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SOLAR GREENHOUSES IN MINNESOTA
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SOLAR GREENHOUSES FOR MINNESOTA

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PREFACE

This report was prepared by Mark Polich of the Minnesota Energy Agency under a contract from the Mid-American Solar Energy Complex. This is not meant to be a comprehensive report on solar greenhouses. Rather, it is intended to provide design criteria to assist individuals in designing a successful solar greenhouse. This report will help estimate the performance of attached solar greenhouses.

A special thanks is due to Mr. Jim Wylie of the Detroit Lakes Vocational Technical Institute for his contribution to the sections dealing with food production in an attached greenhouse. In addition, it should be acknowledged that much of the information on attached solar sunspaces is taken from the work that has been done at the Los Alamos Scientific Laboratory.

It is hoped that this report will further the work being done in the area of solar greenhouses and sunspaces and will provide a springboard for additional work to be done in this area. There remains a lifetime of questions to be asked and answers to be sought.

THE SOLAR GREENHOUSE PHENOMENA AND POTENTIAL FOR HEAT COLLECTION AND FOOD PRODUCTION

It is virtually impossible to look through several issues of any popular home or garden magazine today without finding an article about solar greenhouses. These articles often discuss-- in limited detail--the many benefits of solar greenhouses including energy savings, vegetable or ornamental plant production and a wonderful new living area in your home. There are many people who claim that solar greenhouses will be as popular in the 1980's as outdoor decks were throughout the 1970's.

This explosion of publicity on solar greenhouses in magazines, books and newspapers has created a situation where the demand for information has exceeded the current level of knowledge regarding design, and performance. The solar greenhouse phenomena is simply too new at this point for all the answers to be known.

Unlike active solar systems which have been used in the United States since the early 1900's, solar greenhouses may have totaled a dozen 10 years ago. And although literally thousands of attached solar greenhouses have been built around the country in the past decade, few have been adequately monitored. Performance estimates and optimum design criteria remain in the model T stage.

Perhaps a bit of history on the solar greenhouse phenomena may be useful here. Prior to the Arab oil embargo in 1973, home hobby greenhouses were quite popular with avid gardners. The structures were reasonably priced but more importantly, could be heated during cold periods at a minimal cost. As fuel prices soared, heating these greenhouses became very costly. As a result,

fewer and fewer people could afford such a luxury. At this same time people began looking toward solar energy as a potential way to reduce their rising home heating bills.

In the mid-1970's, solar pioneers Bill and Susan Yanda combined these two ideas and began popularizing what has been known as the attached solar greenhouse.

The term solar greenhouse generally refers to greenhouses whose heating and light requirements are provided largely by solar energy. It is true that all greenhouses use light from the sun, but up until now few used solar energy to provide heat for the structure and even fewer incorporated some type of storage to provide heat for extended cloudy periods.

The association between the hobby greenhouse businesses and solar energy advocates has been all positive, however. Many in the home hobby greenhouse business now claim to be selling a "solar" greenhouse, while many solar energy advocates claim to be horticultural experts. There needs to be more cooperation between these two groups where each utilizes its own expertise in order to develop efficient solar greenhouse structures.

This report has attempted to begin that process by the fact that both solar experts and horticultural experts have played a major role in this final product.

Planning the Solar Greenhouse

Probably the most important step leading to a successful solar greenhouse project is good planning. This process begins by defining the primary goals for the project. The three most common goals are: 1) saving energy; 2) provide a space to grow

plants year-round; or 3) simply create additional living space.

To minimize confusion, the following terms will be used throughout the remainder of this report.

Solar sunspace -	A solar system whose primary function is to provide supplemental heat to the house
Solar greenhouse -	A solar system whose primary function is to provide a space for growing plants
Solarium -	A solar system whose primary function is to provide additional living space
Attached solar structure -	Refers to all three of the above terms

This decision will affect every step beyond the initial discussion of the project so therefore it must be carefully thought out.

Don't make the mistake here of thinking that it is possible to optimize all three of these end uses. It can't be done, or at least there isn't enough information available at this time to know how to do it successfully. Once the design process begins you'll see that a design criteria required for one goal inevitably results in a compromise for another goal. For instance, maximizing food production would require over 80 percent of the floor area to be utilized for growing beds. Maximizing additional living space would mean that most of the space within the greenhouse be open for chairs or tables. You can see the problem if you try to have both growing space and additional living space as the primary goal.

Now this doesn't mean that an attached solar greenhouse can't serve different functions. The example above could be changed to

have only 50 percent of the floor area in growing beds while allowing space for furniture. You can see how compromises must be made.

A similar situation arises when one tries to maximize heat collection and plant production. To maximize the performance of a solar sunspace you would probably allow the temperature to drop into the 40's or 50's at night. However, certain plants may not be able to tolerate these low temperatures. In fact, in the coldest part of the winter a solar greenhouse will probably require additional heat in the night to keep from damaging the plants. Clearly, this is not the way to maximize energy savings.

The designer or owner of an attached solar structure should decide early in the process the primary goal. This isn't to mean that an attached solar structure can't serve multiple functions. In fact, it might make the most sense to try to incorporate a little of each of these ideas. It is recommended that if you desire multiple functions, freely incorporate these ideas while minimizing the negative effects on the primary goal. By following this recommendation, you will have started a solid foundation on which to build a successful project.

To help you select the primary goal of the project, a chart is provided below which highlights the advantages and disadvantages of the three major functions.

Potential Energy Savings with an Attached Sunspace

One of the most common reasons for adding a solar sunspace is for energy savings in the home. The idea being that in the spring and fall and many sunny winter days, the sunspace will

TABLE 1-1

<u>Primary Function</u>	<u>Advantages</u>	<u>Disadvantages</u>
Heat Collection (sunspace)	<ul style="list-style-type: none"> • savings in home heating costs • additional living space possible • eligible for state and federal tax credit 	<ul style="list-style-type: none"> • large temperature variations • may be difficult to evenly distribute heat to entire house • overheating may be a problem in spring and fall
Food Production (greenhouse)	<ul style="list-style-type: none"> • ability to grow plants year-round • potential savings on food bill • possibly eligible for state tax credit • place to start seedlings in spring • adds humidity to house in winter 	<ul style="list-style-type: none"> • requires up to 1 hour each day • potential humidity problem in winter • federal tax credit not applicable • environmental control devices add costs • may require supplemental heat during coldest winter months
Additional Living Space (solarium)	<ul style="list-style-type: none"> • expand size of house without requiring additional heat • provides a pleasant warm place to sit on sunny winter days • excellent space to grow plants throughout the winter • possible state tax credit 	<ul style="list-style-type: none"> • potential large temperature extremes • federal tax credit not applicable

provide additional heat to the home, thereby decreasing the amount of fuel required. Because of the constant interaction of energy flow between the sunspace and home and the endless list of design variables, it is very difficult to accurately predict the performance of an attached sunspace.

In Chapter 5 a procedure is given to estimate the energy savings potential of a sunspace. Using this calculation procedure, we were able to estimate the approximate energy savings for three different size houses, insulated to different levels when different size sunspaces were added (see Table 1-2). The houses in this example included the following: a small one-story house with 1080 square feet of heated living space; a medium sized one- or two-story house with 1,500 square feet of heated living area; to a large two-story house with 2,000 square feet of heated living area. Calculations were done assuming three levels of conservation including: poorly insulated (includes caulking, weather stripping, night temperature setback, and minimal ceiling insulation); moderately insulated (all measures listed above plus additional ceiling and rim joist insulation); and well insulated (all measures listed above plus wall and basement insulation). All of these 27 hypothetical homes in our example were assumed to be located in St. Cloud, Minnesota, 8,868 degree days/year.

To each of these homes three different sized sunspaces were added, 6 feet by 12 feet, 8 feet by 20 feet and 10 feet by 30 feet. The sunspaces have 65 square feet, 108 square feet and 162 square feet respectively of double glazed glass tilted at 55 degrees with R9 night insulation. Additional assumptions about these sunspaces are given in Appendix .

TABLE 1-2

SOLAR SUNSPACE PERFORMANCE

		House Size	Ins. Level	Heating Load	BLC Btu/ft ²	Sunspace Size	Net Glazing Area	L.C.R.	Solar Saving Fraction	\$ Saved Nat. Gas \$4.50 MCF	\$ Saved Oil \$1.20 gal.	\$ Saved Electricity 5¢ kWh
Small House	1.	1080	P	86 MMBtu	9698	6x12	65	149	10.7%	69	125	135
	2.	1080	P	86	9698	8x20	108	90	14.8%	95	172	186
	3.	1080	P	86	9698	10x30	162	60	21.6%	139	251	273
	4.	1080	M	70	7894	6x12	65	121	12.6%	66	119	129
	5.	1080	M	70	7894	8x20	108	73	18.4%	97	174	189
	6.	1080	M	70	7894	10x30	162	49	24.5%	128	232	252
	7.	1080	G	52	5864	6x12	65	90	14.9%	58	104	113
	8.	1080	G	52	5864	8x20	108	54	23.3%	91	164	177
	9.	1080	G	52	5864	10x30	162	36	33.2%	129	234	254
Medium House	10.	1500	P	102	11502	6x12	65	177	8.9%	68	120	133
	11.	1500	P	102	11502	8x20	108	107	12.8%	98	177	192
	12.	1500	P	102	11502	10x30	162	71	18.4%	141	254	276
	13.	1500	M	82	9247	6x12	65	142	10.3%	63	114	123
	14.	1500	M	82	9247	8x20	108	86	15.9%	98	176	191
	15.	1500	M	82	9247	10x30	162	57	21.0%	129	232	252
	16.	1500	G	61	6879	6x12	65	106	12.8%	59	105	114
	17.	1500	G	61	6879	8x20	108	64	20.6%	94	170	185
	18.	1500	G	61	6879	10x30	162	42	28.8%	132	238	258
Large House	19.	2000	P	118	13306	6x12	65	205	7.3%	65	116	126
	20.	2000	P	118	13306	8x20	108	123	12.6%	112	201	218
	21.	2000	P	118	13306	10x30	162	82	16.1%	143	257	278
	22.	2000	M	95	10713	6x12	65	165	9.8%	70	126	136
	23.	2000	M	95	10713	8x20	108	99	14.0%	100	180	195
	24.	2000	M	95	10713	10x30	162	66	20.6%	147	265	287
	25.	2000	G	71	8006	6x12	65	123	11.5%	61	111	120
	26.	2000	G	71	8006	8x20	108	74	18.4%	98	177	192
	27.	2000	G	71	8006	10x30	162	49	24.5%	131	235	255

From Table 1-2 we can see that the annual percent energy savings ranges from a low of 7.3 percent on a poorly insulated large house with a small sunspace added to a high of 33.2 percent on a well insulated small house with a very large sunspace added. The dollar savings range from a low of \$58.00 with a well insulated house heating with natural gas and a small sunspace added to a high of \$287.00 with a moderately insulated large house heated by electricity and a large sunspace added.

It is interesting to note that although the percent energy savings increases for a similar sized sunspace added to a house that is increasingly better insulated, the actual energy saved and therefore dollar savings decreases. This phenomena holds true for any energy conservation measure, the less energy used, the less energy savings can be expected from the same measure.

Keep in mind that each house is different and that the estimates in Table 1-2 are simply that, estimates. However, the range of savings, approximately 10 to 30 percent, is consistent with many computer prediction models as well as actual monitored results. To "ball park" estimate the energy savings from a planned sunspace, select the house size, level of conservation, size of sunspace and back-up heating fuel which is closest to your situation. To get a more detailed estimate, see Chapter 5.

If a sunspace is also planned to be used for growing plants year-round, the energy savings potential will be decreased by as much as 50 percent. This is due to two factors. First, the temperature within the sunspace will possibly have to be kept as high as 65 degrees F. during the evening instead of the 45 degrees F. that it might be allowed to drop to if no plants were involved.

This higher temperature is required to maximize production potential. Secondly, during the coldest winter months, supplemental heat will be required to maintain optimum growing conditions.

If the sunspace is only used for extending the garden season in the fall, only used for cool weather crops in the winter or seedlings in the spring, the negative effect on heat savings may only be 10-25 percent.

Potential for Food Production with an Attached Solar Greenhouse

Although most people add a solar sunspace primarily for energy savings, most have visions of someday harvesting fresh tomatoes in January. And this is not an unrealistic dream. People all over the United States, including here in Minnesota, have discovered it is possible to grow fresh vegetables year-round in a solar greenhouse. However, these same people realize that this requires a time commitment and knowledge of horticultural skills. Surveys done of solar greenhouse owners in the New Mexico and the New England area have shown that when horticultural skills are lacking, production drops due to insect problems, improper watering and improper temperature, humidity, carbon dioxide, and sunlight levels.

An attached solar greenhouse (one properly designed and operated) can supply the majority of fresh produce needs of a family and enhance the nutritional value of the food being consumed. A structure from 70 to 200 square feet should be adequate for a family of four. An average solar greenhouse owner will spend from 15 to 30 minutes each day caring for and harvesting their crops. The actual work by a professional laborer could be accomplished within 6½ minutes. This extra time is a result of

people enjoying the atmosphere within the greenhouse, particularly during the winter.

It is conceivable that a properly designed and operated solar greenhouse in Minnesota could produce up to 6.5 pounds of produce per square foot of growing area annually. Free-standing solar greenhouses in northwest Minnesota have already demonstrated their commercial greenhouse production yields. In today's economy, a solar greenhouse owner could realize a grocery bill savings of \$4.87 to \$6.50 for each square foot of growing space annually. In order to reach this level of production, a solar greenhouse must be designed for the growing environment of the plants and employ a minimum of trade-offs for energy conservation and residential heat production. The greenhouse must be operated with intensive and professional cultural techniques. This does not mean that every solar greenhouse has achieved this level. Many have only produced 25 percent or less of their productive capacity either because of a poorly designed structure, lack of time commitment or lack of horticultural skills.

Vegetable production in a solar greenhouse cannot only help an individual family reduce their grocery bill, but it has some major implications for energy used nationwide for food production, processing and transporting. For an overview of this topic, refer to Appendix B.

Design Recommendations for an Attached Heat Collecting Solar Sunspace

In order to achieve the energy savings from an attached solar sunspace shown in Table 1-2, the sunspace must be well designed and constructed. The main features affecting the overall performance of a solar sunspace include the following:

- numbers of layers and type of glazing,
- tilt of glazing,
- night insulation,
- thermal storage,
- heat distribution,
- thermal resistance of common wall,
- thermostat setting,
- infiltration,
- color of sunspace interior surfaces, and
- lightweight objects within the sunspace.

Since each of these ten factors affect the sunspace performance, designers should pay particular attention to each one.

It is recognized that since a sunspace is usually added to an existing dwelling, compromises must be made. The perfect solar sunspace will never be designed and we probably wouldn't recognize it even if it was built. The task for the designer then becomes designing a sunspace which incorporates as many optimum features as possible while still meeting the needs and objectives of the owner. The following listing of design criteria, therefore, is not meant to restrict those designing sunspaces, but rather to indicate the energy consequences of design decisions.

In addition to the ten design factors just listed, there is an additional very important design parameter which affects overall

sunspace heating performance. This factor revolves around the relationship of the size of the sunspace to the building to which it will be attached. It is called the Load Collector Ratio (LCR) and is defined by

$$LCR = BLC/A_c$$

where BLC, the building load coefficient, is the steady state heat loss through all building surfaces except the south solar wall, and A_c is the area of principal sunspace south-facing glazing or glazings. By studying Table 1-2, you can see that the LCR varies according to the conservation level in each house and the sunspace size. (A more detailed discussion of the LCR is given in Chapter 5.)

The LCR is important to know because it dictates the extent to which the overall sunspace performance is affected by design changes. For example, the performance of a sunspace with a high LCR is less affected by a low glazing tilt angle than if it had a low LCR. The house with the larger LCR probably is not insulated very well and can utilize excess solar heat during the spring and fall whereas a well insulated house with a low LCR probably would not need as much solar heat during those same periods.

Glazing

A. Number of Layers of Glazing

Although single glazing transmits a higher percentage of solar radiation than double or triple glazing, it is not recommended for sunspaces due to increased condensation problems, heat loss and chance breakage. As shown in Appendix A Table A-12, verticle triple pane out performs double pane by 7 percent over the

entire heating season and quad pane by less than 1 percent. For a 60 degree or 45 degree tilt, triple pane is still the winner over quad pane by less than 4 percent, but only 1 percent over double pane. When the increased cost for using triple pane is considered, double pane seems a clear favorite, except for possibly a vertical glazing application. An attractive alternative to double or triple pane might be the use of a double glazed window with a thin layer of high transmission film stretched between the two panes. This window just recently introduced on the market transmits solar radiation nearly like a double pane window, yet insulates like a triple pane. According to manufacturers data, this window can outperform a triple pane window by over 10 percent.

B. Night Insulation

Night insulation is highly recommended for all glazing surfaces. The percentage increase in solar radiation absorbed per square foot over double pane, non-insulated glazing tilted at 60 degrees are as follows:

double glazed, R4 night insulation	48%
triple glazed, R4 night insulation	29%
quad glazed, R4 night insulation	12%

From this we can see that night insulation has a significant effect on overall sunspace performance, particularly for double glazing with night insulation. The percentage increase in performance decreases as additional layers of glazings are added because each additional layer blocks out approximately 10 percent of the solar radiation available.

The energy savings due to night insulation seems to be the greatest when the sunspace minimum temperature is increased. If no

thermal mass is used within the sunspace and the sunspace can be allowed to drop in temperature at night, the energy savings with night insulation is decreased substantially. In this situation, using night insulation on windows in the wall separating the house and the sunspace would be recommended.

In terms of R-value of night insulation; the performance of the sunspace increases as the thermal resistance of night insulation increases, rapidly at lower R-values, more slowly at higher R-values. It is interesting to know that because of this phenomena half of the savings obtained at R9 is obtained at R2 and three-fourths is obtained at R4. The rule here is if the cost increase is small to go from say R4 to R10, then the R10 may be preferable. If the difference is great, the lower R value night insulation might make more sense.

It is important here to know that a high quality, tight fitting, easy to use window insulation is probably more important than the R value of the insulation. Some tests have shown that an R10 night insulation with a poor perimeter seal may only be the equivalent of R1. In addition, if night insulation is not convenient to use, its beneficial effect will be negated.

C. Glazing Tilt

The optimum tilt angle for sunspaces in Minnesota is between 50 degrees and 60 degrees from the horizontal. The optimum is quite broad, however, seasonal performance drops only about 5 percent for tilts ± 15 degrees from the optimum (see Figure 2-1). For double vertical glazing, there is a 15 percent decrease from the optimum in solar radiation transmitted during the heating season. When net heat gain is considered, the performance of double pane vertical

FIGURE 2-1

Percentage Solar Radiation Transmitted Through South
Facing Glass at Various Tilts During the Heating Season
for Mpls./St.Paul

glazing is almost 27 percent less than the optimum tilt angle. If R4 night insulation is used, the penalty for vertical glazing is approximately 18 percent.

If a decision is made to use two glazing panes--one vertical and one tilted as in a lean-to solar sunspace with roof glazing--the performance penalty may be as high as 25 percent compared to a sunspace with glazing tilted at the optimum.

There are other factors that should be considered when deciding on the slope of the south glazing. These include summer-time overheating, reduction in useable floor area, shading within the sunspace, manufacturers warranties, etc. Table 2-1 lists the advantages and disadvantages of various slopes for south facing glass. A designer should consider these factors along with values of solar transmittance when deciding on the tilt angle.

D. Glazed End Walls

There is a clear thermal disadvantage to glazing the east or west walls of a sunspace. It results in higher heat loss, lower sunspace temperatures and a greater home heating load. The performance penalty for glazing east and west walls is approximately 15 percent if night insulation is used or 35 percent if no night insulation is used.

Thermal Storage

Thermal storage in passive solar buildings and particularly sunspaces, is an area where there is still much to be learned.

Thermal storage serves two functions including:

- moderate temperature fluctuations, thus preventing overheating, and
- provide heat for evening hours.

TABLE 2-1

Considerations for Sunspace Glazing Tilt Angles

	<u>Advantages</u>	<u>Disadvantages</u>
Low sloping glass (15°-40°)	<ul style="list-style-type: none"> • Provides for maximum springtime solar gain • may be useful for attached pit solar greenhouses 	<ul style="list-style-type: none"> • Difficult to shade in summer • Loss of head room • Doesn't qualify for state tax credit • Difficult to provide for night insulation
Medium sloped glass (45°-65°)	<ul style="list-style-type: none"> • Provides for optimum solar gain • Good performance during coldest winter months 	<ul style="list-style-type: none"> • Somewhat difficult to shade • Slight loss of head room • More difficult to build than vertical application • Manufacturer may void warranty
Steep sloped glass (70°-90°) and Vertical	<ul style="list-style-type: none"> • Easiest to build • Easiest to shade in summer • Performs best from Nov.-Feb. • Easy to insulate • Useable floor space right up to glass 	<ul style="list-style-type: none"> • Performance drops during fall and spring • May be too high to attach to house • Poor sun penetration in spring and fall

The question with no clear answer at this point is whether a sunspace has a better performance with or without thermal storage. The arguments for incorporating storage within a sunspace include: temperatures will be lower, therefore, decreasing heat loss through the sunspace glazing; minimizing overheating problems in the house during warm spring and fall days; and heat will be provided not only during the daytime but also during evening hours. The main arguments against thermal mass within the sunspace include: heat will be transferred into the house sooner; excess heat will be stored within the main living area of the house rather than in the sunspace; and money can be saved by not using thermal mass.

There are no clear answers. A suggestion might be to use thermal mass within the sunspace if the relationship of the sunspace size to the house is such that not using thermal mass would cause overheating in the house or unwanted venting of excess heat during the heating season. Thermal mass might also be appropriate if the sunspace is a primary living area of the house rather than used primarily as a heat collector.

On the other hand, if the sunspace is fairly small in relation to the house (large LCR) or the sunspace is used primarily as a heat collecting device, one might consider omitting thermal mass. More research is needed in this area in order to arrive at more definite conclusions. If thermal mass is used, it should be a dark color -- although black is not essential -- and positioned in such a way that it receives direct solar radiation between the hours of 9:00 AM and 3:00 PM during the heating season. It is best to distribute the mass over as wide an area as possible for maximum effectiveness.

The most common materials for thermal mass within a sunspace include water, masonry wall, or a concrete or rock floor. If water is the choice, the minimum volume should be 3 to 4 gallons per square foot of common wall between the sunspace and house. Modest increases in performance can be achieved by large volumes up to 10 gallons.

If a masonry wall is used, the optimum thickness is in the range of 8 inches to 1½ feet, but very little performance reduction occurs for thicknesses greater than the optimum. For concrete or rock floors, thickness should be approximately 4 inches.

Venting Excess Heat Into the House

Excess heat collected within the sunspace during the heating season can be distributed into the house either by natural ventilation or a small fan. If natural convection is used, the vent opening should be a minimum of 1 to 2 percent of the area of the common wall between the sunspace and house for each row of vents (top and bottom). For instance, if the common wall is 8 feet high by 20 feet long, the area would be: 8 feet x 20 feet or 160 square feet. Therefore, the top and bottom vents should each be at least 1 to 2 percent or 1.6 to 3.2 square feet. Vent areas up to 10 percent have a minimal effect on sunspace performance. Remember to include tight fitting dampers in the vent areas to prevent reverse thermosiphoning during evening hours. One common approach to venting heat from the sunspace into the house is to open a door, window or sliding glass door during the day. Although this seems acceptable in theory, practice has shown that the heat does not transfer readily into the house and sunspace temperatures

increase which increases the heat loss through the glazing. The overall effect is lower sunspace performance.

If a fan is considered for heat distribution, use the smallest fan possible, maybe sized in the range of 1 to 5 cfm/ft² south glazing. For low mass sunspaces, a slightly larger fan might be more appropriate. The European style room-to-room fans, recently introduced in this country, seem to disperse the air from the sunspace more than conventional duct fans. This means that people sitting within the house will feel less chilled with cool air passing over their skin.

Wall Thermal Resistance

The effect that the thermal resistance of the common wall has on the performance of the sunspace depends on the design and usage of the sunspace. If the sunspace is used primarily as a heat collector and has very little integral mass, insulating the common wall will increase the overall sunspace performance. This is because the common wall will in effect be similar to any exterior wall which when insulated will reduce the overall heating load.

If, on the other hand, the sunspace incorporates a large amount of thermal mass, leaving the common wall uninsulated may slightly increase the overall sunspace performance. This is because the heat will be transferred from the sunspace into the house easier if the wall is uninsulated.

Lower Thermostat Setting

The overall performance of a sunspace may be very sensitive to a lower thermostat set point depending on the sunspace design

and use. Sunspaces with large amounts of thermal mass which are used as living spaces throughout the day and night, can have a higher performance with a lower thermostat set point. A 10°F decrease in the set point from 65°F to 55°F may increase performance by as much as 20 percent. The savings, however, increases very little with temperature set points below 50°F because temperatures will probably seldom drop below 45°F . On the other hand, a low mass sunspace used primarily as a daytime space heater and allowed to drop to ambient at night will perform better than one where supplemental heat is provided at a specified temperature.

Infiltration

The importance of reducing infiltration rates has been made very evident with the popularity of the super-insulated house. Infiltration is a particular problem with exterior doors, operable windows and vents. The performance of the sunspace may drop considerably with increases in infiltration rates, stressing the importance of good tight construction.

Color of Sunspace Interior Surfaces and Free-Standing Objects

A. Wall and Storage Container

Sunspace performance may be increased nearly 20 percent by changing the color of the wall and storage container from white to black. The color of the storage container seems to be twice as important as the wall color. Selective surfaces on storage containers can improve performance slightly but are probably not cost effective.

B. Floor

The floor color should also be a dark color rather than white. The performance may decrease 20 percent with the lighter colored floor.

C. End Wall and Ceilings

The performance of the sunspace is only marginally effected by changes in the color of the end walls and ceiling. Choosing a lighter color for these surfaces seems a good choice.

Lightweight Sunspace Objects

If a large amount of thermal mass is being utilized in the sunspace, the overall sunspace performance may decrease if there are many lightweight objects within the sunspace. These lightweight objects heat up very quickly and transfer excess heat to the air within the sunspace. As the temperature of the air in the sunspace rises, so does the heat loss through the glazing.

A low mass sunspace that has a high LCR will not be penalized as severely as a high mass sunspace. This is because the excess heat in the greenhouse reradiated from the lightweight sunspace objects can be transferred into the house immediately and used or stored within the mass of the house for later use. Lightweight objects in this type of sunspace may only minimally affect the overall sunspace performance.

Design Summary For Attached Heat Collecting Solar Sunspace

As was detailed in this chapter, there are many design variables to consider with a sunspace. Many design decisions must be based on the desired use by the owner. A critical early decision is whether to utilize the sunspace primarily as a heat

collector or expand its functions to include additional year-round living space. The overall recommendations for these two sunspaces are listed below in Table 2-2 and Table 2-3.

TABLE 2-2

Design Recommendations for a Sunspace
Used Primarily as a Heat Collector

- Double glazing tilted at an angle between 50° and 60°
- No night insulation on sunspace south glazing
- Night insulation used on glass in common wall
- Insulated end walls
- Very little thermal storage (depends on LCR)
- Properly sized vents
- Small fan for distributing heat into house
- Insulated common wall
- No minimum thermostat setting
- Low infiltration
- Dark colored interior surfaces

TABLE 2-3

Design Recommendations for Sunspace
Used as Living Space and Heat Collector

- Double glazed windows tilted at an angle between 50° and 90°
- Minimum of R4 night insulation
- Insulated end walls
- Moderate to large amounts of thermal storage
- Properly sized vents
- Uninsulated common wall
- Minimum thermostat setting of 45°F
- Close attention to sealing infiltration leaks
- Dark colored sunspace interior surfaces
- Few lightweight sunspace objects

Design Principles of an Attached Solar Greenhouse in Minnesota

As strange as it may seem, design principles vary little from different areas of the United States and Canada. A common error in designing solar greenhouses has been to consider it a heat collecting structure that grows a few plants. That type of structure should be considered a sunspace. A solar greenhouse allows the plants to intercept the solar radiation first. The plant may use as much as 10 percent of the light for growth and the green leaves will transform much of the remaining high energy white light into infrared heat, as an absorber plate in a solar collector. This heat must be collected for use in the greenhouse and the surplus can be used in the dwelling. A solar greenhouse must have sufficient control to maintain a growing environment. Some designers feel that a minimal growing environment is the best choice when designing a solar greenhouse since these structures can supply a larger amount of surplus heat to the attached dwelling. Other designers, as this paper would basically agree, will design the solar greenhouse for optimum growing environment. In this style of solar greenhouse, the economic return for food produced can be from 6 to 10 times greater than the fuel saved in the home. An optimum environment can be created when maximum light reaches the plant, temperature and humidity is closely controlled, sufficient soil volume is provided for plant roots and there is a high level of cultural management skill employed by the operator. In addition, solar greenhouses always maximize energy conservation and provide storage for solar heat generated during the daytime hours.

GLAZING AND LIGHT

There are two main considerations when installing the south clear glazing; the materials and the slope angle. The following considerations should be made when selecting the glazing material:

- a. White light transmission
- b. Infrared wave transmission
- c. Longevity of material
- d. Ease of installation
- e. Replaceability
- f. Fire resistance
- e. Temperature effect
- g. Heat transfer efficiency
- h. Building code limitations

(Bond, 1977)

TABLE 3-1

Design Options for Attached Solar Greenhouses in Minnesota

Design Principle	Option I	Option II	Option III
Glazing material	Doubled layer glass (thermopane) (Low iron desirable)	Doublewall acrylic or polycarbonate	Double layer of greenhouse fiberglass
South glazing angle	Latitude + 20° (15°) degrees (winter)	Latitude + 10 degree (Fall & spring)	Vertical (less desirable)
Insulated Ceiling	60 degrees Painted white	Horizontal Painted white	Glazed w/ shields
North wall	Specular reflective	Diffused reflective (white)	Light color
End wall	If L=2W then insulated	If L<2W then glazed	East wall glazed
Heating system	Radiator + ground heat	Infrared + ground heat	Infrared
Cooling system	Electric fan	Natural draft	Solar vent
Solar Energy Storage	Soil - under floor	Water - under floor	Isolated storage
Perimeter Insulation	Tundra insulated	4-6 ft. deep	To footing
Solar heat transfer	Fans to dwelling (Retrofit)	Heat Exchanger (New construction)	Thermosiphon
Floor	Ground benches	Porus concrete	Raised benches
Night insulation	Blanket (R-4)	Ridged (R-6)	Reflective (R-2)
Door	Air Lock	From interior	Limited Use

The options can be mixed as desired for each design principle. There is no indication as to the preferred option or the methods to achieve the options in this table.

If a "greenhouse effect" is desired from the glazing, then consideration should be given to the lowest transmission of infrared waves and the lowest heat transfer coefficient (U-factor).

Plants require a full spectrum of light to develop properly. Low iron glass (white glass) is better than regular window glass. Only greenhouse fiberglass coverings should be used while lumberyard fiberglass should be avoided. There is a limit to data availability for some of the newer greenhouse coverings. Plants need 2000-4000 foot candles of good quality light reaching their leaves in order to produce proper yields.

TABLE 3-2

Properties of Double Glazing Materials

Materials	Infrared Transmission %	White Light transmission Percent	Life Year	U-Factor	Comparative Cost Factor
Double Glass	1	78	30	0.58	1.0
Double Flat Fiberglass	1	69.7	5-15	0.66	0.54
Double Corrugated Fiberglass	1	62.3	5-15	0.66	0.66
Poly carbonate	1	73	10	0.62	0.45
Double Polyethylene	63	79.3	2	0.58	0.17
Tedlar	26	84.2	6	0.62	0.60

Sources: Bond, 1977; White, 1980

Maximizing the light reaching the plant leaves requires that the glazing be sloped so the sun rays strike the covering at a 90 degree angle. If the angle of the greenhouse south wall is equal to the latitude plus 10 degrees from the horizontal level, then the greenhouse will perform well over the entire year. As the collector approaches a slope of the latitude plus 20 degrees, winter performance will increase while summer performance will decrease. (Peck, 1976) A selected slope angle for Minnesota would be 55-65 degrees. If a vertical south wall is used, there will be decreased winter performance and very little performance during the summer within the greenhouse.

FIGURE 3-1

FIGURE 3-2

FIGURE 3-3

FIGURE 3-4

Another factor that influences the quantity of light reaching the plants is the reflection of the light towards the plants. The "light path angle" studies presented in this paper gives some feeling for these conditions. Figure 2 with a totally glazed roof shows that light reaching a reflective north wall may be reflected outside the greenhouse. Figure 1 shows that insulating a portion of the roof will have very little effect on the amount of light reaching the plant during the winter. It will reduce heat loss and it can aid in preventing overheating in the summer. Figure 3 shows a sloping north wall reflector connected to the insulated roof which directs the light downward on the plants. This will improve light reaching the plant. (Lawan, 1973, Maes, January, 1979; Maes, May, 1979) Even a small gain in dim winter light, sometimes only 500 foot candles, will have an impact on plant growth. Figure 4 offers a means to incorporate a sloping north wall to an existing south porch. There will be a loss of some marginal growing area but growth should be improved in the front area during the winter.

On sloping reflecting surfaces, a diffused reflective paint should be used. White paint gives the best results. On vertical surfaces, aluminum or mirrors will give best results. These surfaces beam the blue light to the plants which influence plant growth (Piserchio, 1977) In some circumstances, diffuser plates may be necessary to prevent burning of the plant leaves. Even snow banked away from the greenhouse can influence the light reaching the plants. (McCullagh, 1978)

EAST AND WEST WALLS

If the solar greenhouse length is twice as great as the width, then the east and west wall need not be glazed to admit light. The interiors of the end walls can even be painted a non-reflective color since this will have little influence on plant growth. There will be a significant savings in heat loss when these walls are not glazed. If the greenhouse has a small length to width ratio, east wall glazing would be a first choice since plants respond best to morning sunlight. There may be other reasons to glaze the east or west wall but care should be exercised to have good night insulation. (MacKinnon, 1977)

HEATING SYSTEM

In designing an attached solar greenhouse, a supplementary heat system will be necessary to provide environmental control for plant growth. Plants can tolerate a very wide range of temperatures but for maximum quality and yields, it may be necessary to control the environment within 10 degrees or so. Any common domestic heating

Note: Polyethylene, 80psi thin wall lasts 3 to 5 years, offers best economy and can be used with water from 90 to 100 degrees F. Use velocity of 2-3 feet per second or 2.7 - 4.0 GPM flow for a loop up to 400 feet. If water table is within 6 feet, insulate the entire floor. The heat from the ground will supply about 25 percent of the air heat needs, so a radiator, fins or radiant heating system must be installed. Pipes are usually buried 15 to 18 inches. (Ingratta, 1979)

TABLE 3-3

Soil Heat Properties

Soil Condition	Conductivity BTU, M-ft- ^o F	Capacitance BTU-Ft ³ - ^o F
Dry	0.2	25
Damp	0.9	30
Saturated	1.3	67

Fowler, 1977)

Soil volume weight= 100 lbs./cu ft.

Specific gravity 2.65

TABLE 3-4

Heat Transfer for 4 Inch Plastic Pipe to the Ground

Use Nusselts' Equation to determine the transfer of 192,000 BTU/hour at 50 degree difference with 15-4 inch x 60 foot long plastic pipe.

$$hc = 0.0202 \frac{k}{D} (DV_p)^{0.8} \frac{C}{\mu} =$$

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

hc = heat conduct coefficient

k = is a constant for air

D = Diameter of pipe in feet

V = Mass velocity, lbs/ sq ft-hr

μ = The viscously of the fluid

C = 0.00336 (air)

G = pV

system could be used in the greenhouse and it should be sized according to the heat load needs calculated from appendix 2 plus 25 percent. For the greatest heat conservation of from 26 to 45 percent, the solar greenhouse operator may wish to choose a heating system specifically designed for greenhouse energy savings. Either a ground heating system or a radiant energy heating system would be a good choice.

A radiant energy system is either electric or gas that is vented and contains a reflector to reflect the infrared waves to the plants. These waves when striking the leaves, warms the plant but only indirectly the air around the leaves. Therefore, a lower temperature in the greenhouse can be used. On the West Coast, a 62 percent savings of fuel was reported with this system. (White, 1980) This heating system is compatible with the design system employed in the attached greenhouse to handle the infrared waves from the sun efficiently.

Another recent energy conserving heating system for greenhouses is underground heating or root zone heating. If plant materials are being grown in soil in the ground either air or water pipes can be buried in the soil. It can also serve as a storage system. When the soil is heated to proper plant growing temperatures, then the air temperature in the greenhouse can be lowered 10-20 degrees. If the pipes are held at an average temperature of 90 degrees F. and spaced 12 inches apart, then about 21 BTU/hour per square foot will be provided to moist soil, (15-20 BTU/hour/square foot design calculation). (Roberts, 1980) Ground heating is considered the most efficient greenhouse heating system. (Ingratta, 1979) Along with the advantage of energy savings, soil heating has demonstrated increased yields, (Smith, 1979; Ingratta, 1977)

TABLE 3-5

Heat Transfer Value for Ground Heating

Treatment	3/4 inch pipe spacing	
	12 inch	18 inch
Dry floor, no flats	0.62 BTU/hr/ft ² /°F	0.51
Dry floor, dry flats	0.47	0.46
Dry floor, wet flats	0.54	0.44
Wet floor	0.60	0.49

(Roberts, 1980)

the ability to integrate low energy supply from solar radiation into the heating system and to store solar heat for use in the greenhouse for no additional investment or loss of production.

COOLING SYSTEM

Inter-related to the heating and the dwelling solar heat transfer system is the greenhouse cooling system. There are a number of options with advantages and disadvantages but the unit should be sized to remove 1.5 times the air per minute than the volume of the greenhouse. If air flow vents are used, then openings equal to 25 percent of the total glazing should be used. Underground tubes that are buried outside the greenhouse may be used to reduce the air temperature coming into the greenhouse and reduce the amount of air needed. Failure to consider a cooling system besides the heat storage and transfer of heat to the dwelling could seriously affect plant development in the greenhouse.

TABLE 3-6

Calculating Effect of Underground Cooling Tubes

Step 1. Determine air volume needed and air temperature of outside.

Step 2. $V = 3 \text{ CMF} / d^2$
 $V =$ Volume of air flow

Step 3. $ATD = \frac{1}{2} (T_{in} - t_{out}) - T_{earth}$
 $ATD =$ Average Temperature Difference

Step 4. $q = 1.08 (\text{CMF}) (T_{in} - T_{out})$
 $q =$ Cooling in BTU per hour

Step 5. $L = \frac{q}{0.13 ((V \times d))^{0.8} (A+D)}$
 $L =$ Length of underground pipe

Note: This is for slow air movement (Wylie, 1981)

TABLE 3-7

Options for Cooling an Attached Solar Greenhouse

Description	Advantage	Disadvantage
Upper and Side Vents	Low cost and simple	Costly to automate Must be sized Limited cooling effect
Electric Fan	Excellent control Simple to install Can cool home	Costly Drafts
Buffered Soil Pipes	Dry cool air Less air flow	Must dig up yard May need fan
Solar vent	Low cost Self-regulating	Unslightly Not totally proven
Evaporated Cooling	Reduces air flow	May not work in high humidity - damage home
Air Conditioning	Extreme control	Costly to install and operate

NIGHT INSULATION

It is essential for energy conservation to have a night insulating covering for the greenhouse. This is probably the weakest area of the greenhouse design. Although there is little doubt of the energy savings effect, sometimes up to 60 percent, the actual installation and operation can pose many engineering problems. The night insulation requires that it be air tight so there is no transfer of air through or to the glazing. There are a number of accepted methods to use a flexible blanket, (Ross, 1978), but they are hard to automate and use in small attached solar greenhouses. (White, 1979)

TABLE 3-8

Heat Reduction Using Thermal Blankets

Type of Blanket	Heat Reduction (%)
½" Urethane	83%
" polyethylene foam, aluminum foil face	70%
Spun bonded Polyefin, 4 mil	50%
1" rigid Urethane foam aluminum foil face	82%
5 mil black vinyl film	57%

* Infiltration rate assumed two air changes per hour without blankets and 1 air change per hour with blankets. (White, 1979)

ENERGY STORAGE

In order to maintain a controlled environment for plant growth, it is necessary to provide some energy storage in an attached solar greenhouse. In a sunspace, the storage system may be in the space itself and can serve as an absorber of solar radiation. Absorbing surfaces other than the plants will cause a dark green color, less yields and reduced nutritional quality. Since food is the primary consideration and has the greatest economic impact, then every effort should be used to avoid reduction of plant growth.

Those who have adapted solar energy technology to solar greenhouses tend to use dark surfaces on the north wall that have mass to absorb the heat. This nullified all the efforts to collect and direct the maximum amount of light to the plant leaves. A literature review of research work on solar greenhouses shows that the preference for heat storage is under the plants in the same structure. Isolating the storage system from the greenhouse often results in more energy expended to transport the heat than energy actually stored. (Smith, 1977)

As a rule, 30 pounds of water, 42 pounds of soil and 150 pounds of masonry or rock should be used for every square foot of south glazing. (Collett, 1979) Another way to determine storage needs is to calculate maximum solar energy into the greenhouse less 15 percent and size the storage. One system in Michigan employed 1389 BTU's per square foot of underground energy storage. (Currin, 1978) These rules may not be optimum for Minnesota conditions and greenhouse design.

Heat storage can be accomplished in the growing soil using the same transfer system as soil heating. This will permit storage to an 18 inch depth in the soil. Water and air temperatures should range around 90 degrees F. which is ideal for the systems design. In greenhouses where a solid floor is desired, a 12 inch deep porous concrete and crushed rock floor has been used with heat stored in the water of the floor. (Simpkins, 1979)

Greenhouses with benches above the ground to allow pots to set upon them can be used to store heat. Rock or soil with pipes similar to the underground heat systems described earlier can be used or a large water reservoir under the bench with heat transferred by an air tube can be used. (Mears, 1976)

Admittedly, the exact amount of heat storage for Minnesota attached greenhouses is not clear. Oversizing the capacity will result in decreased efficiency and undersizing will mean using the vent to exhaust the excess heat buildup. Limits of storage will be based on cost and available space.

HEAT TRANSFER TO RESIDENCE

It appears that transfer of heat generated in the greenhouse cannot be accomplished properly or with enough control by thermosiphon, so fans are recommended. (Taff, 1979) Fans should be sized to move 1 CFM per cubic foot of greenhouse volume. A resident furnace fan could be used in older homes. Where air changes in the home exceed one volume per hour, there appears to be no damage sustained by the addition of humid greenhouse air.

In new and tight dwellings, a modified heat exchanger is recommended to prevent high humidity and damage to the household.

DESIGN OVERVIEW

- * South wall glazing should be tilted to 55-65 degrees from horizontal
- * 50 percent of the roof should be solid and insulated
- * From the insulated roof to the north wall, a 60 degree angle ceiling should be used
- * The north wall should contain foil or mirrors and possible diffusers
- * The foundation should be insulated
- * The south face should be doubled glazed
- * The end walls should be insulated and can be painted any color
- * The framing and all other surfaces should be painted light colors
- * There should be night insulation - either solid or blanket material
- * An underground heating system should be used
- * Adequate heat storage should be used
- * A fan or heat exchanger should be used to transfer heat from the greenhouse to the residence
- * A cooling system is needed

FIGURE 3-5

HEAT EXCHANGER MODIFICATION
FOR ATTACHED SOLAR GREENHOUSE

Maximizing Heat Collection and Food Production in a Solar Sunspace/Greenhouse

A well designed attached solar sunspace has the potential to supply supplemental heat to a dwelling as well as provide additional living space. Similarly, a well designed and operated attached solar greenhouse can supply a large portion of the fresh produce needs of a family and enhance the nutritional value of the food being consumed.

Designing a single structure capable of maximizing both heat collection and food or plant production is not an easy task. Adequate testing and monitoring has yet to be done, which would provide the optimum design features. However, certain design principles seem appropriate to both functions.

The first step in design is to decide the primary purpose for the planned structure. The two options that will be discussed here are an attached solar sunspace capable of also serving as a year-round growing space for plants and secondly, an attached solar greenhouse which is also capable of providing supplemental heat to the house. The best approach to designing a successful multiple-use attached solar structure is to optimize the design for the primary purpose and then modify the design to be able to also fulfill the secondary function.

In order to judge whether or not a design trade-off is acceptable, the designer must know the consequences of each modification. In Table 4-1, the effect that design modifications have on overall performance are quantifiers. For example, if the primary use of the structure was heat collection, but plants were to be grown, incorporating a 60° north wall would be an acceptable trade-off because it would not decrease the energy savings but it would have a beneficial effect on crop yields.

TABLE 4-1

Energy Conserving and Production Factors to Consider in Designing an Attached
Solar Greenhouse

Design Factor	Effect on Fuel Saving	Crop Yield Effect
Double glazing	+30%	-20%
Solid north wall	+50%	-15%
Sloping north wall 60 degrees	None	+20%
Night insulation	+40-60%	- 5%
Reducing temperature 10°F.	+26%	Some
Pit greenhouse	+25-50%	-25% (?)
Radiant heating	+15%-40%	None
Soil heating	+15%-60%	+10%
Foundation insulation	+10%	None
White painted surfaces	None	+5-10%

(Wylie, 1981.)

Growing Plants in a Heat Collecting Attached Solar Sunspace

This is probably the most common situation, wanting to grow plants in a sunspace. To start with, refer back to Table 2-2 or 2-3 to determine optimum design criteria for the sunspace. Next, a decision should be made whether the structure is to be used for plant production only during the spring and fall or for growing plants throughout the entire winter. If season extending is the type of gardening planned, design features shown in Table 4-2 seem acceptable.

The type of structure would be useful for starting seedlings in the spring for transplanting later into the garden as well as growing leafy greens for direct consumption in the spring. It could also be used for late summer plantings of leafy greens as

TABLE 4-2

Solar Sunspace Design Capable of Plant Production in Spring and Fall

- Double glazing tilted at an angle between 50° and 60°
- Minimum of R2 night insulation on south glazing
- Insulated end walls if structure is twice as long as it is wide, if smaller, glaze portion of east wall
- Use no other thermal storage except soil in planting beds
- Provide for adequate venting
- Small fan for distributing heat into house
- Insulate the common wall
- No auxiliary heating system, open door or window from house during periods of very low temperatures
- Low infiltration
- Light colored interior surfaces

well as provide a space to transplant certain garden vegetables in the fall such as tomatoes or green peppers. It should be possible to harvest these tomatoes and peppers and leafy greens into December. The sunspace would then be left empty until March when planting would begin again. The main potential problem with growing in this structure would be the lack of environmental controls. Overheating in the spring might cause seedlings to be very spindly and poor for transplanting into the garden.

No auxiliary heating system would be included because of the additional expense. During very cold nights, when the temperature might drop considerably, heat should be provided from the house by opening doors or windows into the sunspace. Tight fitting night insulation is a must for this situation.

A sunspace used in this manner may provide up to 25 percent less heat to a house than one not used for growing plants at all. This is due primarily to the fact that heat from the house will need to be provided to the growing space during cold spring and

fall days. Glazing the end walls, if required, would also affect the overall performance.

If the sunspace is planned to be used for a growing space throughout the entire winter, several additional features are recommended, as shown in Table 4-3.

TABLE 4-3

Solar Sunspace Used as Year-round Growing Space

- Double glazing tilted at an angle of between 60°F and 75°F
- Minimum R4 night insulation on south glazing
- Insulated end walls of twice as long as wide, if not, glaze portion of east wall
- Sloping north wall at 60°F
- Provide adequate thermal storage
- Provide for adequate venting
- Small fan for distributing heat into storage and into the house
- Uninsulated common wall
- Minimum thermostat setting (depends on crop)
- Low infiltration
- Pit structure if possible
- Radiant or soil heating system
- Light colored interior surfaces
- Heat exchanger recommended if new construction

This type of structure is capable of providing fresh vegetables throughout the entire winter. The three main changes required are as follows: intensify the amount of light reflected to the plants, provide for good control of environmental conditions such as temperature and humidity, and provide supplemental heating for cold, cloudy periods.

Succession planting would be done throughout the winter. Planting in ground beds is recommended over containers. Ground

heating with coils is probably the best supplemental heating mode. Adequate thermal storage should be provided, but a free standing dark colored mass such as water barrels should not be used. Plant production in such a sunspace is going to depend on crop selection and variety, and skills and knowledge of the operator. The reduction in plant production might be minimal under ideal conditions or as much as 50% for a poor design or where the operator is untrained.

This plant production comes at a cost, however. The overall energy savings from this type of sunspace may be only 50 percent compared to a sunspace used only for heat collection. This is due to the fact that higher temperatures must be maintained in the sunspace during the coldest winter months, thereby increasing the heat loss. And also the fact that much of the excess heat that normally would be transferred into the house must be used for storage within the growing area.

Heat Collection in a Plant Producing Attached Solar Greenhouse

To be able to siphon excess heat for the house from a plant producing solar greenhouse would require several modifications. These modifications include using darker color interior surfaces including thermal mass, providing a mechanism to transfer excess heat to the house and providing more shading to prevent overheating problems. In addition, plants that are more tolerant of temperature fluctuations and lower light levels should be used such as mustard greens and kale. These plants should be low growing and have less layers of leaves due to the decreased light levels.

There are several reasons for being cautious about trying for this type of dual function structure. The greenhouse probably already has relatively expensive controls and the cost effectiveness of adding additional materials (fans, thermal mass) seems questionable. In addition, different crops will have to be grown to accomodate the design changes. The small amount of heat provided to the house may not be worth the additional costs and changes required in crop varieties.

Final Selection of Design Criteria

There is a five step process to designing an attached solar structure.

- STEP 1 Determine if optimum heat gain or optimum production is the primary goal and what trade-offs are desired
- STEP 2 Create a design that is pleasing to the eye for your dwellings architecture
- STEP 3 Add features that will:
 - a. conserve energy
 - b. enhance the growing environment
 - c. store energy for nighttime use
 - d. transfer heat to the dwelling
 - e. maximize light interception
- STEP 4 Calculate expected performance
- STEP 5 Accept or modify the design until a balance of functions is reached

By following these steps, and being aware of the consequences of design changes, a successful solar sunspace/greenhouse can be designed and built.

Estimating the Performance of Attached Sunspaces

One of the most important steps for designers and builders of passive solar systems is predicting the overall performance of each system. Much work has been done in this area over the past five years. During this time, design tools have become more sophisticated and accurate.

Although the attached sunspace may be the easiest type of passive solar structure to incorporate into existing homes, it has been quite difficult to accurately predict its performance. The interaction between heat in the solar sunspace and the primary living area makes modeling the overall performance difficult. This has created a situation where designers have been forced to make "ball park" estimates of the energy they can expect to save through the addition of a solar sunspace. Design criteria have come to be established based on these "ball park" estimates. In order to test the soundness of these design criteria, we need to learn more about the actual performance of solar sunspaces.

The best work to-date on solar sunspace performance is being done by the Los Alamos Scientific Laboratory (LASL). LASL has developed a procedure for predicting the performance of standard sunspace designs. These predictions are based on hour-by-hour computer simulations using computer models developed in the framework of PASOLE, the LASL passive solar energy simulation program. The models have been validated by detailed comparison with actual hourly temperature measurements taken in attached-sunspace test rooms at LASL.

LASL has selected 28 reference sunspace designs based on the two most popular designs (see Figure 4-a and 4-b. Sunspace (a) is

30 feet long by $8\frac{1}{2}$ feet wide by 9 feet high. There is only one glazing surface which is tilted at 50° . The roof is insulated and is four feet deep. This is probably the most common design, although a Knuwall is usually added.

Sunspace (b) is 30 feet long by 5 feet wide by 9 feet high. This design has two south facing planes, a 6 foot high vertical plane and a 30° tilted one above it. This is the second most popular design and is often used for porch retrofits or when the sunspace is to be used primarily as living space.

FIGURE 4-a

FIGURE 4-b

Each of these two basic wall configurations comprises four different designs with insulated or glazed east and west sunspace end walls, and with and without nighttime insulation on the sunspace glazing. (See Appendix D. for details on characteristics of these standard designs.) It is likely that a sunspace design will resemble one of these standard designs but not be identical. Here it is important to know that it is the sunspace shape, not its absolute dimensions, that determines its performance per unit of collection area. For example, geometry (a) is specified as 30 feet wide, 9 feet high with a glazing tilt of 50° , but a sunspace 40 feet wide by 12 feet high with a glazing tilt of 50° is also geometry A, being just one-third larger in all directions but

identical in shape. The effect of the absolute size of the sunspace is accounted for by the collection area, an independent parameter.

For designs substantially different than one of the two standard geometries, the designer can either choose the design most similar or may have to wait until LASL publishes its Passive Solar Handbook, Volume IV. More detailed information on design variations will be included in this book due for release in the spring of 1982.

One of the limitations of the LASL work in solar sunspaces is the fact that the sunspaces they look at are primarily large structures with high levels of integral thermal mass and which utilize thermocirculation heat transfer into the house. Their models don't include smaller sunspaces with little or no thermal mass and sunspaces utilizing fans to distribute excess heat into the house, both very popular designs.

In our opinion, there are no reliable models to determine the performance of these structures for these designs, builders can either choose to estimate the performance using one of the two standard designs or else try to locate other information on sunspace performance.

Calculation Procedure to Determine Solar Contribution from Attached Sunspaces

In order to determine the solar contribution from an attached sunspace, it is necessary to know the heat loss of the building that the sunspace is going to be attached to.

LASL has simplified the ASHRAE technique for calculating the heat loss of a building. The overall heat loss of a building is called the building load coefficient (BLC). The BLC is calculated by adding together several estimated contributions of heat loss.

Start by making rough estimates of the combined area of all floors (Sq. ft.) and the "perimeter" (the combined length of all external walls of all floors (ft)).

Then either estimate the combined area of all east, west, and north windows, or use:

$$\begin{aligned} \text{non-south window area} &= (2/3) \times (\text{perimeter}) \times (\text{ceiling height}) \\ &\quad \times (\text{non-south window fraction}) \end{aligned}$$

The non-south window fraction will normally be between 0.05, for a situation with minimum window area, and 0.10 for a case with ample window area.

Next, carefully estimate the south (solar) window area being careful to only include net exposed portion of the window.

Then, compute the following:

Walls

$$L_w = 24 \times \frac{\text{wall area}}{\text{R value of walls}}$$

where wall area = (perimeter) x (ceiling height)

- (non-south window area) - (south window area)

Non-South Window

$$L_g = 26 \times \frac{\text{non-south window area}}{\text{number of glazings}}$$

Perimeter (slab on grade)

$$L_p = 100 \times \frac{\text{length of perimeter foundation}}{\text{R value of perimeter insulation} + 5}$$

Floor (over vented crawl space)

$$L_f = 24 \times \frac{\text{area of ground floor}}{\text{R value of floor}}$$

Basement (heated basement or other fully-bermed wall, including floor losses)

$$L_b = 256 \times \frac{\text{length of wall}}{\text{R value of wall insulation} + 8}$$

Note: normally only one of L_p , L_f or L_b will apply.

Roof

$$L_r = 24 \times \frac{\text{roof area}}{\text{R value of roof}}$$

Infiltration:

$$L_i = (0.432) \times (\text{average air changes per hour}) \times (\text{ADR}) \\ \times (\text{ceiling height}) \times (\text{combined area of all floors})$$

where ADR is the Air Density Ratio shown in Fig. E-1 to account for other-than-sea-level locations.

Add the appropriate components to obtain the final BLC estimate, for example:

$$\text{BLC} = L_w + L_g + L_r + L_p + L_i$$

Note that the solar glazing is not included in the calculation of the Building Load Coefficient. This is done for three reasons:

- The solar glazing would not be present in a non-solar building which is the principal basis of comparison.
- The solar wall is a net energy gainer, not a loser, and to represent it as part of the load would be misleading.
- The tables which are to be used are given in terms of the BLC defined without the solar wall included.

Example 1

A 1080 sq. ft. single story home is built over a full heated basement. The above grade walls are insulated to R-30, basement walls to R-10, roof area to R-50, 7½% of the east, west and north wall area is in double glazed windows and with 0.65 air change per hour. The house is to be built in Minneapolis, Minnesota (elev. = 1000 ft.). The ceiling height is 8 feet. The south glazing is 80 sq. ft. with R-4 night insulation. The perimeter is 132 ft.

$$\begin{aligned}\text{non-south window area} &= (2/3) \times 132 \times 8 \times 0.075 \\ &= 52.8 \text{ sq. ft.}\end{aligned}$$

Then:

$$\begin{aligned}L_w &= 24 \times (132 \times 8 - 528 - 80)/30 &= 739 \text{ Btu/DD} \\ L_g &= 26 \times 52.8/2 &= 686 \text{ Btu/DD} \\ L_b &= 256 \times 132/10 + 8 &= 1877 \text{ Btu/DD} \\ L_r &= (24) \times 1080/50 &= 518 \text{ Btu/DD} \\ L_i &= (0.432) \times (0.65) \times (0.96) \times 8 \times 1080 &= 2329 \text{ Btu/DD} \\ \text{BLC} &= \text{sum} &= 6149 \text{ Btu/DD}\end{aligned}$$

To calculate the total heat load of the house, multiply

$$6149 \text{ Btu/DD} \times 8159 \text{ DD (Mpls./St. Paul)} = 50,170,000 \text{ Btu/year}$$

Example 2

There is an existing 2 story house built over an unheated basement. There are 720 sq. ft. of living area on the main floor and upper floor. The ceiling is insulated to R-30, wall R-11, 10% of the east, west and north wall area is in double glazed windows and with 1.5 air change per hour. The house is built in Rochester (elev. = 1000ft). The ceiling height is 8 feet. The south glazing totals 40 sq. ft. The perimeter is 108 ft.

$$\begin{aligned}\text{non-south window area} &= (2/3) \times (108 \times 2) \times 8 \times 0.10 \\ &= 115.2 \text{ sq. ft.}\end{aligned}$$

Then:

$$\begin{aligned}L_w &= (24) \times (108 \times 2 \times 8 - 115.2 - 40)/11 &= 3432 \text{ Btu/DD} \\ L_g &= (26) \times (115.2)/2 &= 1498 \text{ Btu/DD} \\ L_b &= 256 \times \frac{108}{2.7 + 8} \quad (2.7 = R \text{ value of} \\ &\quad \text{insulated block foundation} &= 2584 \text{ Btu/DD} \\ L_r &= 24 \times 720/30 &= 576 \text{ Btu/DD} \\ L_i &= (0.432) \times 1.5 \times (0.96) \times 8 \times 1440 &= 7166 \text{ Btu/DD} \\ \text{BLC} &= \text{sum} &= 15,256 \text{ Btu/DD}\end{aligned}$$

To calculate the total heat load for the house, multiply:

$$15,256 \text{ Btu/DD} \times 8227 \text{ DD} = 125,510,000 \text{ Btu/year}$$

The second step to estimating sunspace performance is to determine the total solar radiation absorbed per square foot. The method employed to determine this is a two step process. Step 1 involves obtaining the amount of energy incident on a square foot of vertical south glass per month, while Step 2 involves modifying these values as necessary by a series of factors which take into account conditions which would effect the amount of solar gain achieved by the building.

Complete Table 5A.

STEP A: Complete Column (1). Obtain V.S. values (solar energy incident on a vertical square foot of glazing) from monthly average solar radiation, available. See Table 5-1. Multiply these daily values by the number of days in the month and enter in Column (1). If the building is located far from any of the tabulated sites, use the solar radiation values from the closest city.

STEP B: Apply modifying factors that pertain to the solar sunspace.

- a. Reflectance: The solar radiation values in Table 5-1 have been adjusted to account for increases due to reflection from snow cover. In some cases, this snow cover can increase the solar radiation available by 15 percent. If a snow cover is not likely to be in front of the solar sunspace (i.e. in the case of a tarred driveway) select the multiplier for each month from Table 5-2 appropriate for the sunspace azimuth and tilt angle and enter in Column (2). If a snow cover is anticipated, enter 1.00 for each month.

- b. Tilt: The solar radiation values listed in Table 5-1 are vertical or horizontal surfaces. If the glazing is tilted to a different angle, select the multiplier for each month from Table 5-3 and enter in column (3). If the glazing is vertical, enter 1.00 for each month.
- c. Orientation: If the primary sunspace glazing is not facing true south, in most cases there will be less solar radiation transmitted into the sunspace. For azimuths other than 0, select the multipliers for each month from Table 5-4 and enter in Column (4).
- d. Transmittance: The total amount of solar radiation transmitted through a glazing material depends on many variables, including the tilt of the glazing and the relationship of the sun in the sky compared to the glazing tilt. Select the appropriate tilt angle from Table 5-5 and enter the monthly values in Column (5).
- e. Absorptance: Of the total solar radiation passing through a glazing material, some of it is absorbed by the sunspace interior surfaces while some is reflected right back out through the glazing and never available for heating purposes. For well insulated sunspaces with opaque sidewalls, assume 1.00 absorptance. For sunspaces with glazed end walls, assume 0.70 absorptance. Enter value for absorptance in Column 6.

STEP C: Calculate the product of factors (2-6) and enter in Column 7.

STEP D: Calculate S (Solar Radiation Absorbed per square foot of collection area per month). This is the product of Column (1) and Column (7). The units are Btu per month per square foot. Enter S values in Column (8).

3. SOLAR SAVINGS FRACTION AND AUXILIARY HEATING REQUIREMENT -

TABLE 5B

STEP A: Transcribe S values from Table 5A, Column (8) to Table 5B, Column (1).

STEP B: Select Degree Days per month (DDs) from Table 5-6 and enter in Column 2.

STEP C: Determine quotients of S/DDs (Column (1)/Column (2)) and enter in Column (3).

STEP D: Calculate Load Collector Ratio (LCR)

$$LCR = \frac{BLC}{Ac}$$

STEP E: Determine monthly Solar Savings Fraction (SSF) from figures 5-1 to 5-8 for corresponding type of sunspace, using values of LCR and S/DDs.

STEP F: Determine monthly and annual auxiliary heating requirement (Quax).

$$Quax = 1 - \text{Column (4)} \times \text{Column (2)} \times BLC$$

Total Column (5) to get Quax Annual.

SOLAR SUNSPACE PROJECT WORKSHEETSpecifications

Project Name _____

Date _____

Location _____

Initials _____

Solar Sunspace Type (see Fig. 5-1 to 5-8) _____

Glazing area (Ac) _____ sq. ft.

Calculated Values

Building Load Coefficient, BLC _____ Btu/DD

Load Collector Ratio, LCR = BLC/Ac _____ Btu/DD·sq. ft.Degree-Day Base Temperature for Non-Solar Buildings, T_{bs} _____ FDegree-Days for Non-Solar Building, DD_{ns} _____ DD

TABLE 5A SOLAR RADIATION ABSORBED PER SQUARE FOOT

Location _____ Sunspace Type _____ Collection Area Ac ft²

Column		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		Vertical Solar Radiation x Days/Month TABLE 5-1	Reflectance TABLE 5-2	Tilt TABLE 5-3	Orientation FACTORS TABLE 5-4	Transmittance TABLE 5-5	Absorptance	Product of all Factors	(1) x (7) Solar Radiation
Month	No. Days	Btu month/sq. ft.							Btu month/sq. ft.
Sep	30								
Oct	31								
Nov	30								
Dec	31								
Jan	31								
Feb	29								
Mar	31								
Apr	30								
May	31								

TABLE 5B SOLAR SAVINGS FRACTION AND AUXILIARY HEATING REQUIREMENT

Location _____ Sunspace Type _____

Column	(1)	(2)	(3)	(4)	(5)
	From Table 5A Col. 8 S Btu month/sq ft	From Table 5-6 DD month	(1) ÷ (2) S/DDs Btu month sq ft dd	From Figs. "Monthly SSF"	1-(4) x (2) x BLC Quax 10 ⁶ Btu/month
Month					
Sep					
Oct					
Nov					
Dec					
Jan					
Feb					
Mar					
Apr					
May					

BLC Btu/DDAnnual
Degree Days DDnsLCR Btu/DD sq ft

$$\text{Yearly SSF} = 1 - \frac{(5)}{\text{BLC} \times \text{DDns}}$$

= %ANNUAL AUXILIARY
HEATING REQUIREMENT

S: Solar Radiation Absorbed/Sq. Ft. of Collection Area
 DDs: Degree Days Solar
 SSF: Solar Savings Fraction
 Quax: Auxiliary Heating Requirement

STEP G: Obtain Annual Solar Savings Fraction

$$SSF \text{ Annual} = 1 - \frac{\sum \text{Column (5)}}{HLC \times DDns}$$

DDns = Normal annual degree days with 65°F base temperature

Example 3

In order to familiarize you with this calculation procedure, two example sunspace additions will be used corresponding to the houses in Example 1 and 2.

A double glazed sunspace with dimensions of 14 feet wide, 8 feet high and 6 feet deep (84 square feet of south glazing) is to be added to the one story Minneapolis home in Example 1. The glazing will be vertical and facing true south. The thermostat setting is assumed to be 65°F.

First the project worksheet is completed. From Figures 5-1 to 5-8, the sunspace type which corresponds most closely to the proposed design is chosen (geometry B, insulated ends in this case). The sunspace glazing area and the BLC have already been calculated. The LCR will be explained and calculated later. The degree day base temperature is 65°F and the annual degree days for Minneapolis are shown in Table 5-6.

After the project worksheet is completed, Table 5A is filled out. Column 1 is completed by multiplying the monthly vertical solar radiation values from Table 5-1 by the days per month. Next, the correction factors 2-6 must be completed. For Column 2, the value for reflectance is 1.00 because we have assumed the area directly to the south of the sunspace will be snow covered during the winter months. The tilt factor is also 1.00 since our example sunspace has a vertical south wall. Orientation is 1.00 since the sunspace faces true south. The monthly transmittance

values are from Table 5-5. Absorptance value is 1.00 since the sunspace end walls are not glazed.

The next step is to multiply factors 2 through 6 for each month and enter the value in Column 7. Now multiply these values by monthly solar radiation values in Column 1 and enter products in Column 8. These monthly values represent the useful solar radiation available to each square foot of south facing sunspace glazing.

Next transfer the values from Column 8 Table 5A to Column 1 Table 5B. The monthly degree day values are found in Table 5-6 and should be entered in Column 2. To compute the value of S/DDs, divide Column 1 by Column 2.

In order to calculate the monthly solar savings fractions (SSF), the Load Collector Ratio (LCR) must be calculated.

The LCR is defined as follows:

$$\text{LCR} = \frac{\text{Building Load Coefficient (Btu/DD)}}{\text{Solar Collection Area (sq. ft.)}}$$

The LCR is probably the single most important factor affecting the gross solar heating performance of the building. In one simple ratio it reveals the relationship between energy conservation, which is determined by the Building Load Coefficient and the amount of solar gain, which is determined by the size of the collection area.

In this example, the LCR is equal to:

$$\begin{aligned} \text{LCR} &= \frac{6149 \text{ Btu/DD}}{84} \\ &= 73.2 \end{aligned}$$

The monthly SSF (defined as the monthly solar contribution to the overall heating load of the building) can now be calculated.

Since the geometry of this example sunspace most resembles that of Figure 5-2, Figure 5-7 should be used to calculate the SSF. In Figures 5-3 to 5-10, the vertical axis corresponds to the monthly solar contribution to the building, the horizontal axis to the values in Table 5B, Column 3 and the curved lines each represent a different LCR. For the month of September in our example, locate the value of S/DD (153), follow that line up until it intersects the appropriate LCR (73) and determine the monthly SSF (0.70). Enter this value in Column 5. If the LCR had been smaller -- either a larger sunspace or better insulated home -- the monthly solar contribution would have been higher. Conversely, if the LCR had been larger, a smaller sunspace or poorly insulated house, the monthly solar contribution would have been smaller. The advantage of a better insulated house or larger sunspace is shown quite clearly here. Complete the monthly SSF and fill in Column 5.

To calculate the auxiliary energy required to heat this house, subtract the monthly SSF from 1, multiply by Column 2 and then the BLC. Total these values to determine the annual heating requirements of this house with the addition of the sunspace. To determine the percent solar contribution, complete the yearly SSF equation.

We see that a 14 foot by 6 foot sunspace added to a one story 1080 square foot house in Minneapolis will result in just under a 10 percent reduction in fuel use. If night insulation had been used, the percent fuel reduction would be approximately 16 percent.

SOLAR SUNSPACE PROJECT WORKSHEETSpecificationsProject Name Twin City SunspaceDate 8/12/27Location MINNEAPOLIS, MINNESOTAInitials MJPSolar Sunspace Type (see Fig. 5-1 to 5-8) GEOMETRY B, INSULATED ENDSGlazing area (Ac) 84 sq. ft.Calculated ValuesBuilding Load Coefficient, BLC 6,149 Btu/DDLoad Collector Ratio, LCR = BLC/Ac 73.2 Btu/DD·sq. ft.Degree-Day Base Temperature for Non-Solar Buildings, T_{bs} 65° FDegree-Days for Non-Solar Building, DD_{ns} 8,159 DD

TABLE 5A SOLAR RADIATION ABSORBED PER SQUARE FOOTLocation MINNEAPOLISSunspace Type Geometry B, insulation endsCollection Area Ac 84 ft²

Column		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Month	No. Days	Vertical Solar Radiation x Days/Month TABLE 5-1 Btu month/sq. ft.	Reflectance TABLE 5-2	Tilt TABLE 5-3	Orientation FACTORS TABLE 5-4	Transmittance TABLE 5-5	Absorptance	Product of all Factors	(1) x (7) Solar Radiation Btu month/sq. ft.
Sep	30	38,460	1.00	1.00	1.00	0.686	1.00	0.686	26,384
Oct	31	38,254	1.00	1.00	1.00	0.716	1.00	0.716	27,390
Nov	30	29,326	1.00	1.00	1.00	0.729	1.00	0.729	21,379
Dec	31	29,264	1.00	1.00	1.00	0.731	1.00	0.731	21,392
Jan	31	38,905	1.00	1.00	1.00	0.726	1.00	0.726	28,245
Feb	29	44,856	1.00	1.00	1.00	0.711	1.00	0.711	31,893
Mar	31	46,593	1.00	1.00	1.00	0.687	1.00	0.687	32,001
Apr	30	35,070	1.00	1.00	1.00	0.657	1.00	0.657	23,041
May	31	33,573	1.00	1.00	1.00	0.630	1.00	0.630	21,151

TABLE 5B SOLAR SAVINGS FRACTION AND AUXILIARY HEATING REQUIREMENT

Location MINNEAPOLIS Sunspace Type GEOMETRY B, INSULATED ENDS

Column	(1)	(2)	(3)	(4)	(5)
	From Table 5A Col. 8 S Btu month/sq ft	From Table 5-6 DD month	(1) ÷ (2) S/DDs Btu month sq ft dd	From Figs. "Monthly SSF"	1-(4) x (2) x BLC Quax 10 ⁶ Btu/month
Month					
Sep	26,384	173	153	0.70	0.32
Oct	27,390	472	58	0.30	2.03
Nov	21,379	978	22	0.06	5.65
Dec	21,392	1438	15	0.00	8.84
Jan	28,245	1637	17	0.00	10.07
Feb	31,893	1358	23	0.06	8.02
Mar	32,009	1138	28	0.11	6.37
Apr	23,041	597	39	0.18	3.01
May	21,151	271	78	0.42	0.97
					45.28

BLC 6,149 Btu/DD

Annual Degree Days 8,159 DDns

LCR 73.2 Btu/DD sq ft

Yearly SSF = $1 - \frac{(5)}{BLC \times DDns}$

= 9.7 %

ANNUAL AUXILIARY
HEATING REQUIREMENT

S: Solar Radiation Absorbed/Sq. Ft. of Collection Area
DDs: Degree Days Solar
SSF: Solar Savings Fraction
Quax: Auxiliary Heating Requirement

Example 4

Now lets do a more complicated example. In this example we will add a sunspace to the two story older house from Example 2. The sunspace dimensions are 24 feet long, 8 feet high and 6 feet deep. The south glazing totals 144 square feet and is tilted at a 60° angle. The sunspace faces 30° west of south and has glazed end walls with no night insulation. Directly to the south of the sunspace is a driveway which is always kept clear of snow.

The first step is to complete the sunspace project worksheet. The only value which must be calculated is the LCR, $\frac{15256}{144} = 106 \text{ Btu/DD}\cdot\text{sq. ft.}$ Once the project worksheet is completed, move on to Table 5A.

First Column 1 from Table 5-1 is completed. Since snow will not be present in front of the sunspace, less solar radiation will be available to the glazing. These monthly values are obtained from Table 5-2 and are entered in Column 2. Since the glazing is not vertical, monthly correction factors must be taken from Table 5-2 and entered in Column 3. The sunspace is facing 30° west of south, so therefore the orientation factors from Table 5-4 are used and entered in Column 4. The transmittance values are from Table 5-5. Because the sunspace ends are glazed, the absorptance will be 0.70 and not 1.00 as in our previous example. The factors are all multiplied and entered in Column 7. Multiplying Column 7 by Column 1 gives the monthly solar radiation absorbed per square foot of south glazing. Note the low values in Column 7 due to the compromises that were made on the sunspace addition.

These numbers are transferred from Table 5A, Column 8 to Table 5B, Column 1. The appropriate degree days are selected from Table 5-6 and the monthly S/DDs are calculated. Since this sunspace resembles Figure 5-1, Figure 5-5 is used to calculate the monthly SSF. The remaining steps are completed as in the previous example.

We find that even though this sunspace was considerably larger than the one in the previous example, the overall contribution (5.6 percent) is much lower. This is due to a variety of design compromises and the fact that the house was so poorly insulated. If this sunspace was facing due south, had insulated end walls and a snow cover in front of it, the yearly SSF would be just under 10 percent.

SOLAR SUNSPACE PROJECT WORKSHEETSpecificationsProject Name MAYO SunspaceDate 8/12/27Location ROCHESTER, MINNESOTAInitials M.D.A.Solar Sunspace Type (see Fig. 5-1 to 5-8) GEOMETRY A, GLAZED END WALLSGlazing area (Ac) 144 sq. ft.Calculated ValuesBuilding Load Coefficient, BLC 15,256 Btu/DDLoad Collector Ratio, LCR = BLC/Ac 106 Btu/DD·sq. ft.Degree-Day Base Temperature for Non-Solar Buildings, T_{bs} 65° FDegree-Days for Non-Solar Building, DD_{ns} 8,227 DD

TABLE 5A SOLAR RADIATION ABSORBED PER SQUARE FOOT

Location ROCHESTER, MINNESOTA

Sunspace Type GEOMETRY A, GLAZED End Walls

Collection Area Ac	144	ft ²
--------------------	-----	-----------------

Column		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		Vertical Solar Radiation x Days/Month TABLE 5-1 Btu month/sq. ft.	Reflectance TABLE 5-2	Tilt TABLE 5-3	Orientation FACTORS TABLE 5-4	Transmittance TABLE 5-5	Absorptance	Product of all Factors	(1) x (7) Solar Radiation Btu month/sq. ft.
Month	No. Days								
Sep	30	37,200	1.00	1.29	0.951	0.715	0.70	0.61	22,692
Oct	31	37,665	1.00	1.15	0.917	0.725	0.70	0.54	20,339
Nov	30	28,350	0.99	1.05	0.898	0.731	0.70	0.48	13,608
Dec	31	29,882	0.96	0.99	0.896	0.732	0.70	0.44	13,148
Jan	31	38,874	0.94	0.99	0.898	0.731	0.70	0.43	16,716
Feb	29	43,064	0.94	1.06	0.919	0.724	0.70	0.46	19,809
Mar	31	44,454	0.97	1.20	0.952	0.715	0.70	0.55	24,450
Apr	30	33,270	1.00	1.47	1.00	0.703	0.70	0.72	24,067
May	31	31,775	1.00	1.67	1.03	0.694	0.70	0.84	26,691

TABLE 5B SOLAR SAVINGS FRACTION AND AUXILIARY HEATING REQUIREMENT

Location ROCHESTER, MINNESOTA Sunspace Type GEOMETER A, GLAZED END WALLS

Column	(1)	(2)	(3)	(4)	(5)
	From Table 5A Col. 8 S Btu month/sq ft	From Table 5-6 DD month	(1) ÷ (2) S/DDs Btu month sq ft dd	From Figs. "Monthly SSF"	1-(4) x (2) x BLC Quax 10 ⁶ Btu/month
Sep	22,692	185	123	0.42	1.64
Oct	20,339	485	42	0.12	6.51
Nov	13,608	972	14	0.00	14.8
Dec	13,148	1429	9	0.00	21.8
Jan	16,716	1615	10	0.00	24.6
Feb	19,809	1347	15	0.00	20.5
Mar	24,450	1153	21	0.02	17.2
Apr	24,067	615	39	0.11	8.35
May	26,691	292	91	0.32	3.03
					118.43

BLC 15,256 Btu/DD

Annual
Degree Days 8,227 DDns

LCR 106 Btu/DD sq ft

$$\text{Yearly SSF} = 1 - \frac{(5)}{\text{BLC} \times \text{DDns}}$$

$$= \boxed{5.6 \%}$$

ANNUAL AUXILIARY
HEATING REQUIREMENT

S: Solar Radiation Absorbed/Sq. Ft. of Collection Area
 DDs: Degree Days Solar
 SSF: Solar Savings Fraction
 Quax: Auxiliary Heating Requirement

TABLE 5-1

Average Day Solar Radiation Available on Horizontal
And Vertical Surfaces For Selected Cities*

(All numbers in Btu/ft²/day)

		<u>Jan.</u>	<u>Feb.</u>	<u>Mar.</u>	<u>Apr.</u>	<u>May</u>	<u>June</u>	<u>July</u>	<u>Aug.</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>
Rochester	H	586	881	1148	1364	1681	1914	1947	1668	1235	871	511	436
	V	1254	1538	1434	1109	1025	1019	1093	1186	1240	1215	945	962
Mpls./St. Paul	H	570	894	1170	1395	1722	1939	2009	1693	1240	861	497	416
	V	1255	1602	1503	1169	1083	1064	1163	1241	1282	1234	946	944
Duluth	H	478	788	1096	1328	1629	1778	1890	1547	1083	726	395	344
	V	1113	1488	1484	1177	1086	1032	1159	1206	1181	1097	794	826
Int. Falls	H	437	776	1109	1396	1701	1865	1959	1624	1107	705	357	321
	V	1072	1541	1578	1304	1198	1144	1270	1332	1270	1119	755	814
Moorhead	H	510	826	1164	1428	1818	2005	2162	1832	1288	875	473	397
	V	1191	1565	1580	1269	1216	1167	1330	1427	1409	1324	953	935
St. Cloud*	H	627	925	1349	1559	1839	1994	2046	1810	1327	888	538	453
	V	1510	1547	1474	994	867	859	973	1149	1243	1225	1045	1026
Sioux Falls, S.D.	H	591	939	1221	1493	1877	2114	2190	1850	1394	1007	629	520
	V	1261	1625	1513	1203	1134	1117	1219	1303	1388	1394	1154	1137
La Crosse, WI	H	655	895	1168	1380	1698	1918	1937	1673	1228	864	511	435
	V	1403	1562	1460	1122	1035	1021	1088	1190	1233	1205	945	960

*The solar radiation values shown for vertical surfaces include the effect of snow reflection during the months of November through March.

TABLE 5-2

Multipliers For Solar Radiation Available
Where There is Very Little Snow Cover
Directly in Front of Glazing Surface

<u>Azimuth</u>	<u>Tilt Angle</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>	<u>Jan.</u>	<u>Feb.</u>	<u>March</u>	<u>April</u>	<u>May</u>
0	30	1.00	1.00	1.00	0.99	0.98	0.98	0.99	1.00	1.00
	45	1.00	1.00	0.99	0.98	0.97	0.97	0.98	1.00	1.00
	60	1.00	1.00	0.99	0.96	0.95	0.94	0.97	1.00	1.00
	75	1.00	1.00	0.99	0.95	0.926	0.926	0.95	1.00	1.00
	90	1.00	1.00	0.98	0.926	0.90	0.88	0.926	1.00	1.00
15	30	1.00	1.00	1.00	0.99	0.98	0.98	0.99	1.00	1.00
	45	1.00	1.00	0.99	0.98	0.97	0.97	0.98	1.00	1.00
	60	1.00	1.00	0.99	0.96	0.95	0.94	0.97	1.00	1.00
	75	1.00	1.00	0.99	0.95	0.926	0.926	0.95	1.00	1.00
	90	1.00	1.00	0.98	0.926	0.90	0.88	0.926	1.00	1.00
30	30	1.00	1.00	1.00	0.99	0.98	0.98	0.99	1.00	1.00
	45	1.00	1.00	0.99	0.98	0.96	0.96	0.98	1.00	1.00
	60	1.00	1.00	0.99	0.96	0.94	0.94	0.97	1.00	1.00
	75	1.00	1.00	0.99	0.95	0.92	0.926	0.95	1.00	1.00
	90	1.00	1.00	0.98	0.92	0.89	0.877	0.926	1.00	1.00
45	30	1.00	1.00	1.00	0.98	0.98	0.98	0.99	1.00	1.00
	45	1.00	1.00	0.99	0.97	0.96	0.96	0.98	1.00	1.00
	60	1.00	1.00	0.99	0.95	0.93	0.93	0.97	1.00	1.00
	75	1.00	1.00	0.98	0.94	0.91	0.92	0.95	1.00	1.00
	90	1.00	1.00	0.97	0.90	0.87	0.86	0.926	1.00	1.00

Multipliers For Converting Solar Radiation
Available on a South Facing Vertical Surface
To Other Tilt Angles
(Azimuth = 0)

[illegible]

TABLE 5-4
Multipliers For Converting Solar Radiation
Transmitted Through South Facing Glazing
To Other Azimuths

<u>Azimuth</u>	<u>Tilt Angle</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>	<u>Jan.</u>	<u>Feb.</u>	<u>Mar.</u>	<u>April</u>	<u>May</u>
15	30	0.991	0.986	0.982	0.979	0.981	0.985	0.991	0.998	1.002
	45	0.989	0.981	0.976	0.975	0.976	0.981	0.989	0.999	1.007
	60	0.987	0.977	0.973	0.974	0.973	0.976	0.987	1.000	1.008
	90	0.990	0.968	0.968	0.928	0.968	0.971	0.991	1.024	1.042
30	30	0.966	0.945	0.928	0.918	0.924	0.944	0.965	0.990	1.002
	45	0.958	0.930	0.910	0.903	0.908	0.931	0.957	0.992	1.014
	60	0.951	0.917	0.898	0.896	0.898	0.919	0.952	1.000	1.030
	90	0.961	0.894	0.876	0.877	0.881	0.906	0.964	1.077	1.150
45	30	0.927	0.885	0.850	0.828	0.840	0.882	0.923	0.973	0.998
	45	0.909	0.856	0.817	0.796	0.811	0.858	0.907	0.974	1.017
	60	0.898	0.834	0.795	0.779	0.793	0.839	0.898	0.990	1.049
	90	0.916	0.080	0.755	0.747	0.767	0.826	0.922	1.109	1.264
60	30	0.874	0.809	0.754	0.718	0.738	0.805	0.868	0.947	0.988
	45	0.846	0.766	0.705	0.673	0.695	0.768	0.843	0.944	1.008
	60	0.829	0.735	0.674	0.647	0.672	0.745	0.829	0.960	1.050
	90	0.851	0.696	0.628	0.611	0.646	0.734	0.862	1.109	1.335
75	30	0.812	0.722	0.647	0.599	0.625	0.715	0.802	0.911	0.971
	45	0.771	0.663	0.584	0.542	0.572	0.666	0.765	0.900	0.989
	60	0.746	0.626	0.547	0.512	0.545	0.640	0.746	0.914	1.035
	90	0.768	0.585	0.505	0.481	0.528	0.636	0.784	1.078	1.359
90	30	0.741	0.628	0.535	0.478	0.505	0.619	0.728	0.868	0.947
	45	0.686	0.556	0.464	0.417	0.448	0.560	0.677	0.846	0.956
	60	0.655	0.514	0.426	0.386	0.422	0.531	0.654	0.852	0.997
	90	0.672	0.474	0.390	0.368	0.418	0.538	0.694	1.014	1.335

TABLE 5-5

Transmittance of Solar Radiation Through
South Facing Double Glazing at Various Tilts

<u>Tilt Angle</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>	<u>Jan.</u>	<u>Feb.</u>	<u>Mar.</u>	<u>Apr.</u>	<u>May</u>
30	0.715	0.714	0.710	0.712	0.711	0.715	0.715	0.711	0.709
45	0.716	0.723	0.726	0.728	0.727	0.722	0.717	0.711	0.706
60	0.715	0.725	0.731	0.732	0.731	0.724	0.715	0.703	0.694
75	0.706	0.725	0.732	0.734	0.731	0.722	0.706	0.687	0.672
90	0.686	0.716	0.729	0.731	0.726	0.711	0.687	0.657	0.630

Table 5-6
Degree Day Normals For
Selected Minnesota Cities

	<u>Jan.</u>	<u>Feb.</u>	<u>Mar.</u>	<u>Apr.</u>	<u>May</u>	<u>June</u>	<u>July</u>	<u>Aug.</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>	<u>Total</u>
Duluth	1751	1481	1287	792	484	194	67	104	318	611	1098	1569	9,756
Int'l. Falls	1956	1624	1376	804	462	168	66	112	364	667	1203	1745	10,541
Moorhead	1832	1520	1265	681	334	97	13	33	254	558	1092	1612	9,271
Bemidji	1910	1596	1370	792	435	147	41	74	327	642	1167	1702	10,203
St. Cloud	1739	1448	1212	663	324	85	18	37	228	539	1050	1525	8,861
Brainerd	1792	1487	1249	693	344	96	21	48	241	555	1065	1572	9,163
Morris	1742	1448	1215	669	312	84	14	32	215	514	1035	1535	8,811
Mpls./St. Paul	1637	1358	1138	597	271	65	11	21	173	472	978	1438	8,151
Winona	1528	1280	1066	543	229	49	9	16	132	422	885	1352	7,511
Rochester	1615	1347	1153	615	292	78	21	35	185	485	972	1429	8,221
Marshall	1615	1327	1135	594	262	62	8	16	164	457	969	1423	8,032

FIGURE 5-3

SUNSPACE - GEOMETRY A, INSULATED ENDS

FIGURE 5-5

SUNSPACE - GEOMETRY A, GLAZED ENDS

FIGURE 5-6

SUNSPACE - GEOMETRY A, GLAZED ENDS, NIGHT INSULATION

FIGURE 5-7

SUNSPACE - GEOMETRY B, INSULATED ENDS

FIGURE 5-8

SUNSPACE - GEOMETRY B, INSULATED ENDS, NIGHT INSULATION

FIGURE 5-9

SUNSPACE - GEOMETRY B, GLAZED ENDS

SUNSPACE - GEOMETRY B, GLAZED ENDS, NIGHT INSULATION

APPENDIX A

Solar Radiation Study for Minnesota

The amount of solar radiation that is available as useable heat to a building depends on many factors including the following:

- 1) the tilt of the glazing;
- 2) the direction the glazing
- 3) the surface directly in front of the glazing;
- 4) the transmittance of the glazing material;
- 5) the numbers of layers of glazing;
- 6) the air gap between the glazing layers;
- 7) the absorptance of materials within the building;
- 8) the heat loss back out through the glazing;
- 9) and the cloud cover.

Since each of these values changes constantly, it is necessary to utilize a computer program capable of making multiple changes in solar angles simultaneously and computing the total solar radiation transmitted with each of these changes. Fortunately, the SAFCO program has been developed by Professor Dr. James Ramsey, Mechanical Engineering Department at the University of Minnesota.

This computer program calculates the direct, diffuse and reflected solar radiation striking a tilted surface based on the Liu and Jordan model and computes the total solar radiation that is transmitted through the glazing.

The input parameters include the latitude angle in degrees; surface azimuth; declination angle, collector tilt angle, ground reflectance and glazing transmittance.

Based on these inputs, SAFCO then computes solar transmittance for each half hour of the day and totals this to arrive at average daily solar radiation transmitted for each month of the heating season.

Through the use of SAFCO, a series of tables have been developed that should serve as a valuable reference tool to Minnesotans interested in solar energy. The solar radiation values used in this appendix are based on actual recorded values over a 30 year period at St. Cloud, Minnesota. The values are average day values based on the Liu and Jordan method. For clear day values, see Table A-18. The values used for ground reflectance are based on 10 years of measured data from St. Paul, Minnesota taken by Professor Don Baker, Department of Soil Science, University of Minnesota. These values are shown in Table A-6. Although all of these solar radiation numbers are calculated for St. Cloud, many of the same values can be calculated for other parts of Minnesota by using Table 5-1 and 5A.

The first series of tables, A-1 through A-6, detail solar radiation availability and transmittance through double pane south facing glazing. Table A-1 shows daily average solar radiation available for each month during the heating season for St. Cloud. One can see that for each month, the tilt angle is a major factor determining the amount of solar radiation that strikes a square foot of glazing surface. Also, this table shows that no single tilt angle results in the maximum solar radiation available for each month of the heating season.

Table A-2 shows the average daily solar radiation for each month that is transmitted through a square foot of south facing

glazing, while Table A-3 shows the present solar radiation transmitted for several tilt angles. From Table A-3 we see that the transmittance can vary from 63 to 73 percent. The major determining factor for transmittance is the angle that the solar radiation strikes the glazing surface. The closer to perpendicular that this angle is, the higher the transmittance (a 60° tilt in December). Conversely, the more oblique the angle, such as a 10° tilt in May, the lower the overall transmittance.

In order for designers of sunspaces to determine the optimum tilt angle of the south glazing, the monthly totals must be determined and totaled for the heating season as is shown in Table A-4. Two things should be highlighted here. The first is that the optimum tilt angle is for the heating season -- September 15 to May 15 -- is 55° . If we assume a September 1 to May 31 heating season the optimum changes to 50° . And if we look at October 1 to April 30 as the heating season, the optimum becomes 60° . Now although Table A-4 indicates that 55° is the optimum tilt angle, this doesn't mean that it is the best angle, only that it results in the most solar radiation transmitted into the sunspace during the heating season. (See the discussion on glazing tilt in Section 2.)

The second point to note in this table is how the total values for solar radiation transmitted vary for different tilt angles. It is true that here 55° is the optimum, yet there is less than a 5 percent reduction for tilt angles as low as 35° and as high as 75° . This affords the designer a great deal of flexibility. A vertical tilt results in a 15 percent drop in seasonal solar

transmittance. This may or may not be an acceptable penalty to pay for a vertical south glazing depending on other considerations.

Table A-5 details a month by month comparison of a vertical tilt angle to other tilt angles. One can see that during the months November through February, a vertical tilt angle results in only a 6 percent decrease in total solar radiation transmitted. The real difference comes during the spring and fall months when lower tilt angles actually result in as much as double the solar radiation transmitted.

Table A-6 shows the variations in ground reflectance due to snow cover during the winter months. Although this value becomes as high as 0.80 in January, this does not mean as much of the popular literature implies, that the amount of solar radiation available to a vertical surface will increase by up to 80 percent. The reflection component of total solar radiation available is a small portion of the total value. In fact, our calculations show a maximum of 12 percent increase in solar radiation available to south facing surfaces due to snow cover. (See Table A-17). If you follow the calculation procedure in Table 5A you shouldn't make the mistake of overestimating solar radiation availability due to snow cover.

The second series of tables, A-7 to A-9, deal with solar radiation transmitted through glazing surfaces which do not face true south. This is important to know because often times the house which a sunspace is going to be added does not have a south facing wall.

Table A-7 shows average daily solar radiation transmitted for all heating season months for glazing tilt angles ranging

from 30 to 90 and azimuths ranging from 0 to 90. The azimuth is simply the deviation from true south that a glazing faces. For example, a 45° azimuth would indicate that the glazing faces either southeast or southwest, 45° off true south. A 90° azimuth indicates the glazing is facing either due east or due west. We can see from this table that during the months September through March, the greater deviation from true south, the less solar radiation transmitted. In April and May, however, we see that a glazing surface facing southeast or southwest may actually collect more solar radiation than one facing true south. These percentages are shown in Table A-8. Should a designer then specify that the sunspace actually face some direction other than true south?

We need to go to Table A-9 to find the answer. This table summarizes the seasonal solar radiation transmittance for various tilts and azimuths. We can see at a glance that a south facing glazing will always perform better than one deviating from true south. It is interesting to note on this table the percentage drop in solar radiation transmittance as the deviation from true south increases. For vertical glazing, small deviations such as 15 to 30 degrees result in less than a 10 percent decrease in seasonal solar radiation transmittance while a glazing tilted at 30° can deviate 45° from true south and still capture over 90 percent of that same glazing if it was facing true south. Keep in mind, that this table doesn't show the whole story. Glazing surfaces with large deviations from true south can result in overheating problems in spring, summer and fall if not properly shaded.

Now that we are familiar with solar radiation transmittance through glazings at various tilts and azimuths, we need to compare these values with heat loss factors to determine the net effect of various glazing options. Tables A-10 through A-16 deal with double, triple and quad pane glazing options at various tilts and azimuths and with and without night insulation.

Beginning with Table A-10, we can compare the seasonal solar radiation transmittance for double, triple and quad paned glazings. As expected, double pane glazing has the highest values for all three tilt angles. It outperforms triple pane glazing by 15 percent and quad pane by 34 percent.

To be able to determine the net heating effect, the heat loss from each of these glazing options must be calculated (see Table A-11).

Table A-12 shows the net heat gain for various glazing options without night insulation. We see that regardless of tilt angle, triple pane outperforms double and quad pane glazing, although the differences are very small in most cases. For a vertical surface, triple pane is the winner by almost 7 percent over double pane, but less than 1 percent over quad pane. For a 60 degree tilt, triple pane exceeds double pane by just over 1 percent and quad pane by less than 4 percent. At a 45° tilt, triple exceeds double pane by just over 1 percent and quad pane by just over 3 percent. Overall, these differences are so small that when the cost for each glazing option is factored in, double pane would probably be the most logical choice, except for possibly an application using vertical glazing.

In Table A-13, R4 night insulation is included in the various glazing options. We see that when night insulation is used 14 hours each day, south facing double glazing outperforms triple glazing by 15 percent and quad glazing by over 30 percent regardless of the glazing tilt. By looking back to Table A-12, you can see that double glazing with night insulation significantly outperforms either triple glazing or quad glazing without night insulation. Tables A-12 and A-13 present a very strong case for including night insulation with any glazing option, but particularly for double glazing. The overall increase in net Btu/ft² gained by adding R4 night insulation is almost 50 percent when used with double glazing, 35 percent with triple glazing and 20 percent with quad glazing. These calculations assume a tight fitting window insulation used on a daily basis.

In Table A-14, total monthly and seasonal solar radiation transmitted through east or west facing glazing options is shown. We can easily see that double pane has the most solar radiation transmitted for each month as well as for the entire heating season.

Table A-15 shows the net heat gain results for the same glazing options with and without night insulation. Several things stand out from this table. The first is that if no night insulation is going to be used, quad pane should be the choice. Quad pane glazing will net 200 percent more Btu's for the heating season than double pane and exceed triple pane by 30 percent. However, note that the best option overall would be to use double pane glazing plus night insulation. This will exceed the next

best option, triple pane with night insulation by 15 percent and exceed quad pane without night insulation by almost 100 percent. The designer of a passive solar system needs to use these numbers in conjunction with costs for various options to be able to make a wise decision regarding various glazing options.

The last two remaining tables, A-17 and A-18 should also be of interest to the solar designer. Table A-17 shows the effect of not having a snow cover directly in front of a south facing glazing surface. For example, if a glazing surface is tilted at 60° and faces 30° west of true south, in the month of February it will only receive 94 percent of the solar radiation that a similar glazing surface with snow in front of it would have received. If the glazing surface was vertical and faced 45° east of true south, the value in February would be 86 percent. This table is most helpful when used in calculating solar radiation absorbed per square foot from Table 5A.

The last table, A-18, provides conversion factors for determining solar radiation availability on clear days, based on the average day values shown in Table A-1. For example, in St. Cloud in December, the average daily solar radiation available to 1 square foot of vertical surface is 1,108 Btu/ft²/day.

To determine what the clear day value would be, multiply 1,108 Btu/ft²/day by 1.48 from Table A-18 and the result is 1,640 Btu/ft²/day. This may be useful for designers interested in sizing thermal mass to prevent overheating.

These tables are provided as a reference to the designers or builders of passive solar systems, including but not limited to sunspaces. By becoming familiar with these and learning how to

use them, you take the guess work out of your calculations and learn to feel more confident as you continually make compromises in your designs.

TABLE A-1
 Total Average Day Solar Radiation Available
 During The Heating Season For St. Cloud
 (All numbers in Btu/ft²/day)
 Azimuth = 0

Tilt Angle	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May
Horizontal	1,327	888	538	453	627	925	1,349	1,559	1,839
15	1,504	1,111	747	669	917	1,184	1,557	1,651	1,868
20	1,553	1,175	810	736	1,007	1,263	1,617	1,667	1,858
25	1,592	1,233	868	799	1,092	1,336	1,668	1,673	1,837
30	1,622	1,283	921	858	1,171	1,403	1,711	1,670	1,810
35	1,642	1,325	969	912	1,244	1,442	1,744	1,658	1,772
40	1,653	1,359	1,011	961	1,310	1,513	1,767	1,636	1,725
45	1,654	1,385	1,047	1,005	1,368	1,556	1,781	1,605	1,668
50	1,645	1,402	1,076	1,042	1,419	1,590	1,785	1,567	1,605
55	1,626	1,410	1,099	1,074	1,461	1,616	1,779	1,521	1,532
60	1,598	1,409	1,115	1,099	1,495	1,634	1,763	1,466	1,452
65	1,560	1,400	1,124	1,117	1,521	1,642	1,738	1,403	1,364
70	1,513	1,382	1,127	1,129	1,537	1,641	1,703	1,333	1,274
75	1,458	1,355	1,122	1,134	1,544	1,630	1,659	1,257	1,178
80	1,394	1,320	1,110	1,132	1,542	1,611	1,605	1,174	1,077
85	1,322	1,276	1,092	1,123	1,530	1,583	1,544	1,087	974
Vertical	1,243	1,225	1,066	1,108	1,510	1,547	1,474	994	867

TABLE A-2
 Total Average Day Solar Radiation Transmitted
 Through South Facing Double Glazing
 During The Heating Season For St. Cloud
 (All numbers in Btu/ft²/day)

<u>Tilt Angle</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>	<u>Jan.</u>	<u>Feb.</u>	<u>March</u>	<u>April</u>	<u>May</u>
15	1,061	771	507	451	622	822	1,099	1,170	1,324
20	1,102	825	560	508	697	888	1,149	1,183	1,318
25	1,135	874	609	562	768	948	1,191	1,189	1,305
30	1,159	916	654	611	833	1,003	1,224	1,187	1,284
35	1,176	952	694	656	894	1,037	1,250	1,179	1,256
40	1,184	980	730	696	948	1,091	1,268	1,164	1,220
45	1,185	1,001	760	732	995	1,124	1,277	1,141	1,178
50	1,179	1,015	784	762	1,035	1,151	1,280	1,119	1,127
55	1,165	1,022	802	786	1,067	1,170	1,275	1,075	1,071
60	1,143	1,022	815	805	1,093	1,183	1,261	1,031	1,008
65	1,113	1,016	822	819	1,112	1,188	1,240	981	940
70	1,076	1,003	824	828	1,124	1,186	1,209	925	868
75	1,030	982	821	832	1,128	1,177	1,171	864	792
80	977	954	812	830	1,126	1,159	1,125	798	712
85	918	919	798	823	1,116	1,134	1,071	727	630
Vertical	853	877	777	810	1,097	1,101	1,012	653	546

TABLE A-3

Transmittance of Solar Radiation Through
South Facing Double Glazing at Various Tilts

<u>Tilt Angle</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>	<u>Jan.</u>	<u>Feb.</u>	<u>Mar.</u>	<u>Apr.</u>	<u>May</u>
30	0.715	0.714	0.710	0.712	0.711	0.715	0.715	0.711	0.70
45	0.716	0.723	0.726	0.728	0.727	0.722	0.717	0.711	0.70
60	0.715	0.725	0.731	0.732	0.731	0.724	0.715	0.703	0.69
75	0.706	0.725	0.732	0.734	0.731	0.722	0.706	0.687	0.672
90	0.686	0.716	0.729	0.731	0.726	0.711	0.687	0.657	0.63

TABLE A-4
 Total Average Day Solar Radiation Transmitted
 Through Double Pane South Facing Glazing
 For St. Cloud During Heating Season
 (All numbers in Btu/ft²/month)

Days/Month	15 Sept.	31 Oct.	30 Nov.	31 Dec.	31 Jan.	28 Feb.	31 March	30 April	15 May	Total
Tilt Angle										
Horizontal										
15	15,915	23,901	15,210	13,981	19,282	23,016	34,069	35,100	19,860	200,334
20	16,530	25,575	16,800	15,748	21,607	24,864	35,619	35,490	19,770	212,003
25	17,025	27,094	18,270	16,860	23,808	26,544	36,921	35,670	19,575	221,767
30	17,385	28,396	19,620	18,941	25,823	28,084	37,944	35,610	19,260	231,063
35	17,640	29,512	20,820	20,336	27,714	29,036	38,750	35,370	18,840	238,018
40	17,760	30,380	21,900	21,576	29,388	30,548	39,308	34,920	18,300	244,080
45	17,775	31,031	22,800	22,692	30,845	31,472	39,587	34,230	17,670	248,102
50	17,685	31,465	23,520	23,622	32,085	32,228	39,680	33,570	16,905	250,760
55	17,475	31,682	24,060	24,366	33,077	32,760	39,525	32,250	16,065	251,260
60	17,145	31,682	24,450	24,955	33,883	33,124	39,091	30,930	15,120	250,380
65	16,695	31,496	24,660	25,389	34,472	33,264	38,440	29,430	14,100	247,946
70	16,140	31,093	24,720	25,668	34,844	33,208	37,479	27,750	13,020	243,922
75	15,450	30,442	24,630	25,792	34,968	32,956	36,301	25,920	11,880	238,339
80	14,655	29,574	24,360	25,730	34,906	32,452	34,875	23,940	10,680	231,172
85	13,770	28,489	23,940	25,513	34,596	31,752	33,201	21,810	9,450	222,521
90	12,795	27,187	23,310	25,110	34,007	30,828	31,372	19,260	8,385	212,254

TABLE A-5

Multipliers For Converting Solar Radiation
Available on a South Facing Vertical Surface
To Other Tilt Angles
(Azimuth = 0)

[illegible]

TABLE A-6

Monthly Average Ground Reflectance Values

January	0.80
February	0.69
March	0.46
April	0.22
May	0.18
June	0.19
July	0.21
August	0.22
September	0.22
October	0.21
November	0.38
December	0.67

Source: This data reflects 10 years of monitoring (December 1969 - December 1979) done in St. Paul by Professor Don Baker of the University of Minnesota.

TABLE A-7

Total Average Day Solar Radiation Transmitted
Through Double Glazed Tilted Surfaces
During The Heating Season for St. Cloud, MN
(All numbers in Btu/ft²/day)

<u>Azimuth</u>	<u>Slope</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>	<u>Jan.</u>	<u>Feb.</u>	<u>March</u>	<u>April</u>	<u>May</u>
0	30	1,159	916	654	611	833	1,003	1,224	1,187	1,284
0	45	1,185	1,001	760	732	995	1,124	1,277	1,141	1,178
0	60	1,143	1,022	815	805	1,093	1,183	1,261	1,031	1,008
0	75	1,030	982	821	832	1,128	1,177	1,171	864	792
0	90	853	877	777	810	1,047	1,101	1,012	653	546
15	30	1,149	903	642	598	817	988	1,213	1,185	1,286
15	45	1,172	982	742	714	971	1,103	1,263	1,190	1,186
15	60	1,128	998	793	784	1,063	1,155	1,245	1,034	1,016
15	90	845	849	752	785	1,062	1,069	1,003	669	569
30	30	1,120	866	607	561	770	947	1,181	1,175	1,286
30	45	1,135	931	692	661	903	1,046	1,222	1,132	1,194
30	60	1,087	937	732	721	981	1,087	1,200	1,034	1,038
30	90	820	784	681	710	966	998	976	703	628
45	30	1,074	811	556	506	700	885	1,130	1,155	1,281
45	45	1,077	857	621	583	807	964	1,158	1,111	1,198
45	60	1,026	852	648	627	867	993	1,132	1,021	1,057
45	90	781	702	587	605	841	909	933	724	690
60	30	1,013	741	493	439	615	807	1,063	1,124	1,269
60	45	1,003	767	536	493	692	863	1,076	1,077	1,188
60	60	947	751	549	521	735	881	1,045	990	1,059
60	90	926	610	488	495	709	808	872	724	729
75	30	941	661	423	366	521	717	982	1,082	1,247
75	45	914	664	444	397	569	749	977	1,027	1,165
75	60	853	640	446	412	596	757	941	942	1,043
75	90	655	513	392	390	579	700	793	704	742
90	30	859	575	350	292	421	621	891	1,030	1,216
90	45	813	557	353	305	446	629	865	965	1,126
90	60	749	525	347	311	461	628	825	878	1,005
90	90	573	416	303	298	458	592	702	662	729

TABLE A-8
Multipliers For Converting Solar Radiation
Transmitted Through South Facing Glazing
To Other Azimuths

<u>Azimuth</u>	<u>Tilt Angle</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>	<u>Jan.</u>	<u>Feb.</u>	<u>Mar.</u>	<u>April</u>	<u>May</u>
15	30	0.991	0.986	0.982	0.979	0.981	0.985	0.991	0.998	1.002
	45	0.989	0.981	0.976	0.975	0.976	0.981	0.989	0.999	1.007
	60	0.987	0.977	0.973	0.974	0.973	0.976	0.987	1.000	1.008
	90	0.990	0.968	0.968	0.928	0.968	0.971	0.991	1.024	1.042
30	30	0.966	0.945	0.928	0.918	0.924	0.944	0.965	0.990	1.002
	45	0.958	0.930	0.910	0.903	0.908	0.931	0.957	0.992	1.014
	60	0.951	0.917	0.898	0.896	0.898	0.919	0.952	1.000	1.030
	90	0.961	0.894	0.876	0.877	0.881	0.906	0.964	1.077	1.150
45	30	0.927	0.885	0.850	0.828	0.840	0.882	0.923	0.973	0.998
	45	0.909	0.856	0.817	0.796	0.811	0.858	0.907	0.974	1.017
	60	0.898	0.834	0.795	0.779	0.793	0.839	0.898	0.990	1.049
	90	0.916	0.080	0.755	0.747	0.767	0.826	0.922	1.109	1.264
60	30	0.874	0.809	0.754	0.718	0.738	0.805	0.868	0.947	0.988
	45	0.846	0.766	0.705	0.673	0.695	0.768	0.843	0.944	1.008
	60	0.829	0.735	0.674	0.647	0.672	0.745	0.829	0.960	1.050
	90	0.851	0.696	0.628	0.611	0.646	0.734	0.862	1.109	1.335
75	30	0.812	0.722	0.647	0.599	0.625	0.715	0.802	0.911	0.971
	45	0.771	0.663	0.584	0.542	0.572	0.666	0.765	0.900	0.989
	60	0.746	0.626	0.547	0.512	0.545	0.640	0.746	0.914	1.035
	90	0.768	0.585	0.505	0.481	0.528	0.636	0.784	1.078	1.359
90	30	0.741	0.628	0.535	0.478	0.505	0.619	0.728	0.868	0.947
	45	0.686	0.556	0.464	0.417	0.448	0.560	0.677	0.846	0.956
	60	0.655	0.514	0.426	0.386	0.422	0.531	0.654	0.852	0.997
	90	0.672	0.474	0.390	0.368	0.418	0.538	0.694	1.014	1.335

TABLE A-9

Total Solar Radiation Transmitted Through
Non-South Facing Glazing at Various Tilts
During The Heating Season For St. Cloud*

<u>Azimuth</u>	<u>Glazing Tilt</u>			
	<u>30</u>	<u>45</u>	<u>60</u>	<u>90</u>
0	1.000	1.000	1.000	1.000
15	.989	.986	.983	.982
30	.956	.944	.936	.931
45	.904	.881	.866	.859
60	.839	.803	.781	.773
75	.764	.714	.685	.678
90	.681	.619	.585	.580

*All numbers are a percentage of solar radiation transmitted through south facing glazing.

TABLE A-10

Total Solar Radiation Transmitted
Through South-facing Glazings
During the Heating Season
For St. Cloud, Minnesota
(All numbers in Btu/ft²/month)

Tilt Angle	<u>Double Pane</u>			<u>Triple Pane</u>			<u>Quad Pane</u>		
	<u>90°</u>	<u>60°</u>	<u>45°</u>	<u>90°</u>	<u>60°</u>	<u>45°</u>	<u>90°</u>	<u>60°</u>	<u>45°</u>
Sept.	12,795	17,145	17,775	11,070	14,835	15,375	9,555	12,810	13,275
Oct.	27,187	31,682	31,031	23,529	27,404	26,846	20,305	23,684	23,188
Nov.	23,310	24,450	22,800	20,160	21,120	20,367	17,430	18,240	17,010
Dec.	25,110	24,955	22,692	21,731	21,603	18,990	18,755	18,662	16,957
Jan.	34,007	33,883	30,845	29,419	29,295	26,660	25,420	25,296	23,033
Feb.	30,828	33,124	31,472	26,656	28,644	27,216	23,016	24,724	23,520
Mar.	31,372	39,091	39,587	27,125	33,821	34,255	23,436	29,202	29,574
April	19,260	30,930	34,230	16,920	26,760	29,610	14,640	23,130	25,590
May	<u>8,385</u>	<u>15,120</u>	<u>17,670</u>	<u>7,080</u>	<u>13,080</u>	<u>15,270</u>	<u>6,120</u>	<u>11,295</u>	<u>13,200</u>
Total	212,254	250,380	248,102	183,690	216,562	214,589	158,677	187,043	185,347

TABLE A-11

Total Heat Loss for Various Glazing Options
During the Heating Season for St. Cloud*
(all numbers in Btu/ft²/month)

	<u>Double Pane</u>	<u>Double Pane + N. I.</u>	<u>Triple Pane</u>	<u>Triple Pane + N. I.</u>	<u>Quad Pane</u>	<u>Quad Pane + N. I.</u>
Sept.	1,044	387	702	326	468	266
Oct.	6,473	2,399	4,352	2,031	2,902	1,652
Nov.	13,781	5,108	9,266	4,324	6,178	3,516
Dec.	19,850	7,358	13,347	6,229	8,898	5,065
Jan.	22,871	8,478	15,378	7,177	10,252	5,836
Feb.	18,708	6,935	12,580	5,871	8,387	4,774
Mar.	15,966	5,918	10,736	5,010	7,157	4,074
April	8,352	3,096	5,616	2,621	3,744	2,131
May	<u>1,670</u>	<u>619</u>	<u>1,123</u>	<u>524</u>	<u>749</u>	<u>426</u>
Total	108,715	40,298	73,100	34,113	48,735	27,740

*An indoor temperature of 65°F is assumed and the night insulation is assumed to be R=4 used 14 hours a day during the heating season. See Table A-16 for U-values of glazing options.

TABLE A-12

Net Heat Gain for South-facing Glazing Options
For St. Cloud, Minnesota During Heating Season

	<u>Double Pane</u>			<u>Triple Pane</u>			<u>Quad Pane</u>		
	<u>90°</u>	<u>60°</u>	<u>45°</u>	<u>90°</u>	<u>60°</u>	<u>45°</u>	<u>90°</u>	<u>60°</u>	<u>45°</u>
Sept.	11,751	16,101	16,731	10,369	14,133	14,673	9,087	12,342	12,807
Oct.	20,714	25,209	24,558	19,177	23,052	22,494	17,403	20,782	20,286
Nov.	9,529	10,669	9,019	10,894	11,854	11,101	11,252	12,062	10,832
Dec.	5,260	5,105	2,842	8,384	8,260	5,643	9,857	9,764	8,059
Jan.	11,136	11,012	7,974	14,041	13,917	11,282	15,168	15,044	12,781
Feb.	12,120	14,416	12,764	14,076	16,064	14,636	14,629	16,337	15,133
Mar.	15,406	23,125	23,621	16,389	23,085	23,519	16,279	22,045	22,417
April	10,908	22,578	25,878	11,304	21,144	23,994	10,896	19,386	21,846
May	<u>6,715</u>	<u>13,450</u>	<u>16,000</u>	<u>5,957</u>	<u>11,957</u>	<u>14,147</u>	<u>5,371</u>	<u>10,546</u>	<u>12,451</u>
Total	103,539	141,665	139,387	110,591	143,466	141,489	109,942	138,308	136,612

TABLE A-13

Net Heat Gain for Various South-facing
Glazing Options with R4 Night Insulation
For St. Cloud During Heating Season
(All numbers in Btu/ft²/month)

	<u>Double Pane</u>			<u>Triple Pane</u>			<u>Quad Pane</u>		
	90°	60°	45°	90°	60°	45°	90°	60°	45°
Sept.	12,408	16,758	17,388	10,744	14,509	15,049	9,289	12,544	13,009
Oct.	24,788	29,289	28,632	21,498	25,373	24,815	18,653	22,032	21,536
Nov.	18,202	19,342	17,692	15,836	16,796	16,043	13,914	14,724	13,494
Dec.	17,752	17,597	15,334	15,502	15,374	12,761	13,690	13,597	11,892
Jan.	25,529	25,405	22,367	22,242	22,118	19,483	19,584	19,460	17,197
Feb.	23,893	26,189	24,537	20,785	22,773	21,345	18,242	19,950	18,746
March	25,454	33,173	33,669	22,115	28,811	29,245	19,362	25,128	25,500
April	16,164	27,834	31,134	14,299	24,139	26,989	12,509	20,999	23,459
May	<u>7,766</u>	<u>14,501</u>	<u>17,051</u>	<u>6,556</u>	<u>12,556</u>	<u>14,746</u>	<u>5,694</u>	<u>10,869</u>	<u>12,734</u>
Total	171,956	210,089	207,804	149,577	182,449	180,476	130,937	159,303	157,602

TABLE A-14

Total Solar Radiation Transmitted Through
 East or West Facing Vertical Glazing
 For St. Cloud During Heating Season
 (All numbers in Btu/ft²/month)

	<u>Double Pane</u>	<u>Triple Pane</u>	<u>Quad Pane</u>
Sept.	8,595	7,440	6,420
Oct.	12,896	11,160	9,641
Nov.	9,090	7,860	6,780
Dec.	9,238	7,998	6,913
Jan.	14,198	12,271	10,602
Feb.	16,576	14,336	12,376
Mar.	21,762	18,817	16,244
April	19,860	17,160	14,820
May	<u>10,935</u>	<u>9,450</u>	<u>8,160</u>
Total	123,150	106,497	91,956

TABLE A-15

Net Heat Gain Through
East or West Facing Vertical Glazing
During the Heating Season for St. Cloud
(all numbers in Btu/ft²/month)

	<u>Double Pane</u>	<u>Double Pane + N. I.</u>	<u>Triple Pane</u>	<u>Triple Pane + N. I.</u>	<u>Quad Pane</u>	<u>Quad Pane + N. I.</u>
Sept.	7,551	8,208	6,738	7,114	5,952	6,154
Oct.	6,423	10,497	6,808	9,129	6,739	7,989
Nov.	-4,691	3,982	-1,406	3,536	602	3,264
Dec.	-10,612	1,880	-5,349	1,769	-1,985	1,848
Jan.	-8,673	5,720	-3,102	5,099	350	4,766
Feb.	-2,132	9,641	1,756	8,465	3,989	7,602
Mar.	5,796	15,844	8,081	13,807	9,087	12,170
April	11,508	16,764	11,544	14,539	11,076	12,689
May	<u>9,265</u>	<u>10,316</u>	<u>8,327</u>	<u>8,926</u>	<u>7,411</u>	<u>7,734</u>
Total	+14,435	82,852	+33,397	72,384	43,221	64,216

TABLE A-16

U Values For Various Glazing And
Glazing/Night Insulation Options

	<u>U Value</u> (Btu/hr/ft ² /°F)
Double pane glass, $\frac{1}{4}$ " air space	0.58
Triple pane glass, $\frac{1}{4}$ " air space	0.39
Quad pane glass, $\frac{1}{4}$ " air space	0.26
Double pane glass, $\frac{1}{4}$ " air space and night insulation*	0.215
Triple pane glass, $\frac{1}{4}$ " air space and night insulation*	0.182
Quad pane glass, $\frac{1}{4}$ " air space and night insulation*	0.148
Double pane glass, $\frac{1}{4}$ " air space and R=4 night insulation inserted for entire heating season	0.149
Triple pane glass, $\frac{1}{4}$ " air space and R=4 night insulation inserted for entire heating season	0.132
Quad pane glass, $\frac{1}{4}$ " air space and R=4 night insulation inserted for entire heating season	0.113

*Assumes R=4 night insulation that is placed $\frac{3}{4}$ " away from glazing and used 14 hours each day.

TABLE A-17

Multipliers For Solar Radiation Available
Where There is Very Little Snow Cover
Directly in Front of Glazing Surface

<u>Azimuth</u>	<u>Tilt Angle</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>	<u>Jan.</u>	<u>Feb.</u>	<u>March</u>	<u>April</u>	<u>May</u>
0	30	1.00	1.00	1.00	0.99	0.98	0.98	0.99	1.00	1.00
	45	1.00	1.00	0.99	0.98	0.97	0.97	0.98	1.00	1.00
	60	1.00	1.00	0.99	0.96	0.95	0.94	0.97	1.00	1.00
	75	1.00	1.00	0.99	0.95	0.926	0.926	0.95	1.00	1.00
	90	1.00	1.00	0.98	0.926	0.90	0.88	0.926	1.00	1.00
15	30	1.00	1.00	1.00	0.99	0.98	0.98	0.99	1.00	1.00
	45	1.00	1.00	0.99	0.98	0.97	0.97	0.98	1.00	1.00
	60	1.00	1.00	0.99	0.96	0.95	0.94	0.97	1.00	1.00
	75	1.00	1.00	0.99	0.95	0.926	0.926	0.95	1.00	1.00
	90	1.00	1.00	0.98	0.926	0.90	0.88	0.926	1.00	1.00
30	30	1.00	1.00	1.00	0.99	0.98	0.98	0.99	1.00	1.00
	45	1.00	1.00	0.99	0.98	0.96	0.96	0.98	1.00	1.00
	60	1.00	1.00	0.99	0.96	0.94	0.94	0.97	1.00	1.00
	75	1.00	1.00	0.99	0.95	0.92	0.926	0.95	1.00	1.00
	90	1.00	1.00	0.98	0.92	0.89	0.877	0.926	1.00	1.00
45	30	1.00	1.00	1.00	0.98	0.98	0.98	0.99	1.00	1.00
	45	1.00	1.00	0.99	0.97	0.96	0.96	0.98	1.00	1.00
	60	1.00	1.00	0.99	0.95	0.93	0.93	0.97	1.00	1.00
	75	1.00	1.00	0.98	0.94	0.91	0.92	0.95	1.00	1.00
	90	1.00	1.00	0.97	0.90	0.87	0.86	0.926	1.00	1.00

TABLE A-18

Multipliers for Converting Average Day
Solar Radiation Availability to Clear Day Values

<u>Month</u>	<u>Tilt Angle</u>		
	<u>90°</u>	<u>60°</u>	<u>45°</u>
Sept.	1.36	1.36	1.35
Oct.	1.45	1.43	1.41
Nov.	1.58	1.56	1.54
Dec.	1.48	1.51	1.47
Jan.	1.25	1.25	1.25
Feb.	1.39	1.39	1.38
March	1.34	1.35	1.34
April	1.40	1.48	1.48
May	1.28	1.39	1.41

APPENDIX B

Vegetable Production in Energy Conserving/Solar Greenhouses

Often the worth of a solar greenhouse is based on the cost and return to the individual owner. With agricultural practices becoming more energy intensive -- particularly due to food processing, packaging and distribution -- we should look more closely at the potential energy savings for Minnesota if more of our food was grown locally in solar greenhouses.

A solar greenhouse has the capacity under normal conditions to produce ten times the average field vegetable yields (Roller, 1977). See Table B-1.

TABLE B-1

Comparative Production Energy to Produce Winter Food

<u>Method of Production</u>	<u>Energy Used</u>	<u>Yields/Acre</u>
Field grown shipped fresh	6.8 MBTU/T	5T
Field grown processed	1.1 MBTU/T	20T
Greenhouse Grown - conventional	0.8 MBTU/T	100T
Greenhouse Grown - Conserving	0.6 MBTU/T	160T

Source: Roller, Warren L. "Energy and the Food Chain." Proceedings of a Conference on Solar Energy for Heating Greenhouse and Greenhouse-Residential Combination (Bond, ed.) Ohio Agricultural Research and Development Center, 1977.

In Table B-2, we can see that the energy use per ton of vegetables produced in an energy conserving greenhouse is nearly equal to the energy needed to produce, pack and ship fresh vegetables. This Table was prepared not by results of an actual

study, but rather by calculating values from national agricultural and energy data.

In an actual study -- the Nelson Greenhouse Project -- done at the University of Wisconsin in Madison, the results were very different than shown in Table B-2. The Nelson study showed that a 55 percent savings of energy consumption could be expected when raising fresh, vine ripened greenhouse tomatoes compared to those shipped from California.

Even if we assume that the Nelson Study was inaccurate and Table B-2 more accurately describes the real-life situation, vegetable production in a solar greenhouse would still be the winner. This is because the vegetables would be vine ripened and

TABLE B-2

Total Fossil Energy Used in Winter Vegetable Production

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	0.5	-	-	-
4. Transportation	5.0	11.0	-	-
5. Heating & Cooling	-	-	140.0	17.5
Total MBTU/T	15.6	20.2	142.8	20.1

Source: Same as Table B-1, page 304.

maintain their high nutritional quality. In addition, under good management, the yields would be more dependable. We in Minnesota would not be subject to higher food prices or food shortages due to inclement weather in another part of the country.

APPENDIX C

Option To A Solar Greenhouse

There is an alternative to the building and operating of a solar greenhouse. This option has been titled the "Poor man's Greenhouse," but it is a realistic way to have a fresh food supply extending into the dead of winter. It can also supply garden transplants. This low cost and efficient structure is called a coldframe.

The basic coldframe is about four to six feet deep and any length that is desired. The back side is 6 to 10 inches higher than the front which allows a shallow slope to the front. It is always located with the front to the south. The ends are constructed with a sloping board from the rear to the front. The top is covered with a double glazing similar to that used on a solar greenhouse and it is usually hinged in the back. For durability, a salt treated wood, concrete or other rot resistant material should be used. The coldframe structure must include a night insulating cover and some perimeter insulation is desired. If you use second hand construction materials, a coldframe may cost only \$2.00 per square foot, a more elaborate structure could cost \$13.00 per square foot.

One step beyond the simple coldframe would be a grow frame that employs a solar angle of incident and insulating shields. These units have mass for heat storage and tundra or perimeter insulation. There is insufficient information at this time to determine if such units merit the increased investment.

The coldframe has been used traditionally to supply garden transplants. Coldframe transplants are usually grown in the soil of the frame and soaked and pulled just before transplanting. This contrasts with greenhouse transplants grown in paks and flats. A small coldframe can grow a considerable amount of transplants as shown in Table A. Onion transplants and hardy ornamentals can be seeded in late summer and transplanted

Table A
Transplant Production in a Coldframe

Crop	Production per Square Foot	Seed Needed Per Square Foot
Broccoli	69	0.4 grams
Brussell Sprouts	69	0.4 grams
Cabbage	69	0.4 grams
Cauliflower	69	0.4 grams
Cucumbers (2½ peat pots)	16	0.6 grams
Muskmelon (2½ peat pots)	16	0.6 grams
Squash (2½ peat pots)	16	2.3 - 3.9 grams
Watermelon (2½ peat pots)	16	0.8 - 2.3 grams
Tomatoes	56	0.4 grams
Egg Plants	56	0.8 grams
Pepper	56	0.8 grams

to the garden the next spring.

The coldframe can also be used to extend the garden harvest season for fresh produce. The coldframe limits the type of plants that can be grown because of its height. In northern Minnesota, lettuce was harvested the first of December without a great deal

of care and concern. Other reports have claimed lettuce harvest until January in Minnesota. It seems possible to harvest kale and other cold loving greens throughout the winter if freezing and thawing can be prevented. There may not be as much advantage to early spring crops as the fall. An estimate of a one month lead on the garden seems reasonable.

Serious gardeners may find the coldframe can be used to propagate many different shrubs and woody seeds when properly managed. Shading and/or reverse reflection shields may be required to prevent overheating and drying.

A coldframe could be modified to serve as a solar food dryer, to force winter bulbs and to serve as a plant holding area.

Summary

A coldframe can serve as a low cost season extender, transplant producer, a propagation area, food dryer and plant staging area when reasonably designed, constructed and operated. It can provide experience to a would-be solar greenhouse operator who wishes to develop skills in production before attempting to run a greenhouse. Commercial growers may find a coldframe somewhat less convenient but economical to construct and operate.

Details of construction can usually be secured at the local extension office or horticulture department at many universities.

Appendix D

A summary of the characteristics of the two LASL reference designs is as follows:

Thermal Storage (per unit of common wall)

Masonry wall	30 Btu/ft ² /°F
Insulated wall	62.4 Btu/ft ² /°F

Masonry Properties

Thermal conductivity	1.0 Btu/h-ft-°F
Density	150 lb/ft ³
Specific heat	0.2 Btu/lb-°F
Infrared emittance of surface	0.9

Control Range

Sunspace, heating thermostat setpoint	45°F
Sunspace, cooling thermostat setpoint	95°F
Room, difference between heating and cooling thermostat setpoints	10°F

Thermocirculation Vents

Vent area/collection area (sum of both upper and lower vents)	0.06
Height between vents, reverse flow prevented	8 ft.

Additional Assumptions for Annual Method

Sunspace solar absorptance

common wall, lightweight	0.7
common wall, masonry	0.8
water container	0.9
floor	0.3
other surfaces	0.3

Ground reflectance 0.3

No auxiliary heat generation

Room lower thermostat setpoint 65°F

Sunspace opaque wall thermal
resistance R20

Sunspace infiltration rate 0.5 air changes/hour

Sunspace Glazing Properties

Due south orientation

No shading

Double Pane

Index of refraction 1.526

Extinction coefficient 0.5 in. -1

Thickness of each pane 1/8 in.

Air gap between panes 1/2 in.

Night insulation thermal
resistance, when used R9

APPENDIX E

Solar Greenhouse Heat Loss Calculations

Step 1 List Greenhouse Dimensions in Feet

North wall height , A=
 Head Height , B=
 South slope glazing, C=
 Width to head line, D=
 Width from head to glazing, E=
 Gable height, F=
 Insulated roof, G=
 Glazed roof, H=
 Length, L=

Step 2 Calculate the appropriate surface areas and perimeter

End walls area:

$$2 \text{ (end walls)} \times [DXB + (DXF) + (B \times E)] =$$

Insulated roof area

$$G \times L =$$

Glazed roof area

$$H \times L =$$

South glazed wall area

$$C \times L =$$

Note: If part of south wall is insulated, then divide into two wall sections as for roof

North wall area

$$(B + F) \times L =$$

Perimeter

$$2 (D + E) + L =$$

Step 3 List construction materials for each surface area and U factors from Table 5 and in this appendix table.

Location	Construction Material	U Factor	115
End wall area (Separate walls if different materials used)		$U_1 =$	
Insulated roof area		$U_2 =$	
Glazed roof area (Include night blanket U Factor)		$U_3 =$	
South glazed wall area (Separate if two different materials used and include U factor for night blanket)		$U_4 =$	
North wall		$U_5 =$	
Perimeter		$U_6 =$	

Step 4 Calculate Appropriate Conduction Heat Loss, Q_c

$$Q_c = \text{Area} \times U \times \Delta T$$

ΔT = Inside night temperature (50 degrees F. with ground heat) minus outside temperature (Approximately -15 degrees F) ΔT should range 65 to 70 degrees

$$\text{End wall area} \times U_1 \times \Delta T =$$

$$\text{Insulated roof area} \times U_2 \times \Delta T =$$

$$\text{Glazed roof area} \times U_3 \times \Delta T =$$

$$\text{South glazed wall area} \times U_4 \times \Delta T =$$

$$\text{Perimeter length} \times U_6 \times \Delta T =$$

(The north wall is omitted of dwelling is warmer than greenhouse)

$$\text{Total } Q_c = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6$$

Step 5 Calculate Greenhouse Volume

Gable Volume

$$\frac{1}{2} \times F \times D \times L =$$

Lower Greenhouse Volume

$$(D \times B \times L) + (\frac{1}{2} \times B \times E \times L) =$$

Gable volume + lower greenhouse volume = Total volume

Total volume =

Step 6 Calculate Air Infiltration Losses, Q_a

$$Q_a = 0.10 \times \Delta T \times \text{Volume}$$

(Air exchange assumed at 0.5 per hour)

$$Q_a =$$

Step 7 Calculate Total Heat Loss, Q_t

$$Q_t = Q_c + Q_a$$

$$Q_t =$$

Table of U Factors

Materials

U Factor - BTU/Sq Ft °F Hr.

Glazings - See Table 5 in main text

Wall Materials

Concrete block, 8"	0.5
Poured Concrete, 6"	1.1
Concrete block plus 1" foamed urethane	0.1
Concrete block plus 1" polystyrene	0.2
Soft wood, 1" normal	0.6

Night Blanket

Thin, aluminized or polyethylene film	0.4 - 0.5
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Perimeter

	<u>BTU/linear ft °F hr</u>
Uninsulated	0.8
Insulated	0.4

Source: Ross, 1978

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