONSE IN SOLAR HEATED GREENHOUSES VENTILATED WITH DEEP COAL MINE AIR[1]

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Dean Knavel and John Hartman[2]

ABSTRACT

A mine-air ventilated greenhouse was suitable for the production of many greenhouse crops from mid-February through November. The temperature ranged from 16°C (60°F) to 30°C (85°F) during the day and remained a constant 12 - 13°C (53° - 55°F) at night. High quality lettuce, snapdragons, carnations and bedding plants were grown in the greenhouse during the period.

During the winter the relative humidity remained near 100% day and night. The constant high humidity caused serious diseases and physiological problems on lettuce, carnations and snapdragons.

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Air drawn from mines may be used to heat greenhouses in the winter as well as cool greenhouses in the summer (8). The air temperature in mines throughout the U. S. remains relatively constant throughout the year, varying as little as 3°C (8°F) between summer and winter. In the northern areas of the U. S. the temperature of coal mines averages 5-8°C (42°-47°F) whereas in the southern sections the temperature averages 19-21°C (67-70°F) (6,8). In the coal mining regions of Eastern United States the temperature ranges from 11°C (52°F) to 16°C (60°F). A temperature in the range 11-16°C is suitable for the growth of many greenhouse crops. Air drawn from mines may, therefore, be used to heat greenhouses during the winter as well as cool them during the summer. If no other source of heat other than the natural occurring solar energy is required, the cost to provide a suitable greenhouse environment may be significantly less than conventional systems and provide an economic advantage.

A large number of active and abandoned mines as well as other mines exist in the United States. There also exist many underground caverns or caves which potentially could be used to control the environment in a greenhouse. In 1966 the U. S. Bureau of Mines reported the existence of 88,000 inactive mines of which 67,613 were coal mines (10). Many of these mines are located in the Kentucky, West Virginia,

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Virginia, Pennsylvania and Ohio area (Fig. 1). Because of inaccurate reporting in early years the report suggested that there could be up to 200,000 inactive mines in the U. S. Not every abandoned or inactive mine is suitable for use in conditioning a greenhouse. The usability would depend upon the size of the mine, sunlight exposure, availability of water and electricity, etc. However, a significant number would be suitable for locating a greenhouse complex.

Potential Energy Savings: With a greenhouse ventilated with deep mine air, energy would be required to operate the ventilation fans on a virtually continuous basis since the mine air is the heat source when the greenhouse temperatures fall below desired levels and is the source of cooling on days when the greenhouse temperature rises above desired levels due to solar heating. The total ventilation fan horsepower for a typical greenhouse having 3000 sq. ft. of ground area would be 1 1/2 HP. Assuming continuous operation for the seven month winter heating period as defined by ASHRAE as being October to April inclusive (1), the total estimated energy requirement would be $26 \times 10^6$ BTU's. There would be an additional energy requirement for ventilation during the five summer months; however, it can be assumed that the energy required for this purpose for a conventional and for a mine air ventilated greenhouse would be comparable.

The energy requirement for a double-covered conventional greenhouse of the same size which was heated to approximately the same temperature as the deep ground temperature was also estimated for a number of locations in the United States. The energy required for heating, heat distribution (air circulation), and ventilation were included in this estimate. The hours of ventilation which would be required for the different geographical locations during the seven month heating season was estimated to vary from near zero in Madison, Wisconsin to 1145 hours in Jacksonville, Florida. It was assumed that the ventilation fan horsepower for the conventional greenhouse was comparable to that for the mine-ventilated greenhouse (i.e., 1 1/2 HP). In addition it was assumed 1/2 HP was used for heat distribution and air circulation. The heat requirement was estimated by using the degree-days given by ASHRAE and as recommended by standard greenhouse heating requirement analysis techniques (7). The total energy requirement for the selected locations is given in Table 1.

A ratio was then calculated between the energy required for the winter heating period for environmental control in a conventional greenhouse versus that for a mine-ventilated greenhouse. These ratios are also shown in Table 1 and varied from 4.2 to 12.8. The lower ratios occurred in the warmer parts of the United States where the heating energy requirement was relatively low and the higher values in the more northern or colder areas where the heating requirement was large. The average ratio for the locations evaluated was 8.4 indicating that a mine-ventilated greenhouse would be on the average 8.4 time more energy efficient than a similarly-constructed conventional

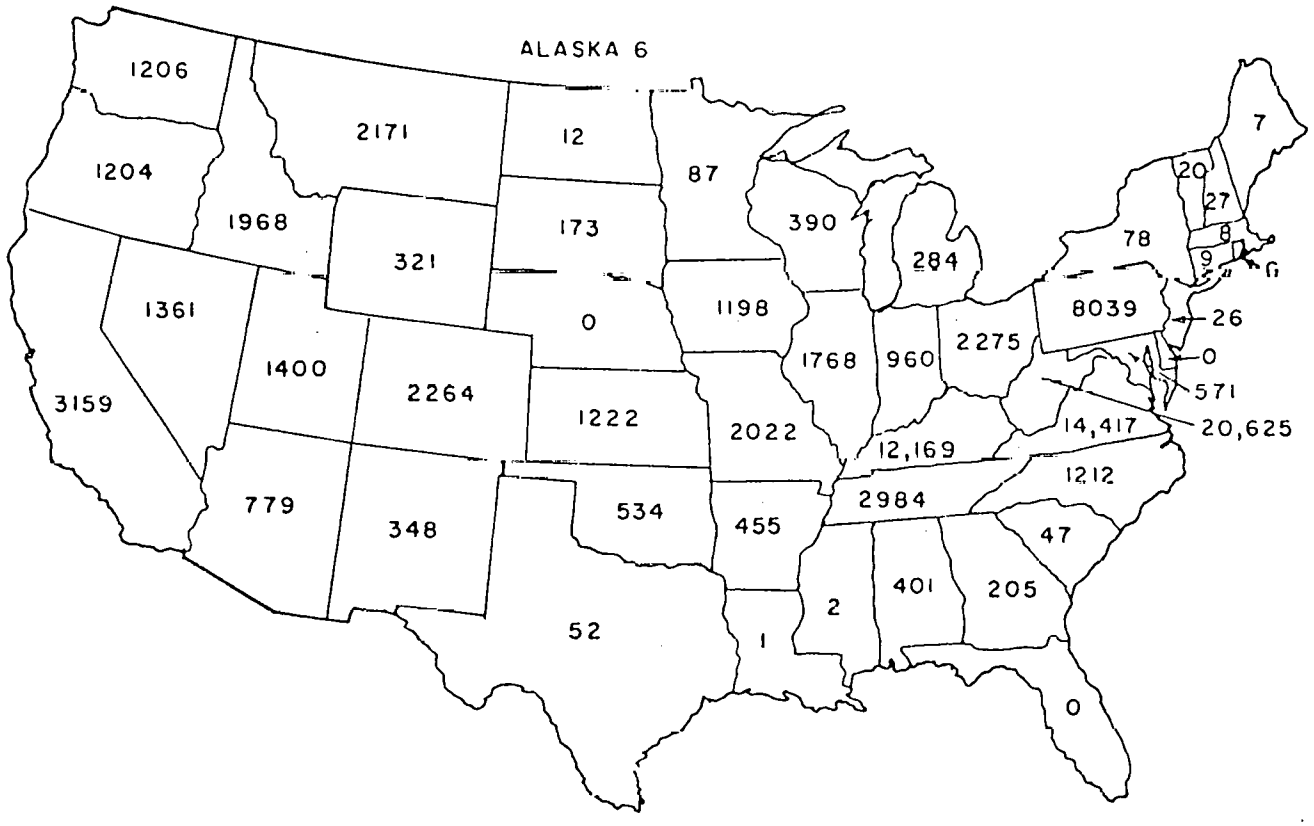



Figure 1: Number of abandoned and inactive mines in the United States in 1965.

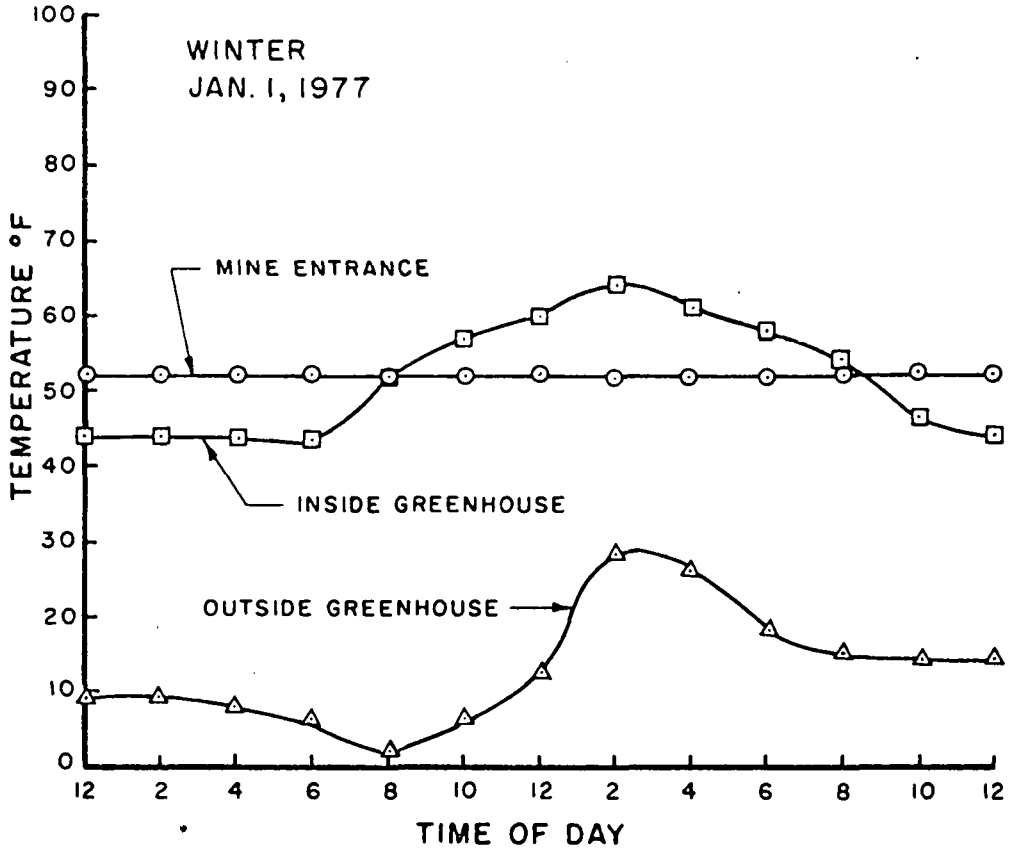



Fig. 3. Temperature outside the greenhouse, inside and at the mine entrance during a 24 hour period on January 1, 1977.

Table 1. Potential Energy Savings by Using Air Drawn from a Deep Mine Compared to Conventional Greenhouses.

| State | City | Normal Outside Design Temp. °F | Interior Design Temp. °F | Conventional Energy Required BTU's x $10^{-6}$ | Ratio Conventional To Mine-Ventilated |
|---|---|---|---|---|---|
| Alabama | Birmingham | 10 | 65 | 247.0 | 9.5 |
| Arkansas | Little Rock | 5 | 65 | 263.5 | 10.1 |
| California | Los Angeles | 40 | 65 | 181.3 | 7.0 |
| | San Francisco | 35 | 60 | 109.7 | 4.2 |
| Colorado | Denver | -10 | 50 | 189.8 | 7.3 |
| Florida | Jacksonville | 25 | 65 | 119.6 | 4.6 |
| Georgia | Atlanta | 10 | 65 | 251.2 | 9.7 |
| Illinois | Chicago | -10 | 50 | 238.0 | 9.2 |
| Kentucky | Lexington | 0 | 55 | 223.8 | 8.6 |
| Louisiana | New Orleans | 25 | 65 | 123.8 | 4.8 |
| Massachusetts | Boston | 0 | 50 | 222.5 | 8.6 |
| Maryland | Baltimore | 5 | 55 | 219.8 | 8.5 |
| Michigan | Lansing | -10 | 50 | 289.7 | 11.1 |
| Nevada | Reno | 0 | 55 | 301.8 | 11.6 |
| New York | Ithaca | -5 | 50 | 271.5 | 10.4 |
| | New York City | 5 | 55 | 269.5 | 10.4 |
| North Carolina | Raleigh | 10 | 60 | 167.3 | 6.4 |
| Ohio | Cleveland | -5 | 50 | 212.4 | 8.2 |
| Oregon | Portland | 10 | 55 | 174.1 | 6.7 |
| Pennsylvania | Pittsburg | -5 | 50 | 182.2 | 7.0 |
| South Carolina | Columbia | 20 | 65 | 218.3 | 8.4 |
| Tennessee | Memphis | 5 | 60 | 182.0 | 7.0 |
| Texas | Dallas | 5 | 65 | 206.0 | 7.9 |
| Washington | Seattle | 15 | 55 | 194.2 | 7.5 |
| Wisconsin | Madison | -20 | 50 | 331.6 | 12.8 |

greenhouse. If the cost difference in the electric energy required to operate the fans is assumed to be 3 times higher than coal which might be used for heating ($.03/KWH electricity is about 3 times as expensive as heat energy from $45/ton coal when burning and equipment efficiencies are considered), then economically the mine-ventilated greenhouse would have an average economic advantage of 2.8 times of a conventional greenhouse.

EXPERIMENTAL FACULITY AND PROCEDURES:

The greenhouse (30' x 96') was constructed adjacent to the opening of an abandoned coal mine in Eastern Kentucky (Fig. 2). The two layer, air inflated, polyethylene greenhouse had a southern exposure. Three fans of 1/2 HP each were installed in the mine opening and were calculated to move 0.5 air exchanges per minute. The air was moved from the mine opening through a plastic tunnel into the end of the greenhouse and exited through vents in the opposite end of the greenhouse. A more detailed discussion of the physical arrangement of the greenhouse is described in more detail in an earlier publication (8).

Ventilation fans were operated continuously day and night as long as solar energy did not cause an increase in the greenhouse temperature. Since the photosynthetic rate may be increased with an increase in temperature, the fans were turned off to allow the temperature in the greenhouse to reach a maximum of 24°C (75°F).

The fans were again turned on when the temperature rose above 24°C (75°F). On bright days the rise in temperature may be very rapid from 12°-24°C (55-75°F). However, on cloudy days the temperature within the greenhouse may reach only 18°C (65°F) in which case the fans would remain off throughout the day.

The temperature and relative humidity were continuously monitored with hygrothermographs located near the mine opening, two locations within the greenhouse and outside the greenhouse. The concentration of selected gases was measured with a mine Safety Appliance Universal Testing Unit consisting of a hand pump and detector tubes.

The following crops were grown in the mine-air ventilated greenhouse during a one year period - lettuce, bedding plants, carnations, snapdragons, and spray and pot chrysanthemums. The crops were selected because of their preference for cool temperatures and because of their commercial importance. Only the results with the lettuce, bedding plants, carnations and snapdragons are presented in this report.

Raised benches 2' x 4' x 6" were used for growing lettuce, carnations and snapdragons. Bedding plants were grown in cell-paks set on raised benches. The growing media for cut flowers and lettuce consisted of one part loam, one part perlite and one part peat. Six pounds of dolomite and three pounds of supersphosphate were added per cubic yard The media was steam sterlized. Seed were germinated and the bedding plants were transplanted into a commercially prepared media.

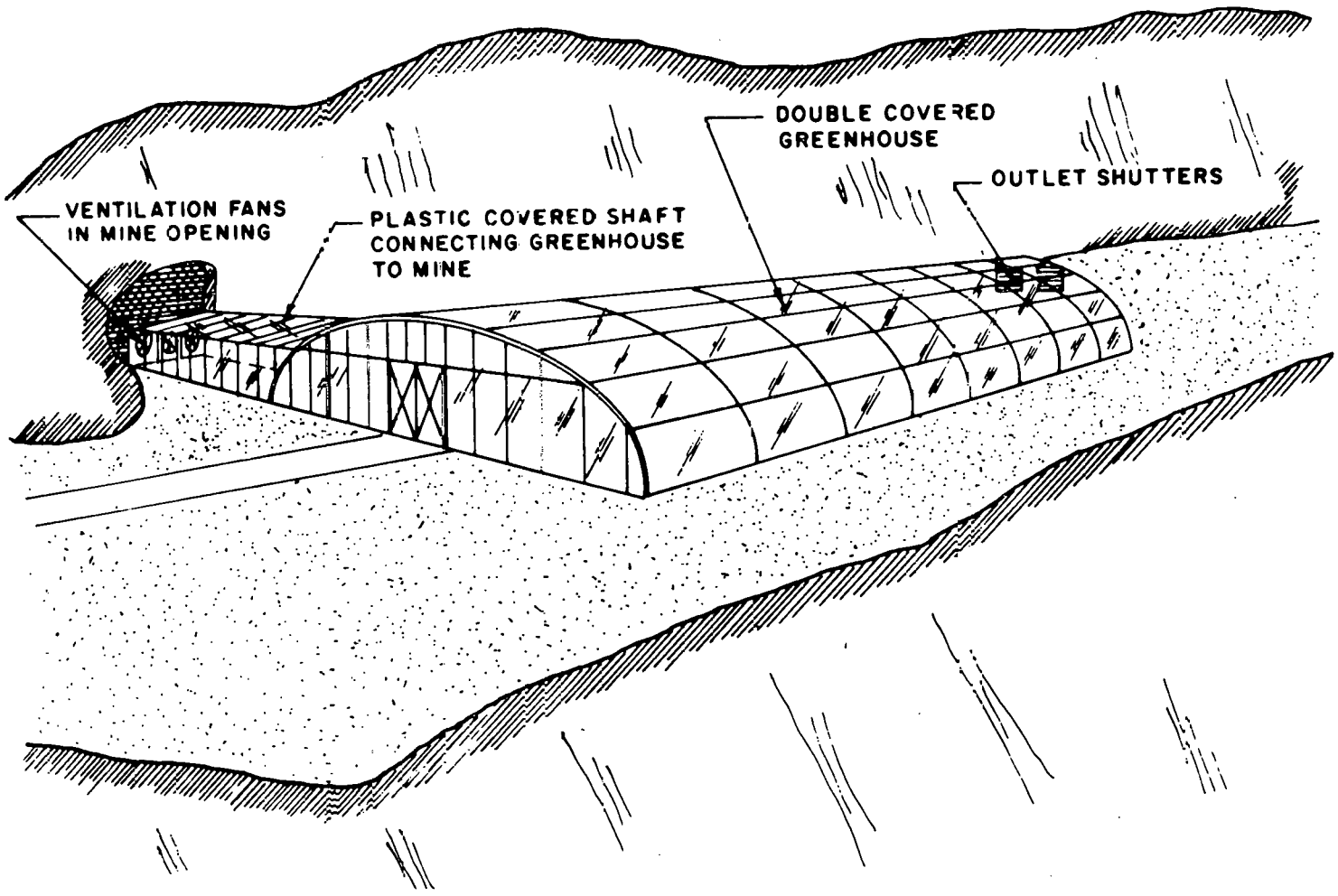



Figure 2. Sketch of the physical arrangement for the experimental mine-air ventilated greenhouse.

Plants were watered with water pumped from an active coal mine. Although the levels of calcium and magnesium were relatively high, the water has generally been satisfactory although some problems believed associated with the unbalanced nutrient level have been observed. Analysis of the water has been included in a previous report (3).

A constant feed program of 200 ppm nitrogen and potassium was used during periods when there was a high requirement for water - late spring to early fall. During the rest of the year 400 ppm nitrogen and potassium were applied on a weekly basis. Trace elements were applied once during the year.

Each planting of an individual crop consisted of three replications. The replications were placed to take into account the temperature and relative humidity differences along the length of the greenhouse. The temperature of the mine air rose 3° to 12°C (5 to 20°F) during the day and dropped 3° - 4°C (5-7°F) at night as it moved the length of the greenhouse (8). The relative humidity within the greenhouse was dependent upon the temperature fluctuation. Therefore, one replication was placed at each end of the greenhouse and the third placed in a central location within the greenhouse. The number of plants per replication depended upon the crop being grown.

The carnation cuttings were received as rooted cuttings from a commercial propagator[3]. The cuttings were planted in benches within a few days of arrival. Lettuce, snapdragon and bedding plant seed[3] were germinated in an area maintained at 70°. The seedlings were transplanted to the final growing container as soon as possible.

ENVIRONMENTAL RESULTS:

The temperature of the mine-air was 11°C (52°F) in the winter and rose to a high of 13°C (55°F) during the summer. The relative humidity remained at 100% throughout the year. The environment in the mine-air ventilated greenhouse during the year varied as the outside temperature, day length and light intensity changed. Three types of environments existed within the greenhouse during the year. The winter environment was cool and very humid, the spring and fall environments were less humid and the temperatures were warmer and the summer environment was warm and very dry.

An example of a typical winter day, January 1, 1977, is shown in Fig. 3. When the outside temperature approached -18°C (0°F), the temperature within the greenhouse remained around 7°C (45°F) at the end of the greenhouse fartherest from the mine opening. During the sunny part of the day the solar energy increased the inside temperature up to 18°C (65°F) when the outside temperature was only

[3] Carnation cuttings were donated from Yoder Bros., Inc.
The bedding plant seed was donated by George J. Ball, Inc.

-1°C (30°F). On cloudy days during the low light period the temperature during the day remained close to the mine-air temperature of 11°C (52°F) (Fig. 6). Because of the decrease in temperature as the air moved through the house at night, water condensed on all surfaces in the greenhouse. Water constantly dropped from the plastic roof during the winter months. The condensation of moisture on the leaves plus the constant dripping resulted in the leaves of plants remaining wet all night and many times throughout the day. The extremely high humidity environment resulted in the potential for very serious disease problems.

On bright days during the spring and fall, the temperature in the greenhouse increased to 24°C (75°F) on many days (Fig. 4). The 24°C (75°F) temperature, as a result of the increase light intensity, resulted in excellent and rapid growth of all crops. The relative humidity again varied depending on light intensity. However, because of longer days and higher light intensity during this period, the relative humidity was not at 100% for as much of each day as during winter months.

During the summer, when the outside temperature at mid-day reached nearly 35°C (95°F), the temperature in the greenhouse with fans in operation was only 29°C (85°F) (Fig. 5). The resultant relative humidity was low during the summer, reaching 45% on many bright days (Fig.6). On cloudy days during the summer, the temperature were proportionately lower depending on light intensity and the resultant humidity was higher. At night the relative humidity approached 100%, but for a shorter length of time than during other seasons.

The concentration of selected gases were determined and reported on previously (5). These measurements were made in subsequent studies to determine if any changes had occurred. No changes were detected from the previous measurements except in the concentration of $CO_2$. The $CO_2$ concentration was previously reported at 600-700 ppm. However, recent measurements show the concentration is now closer to 2300-2500 ppm.

CROP RESPONSES:

Lettuce: Lettuce started in June was harvested on August 4, 50 days after sowing the seed (Table 2). Kentucky Bibb and Buttercrunch varieties started to initiate flowering and therefore were not marketable. The variety, Grand Rapids, did not flower if harvested at a young stage of maturity. Lettuce crops started August 15 and October 15 took 65 and 102 days respectively to reach maturity. The decreased time of production for the crop planted August 15 is the result of an excellent growing environment during the fall period. The length of the growing period was similar to that of lettuce crops grown commercially in Kentucky during the same

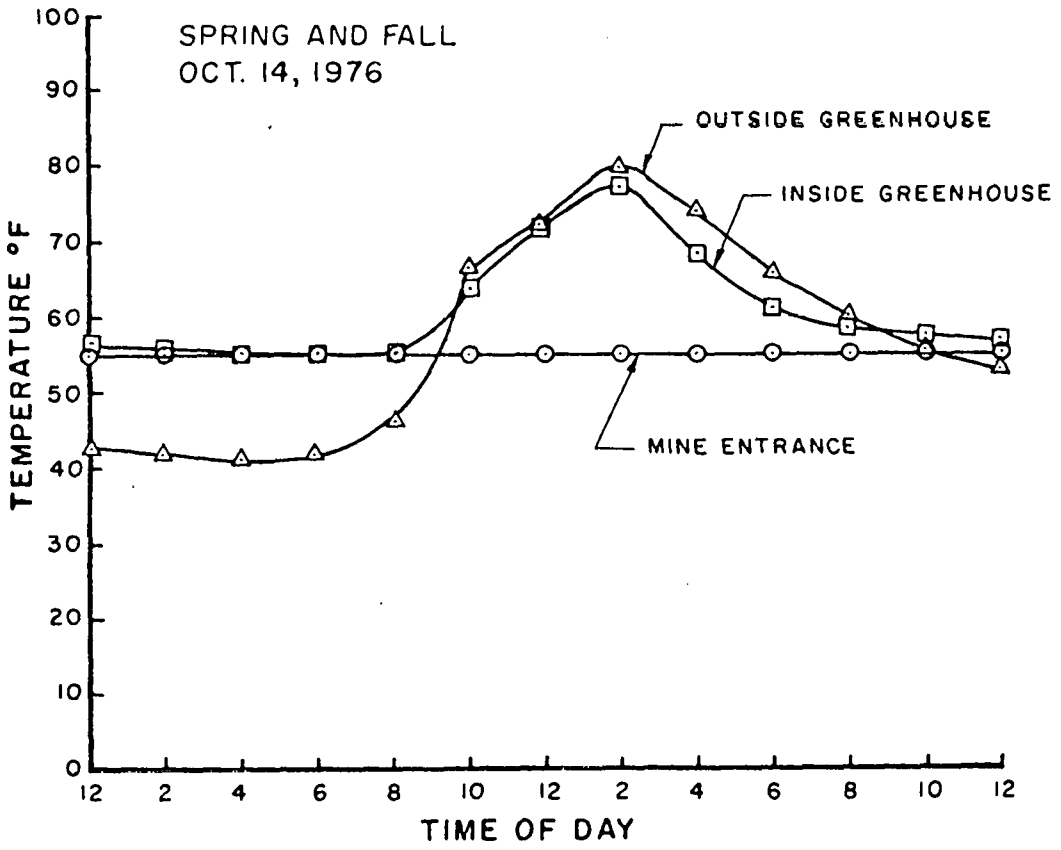



Fig. 4. Temperature outside the greenhouse, inside and at the mine entrance during a 24 hour period on October 14, 1976.

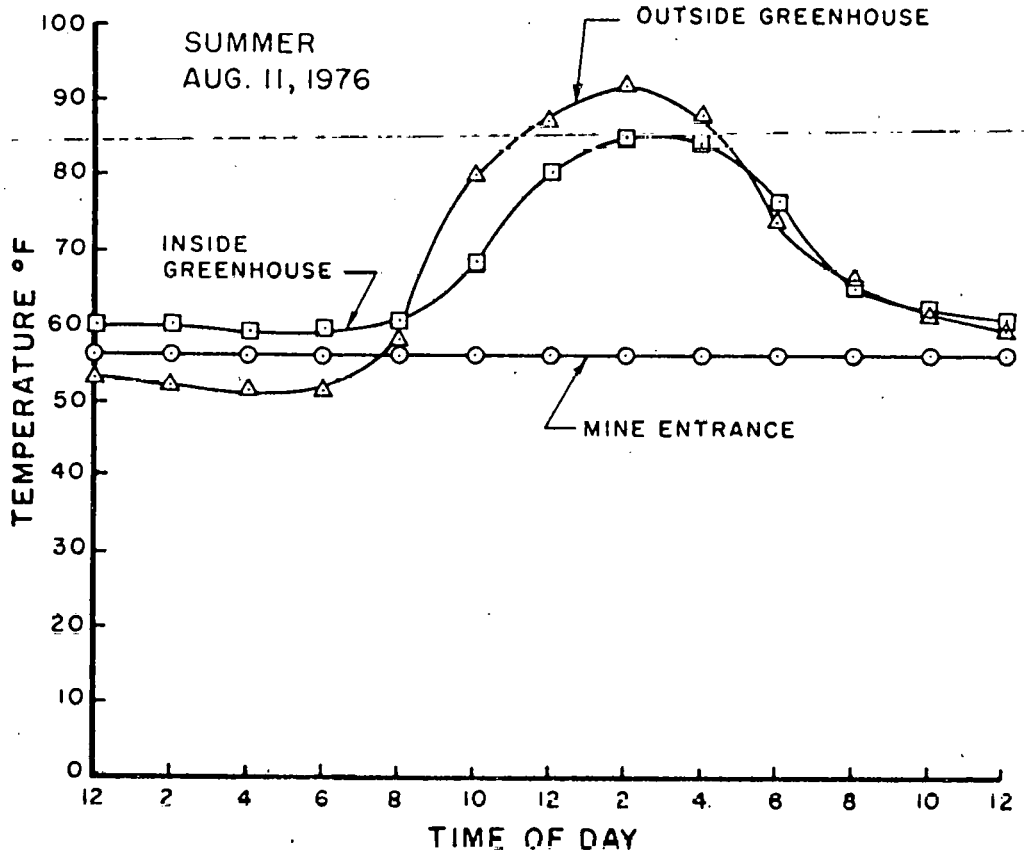



Fig. 5. Temperature outside the greenhouse, inside and at the mine entrance during a 24 hour period on August 11, 1976.

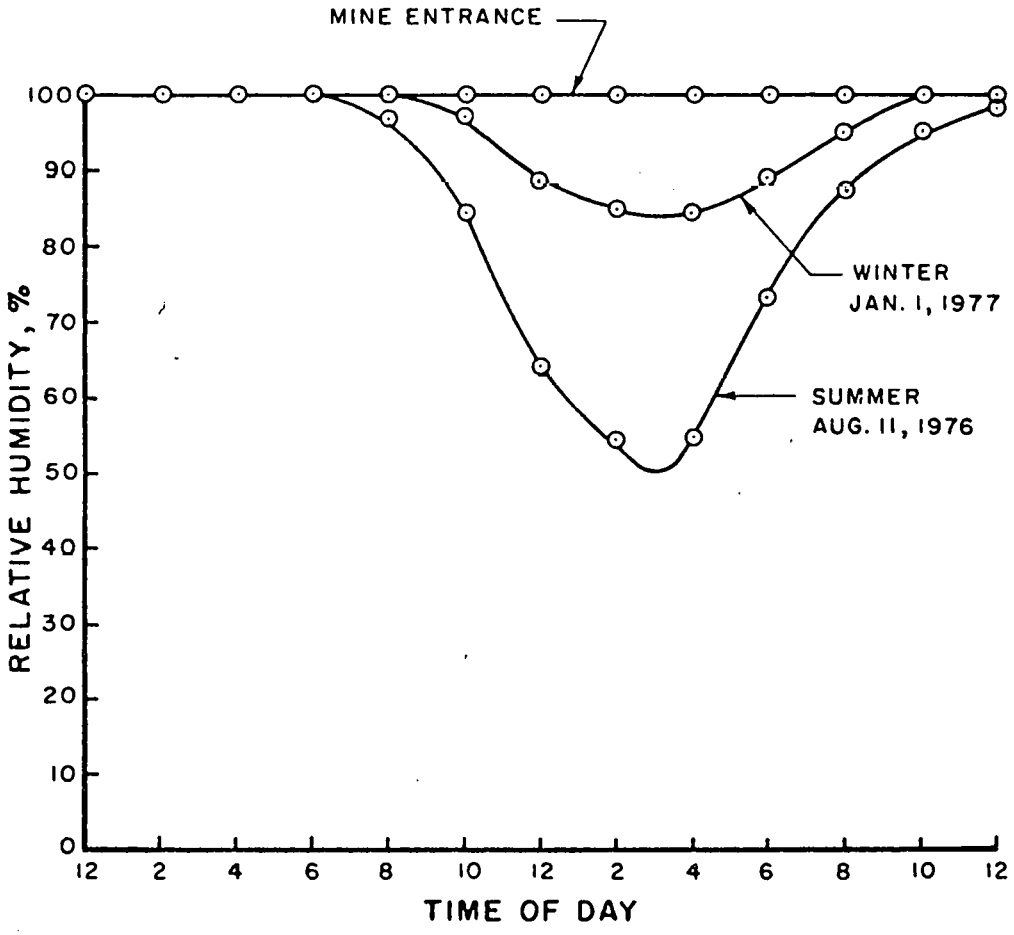



Fig. 6. Relative humidity during a 24 hour period on January 1, 1977 and August 11, 1976.

Table 2. Fresh weight of lettuce grown in a mine-air ventilated greenhouse

| | Fresh weight (g) (average of 18 heads) | | | |
|---|---|---|---|---|
| Seed sowing date: | Jun 15 | Aug 15 | Oct 15 | Comparative [a] |
| Harvest date: | Aug 4 | Oct 19 | Jan 25 | data |
| Varieties | | | | |
| Grand Rapids | 147 | 188 | 173 | 110-200 |
| Kentucky Bibb | Bolted | 111 | 131 | 110-130 |
| Buttercrunch | Bolted | 202 | 156 | 110-200 |

a. unpublished data obtained from crops grown in University of Kentucky greenhouses over several years.



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period and under similar temperature regimes. The lettuce crop harvested on October 19 was of excellent quality. No disease or physiological problems were observed. The spring crops of lettuce reported on in a previous paper were of equal quality to the fall crop.

The crop harvested on January 25 showed physiological problems similar to odema, in which cells of the leaf break because of too much water being absorbed by the root system and because of low transpiration due to high humidity conditions. No disease problems could be detected. The bottom leaves were affected most and could easily be removed without reduction in quality of the rest of the head.

During the summer, in addition to bolting, the lettuce was also infested with botrytis. The low relative humidity during the day, combined with high light intensity, caused leaf tip burn. The botrytis was so severe that the lettuce would not have been marketable. In the spring, fall and winter the light intensity was not high enough nor the humidity low enough to cause leaf burn. As a result no botrytis was observed even though spores were present in the greenhouse.

Carnations: The carnations were grown unpinched with one flower per cutting; all side shoots were removed. Those crops planted and grown during the low light intensity periods grew very slowly. Many flower buds became stalled in development and the bud never developed. If the bud did develop, the stems were very weak and could not support the flower.

As the light intensity increased and days became longer, the growth of carnations in the mine-air ventilated greenhouse was excellent. Crops planted on March 8 and May 4 produced excellent quality carnations in about 85 days. The stems were of sufficient diameter to support the flower head without bending. The flower heads averaged 3" in diameter when fully open. However, split calyx were observed on all the flowers. The calyx were generally split to the receptacle, so that petals fell into the split. Splitting is common in commercially grown carnations; however, the problem was especially bad possibly because of the high humidity conditions.

Carnations planted on October 10 developed a flower bud; however, before the bud reached maturity the entire bud was infected with botrytis. The relative humidty during the period remained high most of the time. Attempts to control botrytis with a regular spray program were not effective.

Table 3. Days to flowering of carnations after planting

| | Days to Flower (average of 24 plants) | | | |
|---|---|---|---|---|
| Transplant date: | Jan 9 | Mar 8 | May 4 | Oct 10 |
| Red Sim | a | 85 (May 19) | 87 (July 30) | b |
| Atlantis | a | 82 (May 16) | 87 (July 30) | b |

a. Very poor quality plants, weak growth
b. Flowers infected with Botrytis

Bedding Plants: Schedules for bedding plant production are established so a few flowers are present within a pack of plants at the time of sale. For the Kentucky area bedding plants should be ready to sell from May 1 to May 15.

In this study, three sowings of bedding plants were made - January 19, February 16 and March 10. Nine of the most common bedding plants were grown (Table 4). The time to reach flowering was determined when the first flower opened in each pack of six plants.

As expected those plants started in January took longer to reach maturity than those started in February and March. Plants started in March generally were in flower near the selling date of May 1 - May 15. The estimated flowering date (2) for the same plants started on March 10 is approximately the same flowering dates as those produced in a mine-air ventilated greenhouse. The packs of bedding plants were of good quality, with dark green foliage and enough foliage to cover the container.

Snapdragons: The two varieties of snapdragons used in this study belong to the Group II response group. Varieties included in Group II are selected to flower from December to May in the southern regions of the U. S. Even though during the summer the day temperatures in a mine-air ventilated greenhouse may reach 30°C (85°F), the night temperatures returned to 13°C (55°F). The seedlings were transplanted to beds approximately two weeks after germination and were grown single stemmed.

Seeds started on May 1 and September 1 flowered near August 10 and December 15 respectively (Table 5). The flowering date of the first planting was similar to that predicted (2); however, the flowering date of the September planting as well as the October 1 planting was nearly two months earlier than predicted (2). The increased level of $CO_2$ could be responsible for the decreased production time. The stems of the plants ranged from 48" to 54" in length and were easily strong enough to support the flower head. The stems were not brittle. The flower heads were well developed and produced a good spike effect. The crop started on October 1 was severely infected with botrytis; the flowers were infected before they were fully developed and were deformed. The overall growth of the plant was stunted.

DISCUSSION:

The mine-air ventilated greenhouse is a suitable environment for the production of plants from mid-February to December 1. The temperatures on a bright day ranged between 18°C (65°F) and 30°C (85°F), and the night temperature remained a relatively constant 12 - 13°C (53 - 55°F) throughout this period. These temperatures regimes were well suited for the production of lettuce, snapdragons, carnations and bedding

Table 4. Days to flowering of bedding plants after sowing seed

| | Days to flowering (average of 12 cell paks-6 cell/pak) | | | Estimated flowering date of seed sown Mar 10 |
|---|---|---|---|---|
| Seeds sown: | Jan 19 | Feb 16 | Mar 10 | Mar 10 |
| Petunia-Carefree Red | 77(Apr5) | 74(Apr20) | 51(Apr30) | 63(May 12) |
| Marigold-Lemon Drop | 80(Apr9) | 73(Apr19) | 48(Apr27) | 56(May 5) |
| Celosia-Fiery Feather | 98(Apr28) | 92(May9) | 70(May19) | 70(May 19) |
| Impatiens-Ripple Scarlet | 95(Apr23) | 86(May3) | 65(May14) | 70(May 19) |
| Zinnia-Peter Pan | 131(May26) | 88(May 5) | 71(May20) | 63(May 12) |

Table 5. Days to flowering of snapdragons after sowing seed

| Seeds Sown: | Days to Flowering (average of 72 plants) May 1 | Sept 1 | Oct 1 |
|---|---|---|---|
| Sonora | 97 (Aug 6) | 106 (Dec 15) | 113 (Jan 22)[a] |
| Rainier | 103 (Aug 12) | 106 (Dec 15) | 113 (Jan 22)[a] |
| Expected Flowering Date [b] | Aug 1 | Feb 6 | Mar 11 |

a. Flowers severely infected with Botrytis
b. Obtained from Ball Red Book ( 2 )

plants. The relative humidity during the spring, winter, fall period was 100% at night; however, during most days the relative humidity decreased as the solar radiation caused an increase in the greenhouse temperature. The relative humidity dropped to a low of 45% on days when the solar intensity caused a rise in the greenhouse temperature up to 85°. On many days the relative humidity was between 70 - 90%.

The poorest growing period in the mine-air ventilated greenhouse was from December 1 to February 1. During the very low light period the day temperature seldom rose above 60° and the relative humidity remained at near 100% at all times. Because of cooler outside temperatures moisture condensed on the plastic and leaf surfaces. For many hours during the day a fog existed in the greenhouse. Under the constant high humidity conditions, coupled with the low light, plants did not grow well. Diseases, especially botrytis, were impossible to control and caused severe damage on many carnations and snapdragons. The constant high humidity was also indirectly responsible for odema on lettuce grown during the winter peiod. The constant high humidity resulted in less frequent watering and resulted in adjustments being made in the fertilization regime. Before the mine-air ventilated greenhouse could be used commercially, systems need to be developed to regulate the relative humidity.

The increased level of $CO_2$, of 2300 - 2500 ppm, may have contributed to an increase in the growth rate or in final quality of the crops produced. However, a true control system was not available to determine the possible benefits of the addition of $CO_2$. Many studies have show that increased levels of $CO_2$ will increase the growth of lettuce from 30 - 100% in conventional greenhouses (4, 9). In conventional greenhouses $CO_2$ may be added to the greenhouse environment only when vents are closed; therefore, on many days in spring through fall, the $CO_2$ level cannot be increased because of ventilation needs. In a mine-air ventilated greenhouse the increased level (2300 ppm) of $CO_2$ can be maintained in the greenhouse throughout the year. The increased concentration should contribute to an increased growth rate and the quality of plants grown in such an environment.

The energy efficiency of a mine-ventilated greenhouse when compared to a conventional greenhouse is very good with an average improved efficiency of 8.4 times. Even when an adjustment is made in the generally higher cost for electric energy the economic advantage of the mine-ventilated greenhouse is near 3 to 1. The wide diversity in the location of existing underground mines or caverns should allow the commercial development of the concept throughout the United States.

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# ENERGY CONSERVATION SYSTEMS FOR GREENHOUSES[1]

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## INTRODUCTION

Grimmer (1975) reported that greenhouse heating costs were 8% of total costs or about 15 to 20% of production costs. Fuel costs have risen since his report and further increases are anticipated. Studies on the use of 'thermal blankets' pulled at night inside the greenhouse were conducted last year. Significant reduction in heat loss were demonstrated.

If the commercial greenhouse industry is to continue as a viable segment of the agricultural economy then greater heat savings will be necessary and more efficient use must be made of the energy collection and holding capabilities of greenhouses. Internal and external solar energy collection and storage systems will have to be combined with energy conservation methods to produce cost effective heating alternatives. The objectives of this study were to design, build and evaluate thermal insulation solar energy recovery and storage systems for greenhouse use.

The present work at Penn State can be subdivided into six major subject areas: (1) thermal blankets for heat conservation, (2) construction materials for heat conservation, (3) greenhouses as solar collectors, (4) computer simulation of greenhouse heat losses, (5) theoretical analysis of natural convection in greenhouses, and (6) solar heated greenhouses.

## THERMAL BLANKETS

### Methods

Thermal blanket materials were laboratory tested and the most promising installed eave to eave in three 25 by 33.5 foot greenhouse sections. The criteria used in selecting material were their: 1) resistance to conductive, convective, and radiative heat transfer, 2) ease of application, 3) handling and wear characteristics, 4) availability, and 5) cost.

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[1]Contribution from the Pennsylvania State University Agricultural Experiment Station, University Park, Pennsylvania, as Journal Series No. 5295 .

[2]White, Prof. Horticulture; Aldrich, Prof. Agricultural Engineering; Duda, Prof. Chemical Engineering; Rebuck, Tesca and Rotz, Graduate Assistants Agriculture Engineering; and Merbaum, Undergraduate, Agricultural Engineering.

The blankets were suspended by a track and pulled during dark periods (< 50 foot candles) by a linear induction motor system[2] (Figure 1). The test sections were glazed with double-strength lapped sheet glass. The control section (A) had no blanket and a north gable exposed to outside temperatures. Test section B was covered from eave to eave and around the four sides with Foylon XA-2425[3] (a porous 44 x 40 thread count, 5 oz., polyester-aluminum foil laminated fabric). Test section C was covered the first year with Al/Blac (a vinyl cloth, black on the roofside and gray on the interior side) from eave to ridge. The first half of the second year with Al/Temp (a vacuum metalized spunbonded polyolefin, Tyvek[4]) and the second half of the second year with a 4 mil black polyethylene. Test section D was covered the first year with Foylon XA-2425 from eave to ridge. The first half of the second year with Tyvek, which is white without the vacuum metalizing, and the second half of the second year with a 4 mil clear polyethylene. The Al/Temp, Tyvek and black and clear poly were pulled from eave to eave and around the four sides. The time of pulling of the blankets was controlled by a light intensity sensor located just under the roof in section B.

Four 20-foot long, baseboard, low-resistance electric heaters served as the only heat source in each section. The heaters were controlled by two aspirated, gas-filled thermostats set at 60°F for the dark period. The electrical energy inputs to the heaters were monitored with Sangamo digital, 15 amp, 240 volt, single-phase watt-hour meters.

In order to minimize the effects of several variables, data were acquired under similar weather conditions. Some criteria to be met were: wind speed near zero, no precipitation, and sky completely overcast or completely clear.

Tests of at least six-hours duration were carried out on selected nights. The blankets were closed for one-half of the test and open for the remaining half. Inside and outside temperatures, as well as the energy input from each part of the test, the wind speed and wind direction were recorded during the tests. Observations were also made on the sky conditions and internal condensation on the greenhouse roof.

The energy input data were averaged for each hour of the test and converted to BTU. These values were then used to calculate the overall

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[3]Foylon and Al/Blac cloth were donated by Duracote Corp., 350 North Diamond Street, Ravenna, Ohio 44266.

[2]Track system and controls were donated by Simtrac Inc., 8243 N. Christina Ave., Skokie, Illinois 60076.

[4]Tyvek was donated by E. I. DuPont De Nemours and Co., Inc., Textile Division, Wilmington, Delaware 19898.

thermal transmission coefficient, U[5], during each part of the test where:

$$Q = A \ (T_2 - T_1)$$

Q = heat transfer, BTU/hr

U = heat transfer coefficient, BTU/hr $ft^2$ $^oF$

A = surface area, $ft^2$

$T_2$ = temperature of media at inner surface, $^oF$

$T_1$ = temperature of media at outer surface, $^oF$

The percent reduction in heat loss was based on the U value of each section calculated during the periods when the curtain was closed, divided by the U value when the curtain was open, times 100 (Table 1).

Results

U values as BTU/hr-$ft^2$-$^oF$ and the percentage reduction in heat use, calculated as a fraction of the heat loss without the blankets, for Thermal blanket systems pulled at night inside glass-covered greenhouse sections is given in Table 1.

The relation between energy transmitted and the temperature difference between crop area temperature and outside temperature (delta T) for section B with or without a Foylon XA-2425 blanket is shown in Figure 2. Although the quantity of BTU's lost increased as the delta T increased, the percentage reduction remained the same over the range of conditions studied. A similar relation occurred in the other sections with different covers, although the slope of the blanket closed line changed with each material and with each installation method.

Discussion

The principal effect of the blankets was two additional surface resistances which reduced the convective currents within the greenhouse. The blankets appeared to provide some conductive resistance, since the convective currents in the air space between the blanket and greenhouse wall were reduced.

The effect of the configuration of the blanket on energy conservation was dependent on the total surface area of the blanket and how effectively infiltration was stopped.

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[5]U is the quantity of heat transferred through a unit area of material of composite of material in unit time, when a unit temperature difference exists between the media of either surface.

The properties of the blanket materials also had an effect on energy conservation. The Foylon and Tyvek had very low transmittance to long-wave radiation and intercepted the radiative transfer to the glass. Although glass is opaque to long-wave radiation, the energy radiated through the Al/Blac and the various polyethylene blankets was transmitted by conduction and convection to the external atmosphere.

Although we had no way of separating conductive, convective or radiative heat transfer, we can speculate that the more porous materials such as Foylon XA-2425 and the two types of Tyvek were permitting some heat loss in water vapor that moved through the pores. The polyethylenes theoretically have higher potential losses of heat by radiation than the aluminum or white coated materials, but being nonporous should have a lower heat transfer in water vapor or by convection. The lack of significant variations in heat loss between the nonporous, nonreflective and the porous, reflective materials (Table 1) suggests that these two factors may have counterbalanced each other. We cannot guarantee that this was the case since we have not yet tried a nonporous, reflective material. Trials in progress include two such materials. Also, the lack of variation in heat loss does not exclude the possibility of tighter seals in one section compared with another. Although an effort was made to provide equal corner and edge seals in each section, some materials were easier to seal than others because of their weight or flexibility.

We selected porous materials initially with the idea that some moisture transfer would be necessary to prevent high humidities in the crop area under the blankets. Since high humidities and the potential concomitant disease problems associated with it have not developed under any of the blankets, we could speculate that blanket porosity was not necessary under the environmental conditions of this study when using roses as the test crop.

Internal blankets were an effective method of energy use reduction. Improvements in blanket materials, resulting in greater resistance properties, should increase their energy conservation potential. In future studies materials such as closed celled polyethylene, urethane foams and isocyanurates will be used as thermal blankets.

The major problem with interior blankets, especially in a small greenhouse, was the storage of the blankets when open. This could result in shading of plants and some inconvenience for personnel movement around the interior perimeter of the greenhouse. The area shaded by the blanket equals about 3 to 4 percent of the production area. But, the effectively shaded area is reduced to about 2 to 3 percent when reflective materials are used with the aluminum on the roof side. Yield and quality of roses were 2 to 4 percent less in the sections with blankets than in the control section. The initial installation of blankets in an existing greenhouse could be awkward, depending on the structure of the greenhouse and the configuration of the blanket

installation. Interior blankets could also require the relocation of the heating system to provide heat within the blanket volume. There is also the possibility of heavier snow loads developing with the use of interior blankets. The temperature of the glass will be several degrees lower than without an interior blanket, increasing the potential for snow loads to accumulate for a longer period of time. The increased snow accumulation beyond the design load of the greenhouse could result in potential danger to the structure, especially if it was combined with high wind loads. Commercial snow load sensors for greenhouses are being developed in Canada and in the U.S.

Other factors which should be considered before buying and installing a blanket system include:

1) The blanket installation must be as tight as possible since convective heat loss represents about 60 percent of the total, while conduction is about 30 percent and radiation 10 percent.
2) Fabric life, and therefore its depreciated cost, will vary with the kind of structural covering within which it is installed. More ultraviolet penetrates polyethylene than glass and, therefore, a polyethylene cover in a poly house will decompose faster than in a glass house.
3) Materials vary greatly in regard to flammability or flame resistance. Check with your insurance company on the effect of various blanket systems on your insurance rates.
4) Tear strength, particularly at the seams, and fabric weight also are important. Not every company that can sew together pieces of fabric will be able to properly fabricate heavy blankets for greenhouse use. A light weight fabric may require less mechanical equipment but more frequent replacement of the blanket.
5) In a tight system, the attic above the blanket may reach temperatures near or below freezing. When the blanket is first opened a down rush of cold air might be injurious to certain crops at certain stages of development. This problem probably could be overcome by using a time delay relay which would allow the blanket to open a few inches but delay its full opening for 15 to 30 minutes. This delay should allow some warm air to rise and mix with the attic air before the blanket is fully opened.

Although the initial costs for a blanket system seems relatively high, it offers a practical and economical energy conservation method. Using your own labor, an installed system will cost between \$0.40 and \$0.80 per $ft^2$. Assuming a 33 percent savings on a yearly heat cost of \$0.80 per $ft^2$, the system can be paid for in three years.

Additional benefits of a blanket would be the option of using it for shading or photoperiod, or summer heat control when appropriate. The Ball Red Book (1975) reported that a large blanket installation would probably pay for inself in seven to eight years of use for photoperiod control only. The potential exists to amortize a thermal blanket system in two years or less when all the benefits are considered, e.g., photoperiod control, summer heat reduction, and energy conservation.

Several commercial greenhouse growers were interested in installing interior blanket systems in their greenhouses this winter. We have been working closely with Bryfogle's greenhouses in Muncy, Pennsylvania and Pinchbeck's greenhouses in Guilford, Connecticut installing these systems. These commercial growers can serve as the first step in introducing the practical application of this concept to the greenhouse industry.

## CONSTRUCTION MATERIALS

### Acrylic

Double-walled acrylics have been used in greenhouses in the Netherlands and in West Germany for several years. Heat savings of up to 40 percent have been reported. Although the material seems quite expensive for greenhouse construction in the U.S.A. (it is apparently government subsidized in Europe), there has been enough interest expressed by American flower growers to encourage us to use it experimentally. A 20 x 20 foot multibarrel vault structure (Figures 3,4 & 5) was built using double-walled acrylic[6] for both the arched roof and side walls. After three months of testing and during a period of decreasing temperatures, the arch roof design failed at the center point of the arc. The roof was reconstructed into a gable design which is being tested this winter. As of March 15, 1977, no structural problems had developed.

### Polycarbonate

This summer another 20 x 20 foot multibarrel vault test unit (House 5) will be built using a double-walled polycarbonate[7].

### Fiberglass

Three 20 x 20 foot fiberglass[8] covered, multibarrel vault, experimental greenhouses were built at the Rock Springs Horticulture Research Center in the summer and fall of 1976 (Figure 5). Three of the units have solar collection, heat storage and reuse systems which will be in use during late winter and early spring of 1977. House 1 has internal energy collection with rock storage which will be discussed in the next section. House 2 has an external commercial collector and water storage system. House 3 is the acrylic structure described above. House 4 combines internal and external hot air energy collection with rock storage. All test units will eventually have internal thermal blanket systems for nighttime use.

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[6]The double-walled acrylic also called Rohaglas SDP or Texotan is a product of Rohm of Darnstadt, Germany and supplied by Chemacryl Plastics Limited, Toronto, Canada; now available as Acrylite® SDP through Cy/Ro Industries, Wayne, New Jersey 07470.

[7]The double-walled polycarbonate Polylux C40, also called TUFFAK-TWINWAL is a product of Rohm and Haas Co., Philadelphia, Pa.

[8]The fiberglasses were all 5 oz. Tedlar-coated, corrugated sheets donated by Resolite or Filon or purchased from Barclite.

Glass

House 6 is a 12 x 16 foot lapped-glass, gable roof greenhouse which will be used as a control unit.

GREENHOUSE AS A SOLAR COLLECTOR

This phase of the Penn State Project is based on the premise that greenhouses are unique structures in that they act as natural solar collectors. The possibility exists of utilizing thousands of acres of existing greenhouses as solar collectors and thereby reducing their net energy consumption. An analysis of the greenhouse is warranted to determine how much heat can be generated, what modifications would improve performance as solar collectors, and the retrofit equipment needed to utilize this resource. In other structures, the three components that must be added before solar energy can be utilized to supplement heating are an energy collector, storage unit, and distribution system. The greenhouse could be modified at a much lower initial cost to facilitate energy collection and supply heat for storage and later use. The collected heat, though, is inherently low grade, i.e., maximum temperature = 32°C (90°F), and therefore, requires a large volume or high thermal capacity for storage. The possible use of a heat pump to upgrade the heat might reduce the necessary storage and possibly replace the more conventional heating system.

Preliminary calculations have been performed in order to evaluate the utility of thermal storage in greenhouses. Our work to date indicates that major modifications and/or additions to existing greenhouses will be required if the thermal energy is stored as sensible heat. Typical sensible heat storage systems are buried piles of rock and storage tanks holding water. Our heat transfer calculations also indicate that such devices would be very inefficient, since small temperature differences will be available for the transfer of heat if the greenhouse's natural solar collector capability is to be used. Calculations indicate that systems, which have large heat capacities and can exchange this heat over small temperature differentials, are essential for this application of thermal storage.

Experimental Work With Internal Collection

The House 1 solar heating system was designed to evaluate the feasibility of collecting and storing excess solar heat from a greenhouse, and utilizing it during the evening heating period to assist existing heating systems.

The system collected excess heat from the ridge area of the house, and stored it in a rock bed heat exchanger located beneath the crop benches.

Heat was collected and stored when the collector air temperature exceeded 75°F, and a 5°F temperature differential existed between the collector air and storage. A high temperature cut off stopped

collection when the differential dropped below $5^{o}$, while the collection temperature remained above 75°F. Stored heat was recovered when the crop temperature dropped to 65°F, and a differential of 5°F existed between the storage and the crop area temperatures. The stored energy supplied heat for the house until the greenhouse temperature reached 60°F. Supplemental heat was then supplied to assist the heat from storage.

The solar heating system became operational the first of January 1977. During January there was no significant excess of solar heat that could be stored. February provided several days that the system could be utilized. The collection of excess solar heat on February 11th was used mainly to charge the storage to the minimum operating point of 65°F. During the nighttime heating period no significant contribution was made by recovering stored heat.

Excess heat on February 24th provided enough energy to supply 8½ percent of the total nighttime heating requirement. During collection about 50% of the heat stored was used to charge the storage to minimum conditions. The storage system had a potential of supplying 20 percent of heat requirement if initial storage recharging was not necessary.

Results from February 26th showed similar results. Although only 20% of the excess was used for recharging the storage, less excess solar heat was available. Only 5 percent of the total heat load was supplied by stored heat. It was apparent from these two days that in order to get the maximum use of excess heat, utilization should be a continuous process.

Additional data will be needed to determine the variability of the system, and to determine to what extent it could be utilized for different environmental conditions.

The effectiveness of collecting excess solar heat was based on the amount of warm stratified air that could be stored. Collection of heat was done in the ridge area of the house without isolating the collection area from the crop area. Measurements showed that mixing of crop and ridge air occurred thus lowering the expected temperature of air entering storage. This was due to the high collection volume of the blower. The effects of decreased collection volume on temperatures entering the storage was evaluated by placing an air buffer at the suction end of the blower. Preliminary results from March 8 showed that air temperature entering the storage increased as collection volume decreased, and at the same time the amount of stored heat decreased. It was apparent that a variable collection flow rate was needed to increase the collection capacity. One possibility considered was the application of a variable speed collection blower to operate at high volumes during high solar excess periods, and low volume during low solar excess periods. This would provide the possibility for larger amounts of stored heat and at the same time provide a cooling effect in the house when needed.

Another possibility that may be investigated is isolating the ridge area from the crop, using perforated polyethylene.

A mathematical model was developed, simulating the effects that thermal blankets would have on reducing the heat load of House 1. A blanket with a U value of 0.14 BTU/hr-ft$^2$-$^o$F, was used as the model blanket material. The model predicted a mean temperature between U values and recorded temperatures of the ambient and greenhouse air.

The average heat loss was calculated and compared to heat supplied by supplemental and solar storage. The recovery of stored heat had the potential for supplying 32 percent of the required heat on February 24th and 22 percent on February 26th. Installation of highly effective thermal blankets has the potential for making a solar heating system of this kind practical for greenhouses located in central Pennsylvania.

Solutions, such as salt hydrates and aqueous eutectic, appear to be the ideal storage media for greenhouse use, since the storage is based on latent heats associated with phase changes. We have extensively reviewed the literature concerning these types of storage systems, and two significant generalizations have emerged:

(1) A number of inexpensive, salt hydrate systems, which show potential as thermal energy storage media, are being developed.
(2) The solution thermodynamics of these systems are very encouraging However, kinetic studies of the phase changes indicate that many technical problems must be overcome before these systems will be the basis of commercial thermal storage systems.

## COMPUTER SIMULATION OF GREENHOUSE HEAT LOSSES

A computer model has been developed to determine the feasibility of solar heating of greenhouses. The model is used to determine the total heat requirement of the greenhouse and the percentage of this total that can be obtained from solar heat. The greenhouse model is used along with a weather simulation model which is capable of generating typical weather conditions for essentially any area of the world. For the current research, the model is being used to determine the costs for several different types of solar heating systems for greenhouse use under Pennsylvania weather conditions.

The greenhouse model was set up to maintain a minimum greenhouse temperature of 15.5$^o$C (60$^o$F) at night and 18.4$^o$C (65$^o$F) during the day with a maximum relative humidity of 75%. The greenhouse temperature was allowed to rise until a condition of 24$^o$C (75$^o$F) under a maximum ventilation of one air change per minute was reached. At this point, mechanical cooling was begun.

Outside weather conditions produced by the weather generating model were typical for this part of the state. Maximum and minimum temperatures were set at 38$^o$C (100$^o$F) and -23$^o$C (-10$^o$F) respectively. The temperature

varied between these extremes according to the time of year and other weather influences. Other outside weather conditions obtained from the program were: dew point, relative humidity, solar radiation, cloud cover, and wind velocity.

Preliminary results indicated that solar heating for greenhouses located in the middle-Atlantic area may not be economically feasible until fuel prices are approximately three times present values, collector costs are reduced or greenhouses better insulated than at present.

If a solar heating system is installed at the current prices, listed below, the solar system will cost 20 percent more than a conventional system over the next 20 years.

Collector Area/Greenhouse Area = 0.5
Solar Collector Cost $100/m$^2$ or $10/ft$^2$
Depreciation, interest, repairs, taxes and insurance 0.123 of collector cost/year
Conventional Fuel Consumption 90,000 gallons/acre/year
Current Fuel Cost $0.35/gallon
Mean Fuel Cost Increase 10%/year

Using a solar heated, non-insulated commercial glass-covered greenhouse in central Pennsylvania, the following performances were predicted for an average heat demand year:

| Area Collector/Area Greenhouses | Solar Heat/Total Heat |
|---|---|
| 0.25 | 18% |
| 0.50 | 31% |
| 1.00 | 51% |

In the future the program will be used for simulating other greenhouse, collector, fuel and environmental conditions.

## THEORETICAL ANALYSIS OF NATURAL CONVECTION IN GREENHOUSES

A theoretical analysis of natural convection in a greenhouse was conducted by solving the basic field equations which describe the coupled fluid mechanics and heat transfer. It was felt that such an analysis would be useful in determining the influence of greenhouse geometry and climatic conditions on warm air stratification. Optimization of the warm air stratification is desirable when a greenhouse is being used as a solar collector. The finite difference technique used to solve the partial differential equations proved to be unstable at the high Grashof Numbers realized in conventional greenhouse structures. This study has been terminated and will only be reactivated if a more promising numerical technique is found in the literature.

SOLAR HEATED GREENHOUSES

Although computer simulation has shown that fuel cost, collector cost and heat loss input factor combinations do not favor solar heating of commercial greenhouses, there are many ways to improve these factor combinations to improve the potential for economical solar heat use. One of these modifications (thermal blankets) was suggested by mathematical modeling studies of Tesca as presented in the section on the greenhouse as a solar collector.

Using the hypotheses that solar energy can contribute a significant proportion of the heat used by a greenhouse, that fuel costs will increase, that greenhouses can be better insulated and that the cost of collectors will decrease; test houses 2, 3 and 4 were constructed.

House 2 will be heated by a conventional hot water system assisted by two cylindrical SAV$^{R}$ commercial water collectors[9] (Figure 6).

Cylindrical collectors were chosen because of the generally diffuse solar radiation in the winter in central Pennsylvania.

House 4 will be heated with shopmade hot air collectors. A composite of the outside and inside of this house are shown in Figure 7. Outside the greenhouse are the 3-A sized limestone rocks which will be used for storage. Inside the greenhouse B are: 1) the rock storage chamber, 2) air intake duct from internal collection to storage, 3) air outlet to growing area, and 4) the control panel for dampers and fans.

Tomatoes, cucumbers and lettuce were planted in each House 1, 2, 3 and 6 the week of February 21, 1977 (Figure 8).

REFERENCES

Grimmer, W. W. 1975. Greenhouse Cost Accounting. Gateway Technical Institute, Kenosha, Wisc.

The Ball Red Book. 1975. Geo. J. Ball Co., Inc., West Chicago, Ill.

[9] SAV high-speed cylindrical solar water heaters were supplied by Fred Rice Productions Inc., Van Nuys, CA. They are patented in New Zealand as NO. 144798/145072.

Table 1. U values and percentage reduction in heat use for thermal blanket systems pulled at night inside glass-covered greenhouse sections. (These values are tentative until more replications are run.)

| Section | System | U value (BTU) | Nighttime Heat Use Reduction (%) |
|---|---|---|---|
| A | Control | 0.85 | 0 |
| C | Al/Blac (eave to ridge) | 0.63 | 26 |
| C | Polytube (eave to eave) | 0.53 | 38 |
| D | Clear 4 mil. poly. (eave to eave) | 0.52 | 40 |
| D | Foylon (eave to ridge) | 0.48 | 42 |
| C | Black 4 mil. poly. (eave to eave) | 0.46 | 46 |
| C | Tyvek alum. (eave to eave) | 0.42 | 51 |
| B | Foylon (eave to eave) | 0.39 | 55 |
| D | Tyvek white (eave to eave) | 0.37 | 57 |



Table 5. Days to flowering of snapdragons after sowing seed

| Seeds Sown: | Days to Flowering (average of 72 plants) May 1 | Sept 1 | Oct 1 |
|---|---|---|---|
| Sonora | 97 (Aug 6) | 106 (Dec 15) | 113 (Jan 22)[a] |
| Rainier | 103 (Aug 12) | 106 (Dec 15) | 113 (Jan 22)[a] |
| Expected Flowering Date [b] | Aug 1 | Feb 6 | Mar 11 |

a. Flowers severely infected with Botrytis
b. Obtained from Ball Red Book ( 2 )

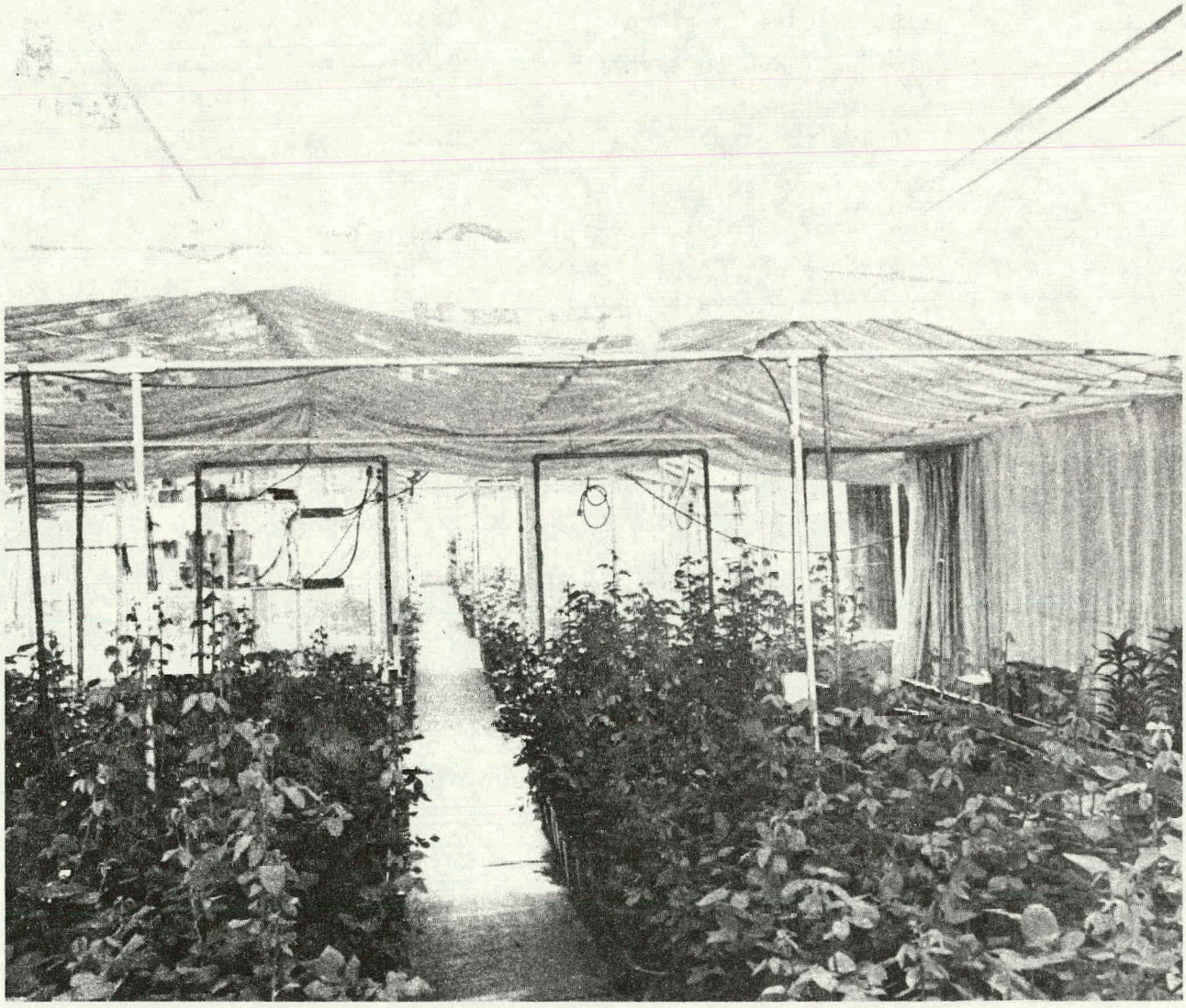


Figure 1. Test section B blanket material is Foylon XA-2425, a porous 44 x 40 count (5 oz) polyester, aluminum foil hybrid fabric. The blanket extends around four sides and across the top under the lower chord of the trusses.

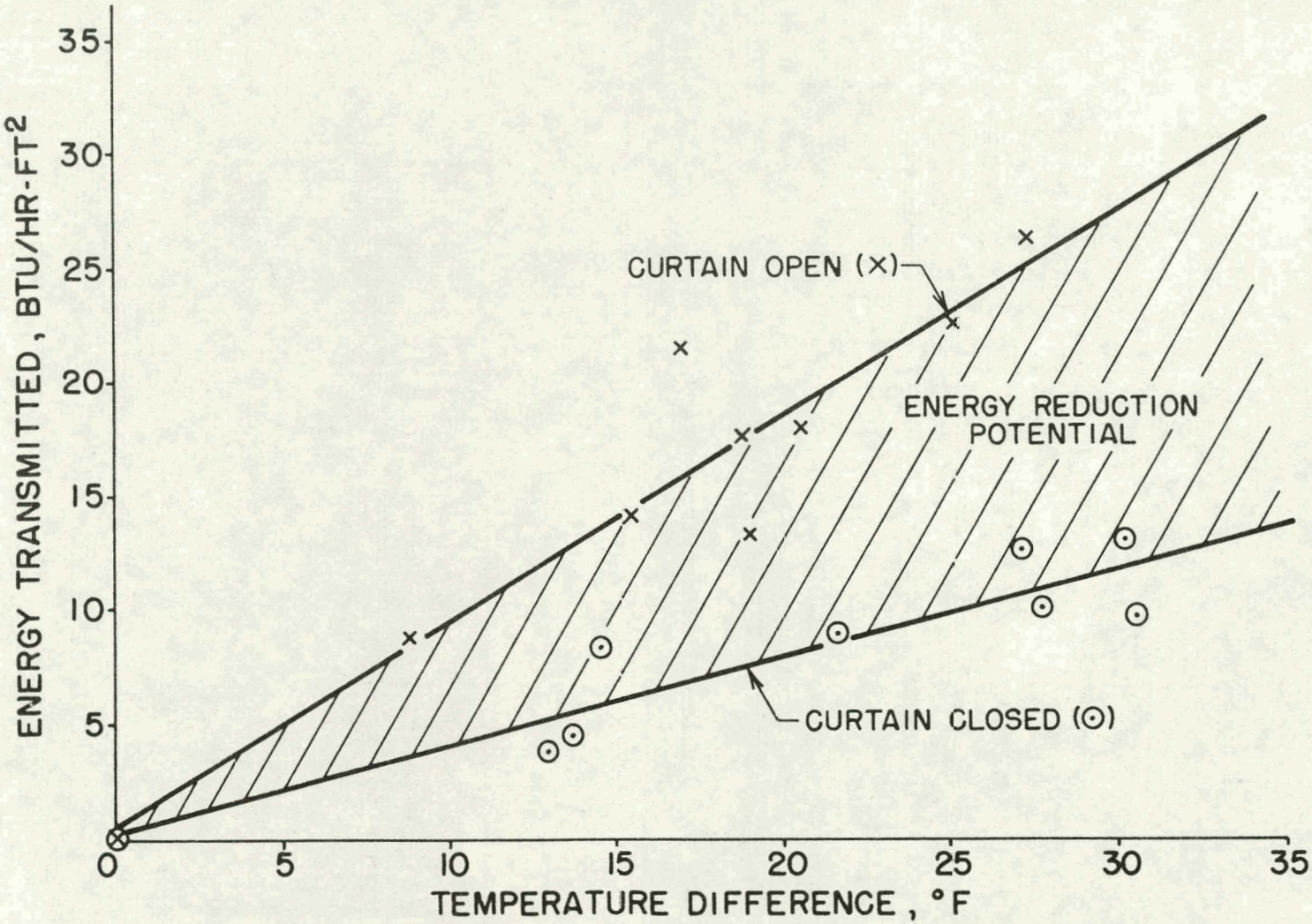



Figure 2. Effect of Foylon XA-2425, used as a thermal blanket, on the energy requirements of a glass-covered greenhouse (Section B).

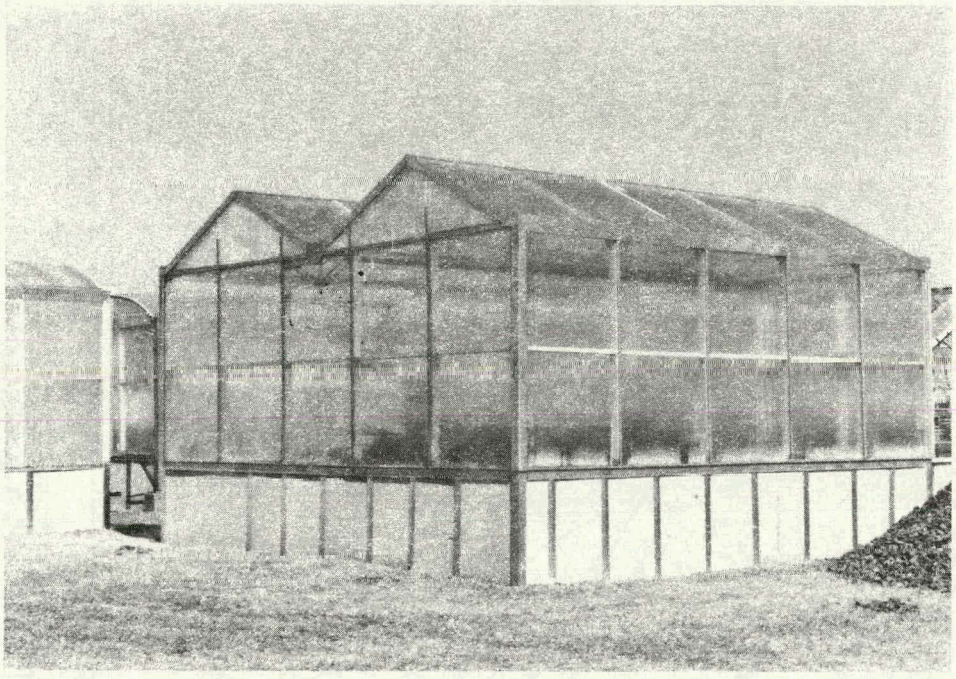


Figure 3. Double-walled acrylic house 3.

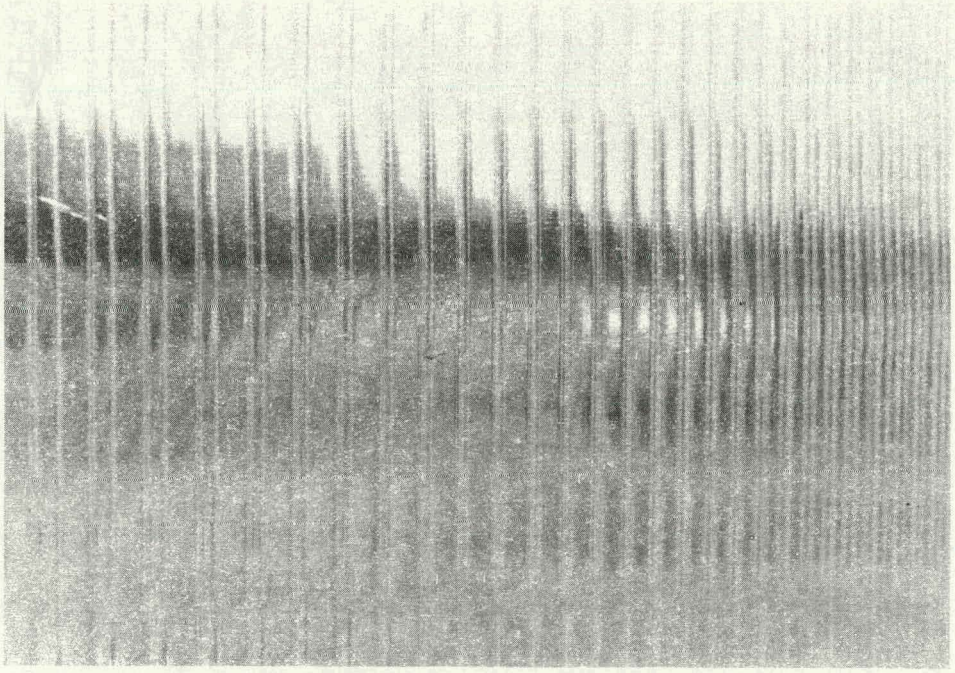


Figure 4. Close view of double-walled acrylic.

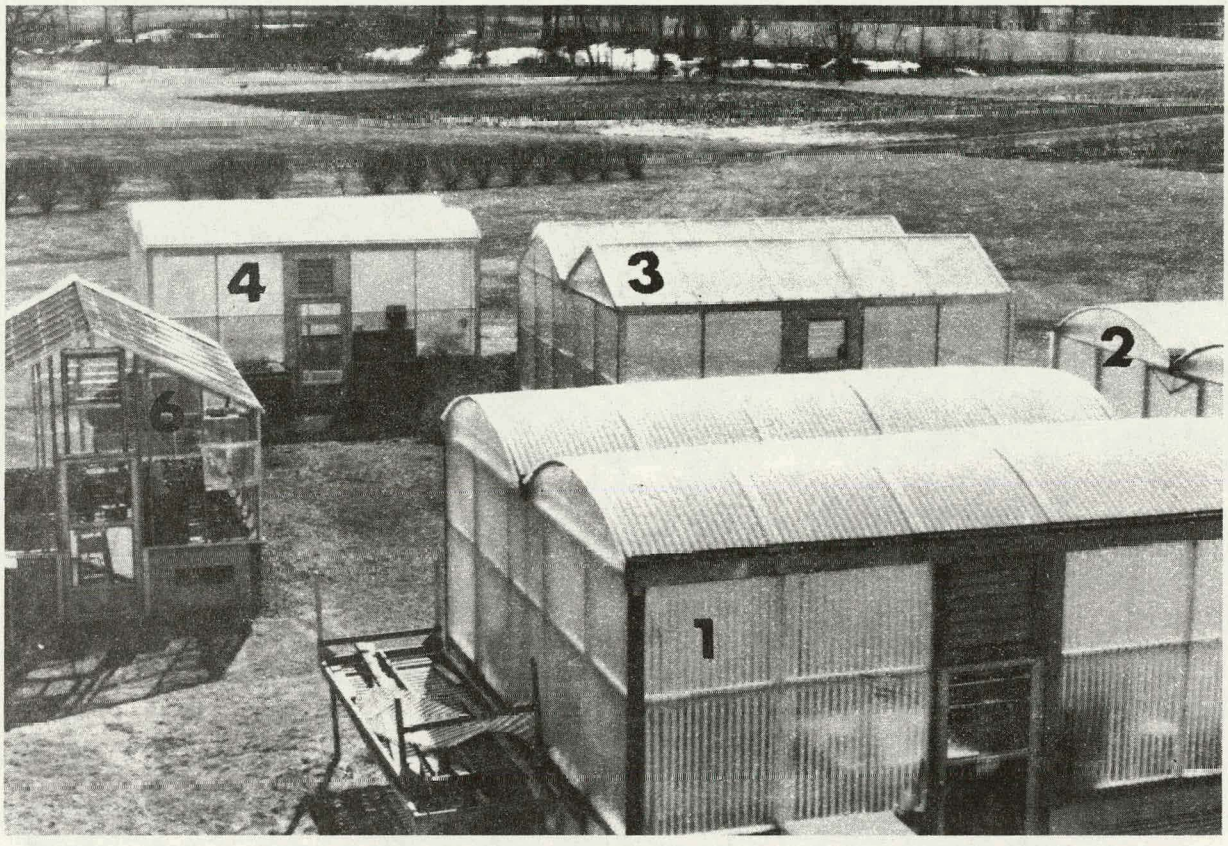



Figure 5. Greenhouses at Rock Springs Horticultural Research Center used for Solar Energy Studies.

House 1 Fiberglass - internal collection - rock storage
House 2 Fiberglass - commercial collector - water storage
House 3 Acrylic - conventional hot water heat
House 4 Fiberglass - internal and external air collectors - rock storage
House 5 Polycarbonate - not constructed yet
House 6 Glass - conventional hot water heat

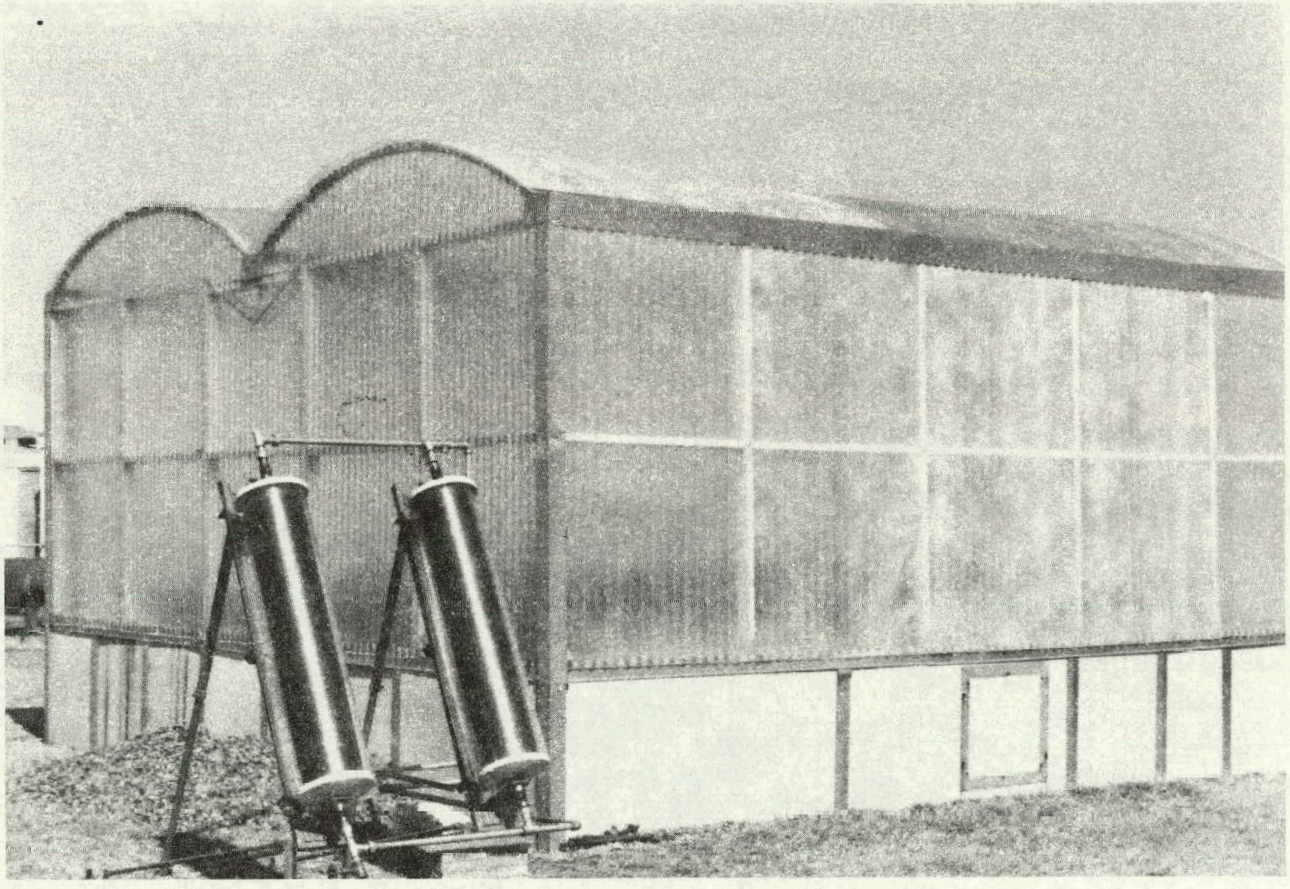


Figure 6. Fiberglass house 2 with external commercial hot water collectors (SAV) and water storage.

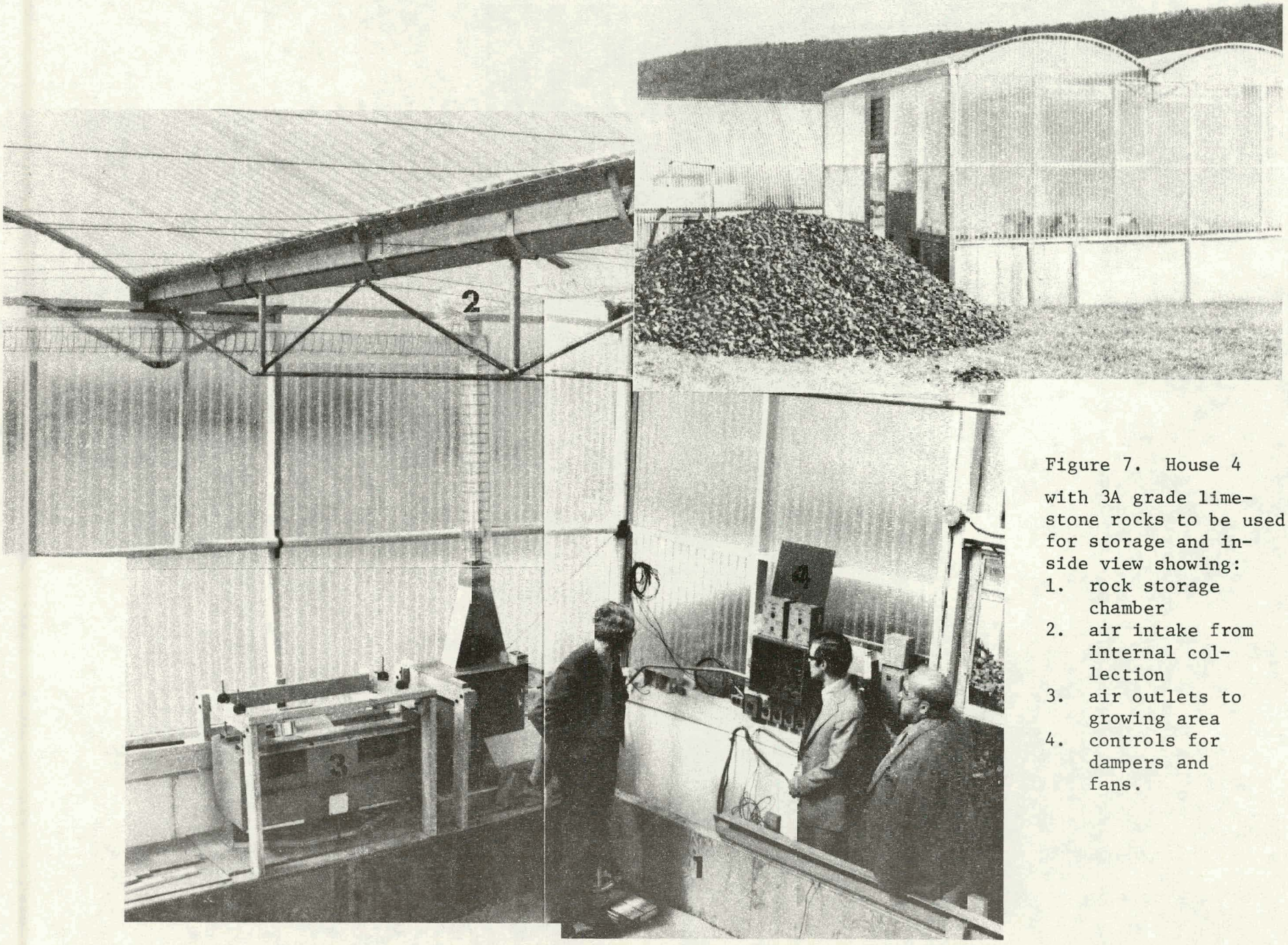



Figure 7. House 4 with 3A grade limestone rocks to be used for storage and inside view showing:

1. rock storage chamber
2. air intake from internal collection
3. air outlets to growing area
4. controls for dampers and fans.

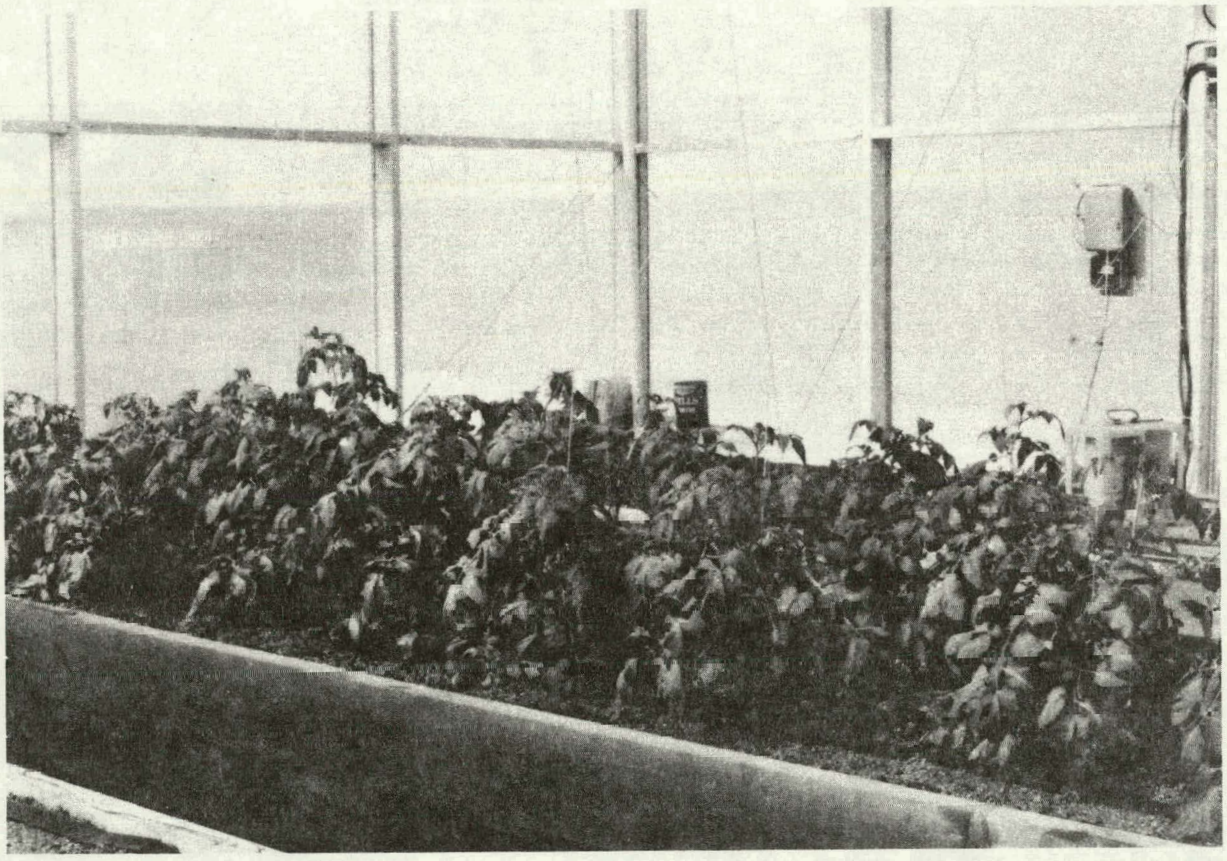


Figure 8. Tomatoes growing in double-walled acrylic house 3.

# COMPUTER SIMULATION OF SOLAR GREENHOUSE HEATING SYSTEMS FOR ECONOMIC OPTIMIZATION

Paul O. McCormick[1]

## INTRODUCTION

The primary objective of this study was to produce a computer simulation that could be used with confidence to analyze the performance characteristics of solar heating systems for commercial greenhouses. To assure the validity of the simulation, a small scale solar heating system and greenhouse were built and tested (Ref. 1). The results of the first winter's test were compared with the computed results and modifications were made in the computer simulation to improve the accuracy.

Accurately predicting the performance of a greenhouse solar heating system, however, is no more than a third of the total problem. The other major considerations are determining the installed system cost and the life cycle operational costs and performance. In order to address these additional facets of the overall problem of applying solar energy for heating greenhouses, the current study was expanded to include: (1 additional performance and maintenance test data and correlation with computer simulation; (2) development of a technique for comparing different types of solar heating systems for greenhouses; and (3) performing an economic analysis and optimization study for a commercial-size solar greenhouse heating system of the type that was tested at Lockheed-Huntsville.

## SOLAR HEATED GREENHOUSE TEST

The solar heated greenhouse at Lockheed-Huntsville is shown in Fig. 1. The greenhouse is a 14 x 20 ft double polyethelene house constructed from a kit. The water heating, single glass covered solar collector was constructed on site such that the solar collector forms an integral part of the south facing roof of a shed used for housing the instrumentation and storage tank. The 1000-gal water storage consists of an insulated concrete block tank under the floor of the shed as shown in Fig. 2. The storage configuration used during the 1975-76 heating season consisted of two 250-gal steel tanks with fiberglass insulation, but the results of that heating season test indicated that a larger tank would provide greater solar collection capability as well as longer storage. Operation of the system is illustrated in the schematic of Fig. 3. Note that two separate water circulation loops are used to: (1) transfer the

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solar energy from the collector to the storage tank, and (2) deliver the stored energy to the greenhouse on demand.

A summary of the results that were obtained from the test solar greenhouse heating system for the 1975-76 and the 1976-77 heating seasons are shown in Fig. 4 as the monthly total energy used and the solar energy provided. The difference between the solar energy provided and the total required was supplied by an auxiliary electrical heater. The heat energy used during the current heating season is shown to be very large compared to the previous year. This is not surprising since the 1976-77 winter has been the coldest on record for much of the country, including Huntsville. What might be surprising is the large increase in solar energy provided this year, corresponding very closely with the increase in total energy required. This increase in the amount of energy provided by the same amount (200 sq ft) of collectors is largely due to the increased storage system size for the current season which was approximately doubled compared to last year. This increased storage not only allows more energy to be stored for longer periods of cloudy weather, but also results in lower operating temperatures for the collector, storage, and heat delivery plumbing. These lower temperatures make the collector more efficient, cause the storage losses to be reduced, and lower the temperature of the heated air delivered to the greenhouse (see Ref. 1).

A comparison of the test results with the calculations from the computer simulation are shown in Fig. 5. The same data are shown as in Fig. 4, except in integrated form. The computer simulation had the benefit of actual weather and solar data that was measured during these two seasons, so the excellent agreement between test and computer simulation during the unusually cold 1976-77 heating season does not represent an ability to predict weather data. Actually, an average year's weather was used with the computer simulation to design and predict the performance of the test system during the summer of 1975 before it was built. The system was sized to provide 75% of the total energy used by the greenhouse, but the solar collectors actually provided 80% last season and has provided 70% through February of this year. (The total for this season should be around 80% at the end of the spring since heating will be required but little or no auxiliary heating will be needed.)

The data shown in Figs. 4 and 5 are the total energy supplied to the greenhouse and the energy supplied by the solar heating system. The difference between the total and the solar energy provided is obviously the auxiliary electrical heat supplied. An additional expenditure of energy for heating the greenhouse is electricity for pumps and blowers. The electricity used for the two pumps in the solar heating systemconsume approximately $1\frac{1}{2}\%$ of the energy that they deliver in electricity. However, the cost of electricity is about three times that of fossil fuel which makes the cost of collecting and using solar energy about 5% of the worth of the delivered energy. In a better designed system this could be as low as 3%, and it could obviously be much larger with a poorly designed system or for an air heating collector (about 20%).

The blower power has not been included in these parasitic energy uses since it is required for our system no matter what the energy source.

After nearly two heating seasons of continuous operation and test evaluation, the following observations are made concerning the operational characteristics of the system. Most important, the system is simple and very dependable in its operation. Two thermostats and two pumps are the only active components in the entire system. The pumps require oiling twice a year, but are long life circulating pumps that have a life expectancy greater than 10 years in continuous service. Due to this dependability, it is quite easy to forget that the solar system is there since it requires so little attention. Even during the summer of 1976, the system was allowed to operate automatically and occasionally supplied some heat. The collector drains when the pump goes off so there is no overheating problem with the collector, even during the summer. The 60 degree tilt of the collector also helps prevent overheating of the collector and water tank during the summer, since the solar flux incident on the collector is at a very low incidence angle. Though no long-term tests were conducted with the collectors drained during the summer, a few days of testing was conducted where the water was not allowed to circulate through the collector on hot, clear days and the collector did not get hot enough to cause any problems.

Upkeep on the system has been essentially non-existent. The collector glass surface has not been cleaned (except by rain) since the original installation. During the nearly two years of test, only two problems arose with the solar heating system, and both were easily remedied. When the new storage tank was installed, a short length of pipe was installed which did not properly drain when the collector pump was turned off. Though this pipe was inside the storage shed, it froze twice during the cold winter. After the problem was isolated, the pipe was reinstalled with the proper slope for complete draining and the pipe never froze again. The other problem that occurred was that the outermost seals between the cover glass and the redwood strips that support the glass became separated from the wood. This seal was made with a silicone rubber glue that apparently was affected by the rain wetting the outer wood supports. This loss of adhesion resulted in both outside rows of glass being blown off in a heavy windstorm this spring. This problem was eliminated by replacing the glass, sealing the exposed wood to prevent it from being soaked by rain, and adding a wood strip holds the outer edges of glass down.

## METHODS FOR EVALUATION OF DIFFERENT GREENHOUSE SOLAR HEATING SYSTEMS

Currently there are several generically different types of solar heating systems being investigated for heating greenhouses and there are several others that have a good possibility of being used. An economic assessment of the economic competitiveness of each system relative to each other and to conventional fossil fuel heat is desirable for two reasons:

(1) to judge the relative merit of each system so that the most promising systems can get the attention and funding they deserve, and (2) potential commercial users can make a reasonable judgment as to which, if any, system is best for them. It is the intent of this study to provide some insight into the general problem of determining the cost effectiveness of different systems, to point out the parameters that must be considered, and to recommend a method for determining the relative cost effectiveness of different solar heating systems for greenhouses.

The necessity of performing a cost effectiveness study of the different systems is the result of lack of attention by researchers to the difficult problem of life cycle cost of solar heating systems. Most researchers do a very poor job of determining the life cycle cost of their systems and those that do investigate costs do not have a uniform approach and set of assumptions that allow the cost effectiveness of each system to be compared with any degree of confidence.

The parameters that must be included in a cost effectiveness analysis are shown in Table 1. Obviously some are more important than others, but all should be considered.

Defining the parameters to be included in a standardized analysis is necessary but not sufficient, and further standardization of procedure is necessary. There are many methods of rating cost effectiveness, but the most generally used seems to be the payback period which is defined to be the period in which the savings accrued by implementing some process or procedure just equals the cost of the system. The major drawback to this method is that it does not give proper credit for the value of the system after the payback period for those systems which have a long life, and is generally inconclusive for short lived systems where the payback period may be only slightly shorter than the expected life of the system. A more general method that does account for short and long lived systems and gives at least an estimate of the value of the system after the payback period is described in Refs. 2 and 3. Basically the method determines the cost of the solar energy provided and the value of the fossil fuel replaced over the life cycle of the system. The cost per unit of solar energy provided (normally $/MBtu) is determined and can be compared either with another solar heating system or with fossil fuels at different current prices and cost escalation rates. This method has been used in the following economic optimization study and will be explained more fully.

## OPTIMIZATION OF SOLAR HEATING SYSTEM

The greenhouse solar heating system built and tested at Lockheed-Huntsville has been very beneficial as an experiment, but is somewhat misleading when potential users try to scale it up to normal commercial size. For this reason an analysis was conducted to determine the optimum solar system configuration to heat a representative commercial greenhouse.

A typical Ohio location was selected because of the large number of greenhouses and the large amount of energy expended for heating in the area. It was assumed that the greenhouse temperature would be maintained at the existing level (typically 62 F for floral crops). A glass greenhouse was selected with approximately 8500 sq ft of growing area. The greenhouse is formed of two bays, gutter connected, that are approximately 42 ft wide and 100 ft long. A second case was analyzed which assumed that the greenhouse would be insulated with inflated polyethelene bags on the roof and north wall.

The greenhouse heating loads were calculated using a real year's weather data that compared well with long-term average data. The energy that was calculated to be used by the two greenhouse configurations during an average year is shown in Fig. 6 compared to the 1974 actual fuel use for the existing glass house.

It was assumed that a collector and storage system of the type tested at Lockheed-Huntsville would be used, but that finned-pipe heat exchangers would be used under the benches to integrate with the existing steam pipes which are also under the benches. A cost model was constructed for the solar heating system and the costs were allocated by major components. The costs were determined for a nominal 4000 square ft collector system, and extrapolation of the costs are anticipated to be reasonably linear between 2000 and 8000 sq ft of collector. The cost for installing the entire solar heating system, (including material and labor) is:

$$\begin{aligned}\text{Total Cost} = {} & 5.4 \times \text{Collector Area } (\text{ft}^2) \\ & + 0.011 \times \text{Storage Mass (lbm)} \\ & + 3.75 \times \text{Heat Exchanger Length (ft)} \\ & + 5100\ (\$)\end{aligned}$$

The lump sum of $5100 was determined to be required for system costs not directly a function of collector, storage, nor heat exchanger length. (This includes controls, part of the plumbing, and pumps.) The operating costs, insurance, and maintenance was estimated at 1% of the initial installed cost per year (see Ref. 3).

The value of the system (in reduced fossil fuel consumption) was determined by use of the computer simulation mentioned previously. Parametric variations in each major system component size were analyzed, and the solar energy provided for each case was determined. The solar energy provided is then used as an input into a cost analysis program which determines the life cycle cost of the solar energy for each configuration. The major assumptions for the cost analysis are shown in Table 2. A more complete discussion of the analysis is presented in Ref. 3.

The results of this combined performance/cost analysis are optimum combinations of solar collector, storage and heat exchanger sizes to

provide any given portion of the total energy required by the greenhouse. The solar energy costs are plotted in Fig. 7 as a function of the percent of total energy supplied. The cost of the solar energy for the glass and insulated greenhouses are shown as well as the cost of fuel oil for several differential fuel escalation rates. In addition, the optimum collector area to provide any desired portion of the total energy required is shown.

Several interesting facts can be observed from Fig. 7. The most obvious feature of Fig. 7 is the identification of the optimum solar system size for minimum solar energy costs. This occurs at acout 5000 $ft^2$ of collector which will provide about 55% of the energy used by the greenhouse. It is interesting that the 5000 $ft^2$ of collector will provide about the same percent of the total energy required by both the glass and insulated greenhouse. The principal reason for this is that the glass greenhouse needs more energy all year long so that the collectors are utilized more in the spring and fall than for the insulated greenhouse (See Fig. 8). The greater utilization of the collectors by the glass greenhouse is the reason that the solar energy cost is significantly less than for the insulated greenhouse. One should not construe that, based on these results, solar heating systems should only be used with uninsulated greenhouses; however, there definitely is a penalty associated with solar heating systems that supply energy to a well insulated greenhouse. The problem is much like the problem facing application of solar energy to a process, such as crop drying, that uses energy only a short period of the year.

A very significant benefit of using solar energy for greenhouse heating is the additional protection against freeze and loss of crop that is inherent in a dual heating system. Figure 9 shows the capability of a solar heating system (which was designed to provide 60% of the total energy required to maintain the greenhouse at 62 F) to maintain the greenhouse at different lower temperatures for prolonged periods of time during the heating season. These data indicate that the system can maintain the greenhouse at 40 F or greater with no appreciable fossil fuel usage if necessary. A more realistic situation, however, is the capability of the system to provide freeze protection for the crop during a short period of fuel interruption (one or two days). The analysis showed that only three times during the winter would the solar system not be capable of maintaining the greenhouse at 40 F for at least one day without fossil fuel backup. Most of the year the system could provide more than three days of freeze protection, even though the days were totally overcast. It is obvious that some electrical power would be required for a pump, but this would be only about one kilowatt that could be provided by a small generator.

## ACKNOWLEDGEMENTS

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2. Ruegg, Rosalie T., "Solar Heating and Cooling in Buildings: Method of Economic Evaluation," NBSIR 75-712, National Bureau of Standards, Washington, D. C., July 1975.

3. Robertson, S. James, and Paul O. McCormick, "Solar Industrial Process Heat for Kiln Drying Lumber, Final Report – Phase I," LMSC-HREC TR D497234, Lockheed Missiles & Space Company, Huntsville, Ala., 30 March 1977.

Table 1 – Factors Affecting Cost Effectiveness

| Total Cost | Total Value |
|---|---|
| Initial Costs | Installed System Performance |
| Hardware | Collector Performance |
| Installation | Storage Losses |
| Operational Cost | Heat Addition to the Greenhouse |
| Personnel | Heat Requirements of Greenhouse |
| Electrical Energy Required | Availability of Solar Energy |
| Maintenance and Replacement | Phasing of Solar Availabilities and Energy Required |
| Taxes | Value of Fossil Fuel Replaced |
| Insurance | Current Fuel Cost |
| Financial Considerations | Fuel Escalation Rate (Fuel-General Inflation) |
| Interest on Money | Conversion and Delivery Efficiency |
| Depreciation Allowance | O&M Cost for Conventional System |
| Investment Credits | Tax Breaks |
| Tax Breaks | Intangibles |
| | Future Fuel Prices and Availability |
| | Insurance Against Freeze |
| | "Free" Energy During Mild Weather That May Have Some Value by Increasing Greenhouse Temperatures |
| | "Do-It-Yourself" Construction |

Table 2 – Economic Analysis Assumption

| |
|---|
| O&M, Replacement Insurance – 1% of Installed Cost per Year |
| 20-Year Life with Linear Depreciation |
| 10% Investment Tax Credit |
| 50% Income Tax Bracket |
| 10% Interest on Money |
| $15/bbl of Fuel Oil ($0.36/gal) |
| 70% Boiler Efficiency |



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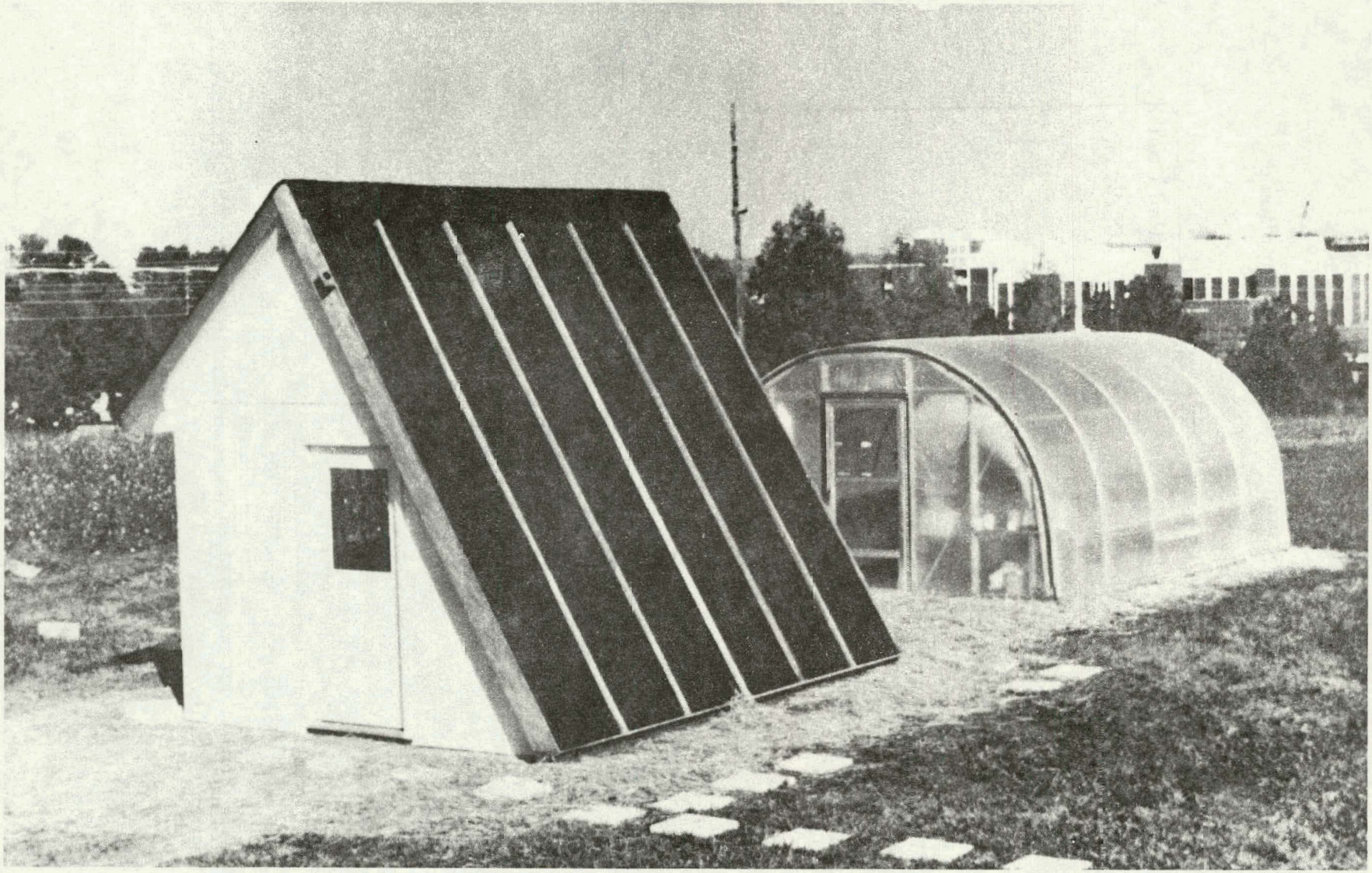


Fig. 1 - Solar Heated Greenhouse at Lockheed-Huntsville

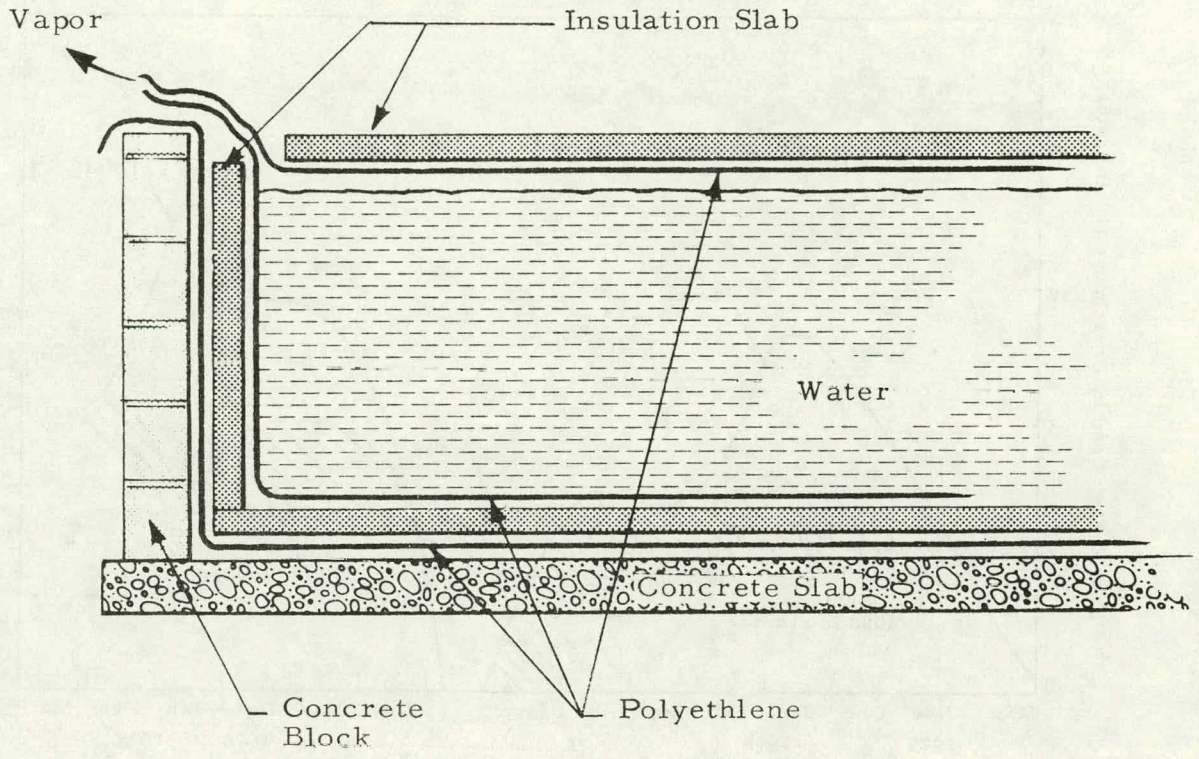



Fig. 2 - Open Concrete Storage Tank

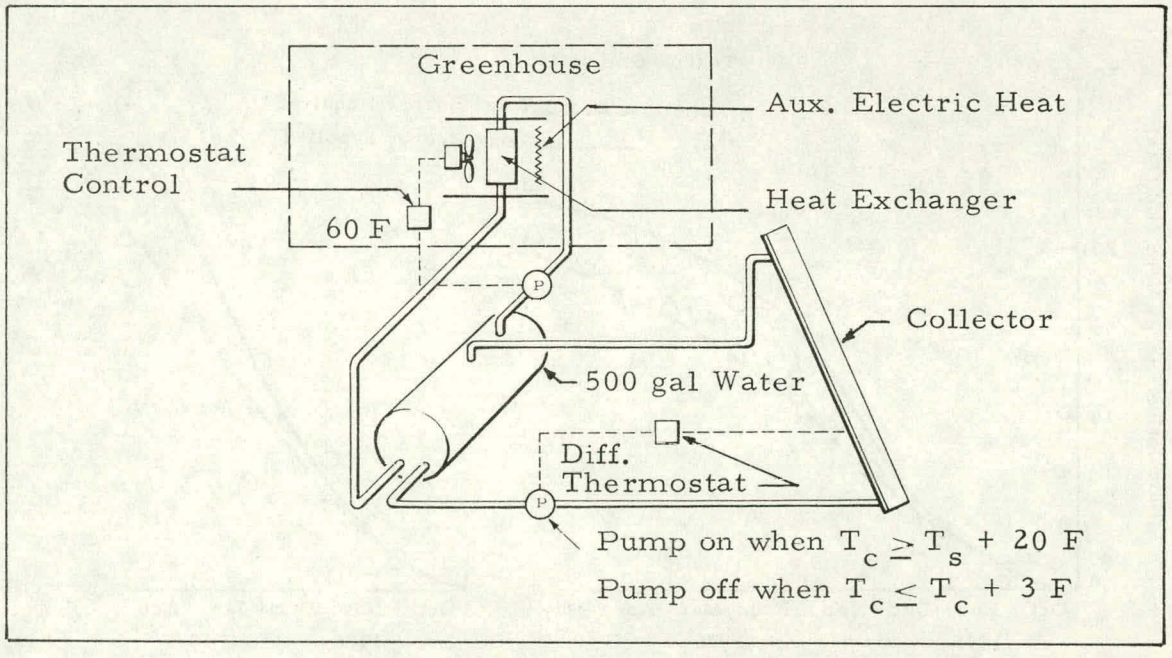



Fig. 3 - Schematic of Greenhouse Heating System

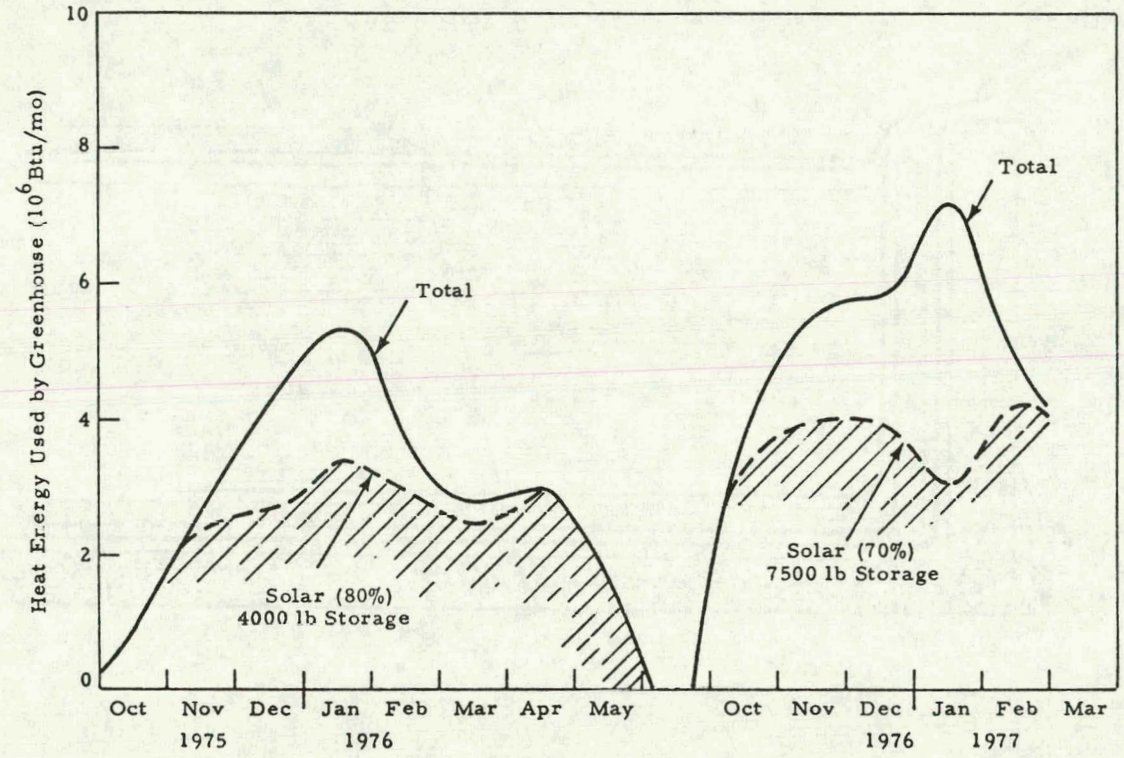



Fig. 4 - Summary of Greenhouse Solar Heating Test for 1975-76 Season and 1976-77 Season Through 28 February 1977

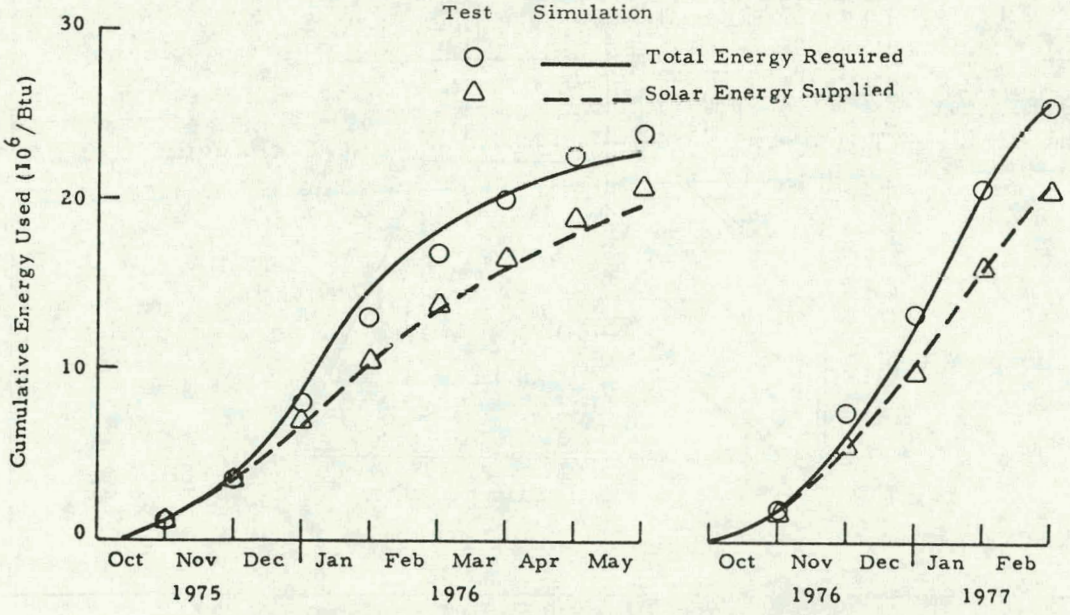



Fig. 5 - Comparison of Calculated and Measured Performance of Solar Heated Greenhouse Experiment

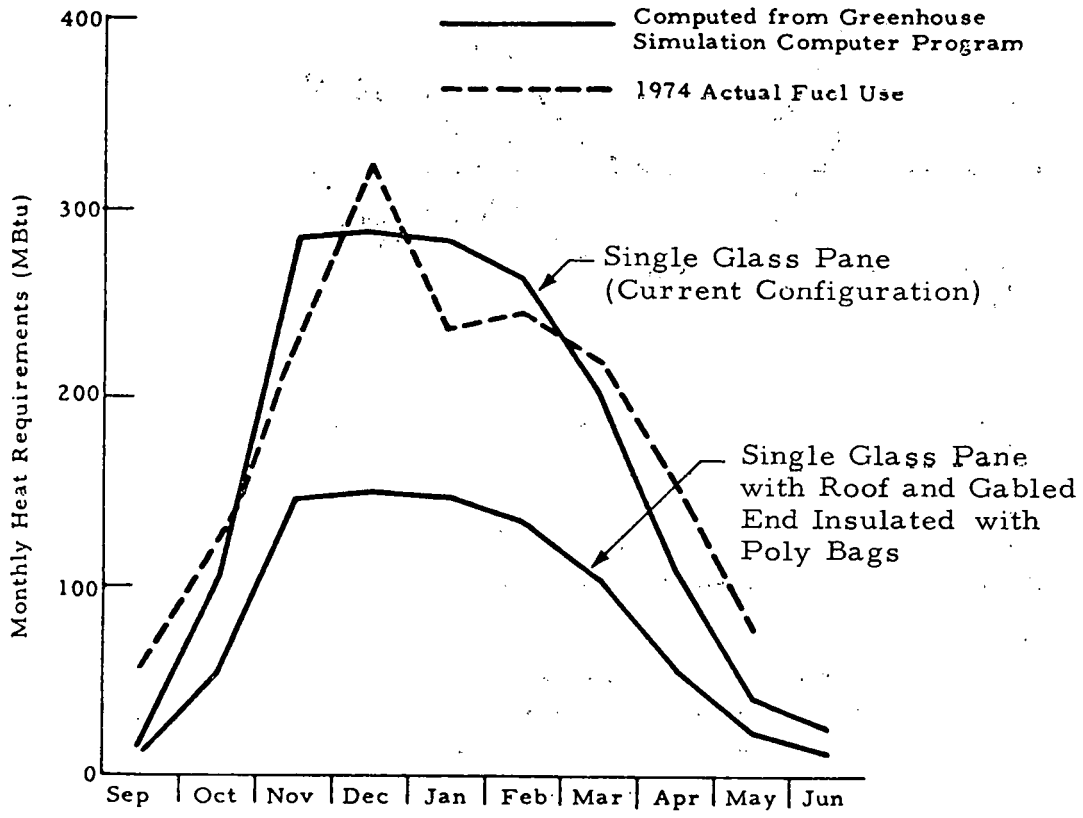



Fig. 6 - Estimated Greenhouse Heat Load Requirements

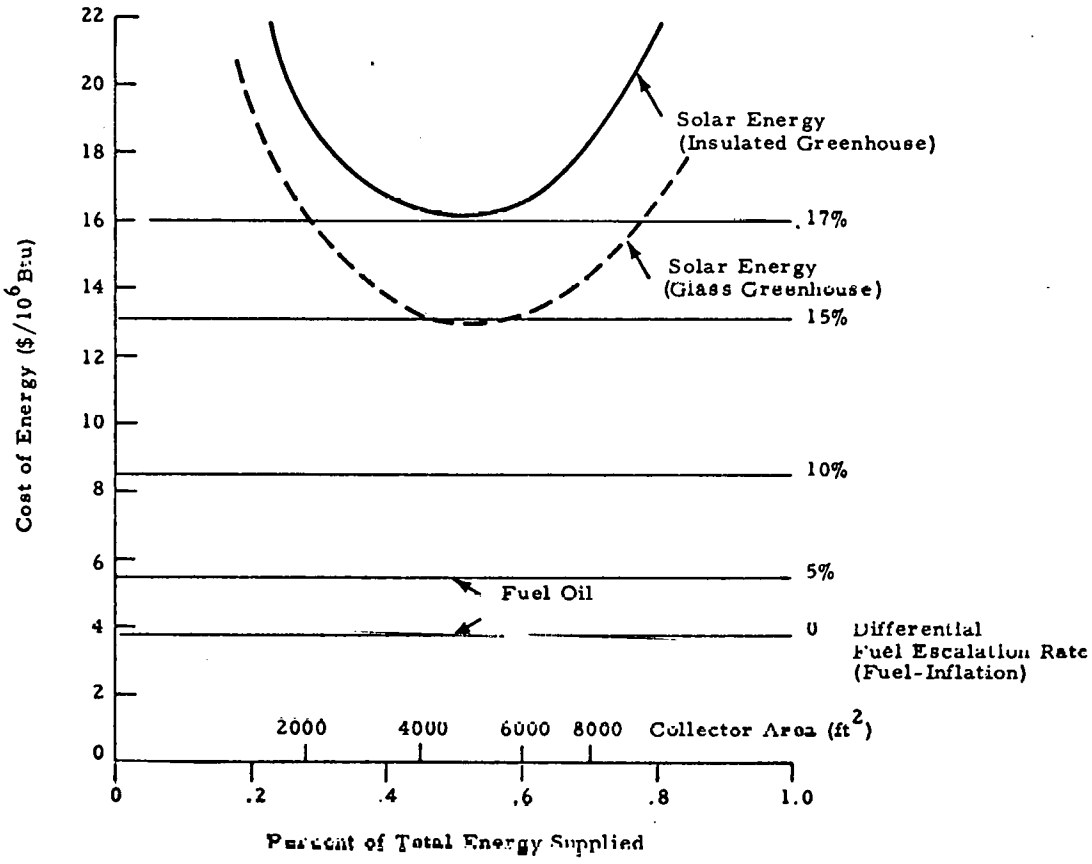



Fig. 7 - Comparison of Energy Costs for Solar and No. 2 Oil for Heating Greenhouse

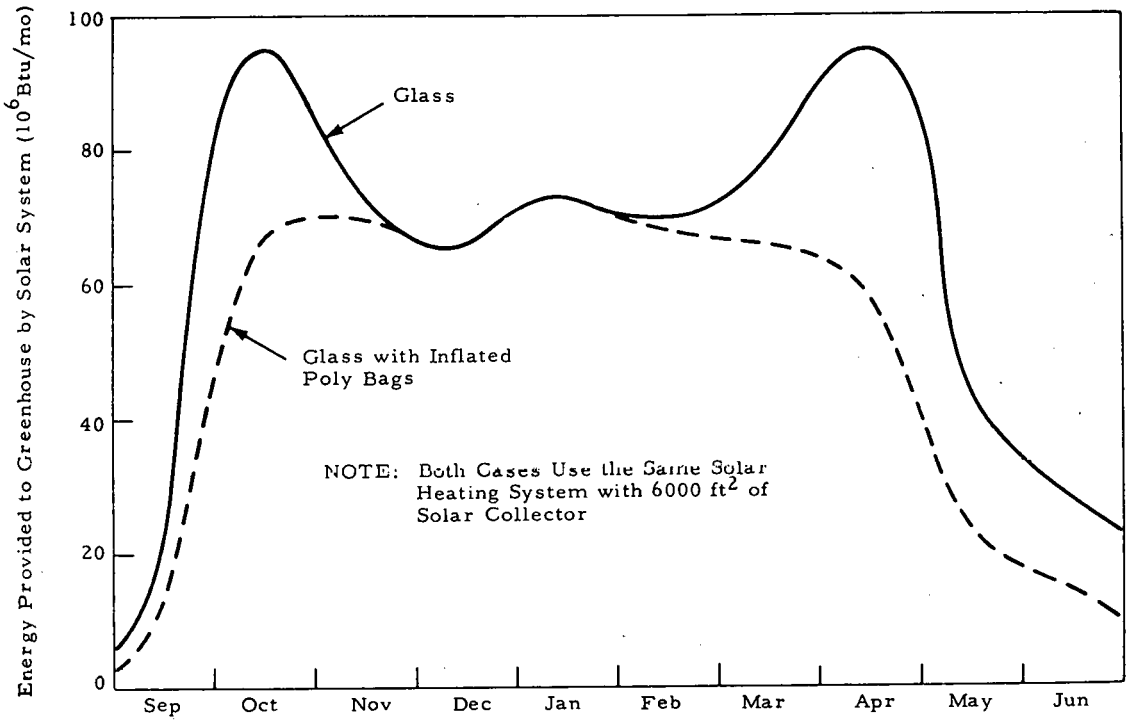



Fig. 8 - Effect of Insulating a Glass Greenhouse on Performance and Cost Effectiveness of Solar Heating System

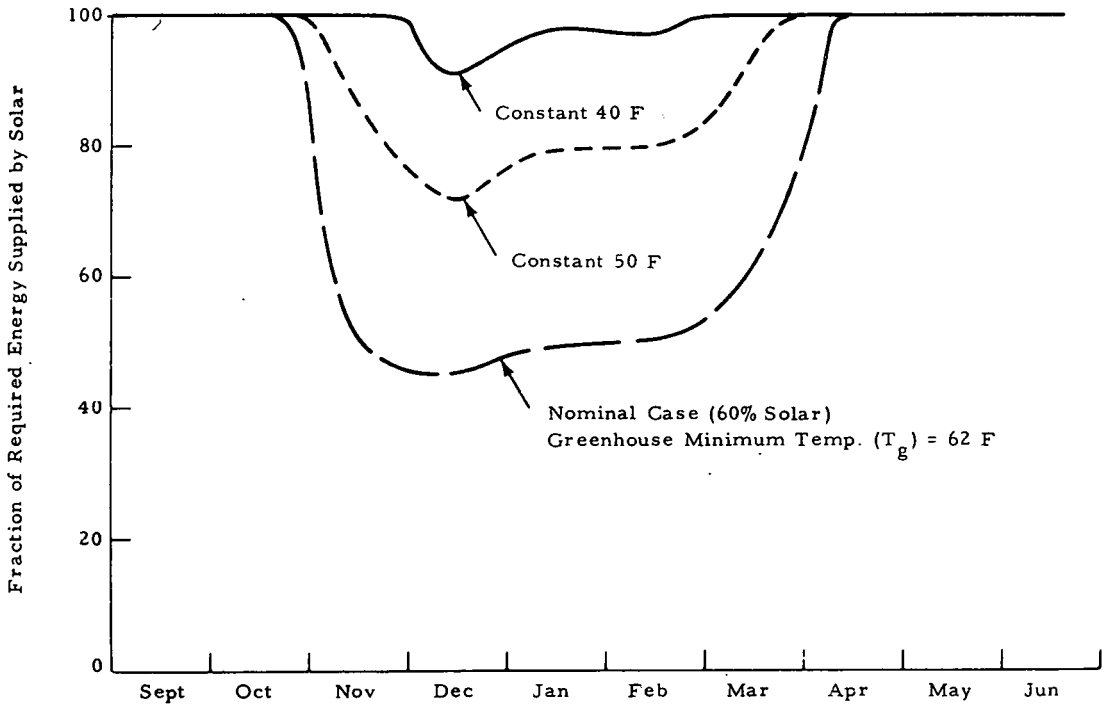



Fig. 9 - Capability of Cost Optimized Solar Heating System to Protect Against Complete Loss of Crop for Long Term Loss of Fossil Energy

# A SOLAR POND FOR HEATING GREENHOUSES AND RURAL RESIDENCES

Ted H. Short, Phillip C. Badger and Warren L. Roller*

Solar energy has a relatively low power density per unit area along with a highly variable intensity. The average intensity in winter, when heat is needed, is much lower than in summer. For instance, typical daily solar radiation for each month at Wooster, Ohio (41°N latitude) is shown in Figure 1 to be 3-4 times greater in June than in December. Any system that can economically and efficiently store large quantities of heat might utilize the annual variability. Solar ponds appear to be a type of solar system that can both collect and store year-round radiation for use primarily in the winter.

Solar ponds are heated by absorption of short wave radiation throughout the vertical profile and on the pond liner. The pond is intended to be transparent and the lower levels absorb primarily visible and ultra-violet light. Most of the infra-red light is absorbed at or near the surface of the pond and tends to be lost to the air by evaporation and conduction-convection. The solar pond, as established for this study, has a high density convective zone of approximately 20% sodium chloride in the bottom half. The top half of the pond is composed of a concentration gradient that goes from 20% at the center to nearly 0% at the surface. Such gradients are non-convective and no circulation occurs. Heat can only be lost to the surface by conduction through the gradient, which is relatively slow. For example, the brine gradient has similar heat conductivity characteristics as water with a conductivity of 2240 J-m/hr-$m^2$-°C at 38°C.

Natural solar ponds were first discovered in the early 1900's in Hungary as noted by Kalecsinsky (1902). Tabor (1963) studied pond feasibility for power generation and was able to achieve small pond temperatures up to 90°C (194°F), but had numerous technical problems with large ponds. Rabl and Nielsen (1975) have studied the solar pond as a solution to space heating of residences in Ohio and similar areas. Rabl calculated that a pond equal in volume to a well insulated three bedroom home could meet all of the winter space heat requirements of that home. Nielsen (1975) further developed a unique salt gradient establishment procedure using a small pool and laboratory models.

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Based on Rabl and Nielsen's work, a full-scale experimental solar pond shown in Figure 2 was constructed adjacent to the Department of Agricultural Engineering Greenhouse at the Ohio Agricultural Research and Development Center (OARDC). The pond was designed to meet all of the winter heat requirements of a 186$m^2$ (2000 $ft^2$) three bedroom home or a 98$m^2$ (1000 $ft^2$) greenhouse in Wooster, Ohio.

## DESIGN AND ESTABLISHMENT OF THE SOLAR POND

The OARDC pond is 3.6 meters deep, 8.5 meters wide and 18.3 meters long (12 ft. x 28 ft. x 60 ft.). The pond has post and plywood construction walls and a sand bottom. Two 0.75 mm (30 mil) chlorinated-polyethylene liners with a nylon scrim were fabricated to fit the structure and contain the brine. The side walls were insulated with 10 cm of polysytrene in the top 1.8 m and 5 cm in the bottom 1.8 m. The bottom surface was expected to become insulated if pond heat dried out the surrounding soil.

The top of the pond walls were designed to accommodate the pipe framing for a commercial plastic covered greenhouse. The plastic cover was installed to 1) help insulate the pond, 2) minimize dirt and trash contamination, 3) quiet the surface to reduce light scatter and gradient mixing, and 4) raise the humidity above the water surface to control evaporation. An aluminized cloth reflector was designed for the inside north greenhouse wall to increase the effective collection area of the pond (Figure 3).

A 1.8 m (6 ft.) convective zone of approximately 20% salt (sodium chloride) was established in the bottom half of the pond. The top half has a concentration gradient that varies from the approximate 20% concentration at the 1.8 m (6 ft.) depth to zero at the surface. This top section is non-convective (no circulation occurs) since every layer is lighter than the layer beneath it.

The salt concentration gradient was established according to a technique developed by Nielsen (1975). The pond was filled to the three-quarter level with a 20% solution. Fresh water was carefully distributed over a floating sheet of plywood until the pond was full. The sizeable density difference of the freshwater and concentrated brine resulted in two distinct sections with little mixing. A pump with two inlets was then used to extract equal amounts of fluid from each section. The pump mixed the 20% solution with the fresh water to get a 10% solution. The 10% solution was injected between the original sections creating a new concentration zone occupying one-third of the top half of the pond. Subsequently, the three (0%, 10%, 20%) zones were used to form five zones (0%, 5%, 10%, 15%, and 20%) and the 5 zones were used to form nine final zones. The nine final zones were approximately 20 cm (8 in.) thick which was small enough for a linear gradient to eventually form by diffusion and mixing. The change from a step-wise gradient to a linear gradient can be seen during the first year of operation (Figure 4). The concentration remained uniform below 180 cm as the 20 cm layers

developed into a gradient. The pond tends to remain extremely stable except for near the surface. After 3 to 6 months of operation, a convective zone tends to grow very slowly at the surface as shown on the January 22, 1977 curve in Figure 4.

A COVERED POND

Previous research by Tabor (1963) and Weinberger (1964) had indicated that pond gradient maintenance was a problem because of wind action mixing the surface. There can also be problems with organic debris falling into the pond and blocking light to the lower zones. Thus, a greenhouse was modified to cover the pond surface and internal aluminized cloth reflectors were added to the north wall to improve collection efficiency. The internal reflectors were 2.7 m high and fixed at 75° to coincide with the maximum altitude of the summer mid-day sun at 41° N. latitude.

A UV-resistant grade of polyethylene (Monsanto 602) was initially used for the solar pond covers. The double-cover was air separated and maintained at 1 cm water pressure with an (1/30 hp) air inflation fan. The double cover was over the pond from November, 1975 until June, 1976. The pond was essentially uncovered from July 1976 until November 1976. A single plastic cover of laminated vinyl and Tedlar was put over the pond in November, 1976 and was removed in March, 1977. The single cover was stabilized by pressurizing the space between the pond surface and the cover. However, maintaining uniform and adequate pressure for the single cover was difficult due to air leakage around the doors and fiberglass at the ends of the structure.

Pond surface radiation profiles were recorded during the summer of 1976, at the pond center along the north-south axis with a floating pyranometer. This surface radiation along with the measured available radiation was used to calculate the transmissivities along the N-S axis for three levels of polyethylene covers with and without reflectors.

The transmissivities across the pond for no cover or reflector were equal to 1.0 except when the pipe framing for the covers cast a shadow on the radiometer (Figure 5). The addition of a reflector on the north wall increased the noon-time radiation at the water surface close to the reflector, but it had little effect on the total accumulated radiation. In fact, the reflector effectively shaded part of the pond surface in the early morning and late afternoon when the solar azimuth was greater than 90° from solar noon. The addition of one plastic cover greatly increased the radiant transmission variability across the pond and reduced the overall magnitude of the transmissivity to 0.819 (Figure 6). The cover tends to be diffusive to the point of making the north wall reflector somewhat ineffective. The transmissivity at the reflector is especially low for the double plastic cover (Figure 7). The reflector effectively is opaque to any diffuse light that may penetrate the north wall and the light attenuation and reflection probably increases from South to North across the cover surfaces with the double-

cover system. The mean transmissivity values for each of the cover and reflector systems are given in Table 1. The addition of a reflector may have more value in the winter months than is shown by this data which was recorded in the summer. Models by Husseini (1977) of average year-round available radiation demonstrate that in winter months, and for direct radiation, the reflector may increase the effective pond area up to 160%. However, winter radiation is typically of low intensity and very diffuse. The addition of plastic covers tends to further diffuse the light and decrease the effectiveness of a reflector.

## STABILITY AND TEMPERATURE PROFILES

The data processing on solar pond temperature, concentration, and density profiles was greatly automated in 1976-77. Equipment was designed and developed to accurately measure vertical profiles of pond temperature and specific conductivity. Computer programs were developed by Badger (1977) to calculate and process this data into quantities of energy storage and density profiles. Elwell (1977) has used the density profile information to evaluate theoretical analyses of dynamic stability, and the energy storage has been used to calculate pond collection and storage efficiencies.

After draining the pond to repair a small leak in the pond liner in February 1976, the pond was re-filled in early March. The resultant density, temperature and concentration profiles for March 25, 1976 are shown in Figure 8. The pond brine had effectively cooled down to 4.5°C while being held in temporary storage tanks. The gradient region from 0 to 150 cm was stable, but not uniform. In September, the pond reached a maximum temperature of 43.3°C as shown in Figure 9. A most interesting display in Figure 9 is the 50 cm convective zone in the upper part of the pond. About every three months 10 to 20 cm of the low concentration surface brine is usually pumped off and replaced by fresh water. Brine in the 20-50 cm zone is pumped down and mixed into the 60-80 cm zone until a rough gradient is re-established. The pumping process is monitored by periodic conductivity profiles. On November 17, 1976, the pond temperature had remained relatively constant and at least two gradients are visible in Figure 10 as a result of the October 19, 1976 pumping. One gradient is from 30-80 cm and another is from 80-180 cm. These gradients tend to smooth over long periods of time as evidenced by the February 25, 1977 profiles in Figure 11. Up to 15 cm of ice was on the pond surface during January and February 1977. The profiles that were measured in Figure 11 were taken through a hole cut in the ice.

The overall interest in the data analysis has been to determine the magnitude of the annual solar pond heat collection and the collection and storage efficiencies in the bottom 1.8 m of pond. From Figure 12, one can see that the weekly solar radiation and the combined collection/storage efficiency can fluctuate markedly while the actual heat stored

changes very slowly. This slow change in heat storage is very desirable going into winter. However, a much steeper slope is necessary during the summer heat charging period. The collection/storage efficiency at a maximum of 12% is much lower than desirable for good pond operation. It can at best be around 30% if there are no storage losses since the open pond can only capture and store the ultra-violet and visible radiation. Current research efforts are under way to separate and evaluate collection and storage efficiencies by measuring underwater radiation profiles.

## HEATING REMOVAL SYSTEM

A schematic of the planned heat removal system is shown in Figure 13. Pond brine will be pumped through the shell of a shell and tube heat exchanger. Fresh water in the tubes will transfer heat to: 1) a unit heat exchanger in the greenhouse when the pond temperature is between 40°C and 80°C; and 2) a heat pump system when the pond temperature is between 5°C and 40°C. This system is to be installed in 1977. A temporary installation of a heat removal system was made during the spring of 1977. It consisted of a brine handling system between the pond and a (10 ton) Heat-X brine chiller; a water storage tank; and a fan coil unit matching the heat pump. The system has operated successfully without disturbing the pond gradient, but no meaningful heat transfer data has been collected.

## FUTURE EFFORTS

The overall objective of this research has been to determine the feasibility of heating greenhouses and rural residences with a solar pond. However, much of the work to date has been limited to establishing a better understanding of solar ponds since very little previous data and experience exists. Many people assume solar ponds may not be feasible because of stability and maintenance problems. This, however, has been remarkably easy while the more critical problem has been to achieve adequate collection and storage efficiencies to meet the demands for space heating. These collection and storage efficiencies take long periods of time to establish and are highly dependent on the location, size and shape of the pond; type of cover; type of insulation; available radiation; and surrounding disturbances such as wind, rain, and debris. Until one adequately understands many of the design factors and optical characteristics of the solar pond, one can only guess at some of the numbers necessary to design solar ponds for proper operating characteristics. Such limited knowledge makes economic analyses even more dubious when one can choose any numbers he may wish to believe.

Future efforts will be toward establishing an economic analyses of the solar pond based on well defined assumptions. Costs can certainly be minimized if ponds can be easily operated and maintained without covers. The covers have been detrimental to heat collection and storage by

reducing solar input, but the opposing effects of debris and wind are not fully understood. Wall construction in any large ponds will likely be earthen and plastic lined to minimize cost, but liners must be leak proof to prevent ground water contamination and loss of the brine.

The future of solar ponds already looks very promising especially for special applications where space and potential ground water contamination is not a serious problem. When leakproof ponds can be designed in many sizes, the potential for many applications exist if space is available. It is obvious, that somewhere in the spectrum of solar energy applications lies the potential for applications of the solar pond.

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TABLE I. Measured mid-day and half-day transmissivities at the surface of a solar pond for polyethylene cover and reflector combinations on clear days.

| Treatment | Mid-Day Trans. | Half-Day* Trans. |
|---|---|---|
| 0 poly. w/o ref. | 1.022 | .931 |
| 0 poly. with ref. | 1.016 | .923 |
| 1 poly. w/o ref. | .819 | .761 |
| 1 poly. with ref. | .847 | .731 |
| 2 poly. w/o ref. | .636 | .565 |
| 2 poly. with ref. | .607 | .546 |

* A weighting factor was applied to the average transmissivity per transverse. The weighting factor was proportional to solar altitude to give more weight to the mid-day values.

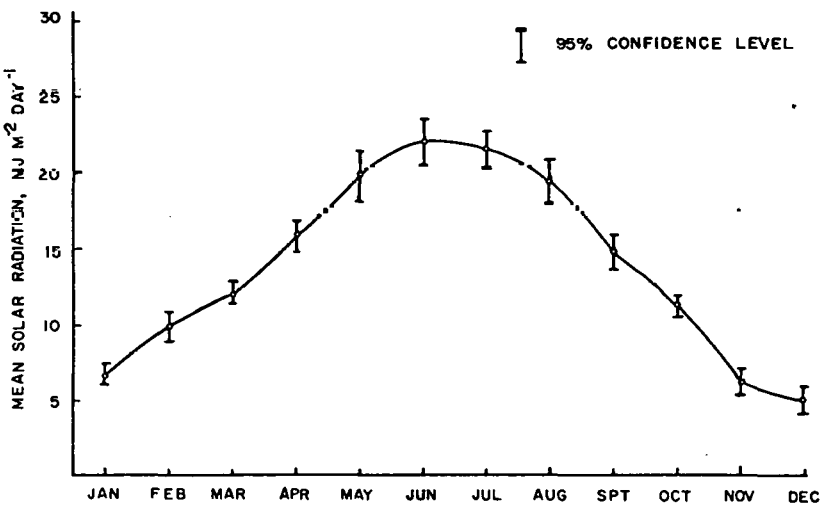



Figure 1. Average daily solar radiation on a flat horizontal surface at Wooster, Ohio, 40° 45' N latitude. Each point is based on 13 years data, 1962-1974. (Meyer, 1975).

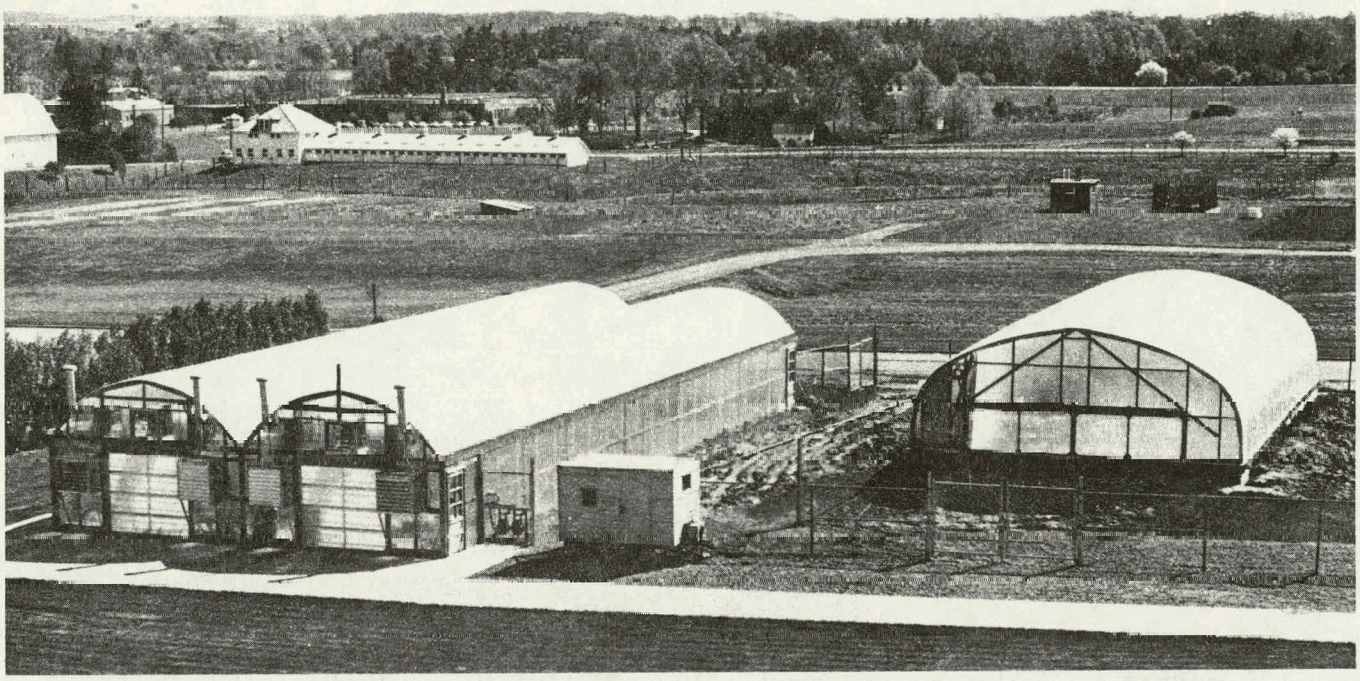


Figure 2. The solar pond is under the clear-span air inflated double plastic greenhouse at right. Heat from the pond will be used for heating the nearest greenhouse module while the furthest module (at left) will be heated conventionally.

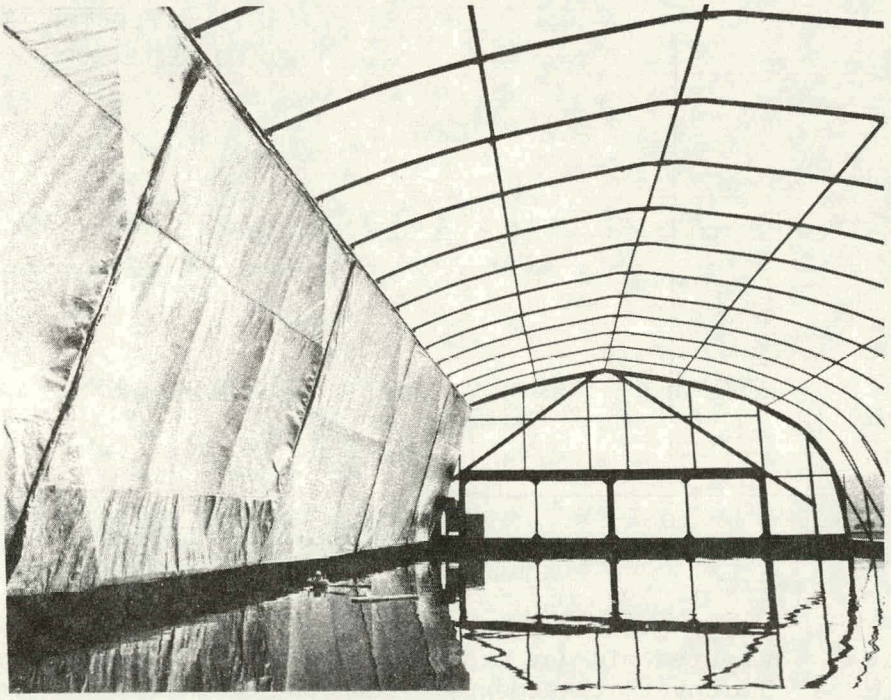


Figure 3. This interior view shows the pond surface and the reflector which has been installed along the north wall of the greenhouse to increase effective radiation collection area of the pond. The solar radiometer is on the surface of the pond near the base of the reflectors.

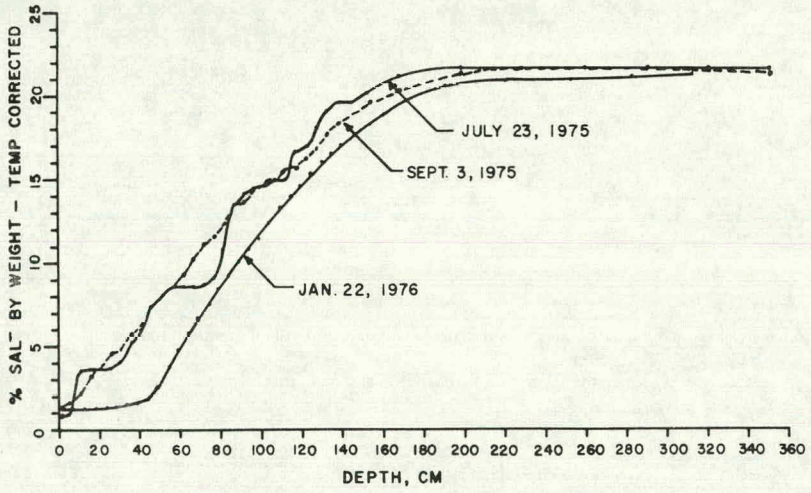



Figure 4. Solar pond concentration profiles for three different dates after pond establishment.

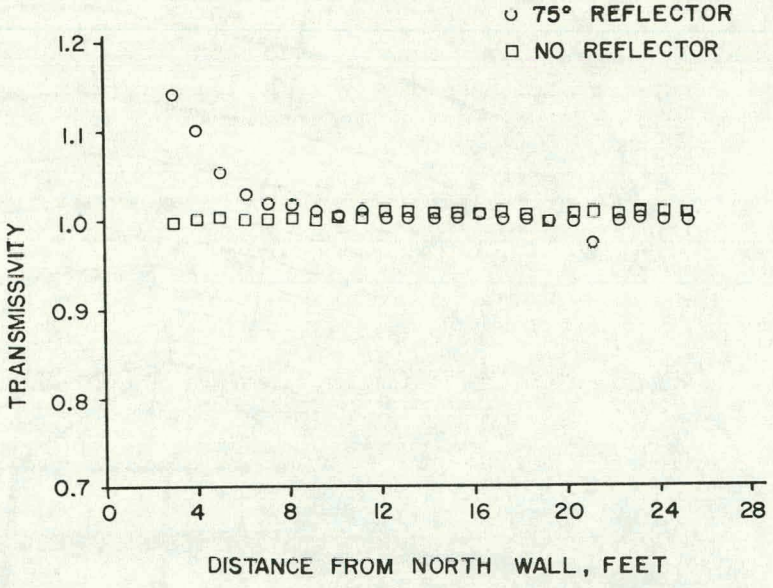



Figure 5. Measured mid-day transmissivities versus position during the "no cover" treatments. The values plotted are arithmetic means of measurements taken on clear days within two hours of solar noon.

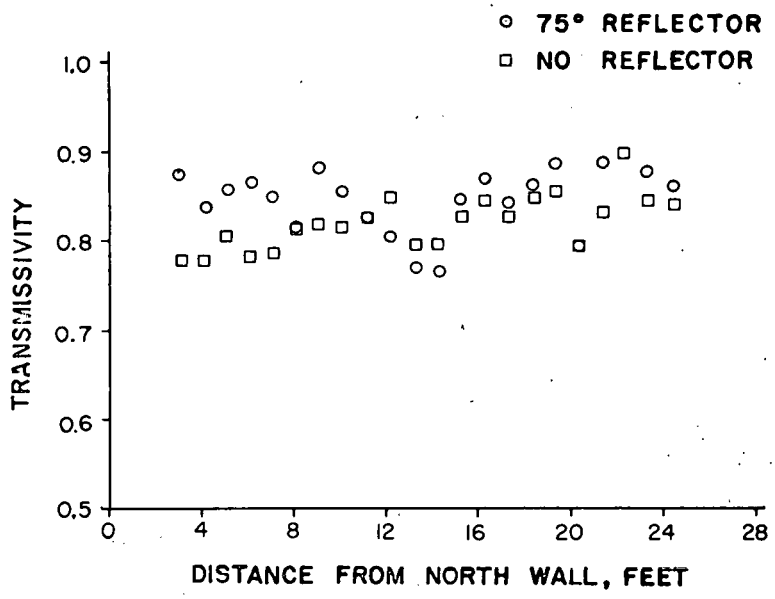



Figure 6. Measured mid-day transmissivities versus position during the "one polyethylene cover" treatments. The values plotted are arithmetic means of measurements taken on clear days within two hours of solar noon.

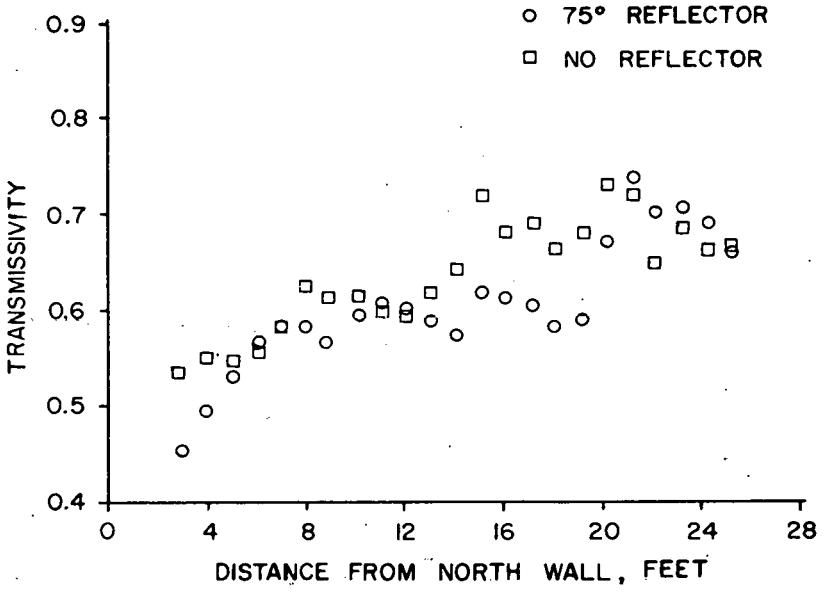



Figure 7. Measured mid-day transmissivities versus position during the "two polyethylene cover" treatments. The values plotted are arithmetic means of measurements taken on clear days within two hours of solar noon.

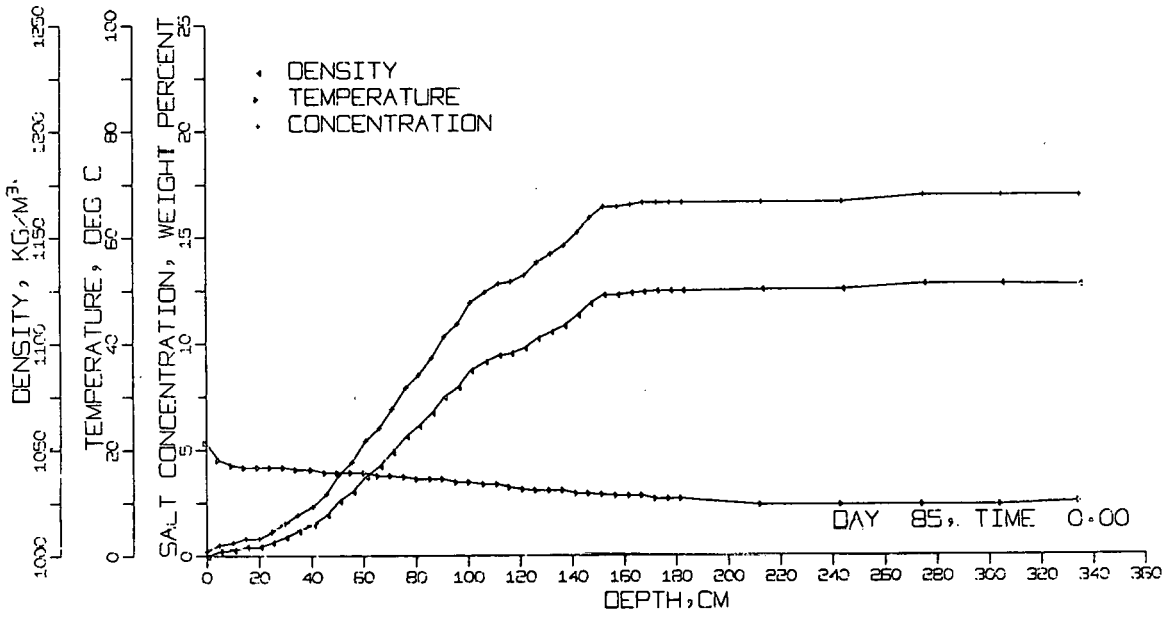



Figure 8. Vertical profiles of density, temperature, and concentration gradients in the solar pond on March 25, 1976.

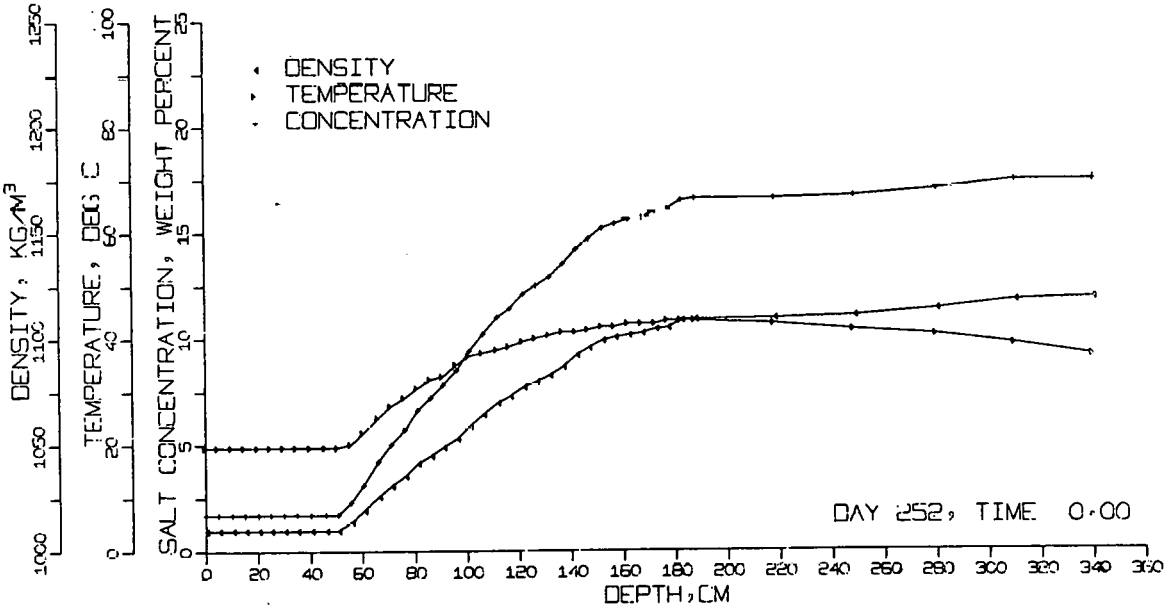



Figure 9. Vertical profiles of density, temperature, and concentration gradients in the solar pond on September 8, 1976. A 50 cm convective zone is illustrated near the pond surface.

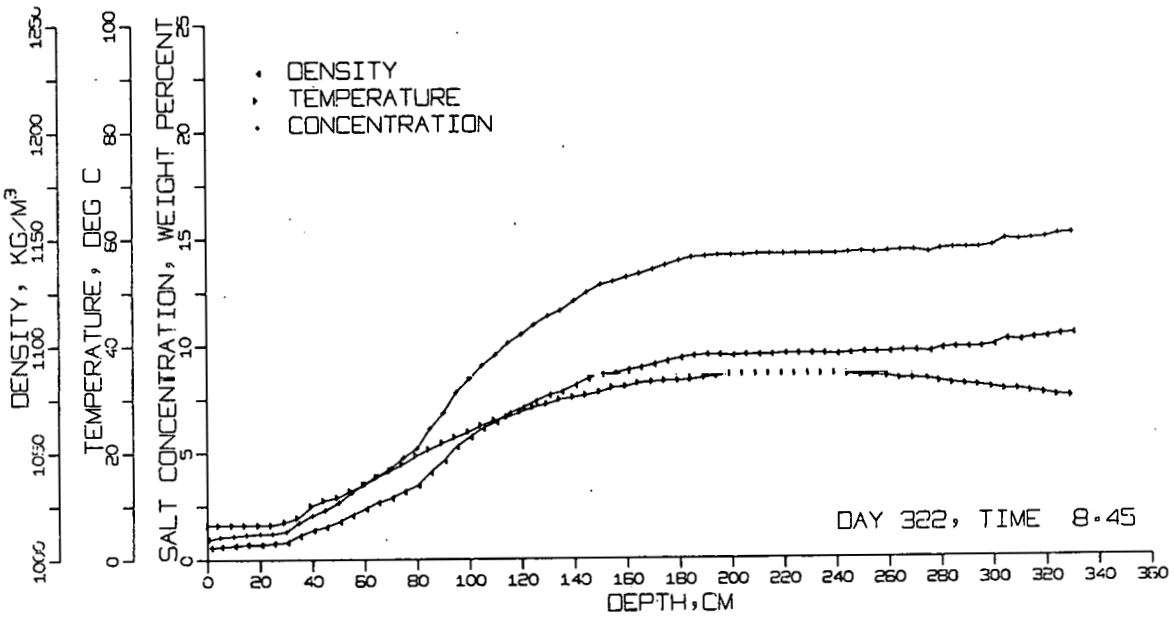



Figure 10. Vertical profiles of density, temperature and concentration gradients in the solar pond on November 17, 1976.

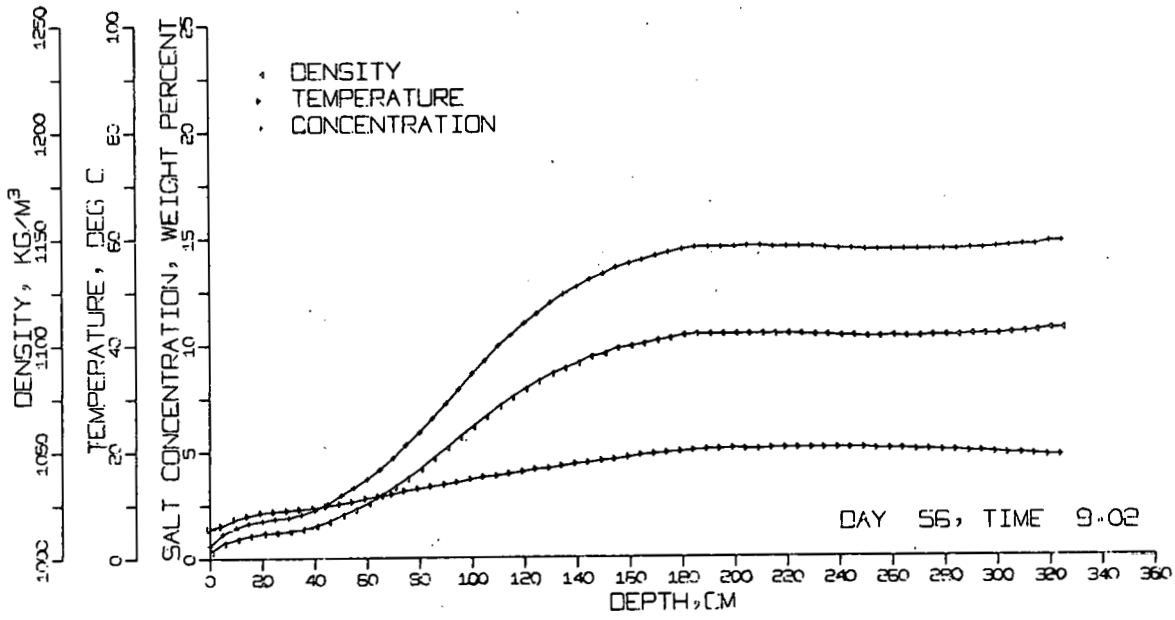



Figure 11. Vertical profiles of density, temperature, and concentration gradients in the solar pond on February 25, 1977. Up to 10 cm of ice was on the pond surface in January and February, 1977.

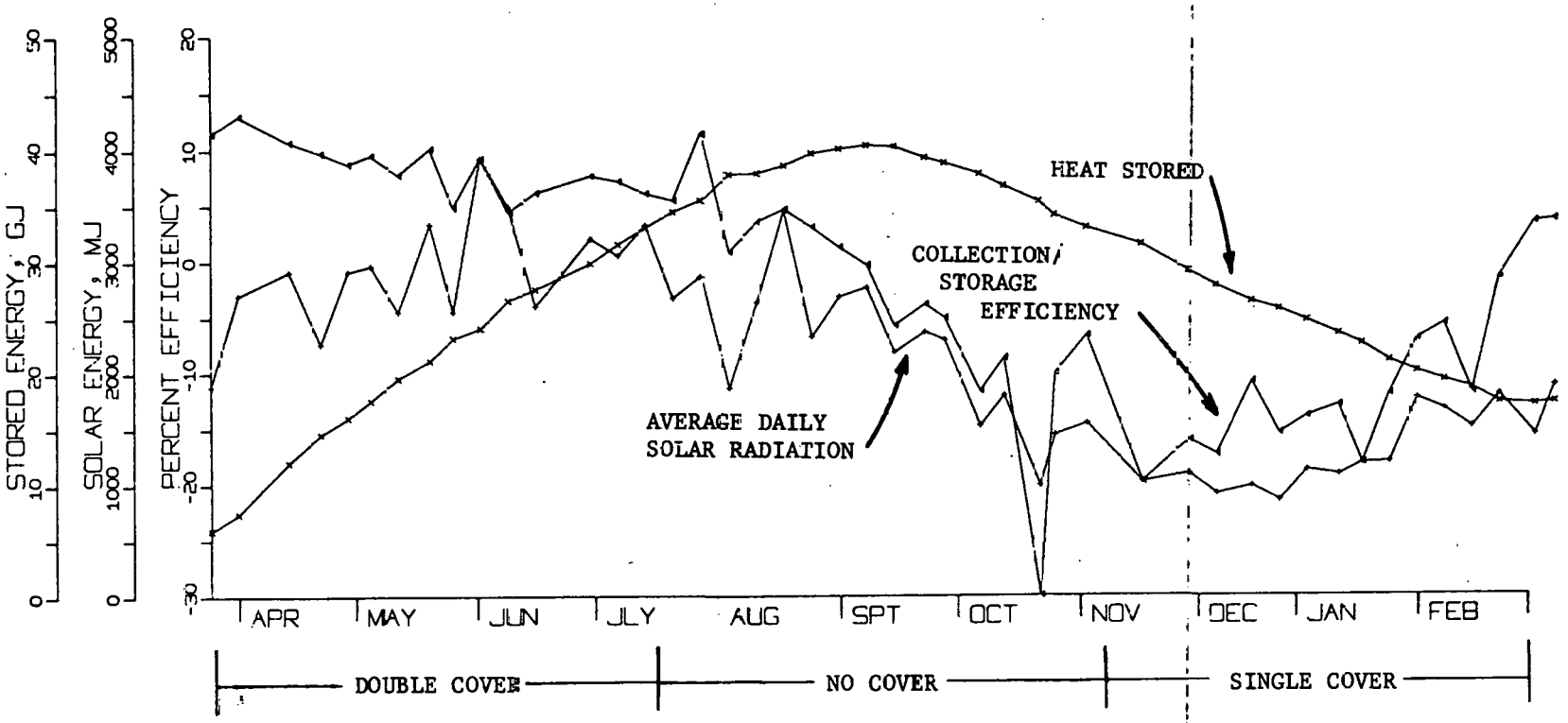



Figure 12. An annual summary of the solar radiation, average daily heat stored, type of cover and the solar pond collection and storage efficiency. Energy storage is based on the bottom 180 cm of brine and a 4.5°C reference temperature.

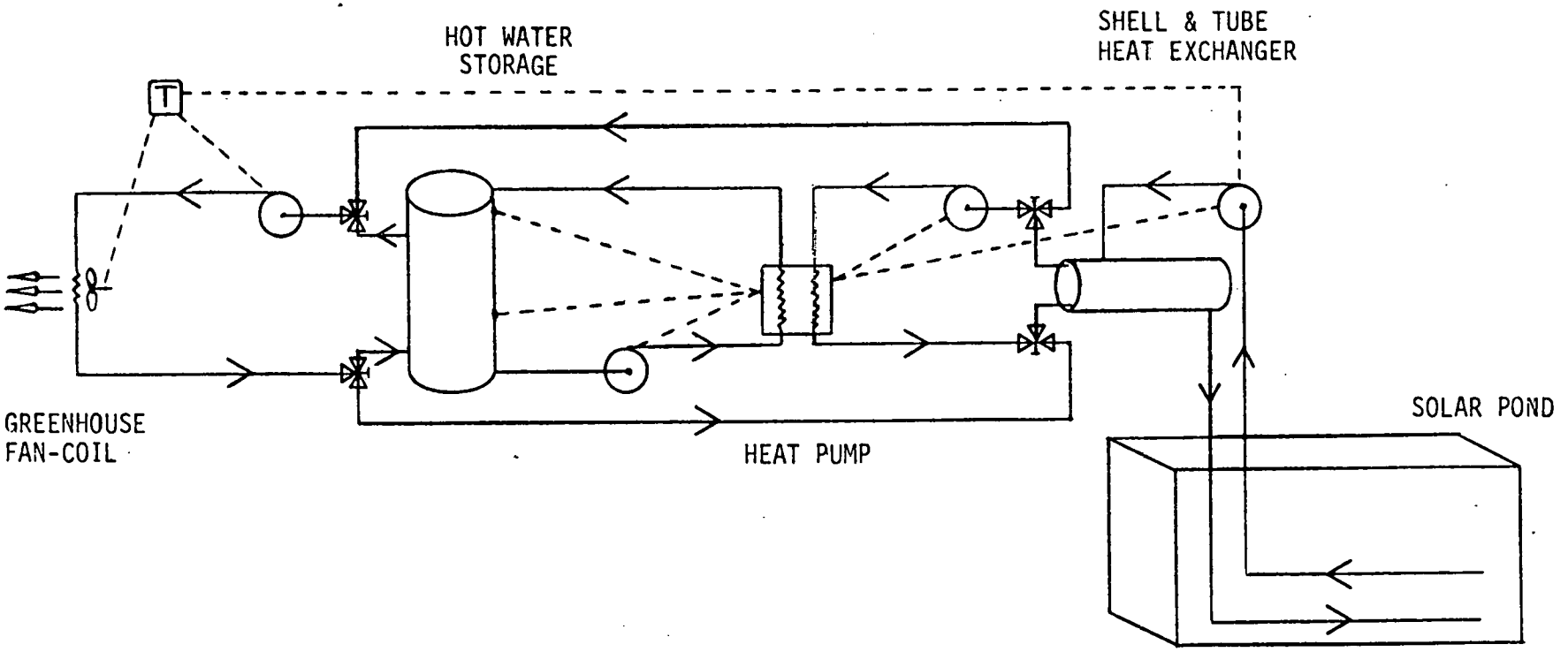



Figure 13. A schematic of the planned solar pond heat removal system. The heat pump will be used when the pond temperature is between 5°C and 40°C and a direct unit heater will be used when the pond temperature is between 40°C and 80°C.

# SOLAR, LONG WAVELENGTH, AND PHOTOSYNTHETIC ENERGY TRANSMISSION OF GREENHOUSE COVER MATERIALS

T. E. Bond, L. C. Godbey, and H. F. Zornig[1]

The Rural Housing Research Unit of the Agricultural Research Service, in cooperation with Clemson University, is developing practical greenhouse-residence combinations that can be used by families to conserve fossil fuel, utilize solar energy, and produce homegrown food. In the early stages of this project, we did not feel that radiant energy transmission characteristics were adequately defined for many possible greenhouse or solar collector covering materials to guide our selection of these materials for our uses. This paper describes the method of measurement and resulting values of radiant energy transmission characteristics we feel are important in the selection of cover materials for greenhouses or for solar collectors.

## MEASURED TRANSMISSION CHARACTERISTICS

The radiant energy transmission characteristics that we evaluated for cover materials for greenhouses are discussed below. Several, but not all, of these characteristics are equally useful in the selection of cover materials for solar collectors.

A. Long wavelength radiation (wavelengths greater than 2.8 μm[2]): This is radiation originating from sources at temperatures near ambient and is often called thermal or low temperature radiation; its transmission rate is important for both greenhouses and solar collectors as these are designed to warm the surfaces they cover, and these surfaces emit long wavelength radiation because of this warm temperature. This radiation would be lost through the cover material to the surrounding cooler sky, or any other cooler surface, if the greenhouse or solar collector cover was not opaque to some degree to this radiation (low transmission rate). The lower the transmission rate for long wavelength radiant energy, the less heat is lost through the cover materials.

B. Short wavelength radiation (wavelengths between 0.3 and 2.8 μm): This is properly called solar radiation and is received at the

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[2] μm = micrometers = $10^{-6}$ meters.

greenhouse or solar collector cover as either direct-beam or diffuse radiation. The greenhouse or collector cover should, of course, transmit a high percentage of this solar radiation to the inside of either structure.

C. Direct-beam and diffuse radiation (wavelengths between 0.3 and 2.8 μm): Some direct-beam solar radiation can be diffused by a cover material as it is transmitted through it. Also, some diffuse atmospheric radiation can be transmitted by the cover. As a result, plants or a solar collector absorber plate will receive part of the solar radiation as direct-beam energy and some as diffuse energy. The respective amounts of each type of solar radiation have little effect on the amount of energy absorbed by a flat-plate solar collector absorber plate. In a greenhouse, however, diffused light is generally preferred because it is more evenly distributed to the plants.

D. Photosynthetically active radiation, PAR (wavelengths between 0.4 and 0.7 μm): The photosynthetic rate of plants depends primarily on illumination by energy with wavelengths between 0.4 and 0.7 μm, according to Cathey and Campbell (5). This radiation is called photosynthetically active radiation (PAR) and is in the same range of wavelength as the visible radiation seen by the human eye. Radiation in the wavelength range of 0.4 to 0.7 μm accounts for only about 42 percent of the total solar energy; about 51 percent has wavelengths greater than 0.7 μm and about 7 percent has wavelengths of less than 0.4 μm (6). Plants actually utilize only a small part of the solar energy they receive for growth, but it is important that they receive this, hence, a high rate of transmission for PAR is important.

MEASUREMENT METHODS

Long wavelength radiant energy transmission was measured with a directional thermopile radiometer (4). Emitted radiation from two black objects at two different temperatures was measured both with and without a sample of cover material between the radiometer and the black objects. A black hohlraum (Leslie Cube) in a constant temperature water bath was used for the black object with a temperature above room temperature, usually around 50 C (120°F). A black metal plate was used as a room temperature object. The transmission was then calculated as (3):

$$\gamma = \frac{E_{bf} - E_{sf}}{E_b - E_s}$$

where: $\gamma$ = transmission of the cover material, percent

$E_b$ and $E_s$ are thermopile voltages when the radiometer views the black hohlraum or the room temperature black plate

b = black hohlraum

f = measurement through cover material

s = black plate at air temperature

The four thermopile voltage readings $E_{bf}$, $E_{sf}$, $E_b$ and $E_s$ were made as rapidly as possible so the black plate and hohlraum temperature would not change appreciably. Four sets of measurements were taken on each sample. The measurements were made indoors in a protected area so the assumption could be made that no short wavelength solar energy was present.

Total short wavelengh radiant energy transmission was measured with an Eppley 50-junction black and white pyranometer. This has a 180-degree field of view and when facing up, or facing the sun, it measures both direct-beam energy from the sun and diffuse sky radiation.

Photosynthetically active radiation (PAR) was measured with a Lambda Instrument Quantum Sensor that measures energy only in the wavelength region of 0.4 to 0.7 μm.

Direct-beam solar energy from the sun was measured with an Eppley pyrheliometer. This instrument has a very small field of view so that when it is pointed directly at the sun, it measures only the direct-beam radiation from it. When both the pyranometer (total sun and sky short wavelength energy) and the pyrheliometer (direct-beam sun energy) are facing the sun, the difference in the energy they both measure is diffuse solar radiation.

The procedure for the solar energy measurements was a modified version of Method B recommended by the American Society for Testing Materials (2). The Eppley pyranometer, the Eppley pyrheliometer, and the Lambda Quantum Sensor were all mounted in a shallow black-painted box that was 12-inches (0.3 meter) square. This box was mounted on an adjustable tripod so that the plane of the sensors of all three instruments could be positioned normal to the direct beam of the sun. The responses of all three instruments were recorded alternately with and without a 0.3 meter (12-inch) square test sample of cover material placed over the opening of the box. Three sets of measurements were taken at each of five angles between the normal to the sample surface and the direct beam of the sun. The sun incidence angles used were 0°, 14°, 30°, 60°,

and 67°. These angles represent differences of about 1 solar hour in sun movement, and 67° was the limit of angle adjustment.

## RESULTS

The data of Table 1 provide three of the most important and useful characteristics of nine single-layer samples and of 81 possible two-layer combinations of the single-layer samples. The long wavelength transmission rates in Table 1 are the measured values that are also shown in Tables 2-12. The average daily short wavelength transmission rates of Table 1, however, were calculated from the measured angular transmission rates for "total" solar radiation that are listed in Tables 2-12. The total solar radiation (direct-beam plus diffuse) at each hour of the day for January 15 at Clemson, South Carolina, was multiplied by the respective transmission rate at that hour of the day, corresponding to the appropriate sun incidence angles in Tables 2-12. The average daily short wavelength transmission was then calculated as the ratio of the total daily transmitted radiation to the total daily solar radiation received by the surface.

The third important characteristic of the materials listed in Table 1 is cost per unit area.

The effect, shown in Tables 2-12, of the angle of incidence between a normal to the transmitting surface and the sun on transmission of solar energy has been recognized and utilized before in considering optimal shapes for greenhouses by Aldrich and White (1) and Manbeck and Aldrich (7). The angle of incidence effect on transmission of diffuse solar energy and photosynthetically active radiation, to the best of our knowledge, has not been measured before. We included these measurements in our study primarily to provide data for later use in evaluating greenhouse shapes for optimal energy transmission.

## SELECTION OF COVER MATERIALS

There are several factors, in addition to those shown in Table 1, that deserve critical examination. These are:

a. Longevity of exposed materials
b. Ease of installation and labor costs
c. Ease of replacement if damaged
d. Fire resistance
e. Effect of extreme temperatures
f. Coefficient of heat transfer (U-valve)
g. Building code limitations

Our knowledge is limited on several of these factors so, assuming a user could investigate the properties of a particular material of interest, we have tried to develop an index, based only on transmission characteristics and costs, that would be useful in a selection process. This

index, and a selection chart for the tested materials, is shown in Table 13. By assigning certain values to long wavelength transmission, short wavelength transmission, and cost, as indicated in the legend of Table 13, a three-number index was developed for each cover material and combination. Presumably, the lower the index number, the better the material or combination of materials for greenhouse or solar collector use.

We realize that this index has many limitations, including the fact it does not account for the seven properties listed above. It does, however, offer a start in the selection process and we feel that a more comprehensive index could and should be developed. Usually, someone needing to make selections for greenhouse or solar collector has preconceived ideas about cover materials based on experience or information. This index can be used for quick comparison of the relative value of various cover materials. Final selection should be tempered with whatever additional material properties are known.

SUMMARY

Methods of measurement, and results, are presented for the most important radiant energy transmission characteristics of nine common materials that might be considered for covering greenhouses or solar collectors, and for 81 two-layer combinations of the materials. Long wavelength energy transmission rate is shown as well as the average daily short wavelength energy transmission. The change in solar energy transmission for these materials and combinations with angle of incidence between a normal to the material surface and the solar direct-beam, is also shown. A numerical index for each material and combination is presented as an aid in selecting the most useful types of covering materials for greenhouses or solar collectors.

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DISCLAIMER: Mention of a trademark or propriatory product does not constitute a guarantee or warranty of the product by the U. S. Department of Agriculture, and does not imply its approval to the exclusion of other products that may also be suitable.

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TABLE 1.--Energy transmission and costs of nine cover materials single glazing or two-layer combination glazing

| Reference Number | Material Identification[1] |
|---|---|
| 1 | Polyethylene, 4-mil |
| 2 | Flat Fiberglass, Regular, 25-mil |
| 3 | Flat Fiberglass, Premium, 40-mil |
| 4 | Polyester, Weatherable, 5-mil |
| 5 | Corrugated Fiberglass, 40-mil |
| 6 | Corrugated Fiberglass, 40-mil |
| 7 | Glass, Double Strength Window, 1/8-in |
| 8 | Polycarbonate, 1/16-in |
| 9 | Polyvinylflouride, 3-mil |

[1] NOTE: Sample No. 4, polyester, was Mylar (registered by E. I. DuPont de Nemours and Co.) with a weatherable surface treatment by Martin Processing Co., Martinsville, Virginia.

Samples No. 5 and 6, corrugated fiberglass, were both polyvinylflouride coated, but from different manufacturers.

Sample No. 8, polycarbonate, was Lexan (registered by General Electric Co.).

Sample No. 9, polyvinylflouride, was Tedlar (registered by E. I. DuPont de Nemours and Co.).

| Reference Number | Longwave Transmission, % | Daily Average Shortwave Transmission, % | Cost[2] ¢/ft$^2$ |
|---|---|---|---|
| | | Single Glazing | |
| 1 | 80 | 88.8 | 2 |
| 2 | 12 | 83.1 | 28 |
| 3 | 6 | 72.9 | 42 |
| 4 | 32 | 86.5 | 18 |
| 5 | 8 | 79.2 | 55 |
| 6 | 7 | 78.1 | 49 |
| 7 | 3 | 87.8 | 50 |
| 8 | 6 | 84.4 | 250 |
| 9 | 43 | 91.0 | 17 |

TABLE 1.--(continued)

| Reference Number | Longwave Transmission, % | Daily Average Shortwave Transmission, % | Cost, ¢/ft$^2$ |
|---|---|---|---|
| | | Double Glazing | |
| 1-1 | 63 | 79.3 | 4 |
| 2-2 | 1 | 69.7 | 56 |
| 3-3 | 1 | 50.5 | 84 |
| 4-4 | 13 | 78.2 | 36 |
| 5-5 | 1 | 62.3 | 110 |
| 6-6 | 1 | 60.3 | 98 |
| 7-7 | 1 | 78.0 | 100 |
| 8-8 | 1 | 73.2 | 500 |
| 9-9 | 26 | 84.2 | 34 |
| | | Combination Glazing - Polyethylene As Top Cover (No. 1) | |
| 1-1 | 63 | 79.3 | 4 |
| 1-2 | 5 | 74.9 | 30 |
| 1-3 | 3 | 62.1 | 44 |
| 1-4 | 21 | 78.9 | 20 |
| 1-5 | 4 | 68.6 | 57 |
| 1-6 | 4 | 66.9 | 51 |
| 1-7 | 1 | 78.6 | 52 |
| 1-8 | 2 | 73.3 | 252 |
| 1-9 | 31 | 82.1 | 19 |
| | | Combination Glazing - Flat Fiberglass As Top Cover (No. 2) | |
| 2-1 | 9 | 72.5 | 30 |
| 2-2 | 1 | 69.7 | 56 |
| 2-3 | 1 | 58.5 | 70 |
| 2-4 | 3 | 73.8 | 46 |
| 2-5 | 1 | 65.2 | 83 |
| 2-6 | 1 | 64.0 | 77 |
| 2-7 | 1 | 73.1 | 78 |
| 2-8 | 1 | 70.4 | 278 |
| 2-9 | 5 | 76.6 | 45 |
| | | Combination Glazing - Flat Fiberglass As Top Cover (No. 3) | |
| 3-1 | 5 | 62.1 | 44 |
| 3-2 | 1 | 58.9 | 70 |
| 3-3 | 1 | 50.5 | 84 |
| 3-4 | 2 | 62.1 | 60 |
| 3-5 | 1 | 56.0 | 83 |
| 3-6 | 1 | 51.8 | 77 |
| 3-7 | 1 | 62.4 | 92 |
| 3-8 | 1 | 60.2 | 292 |
| 3-9 | 2 | 64.9 | 59 |

TABLE 1.--(continued)

| Reference Number | Longwave Transmission, % | Daily Average Shortwave Transmission, % | Cost, ¢/ft$^2$ |
|---|---|---|---|
| | Combination Glazing - Polyester As Top Cover (No. 4) | | |
| 4-1 | 29 | 78.2 | 20 |
| 4-2 | 2 | 72.5 | 46 |
| 4-3 | 1 | 60.7 | 60 |
| 4-4 | 13 | 78.2 | 36 |
| 4-5 | 3 | 66.5 | 73 |
| 4-6 | 3 | 66.0 | 67 |
| 4-7 | 1 | 78.2 | 68 |
| 4-8 | 1 | 74.2 | 268 |
| 4-9 | 21 | 81.1 | 35 |
| | Combination Glazing - Corrugated Fiberglass As Top Cover (No. 5) | | |
| 5-1 | 6 | 71.1 | 57 |
| 5-2 | 1 | 68.2 | 83 |
| 5-3 | 1 | 57.7 | 97 |
| 5-4 | 2 | 71.4 | 73 |
| 5-5 | 1 | 62.3 | 110 |
| 5-6 | 1 | 66.5 | 104 |
| 5-7 | 1 | 70.6 | 105 |
| 5-8 | 1 | 68.0 | 305 |
| 5-9 | 3 | 74.0 | 72 |
| | Combination Glazing - Corrugated Fiberglass As Top Cover (No. 6) | | |
| 6-1 | 6 | 69.0 | 51 |
| 6-2 | 1 | 66.5 | 77 |
| 6-3 | 1 | 54.5 | 91 |
| 6-4 | 2 | 68.3 | 67 |
| 6-5 | 1 | 60.1 | 104 |
| 6-6 | 1 | 60.3 | 98 |
| 6-7 | 1 | 68.1 | 99 |
| 6-8 | 1 | 68.4 | 299 |
| 6-9 | 3 | 71.8 | 63 |
| | Combination Glazing - Glass As Top Cover (No. 7) | | |
| 7-1 | 2 | 77.5 | 52 |
| 7-2 | 1 | 72.8 | 78 |
| 7-3 | 1 | 62.6 | 92 |
| 7-4 | 1 | 76.7 | 68 |
| 7-5 | 1 | 67.8 | 105 |
| 7-6 | 1 | 68.2 | 99 |
| 7-7 | 1 | 78.0 | 100 |
| 7-8 | 1 | 74.2 | 300 |
| 7-9 | 2 | 80.9 | 67 |

TABLE 1.--(continued)

| Reference Number | Longwave Transmission, % | Daily Average Shortwave Transmission, % | Cost ¢/ft$^2$ |
|---|---|---|---|
| | Combination Glazing - Polycarbonate As Top Cover (No. 8) | | |
| 8-1 | 3 | 74.4 | 252 |
| 8-2 | 1 | 71.7 | 278 |
| 8-3 | 1 | 62.1 | 292 |
| 8-4 | 1 | 74.7 | 268 |
| 8-5 | 1 | 67.1 | 305 |
| 8-6 | 1 | 66.8 | 299 |
| 8-7 | 1 | 75.2 | 300 |
| 8-8 | 1 | 73.2 | 500 |
| 8-9 | 1 | 77.9 | 267 |
| | Combination Glazing - Polyvinylflouride As Top Cover (No. 9) | | |
| 9-1 | 36 | 80.0 | 19 |
| 9-2 | 4 | 76.4 | 45 |
| 9-3 | 2 | 64.3 | 59 |
| 9-4 | 14 | 80.2 | 35 |
| 9-5 | 3 | 70.2 | 72 |
| 9-6 | 3 | 69.3 | 66 |
| 9-7 | 1 | 80.9 | 67 |
| 9-8 | 1 | 76.7 | 267 |
| 9-9 | 26 | 84.2 | 34 |

TABLE 2. Single Glazing Materials

| Ref. No. | Cover Material | Longwave[1] Transmission % | Type[2] | Solar Energy Transmission[3], % Angle of Incidence, Degrees[4] 0 | 14 | 30 | 45 | 60 | 67 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Polyethylene | 80 | Tot. | 92 | 91 | 88 | 86 | 82 | 67 |
| | | | Dir. | 84 | 84 | 82 | 80 | 71 | 60 |
| | | | Dif. | 20 | 12 | 16 | 24 | 78 | 45 |
| | | | PAR | 83 | 82 | 82 | 83 | 74 | 58 |
| 2 | Flat Fiber Glass | 12 | Tot. | 87 | 84 | 82 | 80 | 73 | 57 |
| | | | Dir. | 65 | 66 | 62 | 60 | 51 | 34 |
| | | | Dif. | 82 | 59 | 78 | 99 | 176 | 262 |
| | | | PAR | 83 | 82 | 83 | 79 | 69 | 57 |
| 3 | Flat Fiber Glass | 6 | Tot. | 77 | 78 | 75 | 65 | 46 | 33 |
| | | | Dir. | 11 | 10 | 9 | 8 | 7 | 6 |
| | | | Dif. | 200 | 220 | 227 | 257 | 254 | 191 |
| | | | PAR | 75 | 74 | 76 | 65 | 44 | 30 |
| 4 | Polyester | 32 | Tot. | 88 | 88 | 88 | 86 | 81 | 72 |
| | | | Dir. | 87 | 87 | 86 | 84 | 79 | 72 |
| | | | Dif. | -7 | -8 | -5 | -5 | 3 | -23 |
| | | | PAR | 85 | 85 | 84 | 81 | 77 | 70 |
| 5 | Corrugated Fiber Glass | 8 | Tot. | 83 | 83 | 82 | 80 | 62 | 43 |
| | | | Dir. | 38 | 37 | 32 | 24 | 21 | 12 |
| | | | Dif. | 132 | 139 | 171 | 252 | 273 | 318 |
| | | | PAR | 79 | 84 | 82 | 71 | 62 | 51 |
| 6 | Corrugated Fiber Glass | 7 | Tot. | 81 | 80 | 78 | 75 | 64 | 43 |
| | | | Dir. | 52 | 55 | 51 | 45 | 33 | 21 |
| | | | Dif. | 66 | 64 | 76 | 118 | 182 | 174 |
| | | | PAR | 70 | 72 | 73 | 63 | 54 | 43 |
| 7 | Glass | 3 | Tot. | 89 | 89 | 88 | 85 | 82 | 74 |
| | | | Dir. | 88 | 88 | 87 | 85 | 81 | 70 |
| | | | Dif. | -10 | -9 | -11 | -9 | -14 | -6 |
| | | | PAR | 88 | 90 | 89 | 86 | 81 | 73 |
| 8 | Polycarbonate | 6 | Tot. | 86 | 85 | 84 | 83 | 80 | 72 |
| | | | Dir. | 84 | 84 | 83 | 82 | 76 | 68 |
| | | | Dif. | -6 | -7 | -10 | -10 | 17 | 28 |
| | | | PAR | 84 | 85 | 84 | 81 | 76 | 70 |
| 9 | Polyvinylflouride | 43 | Tot. | 93 | 92 | 91 | 90 | 83 | 65 |
| | | | Dir. | 85 | 85 | 85 | 78 | 66 | 48 |
| | | | Dif. | 22 | 17 | 16 | 52 | 122 | 136 |
| | | | PAR | 89 | 90 | 89 | 86 | 80 | 69 |

[1]Longwave > 2.8μm

[3]Shortwave < 2.8μm

[4]Angle of incidence between collector & sun, degrees

[2]Type of solar energy flux transmission measurement:

Tot. - Total solar energy - direct plus diffuse(0.28 to 2.8μm)

Dir. - Direct beam component of the total solar energy

Dif. - % of change in diffuse radiation due to cover materials.

PAR - Photosynthetic Active Radiation (0.4μm to 0.7μm)

TABLE 3. Double Glazing Materials

| Ref. No. | Cover Material | Longwave[1] Transmission % | Type[2] | Solar Energy Transmission[3],% Angle of Incidence, Degrees[4] 0 | 14 | 30 | 45 | 60 | 67 |
|---|---|---|---|---|---|---|---|---|---|
| 1-1 | Polyethylene | 63 | Tot. | 83 | 82 | 81 | 75 | 59 | 37 |
| | | | Dir. | 58 | 56 | 53 | 45 | 30 | 17 |
| | | | Dif. | 151 | 152 | 193 | 262 | 527 | 844 |
| | | | PAR | 76 | 78 | 76 | 70 | 57 | 40 |
| 2-2 | Flat Fiber Glass | 1 | Tot. | 73 | 72 | 70 | 66 | 53 | 33 |
| | | | Dir. | 46 | 46 | 41 | 38 | 26 | 13 |
| | | | Dif. | 120 | 136 | 176 | 219 | 321 | 267 |
| | | | PAR | 69 | 70 | 70 | 65 | 52 | 38 |
| 3-3 | Flat Fiber Glass | 1 | Tot. | 58 | 56 | 51 | 38 | 22 | 16 |
| | | | Dir. | 3 | 4 | 4 | 3 | 3 | 2 |
| | | | Dif. | 297 | 295 | 341 | 341 | 298 | 317 |
| | | | PAR | 47 | 49 | 47 | 39 | 21 | 13 |
| 4-4 | Polyester | 13 | Tot. | 81 | 79 | 77 | 76 | 69 | 59 |
| | | | Dir. | 76 | 75 | 74 | 72 | 63 | 57 |
| | | | Dif. | -1 | -7 | -13 | 3 | 19 | -8 |
| | | | PAR | 72 | 75 | 70 | 69 | 63 | 55 |
| 5-5 | Corrugated Fiber Glass | 1 | Tot. | 66 | 66 | 65 | 55 | 38 | 23 |
| | | | Dir. | 17 | 17 | 13 | 11 | 8 | 4 |
| | | | Dif. | 157 | 177 | 209 | 237 | 234 | 193 |
| | | | PAR | 62 | 62 | 63 | 57 | 44 | 29 |
| 6-6 | Corrugated Fiber Glass | 1 | Tot. | 66 | 65 | 61 | 52 | 32 | 17 |
| | | | Dir. | 24 | 22 | 22 | 16 | 9 | 4 |
| | | | Dif. | 269 | 291 | 304 | 401 | 454 | 511 |
| | | | PAR | 56 | 62 | 55 | 47 | 32 | 19 |
| 7-7 | Glass | 1 | Tot. | 80 | 79 | 78 | 75 | 70 | 59 |
| | | | Dir. | 78 | 77 | 75 | 73 | 67 | 54 |
| | | | Dif. | -9 | 5 | 13 | 9 | 62 | 180 |
| | | | PAR | 81 | 82 | 80 | 77 | 71 | 61 |
| 8-8 | Polycarbonate | 1 | Tot. | 75 | 74 | 73 | 71 | 66 | 53 |
| | | | Dir. | 69 | 71 | 70 | 68 | 61 | 53 |
| | | | Dif. | 3 | -9 | -2 | -1 | 3 | -72 |
| | | | PAR | 75 | 76 | 75 | 72 | 66 | 65 |
| 9-9 | Polyvinylflouride | 26 | Tot. | 88 | 87 | 83 | 82 | 65 | 43 |
| | | | Dir. | 73 | 71 | 68 | 61 | 43 | 26 |
| | | | Dif. | 60 | 94 | 113 | 195 | 236 | 370 |
| | | | PAR | 82 | 84 | 83 | 79 | 65 | 50 |

[1]Longwave > 2.8μm

[3]Shortwave < 2.8μm

[4]Angle of incidence between collector & sun, degrees

[2]Type of solar energy flux transmission measurement:

Tot. - Total solar energy - direct plus diffuse (0.28 to 2.8μm)

Dir. - Direct beam component of the total solar energy

Dif. - % of change in diffuse radiation due to cover materials

PAR - Photosynthetic Active Radiation (0.4μm to 0.7μm)

TABLE 4. Combination Glazing Materials (Polyethylene as Top Cover)

| Ref. No. | Bottom Cover Material | Longwave[1] Transmission % | Type[2] | Solar Energy Transmission[3],% Angle of Incidence, Degrees[4] 0 | 14 | 30 | 45 | 60 | 67 |
|---|---|---|---|---|---|---|---|---|---|
| 1-1 | Polyethylene | 63 | Tot. | 83 | 82 | 81 | 75 | 59 | 37 |
| | | | Dir. | 58 | 56 | 53 | 45 | 30 | 17 |
| | | | Dif. | 151 | 152 | 193 | 262 | 527 | 844 |
| | | | PAR | 76 | 78 | 76 | 70 | 57 | 40 |
| 1-2 | Flat Fiber Glass | 5 | Tot. | 77 | 78 | 75 | 72 | 59 | 35 |
| | | | Dir. | 55 | 58 | 54 | 45 | 34 | 16 |
| | | | Dif. | 82 | 94 | 119 | 212 | 315 | 272 |
| | | | PAR | 73 | 76 | 73 | 69 | 54 | 44 |
| 1-3 | Flat Fiber Glass | 3 | Tot. | 67 | 67 | 64 | 53 | 33 | 22 |
| | | | Dir. | 7 | 7 | 8 | 6 | 5 | 3 |
| | | | Dif. | 327 | 336 | 420 | 520 | 590 | 551 |
| | | | PAR | 63 | 63 | 61 | 55 | 35 | 21 |
| 1-4 | Polyester | 21 | Tot. | 81 | 81 | 78 | 77 | 67 | 52 |
| | | | Dir. | 70 | 71 | 67 | 63 | 59 | 41 |
| | | | Dif. | 132 | 98 | 195 | 506 | 360 | 1362 |
| | | | PAR | 73 | 75 | 73 | 68 | 58 | 49 |
| 1-5 | Corrugated Fiber Glass | 4 | Tot. | 72 | 72 | 71 | 61 | 49 | 23 |
| | | | Dir. | 26 | 27 | 24 | 20 | 18 | 6 |
| | | | Dif. | 146 | 150 | 185 | 192 | 378 | 166 |
| | | | PAR | 65 | 66 | 65 | 59 | 48 | 37 |
| 1-6 | Corrugated Fiber Glass | 4 | Tot. | 70 | 71 | 68 | 61 | 47 | 22 |
| | | | Dir. | 45 | 45 | 45 | 33 | 24 | 8 |
| | | | Dif. | 71 | 85 | 83 | 165 | 185 | 59 |
| | | | PAR | 65 | 65 | 63 | 60 | 42 | 31 |
| 1-7 | Glass | 1 | Tot. | 81 | 80 | 79 | 76 | 66 | 54 |
| | | | Dir. | 73 | 68 | 67 | 64 | 57 | 45 |
| | | | Dif. | 48 | 83 | 116 | 144 | 231 | 524 |
| | | | PAR | 78 | 79 | 78 | 74 | 65 | 47 |
| 1-8 | Polycarbonate | 2 | Tot. | 78 | 75 | 72 | 70 | 57 | 36 |
| | | | Dir. | 65 | 65 | 60 | 56 | 39 | 23 |
| | | | Dif. | 88 | 69 | 96 | 138 | 171 | 280 |
| | | | PAR | 76 | 75 | 74 | 72 | 62 | 48 |
| 1-9 | Polyvinylflouride | 31 | Tot. | 86 | 84 | 82 | 78 | 66 | 45 |
| | | | Dir. | 70 | 68 | 66 | 59 | 44 | 28 |
| | | | Dif. | 155 | 160 | 181 | 335 | 724 | 1677 |
| | | | PAR | 79 | 79 | 78 | 75 | 61 | 46 |

[1]Longwave > 2.8 m

[3]Shortwave < 2.8μm

[4]Angle of incidence between collector & sun, degrees

[2]Type of solar energy flux transmission measurement:

Tot. - Total solar energy - direct plus diffuse (0.28 to 2.8μm)

Dir. - Direct beam component of the total solar energy

Dif. - % of change in diffuse radiation due to cover materials

PAR - Photosynthetic Active Radiation (0.4μm to 0.7μm)

TABLE 5. Combination Glazing Materials (Flat Fiber Glass as Top Cover)

| Ref. No. | Bottom Cover Material | Longwave[1] Transmission % | Type[2] | Solar Energy Transmission[3],% Angle of Incidence, Degrees[4] 0 | 14 | 30 | 45 | 60 | 67 |
|---|---|---|---|---|---|---|---|---|---|
| 2-1 | Polyethylene | 9 | Tot. | 76 | 75 | 73 | 68 | 55 | 35 |
| | | | Dir. | 52 | 51 | 50 | 44 | 29 | 17 |
| | | | Dif. | 72 | 84 | 70 | 120 | 184 | 224 |
| | | | PAR | 72 | 73 | 73 | 67 | 53 | 38 |
| 2-2 | Flat Fiber Glass | 1 | Tot. | 73 | 72 | 70 | 66 | 53 | 33 |
| | | | Dir. | 46 | 46 | 41 | 38 | 26 | 13 |
| | | | Dif. | 120 | 136 | 176 | 219 | 321 | 267 |
| | | | PAR | 69 | 70 | 70 | 65 | 52 | 38 |
| 2-3 | Flat Fiber Glass | 1 | Tot. | 65 | 62 | 60 | 49 | 33 | 20 |
| | | | Dir. | 7 | 6 | 7 | 6 | 4 | 3 |
| | | | Dif. | 322 | 280 | 372 | 368 | 322 | 603 |
| | | | PAR | 58 | 56 | 58 | 50 | 33 | 20 |
| 2-4 | Polyester | 3 | Tot. | 76 | 76 | 73 | 72 | 63 | 45 |
| | | | Dir. | 56 | 55 | 51 | 48 | 41 | 24 |
| | | | Dif. | 58 | 59 | 71 | 106 | 152 | 230 |
| | | | PAR | 72 | 73 | 73 | 69 | 60 | 45 |
| 2-5 | Corrugated Fiber Glass | 1 | Tot. | 70 | 68 | 67 | 58 | 43 | 24 |
| | | | Dir. | 20 | 20 | 18 | 15 | 12 | 5 |
| | | | Dif. | 151 | 150 | 178 | 198 | 164 | 166 |
| | | | PAR | 61 | 63 | 63 | 58 | 47 | 32 |
| 2-6 | Corrugated Fiber Glass | 1 | Tot. | 68 | 68 | 64 | 59 | 42 | 22 |
| | | | Dir. | 34 | 36 | 36 | 26 | 18 | 7 |
| | | | Dif. | 108 | 108 | 112 | 187 | 214 | 152 |
| | | | PAR | 61 | 63 | 61 | 55 | 42 | 28 |
| 2-7 | Glass | 1 | Tot. | 75 | 76 | 73 | 69 | 62 | 44 |
| | | | Dir. | 56 | 55 | 49 | 47 | 39 | 24 |
| | | | Dif. | 122 | 148 | 238 | 242 | 768 | 3018 |
| | | | PAR | 78 | 75 | 78 | 73 | 59 | 46 |
| 2-8 | Polycarbonate | 1 | Tot. | 74 | 72 | 71 | 65 | 57 | 35 |
| | | | Dir. | 57 | 51 | 55 | 51 | 41 | 24 |
| | | | Dif. | 142 | 128 | 98 | 94 | 222 | 248 |
| | | | PAR | 72 | 73 | 69 | 67 | 56 | 46 |
| 2-9 | Polyvinylflouride | 5 | Tot. | 80 | 79 | 76 | 73 | 62 | 38 |
| | | | Dir. | 53 | 53 | 48 | 43 | 33 | 17 |
| | | | Dif. | 174 | 173 | 185 | 243 | 465 | 475 |
| | | | PAR | 76 | 75 | 77 | 74 | 56 | 41 |

[1]Longwave > 2.8μm
[3]Shortwave < 2.8μm
[4]Angle of incidence between collector & sun, degrees
[2]Type of solar energy flux transmission measurement:
Tot. - Total solar energy - direct plus diffuse (0.28 to 2.8μm)
Dir. - Direct beam component of the total solar energy
Dif. - % of change in diffuse radiation due to cover materials
PAR - Photosynthetic Active Radiation (0.4μm to 0.7μm)

TABLE 6. Combination Glazing Materials (Flat Fiber Glass as Top Cover)

| Ref. No. | Bottom Cover Material | Longwave[1] Transmission % | Type[2] | Solar Energy Transmission[3], % Angle of Incidence, Degrees[4] 0 | 14 | 30 | 45 | 60 | 67 |
|---|---|---|---|---|---|---|---|---|---|
| 3-1 | Polyethylene | 5 | Tot. | 68 | 67 | 62 | 53 | 36 | 24 |
| | | | Dir. | 8 | 8 | 7 | 6 | 5 | 4 |
| | | | Dif. | 253 | 249 | 266 | 261 | 276 | 283 |
| | | | PAR | 59 | 63 | 61 | 49 | 33 | 22 |
| 3-2 | Flat Fiber Glass | 1 | Tot. | 66 | 63 | 58 | 51 | 33 | 22 |
| | | | Dir. | 7 | 8 | 7 | 6 | 4 | 4 |
| | | | Dif. | 601 | 667 | 671 | 975 | 2667 | 7556 |
| | | | PAR | 61 | 63 | 60 | 51 | 32 | 20 |
| 3-3 | Flat Fiber Glass | 1 | Tot. | 58 | 56 | 51 | 38 | 22 | 16 |
| | | | Dir. | 3 | 4 | 4 | 3 | 3 | 2 |
| | | | Dif. | 297 | 295 | 341 | 341 | 298 | 317 |
| | | | PAR | 47 | 49 | 47 | 39 | 21 | 13 |
| 3-4 | Polyester | 2 | Tot. | 69 | 66 | 60 | 57 | 38 | 26 |
| | | | Dir. | 8 | 9 | 8 | 7 | 6 | 5 |
| | | | Dif. | 217 | 185 | 169 | 206 | 210 | 220 |
| | | | PAR | 58 | 66 | 62 | 53 | 35 | 24 |
| 3-5 | Corrugated Fiber Glass | 1 | Tot. | 61 | 60 | 58 | 48 | 30 | 20 |
| | | | Dir. | 6 | 6 | 5 | 5 | 3 | 3 |
| | | | Dif. | 166 | 179 | 195 | 201 | 182 | 134 |
| | | | PAR | 58 | 61 | 59 | 47 | 29 | 20 |
| 3-6 | Corrugated Fiber Glass | 1 | Tot. | 58 | 57 | 51 | 43 | 25 | 10 |
| | | | Dir. | 7 | 7 | 6 | 4 | 4 | 4 |
| | | | Dif. | 169 | 180 | 192 | 204 | 147 | 166 |
| | | | PAR | 56 | 57 | 52 | 42 | 24 | 15 |
| 3-7 | Glass | 1 | Tot. | 70 | 66 | 62 | 54 | 35 | 24 |
| | | | Dir. | 7 | 7 | 7 | 6 | 5 | 4 |
| | | | Dif. | 560 | 549 | 612 | 761 | 960 | 2152 |
| | | | PAR | 64 | 67 | 64 | 55 | 37 | 24 |
| 3-8 | Polycarbonate | 1 | Tot. | 64 | 66 | 62 | 52 | 33 | 22 |
| | | | Dir. | 8 | 9 | 8 | 6 | 5 | 3 |
| | | | Dif. | 263 | 330 | 337 | 461 | 370 | 393 |
| | | | PAR | 61 | 62 | 62 | 57 | 39 | 25 |
| 3-9 | Polyvinylflouride | 2 | Tot. | 72 | 69 | 66 | 55 | 35 | 24 |
| | | | Dir. | 8 | 8 | 7 | 6 | 4 | 3 |
| | | | Dif. | 420 | 406 | 418 | 401 | 417 | 924 |
| | | | PAR | 64 | 67 | 65 | 55 | 35 | 23 |

[1]Longwave > 2.8μm
[3]Shortwave < 2.8μm
[4]Angle of incidence between collector & sun, degrees
[2]Type of solar energy flux transmission measurement:
Tot. - Total solar energy - direct plus diffuse (0.28 to 2,8μm)
Dir. - Direct beam component of the total solar energy
Dif. - % of change in diffuse radiation due to cover materials
PAR - Photosynthetic Active Radiation (0.4μm to 0.7μm)

TABLE 7. Combination Glazing Materials (Polyester as Top Cover)

| Ref. No. | Bottom Cover Material | Longwave[1] Transmission % | Type[2] | Solar Energy Transmission[3],% Angle of Incidence, Degrees[4] 0 | 14 | 30 | 45 | 60 | 67 |
|---|---|---|---|---|---|---|---|---|---|
| 4-1 | Polyethylene | 29 | Tot. | 81 | 80 | 79 | 75 | 63 | 45 |
| | | | Dir. | 69 | 87 | 65 | 61 | 47 | 34 |
| | | | Dif. | 78 | 98 | 106 | 154 | 385 | 784 |
| | | | PAR | 74 | 76 | 75 | 71 | 62 | 48 |
| 4-2 | Flat Fiber Glass | 2 | Tot. | 77 | 75 | 70 | 68 | 60 | 39 |
| | | | Dir. | 54 | 57 | 55 | 57 | 42 | 24 |
| | | | Dif. | 227 | 172 | 174 | 239 | 1283 | 8707 |
| | | | PAR | 72 | 75 | 69 | 69 | 59 | 49 |
| 4-3 | Flat Fiber Glass | 1 | Tot. | 66 | 66 | 62 | 51 | 33 | 21 |
| | | | Dir. | 7 | 6 | 7 | 6 | 4 | 3 |
| | | | Dif. | 383 | 447 | 473 | 551 | 704 | 890 |
| | | | PAR | 56 | 59 | 58 | 53 | 37 | 22 |
| 4-4 | Polyester | 13 | Tot. | 81 | 79 | 77 | 76 | 69 | 59 |
| | | | Dir. | 76 | 75 | 74 | 72 | 63 | 57 |
| | | | Dif. | -1 | -7 | -13 | 3 | 19 | -8 |
| | | | PAR | 72 | 75 | 70 | 69 | 63 | 55 |
| 4-5 | Corrugated Fiber Glass | 3 | Tot. | 70 | 68 | 69 | 61 | 50 | 25 |
| | | | Dir. | 25 | 25 | 23 | 19 | 18 | 6 |
| | | | Dif. | 146 | 137 | 177 | 179 | 225 | 172 |
| | | | PAR | 65 | 64 | 64 | 60 | 53 | 40 |
| 4-6 | Corrugated Fiber Glass | 3 | Tot. | 69 | 69 | 67 | 62 | 47 | 21 |
| | | | Dir. | 45 | 45 | 43 | 34 | 25 | 8 |
| | | | Dif. | 74 | 72 | 88 | 152 | 185 | 123 |
| | | | PAR | 66 | 65 | 61 | 60 | 48 | 37 |
| 4-7 | Glass | 1 | Tot. | 81 | 79 | 78 | 75 | 68 | 58 |
| | | | Dir. | 76 | 75 | 74 | 71 | 63 | 55 |
| | | | Dif. | 22 | 22 | 27 | 43 | 157 | 731 |
| | | | PAR | 78 | 78 | 77 | 73 | 67 | 62 |
| 4-8 | Polycarbonate | 1 | Tot. | 75 | 76 | 74 | 73 | 66 | 55 |
| | | | Dir. | 72 | 71 | 71 | 68 | 60 | 52 |
| | | | Dif. | -13 | 0 | -6 | 20 | 42 | 21 |
| | | | PAR | 74 | 75 | 74 | 72 | 65 | 57 |
| 4-9 | Polyvinylflouride | 21 | Tot. | 84 | 83 | 81 | 77 | 67 | 51 |
| | | | Dir. | 73 | 71 | 69 | 65 | 51 | 38 |
| | | | Dif. | 57 | 56 | 108 | 111 | 274 | 292 |
| | | | PAR | 77 | 79 | 78 | 74 | 64 | 52 |

[1]Longwave > 2.8μm

[3]Shortwave < 2.8μm

[4]Angle of incidence between collector & sun, degrees

[2]Type of solar energy flux transmission measurement:

Tot. - Total solar energy - direct plus diffuse (0.28 to 2.8μm)

Dir. - Direct beam component of the total solar energy

Dif. - % of change in diffuse radiation due to cover materials

PAR - Photosynthetic Active Radiation (0.4μm to 0.7μm)

TABLE 8. Combination Glazing Materials(Corrugated Fiber Glass as Top Cover)

| Ref. No. | Bottom Cover Material | Longwave[1] Transmission % | Type[2] | Solar Energy Transmission[3],% Angle of Incidence, Degrees[4] 0 | 14 | 30 | 45 | 60 | 67 |
|---|---|---|---|---|---|---|---|---|---|
| 5-1 | Polyethylene | 6 | Tot. | 75 | 75 | 72 | 65 | 47 | 28 |
| | | | Dir. | 31 | 30 | 26 | 19 | 14 | 7 |
| | | | Dif. | 181 | 196 | 239 | 298 | 325 | 217 |
| | | | PAR | 66 | 67 | 66 | 59 | 46 | 32 |
| 5-2 | Flat Fiber Glass | 1 | Tot. | 72 | 72 | 70 | 61 | 45 | 27 |
| | | | Dir. | 28 | 26 | 20 | 15 | 12 | 6 |
| | | | Dif. | 444 | 528 | 685 | 1174 | 3252 | 3136 |
| | | | PAR | 67 | 68 | 67 | 60 | 46 | 31 |
| 5-3 | Flat Fiber Glass | 1 | Tot. | 65 | 64 | 57 | 46 | 29 | 18 |
| | | | Dir. | 5 | 5 | 4 | 3 | 3 | 3 |
| | | | Dif. | 428 | 445 | 494 | 558 | 1276 | 897 |
| | | | PAR | 50 | 55 | 54 | 45 | 27 | 16 |
| 5-4 | Polyester | 2 | Tot. | 75 | 74 | 72 | 67 | 52 | 33 |
| | | | Dir. | 35 | 32 | 30 | 22 | 18 | 9 |
| | | | Dif. | 121 | 129 | 152 | 217 | 274 | 328 |
| | | | PAR | 69 | 70 | 66 | 62 | 50 | 39 |
| 5-5 | Corrugated Fiber Glass | 1 | Tot. | 66 | 66 | 65 | 55 | 38 | 23 |
| | | | Dir. | 17 | 17 | 13 | 11 | 8 | 4 |
| | | | Dif. | 157 | 177 | 209 | 237 | 234 | 193 |
| | | | PAR | 62 | 62 | 63 | 57 | 44 | 29 |
| 5-6 | Corrugated Fiber Glass | 1 | Tot. | 68 | 67 | 64 | 53 | 35 | 20 |
| | | | Dir. | 17 | 17 | 15 | 11 | 7 | 4 |
| | | | Dif. | 185 | 188 | 228 | 232 | 256 | 128 |
| | | | PAR | 61 | 65 | 59 | 51 | 36 | 25 |
| 5-7 | Glass | 1 | Tot. | 74 | 73 | 73 | 65 | 51 | 32 |
| | | | Dir. | 33 | 31 | 27 | 19 | 16 | 9 |
| | | | Dif. | 372 | 406 | 531 | 747 | 1019 | 1514 |
| | | | PAR | 71 | 73 | 73 | 66 | 51 | 38 |
| 5-8 | Polycarbonate | 1 | Tot. | 71 | 72 | 69 | 63 | 48 | 27 |
| | | | Dir. | 26 | 28 | 26 | 21 | 16 | 8 |
| | | | Dif. | 208 | 222 | 244 | 338 | 416 | 247 |
| | | | PAR | 69 | 66 | 64 | 62 | 53 | 39 |
| 5-9 | Polyvinylflouride | 3 | Tot. | 78 | 77 | 76 | 69 | 50 | 33 |
| | | | Dir. | 31 | 29 | 26 | 21 | 13 | 8 |
| | | | Dif. | 261 | 270 | 343 | 408 | 527 | 675 |
| | | | PAR | 73 | 74 | 73 | 69 | 50 | 35 |

[1]Longwave > 2.8μm
[3]Shortwave < 2.8μm
[4]Angle of incidence between collector & sun, degrees
[2]Type of solar energy flux transmission measurements:
Tot. - Total solar energy - direct plus diffuse (0.28 to 2.8μm)
Dir. - Direct beam component of the total solar energy
Dif. - % of change in diffuse radiation due to cover materials
PAR - Photosynthetic Active Radiation (0.4μm to 0.7μm)

TABLE 9. Combination Glazing Materials (Corrugated Fiber Glass as Top Cover)

| Ref. No. | Bottom Cover Material | Longwave[1] Transmission % | Type[2] | Solar Energy Transmission[3],% Angle of Incidence, Degrees[4] 0 | 14 | 30 | 45 | 60 | 67 |
|---|---|---|---|---|---|---|---|---|---|
| 6-1 | Polyethylene | 6 | Tot. | 73 | 72 | 70 | 64 | 47 | 31 |
| | | | Dir. | 39 | 42 | 40 | 34 | 21 | 11 |
| | | | Dif. | 133 | 114 | 136 | 177 | 222 | 246 |
| | | | PAR | 63 | 65 | 63 | 55 | 42 | 30 |
| 6-2 | Flat Fiber Glass | 1 | Tot. | 72 | 69 | 66 | 62 | 45 | 24 |
| | | | Dir. | 37 | 37 | 35 | 28 | 16 | 10 |
| | | | Dif. | 80 | 355 | 410 | 731 | 3303 | 6513 |
| | | | PAR | 65 | 67 | 62 | 61 | 45 | 29 |
| 6-3 | Flat Fiber Glass | 1 | Tot. | 62 | 59 | 54 | 44 | 27 | 16 |
| | | | Dir. | 4 | 5 | 4 | 3 | 3 | 3 |
| | | | Dif. | 428 | 439 | 513 | 629 | 880 | 732 |
| | | | PAR | 46 | 50 | 49 | 40 | 24 | 15 |
| 6-4 | Polyester | 2 | Tot. | 72 | 70 | 68 | 65 | 53 | 31 |
| | | | Dir. | 50 | 50 | 46 | 40 | 27 | 13 |
| | | | Dif. | -59 | -49 | -45 | -56 | -62 | -84 |
| | | | PAR | 63 | 64 | 61 | 55 | 45 | 35 |
| 6-5 | Corrugated Fiber Glass | 1 | Tot. | 64 | 64 | 62 | 55 | 34 | 20 |
| | | | Dir. | 17 | 17 | 15 | 12 | 8 | 3 |
| | | | Dif. | 155 | 170 | 209 | 251 | 150 | 143 |
| | | | PAR | 61 | 60 | 58 | 52 | 38 | 25 |
| 6-6 | Corrugated Fiber Glass | 1 | Tot. | 66 | 65 | 61 | 52 | 32 | 17 |
| | | | Dir. | 24 | 22 | 22 | 16 | 9 | 4 |
| | | | Dif. | 269 | 291 | 304 | 401 | 454 | 511 |
| | | | PAR | 56 | 62 | 55 | 47 | 32 | 19 |
| 6-7 | Glass | 1 | Tot. | 73 | 70 | 68 | 64 | 49 | 31 |
| | | | Dir. | 45 | 46 | 41 | 36 | 24 | 13 |
| | | | Dif. | 223 | 205 | 272 | 412 | 592 | 911 |
| | | | PAR | 67 | 68 | 65 | 60 | 47 | 35 |
| 6-8 | Polycarbonate | 1 | Tot. | 73 | 72 | 68 | 62 | 48 | 25 |
| | | | Dir. | 40 | 39 | 34 | 33 | 23 | 9 |
| | | | Dif. | 161 | 172 | 207 | 193 | 324 | 300 |
| | | | PAR | 65 | 66 | 59 | 50 | 41 | 32 |
| 6-9 | Polyvinylflouride | 3 | Tot. | 77 | 75 | 71 | 67 | 49 | 32 |
| | | | Dir. | 37 | 41 | 37 | 33 | 19 | 10 |
| | | | Dif. | 206 | 168 | 210 | 256 | 453 | 510 |
| | | | PAR | 64 | 65 | 64 | 55 | 43 | 31 |

[1]Longwave > 2.8μm

[2]Type of solar energy flux transmission measurement:
Tot. - Total solar energy - direct plus diffuse (0.28 to 2.8μm)
Dir. - Direct beam component of the total solar energy
Dif. - % of change in diffuse radiation due to cover materials
PAR - Photosynthetic Active Radiation (0.4μm to 0.7μm)

[3]Shortwave < 2.8μm

[4]Angle of Incidence between collector & sun, degrees

TABLE 10. Combination Glazing Materials (Glass as Top Cover)

| Ref. No. | Bottom Cover Material | Longwave[1] Transmission % | Type[2] | Solar Energy Transmission[3],% Angle of Incidence, Degrees[4] 0 | 14 | 30 | 45 | 60 | 67 |
|---|---|---|---|---|---|---|---|---|---|
| 7-1 | Polyethylene | 2 | Tot. | 80 | 79 | 77 | 77 | 62 | 46 |
| | | | Dir. | 69 | 70 | 67 | 63 | 52 | 38 |
| | | | Dif. | 30 | 25 | 47 | 79 | 73 | 75 |
| | | | PAR | 78 | 80 | 79 | 74 | 64 | 51 |
| 7-2 | Flat Fiber Glass | 1 | Tot. | 76 | 74 | 72 | 71 | 60 | 39 |
| | | | Dir. | 56 | 58 | 49 | 49 | 37 | 24 |
| | | | Dif. | 167 | 151 | 282 | 384 | 997 | 1831 |
| | | | PAR | 78 | 75 | 76 | 72 | 63 | 52 |
| 7-3 | Flat Fiber Glass | 1 | Tot. | 69 | 67 | 63 | 53 | 35 | 21 |
| | | | Dir. | 7 | 6 | 5 | 5 | 4 | 3 |
| | | | Dif. | 530 | 550 | 651 | 804 | 971 | 1659 |
| | | | PAR | 57 | 62 | 62 | 54 | 35 | 23 |
| 7-4 | Polyester | 1 | Tot. | 78 | 78 | 76 | 76 | 70 | 61 |
| | | | Dir. | 76 | 74 | 73 | 71 | 65 | 53 |
| | | | Dif. | -11 | -6 | -15 | 5 | 6 | 59 |
| | | | PAR | 78 | 77 | 75 | 72 | 67 | 62 |
| 7-5 | Corrugated Fiber Glass | 1 | Tot. | 71 | 71 | 69 | 61 | 51 | 30 |
| | | | Dir. | 25 | 26 | 23 | 19 | 18 | 6 |
| | | | Dif. | 156 | 156 | 181 | 171 | 353 | 282 |
| | | | PAR | 72 | 68 | 66 | 63 | 58 | 45 |
| 7-6 | Corrugated Fiber Glass | 1 | Tot. | 71 | 72 | 68 | 64 | 50 | 28 |
| | | | Dir. | 45 | 45 | 47 | 34 | 25 | 12 |
| | | | Dif. | 157 | 169 | 155 | 337 | 516 | 604 |
| | | | PAR | 70 | 72 | 67 | 63 | 53 | 40 |
| 7-7 | Glass | 1 | Tot. | 80 | 79 | 78 | 75 | 70 | 59 |
| | | | Dir. | 78 | 77 | 75 | 73 | 67 | 54 |
| | | | Dif. | -9 | 5 | 13 | 9 | 62 | 180 |
| | | | PAR | 81 | 82 | 80 | 77 | 71 | 61 |
| 7-8 | Polycarbonate | 1 | Tot. | 76 | 75 | 74 | 72 | 67 | 55 |
| | | | Dir. | 73 | 70 | 72 | 68 | 61 | 51 |
| | | | Dif. | -8 | 5 | -17 | 7 | 57 | 87 |
| | | | PAR | 78 | 78 | 77 | 74 | 69 | 58 |
| 7-9 | Polyvinylflouride | 2 | Tot. | 83 | 83 | 81 | 79 | 68 | 48 |
| | | | Dir. | 75 | 72 | 71 | 65 | 50 | 34 |
| | | | Dif. | 35 | 49 | 58 | 108 | 227 | 254 |
| | | | PAR | 81 | 83 | 80 | 79 | 67 | 56 |

[1]Longwave > 2.8μm

[3]Shortwave < 2.8μm

[4]Angle of incidence between collector & sun, degrees

[2]Type of solar energy flux transmission measurement:

Tot. - Total solar energy - direct plus diffuse (0.28 to 2.8μm)

Dir. - Direct beam component of the total solar energy

Dif. - % of change in diffuse radiation due to cover materials

PAR - Photosynthetic Active Radiation (0.4μm to 0.7μm)

TABLE 11. Combination Glazing Materials (Polycarbonate as Top Cover)

| Ref. No. | Bottom Cover Material | Longwave[1] Transmission % | Type[2] | Solar Energy Transmission[3],% Angle of Incidence, Degrees[4] 0 | 14 | 30 | 45 | 60 | 67 |
|---|---|---|---|---|---|---|---|---|---|
| 8-1 | Polyethylene | 36 | Tot. | 77 | 76 | 74 | 72 | 60 | 44 |
| | | | Dir. | 61 | 59 | 57 | 58 | 48 | 35 |
| | | | Dif. | 75 | 92 | 121 | 135 | 226 | 277 |
| | | | PAR | 75 | 76 | 73 | 71 | 63 | 50 |
| 8-2 | Flat Fiber Glass | 4 | Tot. | 74 | 72 | 72 | 70 | 62 | 39 |
| | | | Dir. | 53 | 45 | 47 | 46 | 39 | 21 |
| | | | Dif. | 228 | 236 | 373 | 505 | 1546 | 3438 |
| | | | PAR | 74 | 73 | 73 | 66 | 60 | 45 |
| 8-3 | Flat Fiber Glass | 2 | Tot. | 66 | 65 | 64 | 57 | 37 | 23 |
| | | | Dir. | 7 | 5 | 7 | 4 | 3 | 2 |
| | | | Dif. | 627 | 604 | 628 | 936 | 1108 | 2441 |
| | | | PAR | 58 | 61 | 59 | 51 | 36 | 25 |
| 8-4 | Polyester | 14 | Tot. | 77 | 76 | 75 | 71 | 66 | 58 |
| | | | Dir. | 74 | 73 | 72 | 70 | 64 | 54 |
| | | | Dif. | 9 | 13 | 14 | 34 | 129 | 125 |
| | | | PAR | 74 | 75 | 74 | 70 | 64 | 54 |
| 8-5 | Corrugated Fiber Glass | 3 | Tot. | 70 | 70 | 69 | 62 | 50 | 26 |
| | | | Dir. | 36 | 36 | 35 | 27 | 20 | 8 |
| | | | Dif. | 167 | 183 | 222 | 262 | 275 | 187 |
| | | | PAR | 65 | 64 | 63 | 60 | 54 | 41 |
| 8-6 | Corrugated Fiber Glass | 3 | Tot. | 70 | 70 | 67 | 63 | 47 | 22 |
| | | | Dir. | 45 | 44 | 44 | 32 | 24 | 9 |
| | | | Dif. | 194 | 212 | 152 | 447 | 552 | 1165 |
| | | | PAR | 67 | 70 | 63 | 60 | 49 | 39 |
| 8-7 | Glass | 1 | Tot. | 77 | 76 | 75 | 75 | 67 | 56 |
| | | | Dir. | 74 | 71 | 71 | 71 | 62 | 53 |
| | | | Dif. | 51 | 52 | 66 | 117 | 491 | 636 |
| | | | PAR | 78 | 78 | 77 | 75 | 68 | 61 |
| 8-8 | Polycarbonate | 1 | Tot. | 75 | 74 | 73 | 71 | 66 | 53 |
| | | | Dir. | 69 | 71 | 70 | 68 | 61 | 53 |
| | | | Dif. | 33 | 38 | 46 | 106 | 243 | 340 |
| | | | PAR | 75 | 76 | 75 | 72 | 66 | 55 |
| 8-9 | Polyvinylflouride | 1 | Tot. | 80 | 79 | 78 | 76 | 65 | 47 |
| | | | Dir. | 70 | 70 | 68 | 64 | 50 | 36 |
| | | | Dif. | 60 | 94 | 113 | 195 | 236 | 370 |
| | | | PAR | 78 | 79 | 78 | 76 | 67 | 56 |

[1]Longwave > 2.8μm

[3]Shortwave < 2.8μm

[4]Angle of incidence between collector & sun, degrees

[2]Type of solar energy flux transmission measurement:

Tot. - Total solar energy - direct plus diffuse (0.28 to 2.8μm)

Dir. - Direct beam component of the total solar energy

Dif. - % of change in diffuse radiation due to cover materials

PAR - Photosynthetic Active Radiation (0.4μm to 0.7μm)

TABLE 12. Combination Glazing Materials (Polyvinylflouride as Top Cover)

| Ref. No. | Bottom Cover Material | Longwave[1] Transmission % | Type[2] | Solar Energy Transmission[3],% Angle of Incidence, Degrees[4] 0 | 14 | 30 | 45 | 60 | 67 |
|---|---|---|---|---|---|---|---|---|---|
| 9-1 | Polyethylene | 3 | Tot. | 82 | 83 | 81 | 77 | 64 | 45 |
| | | | Dir. | 62 | 60 | 58 | 54 | 41 | 26 |
| | | | Dif. | 52 | 73 | 76 | 75 | 84 | 90 |
| | | | PAR | 79 | 78 | 76 | 73 | 58 | 46 |
| 9-2 | Flat Fiber Glass | 1 | Tot. | 79 | 79 | 78 | 73 | 58 | 35 |
| | | | Dir. | 57 | 58 | 52 | 48 | 35 | 16 |
| | | | Dif. | 197 | 294 | 375 | 624 | 1716 | 2030 |
| | | | PAR | 76 | 78 | 74 | 74 | 58 | 43 |
| 9-3 | Flat Fiber Glass | 1 | Tot. | 72 | 69 | 64 | 55 | 33 | 21 |
| | | | Dir. | 6 | 6 | 5 | 5 | 3 | 3 |
| | | | Dif. | 575 | 584 | 692 | 910 | 1389 | 1233 |
| | | | PAR | 58 | 63 | 63 | 55 | 35 | 21 |
| 9-4 | Polyester | 1 | Tot. | 83 | 82 | 80 | 77 | 69 | 47 |
| | | | Dir. | 75 | 74 | 73 | 67 | 54 | 35 |
| | | | Dif. | -14 | -8 | -15 | -33 | -13 | 19 |
| | | | PAR | 77 | 78 | 75 | 74 | 63 | 47 |
| 9-5 | Corrugated Fiber Glass | 1 | Tot. | 73 | 74 | 73 | 64 | 48 | 25 |
| | | | Dir. | 25 | 26 | 22 | 18 | 14 | 6 |
| | | | Dif. | 156 | 164 | 199 | 243 | 319 | 237 |
| | | | PAR | 69 | 67 | 66 | 63 | 53 | 36 |
| 9-6 | Corrugated Fiber Glass | 1 | Tot. | 74 | 73 | 69 | 65 | 45 | 22 |
| | | | Dir. | 45 | 43 | 44 | 31 | 20 | 8 |
| | | | Dif. | 175 | 187 | 194 | 427 | 631 | 433 |
| | | | PAR | 69 | 72 | 68 | 63 | 33 | 32 |
| 9-7 | Glass | 1 | Tot. | 84 | 82 | 81 | 78 | 68 | 47 |
| | | | Dir. | 76 | 74 | 73 | 67 | 51 | 33 |
| | | | Dif. | 2 | 25 | 50 | 62 | 136 | 361 |
| | | | PAR | 81 | 82 | 81 | 78 | 65 | 48 |
| 9-8 | Polycarbonate | 1 | Tot. | 79 | 78 | 77 | 75 | 65 | 47 |
| | | | Dir. | 69 | 68 | 66 | 62 | 49 | 35 |
| | | | Dif. | 3 | -9 | -2 | -1 | 3 | -72 |
| | | | PAR | 77 | 78 | 77 | 77 | 65 | 53 |
| 9-9 | Polyvinylflouride | 26 | Tot. | 88 | 87 | 83 | 82 | 65 | 43 |
| | | | Dir. | 73 | 71 | 68 | 61 | 43 | 26 |
| | | | Dif. | 34 | 39 | 58 | 96 | 206 | 226 |
| | | | PAR | 82 | 84 | 83 | 79 | 65 | 50 |

[1]Longwave > 2.8μm

[3]Shortwave < 2.8μm

[4]Angle of incidence between collector & sun, degrees

[2]Type of solar energy flux transmission measurement:

Tot. - Total solar energy - direct plus diffuse (0.28 to 2.8μm)

Dir. - Direct beam component of the total solar energy

Dif. - % of change in diffuse radiation due to cover materials

PAR - Photosynthetic Active Radiation (0.4μm to 0.7μm)

TABLE 13.--Value indices of single and two-layer combinations of greenhouse and solar collector glazing materials based on percent longwave energy transmission, percent shortwave energy transmission, and material cost.

| TOP COVER | BOTTOM COVER | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Single Cover | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 1 | 311 | 331 | 142 | 162 | 331 | 153 | 153 | 133 | 147 | 321 |
| 2 | 222 | 242 | 153 | 173 | 142 | 154 | 164 | 144 | 147 | 132 |
| 3 | 142 | 162 | 173 | 174 | 163 | 174 | 174 | 164 | 167 | 163 |
| 4 | 311 | 331 | 142 | 163 | 232 | 153 | 153 | 133 | 147 | 322 |
| 5 | 233 | 143 | 154 | 174 | 143 | 165 | 165 | 145 | 157 | 144 |
| 6 | 232 | 153 | 154 | 174 | 153 | 165 | 164 | 154 | 157 | 143 |
| 7 | 112 | 133 | 144 | 164 | 133 | 155 | 154 | 134 | 147 | 123 |
| 8 | 127 | 147 | 147 | 167 | 147 | 157 | 157 | 137 | 147 | 137 |
| 9 | 311 | 321 | 132 | 163 | 222 | 143 | 153 | 123 | 137 | 322 |

LEGEND FOR NUMBERS IN TABLE 2

| 1st Number of Index | Longwave Trans., % | 2nd Number of Index | Shortwave Trans., % | 3rd Number of Index | Cost ¢/ft$^2$ |
|---|---|---|---|---|---|
| 1 | 6 or Less | 1 | >85 | 1 | 25 or Less |
| 2 | 7-20 | 2 | 80-85 | 2 | 26-50 |
| 3 | >20 | 3 | 75-80 | 3 | 51-75 |
| | | 4 | 70-75 | 4 | 76-100 |
| | | 5 | 65-70 | 5 | 101-150 |
| | | 6 | 60-65 | 6 | 151-200 |
| | | 7 | <60 | 7 | >200 |

# EXPERIMENTAL RESULTS OF A GREENHOUSE SOLAR COLLECTION AND MODULAR GRAVEL STORAGE SYSTEM

G. E. Wilson[1], D. R. Price[1], L. D. Albright[1]
N. R. Scott[1], R. W. Langhans[2], Pitam Chandra[1]

The Cornell University Department of Agricultural Engineering project on solar heating of greenhouses has, from nearly the beginning, adopted the stance that a greenhouse is a solar heat collector and that this naturally collected energy should be stored for later use rather than vented as is common practice. This heat is in the true sense free to any greenhouse owner. Taking this stance does not preclude the use of external solar collectors but merely postpones the decision to add them until adequate knowledge is gained of the potential for a greenhouse to supply its own heat. Then the difficult problems of placement, sizing, and typing can be confronted realistically.

This approach has led us along 3 distinct lines of research which are:

1. Devising a method of storing excess greenhouse heat
2. Improving the collection efficiency of the greenhouse
3. Mathematical modelling of the greenhouse thermal behavior -- this to be used to further the aims of numbers 1 and 2.

These efforts will be described in detail below. However it is probably useful to outline the essential results at the outset. They are:

1. A practical and inexpensive system has been devised to store excess greenhouse heat.
2. A result of the above has been the ability to measure the solar collection efficiency of the greenhouse.
3. A method has been explored by which both day and night greenhouse heating loads may be reduced. This is noted as an increase in solar collection efficiency.

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4. The mathematical model is being refined and used as an effective research tool.

SOLAR HEAT STORAGE SYSTEM

A 6.71m x 14.63m (22' x 48') barrel vault double polyethylene covered greenhouse (fiberglass ends) has been equipped with 4 rows of combination greenhouse bench rock storage units (Fig. 1). These units have been described elsewhere[1], but in brief, they are 12.19m (40') long, .767m (2 1/2' high), and .767m (2 1/2') wide. They are simply fabricated from 1.22m (4') long modules of plywood and steel construction (Fig. 2). The benches are filled to within .127m (5") of the upper cover with #1 crushed limestone which ranges in size from .00847m (5/16") to .0159m (5/8"). The .127 (5") space at the top is all important as it allows a free air passage from the inlet at one end of the bench to the far end. Laboratory tests have shown that air introduced this way will distribute itself uniformly within 10% for downward travel through the rocks at the maximum flow rate. The air exits through steel mesh slots located along the bottom edge of the benches.

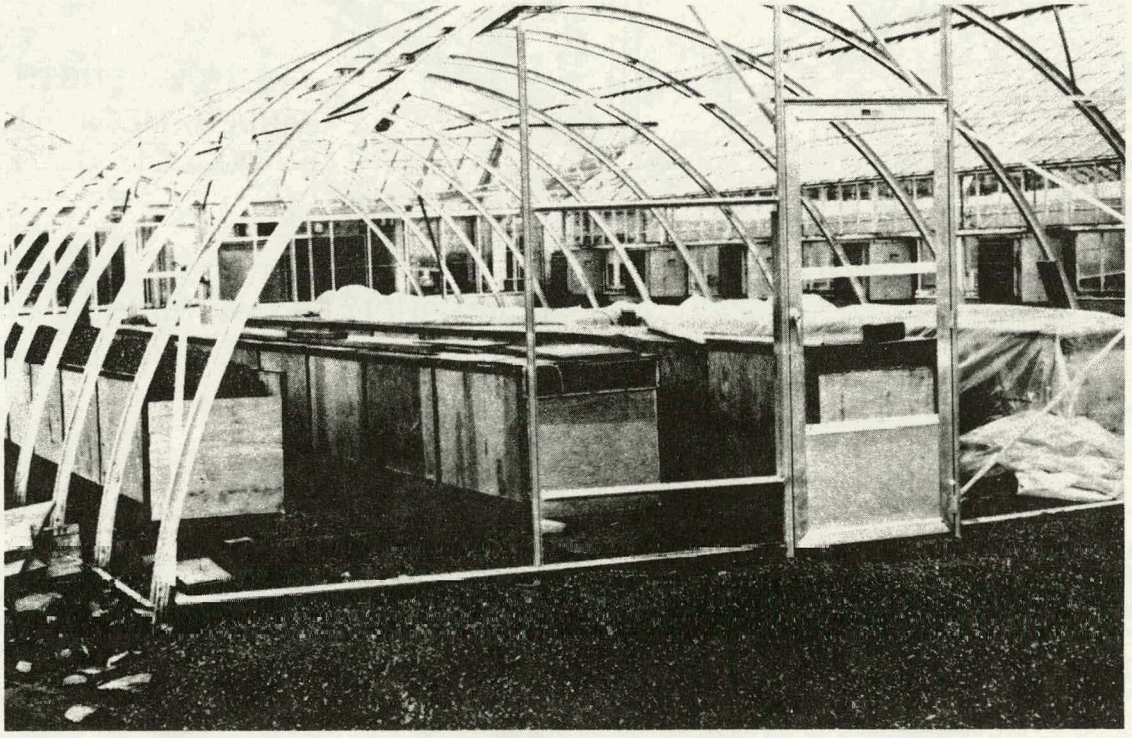


Figure 1.

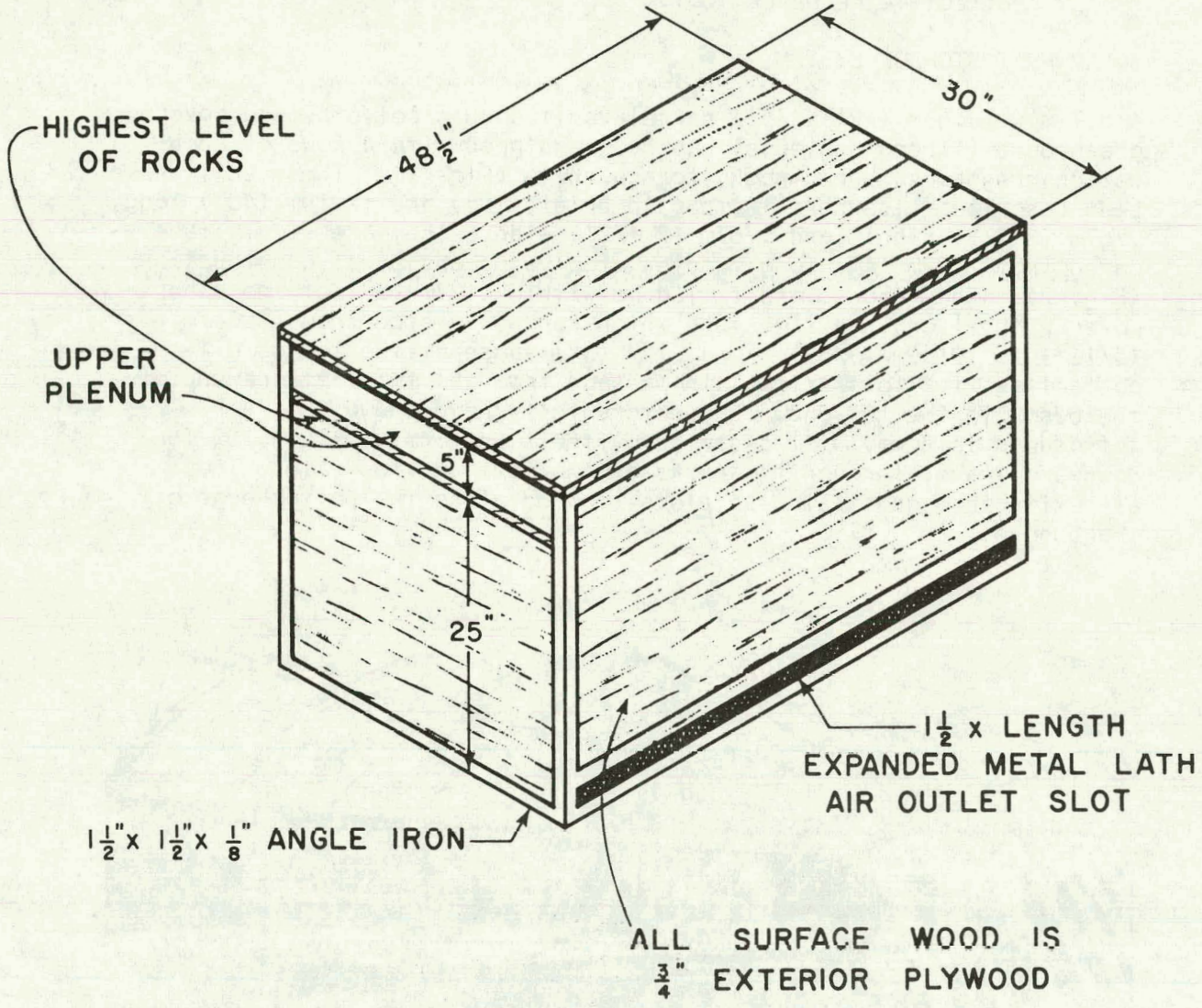



Figure 2. Schematic of design selected for rock storage bed modules.

Air handling apparatus and all controls are located at one end of the greenhouse. A tapered duct with a uniform width .0159m (5/8") slot at the top is mounted at the uppermost point in the greenhouse, running its entire length. This duct is used to collect solar heated air from the upper portion of the greenhouse by use of a centrifugal fan located atop the air handling tower. The fan forces warm air collected in the duct down to a manifold duct which delivers air to each bench-rock storage unit. To recover the heat, a separate fan reverses the flow of air in the storage benches, drawing cool air in through the bottom slots, and directing warmed air out into the greenhouse (Fig. 4). The collection duct and fan are closed off automatically during heat recovery by a motorized damper.

The total amount of rock in the storage benches is forty tons. The total heat capacity of sensible heat storage depends on the difference in temperature between the maximum temperature attainable and the minimum temperature obtained from storage that is considered useful. The minimum temperature of our rocks is approximately the normal minimum greenhouse temperature of 12.78°C (55°F). A 9602 joules/sec (9.6 KW) electric duct heater located in the vertical duct can be used to boost the temperature of the solar heated air about 11°C (20°F) so that air at a temperature above 12.78°C (55°F) may be considered as useful for heating the greenhouse. We envision the maximum collection temperature to be about 40.55°C (105°F) as higher internal temperature may have a serious effect on the plants in the greenhouse. Using the temperature range of 12.78°C (55°F) to 40.55°C (105°F), we have a total storage capacity of 843.8 megajoules (800,000 BTU), or the equivalent of about 8 gallons of fuel oil burned at 70% efficiency. Before installation in the greenhouse, the storage units were laboratory tested for heat loss during storage. A typical graph showing temperatures within the rocks at various times after heating is shown in Fig. 3.

The control system is relatively simple. The heat return fan and the duct booster heater are activated by simple household thermostats. The return fan is activated on a temperature drop below a specified level in the greenhouse. If there is sufficient heat in the rocks to stem this drop, only solar heat will be delivered to the greenhouse. If the internal temperature continues to fall, the duct heater will be activated to boost the temperature of the air extracted from the stone. If the combination of solar heat and duct heater boost is insufficient to maintain the greenhouse temperature, a 6001 Joules/sec (6 KW) auxiliary heater is activated to add more heat.

The collection mode is activated by a series arrangment of common thermostat and differential thermostat. The differential thermostat will start the collection fan when the ridge temperature is higher than the minimum rock bed temperature. However, this situation could occur during the heating mode, if, say, the greenhouse were being maintained at a temperature of 15.56°C (60°F) by heat extracted from the rocks at perhaps 12.78°C (55°F) and boosted by the duct heater. Therefore,

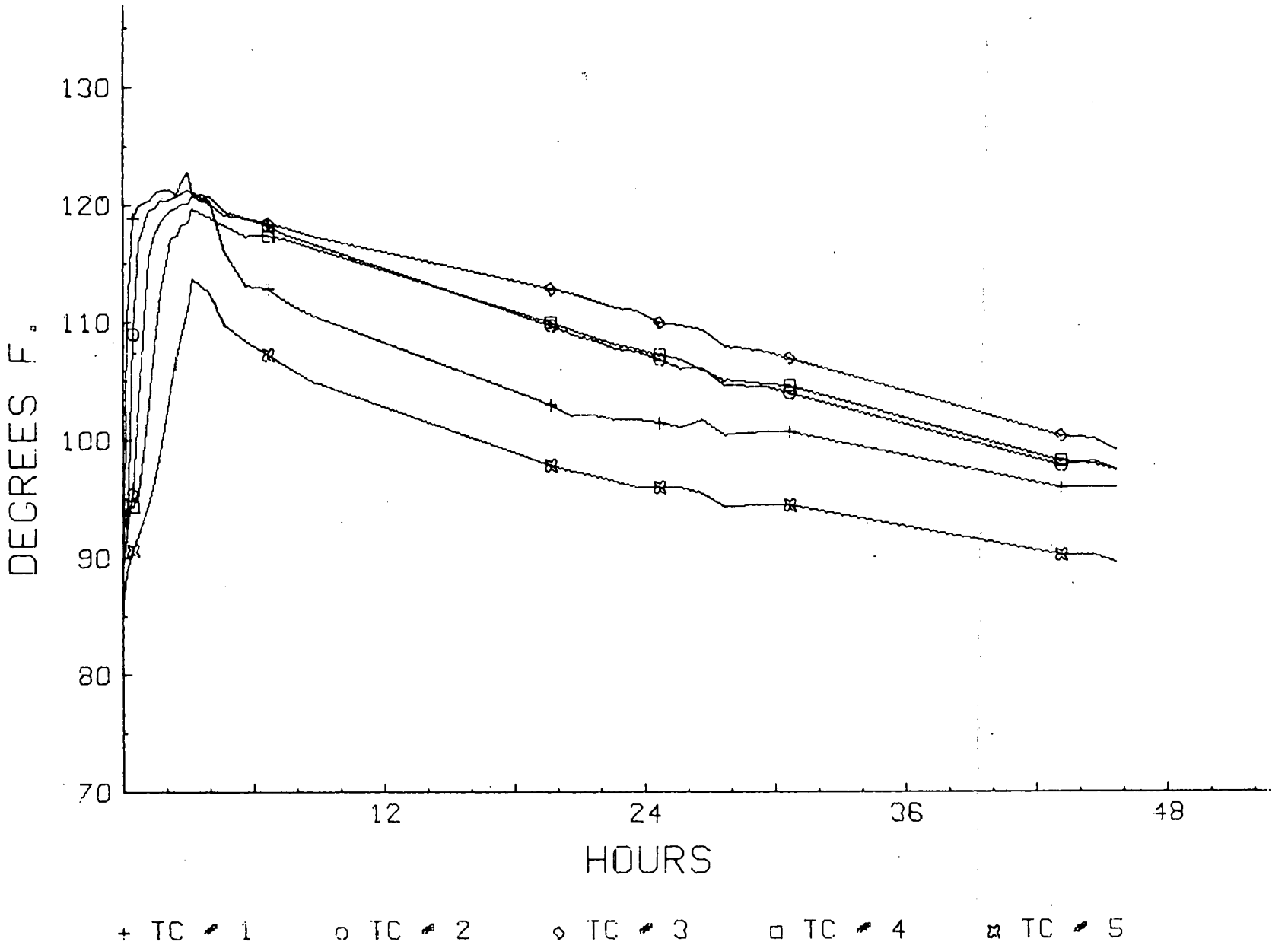



Figure 3. Time-temperature history at the locations indicated by the thermocouples 1-5 in the rock bed thermal storage system with the heating duct blocked during cooling.

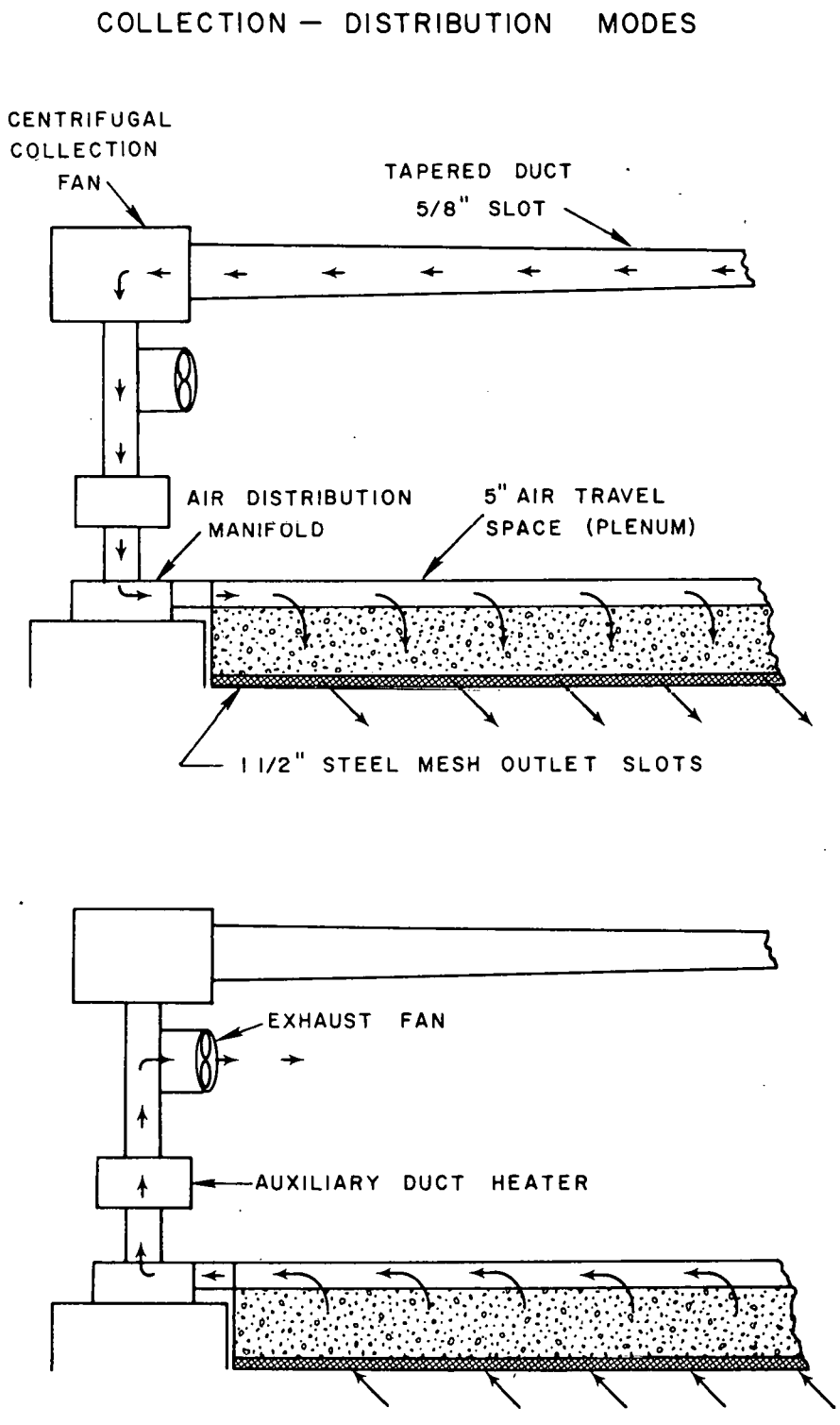



Figure 4. Solar Collection and Air Handling Systems

a common household thermostat is mounted in the greenhouse ridge to allow collection only if the temperature at that location is above 21.11°C (70°F). Thus, collection takes place only if the ridge temperature is above 21.11°C (70°F) and the ridge temperature is higher than the minimum rock temperature.

To this date, the control system works reasonably well, except that on occasion, especially early on a sunny day, the distribution fan may come on during collection. This is of no real consequence as the motorized damper plate covers the opening to the distribution fan during collection. It merely wastes a small amount of energy. The reason for this occurrence is that the exhaust fan thermostat is mounted on the side of one of the greenhouse benches rather near the ground. During collection, cold air is returned through the bottom slot in the benches, and slowly fills the greenhouse from the bottom up. Thus the thermostats are eventually submerged in air cooler than the average temperature within the greenhouse. This problem could easily be solved by relocating the thermostats or asperating them at present location.

Of special concern to us has been a precise estimate of the effective collection efficiency of the greenhouse. To our knowledge, only T.A. Lawand has made a study of the solar contribution to greenhouse heating loads[2] and one interpretation of his results is that the greenhouse has a collector efficiency of about 30%. This estimate is made assuming the greenhouse to be a horizontal flat plate collector of area equal to its floor area. Intuitively most greenhouse operators will testify that a greenhouse collects a great deal of excess heat. Nevertheless, at the beginning of our project we were lacking a firm estimate of just how effective a greenhouse is at collecting heat.

Our experimental solar heated greenhouse, set up as it is for careful monitoring of all energy inputs and instrumented to measure temperatures in numerous locations in the greenhouse, has allowed us to make a reliable estimate of the greenhouse collection efficiency. Our electric meters are read daily at 8:00 a.m. and 5:00 p.m. and inside and outside temperatures are recorded continuously on potentiometer thermocouple reading chart recorders. During the period of the study, there was no appreciable insolation outside the 8:00 a.m. to 5:00 p.m. day period. The electric meters give an accurate measure of night heating loads but the day heating loads are partially offset by solar pickup. Nevertheless, the day and night heat losses to the exterior must be the same.

The heating load clearly depends on the difference in temperature inside and outside the greenhouse. This difference is continually changing, but a reasonably accurate accounting is obtained by noting the hourly difference and then taking the cumulative sum of these differences for the hours between meter readings. The cumulative sum between 5:00 p.m. and 8:00 a.m. is called the night time DH (degree hours) and the sum between 8:00 a.m. and 5:00 p.m. is called the day

time DH. Considering the night DH alone we divide the total electric heat delivered in that period by the corresponding DH to obtain a heat load factor. This factor is relatively constant from night to night, the variations being both statistical and dependent upon wind or other conditions.

The heat load factor obtained from measuring night heating loads must be the same during the day. However, the heat added to the greenhouse is comprised of electric and solar. Using the value of HEAT LOAD FACTOR obtained from night measurements we have the equation

$$\text{HEAT LOAD FACTOR} = \frac{\text{ELECTRIC + SOLAR}}{\text{DH}}$$

This equation can be solved for the solar heat acquired by the greenhouse by using the daytime DH value and the electric heat consumed during the day. By dividing the solar heat obtained by the total solar input on the floor of the greenhouse for that day, we obtain a daily efficiency of conversion of solar energy into greenhouse heat. To date, our average efficiency has been 25.25% (Tables I and 2).

More operating time will give us a better figure for greenhouse collection efficiency. However, we are confident that the efficiency lies between 20% and 30%. This is a very encouraging result as even flat plate collector efficiencies fall to about 40% during winter collection. One must realize that in talking about a collector area equal to the floor area of the greenhouse we are talking about a very large collector. At present, however, much of this heat is quickly lost from the greenhouse, leaving little excess to hold for night heating. It is this problem that must be solved if greenhouses are to function effectively as self heat producers and an approach to this solution is the subject of the next section.

It is too early to estimate the total percentage of heating load provided by solar. Less than a month's operating time has passed. Our design target was to devise a heating system that would offset total winter heating loads by 25%. This would mean night time heating loads primarily as all greenhouses are heated by the sun during the day. A rough preliminary estimate of performance to date can be obtained by multiplying the total number of night time degree hours by the average of the BTU/DH factor for nights during which no heat recovery took place. This yields the theoretical total night time heating load which is 13,227,796 BTU. The actual heating loads were 11,810,687 or 10.7% lower. Note that this is based on data collected in a part of the year when we concede that little excess heat will be available. Our design goals are primarily for spring-fall heating. Note also that some of the solar heat collected during the day was used to heat the greenhouse near the end of the day and would not be recorded as offsetting night time heating loads.

Table 1.

Night Heating Loads

| Date | KWH | BTU | Degree Hours | BTU/DH |
|---|---|---|---|---|
| Feb. 9-10 | 174.5 | 596,251 | 393 | 1517 |
| 10-11 | 183.2 | 625,262 | 351 | 1781 |
| 11-12 | 122.4 | 417,751 | 354 | 1180* |
| 12-13 | 142.4 | 486,011 | 328 | 1482* |
| 13-14 | 146.0 | 498,298 | 423 | 1178* |
| 14-15 | 154.7 | 527,991 | 413 | 1278 |
| 15-16 | 187.9 | 641,303 | 576 | 1113 |
| 16-17 | 188.3 | 642,668 | 557 | 1154 |
| 17-18 | 196.1 | 669,289 | 611 | 1095* |
| 18-19 | 169.8 | 579,527 | 452 | 1282* |
| 19-20 | 167.7 | 572,360 | 488 | 1173 |
| 20-21 | 179.8 | 613,657 | 570 | 1076 |
| 21-22 | 184.9 | 631,064 | 626 | 1008 |
| 22-23 | 97.8 | 333,791 | 391 | 854* |
| 23-24 | 93.6 | 319,457 | 304 | 1050* |
| 24-25 | --- | --- | --- | --- |
| 25-26 | 141.5 | 482,940 | 353 | 1368 |
| 26-27 | 61.1 | 208,534 | 341 | 612* |
| 27-28 | 116.9 | 398,980 | 365 | 1093* |
| Feb. 28 - March 1 | 163.0 | 556,319 | 461 | 1207 |
| Mar. 1-2 | 171.1 | 583,964 | 546 | 1069* |
| 2-3 | 106.0 | 361,778 | 438 | 826* |
| 3-4 | 68.2 | 232,767 | 282 | 825* |
| 4-5 | 118.6 | 404,782 | 276 | 1467 |
| 5-6 | 125.0 | 425,625 | 387 | 1102* |

Starred (*): heat recovery during the night

Unstarred: no heat recovery at night

Avg. starred: 1050 BTU/DH

Avg. unstarred: 1286 BTU/DH

Table II.

Day Heating Loads

| | KWH | BTU | Solar | DH | Efficiency (%) |
|---|---|---|---|---|---|
| Feb. 9 | 95.8 | 326,965 | 327,318 | 301 | 18.4 |
| 10 | 62.1 | 211,947 | 518,253 | 250 | 21 |
| 11 | 2.4 | 8,191 | 849,468 | 141 | 20.4+ |
| 12 | 35.1 | 119,796 | 483,183 | 187 | 25 + |
| 13 | 22.4 | 76,451 | 674,119 | 211 | 28.9+ |
| 14 | 15.9 | 54,267 | 752,052 | 246 | 34.9 |
| 15 | 46.4 | 158,363 | 845,571 | 311 | 28.6 |
| 16 | 43.2 | 147,442 | 966,367 | 388 | 36.4 |
| 17 | 46.9 | 160,070 | 853,364 | 370 | 37 |
| 18 | 7.7 | 26,280 | 553,323 | 302 | 65.4+ |
| 19 | 26.4 | 90,102 | 420,837 | 188 | 36 |
| 20 | 67.9 | 231,743 | 1,352,134 | 256 | 7 |
| 21 | 17.5 | 59,728 | 1,044,300 | 296 | 31.4 |
| 22 | 35.9 | 122,527 | 1,020,920 | 238 | 18 + |
| 23 | 11.5 | 39,250 | 1,032,610 | 246 | 26.8+ |
| 24 | -- | -- | 366,284 | -- | -- |
| 25 | 55.8 | 190,445 | 218,212 | 177 | 17 |
| 26 | 10.6 | 36,178 | 1,239,132 | 227 | 20.6+ |
| 27 | 5.4 | 18,430 | 631,256 | 138 | 25.2+ |
| 28 | 22.1 | 75,427 | 732,568 | 205 | 25.7 |
| Mar. 1 | 5.5 | 18,772 | 1,071,576 | 243 | 27.4+ |
| 2 | 13.0 | 44,369 | 1,554,759 | 237 | 16.7+ |
| 3 | 2.3 | 7,850 | 1,359,927 | 212 | 19.5+ |
| 4 | 35.2 | 120,138 | 296,145 | 136 | 18.5 |
| 5 | 39.0 | 13,312 | 674,119 | 137 | 24.2+ |
| 6 | 44.5 | 151,879 | 385,767 | 167 | 16.3 |

Avg. 25.25%
(only values without +'s considered)

Two questions with regard to using the greenhouse as a solar collector need to be answered. They are - will the greenhouse collect enough heat? and will allowing the temperature of the greenhouse to rise above normal interfere with plant development? The first of these is quite easy to answer based on our experience. The collector efficiency of the greenhouse is about 25% even assuming the most conservative way of estimating collector area, i.e., that the greenhouse is a horizontal flat plate collector with area equal to its floor area. Our design criterion of attempting to reduce greenhouse heating loads by 1/2 and to supply 1/2 the remaining heat load (1/4 the orginial heat load) by solar appears to be within reach. It is too early to flatly state that 1/4 the annual heating load of an uninsulated greenhouse can be provided by our solar storage technique, but the best guess is that this figure is not too far off.

There are some who discount the potential of the greenhouse as a collector. An article by Hanan[3] stated that a greenhouse could not be used as a solar collector. Hanan contends that plant transpiration will consume 80% of incoming solar energy, leaving little excess for storage. This analysis is in error. The figure quoted for energy dissipated in transpiration may be true for open field conditions where continual replenishment of low relative humidity air is available, but not under tight greenhouse conditions where the relative humidity is usually high. Under these conditions, plants cannot transpire at the high open field rate and consume far less energy than that estimated by Hanan[4].

The dilemma of conflicting needs between plant growth conditions and the desire to allow the greenhouse temperature to rise above normal for good solar collection temperatures is more difficult to deal with. There are indications that some crops will do as well or better under increased temperature conditions[5,6]. Undoubtedly any grower could state examples of crops that would suffer from increased temperatures. Nonetheless, higher than average temperatures sometimes occur both in open field conditions and in greenhouses and are unavoidable. Experience has shown us that our storage system usually serves to lower return air temperatures <u>below</u> outside ambient temperatures so that if ventilation were to occur at the same rate as collection, higher internal greenhouse temperatures would result from ventilation than from collection. There may be some crops that will be adversely affected by temperatures of up to 40.56°C (105°F) although none immediately come to mind. We accept this problem within our philosophy of using the greenhouse as a collector. Future work should serve to identify the severity of any problems that exist and guide us in its solution.

## INCREASING GREENHOUSE COLLECTION EFFICIENCY

The collection efficiency of a greenhouse is sufficiently high that using the greenhouse as a solar collector would appear to be an acceptable approach. At present, however, much of the heat collected

by a greenhouse is used to maintain daytime temperature differential over outside ambient air. This is because greenhouse heating loads are excessively high and much of the collected heat is immediately lost to the outside. A plot of flat plate collector efficiency versus the difference between plate temperature and outside temperature always yields a straight line with a negative slope. This is not because less energy is collected when the plate temperature is higher; it is because all heat loss mechanisms are (approximately) linearly proportional to the inside-outside temperature difference and more heat is lost during collection when the plate is at a higher temperature. Solar collectors are made more efficient by insulating to decrease the heat loss so that more total heat is retained.

Looking at the greenhouse as a solar collector, we can see that to improve its efficiency daytime heating loads must be reduced. This is an important point because while many researchers have noted that greenhouse heating loads are high, most have devoted their efforts to reducing night time heating loads only. This is done by covering the greenhouse at night with moveable insulation or by other methods but removing this insulation during the day to allow sufficient light to pass into the greenhouse. This approach ignores the natural capability of the greenhouse to collect heat during the day and concentrates on the natural tendency of a greenhouse to lose heat at a rapid rate at night.

An improvement in collection efficiency can only be obtained by reducing daytime heating loads thus making more excess heat available for storage. One approach to this problem is to add additional transparent covers to the greenhouse as has been done at the Ohio Research Station[7]. A great reduction in both day and night heating loads is possible while 20% of the incoming light is lost. This appears to be a promising method of increasing existing greenhouse collection efficiency.

T. A. Lawand[8] has suggested another method of reducing day and night heat losses for new greenhouse construction. This is to use a non-transparent, sloping north roof-wall that is reflectorized on the inside surface. This is presuming an east-west oriented greenhouse. The north roof-wall screens out diffuse light from the northern sky but the reflective materials enhance the light emanating from the south. In northern parts of the country, the sun is always low in the southern sky in winter. Lawand has reported greatly enhanced light levels in his greenhouses on sunny days but reduced light levels on cloudy days. Heating loads are always reduced by about 1/3 and tomatoes grown in reflective greenhouses yielded better and earlier than those grown in totally transparent greenhouses.

There are other methods that have been tried such as installing a layer of polyethylene film at ceiling level. All these methods are effective at increasing greenhouse collector efficiency and all have their short-

comings. Polyethylene has a lifetime of two years at best and thus it is a recurring maintenance problem. Light reduction is also a problem and ceiling level films are height limiting for certain crops. The reflective coating on Lawand's interior wall may also deteriorate in time and under certain conditions of exceptionally cloudy weather more light is lost that is gained by the technique. In addition, Lawand's greenhouse has a large low angle (35°) south facing glazed roof which has been said to cause a high heat buildup in summer.

In order to determine if some of Lawand's techniques could be used to retrofit existing greenhouses, greenhouse 2A, a standard 10.97m x 10.97m (36' x 36') glass greenhouse oriented east-west with a double pitch roof slope of 26° facing north and south was fitted out with varying amounts of reflective insulation to north roof and wall areas. An identical greenhouse (3A) is located just to the south of greenhouse 2A and was used as a control. The period between October 12 and November 18, 1976 was used to compare the heating loads between the two house with no alterations. During this period, greenhouse 2A used about 12% more heat than 3A, measured as water condensed from the low pressure steam system. In the period, November 19 to December 21, 1976, the north glass wall of greenhouse 2A was covered with sheets of .0254m (1") urethane foam insulation foil backed on both sides (R=9). The test greenhouse 2A condensed 88% as much steam as greenhouse 3A during this period. From December 22, 1976 to January 18, 1977 the lower 1/2 roof above the north wall was covered with insulation in addition to the north wall covering. In this period greenhouse 2A used only 57% of the heat used in greenhouse 3A. From January 19 to February 4, 1977, another 1/4 roof was insulated and greenhouse 2A consumed 46% the heat of 3A. Finally, from February 7 to 22, 1977, the entire north roof and wall was insulated. During this time greenhouse 2A consumed but 29% the heat of greenhouse 3A.

The reason that greenhouse 2A consumed a greater amount of heat than 3A during the control period is not known for certain. It is believed that temperature control in the two greenhouses was slightly inaccurate and this may be the explanation. Because of this uncertainty, we plan to redo the control period and the north wall insulation experiment this year to attempt to get a more reliable number for the percentage heat reduction. Temperatures were very carefully controlled during the latter experiments.

Another question that may occur to the observer is: how is it possible to obtain a greater than 50% reduction in heating load while insulating less than half the greenhouse? The answer to this must certainly be that some major source of heat loss is very much reduced by the technique. A prime candidate would seem to be the infiltration rate. Covering the north roof and wall of a leaky glass greenhouse is probably the functional equivalent of closing the north window of a room which previously had both a north and south window open. Closing one window also reduces the amount that travels through the other so that more than 50% reduction in infiltration is realized.

Clearly the results are a dramatic demonstration of how greenhouse heating loads can be slashed by permanent insulation of selected glazed portions. To investigate the effect of this technique on light levels an Epply black and white pyranometer was read at each of six stations (figure 5) in identical locations in each greenhouse. Only one pyranometer was used in early experiments so that the readings were not taken simultaneously. The results for the period December 22, 1976 to January 6, 1977 are shown in Tables III and IV. The cumulative sums show (Table V) no evidence of reduced light levels in greenhouse 2A. From January 6, 1977 to the end of the experiment, two black and white pyranometers were used in station 2 of greenhouses 2A and 3A respectively. A continuous trace of the output of each of the pyranometers was made by two potentiometric millivolt chart recorders. Representative traces for cloudy and sunny days during each of the remaining experiments is shown in figures 6-13.

It must be pointed out that the experiments took place at different times of the year and therefore the angle of the sun was different during the various experiments. Generally it may be stated that the reflective insulation reflects enough light from the south during mid-winter to at least partially make up for the losses from the north. This general tendency diminishes as the sun reaches higher and higher angles in the sky, and by March there appears to be light losses even on sunny days. Thus, for retrofitting existing conventionally shaped greenhouses, the greenhouse operator must consider the tradeoff between reduced heating loads and light losses.

In new construction, the Lawand wall could be used to advantage. It seems possible that even more glazed areas could be covered with reflective insulation to reduce day and night heating loads. Perhaps a greenhouse could be constructed with a single glazed face at an appropriate angle for solar collection (45° to 60° in northern states). This single glazed face would then involve less cost to double glaze and would lend itself to mechanized night time insulation better than a totally glazed greenhouse structure. Also, taller greenhouses will enhance temperature stratification within the greenhouse to allow higher collection temperatures without endangering plants at the bench level. Several possibilities are illustrated in figure 14.

## MATHEMATICAL MODELLING

Further effort has been committed to refine the mathematical model (previously developed by Froehlich, et. al., 1976) into a user oriented design tool. First, the model and its attendant computer simulation program have been "inverted" so a greenhouse's inside air temperature can be specified, and the required heating/cooling loads predicted. Froehlich's initial model predicted air temperatures when heat inputs were known or computable. The model can now be used in either mode - specify the heat inputs and predict temperatures, or specify the temperatures and predict needed heating or cooling. The latter is likely the more useful for design.

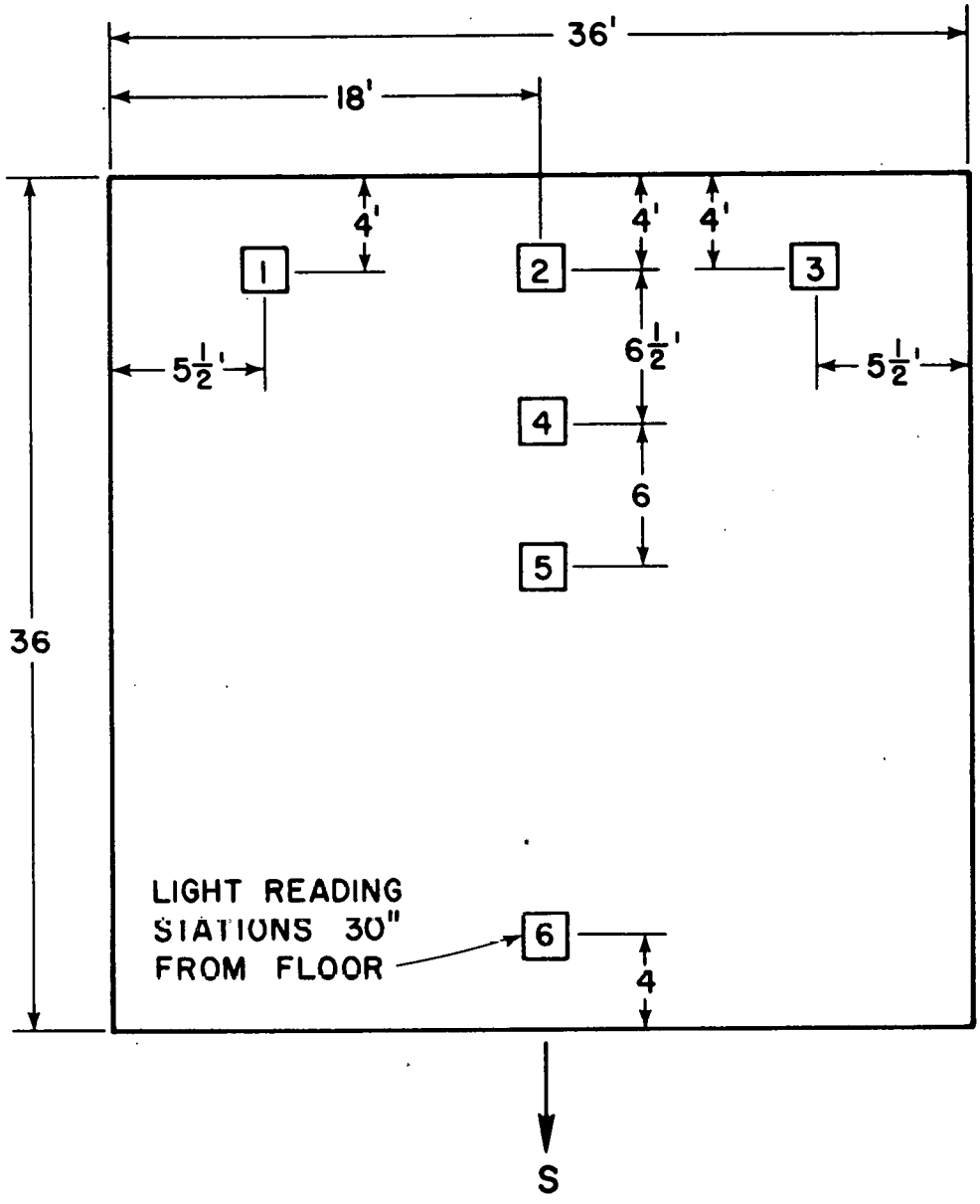



Figure 5. Diagram of Six Light Reading Stations Used in Greenhouses 2A and 3A, Dec. 22, 1976 to Jan. 6, 1977

Table III (continued)

Units Millivolts (for comparison only)

| Date | Time | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| 12-30-76 | 9:00 AM | 1.36 | .50 | .39 | .42 | .48 | .50 |
| | 11:30 AM | 3.28 | 3.30 | 1.72 | 1.42 | 2.21 | 2.97 |
| | 2:30 PM | .18 | .22 | .22 | .36 | .42 | .54 |
| 12-31-76 | 9:00 AM | 1.19 | .68 | .35 | .45 | .45 | .52 |
| | 11:30 AM | 5.00 | 6.06 | 1.58 | 1.88 | 3.38 | 1.48 |
| | 2:30 PM | .54 | 1.28 | 2.38 | 1.40 | 1.61 | 1.18 |
| 1-1-77 | 9:00 AM | .12 | .10 | .09 | .22 | .29 | .33 |
| | 11:30 AM | .21 | .13 | .12 | .33 | .48 | .66 |
| | 2:30 PM | .19 | .18 | .18 | .36 | .52 | .64 |
| 1-2-77 | 9:00 AM | .07 | .07 | .06 | .14 | .16 | .24 |
| | 11:30 AM | .45 | .36 | .35 | .81 | 1.07 | 1.40 |
| | 2:30 PM | .30 | .32 | .30 | .62 | .74 | .89 |
| 1-3-77 | 9:00 AM | .24 | .26 | .20 | .44 | .47 | .66 |
| | 11:30 AM | | | | | | |
| | 2:30 PM | .12 | .12 | .08 | .19 | .29 | .35 |
| 1-4-77 | 9:00 AM | .09 | .11 | .10 | .23 | .28 | .32 |
| | 11:30 AM | 4.00 | 4.55 | 1.23 | 2.33 | 3.28 | 2.54 |
| | 2:30 PM | .42 | 1.15 | 2.77 | .82 | 1.36 | .87 |
| 1-5-77 | 9:00 AM | .12 | .09 | .09 | .24 | .32 | .37 |
| | 11:30 AM | .35 | .37 | .33 | .79 | .33 | .52 |
| | 2:30 AM | .24 | .36 | .38 | .55 | .66 | .77 |
| 1-6-77 | 9:00 AM | .24 | .20 | .20 | .41 | .51 | .64 |
| | 11:30 AM | 3.56 | 3.93 | 1.06 | 1.81 | 2.31 | 3.05 |
| | 2:30 PM | .44 | 1.28 | 1.73 | 1.41 | 1.62 | 1.93 |
| SUM | | 22.71 | 25.62 | 15.91 | 17.63 | 23.24 | 23.37 |

Table III.

GREENHOUSE #2A: LIGHT READINGS

Units Millivolts (for comparison only)

| Date | Time | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| 12-22-76 | 9:00 AM | .13 | .12 | .13 | .30 | .32 | .39 |
| | 11:30 AM | .70 | .54 | .50 | .87 | 1.10 | 1.32 |
| | 2:30 PM | .36 | .76 | .46 | .88 | 1.08 | 1.05 |
| 12-23-76 | 9:00 AM | .16 | .16 | .15 | .36 | .44 | .53 |
| | 11:30 AM | .78 | .64 | .58 | 1.24 | 1.54 | 1.78 |
| | 2:00 PM | .24 | .26 | .27 | .45 | .54 | .63 |
| 12-24-76 | 9:00 AM | .99 | .76 | .39 | .46 | .43 | .48 |
| | 11:30 AM | .64 | 4.84 | 3.32 | 3.15 | 1.93 | 3.90 |
| | 2:30 PM | .55 | .36 | .89 | .39 | .39 | .59 |
| 12-25-76 | 9:00 AM | 1.05 | .60 | .34 | .46 | .50 | .54 |
| | 11:30 AM | .49 | .58 | .51 | .78 | .84 | .92 |
| | 2:30 PM | .10 | .12 | .10 | .25 | .32 | .40 |
| 12-26-76 | 9:00 AM | .08 | .08 | .08 | .19 | .24 | .31 |
| | 11:30 AM | 2.98 | 4.12 | 1.99 | 1.71 | 2.04 | 3.43 |
| | 2:30 PM | .23 | .20 | .23 | .40 | .50 | .62 |
| 12-27-76 | 9:00 AM | 1.13 | .27 | .28 | .41 | .40 | .50 |
| | 11:30 AM | 5.80 | 5.32 | 2.06 | 1.79 | 3.85 | 3.29 |
| | 2:30 PM | .44 | .70 | 1.24 | 1.20 | 1.01 | .89 |
| 12-28-76 | 9:00 AM | .07 | .07 | .07 | .16 | .22 | .28 |
| | 11:30 AM | .23 | .20 | .20 | .42 | .60 | .72 |
| | 2:30 PM | .12 | .13 | .14 | .27 | .37 | .46 |
| 12-29-76 | 9:00 AM | .36 | .37 | .27 | .66 | .76 | .89 |
| | 11:30 AM | .23 | .23 | .22 | .37 | .51 | .64 |
| | 2:30 PM | .42 | .90 | 1.93 | 1.47 | 1.52 | 1.04 |
| SUM | | 18.28 | 22.33 | 17.15 | 18.64 | 21.40 | 25.60 |

Table IV

GREENHOUSE 3A: LIGHT READINGS

Units Millivolts (for comparison only)

| Date | Time | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| 12-22-76 | 9:00 AM | | .54 | | .56 | .52 | .55 |
| | 11:30 AM | | 1.32 | | 1.35 | 1.28 | 1.21 |
| | 2:30 PM | | 1.11 | | 1.07 | 1.08 | 1.11 |
| 12-23-76 | 9:00 AM | | .50 | | .50 | .48 | .53 |
| | 11:30 AM | | 2.11 | | 2.68 | 4.60 | 2.38 |
| | 2:00 PM | | .67 | | .66 | .61 | .54 |
| 12-24-76 | 9:00 AM | | .44 | | .47 | .42 | .43 |
| | 11:30 AM | | 1.28 | | 1.14 | .99 | .94 |
| | 2:30 PM | | .62 | | .83 | 1.11 | .75 |
| 12-25-76 | 9:00 AM | | .62 | | .58 | .62 | .57 |
| | 11:30 AM | | .86 | | .88 | .82 | .73 |
| | 2:30 PM | | .32 | | .39 | .33 | .30 |
| 12-26-76 | 9:00 AM | | .17 | | .16 | .15 | .13 |
| | 11:30 AM | | 2.40 | | 1.46 | 3.54 | 1.62 |
| | 2:30 PM | | .67 | | .61 | .59 | .56 |
| 12-27-76 | 9:00 AM | | .58 | | .59 | .58 | .66 |
| | 11:30 AM | | 2.68 | | 2.30 | 2.88 | 1.60 |
| | 2:30 PM | | .80 | | .86 | 1.09 | .69 |
| 12-28-76 | 9:00 AM | | .27 | | .30 | .25 | .22 |
| | 11:30 AM | | .62 | | .62 | .60 | .60 |
| | 2:30 PM | | .40 | | .41 | .36 | .38 |
| 12-29-76 | 9:00 AM | | .82 | | .84 | .79 | .76 |
| | 11:30 AM | | .51 | | .50 | .45 | .45 |
| | 2:30 PM | | .75 | | .69 | .54 | .50 |
| SUM | | | 21.06 | | 20.45 | 24.68 | 18.21 |

Table IV (continued)

Units Millivolts (for comparison only)

| Date | Time | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| 12-30-76 | 9:00 AM | | .85 | | .55 | .52 | .56 |
| | 11:30 AM | | 1.08 | | 1.08 | 1.22 | .97 |
| | 2:30 PM | | .62 | | .58 | .57 | .50 |
| 12-31-76 | 9:00 AM | | .54 | | .68 | .64 | .58 |
| | 11:30 AM | | 1.64 | | 1.44 | 3.22 | 1.26 |
| | 2:30 PM | | 1.12 | | 1.26 | 1.15 | .97 |
| 1-1-77 | 9:00 AM | | .40 | | .42 | .40 | .38 |
| | 11:30 AM | | .52 | | .58 | .62 | .59 |
| | 2:30 PM | | .51 | | .50 | .50 | .48 |
| 1-2-77 | 9:00 AM | | .22 | | .20 | .21 | .20 |
| | 11:30 AM | | 1.37 | | 1.37 | 1.36 | 1.28 |
| | 2:30 PM | | .81 | | .75 | .68 | .62 |
| 1-3-77 | | | .58 | | .52 | .47 | .43 |
| | | | .34 | | .33 | .32 | .31 |
| 1-4-77 | 9:00 AM | | .37 | | .37 | .36 | .35 |
| | 11:30 AM | | 2.35 | | 1.90 | 4.10 | 2.11 |
| | 2:30 PM | | .77 | | 1.76 | 1.47 | .70 |
| 1-5-77 | 9:00 AM | | .41 | | .39 | .35 | .32 |
| | 11:30 AM | | 1.18 | | 1.18 | 1.04 | .94 |
| | 2:30 PM | | .74 | | .76 | .69 | .61 |
| 1-6-77 | 9:00 AM | | .75 | | .73 | .64 | .72 |
| | 11:30 AM | | 2.64 | | 2.73 | 2.74 | 1.39 |
| | | | 1.21 | | 1.40 | .99 | .94 |
| SUM | | | 21.02 | | 21.48 | 24.26 | 17.21 |

Table V.

Accumulative Sums of Light Levels in Greenhouse 2A

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 12-22 to 12-29 | 18.28 | 22.33 | 17.15 | 18.64 | 21.40 | 25.60 |
| 12-30 to 1-6 | 22.71 | 25.62 | 15.91 | 17.63 | 23.24 | 23.37 |
| SUM | 40.99 | 47.95 | 33.06 | 36.27 | 44.64 | 48.97 |

Accumulative Sums of Light Levels in Greenhouse 3A

| | | | | |
|---|---|---|---|---|
| 12-22 to 12-29 | 21.06 | 20.45 | 24.68 | 18.21 |
| 12-30 to 1-6 | 21.02 | 21.48 | 24.26 | 17.21 |
| SUM | 42.08 | 41.93 | 48.94 | 35.42 |

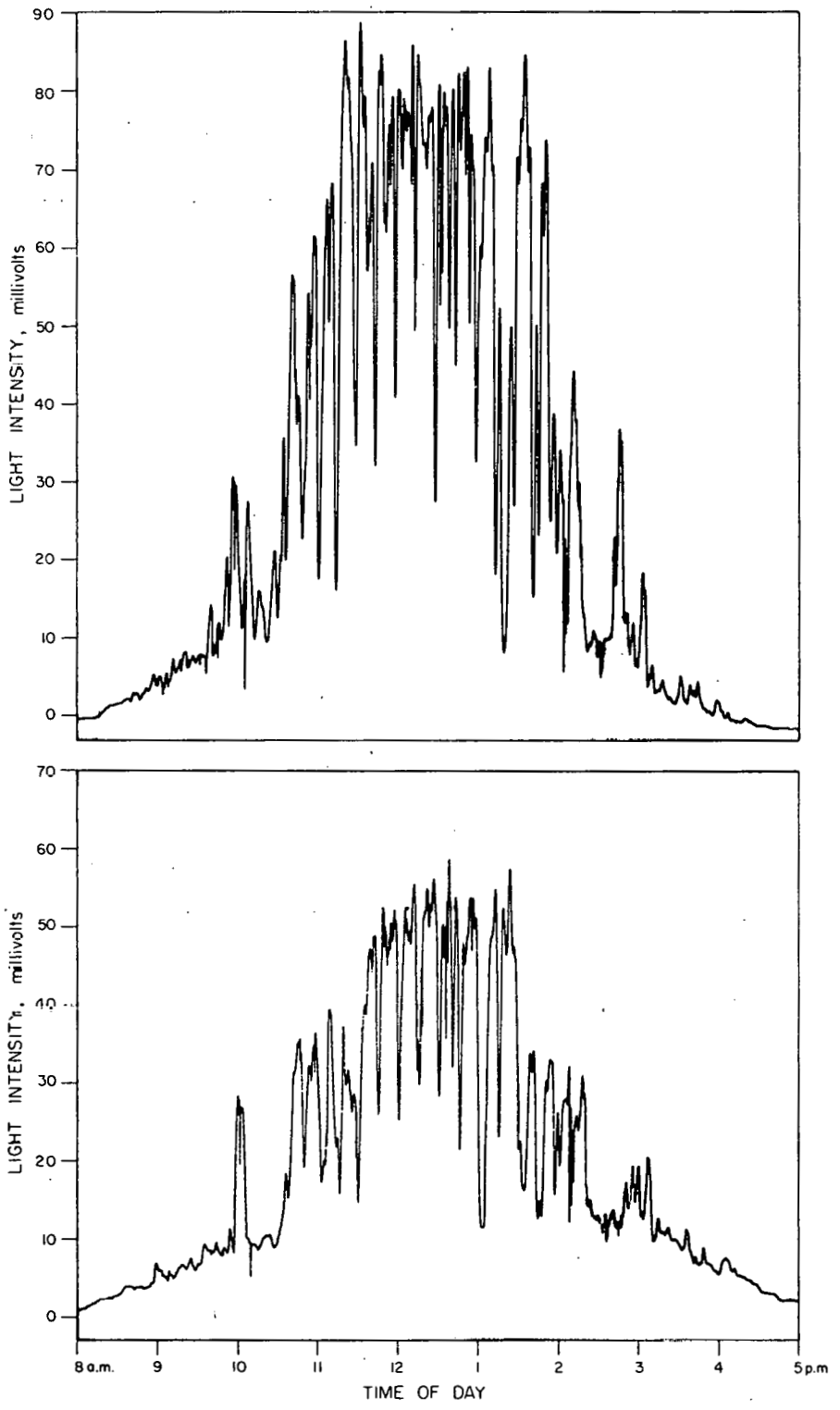



Figure 6. January 27, greenhouse light data. One half north roof insulated, vertical scale millivolts, 2A upper, 3A lower, total insolation 216 gm cal/cm$^2$. Solar angle at solar noon: 28.7°.

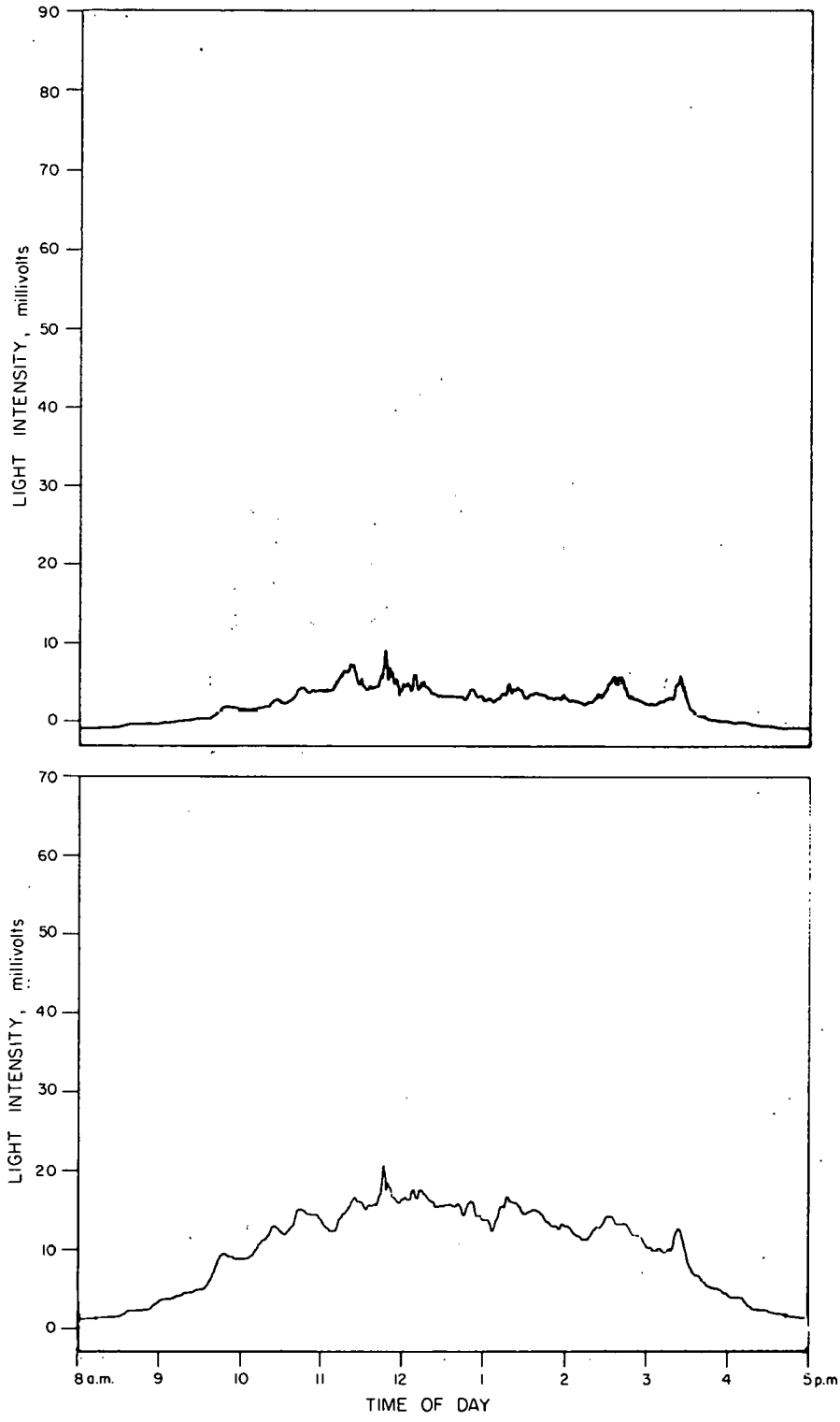



Figure 7. January 12, greenhouse light data. One half north roof insulated, vertical scale millivolts, 2A upper, 3A lower, total insolation 98 gm cal/cm$^2$. Solar angle at solar noon: 25.8°.

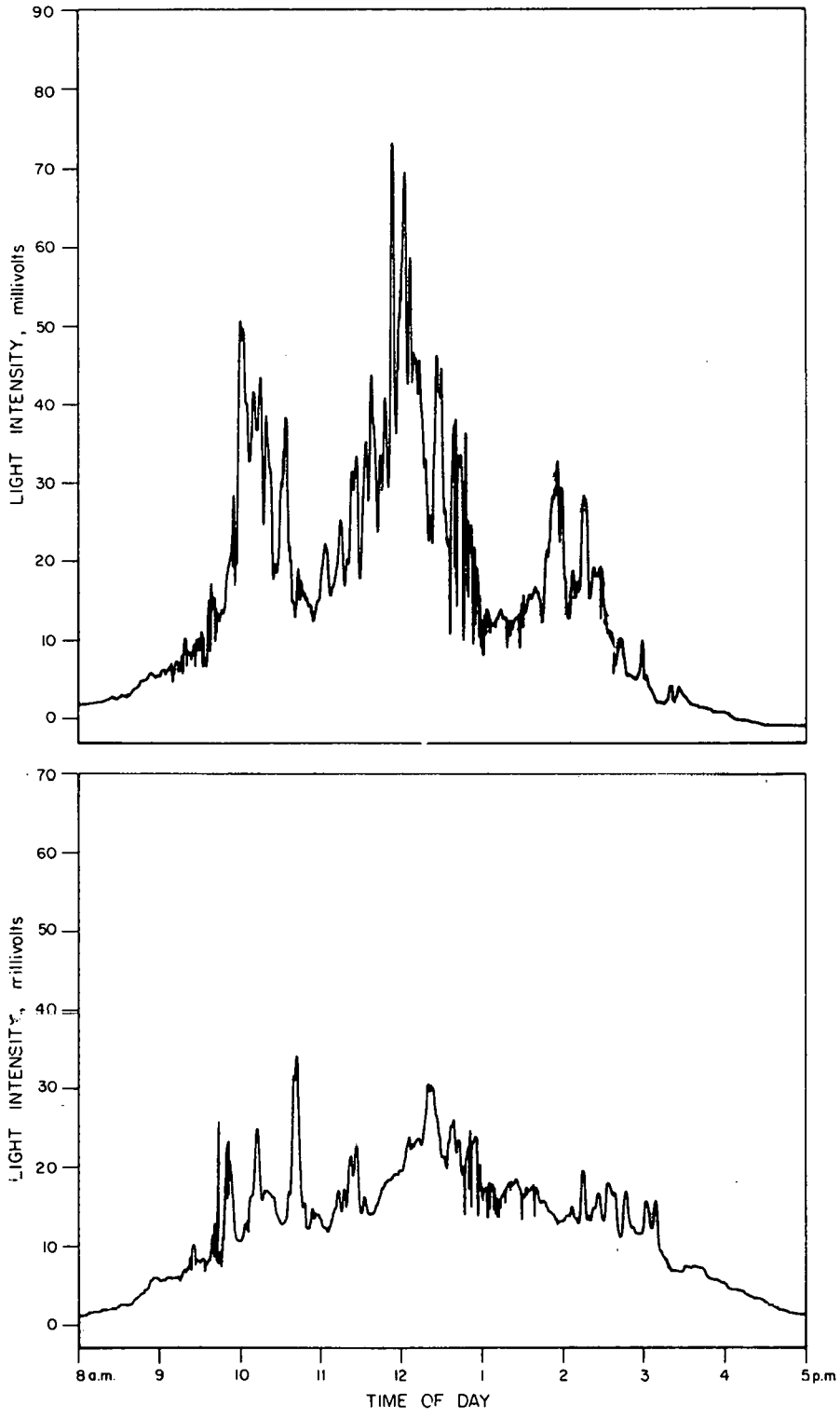



Figure 8. January 18, greenhouse light data. One half north roof insulated vertical scale in millivolts. 2A upper, 3A lower total insolation 181 gm cal/cm$^2$. Solar angle at solar noon: 26.8°.

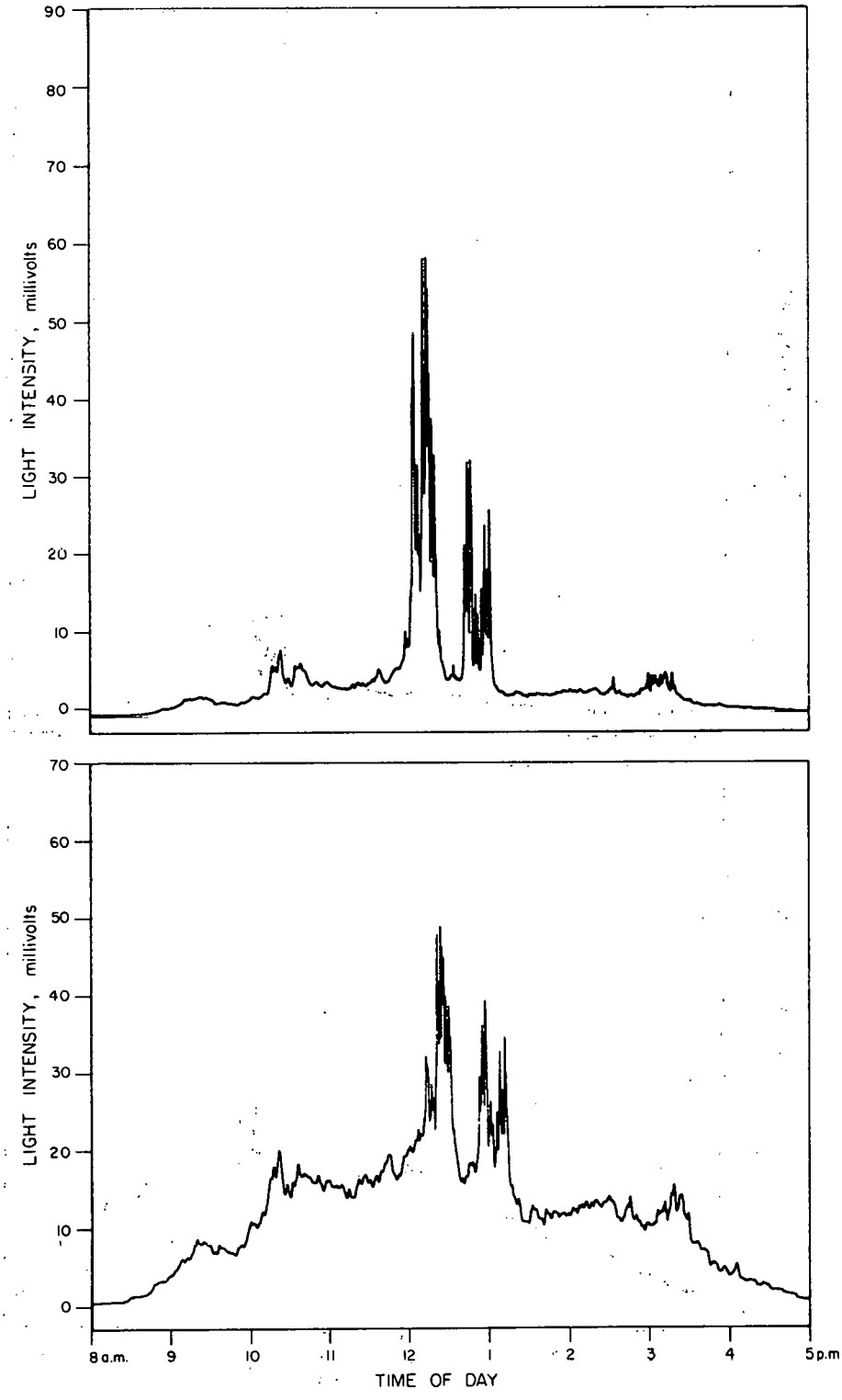



Figure 9. January 22, greenhouse light data, three quarters north roof insulated, vertical scale millivolts; 2A upper, 3A lower, total insolation 123 gm cal/cm$^2$. Solar angle at solar noon: 27.6°.

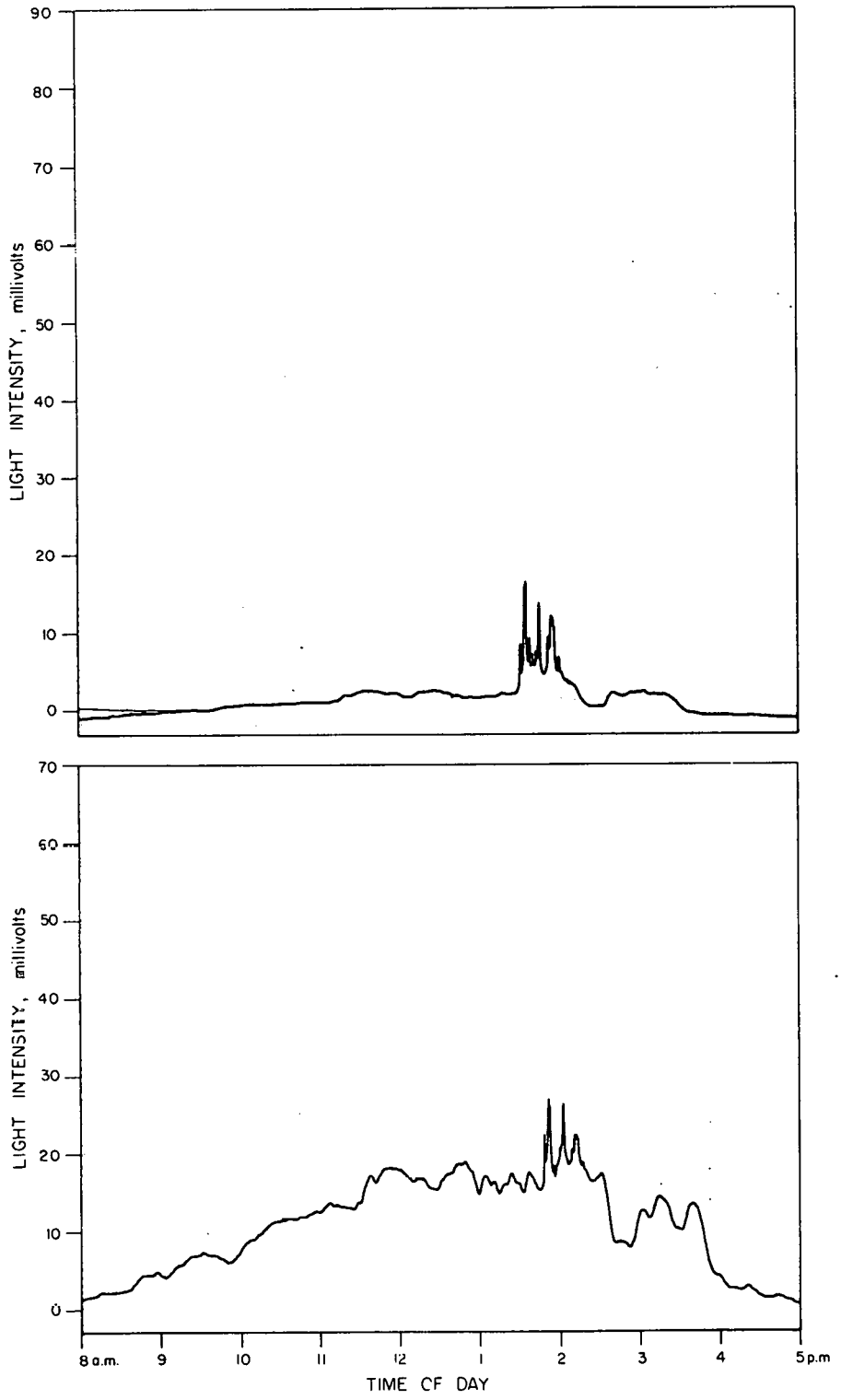



Figure 10. January 24, greenhouse light data. Three quarters north roof insulated, vertical scale millivolts. 2A upper, 3A lower, total insolation 104 gm cal/cm$^2$. Solar angle at solar noon: 28°.

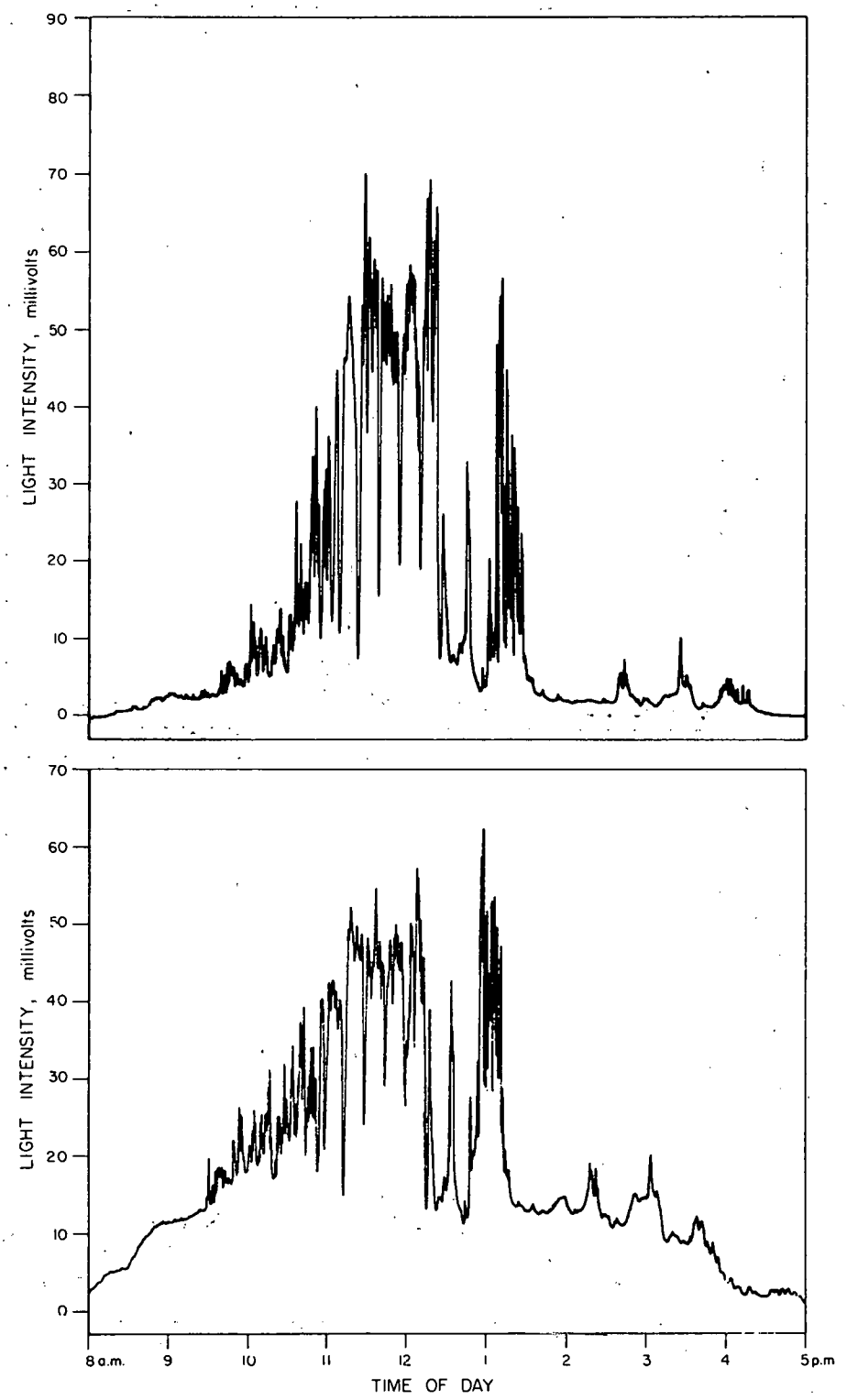



Figure 11. February 11, greenhouse light data. Whole north roof insulated, vertical scale millivolts, 2A upper, 3A lower, total insolation 177 gm cal/cm$^2$. Solar angle at solar noon: 32.9°.

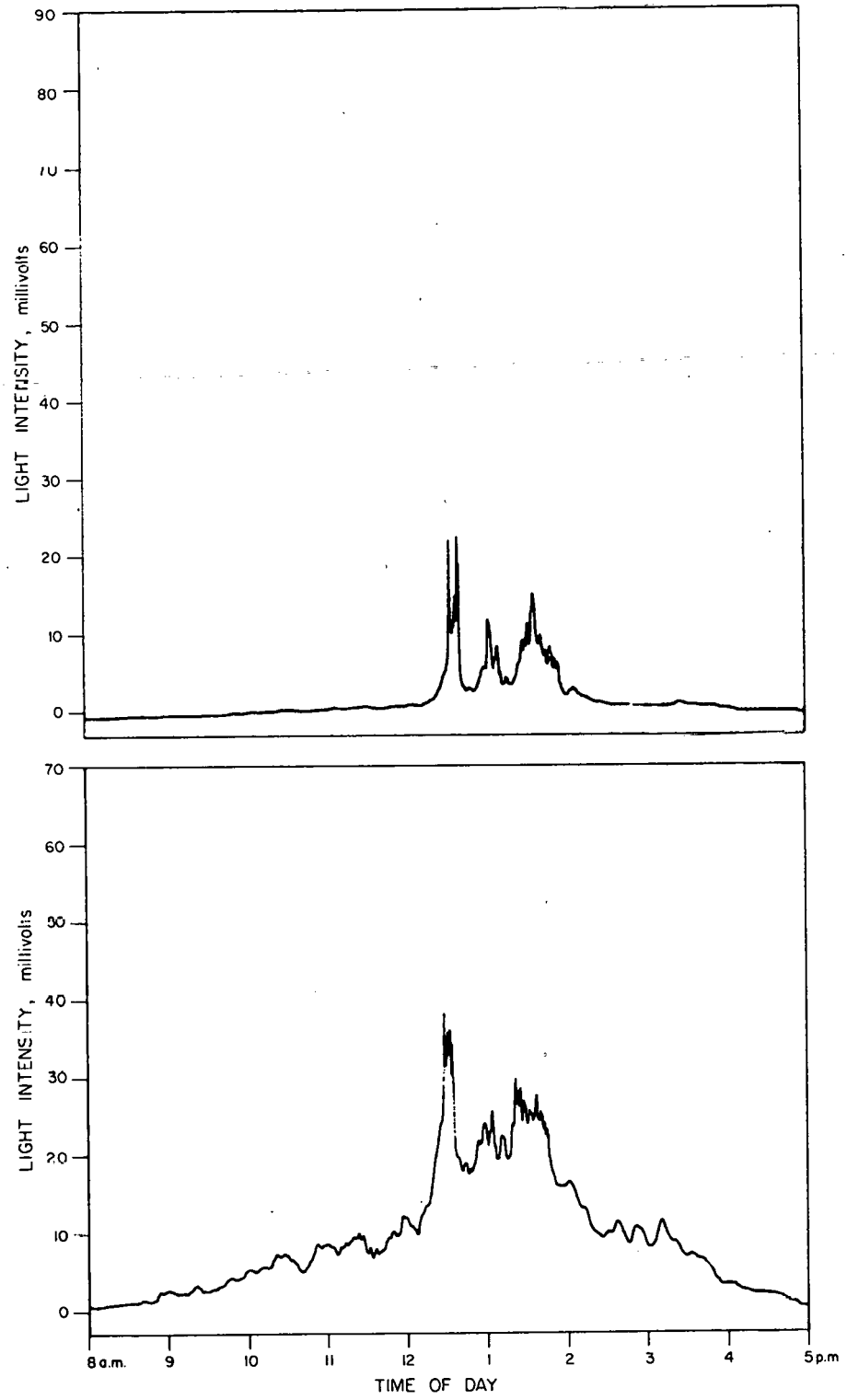



Figure 12. February 12, greenhouse light data. Whole north roof insulated, vertical scale millivolts, 2A upper, 3A lower, total insolation 93 gm cal/cm$^2$. Solar angle at solar noon: 33.2°.

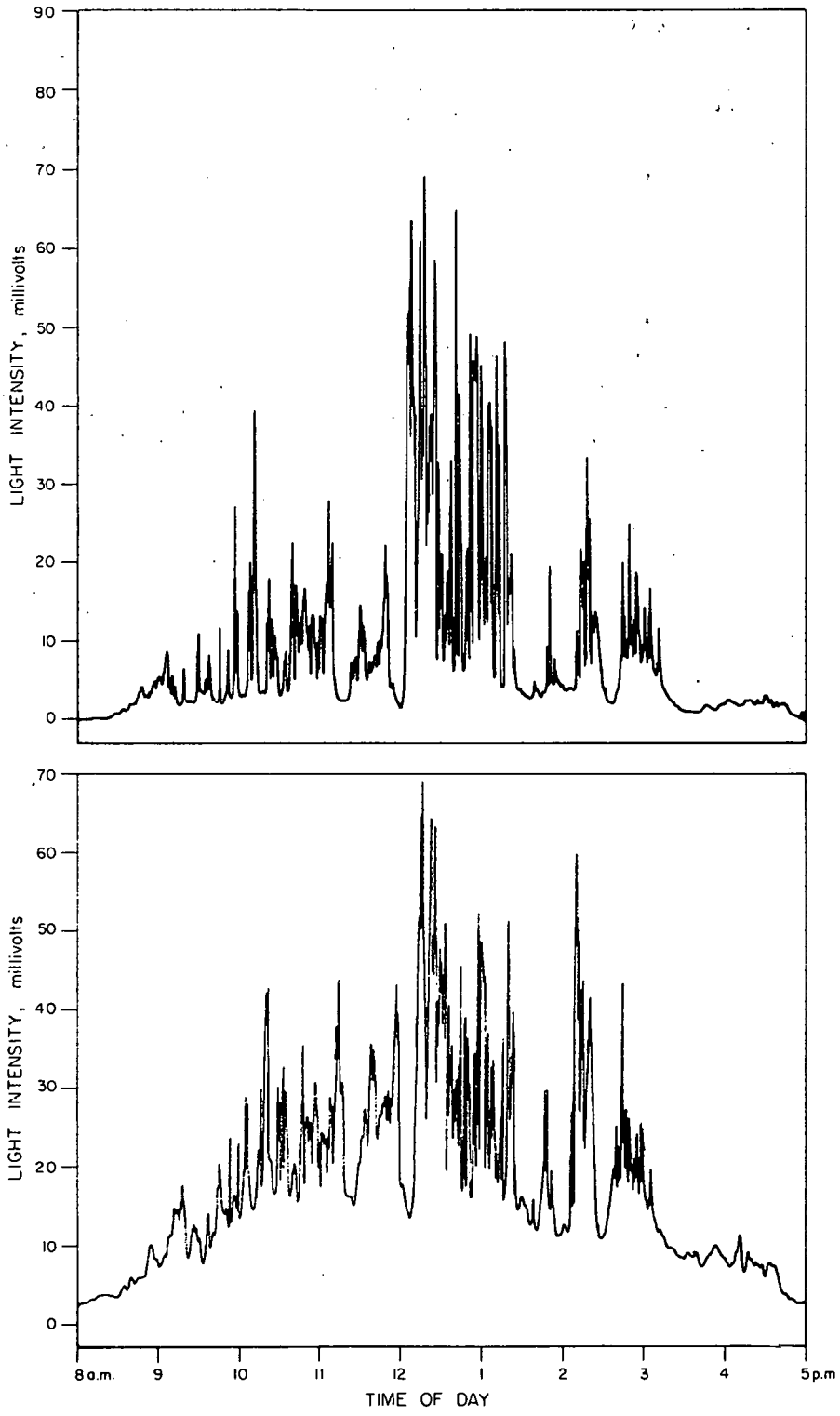



Figure 13. February 16, greenhouse light data. Whole north roof insulated, vertical scale millivolts, 2A upper, 3A lower, total insolation 193 gm cal/cm$^2$. Solar angle at solar noon: 34.5°.

Concomitant with the change in the model has been a considerable effort to reduce the size of the program without a sacrifice of utility or accuracy. Much progress has been made. The current simulation program requires 160K of core (IBM 360) compared to the prior need of 260K. The major reduction has been achieved using general variables and matrices for multiple purposes at different, non-conflicting points in the program.

## SUMMARY

The greenhouse can be used as a collector; it does collect more heat than needed during the day to maintain inside growing temperatures especially in the spring and fall. There is enough space within or under a greenhouse to use rocks to store the heat drawn off from the greenhouse ridge. We have developed considerable expertise in designing rock storage systems and again emphasize the advantages of using small size crushed rock or gravel. We also feel that present day greenhouse designs are outmoded and that much less glazed area can be afforded if reflection is used to multiply incoming southern light. This should increase collection efficiencies. While we are not completely settled on the optimum design for new greenhouses we feel that ideas suggested in figure 14 have possibilities for future, energy conserving, solar heated greenhouse design.

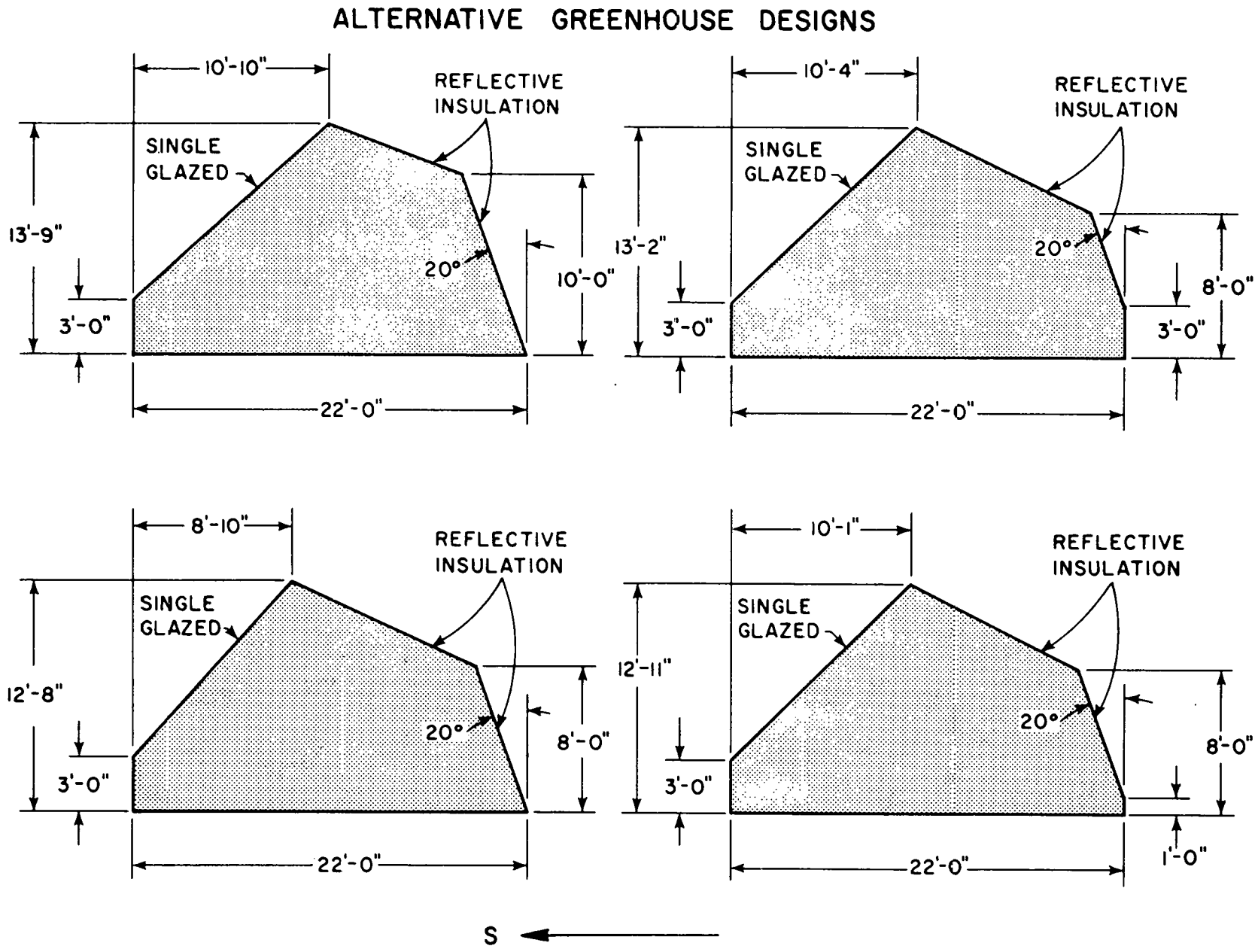



Figure 14. Alternative Greenhouse Designs

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1. Wilson, G. E., D. R. Price & D. P. Froehlich. 1976. Solar Heating Commercial Greenhouses. Proceedings of the New England Solar Energy Association Annual Conference. Amherst, MA.

2. Lawand, T. A., M. A. G. Malik, R. Alward & R. Hopley. 1973. An Investigation of the Contribution of Solar Energy in Heating Greenhouses in Quebec. Transactions of ASME, Journal of Engineering for Power. p. 114.

3. Colorado Flower Growers Association Bulletin 315. 1976. p. 4.

4. Private Communication with B. A. Kimball. U. S. Water Conservation Laboratory, Phoenix, AZ.

5. Biamonte, R. L. 1977. An Investigation of the Net Photosynthesis of Rose Under Varying $CO_2$ Concentration, Temperature and Light Intensities from Sunlight and High Pressure Sodium (SO N) Lamps. Ph.D. Thesis, Cornell University.

6. Experiment showed increased rose production up to 105°F (no sign that this was the upper limit of temperature). R. W. Langhans. 1976.

7. Bauerle, W. & T. H. Short. 1977. Conserving Heat in Glass Greenhouses with Surface Mounted Air Inflated Plastic. Special Circular 101, Ohio Agricultural Research and Development Center. Wooster, OH.

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# ENERGY AND THE FOOD CHAIN

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Ohio Agricultural Research and Development Center

If the present fuel crisis has not gained your attention, then you can be sure that the next one will! Unless you have one foot in the grave and the other on a banana peel.

I will attempt to show you:

1. Energy use in the Food Chain.
2. Extent of our Energy Problems.
3. How energy availability may alter the Food Chain.
4. What greenhouse managers can do to stay competitive and effective.

72 quadrillion BTU's/yr. in U.S. - 72 with 15 zeros following it! That is a lot of energy for us to pump, dig or otherwise capture - yet all of it is just about enough to warm Lake Superior by 10°F - not much when compared to the Sun's Heat Supply! About 1/7 was used in the Food System.

U.S. ENERGY CONSUMPTION

IN 1975 WAS

72,000,000,000,000,000 BTU

1/7 WAS USED TO PROVIDE

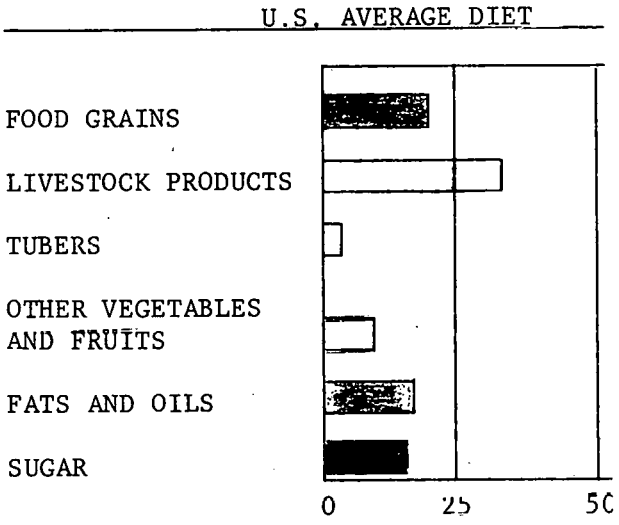
AND PREPARE OUR FOOD

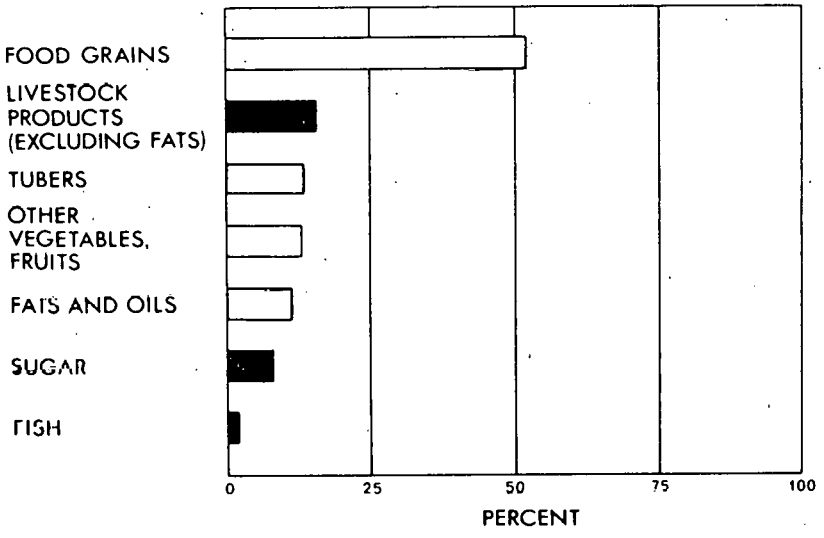
% Energy Required and Provided by the three major classes of foods. Tonight I want to concentrate on the main food constituents of Cereal Grains, Livestock Products and Vegetables and Fruits. These figures are percentages of the 14% of fossil fuel Required and of the U.S. Diet Provided. Most of my attention will be focused on vegetables, however. These three classes make up 2/3 of our diet. They supply all of the Protein, Vitamins and Minerals. There is some interchangeability between these, and we may need to make use of this fact in the future.

| | ENERGY - % | |
|---|---|---|
| | REQUIRED | PROVIDED |
| CEREAL GRAINS - | 8 | 20 |
| LIVESTOCK PRODUCTS - | 31 | 33 |
| VEGETABLES & FRUITS - | 11 | 13 |

U.S. Diet Illustrated. You see the U.S. Diet.

1. Large dependence upon Livestock Products.
2. Medium dependence upon Cereal Grains.
3. Very low dependence on Tubers.
4. Low dependence on Vegetables and Fruits.
5. 1/3 of our diet from Fats, Oils and Sugars which have no nutritive value other than calories of energy and/or body weight gain.




World Food Diet.

1. Large dependence upon cereal Grains.
2. Medium dependence upon livestock products.
3. 1/3 from tubers, vegetables and fruits.
4. Only 1/5 from fats, oils and sugars.

Mix is not that bad, if total quantity can be maintained and increased with population. We in U.S. could profit healthwise from switching the 1/3 from sugars and fats to vegetables and fruits as the world diet shows.

% Energy Used in Agriculture. Of the total U.S. Energy Usage, the Food System requires maybe 14% or 1/7. Of this 14% - 1-2% is in Agricultural Production inputs like fertilizer, pesticides, machinery manufacturing, etc. 1-2% is used "on-the-farm" in the form of fuels and electricity. This adds up to 3-4% by the time the food materials leave the producers' control.

FOOD INPUT ENERGY

| | |
|---|---|
| Production | 18% |
| Processing | 33% |
| Transportation | 3% |
| Merchandising | 16% |
| Preparation | 30% |

Breakdown of Food System Energy. Processing and preparation are probably the places for the non-Agricultural engineers and scientists to concentrate as Energy Conservation gets critical in the food chain, as it must be in other aspects of U.S. Energy Policy. In the meantime, we who attempt to service mostly the production phase of the food chain must work on the production energy as a matter of economic necessity.

| FOOD MATERIAL | ENERGY RATIO | PROTEIN RATIO |
|---|---|---|
| SUGARS, FATS & OILS | 2.7 | ∞ |
| FLOUR & CEREALS | 4.2 | 625 |
| FRESH VEGETABLES | 5.0 | 500 |
| MILK & MILK PRODUCTS | 7.6 | 625 |
| MEAT & POULTRY | 9.8 | 675 |
| EGGS | 10.0 | 500 |
| FRESH FRUITS | 10.4 | 3600 |
| FISH | 14.9 | 450 |
| PROCESSED FRUITS & VEGETABLES | 16.0 | 2090 |

(Eric Hirst, 1974)

Energy Ratio & Protein Ratio Going to Energy Penalty paid by class of Food Supplied. Note that we pay an energy penalty in all forms of food production. Only question is "how much"? Work Reported by Eric Hirst.

$$\text{Energy Ratio is } \frac{\text{Fossil Energy Used}}{\text{Food Energy Supplied}}$$

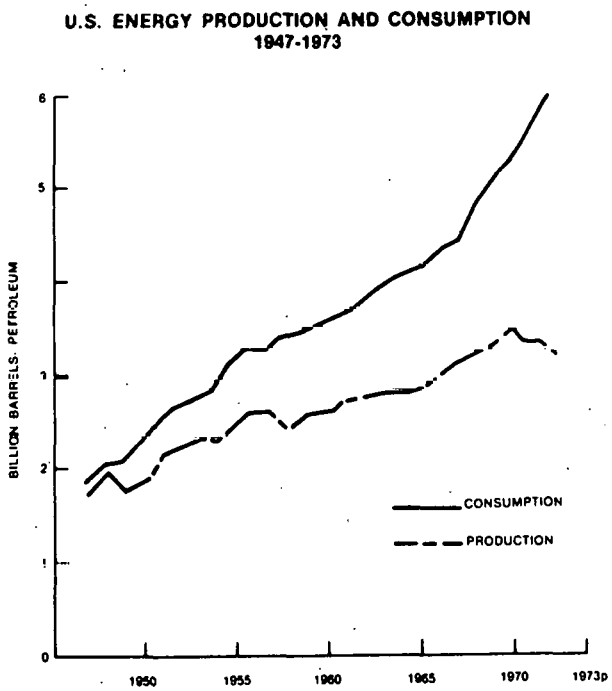
Note that fresh vegetables look pretty good but that processed vegetables are the worst of the list.

$$\text{Protein Ratio is } \frac{\text{Fossil Energy Used}}{\text{Food Protein Supplied}}$$

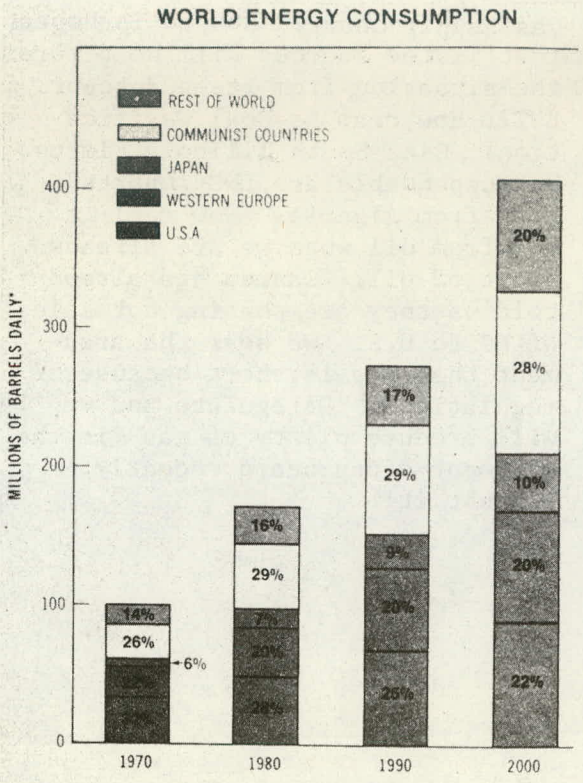
Note that fresh vegetables are beaten only by Fish. Processed Fruits and Vegetables and Fresh Fruits are very energy intensive. Sugars, Fats and Oils provide no protein so $\infty$ = infinity. That gives background on Energy use in Food Chain.

Now, let's consider our energy Plight in U.S. What do we have? And What do we want?

Energy Supply and Demand - U.S. Shows us very vividly that we have been working our way into a real bind for years and the size of the deficiency gap is growing at an accelerating rate! MAY ALLAH HELP US!? Since Allah controls most of the World's oil supply, He may or He may not help us.

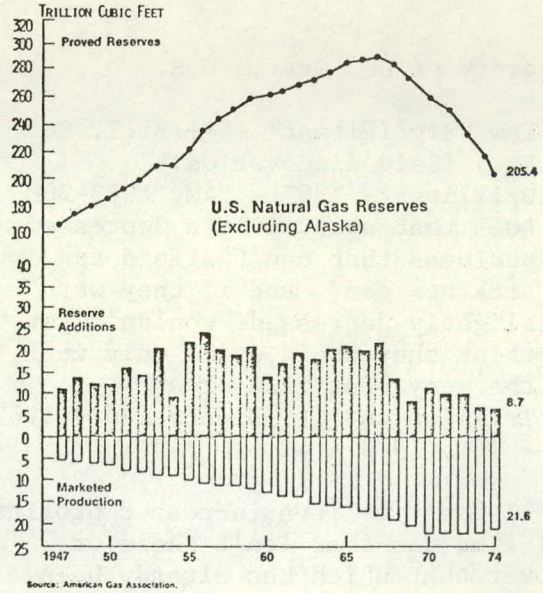


World Appetite for Energy. World Continues to have a doubling time of 15 years for Energy demand. Under these circumstances, what are the prospects for great sympathy from the rest of the world for our growing gap between what we have and what we want? U.S. with 1/16 of World's Population use about 1/3 of the world energy but don't forget that we produce almost 1/2 of the World's tradeable goods, including food.

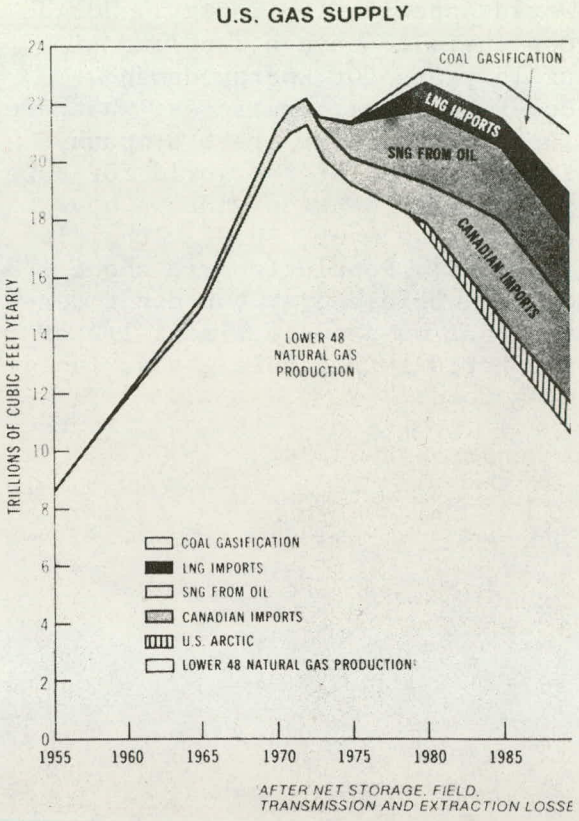



Now let's get specific about the Supply and Demand of specific fuels we need.

Take Natural Gas First - As demand persists, and discovery decreases, the reserves drop drastically! This is the recent history. Can it be turned around? The next slide shows what the basic facts are with respect to reality and hopes.



Gas Supply Chart. How, it is hoped, that listed sources will help turn the situation from steep descent. BUT? How real is Coal Gasification? Cite South Illinois Fiasco. How dependable are LNG imports? Most from Algeria. How real is gas from oil when we are already short of oil? Canada has already told us they are phasing out sales of NG to U.S. We hear the argument that gas is short because of regulation. "Deregulate and we will produce plenty of gas" is the argument often heard recently. I doubt it!




Discovery of New Gas in U.S.

1. New "Significant" (6 + Bill. Cu. Ft.) field discoveries.
2. Drillings - 1967 - 24M, 1973-36M Does that sound like a depressed business that can't afford to seek new gas? and if they were slightly depressed, wouldn't you think they would drill only in the very best risk areas?
3. Trillion cu. ft. Discovered - 1967 - 16T, 1973 - 4T.

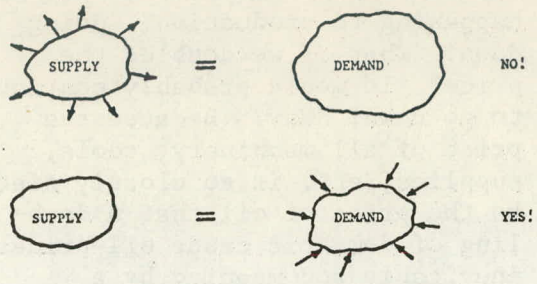
No! I don't believe increased profits will find gas that isn't there or recover that which has already been flared! But, nevertheless, I believe that deregulation is probably desirable and will lead to a workable balance between supply and demand for Natural Gas.

DISCOVERY OF NEW NATURAL GAS IN U.S.

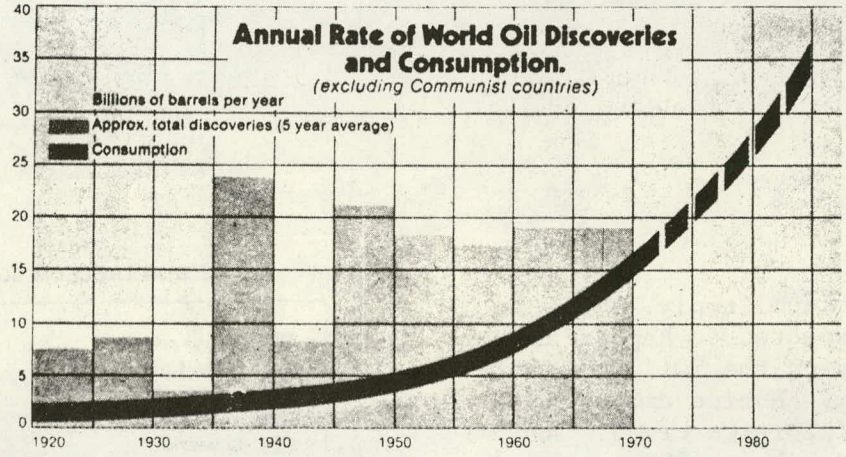
| | 1957 | 1966-67 | 1973 |
|---|---|---|---|
| Significant New Gas Fields Discovered, (6+ Billion Cu. ft.)- | 99 | 41 | |
| Drillings for Natural Gas, Million Feet Drilled - | | 24 | 36 |
| New Gas Discovery adding to the reserves, Trillion Cu. ft. Discovered | | 16 | 4 |

"A Realistic View of U.S. Natural Gas Supply" - FPC Report 12/74.

Gas Bubbles. Will supply expand to meet the demand? NO! Will demand shrink to match the supply? YES! Price will force out marginal uses of Natural Gas and act to conserve our remaining supply for fewer uses. Allocation may have to eventually be used to assure that remaining uses are <u>important</u>, not just lucrative!



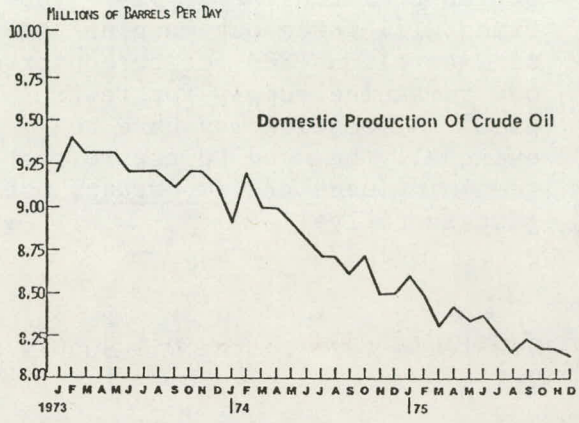

Now let's turn to the Oil Supply Situation.



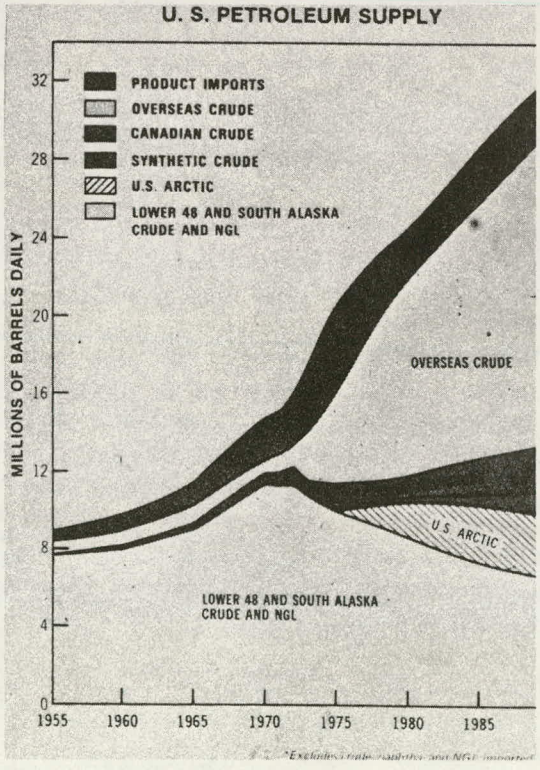

Oil discoveries until now have exceeded consumption. Most experts agree that future discoveries are unlikely to keep pace with consumption

Oil Discovery and Consumption. Can anyone tell me what year the bars of discovery and the line of consumption appear to cross? 1973! What happened that year? Do you suppose OPEC oil ministers studied economics? What do <u>you</u> as a <u>supplier</u> do in a condition of a shrinking supply? Put on a "Bargain-Basement" sale? Not likely! Raise the price? You bet! If you can. Normal? Perfectly! Can OPEC get away with it? They have! Why? They that have - sell! They that don't - Buy!

Domestic Crude Oil Production. Even at the greatly increased price for "new" domestic crude, what is happening to production? Going down! What if we doubled the price? It would probably continue to go down! Why? Because the price of all machinery, tools, supplies, etc. is so closely tied to the price of oil that a doubling of domestic crude oil prices, inevitably accompanied by a doubling of the cost of exploration and drilling, yields no more incentive to drill in the future than now.



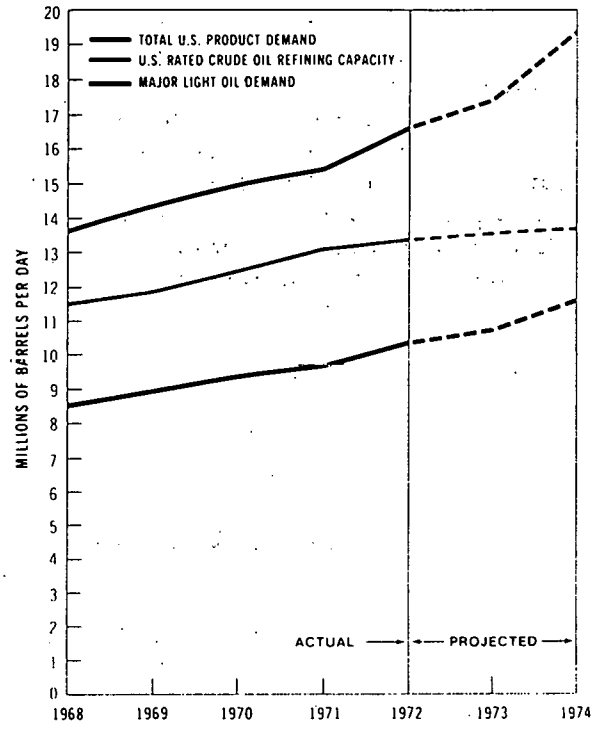

U.S. Petroleum Supply. Here is what is expected to happen as long as we stay on the "Oil Standard" for Energy. Notice amount to be made up of foreign crude. And we are already about 1983 on this chart, and this chart was prepared only about 4 years ago.



Another interesting situation - Let's look at our refinery capacity.

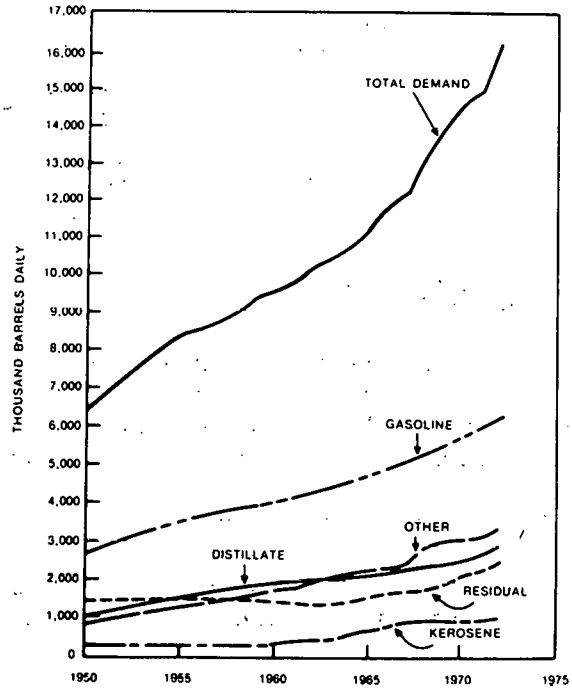
U.S. Refinery Capacity. Even if we could increase our Domestic Crude production drastically in a short time we would have to send it out of the country to get it refined for at least another 10 years. The only solution in Oil is to drastically curtail our demand through a strong conservation program. This next slide shows one logical place -

**U.S. REFINERY CAPACITY VERSUS DEMAND**




**DOMESTIC DEMAND FOR PETROLEUM**

Domestic Demand for Petroleum. About 40% of our petroleum demand is for gasoline. That's just about the percent of our supply we import. Every percent of gasoline saved by either voluntary or price/tax forced conservation is that much less foreign crude we have to purchase. But the present trend is in the opposite direction.




SOURCE: BUREAU OF MINES

Let us look at other energy sources.

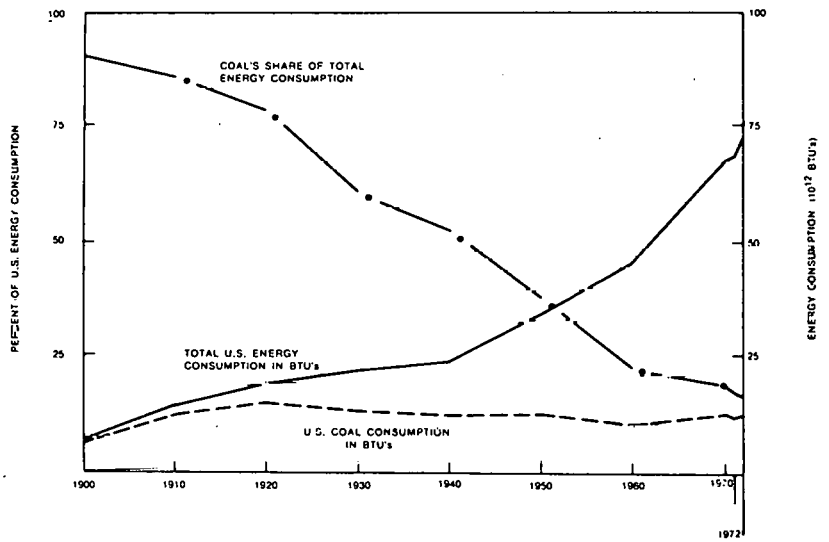
Proved Reserves - Fossil & Nuclear. Look at Coal. Vast amounts of Coal in U.S. We could exhaust World's reserve of Crude oil by U.S. Energy Consumption in 1975-1990, But we in U.S. have 23 times that much coal. Dig That! Yet we are not Digging It!

PROVED RESERVES OF FOSSIL & NUCLEAR FUELS

| | Crude Oil | Coal | Oil Shale | Uranium |
|---|---|---|---|---|
| World - (Trillion Bbl.) | 350 | ? | ? | ? |
| U.S. - Trillion Bbl. | 36 | 6800 | 1600 | 260 |
| Recoverable with Present Technology | | 640 | 55 | 86 |
| Estimated U.S. Energy Consumption 1975-1990 | (300) | | | |

"Energy Policy in U.S.", David J. Rose, Scientific American, Jan. 1974.

COAL'S DECLINING SHARE OF TOTAL UNITED STATES ENERGY CONSUMPTION

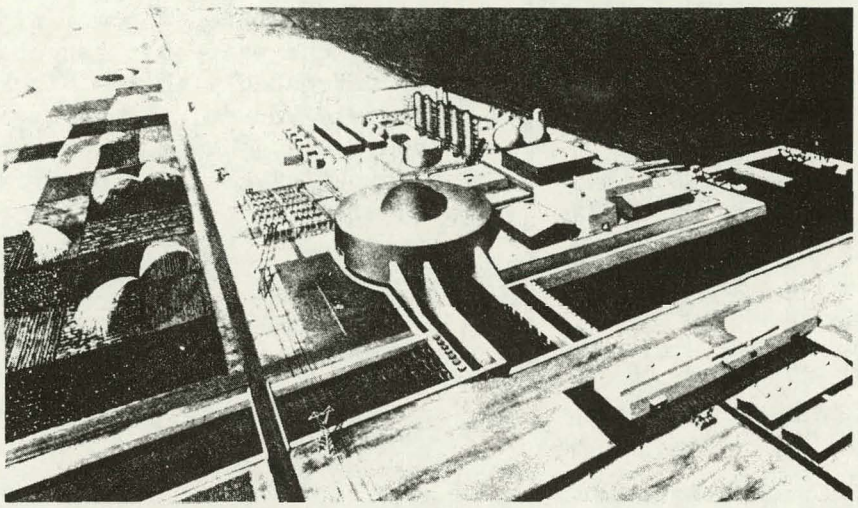



Drop in Coal usage. Due to:

1. Environmental Restrictions that are objectively desirable but procedurally ridiculous.
2. Artificially cheap natural gas and oil.
3. Ridiculously naive projections for Nuclear Energy some 30 years ago.
4. Federal Tax anomalies.

(Oil depletion allowances at the same time that railroads that carried coal were being taxed and regulated into oblivion.)

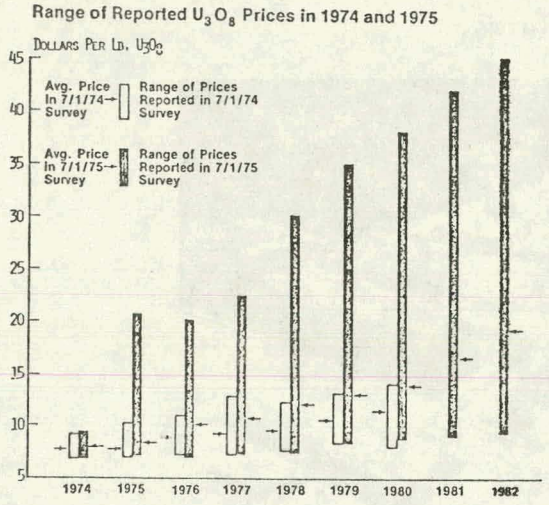
Let's closely examine Nuclear Energy Claims.



Nuclear-Powered Food and Water. Artist's sketch of nuclear bonanza to desalt seawater, supply power for communities and make the deserts bloom with food and flowers. You can all remember these claims of a few years ago. But the promise has run into some harsh reality. One of these is -

If the government stops paying for finding, mining, refining, enriching, transporting and disposing of Uranium fuel, who will? Why the utilities that use it, of course!! "Horrors - nobody ever told us that!!" Seems to be the response of the utilities. Cost of construction of atomic plants has increased 7-fold in 7 years*. Thirteen plant orders have recently been cancelled and another 33 postponed*. Sometimes "Environmentalists" are being blamed for this - in a way it is true, since the cost of all this uranium fuel handling is greater if the environment is adequately protected. But let's look at some economics.

*Testimony included in ERDA 76-1 (PM-4)




Costs of Uranium. Projected by two different surveys one year apart. If you had planned a power plant based on the white bar range, but were confronted with the black bars, what would you do? Probably cancel if you could. How does this affect the competitive situation of Nuclear-vs.-Coal?

Projected Cost of Generation. By what factor do we have to multiply the cost of the nuclear fuel before the whole operation becomes less economical than coal? Remember this is based on $13/# where the black bars in the last slide were running many times that. ($40-50/#). If this cost in the table of 3.0 were multiplied by

$$\frac{\$39/\#}{\$13/\#} - 3.0 = 9.0$$

this makes Nuclear power generation costs higher than with High Sulphur Coal.

OPERATING COSTS FOR UTILITY GENERATING PLANTS
(Mills/kWh)

| | | 1985 | | | |
|---|---|---|---|---|---|
| | | Base Load Plant (.70 capacity factor) | | | Peak Load (.08 capacity factor) |
| | Composite System (.48 capacity factor) | | Coal | | |
| | Existing 1974* | Nuclear | Low Sulfur without Scrubber | High Sulfur with Scrubber | Simple Cycle Turbine |
| Capital Costs | 6.2 | 13.5 | 9.3 | 11.7 | 30.0 |
| Operating & Maintenance | 2.0 | 1.8 | 2.0 | 3.5 | 3.0 |
| Fuel** | 9.0 | 9¢ 3.0 | 10.1 | 6.9 | 28.7 |
| Total | 17.2 | 18.3 24.3 | 21.4 | 22.1 | 61.7 |

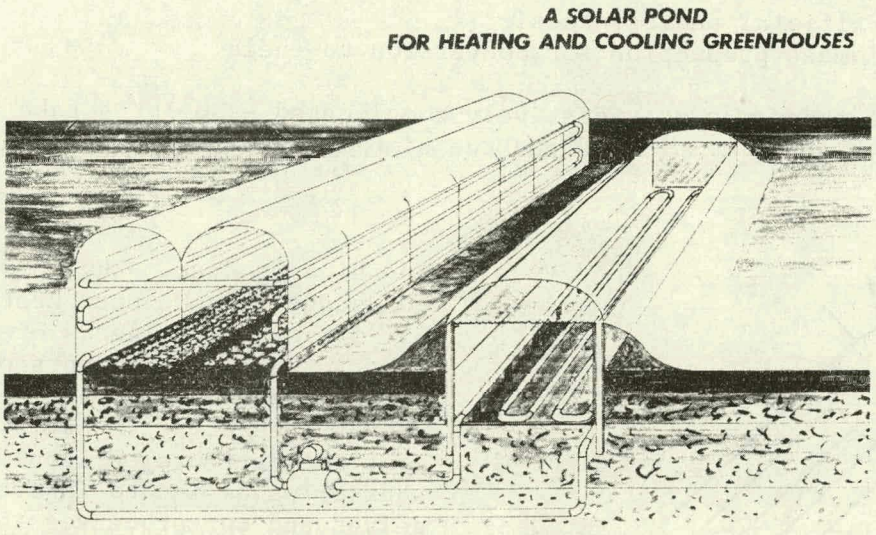
* 1974 figure derived from preliminary operating data adjusted to .48 capacity factor for comparison.

** Fuel costs are from the $13 Reference Scenario: Uranium averaging $13 per pound (with SWU's at $75), low sulfur coal at $24.73 per ton; high sulfur coal at $15.96 per ton; and distillate fuel at $13.90 per barrel.

In addition to the cost of this Nuclear Fuel let's look at Nuclear Plant Fuel Efficiency - Environmental Impact statements for Nuclear Plants assume an efficiency in the reactor of 80% or 33,000 Megawatt-Days/Ton of Uranium Fuel but, 16,500 is the average for the largest Westinghouse reactor; 11,000 is the average for the General Electric reactors; overall average only 49% as efficient as "advertised".* Atomic Fission Power is becoming the economic disaster of the Century! Now that all of the costs are beginning to be realistically considered.

*Testimony Included in ERDA 76-1 (PM-4)

BUT ENOUGH OF THIS PESSIMISM - LET'S LOOK ON THE SUNNYSIDE!




Solar Energy for Greenhouse Heating.

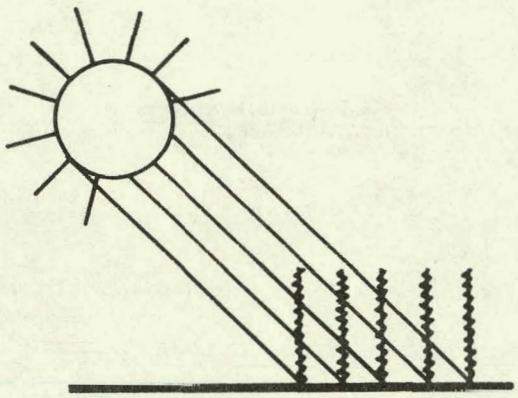


OARDC Solar Grain Drying Unit. There are lots of experimental projects with Solar Energy.

Others being conducted in Industry and Academia include:

a. Photovoltaic cells to produce electricity directly.
b. Beam-focusing steam generation plants.
c. Satellite collection and microwave beaming to earth.
d. Water electrolysis to hydrogen and $O_2$ by Sunshine and a catalyst.
e. Artificial photosynthesis
f. Biomass production for conversion to fuels.

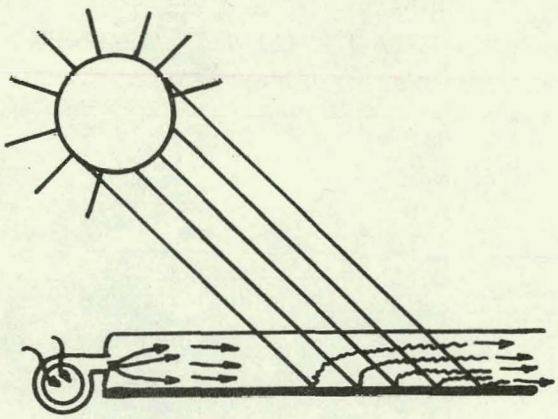
But all of these may be excessively complicated - so let's take a closer look at "Old Sol" and see the simplicity of the usefulness.



Sunshine <u>is</u> Heat. Why do we try to change it? We need heat. 30 35% of our Energy needs are for heat. Tremendous amounts of heat are available from sunshine. It is not free at all. But it will heat the earth relentlessly whether we <u>design</u> to insert ourselves and our processes <u>into the heat path</u> or whether we don't. And the way we design to put ourselves into this heat pathway is to collect this heat in some working fluid -

Collecting Solar Heat.
- and proceed to use the warmed fluid for some of our heating needs like:

1. Homes & Buildings
2. Drying Processes
3. Growing Processes - Plant and Animal
4. Cleaning Processes - Sterilization



There can be a great reduction in the fossil fuel needed to provide the right environment for Humans, Animals and Plants if we just design properly to use Solar Heat.

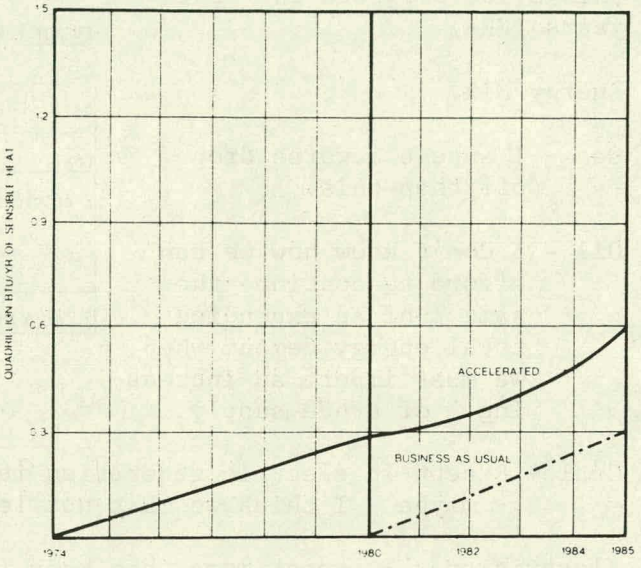
Potential for Buildings.
Projection by the Government Experts in ERDA -

1980 - 0.4%
1985 - 0.7%

I think this is probably <u>less</u> than what we will need to achieve in order to survive in comfort, given the decrease in Gas and Oil prospects. We have to do better than this and I think this group at this meeting can chart the course and assemble the facts to do so!

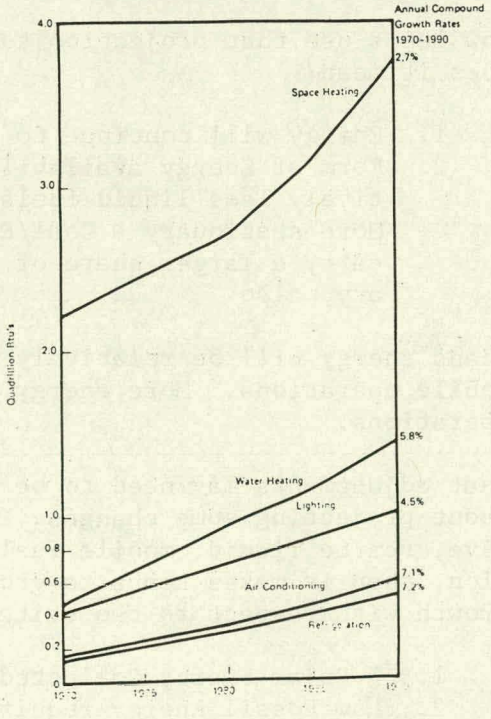
Given the great increase in demand for building heating and cooling as shown in this next slide, we must pursue this utilization of Solar Heat.

**POTENTIAL FOR SOLAR HEATING AND COOLING OF BUILDINGS**




Growth in commercial energy demand. If this takes place, it is apparent to me that we <u>must</u> find ways to carry this burden on the backs of Coal and Solar Heat, because there are no sounder sources to be had in the foreseeable future!

**1970-1990 GROWTH IN COMMERCIAL ENERGY DEMAND BY END USE**



Summarizing our Energy Problems. This slide projects the next years (FEA)

U.S. ENERGY SUPPLY MIX - %
FEA Prediction - 1976

| ENERGY FORM | | 1974 | | 1985 | |
|---|---|---|---|---|---|
| Gas | | 30 | | 22 | |
| Oil | - Domestic | 19 | | 13 | |
| | - Imported | 11 | | 17 | |
| Coal | | 10 | | 9 | |
| Electricity | - Hydro | 4 | | 4 | |
| | - Gas | 5 | | 3 | |
| | - Coal | 13 | 29 | 17 | 36 |
| | - Oil (Domestic) | 5 | | 4 | |
| | - Nuclear | 2 | | 8 | |
| Solar & Other | | 1 | | 3 | |

Energy Mix.

Gas - I expect a worse drop off than this.

Oil - I don't know how we can afford to continue the same % of an expending total energy demand when we must import an increasing % of crude supply.

Coal - Except in electric generation it is predicted to decrease.
- maybe - I think we must not let it decrease.

Electricity - I expect more than this from coal and less from nuclear but at least this growth in the energy load carried by electricity from all sources.

Solar & Other - I expect more than this in the home and commercial heating area.

Now let's use that projection to shift back to the Food Chain. What does it mean?

1. Energy will continue to get more expensive.
2. Form of Energy availability will change; less mobile - relatively less liquid fuels available for mobility of energy use. More stationary - Coal/Electricity is stationary and they will carry a larger share of energy demand. Solar Heat is stationary, also.

Means energy will be relatively more available at point sites than for mobile operations. More energy for Food Factories - Less for field operations.

What adjustments may need to be made? Fortunately we know something about projecting some changes. If you want to make best use of expensive, scarce liquid, mobile fuels that are available for field operation, then it makes sense to grow field crops that have efficient growth with respect to two criteria -

1. % Solar Energy Collected.
2. Low Fossil Energy requirements for production.

CONVENTIONAL FOOD ENERGY PATTERNS

| FOOD | % SOLAR ENERGY EFFICIENCY |
|---|---|
| Tubers & Roots | 0.6—2.0% |
| Green Vegetables | 0.4—1.2% |
| Cereal Grains | 0.3—1.0% |
| Milk | 0.2—0.4% |
| Eggs | 0.1—.25% |
| Catfish | .07—.20% |
| Poultry Meats | .06—.18% |
| Pork | .04—.15% |
| Beef | .01—.10% |
| Lamb | .01—.08% |

Efficiencies of Solar Collection. Study the ranking of these efficiencies. We may note a trend

Higher Protein - Lower Solar Efficiency
Higher Fats and Oils - Lower Solar Efficiency.

Fact: The more complicated the molecule you build in the field, the lower is the Solar Collection Efficiency in terms of Energy. That is in accordance with the Entropy Concept.

Efficiencies in Use of Fossil Energy. We have calculated this out for 4 crops that represent a spectrum from Simple Vegetative growth (sugar beets) to complicated protein and oil molecule construction (soybeans). Based it upon units of Fossil Energy input. Corn is higher even though it does produce more protein and oil than sugar beets mainly because the maize family has the unique $C_4$ metabolism which is greatly superior to the $C_3$ metabolism of the rest of the plant kingdom.

| | Corn | Sugar Beets | Alfalfa | Soybeans |
|---|---|---|---|---|
| 1. Input of Fossil Energy - gal/acre | 9.34 | 9.64 | 11.34 | 9.04 |
| 2. Yield of Dry Matter - Tons/acre | 8.60 (3.43) | 6.23 (4.67) | 5.41 | 1.20 |
| - MBTU/acre | 133 (56) | 92 (70) | 83 | 19 |
| 3. Energy Ratio Output/input | 112 (47.4) | 75 (57.2) | 57 | 16 |
| 4. Protein yield - #/acre | 1306 (660) | 1185 (635) | 1936 | 1003 |
| 5. Protein yield per Fossil Fuel Unit - lbs/gal. | 140 (70) | 123 (65) | 170 | 110 |

Conclusion: Form of energy availability may dictate that more solar energy be collected from the field or greenhouse in the form of vegetative growth and (1) some of this be consumed directly and (2) the rest be used as a Feedstock for the production of proteins, oils, etc. in stationary locations, where electrical energy is available, by the use of lower forms of life (like yeasts and small animals), in what might truly be called Food Factories.

Because I am probably running over my time, I do not wish to get into a discussion of all of the ramifications of food factories containing a microcosm of the whole biosphere, or even a processing plant to ferment whole corn biomass into various food nutrients. But I do want to focus briefly on how to efficiently produce that vegetative material we will consume directly. Taking this a step closer to home -

I say that I expect more of our nutrient feedstuff to be vegetative material. Remember way back near the beginning when we showed that fresh vegetables ranked high in both the energy return ratio and the protein yield ratio? We have 3 ways of getting fresh or nearly-fresh quality.

1. Field grown and frozen.
2. Field grown and shipped long distances.
3. Greenhouses.

The first two will be in more trouble from scarce mobile energy than is a greenhouse if solar and electrical energy are available. So I and my colleagues did a lot of digging and pencil pushing last week.

We came up with the figures in the next table. We do not guarantee the accuracy of the individual figures because good data are hard to find. But we do believe that we are presenting a reasonably accurate total picture of these relationships.

Winter Vegetable Supply - Fossil Energy used in Production.

WINTER VEGETABLE SUPPLY

| Cultural Energy: | Field Grown | | Greenhouse Grown | |
|---|---|---|---|---|
| Application | Processed | Shipped Fresh | Conventional | Possible? |
| 1. Tillage | 1.2 | 1.1 | 1.3 | 1.5 |
| Plastic Mulch | - | .7 | - | - |
| 2. Pesticide | 3.4 | 4.2 | 10.0 | 2.5 |
| 3. Fertilizer | 9.4 | 18.0 | 55.0 | 75.0 |
| 4. Water | 8.0 | 10.0 | 17.0 | 18.0 |
| TOTAL - MBTU/acre | 22.0 | 34.0 | 83.0 | 97.0 |
| 5. Yield - Tons/acre | 20T/Acre | 5T/Acre | 100T/Acre | 160T/Acre |
| TOTAL - MBTU/Ton | 1.1 MB/T | 6.8 MB/T | 0.8 MB/T | 0.6 MB/T |

Total Fossil Energy Used in the Whole Chain. Carrying the figures for cultural energy on into this table and adding on other energy uses. Call in terms of MBTU/Ton.

WINTER VEGETABLE SUPPLY

| Energy Input | Field Grown | | Greenhouse Grown | |
|---|---|---|---|---|
| | Processed | Fresh | Conventional | Possible? |
| 1. Cultural Energy | 1.1 | 6.8 | 0.8 | 0.6 |
| 2 Proc. & Containers | 9.0 | 2.4 | 2.0 | 2.0 |
| 3. Storage | .5 | - | - | - |
| 4. Transportation | 5.0 | 11.0 | - | - |
| 5. Heating & Cooling | - | - | 140.0 | 17.5 |
| TOTAL | 15.6 | 20.2 | 142.8 | 20.1 |

As you see, the conventional greenhouse is very competitive on a fossil energy basis until you get down to heating and cooling energy. But we know that work has been reported right here on Monday to indicate that this 140 could be cut to 20% or 28 MBTU/Ton by use of:

1. Double-Plastic, air-supported structures.
2. Nighttime insulating systems.
3. Day-time light reflectors and soil or floor heat storage.

Then the next step is to increase the production in the same space by 60% by use of better culture, more mechanization and breeding. This gets this figure down to 17.5 MBTU/Ton and a greenhouse becomes competitive with any other way of getting these fresh vegetables for a higher percent of the U.S. diet. And it makes it possible to produce them on a local, year-around basis needed to establish fresh vegetables as a stable input at a higher level of diet percent. Then, if this 17.5 MBTU/Ton can be provided by stored solar heat and/or waste heat from electric power plants, the well-designed and managed greenhouse should be an even more desirable urban neighbor.



Now that, Ladies and Gentlemen, concludes my analysis of: (1) Why vegetables will become a more important part of the U.S. diet; (2) Why solar energy and coal for electric generation will have to become a more important part of our energy supply mix; (3) How these two necessities do in fact complement each other for a more efficient bio-harvest of solar energy in our production facilities; and (4) how locally-produced fresh vegetables from greenhouses of a new design and management can play a vital, efficient and economical part in this whole food system.

# FUTURE PROSPECTS FOR WORLD FOOD PRODUCTION

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From the time man first inhabited the earth, his top priority has been the task of obtaining sufficient food to sustain his life. This task occupied the working lives of most Americans at the time our nation began, and for many years thereafter as our population migrated westward to settle the huge expanse of middle America and the intermountain as well as Pacific coastal areas. Beginning about a century ago, however, the application of science and technology to agriculture started a revolution which, like the one in 1776, is cause for celebration today.

As technology became more advanced, farmers responded by opening new lands to crop and livestock production. Working together, scientists and farmers have fought and won scores of battles with diseases and insects. Their joint efforts have led to the doubling and redoubling of crop yields. The fertile land, assisted by fertilizers, pesticides and new crop varieties made possible by research and the application of agricultural science, has thus produced an ever-more-bountiful harvest. Advances in animal breeding, and the achievement of new levels of livestock production efficiency through improved nutrition and management technology have made possible an increasing supply of high quality livestock and poultry products. Advancements in food processing technology have led to the development of our modern food industry, and the identification (through research) of causes and cures for a wide range of nutritional deficiencies has largely banished malnutrition and the ills associated with an inadequate supply of essential food nutrients. Today, as a result of scientific and technological advances, only one farmer is needed to produce the food for 55 of his fellow citizens with huge tonnages left over to supply an expanding export market. Consumers throughout our land have available to them an abundant quantity of safe, wholesome, and high quality food, in such wide variety as to almost boggle the mind. Thus, as our nation enters its third century of progress, we can look back with pride on the tremendous growth which has occurred in agricultural productivity.

Of growing significance in our interdependent world is America's capability not only to feed its own rapidly increasing population, but also to produce ever larger tonnages of wheat, corn and soybeans for export. Our food aid to the developing nations has totaled approximately $30 billion since 1950, and has accounted for over four-fifths of all food aid throughout the world during the past twenty-five years. As our nation enters its third century, all of us will most assuredly

continue to be vitally affected and influenced by worldwide food production trends. Let us, therefore, take a look at those trends, past, present, and projected.

As we see it, the past "track record" of agriculture in the United States and other developed nations offers considerable assurance that an ample world food supply can one day be assured. Because of past advances in agricultural science and technology, the gloomy predictions of mass starvation throughout the world, made nearly two centuries ago by the Reverend Thomas Malthus, and repeated since then by many other prophets of gloom and doom, have not yet come to pass. Happily, agricultural science and technology have, over the past fifty years, provided solid evidence to refute the Malthusian Theory. Improvement in world grain yields during the past several decades has been spectacular, with per acre yields of wheat, corn, barley and several other crops having doubled in just thirty years. From the early 50's to the early 70's, per capita food production worldwide increased 17 percent. In other words, world food production grew 17 percent faster than population. Much of this gain was due to what has been called the Green Revolution. This peaceful and peace-building revolution has made the difference between life and death for many millions of people in the developing countries since the mid-sixties. Keeping pace with increased crop production, worldwide production of animal products has been moving upward also, as a result of demand for dietary improvement from those whose incomes have been rising. Furthermore, worldwide fish production has increased more than ten times since the beginning of this century. The gains in food production which I have just recounted are, of course, highly encouraging. That those gains cannot be taken for granted has been made evident during the past several years of declining grain reserves and unprecedented fluctuations in food prices. The stark reality of severe food shortages in several areas during the recent past has triggered a widely publicized reassessment of our worldwide capability to meet future world food needs.

We, too, have been analyzing the outlook for future world food supplies and our analysis leads us to believe that there is plenty of basis for optimism, despite the fact that world population is expected to increase by nearly 40 percent by the year 2000, reaching a minimum of 5.5 billion, with about 4 billion of that total living in the so-called developing countries. Besides the demand for food created by population growth, per capita demand will continue to rise as income levels are--and they are rising rather dramatically in many areas of the world! The result of this dual stress on future world food supplies is simply that the overall supply of food in the world must at least double by the year 2000. As we all know so well, there are basically only two ways to increase the world food supply--No. 1, we can cultivate acres not now being cultivated, and No. 2, we can increase per-unit yields of both crops and livestock. Worldwide, about 3.6 billion acres are under cultivation at the present time. Fortunately, there are in Africa, Brazil and other nations in Latin America, as well as

in the Soviet Union, and in various other countries, an additional 4.2 billion acres of reasonably good land which could, and eventually will be, brought under cultivation. Furthermore, through the development of new crop varieties, higher productivity of forage crops, and other improvements resulting from agricultural research and development, agricultural production can be expanded into land now thought to be too cold, too dry, too wet, too steep, or otherwise unfit for cultivation.

Encouraging as the outlook for expanding world crop acreage is, the greater possibility for increasing world food production lies in boosting per-acre yields. The potential for increasing per-acre yields is illustrated by the fact that average yields of many crops are far below the record yields of these crops. The Green Revolution techniques which could result in improvement of root crops such as potatoes, cassava and yams--which are staples in the diets of many of the world's citizens--are just now getting underway. As we see it, the available evidence suggests that with adequate research and education in the developing nations, per acre yields of food and feed grains throughout the world can be at least doubled over the next 25 years. Since the world's cropland can be more than doubled, and since food and feed grain yields can be at least doubled, and since most population projections predict that the number of people on our planet will, at most, increase only 50-60 percent by the year 2000, it seems likely that dietary levels, in terms of caloric intake only, can be appreciably improved over the next two decades.

However, if by the year 2000, every person living in our world is to have adequate protein nutrition, protein production in that year will have to be five or six times the current level. During the sixties, products such as single cell protein, fish protein concentrate, and several high-protein synthetic foods were widely heralded as providing the answer to meeting the world's protein needs. Although the new foods are a technological success, their use has been extremely limited, either because hungry people in the developing countries can't afford them, or because ingrained cultural patterns and taste habits limit their acceptance. As a result, protein-fortified foods have not reached large numbers of people in the developing countries, and their effect on nutritional status has been minimal. More recently, the emphasis on meeting world protein needs seems to be shifting back toward conventional agriculture. It may come as a surprise to many of those who have repeatedly predicted the demise of the world's animal industries, but there is considerable evidence that the greatest increase in protein production can and will come about through expansion of the world's animal industries. It is a fact that livestock and poultry yield products which are acceptable to, and desired by, an increasing proportion of the world's population. One thing that is not well understood by those who advocate reduced consumption of animal products is that ruminant animals--cattle, sheep, and goats--consume roughages that human beings, even very hungry human beings, cannot or will not consume, let alone digest or metabolize even if consumed. In fact, feed-

stuffs which are inedible to man account for 75-80 percent of the rations of ruminant animals. Ruminants can utilize processed garbage, waste paper, citrus pulp, wood pulp, processed livestock waste and many other materials formerly considered to be nutritionally useless. Even though 64 percent of the earth's surface is not suitable for cultivation of crops, much of this less productive land can be used, and is being used for pastures, and for the production of harvested forages which can be consumed by ruminants. Furthermore, yields from much of the world's hay, pasture and range lands can be dramatically increased above present levels. While the non-ruminants--swine and poultry--cannot consume large quantities of roughages, those species are being genetically improved to the point where their conversion of grain to meat assures them of increasingly greater consideration for food production in the developing countries. In short, it seems clear that with continuing advances in technology, livestock and poultry products can be made available at reasonable prices to more and more people in both the developed and developing nations.

One of the often overlooked but truly excellent animal proteins is represented by seafoods. The world yield of fish from the oceans can be at least doubled by the year 2000. When we stop to think about the fact that the oceans occupy 70 percent of the earth's surface we can appreciate the incredible long-run potential of the oceans for supplying a significant portion of man's food needs. Therefore, it seems very clear that the potential exists for improving the quality as well as the quantity of our world's food supply through greatly increased harvests from the world's crop and pastureland as well as from its oceans and inland waters. But whatever our individual beliefs may be relative to the potential for future world food supplies, the challenges confronting us and the problems which must be overcome cannot be taken lightly.

In the first place, we all know that immediate steps must be taken to curb population growth, especially in the developing countries. It is obvious, however, that progress in this effort will be slow. Major birth control successes thus far have been limited primarily to the developed nations, with China standing out as a major exception. Furthermore, population control, no matter how effective, will have minimal effect on demand for food in the short run. Nevertheless, the experience of present day industrialized nations in controlling their populations is quite encouraging. There is evidence that patterns in many of the developing nations will follow those of the presently-developed countries, although several decades may be required for a similar response. The difficulty stems from the prospect that unless brought under control our present world population could quadruple over the next one hundred years, and the task of feeding a population of that size is truly frightening. It is essential, therefore, that food production in the developing nations be increased and population growth decreased just as rapidly as possible. The only sensible approach for the developing nations to take will be to include in their plans a

high priority goal for development and maintenance of strong agricultural economies so that many of those nations will achieve the goal of producing enough food to meet their domestic needs.

The only viable alternative to rapidly increasing food production in the developing nations to the point of their becoming self-sufficient, will be for some nations to promote rapid development in the industrial sectors of their economies, thereby affording them the opportunity to expand their exports of non-food items in order to pay for food imports. Continuing expansion of world trade will enable nations to specialize in those products, food or non-food, in which they have comparative advantages.

Although most studies indicate that overall, enough food will be available to feed all of the world's people through 1985, we know that per-capita food production will continue to vary widely from one nation to another. There is just not enough high quality farm land in many heavily populated areas of the world to permit self-sufficiency in food production. Nearly 100 percent of the arable land in South Asia, China, and the Near East is now under cultivation. By contrast, only one tillable acre in six is being farmed in Central Africa and in Latin America. In short, if answers are to be found to the challenge of future world food shortages, they can only be found in the reality of increased international trade and cooperation on the part of all nations. If such efforts are to be effective in improving diets, however, individual purchasing power must be increased in the developing countries. In addition, developing nations must plan to build up their own food reserves sufficiently to carry them through bad crop years, because it will be unwise for them to depend entirely on the United States and other developed countries to bear the burden of carrying food reserves for the entire world. It will be extremely important for the developing nations to recognize that free or subsidized food aid is counter-productive to their best interests. Such aid tends to cause nations to relax their own efforts toward increasing agricultural production. This is not to say, however, that the United States should, or will, abandon hungry nations in time of severe famine so long as food is available in the United States for shipment to those who really need it. The point to be made is that just as the developed nations have done in years past, many of the developing nations must now place high priority on the modernization of their agricultural systems, especially in terms of mechanization.

History has revealed the importance of mechanization in order to release people from subsistence farming, so that they can provide off-farm agricultural and non-agricultural goods and services, thereby improving the standard of living of all people in the nation. Even more fundamental is the fact that mechanization is essential if sufficient quantities of food are to be produced and harvested in the developing countries. The developing nations must find ways to build modern agricultural supply and service organizations as well as marketing,

storage and transportation systems. Those nations must give greatly increased attention to providing incentives which encourage agricultural development. Even though the technology for greatly increased agricultural production is available, farmers will not adopt such technology unless they have incentives to do so. Fortunately, there is evidence that the governments of many developing nations throughout the world are placing greater emphasis on strengthening their agricultural economies and on providing more encouraging incentives to farmers.

A major challenge ahead relates to the development, the management, and the preservation of natural resources needed for future food production. As the developed nations of the world contemplate their priorities they must give greater attention to the task of retaining sufficient land for future agricultural production. In the highly industrialized nations top priority must be placed upon wise land use. And careful consideration must be given to the concept of incentives to insure that the best farmland remain available for agricultural use instead of being utilized for urban and industrial development. On the other hand, the development of presently unused or underused agricultural land holds the key to increased production in many of the developing countries. Unfortunately, some of the land which could be used for crop production cannot be farmed profitably under the constraints of present-day economics and currently available technology. Some provision must be made to meet the large capital investments that will have to be made, and to provide the support for research and education which will be essential in bringing presently unused land into production.

One of the greatest challenges to improving the nutritional status of people in the less-developed nations involves development of their water resources. Tremendous quantities of food can be produced on many of the arid and semi-arid lands available for crop production if irrigation water can be made available. Worldwide, there is ample water to meet the irrigation needs of agriculture, but unfortunately its distribution is less than ideal. However, there is evidence that enough water is available to irrigate all of the land in the less-developed nations which is potentially irrigable. The challenge, then, is really two-fold: to effect more efficient utilization of the water now available and to tap new sources. Greater availability of water for irrigation can be achieved by capturing that one-third of the rainfall which now runs off the land. Furthermore, much of the water presently used for irrigation can be utilized more efficiently through such methods as trickle or drip irrigation. An entirely new source of water for growing crops awaits the development of less costly technology for desalinization of ocean water, which can then be used for irrigation. Such technology is already being utilized to a limited extent in various agricultural-industrial nuclear complexes located along several arid seacoast areas in Saudi Arabia and other Middle Eastern countries. Although these and similar irrigation projects will require large capital investments and have a long-term payout, others can be put into operation rather quickly. An example of the latter is

the rapidly-growing use of the so-called tube wells in India. Irrigation is currently practiced on only about 15 percent of the world's cropland, but this land produces about 30 percent of the world's food. While these percentages can be, and are being substantially increased, much of the world's food supply must continue to depend on the availability of adequate and timely rainfall.

Recurrent droughts and floods can be expected in the future, just as in the past, unless and until we find ways to control, or at least favorably influence, the weather. Thus far, accomplishments in weather modification have been extremely limited, and much more research is needed to determine the feasibility of, and techniques for, weather modification. To help farmers cope with weather variations, improved weather monitoring and forecasting methods are being implemented albeit slowly and in limited areas only. Use of earth resources satellites, as well as ground-based computerized monitoring systems for assessing worldwide crop conditions, will become increasingly important in the years ahead.

A most important resource for increasing food production is fertilizer. Many soils around the world are lacking in some or all of the major fertilizer elements, and trace element deficiencies are likewise widespread. It has been estimated that as much as half of the increase in world food production during the next 20 years will be dependent upon adequate fertilizer use. Recent shortages and the resulting high costs of fertilizers have been especially restrictive to their use in the less-developed nations, many of which are short of fertilizer manufacturing capacity, and which, therefore, have to import a substantial proportion of the fertilizers they use. It is highly unlikely that the developing nations will be able to build enough new fertilizer plants to allow them to become self-sufficient in the foreseeable future. Fortunately, it appears that because of new facilities already built or under construction in several areas around the world, output of nitrogen and phosphate fertilizers in the developed nations will soon be more than adequate to meet demands. Fertilizer use in the developing nations is expected to increase nearly 10 percent per year in the immediate future or almost twice the rate of increase anticipated for the United States and other developed countries. Demand in the developing nations is expected to increase five-fold by the year 2000. Our greatest concern recently has involved short supplies of nitrogen fertilizer, which has been limited by both inadequate production capacity and a shortage of natural gas for use as a feedstock in the production of ammonia.

Although natural gas shortages are expected to continue, the hydrogen required to produce ammonia can be obtained by electrolysis, or through gasification of coal, the supply of which will last for at least three centuries. Unfortunately, obtaining hydrogen from coal is much more expensive than deriving it from natural gas. However, hydrogen can also be obtained as a by-product of the operation of the fast breeder reactor, as well as from nuclear fusion, should the latter become a practical reality. In summary, then, there appears to be no significant techni-

cal obstacles or resource limitations to continued increases in production of the fertilizer supply which will be needed to meet food needs over the next several centuries.

Finding an alternative way to produce greatly increased quantities of nitrogen fertilizer is but one aspect of the critical role of energy in food production for the future. It is in the securing of adequate supplies of energy that our world food production capability faces its most severe challenge. Worldwide energy requirements for all purposes are expected to triple by the end of this century. Fortunately, even needs of that dimension can be met by developing the large reserves of oil and gas which are being discovered in many nations at the present time, along with world coal deposits, which represent 90 percent of the world's fossil fuel reserves; plus greater use of the unlimited quantities of energy which can be made available in the form of nuclear and solar energy, as well as hydrogen and other less familiar sources of energy. While the possibilities are excellent for meeting world energy needs of the future, the immediate challenge of providing sufficient energy in the developing nations so that they can increase food production as well as meet their other urgent needs is truly monumental. Those who have attempted to discourage the increased use of fossil-fuel energy for production of food in the developing nations have stated that adopting U.S. agricultural production methods would require more energy than is currently used throughout the entire world for all purposes. Fortunately that statement is patently false. The facts reveal that by using U.S. agricultural methods, all the food needed in the entire world could be produced by utilizing only 5 percent of the fossil-fuel energy now consumed in the world. A relatively small but highly significant proportion of future energy requirements in the U.S. will be for the production of food. In a number of articles written since 1973, agriculture in the United States has been unfairly criticized for allegedly contributing to the energy crisis by utilizing much more energy per unit of food energy output than is the case in underdeveloped nations. In this connection, it should be pointed out that United States agriculture does produce considerably more calories of energy than are consumed in the production of agricultural products in this country. Furthermore, agricultural producers simply cannot shift back to lower energy-consuming technology without bringing about catastrophic losses to all segments of our economy. Even so, agriculture cannot excape responsibility for improving its energy efficiency whereever and whenever it is feasible to do so. The real challenge facing us is to identify the most promising avenues of energy research and then follow up our research findings with production methods which will conserve energy consumption but will not reduce productivity or profitability.

Beyond conservation, we need to face up to the challenge of research on radically new technology which will drive farm power units when we run out of fossil fuels. The use of fuel cells is a possibility, but an even more promising prospect is the use of hydrogen, not only for

powering tractors and trucks, cars, airplanes and other vehicles, but also for generating heat and electricity for our homes and for industrial uses. Solar energy can be used quite efficiently on our farms to dry crops. Through use of solar ponds, the energy of the sun can be captured and used to heat homes, farm buildings and greenhouses. Such innovations will be absolutely necessary for the future, because it is a fact, of course, that the rationing of fuel on our farms and in our agriculturally-related industries would quickly lead to the rationing of food for our tables.

In any discussion of this nature, it should be kept in mind that severe restrictions on agricultural production as a means of accomplishing environmental quality goals will have effects similar to those which would be caused by energy shortages. Environmentally related constraints on food production, or on food processing will have direct and costly consequences on both the quantity and quality of available food supplies as well as on food prices. Dr. Norman Borlaug, recipient of the 1970 Nobel Peace Prize for his distinguished contributions to the Green Revolution, has stated that, and I quote: "If agriculture is denied the use of chemical fertilizers and pesticides the world will be doomed, not by chemical poisoning, but by starvation." End of quote. Many alternatives to chemical pesticides are being discussed and used with increasing frequency. But use of chemical pesticides remains the primary means of controlling pests, at least in those nations of the world in which agricultural productivity has achieved significant commercial proportions. The worldwide use of chemical pesticides is expected to increase fivefold between now and the year 2000. Nevertheless, future pest control will likely be accomplished increasingly by means of integrated control, which incorporates the use of pesticides with biological, cultural and other non-chemical control methods. It has been estimated that world losses caused by weeds, insects and diseases could be cut by as much as 30 to 50 percent through application of pest control techniques already available. Achieving this level of control would increase our world food supply by 10 to 15 percent.

Controlling pests is but one aspect of boosting crop yields through expanded agricultural research and education. There is great potential for increasing yields of many different crops. I am of the opinion that agricultural scientists are on the verge of making a major breakthrough in soybean yields. They are presently in process of screening varieties of soybeans and other legumes as well as strains of bacteria, to find combinations which will result in substantially more efficient nitrogen fixation and therefore much higher yields as well as reduced costs for nitrogen fertilizer in succeeding crop years. Another research area which promises to increase yields while minimizing the need for additional inputs of mechanical energy and other purchased inputs relates to maximizing the efficiency of the photosynthetic process. Sunlight is available in almost unlimited quantities and it is free, but most cultivated crops utilize less than 2 percent of the solar energy which reaches the land. Another new frontier which needs to be

explored further includes multiple cropping, to produce two, three and even four crops on the same piece of land in a single year at favorable locations on the earth's surface. Development of new edible crop species which are adaptable to extreme temperatures, to shortages of water and sunlight, and even to polluted environments, will enable expansion of agriculture onto land which is not now considered useable. We need much more research related to the reduction of soil salinity, a condition which is becoming a serious problem in some parts of the world because of the high mineral content in irrigation water accompanied by inadequate surface and sub-surface drainage. Salinity is a problem even in unirrigated areas where the amount of rainfall is insufficient for adequate leaching, or where drainage is poor.

We believe that there is dramatic potential for improving the efficiency of livestock and poultry production and thereby making available larger quantities of meat, milk and eggs at reasonable cost. In many parts of the world, animal agriculture has yet to be advanced from a subsistence to a commercial basis. There is especially great opportunity for progress in the management of livestock in the tropics and sub-tropics, where the efficiency of animal production is much lower than in the developed nations which are located in the more temperate zones. Better control of livestock diseases and insect pests will help greatly in increasing the output of livestock products in all parts of the world, through adoption of scientific knowledge which is already available, as well as through implementation of new techniques. There are dramatic opportunities for improvement of reproductive efficiency in all species of our livestock. Goals which appear to be achievable include producing two calves from each beef cow each year instead of the usual one, and the transplanting of fertilized ova from superior cows into less valuable recipient cows, thereby producing as many as 20 calves or more from a superior donor cow each year. With swine, it may well be possible to double the number of pigs which go to market each year from each sow, through use of mechanical pig nursers, as well as improved reproductive performance of both boars and sows. Research in animal nutrition must be intensified not only for the purpose of increasing livestock and poultry feed conversion efficiency, but also to reduce the consumption of animals of feedstuffs that are edible by human beings.

A concluding point with regard to the wisdom of a greater investment on both animal and plant research stems from the fact that the tremendous genetic variation which exists in today's livestock and crop species clearly suggests that the biological potential for efficiency improvement and cost reduction may well be greater than any of us can presently foresee. In short, we can, through research, minimize many of the biological limitations to meeting world food needs in the years ahead.

A truly vexing challenge to meeting world food needs involves the problem of ingrained dietary patterns. There is little value in providing more nutritious plant and animal products if local customs, religious beliefs, superstitions and illiteracy rule out the consumption of those

foods. Various cultures and subcultures in the developing nations often have rigid rules with respect to the preparation and consumption of food, and these patterns must be taken into account. It is for reasons such as these, as well as cost factors, that some of the newer high-protein foods have not been widely accepted in the so-called developing nations. Nutrition research and education which take into consideration the difficulty of changing food habits and social values with respect to food consumption is therefore a necessity.

At this point it is, perhaps, important to summarize the outlook for meeting food needs for our own U.S. citizens in the century ahead. If our United States population grows to 250 million or more by the year 2000 (as has been projected), and if purchasing power continues to increase, the additional millions of people in the U.S. will consume substantially more crop products as well as considerably more livestock and poultry products than our United States population is consuming at present. I am convinced that those domestic needs, along with the production of increasing quantities of grain and oilseeds for export, can be met rather easily if we will take steps to make sure that our productive land is kept available for food production and if we will provide more adequate support for research and education to optimize production on our available land areas. Fortunately, recent studies have indicated that we are not in danger of running out of land even if our exports reach the highest predicted levels. We are now using about 330 million acres of land for agricultural purposes, and until the past several years the long-term trend had been downward because of increased yields. If needed, as many as 450 million acres could be made available for cultivation, and therefore, over the long run, our United States crop acreage could be increased by one-third, provided, of course, that our nation's farmers were afforded the needed economic incentives for land clearing, drainage and irrigation, along with access to the essential inputs of energy, fertilizer and pesticides. Extensive soil conservation measures will be needed on much of the additional land which might be brought into production.

Past evidence suggests that most of the increase in agricultural output to meet rising domestic demands, as well as export potentials, over the next several decades will be through higher crop yields. There is reason to believe that average per acre corn yields can be doubled. Adequate support for agricultural research and technology transfer, through extension education, will lead to <u>average</u> corn yields of 175 bushels per acre by the year 2000. Potential breakthroughs in plant breeding and plant nutrition along with new and improved techniques of insect and disease control will permit <u>average</u> soybean yields to double, triple, or even quadruple over the next 25 years. With widespread use of hybrid wheat, and continually improving wheat varieties, <u>average</u> wheat yields will more than double, reaching an average of at least 80 bushels per acre before the end of this century. The potential for production achievements of the dimensions to which reference has just been made indicate that American agriculture will have the capacity to

produce a super-abundance of food for American citizens into the foreseeable future, as well as huge quantities of food for export.

The most critical question may well be one of whether our nation's food can be produced at reasonable cost. Again, there is reason to believe that the answer is yes. Given the most favorable conditions, the long term downward trend in the proportion of income spent by our United States citizens for food could be resumed with the percentage dropping as low as 12.5 percent by the year 2000. This prediction is based on a number of vital assumptions including: reasonable prices for production inputs such as energy, pesticides and fertilizer, along with minimal environmental constraints and the implementation of sound land-use policies as well as minimal governmental interference with export volume or consumer price levels. The most vital assumption, however, may well involve the adequacy of governmental support for agricultural research and agricultural extension education above and beyond that which has prevailed in recent years. Research and extension education are vitally important because production efficiency must improve steadily if food prices are to decline relative to income, and if farmers are at the same time to have adequate price incentives for increasing production.

Aside from the question of maintaining reasonable food costs to the consumer, a second question of critical importance to all of us involves concern as to whether it will be necessary in the future for our United States citizens to sacrifice dietary quality. Since the 1972 shortfall in world grain production, many of the so-called "gloom and doom cult" have jumped on the "bandwagon" of morality relative to consumption of animal products. They have tried their best to make American citizens feel that it is somehow sinful for them to consume meat, milk and eggs when there are hungry and malnourished people in many of the developing nations. Such an argument is appealing from an humanitarian standpoint but is laced with fallacies. First, it implies that plant and animal products are dietary equivalents. That this is simply not the case is so obvious that it requires no further elaboration. Second, merely decreasing production of livestock in this country will not necessarily put more food on the tables of families overseas. The question that must be answered is "who will pay for the grain to be shipped to other nations?" On the other hand, if we agree that we do have a moral obligation to help feed hungry people throughout the world, our obligation is best met when, after having provided a high-quality diet for our own people, we maintain the strength and efficiency of our United States agricultural industry, and of our United States economy, by producing as much food, feed and industrial products as we possibly can for export sales. Our entire economy, both on-farm and off-farm, benefits from exports by way of higher income, increased employment and greater strength for our dollar in world money markets.

Agricultural exports represent a vital dimension of our foreign policy, as we attempt to solidify our relationships with friendly nations and close the gap of hostility with less-friendly nations. Our growing "agripower" can and should be used judiciously to accomplish vital

foreign policy and trade goals. There is good reason to believe that we will see continuously expanding export demand for our United States grain crops, because of continued population growth, rising incomes, and changing dietary goals in many other areas of the world. Besides producing food for export sales, we can be of great help to the developing nations by working more intensively with them in providing the scientific and technical assistance which they need to improve and expand their own agricultural production capabilities. It is obvious that we must be continually concerned about the challenge of avoiding potential world famine at some future date. We must also recognize that there is no simple or single answer to this challenge.

Fortunately, a great many dedicated people are now, and will continue to be, working toward solutions to our world food problems. This leads one to conclude that there is sound basis for optimism about future world food supplies. But we're not going to meet the challenges by adopting an attitude of despair. The time to be optimistic is now! What you do, and what I do, along with what all of our fellow Americans do during the years immediately ahead will determine whether our great country will meet its continuing committment to feed its own people even as we assist in the feeding of others all around the world.

Thank you.

# APPENDIX A

## SUMMARY OF 2ND YEAR RESEARCH PROGRAMS
## For
## SOLAR HEATING & COOLING OF GREENHOUSES & RURAL RESIDENCES

(Financed by the U.S. Energy Research and Development Administration and managed by the Agricultural Research Service of the U.S. Department of Agriculture for the period May 15, 1976 to May 15, 1977.)

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P.O. Box 792
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1. LOCATION: University of Arizona, Tucson (Continuing Project)

   TITLE: Residential Environmental Control Utilizing a Combined Solar Collector Greenhouse

   PROJECT MANAGER: Dr. Carl N. Hodges, Director
   Environmental Research Lab.
   University of Arizona
   Tucson, Arizona 85721 (602) 884-2931

OBJECTIVES: 1. Extend systems of operation from the completion of Phase I through the summer and winter of 1976-77 to compile a full year's data on solar heating and storage, evaporative cooling and storage, and to confirm seasonal variations of crop production in the greenhouse chamber.

2. Integrate improvements into the system, particularly in regard to the ERL-type solar collector and techniques of foam insulations for greenhouse roofs.

3. Develop appropriate greenhouse/rural residence designs for the U.S. Southwest desert in cooperation with architects.

APPROACH: Complete greenhouse/residence (office) combination including rock storage bed adjacent to greenhouse, "clear-view" solar collector in south wall, and evaporative cooling system. Instrument the system to study the environmental variables and start growth of various plants and vegetables to study their response to conditions obtained in the greenhouse.

2. LOCATION: ARS-USDA Rural Housing Research Unit, Clemson, S. C. (Continuing Project)

TITLE: Solar Energy and Waste Heat Utilization With Greenhouse/Residence Combo

PROJECT MANAGER: Dr. T. E. Bond, Research Leader
Rural Housing Research Unit, ARS/USDA
P. O. Box 792
Clemson, South Carolina 29631 (803) 654-3646

OBJECTIVES: 1. Construct prototype greenhouse-residence combination developed in Phase I and test and evaluate the prototype for cost-benefit of added greenhouse and equipment in terms of food and fossil fuel costs saved.

2. Determine greenhouse area required per family member for year-around food growth, and develop and test cropping programs for maximum family utilization of the greenhouse area.

3. From operational and technical data, check unproven design parameters and plan modifications for optimizing operation during Phase III.

4. Analyze all prototype cost and performance data and determine or predict economic feasibility and acceptability in each of the major geographical and climatological areas.

APPROACH: One greenhouse-residence combination plan has been developed. This is to be constructed on Clemson University property near the RHRU. This will be instrumented for complete evaluation and engineering analysis. A second greenhouse-residence combination, developed by the Clemson University College of Architecture during Phase I will be built on a Clemson University Experiment Station at Florence, S.C. This will

be instrumented for complete testing and evaluation. Other concepts will be developed and design improvements will be made as dictated by test results.

3. LOCATION: Solar Energy Applications Laboratory, Colorado State University, Fort Collins, CO (New Project)

TITLE: Solar Heating of Greenhouses Combined with Space Heated Buildings

PROJECT MANAGER: Dr. C. C. Smith, Solar Applications Laboratory, Colorado State University
Fort Collins, CO 80523 (303) 491-1101

OBJECTIVES: 1. Design an optimized solar heated greenhouse/space heated building combination.

2. Construct an energy conserving greenhouse which is connected to an existing space heated building and provided with solar collectors and heat storage.

3. Provide solar heating capacity to meet 50 to 70 percent of the total space heating requirements of the combination.

4. Operate the greenhouse under actual plant growing conditions through a heating season and monitor both thermal and plant growth performance.

APPROACH: A greenhouse will be built onto or adjacent to our existing building. The greenhouse will have about the same floor area as the building. The system will consist of an integrated arrangement of the building, greenhouse, heat storage unit, and solar collectors. The greenhouse will be constructed to have a heat load of about 30 Btu/day per $ft^2$ and the building about 15 Btu/day per $ft^2$. Solar heat will be collected and distributed by forced air and collection and storage will be sized to carry about 50 to 75% of the heating requirements of the greenhouse and building. The collector area will be the same as the greenhouse area and the storage will have about 70 lb of 1-1/2 in sized pebbles per $ft^2$ of collector. Four tasks visualized are: (1) design of greenhouse and components; (2) construction; (3) instrument and monitor through a winter season; and (4) reporting.

4. LOCATION: Cornell University, Ithaca, N.Y. (Continuing Project)

TITLE: Heating Greenhouses and Rural Residences with Solar Energy

PROJECT MANAGER: Dr. D. R. Price, Associate Professor
Dept. of Agricultural Engineering
Cornell University
Ithaca, NY 14853 (607) 256-4548

OBJECTIVES: 1. Optimize the design of greenhouse solar system for the northeast by computer simulation of various systems of solar collection, transport and heat storage.

2. Test and evaluate alternative designs of greenhouse structures and components including: (a) type of collection by the greenhouse itself or by in conjunction with external collectors; (b) heat storage systems utilizing earth, stones, or buried pipe; (c) heat transport systems including both water and air; and (d) insulation techniques.

APPROACH: A 22' x 48' greenhouse will be used to test and evaluate three different heat storage methods (earth, stones, and buried pipe), several different low-cost external collectors, and both air and water heat transport systems. The mathematical model developed in Phase I will be used to optimize designs of collection, transport, and storage systems by computer simulation. Instrumentation will be completed for evaluation of a unique experimental solar heated residence, and the solar systems components, for application as low-cost rural housing.

5. LOCATION: Georgia Institute of Technology, Atlanta, Ga. (New Project)

TITLE: Design of Solar Collector and Energy Storage System for Heating Greenhouses and Rural Residences

PROJECT MANAGER: N. E. Poulos
Georgia Institute of Technology
Atlanta, GA 30332 (404) 894-3656

OBJECTIVES: To design, fabricate, test and furnish plans for a solar collector and storage system suitable for heating farm buildings, and rural residences with possible secondary use as an agricultural dryer.

APPROACH: Build low-profile rock-bed storage 50' x 16' to collect 0.59 x $10^6$ Btu/day at 50% efficiency and have a storage capacity of 1.48 x $10^6$ Btu. Will study various rock coating techniques for increasing

absorptivity. A number of glazing materials, rock sizes, air flow rates, air directors, controls and collector orientations will be studied.

6. LOCATION: University of Kentucky, Lexington, Ky. (Continuing Project)

TITLE: Solar Heated Greenhouses Ventilated with Deep Mine Air

PROJECT MANAGER: Dr. J. N. Walker, Chairman
Department of Agricultural Engineering
University of Kentucky
Lexington, KY 40506 (606) 258-5657

OBJECTIVES: To determine if deep mine air can be economically used to improve the solar energy utilization of greenhouses.

APPROACH: Growth studies will be continued in a greenhouse connected to an abandoned coal mine to evaluate the suitability of the environment for plant growth when continuously ventilating the greenhouse with deep mine air and to evaluate those greenhouse crops and cropping practices which provide optimum plant growth in the resulting cool temperatures, high humidity environment. The quality and consumer acceptability of plants and flowers grown in cool-high humidity environments will be evaluated.

An engineering analysis will be made of methods other than direct ventilation of using deep mine air to condition the air within solar-heated greenhouses and those concepts which exhibit promise will be experimentally evaluated. An engineering analysis will be made of the mass and energy exchange that takes place between ventilation air and a coal mine wall face to derive prediction relationships which will permit the determination of the mine size required to provide adequate contact time to bring the ventilation air in approximate equilibrium with deep ground temperatures.

7. LOCATION: Lockheed Missiles & Space Co., Huntsville, Ala. (Continuing Project)

TITLE: Greenhouse Heating and Cooling

PROJECT MANAGER: Mr. P. O. McCormick, Research Engineer
Lockheed Missiles & Space Co., Inc.
4800 Bradford Drive, N.W.
Huntsville, AL 35807 (205)837-1800

OBJECTIVES: To acquire data on a non-integral greenhouse/solar heating system and compare the data with computer model results. Modify analytic models as necessary so as to provide an accurate analytical model.

APPROACH: Add additional instrumentation to the present greenhouse test facility and conduct a detailed performance test of the system during the spring, fall and winter of 1976. Complete weather and solar flux data and system performance parameters will be monitored so that theory and test can be compared. The analytical models will be used to: (1) define a common basis for comparing different heating systems, including the effects of initial cost, operating cost, and performance on greenhouse productivity; (2) conduct an economic optimization study on a greenhouse heating system with separate collector and storage; and (3) identify the factors (hardware and basic design concept) which will affect the reliability of solar heating systems currently being considered.

8. LOCATION: Ohio Agricultural Research and Development Center, Wooster, Ohio (Continuing Project)

TITLE: Continuation of Experimental Studies on a Solar Pond for Heating and Cooling Greenhouses and Residences

PROJECT MANAGER: Dr. T. H. Short, Associate Professor
Dept. of Agricultural Engineering
Ohio Agricultural Research and
Development Center
Wooster, Ohio 44691 (216) 264-1021

OBJECTIVES: 1. Determine the feasibility and efficiency of a "bubble" covered solar pond (sized for a single family residence) as an integrated solar collector and heat storage unit for greenhouses and homes.

2. Devise methods of moving heat into or out of the solar pond directly or via a heat pump for use in a greenhouse.

3. Study alternatives and develop a closed-cycle gradient maintenance system for the pond.

4. Develop and test different mechanized methods of adding or subtracting insulation to greenhouse covers.

APPROACH: The pond will be monitored for daily temperature gradients and salt concentration gradients. A double wall polyethylene cover with a reflector inside the cover and above the north wall will be evaluated for collection efficiency. Heat exchanger water from the

pond will either go directly into the greenhouse or to a heat pump. The heat pump will be used to raise the temperature of the heat exchanger water after the pond has been cooled below the design temperature of the greenhouse. Methods will be investigated for maintaining the salt concentration gradient. Techniques for mechanically adding or subtracting insulation at night to the solar heated greenhouse will be evaluated and several materials will be studied.

9. LOCATION: Penn State University, University Park, Pa.
(Continuing Project)

TITLE: Energy Conservation Systems for Greenhouses

PROJECT MANAGER: Dr. J. H. White, Associate Professor
Horticulture Department
Pennsylvania State University
University Park, PA 16802 (814) 865-6595

OBJECTIVES: 1. Develop a greenhouse structure and control system that will make efficient use of solar energy.

2. Develop a solar heat storage and recovery system using the greenhouse as a collector.

APPROACH: Continue the first year's work on heat collection data acquisition. An additional greenhouse (20' x 20') will be used to test storage systems. A commercial solar collector will be joined to the greenhouse collector to test the efficiency of a combined system. Selected horticultural crops will be grown to provide data for evaluation of the systems as greenhouses. A demonstration unit will be put in operation with a cooperating grower.

10. LOCATION: Purdue University, West Lafayette, Indiana
(New Project)

TITLE: Solar Energy for Heating and Cooling Greenhouses and Rural Residences

PROJECT MANAGER: Dr. Alvin C. Dale, Professor
Dept. of Agricultural Engineering
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OBJECTIVES: 1. To develop an improved solar energy collection method utilizing a system of reflectors to concentrate the solar energy

entering an insulated air collector, devise a system for the transfer of the collected energy to a soil and groundwater storage, and determine the rates of energy gains and losses of the insulated storage field of soil with a high groundwater table.

2. To determine the feasibility of using direct air flow from the energy storage through a greenhouse to serve as its energy source for heating, and determine the possibility of using the cool air in the later winter and early spring to cool the soil and groundwater and then using this cooled mass as a supplement for cooling greenhouses.

3. To determine the overall efficiency of the system and compare it with a heat pump system for supplementing the energy required for heating greenhouses and houses.

APPROACH: An insulated solar energy collector is to be fabricated with two reflectors to concentrate the solar energy. The reflectors are to be placed at the top and bottom of the collector at such an angle so as to reflect additional solar energy into the collector at maximum efficiency. Air is to serve as the energy exchange medium between the collector and storage field. The solar heated air will be blown through an insulated energy storage field of soil and groundwater at a depth of eight feet for transfer of the heat to these materials. Starting in late August or early September, the collector will be placed in operation to build up the stored energy for the winter. In the late winter or early spring (about the first of March), the solar energy collector will be covered with white plastic and the cool air circulated through the field to cool the storage. During the summer air will be circulated through the storage field to provide cool air for ventilation and cooling of greenhouses and houses.

11. LOCATION: Rutgers University, New Brunswick, N.J.
(Continuing Project)

TITLE: Heating Greenhouses With Solar Energy

PROJECT MANAGER: Dr. D. R. Mears
Dept. Biological and Agricultural Engineering
Rutgers University
New Brunswick, NJ 08903 (201) 932-9752

OBJECTIVES: 1. Develop and evaluate practical systems for heating greenhouses with warm water obtained from low cost collectors.

2. Study conduction heat loss, radiation heat loss, and

heat exchange from the floor and beds, and develop and test techniques which utilize the floor, wall, and roof areas as heat exchange surfaces.

3. Investigate and evaluate various dye concentrations to reduce insolation during summer months.

APPROACH: Two solar collectors designed to utilize black and clear polyethylene film have been built and will be tested during the winter and spring period. These are 10 ft wide by 24 ft long. Small flat collectors of black and clear vinyl film will be studied to determine their use in soil and bed-warming systems. A full-scale system of drawing a reflective curtain horizontally over the growing area, and vertically parallel to the walls will be installed and tested in a 36 ft by 100 ft fully operational greenhouse used for tomato and cucumber productions. These data will be analyzed and the system modified as necessary. Techniques for sheet water flow in the plastic envelope of roof and walls will be further evaluated and improved. Tests will be conducted to determine heat transfer rates for various flows and water temperatures. Warm water heating of soil beds by buried pipe, and by a plastic sleeve located under the bed, has been tried. A third method will be tried, where warm water will be circulated through a floor of rocks and porous concrete. Heat transfer characteristics as well as mechanical and structural features will be tested and evaluated.

# APPENDIX B

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# APPENDIX D

## GREENHOUSE INDUSTRY TOUR

March 22, 1977

The Cleveland Greenhouse Industry tour was arranged and coordinated by the Cleveland Area Vegetable and Flower Growers Associations, the Ohio Cooperative Extension Service, and the Ohio Agricultural Research and Development Center. The Cleveland area has one of the oldest and largest concentrations of greenhouses in the United States with approximately 250 acres of vegetables and 250 acres of floral crops. Size of operations range from very small to 30 acres with the average being approximately 2.5 acres. In the last 10 years, the largest growth has occurred in the greenhouse bedding plant industry. This was exemplified by the 10 year old, 30 acre complex at Great Lakes Growers. Slow growth has occurred in the traditional or seasonal floriculture greenhouse industry with the broad consumer interest in foliage plants. The vegetable industry has seen declining growth in recent years due to high labor and fuel costs. Yet productive growers remain profitable by producing high quality yields that are 5 to 10 times greater than distant or local field yields.

### GENERAL INFORMATION ABOUT THE GREENHOUSES ON TOUR

Great Lakes Growers Greenhouse is owned and operated by John and Len VanWingerden. It was started by their father, Aart VanWingerden in the early 1960's. The basic double plastic air-inflated roof with the gutter connected design was developed at this site. The VanWingerden family owns and operates a company which sells the structures. The present operation is approximately 30 acres and still growing. Primary crops are spring bedding plants, foliage plants, violets, and greenhouse tomato plants.

Gerhart & Son Greenhouse is owned and operated by Al Gerhart and family. The 3 acre glass range can be heated by either natural gas, oil, or coal. The fuel choice depends on price, allocation and environmental restrictions. Crops grown are tomatoes and European type cucumbers. Al Gerhart has done much to promote greenhouse grown European cucumbers in the U.S. and presently sells and distributes Dutch seed and cucumber wrapping equipment. Gerharts conserve energy by efficient boiler operation, minimum ventilation, double plastic on side walls, and reflective materials behind perimeter steam pipes.

Hydes Greenhouse is owned by Bill Hyde and managed by Mr. Dale Scheidler. Seasonal flower type crops are grown in most of the two acre glass range. The Easter crop was near full bloom during the tour and consisted of 5000 pots of hyacinths and tulips, 7000 mums, 15,000 azaleas, 8000 lilies and numerous hanging baskets of flowers and foliage. An automatic chrysanthemum shading system is used on about 3/4 of an acre and is being considered for use as a nighttime insulator.

# APPENDIX E

## TOUR OF GREENHOUSE ENERGY RESEARCH

Tour of Greenhouse Energy Research at the Ohio Agricultural Research and Development Center in conjunction with the Annual Greenhouse Vegetable Day.

Morning: Tours of Energy Research related to Greenhouse Production Systems

Stop #1 A Solar Pond for Heating Greenhouses and Rural Residences
Phillip C. Badger, Department of Agricultural Engineering

Stop #2 Power Plant Waste Heat Experiments for Greenhouse Soil Heating
Warren L. Roller, Department of Agricultural Engineering

Stop #3 A Polystyrene Bead Transport System for Nighttime Insulation in a Double Plastic Greenhouse
Ted H. Short, Department of Agricultural Engineering

Stop #4 Energy and Plant Responses due to Double-Plastic Covers Over Glass Greenhouses
William L. Bauerle, Department of Horticulture

Stop #5 Experiments on the Interactions of Light Intensity, Temperature and Space Utilization on Greenhouse Plant Growth
Hugh Poole, Department of Horticulture

Stop #6 The Effects of Soil Heating on Tomato Plant Growth
Johnny Carter, Department of Horticulture

Luncheon: Program (Fisher Auditorium)

Presiding: R. G. Hill, Associate Chairman, Department of Horticulture, Ohio Agricultural Research and Development Center, Wooster, Ohio.

FUTURE PROSPECTS FOR WORLD FOOD PRODUCTION
R. M. Kottman, Director, Ohio Agricultural Research and Development Center, Wooster, Ohio.

Afternoon: Tours of Horticulture, Plant Pathology, and Entomology Research related to Greenhouse Vegetable Crops.

Stop #1 Control of Fusarium Root and Crown Rot of Greenhouse Tomatoes
Randy Rowe, Department of Plant Pathology

Stop #2 Breeding Greenhouse Tomatoes for the Future
Jay Scott, Department of Horticulture

Stop #3 Breeding Disease Resistance into Greenhouse Tomato Cultivars - Present and Future
James Farley, Department of Plant Pathology

Stop #4 Integrated Control of Greenhouse Insects and Mites
Richard K. Lindquist, Department of Entomology

Stop #5 Fertilizer Recommendations for the New Greenhouse Tomato Hybrids
William L. Bauerle, Department of Horticulture

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