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PASSIVE SOLAR HEATING OF BUILDINGS
WITH ATTACHED GREENHOUSE

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Abstract

Research has been conducted on the attached-greenhouse type of passive solar heating system in the north-central region. The thermal performance of attached-greenhouse buildings was analyzed in order to determine the component sizes and configurations which optimize performance. The analytical method is dynamic computer simulation using a thermal network model and actual hourly meteorological and solar radiation data from the north-central region. The project has consisted of a large number of computer simulation runs and resulting performance estimates for certain designs. Conclusions on design guidelines emerge from the results. The overall result of the project is the development of specific design guidelines useful to architects and builders.

Introduction

Research is being conducted on the attached-greenhouse type of passive solar heating system in the north-central region. General goals of the research are:

- 1) To evaluate attached-greenhouse passive solar heating in terms of the expected fraction of the total heating load provided by solar energy.
- 2) To investigate the constraints imposed on performance by traditional, wood-frame design and construction practices, especially for use of an insulated frame wall between the greenhouse and the residence.
- 3) To develop specific design guidelines for an attached greenhouse incorporated in new construction, or in a retrofit to an existing building, of traditional design and construction.
- 4) To investigate non-traditional designs appropriate to optimum performance, and to develop specific guidelines for any such designs.

The analytical method was dynamic computer simulation using a thermal network model of the building. Actual hourly meteorological and solar radiation data from the north-central region, principally the hourly typical meteorological year (TMY) data for Bismarck, North Dakota, drove the computer simulations.

The measure of performance is the Solar Savings Fraction (SSF) defined by

$$SSF = \frac{QLOAD, REF - QHEAT, TOT}{QLOAD, REF}$$

where QLOAD,REF is the room heat loss (excluding south-wall losses) on the basis of a reference room temperature of 65°F, and QHEAT,TOT is the total auxiliary heat added to the sunspace and the room to keep their air temperatures within their respective thermostat set points.

The thermal integrity of the building is characterized by a Building Load Coefficient (BLC) such that

$$QLOAD, REF = BLC \times DD$$

where DD is the number of Fahrenheit degree-days at the building site.

The most important parameter affecting heating performance is the Load/Collector Ratio (LCR) which is

$$LCR = BLC/A_c$$

where A_c is the solar collection area defined by the area of the principal greenhouse south-facing glazing or glazings projected on a vertical surface.

Building Model

A reference building with an attached-greenhouse was represented by a mathematical model of its important thermal properties as described below.

The sunspace geometry is shown in Figure 1. A single, tilted plane of glazing faces due south. The glazing consists of two panes with a half-inch air gap. The transmitted sunlight is assumed to be perfectly diffuse. The radiation eventually absorbed by each internal surface is the result of multiple internal reflections.

In order that the reference design resemble a conventional, frame-construction building, the wall between the greenhouse and the living space is assumed lightweight and insulated. Thermal storage is in the form of a container of water in the greenhouse. The container is detached from but adjacent to the wall and floor; it is thermally coupled to them by radiation and indirectly by convection through the sunspace air.

Thermal losses from the sunspace include those through the glazing, the insulated ceiling and end walls, the insulated perimeter of the greenhouse floor slab, and outside air infiltration. No account is taken of the possibility of losses due to evaporation of water in the greenhouse as would be the case when plants are present.

Specific design parameters are listed in Table 1.

Results

In terms of the four goals of research, the findings are as follows:

- 1) An evaluation of attached-greenhouse passive solar heating is provided in the form of the expected solar savings fraction (SSF) as a function of the building load/collector ratio (LCR). For example, this relationship for the reference design in Bismarck is shown in Figure 2. Very comprehensive results of this type are reported in Reference 1 (reprinted in the Appendix), a joint effort with the Los Alamos Scientific Laboratory. Here there are tables of SSF versus LCR for 16 reference designs in 208 locations.
- 2) There are no severe constraints imposed on performance by traditional, wood-frame design and construction practices. In particular, the use of an insulated frame wall between the greenhouse and the residence, with thermocirculation vents for heat transfer, has a comparable performance to other types of solar walls. Figures 4 and 5 illustrate the performance compared to the water wall and masonry wall. The water wall outperforms the insulated wall for storage volumes above 0.2 cu ft/sq ft. Some of this difference is accounted for simply by the chosen shape of the storage container in the insulated-wall reference design. A high, thin container performs more nearly like a water wall. (See Figure 6 for the sensitivity of the solar savings fraction to storage shape.) The performance is more nearly comparable to that of a masonry wall for storage volumes above 0.4 cu ft sq ft. The main difference is that there is normally an optimum masonry-wall thickness of about one foot while performance continues to improve indefinitely with increased water storage.
- 3) Specific design guidelines follow from the studies of the SSF sensitivity to the variation of design parameters shown in Figures 3-27. These guidelines are the main result to be reported and are presented under a separate heading below.
- 4) Non-traditional designs appear to be unnecessary for good thermal performance, meaning primarily that an insulated wall with vents performs almost as well as thermal-storage walls (see Figures 4 and 5).

A design tool of great importance is the Los Alamos Scientific Laboratory (LASL) solar/load ratio (SLR) method of performance estimation. This method allows a designer to estimate the performance of a design on the basis of just one parameter, the solar/load ratio. This method has been extended to include attached-greenhouse systems, as one aspect of the present project, jointly with LASL. Current progress in this aspect is described in a paper presented at the 25th Annual Meeting of the Americal Section of the International Solar Energy Society, June 2-6, 1980, Phoenix, Arizona. Results most directly related to the present report are to be presented at the 5th National Passive Solar Conference, October 19-26, 1980, Amherst, Massachusetts. Both papers are reprinted in the Appendix.

Design Guidelines

Under the design parameter headings which follow, the Figures from which the conclusions are drawn are indicated in parentheses. The studies are based primarily on Bismarck, North Dakota, chosen as a relatively severe test of passive solar design. The conclusions are believed to apply in broad, qualitative terms to other parts of the north-central region. It is important to note that the performance sensitivity curves of Figures 3-27 are not to be used for estimating the absolute SSF values for various locations. The annual SSF-versus-LCR tables in the Appendix, or the monthly solar/load ratio procedures presented in the Appendix, are to be used for that purpose. Rather, the sensitivity curves are to be used in a more qualitative way to assess the significance of various design parameters to performance, or quantitatively to estimate the percentage change in performance produced by parameters which depart from their reference values.

- 1) Storage volume (Figures 3-5). Performance increases sharply with storage volume for all glazing systems up to about 0.2 or 0.3 cubic feet of water per square foot of wall area, after which the performance continues to improve but more slowly. This suggests a minimum storage volume of 0.2 or 0.3 cubic feet per square foot of wall area, and a maximum storage volume limited only by other considerations such as available space.
- 2) Glazing system (Figure 3). The options studied were double and triple glazing both with and without night insulation. The percentage improvement in solar savings over the double-glazed, non-night-insulated case are as follows (approximate values for storage volumes in the range 0.3 to 1.0 cu ft per sq ft):

triple-glazed, no night insulation	30%
double-glazed, night insulation	65%
triple glazed, night insulation	75%

Adding night insulation to double glazing has more than double the benefit of adding a third pane to the glazing. Adding a third pane to a night-insulated, double-glazed system adds only ten percent to the solar savings. These facts argue for night insulation rather than triple glazing, but the relative inconvenience and/or expense of night insulation is a disadvantage. Which is preferable in a given situation would depend on more specifics than have been studied here.

- 3) Glazed end walls (Figure 3). Glazed east and west end walls are a clear thermal disadvantage. For the reference design, they reduce the solar savings by 15% when there is night insulation and by 35% where there is no night insulation. The end walls taken together comprise 35% of the south glazing area. The design rule is to avoid east and west glazings unless they are considered important for non-thermal reasons such as added light for plant growth.

- 4) Storage shape (Figure 6). The solar savings fraction is not strongly sensitive to storage shape, at least within the limits of this study, in which the height-to-depth ratio of the container was varied. The range of solar savings variation with shape is about 5% without night insulation and 10% with night insulation. The design rule is that a low, flat container which covers the sunspace floor (provided that such a container is practical and can be directly illuminated), or a tall, thin container which covers the wall (such as a row of Kalwall water tubes), or (presumably) both, are the best shapes, but relatively square shapes do not reduce the solar savings by more than about 5% without night insulation or 10% with night insulation.
- 5) Color of wall and storage container (Figures 7-10). The solar savings increases linearly with wall and storage container absorptances, at least within the range of normal variability of these parameters. Between 0.9 (corresponding roughly to flat black paint) and 0.3 (corresponding roughly to white paint) the solar savings reduction is about 6% when the wall color is changed and about 12% when the storage container color is changed. The effect is almost exactly linear: if both the storage container and wall color are changed from absorptivities of 0.9 to 0.3, the solar savings reduction is 18%. These results apply to the reference design in which the storage container covers 47% of the wall area. The design rule is that, area for area, the color of the storage container is twice as important as that of the wall. Both should be made as near to flat black as is compatible with other design considerations, such as even illumination of plants, but other dark colors such as brown or blue can be used without a substantial performance penalty.

The effect of a selective surface on the storage container was investigated with the result that the solar savings is slightly improved by a low infrared emissivity, but the effect is so small as to be negligible. The design rule is that selective surfaces need not be considered.

- 6) Color of floor (Figure 11). The solar savings depends significantly on the absorptivity of the floor. For the reference design the solar savings is reduced by 22% if the absorptivity is reduced from 0.9 to 0.3. Area for area the floor color is as important as the wall and storage container color. The same design rule which applies to the wall and storage container applies to the floor.
- 7) Color of end walls and ceiling (Figure 12). These are the lightweight surfaces which do not store solar heat. The solar savings increases only slightly with increased absorptivity of these surfaces. Their color may be chosen on some other basis than thermal performance such as light colors chosen for more uniform plant illumination.
- 8) Wall conductance (Figures 13-14). An uninsulated wall performs marginally better than a well-insulated wall in a night-insulated system and slightly

worse in a non-night-insulated system, but the difference is very small. The design rule is that the average performance does not depend significantly on the wall conductance except for very small LCR buildings without night insulation in which case the wall should be well-insulated.

- 9) Vent area (Figure 15). The thermocirculation vent area is expressed as the area of either the upper or lower vents (assumed to be equal) divided by the wall area. As such, the solar savings increases with vent area up to at least a vent area of 0.1. The increase is rather abrupt up to a vent area of about 0.01 or 0.02, then is very slow after about 0.03. The design rule is to size the vents at 0.03 of the wall area or more.
- 10) Lower thermostat set points (Figures 16 and 17). The solar savings is very sensitive to the living space lower thermostat set point. For the reference design in Bismarck, for example, a 100°F decrease in the set point from 65°F to 55°F increases the solar savings fraction by 20%. But the reference load has also been reduced by 29%. The total solar savings compared to the 65°F reference load is 39%. These facts do not bear directly on design except to show that performance is not a matter of design only, but occupant behavior can have a large impact. The greenhouse lower thermostat set point has a negligible effect for night-insulated systems up to 60°F or more. The point is that very little greenhouse auxiliary heat is required by the reference design up to these temperatures. The design rule is that no special consideration need be given to a minimum temperature requirement in the greenhouse (due, for instance, to plants which are intolerant of low temperatures). This is not to say that an occupant need not protect the greenhouse against occasional low temperatures, but that the occurrence is rare enough that it does not affect the average annual performance of the system. Note that this conclusion is under the assumption of a very tight greenhouse reference design of R20 end walls and ceiling, well-insulated floor perimeter, and an outside air infiltration rate of 0.2 air changes per hour. Certainly for a substantially less tight greenhouse, the effect of the greenhouse lower thermostat set point would be more significant.
- 11) Greenhouse infiltration rate (Figure 18). The reference design assumes a very tight greenhouse with an outside air infiltration rate of 0.2 air changes per hour. This low rate of infiltration is attainable only by very close attention to construction details such as vapor barriers, caulking, and glazing seals. It may not be attainable at all if the greenhouse has doors to the outside or openable windows or vents. Since these amenities may be desirable, a designer should be aware of the performance penalty to be paid for them. The penalty is significant but not prohibitive. For example, in Bismarck, in going from 0.2 to 1.0 air changes per hour (the higher figure being typical of good residential construction) there is a solar savings reduction of normally about 15%. The reduction could be as much as 25% for very low LCR buildings with no night insulation.

12) Resistance of night insulation (Figure 19). The solar savings increases as the thermal resistance of night insulation on the greenhouse glazing increases, rapidly at lower R-values, more slowly at higher R-values. Half of the solar savings increase obtained at R9 is obtained at R2, and three-fourths is obtained at R4. No clear design rule emerges from these facts alone. Cost and convenience factors must be taken into consideration, too. For instance, if R3 or R4 can be exceeded only at considerable additional cost or inconvenience, then it may not be advisable. On the other hand, if R9 can be achieved as easily as R5 with only modest cost increase (as might be the case with moveable panels), then the R9 may be preferable.

13) Extent of lightweight objects in the greenhouse (Figures 20 and 21). The effect of lightweight objects in the greenhouse, such as plants and furniture, is that some sunlight is absorbed on their surfaces before it has an opportunity to strike the surfaces of massive objects, namely, the floor or the water storage containers. The surfaces of lightweight objects then warm up rapidly and heat is rapidly transferred to the greenhouse air. If the extent of this effect is such that more heated air is available than can be used effectively in the daytime, then there is wasted heat and consequently a reduction in solar savings. The effect may be expressed in terms of the fraction of shading of mass surfaces by lightweight objects. When the fraction is less than 0.10, the heating performance penalty is not significant. When the fraction is between 0.10 and 0.30, the penalty is significant but modest (normally less than a 10% reduction in solar savings). Beyond 0.30, the performance penalty begins to be severe. A design rule is that the shading of mass surfaces by lightweight objects should be kept below 30%.

14) Glazing tilt (Figure 22). The optimum glazing tilt for Bismarck is roughly in the range of 50° to 70° , depending on the particular SSF achieved at the optimum. In general, optimum glazing tilts closely corresponds to optimum collector tilts found in active system studies.

15) Sunspace geometry

a) One glazing plane (Figures 23 and 24). The design variable in question is the glazing tilt. Unlike the study shown in Figure 22, a designer would probably have no reason to keep the glazing area constant for various tilts. So, the variation in solar savings with glazing tilt is also partly due to the variation in glazing area. In fact, the glazing area decreases with increasing tilt, so the optimum glazing tilt is shifted to a smaller angle. Without night insulation the optimum is in the range 50° - 60° for Bismarck, 40° - 50° for Madison, the higher tilts being for higher SSF designs. Somewhat surprising behavior is found for higher LCR designs with night insulation; the optimum is much less well defined, but is in the vicinity of 20° - 30° . Nevertheless, low-tilt geometries should be avoided due to the risk of problems such as poor head room, poor rain drainage, snow buildup, and summer over heating. A rough design

rule for a single-glazing-plane geometry is that the glazing tilt should be in the range 50° - 60° for latitudes in the range 40° N to 50° N.

b) Two glazing planes (Figures 25 and 26). A designer often decides to use two glazing planes in a sunspace geometry, one vertical and one tilted. There are legitimate design reasons for this decision, but a substantial performance penalty is incurred. In the case of the reference design for Bismarck, retaining the same sunspace depth but using a six-foot vertical glazing and a tilted one above it reduces the solar savings by about 25% for a night-insulated system and 40% for a non-night-insulated system.

Suppose certain non-thermal criteria have led the designer to choose two glazing planes, one vertical and one tilted. The question then is what sunspace depth, or equivalently what angle for the tilted glazing segment, leads to an optimum performance. For Bismarck there is a broad maximum in the solar savings for a tilt in the range of 50 to 60 degrees. An entirely vertical glazing reduces the solar savings by about 8% for either a night-insulated system or a non-night insulated one.

c) Ceiling depth (figure 27). The sunspace may have a horizontal, unglazed ceiling. Some benefits include an increase in the useable floor space for a given glazing geometry and a decrease in summer over-heating. The penalty in terms of winter heating performance is not great, being about a 1% reduction in solar savings per foot of ceiling depth.

TABLE 1. Sunspace Reference Case Parameters

Description	Name	Value
Wall height	HWAL	9.0 ft
East-west width	WDTH	30.0 ft
Ceiling depth	XTOP	4.0 ft
Tilt of glazing	TILTG	50 degrees
Emissivity of storage container	EPSST	0.9
Conductance of sunspace back wall	UWALL	0.05 Btu/hr.°F.sqft
Minimum sunspace temperature	TGHMN	45 °F
Maximum sunspace temperature	TGHMX	95 °F
Height of thermocirculation loop	HGHT	8.0 ft
Absorptivity of sunspace back wall	ALFS(1)	0.9
Absorptivity of storage container	ALFS(8) & ALFS(9)	0.9
Resistance of night insulation (when used)	RESNI	9.0 hr.°F. sqft/Btu
Number of glazings	NGL	2

Figure 1. The greenhouse reference design. A single plane of double glazing is tilted at 50° and faces due south. A water storage container 4.24 ft high by 2.12 ft wide is adjacent to the back wall and floor.

Figure 2. The annual solar savings fraction versus the load/collector ratio.

Figure 3. The annual solar savings fraction versus the volume of water storage per unit wall area, for various glazing systems.

Figure 4. The annual solar savings fraction versus the volume of water storage per unit wall area, for the reference design (insulated wall plus water storage container) and for an uninsulated water wall.

Figure 5. The annual solar savings fraction versus the volume of water storage per unit wall area, for the reference design (insulated wall plus water storage container) and for an uninsulated masonry wall.

Figure 6. The annual solar savings fraction versus the height-to-depth ratio of the water storage container.

Figure 7. The annual solar savings fraction versus the solar absorptance of the greenhouse-living-space wall outer surface.

Figure 8. The annual solar savings fraction versus the solar absorptance of the water storage container surface.

Figure 9. The annual solar savings fraction versus the solar absorptance of the greenhouse-living-space wall and water storage container surfaces.

Figure 10. The annual solar savings fraction versus the infrared emissivity of the water storage container.

Figure 11. The annual solar savings fraction versus the solar absorptance of the greenhouse floor.

Figure 12. The annual solar savings fraction versus the solar absorptance of the greenhouse lightweight surfaces, the end walls and ceiling.

Figure 13. The annual solar savings fraction versus the thermal conductance of the greenhouse-living-space wall, including the film conductance of the inner wall surface.

Figure 14. The annual solar savings fraction versus the thermal resistance ("R-value") of the greenhouse-to-living-space wall, including the film resistance of the inner wall surface.

Figure 15. The annual solar savings fraction versus the area of the thermocirculation vents (one row) per unit wall area, for the reference design (insulated wall plus water storage for the insulated masonry wall).

Figure 16. The annual solar savings fraction versus the living space lower thermostat set point.

Figure 17. The annual solar savings fraction versus the greenhouse lower thermostat set point.

Figure 18. The annual solar savings fraction versus the greenhouse outside air infiltration rate.

Figure 19. The annual solar savings fraction versus the thermal resistance of night insulation on the greenhouse glazing.

Figure 20. The annual solar savings fraction versus the fraction of transmitted solar radiation transferred directly to the greenhouse air, Bismarck, ND.

Figure 21. The annual solar savings fraction versus the fraction of transmitted solar radiation transferred directly to the greenhouse air, Madison, WI.

Figure 22. The annual solar savings fraction versus the glazing tilt relative to the horizontal, glazing area constant.

Figure 23. The annual solar savings fraction versus the glazing tilt relative to the horizontal, glazing area variable, Bismarck, ND.

Figure 24. The annual solar savings fraction versus the glazing tilt relative to the horizontal, glazing area variable, Madison, WI.

Figure 25. The annual solar savings fraction versus the height of the vertical glazing segment in a two-glazing-plane geometry.

Figure 26. The annual solar savings fraction versus the tilt of the upper glazing segment in a two-glazing-plane geometry.

Figure 27. The annual solar savings fraction versus the ceiling depth.