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SLR METHODS FOR ATTACHED SUNSPACES*

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ABSTRACT

Solar load ratio (SLR) methods applied to sunspaces are reviewed. Procedures are described both for the 28 sunspace basic design types and for the design variations that can be accommodated within the SLR method. Emphasis is placed on aspects of design, operation, and analysis that relate to the production of both plants and heat. Issues discussed include geometry, shading of mass, temperature limits, and energy loss caused by the exfiltration of water vapor.

1. INTRODUCTION

The goal of an attached sunspace as a passive solar heating system is the reduction of the annual auxiliary heat requirement of an adjoining building. The design objective then is relatively simple: to minimize the annual auxiliary heat consumption within specified design and budget constraints. A design process that achieves this objective must include an estimate of the auxiliary heat at various stages. Among the tools available to provide estimates of the auxiliary heat, those based on the monthly solar load ratio (SLR) correlations are well suited to routine and frequent application. The necessary calculations are simple enough to be done by hand in an hour or two, or on an inexpensive microcomputer in a few seconds.

The basis of the SLR correlations is the computer simulation of passive solar heating systems using mathematical models that have been validated against data measured in experimental buildings. A large set of simulated performance data may be developed quickly and cheaply for numerous passive system types, locations, and building heating loads. The essential performance data are the values of the auxiliary heat requirement. It is convenient to express these in dimensionless form as certain fractions called solar savings fractions (SSF):

$$SSF = 1 - \frac{\text{auxiliary heat}}{\text{net reference load}} \quad . \tag{1}$$

The net reference load is the steady-state heating load of the nonsolar portions of the building assuming that the indoor temperature is a constant reference temperature. It may be written

$$\text{Net reference load} = NLC \times DD \quad , \tag{2}$$

where NLC is the net load coefficient and DD is the heating degree days.

The SLR correlations are correlations of the monthly values of SSF with the monthly values of the correlating parameter SLR. In general terms, SLR is defined as the ratio of a solar gain to a heat loss, thereby expressing the most fundamental of the energy relationships that occur in the building. The exact definition of SLR depends on the system type. The definition that applies to sunspaces is stated in the next section.

The application of the SLR correlations to an estimate of the auxiliary heat begins with a calculation of the monthly values of SLR. Then the monthly values of SSF are determined from their correlation with SLR. The monthly values of the auxiliary heat are then found by use of Eq. (1) solved for the auxiliary heat and Eq. (2) for the net reference load:

$$\text{Auxiliary heat} = (1 - SSF) \times NLC \times DD \quad . \tag{3}$$

This procedure is described in detail in Refs. 1-3. Specifics for sunspaces are discussed in Section 2 and in Refs. 2 and 3.

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An attached sunspace usually has the secondary role of providing occasional living space and space for plants. When plant production is a major goal, roughly coequal with heat production, we may call the sunspace an attached greenhouse. The design objective is then more complex, requiring a joint optimization of the heat- and plant-production capability of the structure. This question is discussed in Section 3, but only from the limited perspective afforded by sunspace models and correlations that take no explicit account of plants.

We assume that heat production remains a major objective, and that the designer and operator seek a situation in which the desired plant production can be achieved with the least possible compromise in heating performance. Three aspects of this problem can be identified: design principles, operation principles, and performance analysis tools. Design principles are sought that lead to a greenhouse structure capable of effective production of both heat and plants. Operation principles are sought that take the best advantage of the structure, and analysis tools are sought that are capable of estimating greenhouse performance when plants are present. In this context, we discuss geometry and light, temperature limits, shading of mass by plants, and water vapor loss by exfiltration.

2. SLR METHODS FOR SUNSPACES

2.1. No Frills

A. The Equations. The core of SLR methods for sunspaces consists of both the definition of SLR itself and the equation that expresses the SLR correlations. These are

$$SLR = (S/DD - LCR_s \times H)/LCR \qquad (4)$$

and

$$SSF = 1 - C \exp(-D \times SLR) \quad . \qquad (5)$$

The function exp is the exponential function; that is, $\exp(x) = e^x$ where e is 2.718..., the base of natural logarithms.

The quantities S and DD are the monthly variables that make SLR a monthly method. The other quantities are all constant parameters of the sunspace and adjoining building. In particular, S is the monthly total solar radiation absorbed in the sunspace per unit of projected area (defined below), Btu/ft²; DD is the monthly heating degree days, °F day; and the constants C, D, LCR_s, and H depend on the sunspace design type and are listed in Table 1.

TABLE 1
SUNSPACE SLR CONSTANTS

Type	C	D	H	LCR_s	U_c
A1	0.9587	0.4770	0.83	18.6	0.27
A2	0.9982	0.6614	0.77	10.4	0.21
A3	0.9552	0.4230	0.83	23.6	0.30
A4	0.9956	0.6277	0.80	12.4	0.23
A5	0.9300	0.4041	0.96	18.6	0.04
A6	0.9981	0.6660	0.86	10.4	0.04
A7	0.9219	0.3225	0.96	23.6	0.04
A8	0.9922	0.6173	0.90	12.4	0.04
B1	0.9683	0.4954	0.84	16.3	0.26
B2	1.0029	0.6802	0.74	8.5	0.19
B3	0.9689	0.4685	0.82	19.3	0.28
B4	1.0029	0.6641	0.76	9.7	0.21
B5	0.9408	0.3866	0.97	16.3	0.04
B6	1.0068	0.6778	0.94	8.5	0.04
B7	0.9395	0.3363	0.95	19.3	0.04
B8	1.0047	0.6469	0.87	9.7	0.04
C1	1.0087	0.7683	0.76	16.3	0.38
C2	1.0412	0.9281	0.78	10.0	0.28
C3	0.9699	0.5106	0.79	16.3	0.08
C4	1.0152	0.7523	0.81	10.0	0.08
D1	0.9889	0.6643	0.84	17.8	0.36
D2	1.0493	0.8753	0.70	9.9	0.26
D3	0.9570	0.5285	0.90	17.8	0.07
D4	1.0356	0.8142	0.73	9.9	0.07
E1	0.9968	0.7004	0.77	19.6	0.41
E2	1.0468	0.9054	0.76	10.8	0.29
E3	0.9565	0.4827	0.81	19.6	0.08
E4	1.0214	0.7694	0.79	10.8	0.08

The quantity LCR is the load collector ratio, defined by

$$LCR = NLC/A_p \quad . \qquad (6)$$

where NLC is the net load coefficient already discussed, and A_p is the projected area. The projected area is the area of the sunspace glazing projected on a vertical plane. This is equivalent to the sunspace glazing area measured on an elevation drawing. In calculating A_p, we do not include east or west end walls.

Calculating NLC is the first step in the SLR method, both to evaluate LCR from Eq. (6) and to calculate the auxiliary heat from Eq. (3). There is a simple procedure in Ref. 1. (NLC is the same as BLC, the building load coefficient, in Refs. 1 and 2.)

B. The Design Types. The SLR correlations apply specifically to 28 different sunspace design types. The properties that distinguish the 28 types are summarized in Table 2. The sunspaces are all double glazed and face due south. The glazing tilt, measured from horizontal, is indicated in Table 2; the designation 90/30 refers to equal areas of 90-degree (vertical) and 30-degree tilted glazing. The attached sunspace types A and B have 1.0 ft³ of thermal storage mass per ft² of projected area; the semienclosed

TABLE 2
SUNSPACE DESIGN TYPES

Type	Class	Tilt (deg)	Common Wall	End Walls	Night Insulation
A1	attached	50	masonry	opaque	no
A2	attached	50	masonry	opaque	yes
A3	attached	50	masonry	glazed	no
A4	attached	50	masonry	glazed	yes
A5	attached	50	insulated	opaque	no
A6	attached	50	insulated	opaque	yes
A7	attached	50	insulated	glazed	no
A8	attached	50	insulated	glazed	yes
B1	attached	90/30	masonry	opaque	no
B2	attached	90/30	masonry	opaque	yes
B3	attached	90/30	masonry	glazed	no
B4	attached	90/30	masonry	glazed	yes
B5	attached	90/30	insulated	opaque	no
B6	attached	90/30	insulated	opaque	yes
B7	attached	90/30	insulated	glazed	no
B8	attached	90/30	insulated	glazed	yes
C1	semi-enclosed	90	masonry	common	no
C2	semi-enclosed	90	masonry	common	yes
C3	semi-enclosed	90	insulated	common	no
C4	semi-enclosed	90	insulated	common	yes
D1	semi-enclosed	50	masonry	common	no
D2	semi-enclosed	50	masonry	common	yes
D3	semi-enclosed	50	insulated	common	no
D4	semi-enclosed	50	insulated	common	yes
E1	semi-enclosed	90/30	masonry	common	no
E2	semi-enclosed	90/30	masonry	common	yes
E3	semi-enclosed	90/30	insulated	common	no
E4	semi-enclosed	90/30	insulated	common	yes

sunspace types C, D, and E have, respectively, 2.0, 1.69, and 1.93 ft^3 of thermal storage mass per ft^2 of projected area. The thermal storage is in the form of either a 1-ft-thick, uninsulated masonry common wall or water in containers in the sunspace with an insulated common wall. If night insulation is used, it is R9. There is natural convection air flow between the sunspace and the adjoining building in all cases, with reverse flow prevented by backdraft dampers. The air flow vents are assumed to be in pairs separated by an 8-ft height and to have a total area of 6% of the projected area.

The sunspace heat loss characteristics are:

- Double glazing, 1/2-in. air gap,
- Infiltration rate = 0.5 air changes/h,
- Opaque ceiling and end wall thermal resistance = R20,
- Perimeter insulation = R12, and
- No water vapor loss by exfiltration.

For more details on the characteristics of the design types, see Refs. 2-4.

C. Determining S, Restricted Case. When the sunspace is one of the 28 basic design types, a simplified method exists. The method is restricted to cases that have exactly the same glazing transmission and solar absorption characteristics as one of the 26 basic design types. These characteristics are:

- Two glazing layers,
- Each layer equivalent to 1/8-in. glass (index of refraction = 1.525, extinction coefficient x thickness = 0.0625),
- Due south orientation,
- Glazing relative dimensions and tilts exactly as in the basic design types,
- Sunspace relative dimensions and absorptances exactly as in the basic design types, and
- No site shading.

There are three steps. First, determine the monthly total solar radiation incident on a horizontal surface (Btu/ft^2), Q_h, for your location. Values for numerous US and Canadian locations are tabulated in Refs. 1 and 2 (where they are expressed as daily averages and thus must be multiplied by the number of days in the month). Second, determine the ratio of S to Q_h using the equation

$$S/Q_h = B_1 + B_2Y + B_3Y^2 + K_T(B_4 + B_5Y + B_6Y^2) \quad , \qquad (7)$$

where Y = (LAT - DEC)/100,
LAT = latitude,
DEC = midmonth solar declination, and
K_T = average monthly clearness ratio.

The quantities LAT-DEC and K_T are tabulated along with the horizontal solar radiation in Ref. 2. The constants B_1 to B_6 depend on the design type and are given in Table 3. Third, S is the product of Q_h and S/Q_h:

$$S = Q_h \times (S/Q_h) \quad . \qquad (8)$$

D. Determining DD. Monthly values of the heating degree days for your location may be determined, for example, from the tables in Refs. 1 and 2. The degree days are tabulated for numerous locations in the US and Canada and for several base temperatures. The correct degree days base temperature is the building balance point temperature, which can be estimated by

$$T_b = T_{set} - Q_{int}/TLC \quad , \qquad (9)$$

where T_{set} = building thermostat setting, ^oF,
Q_{int} = building internal heat generation rate, Btu/day,
and TLC = building total load coefficient, Btu/^oF day, calculated from

$$TLC = NLC + 24\ U_c\ A_p \quad . \qquad (10)$$

The quantity U_c is the steady-state collector-wall conductance, Btu/^oF h ft^2. Values for the 28 sunspace design types are given in Table 1. The quantities NLC and A_p, the net load coefficient and the projected area, have already been defined.

E. Step-by-Step Procedure. The no-frills SLR calculation described above may be summarized by the following steps.

(1) Obtain building information:
  a. Net load coefficient, NLC (Ref. 1).
  b. Projected area, A_p.
  c. Load collector ratio, LCR, Eq. (6).
  d. Thermostat setting, T_{set}.
  e. Internal heat rate, Q_{int}.
  f. Total load coefficient, TLC, Eq. (10).
  g. Balance point temperature, T_b, Eq. (9).

(2) Obtain climate and solar information, monthly:
  a. Latitude minus midmonth declination, LAT-DEC (Ref. 2).
  b. Clearness factor, K_T (Ref. 2).
  c. Incident solar radiation, horizontal surface, Q_h (Ref. 1 or 2).
  d. Ratio of incident horizontal to absorbed solar radiation, monthly, S/Q_h, Eq. (7).
  e. Solar radiation absorbed, S, Eq. (8).
  f. Degree days, DD (Ref. 1 or 2).

(3) Calculate solar savings fractions, monthly, SSF:
  a. Calculate SLR, Eq. (4).
  b. Calculate SSF, Eq. (5).

(4) Calculate auxiliary heat:
  a. Monthly, Eq. (3).
  b. Annual, sum of monthly values.

(5) Calculate annual solar savings fraction, SSF, Eq. (1) (optional).

F. The Results. For a given location and design type, the annual SSF depends only on the building balance point temperature and on LCR. It is possible, therefore, to prepare tables of SSF for various locations. A designer then must determine only the needed building information, Step 1 above; the tables take the place of the rest of the procedure, Steps 2-5. The annual auxiliary heat may then be calculated from Eq. (3).

Tables of annual SSF vs LCR are called LCR tables, and the determination of the annual SSF using them is called the annual method or LCR method. LCR tables for 209 US and 10 Canadian locations appear in Ref. 2. These tables include the 28 sunspace design types and 66 other passive system types (Trombe wall, water wall, and direct gain systems). The building balance point is 65^{o}F in these tables.

TABLE 3
SOLAR RADIATION CORRELATION COEFFICIENTS
FOR THE SUNSPACE REFERENCE DESIGNS

$$S/Q_h = B_1 + B_2Y + B_3Y^2 + K_T(B_4 + B_5Y + B_6Y^2)$$

Type	B_1	B_2	B_3	B_4	B_5	B_6
A1,2,5,6	0.72008	-0.15181	0.49973	-0.15039	0.14384	3.6374
A3,4,7,8	0.81554	-0.23988	0.60252	-0.16445	0.33730	3.1695
B1,2,5,6	0.58932	-0.09693	0.38955	-0.14699	-0.39149	3.9171
B3,4,7,8	0.62569	-0.13941	0.43331	-0.14982	-0.26401	3.5685
C1,2,3,4	0.39436	-0.21103	0.58815	-0.24083	-0.60746	4.6546
D1,2,3,4	0.73147	-0.15418	0.50763	-0.15276	0.14608	3.6950
E1,2,3,4	0.61561	-0.10127	0.40733	-0.15367	-0.40940	4.0969

Table 4 is an LCR table for Boston. Annual SSFs are tabulated for the 28 sunspace design types, for both 55 and 65°F balance points, and for 8 values of LCR. For LCRs and balance points other than those in the table, SSF can be estimated by linear interpolation.

2.2. Some Frills

The no-frills SLR method described above applies to the sunspace design types exactly as they are defined. It is possible, however, to vary certain characteristics of the sunspace designs and still estimate the auxiliary heat with the SLR method.

The variations are accomplished in the evaluation of SLR. Two quantities in SLR are involved: S and LCR_s [refer to Eq. (4)]. The permissible design variations and procedures to determine the corresponding values of S and LCR_s are outlined below.

A. Determining S, General Case. The quantity needed is S/Q_h; S itself is then determined simply with Eq. (8).

When the glazing system and solar absorption characteristics do not correspond exactly to one of the 28 design types, S/Q_h may be determined from the formula

$$S/Q_h = (I/Q_h)[(T/I)(Abs/T) + G](A/A_p) \quad , \quad (11)$$

where I/Q_h = ratio of monthly total solar radiation incident on a unit area of the glazing plane to that on a horizontal plane,

T/I = ratio of monthly total transmitted solar radiation to incident solar radiation (transmittance),

Abs/T = ratio of monthly total absorbed solar radiation to transmitted solar radiation (absorption factor),

G = correction term for single and triple glazing, and

A/A_p = ratio of actual glazing area to projected area.

When the glazing system is composed of two or more distinct glazing planes, Eq. (11) is used to calculate the contribution of each glazing plane to S/Q_h. Then A is the actual glazing area of each individual plane and A_p is the total projected area. The total S/Q_h is the sum of the individual contributions.

The factors I/Q_h, T/I, and Abs/T are given in Appendix E of Ref. 2 for various tilts, orientations, numbers of glazing layers, extinction coefficients, thicknesses, indices of refraction, sunspace dimensions, and absorptances. The quantity G accounts for the different amounts of solar radiation absorbed in one or three glazing layers that are useful to the sunspace. The values of G are:

Number of Glazing Layers	G
1	-0.031
2	0
3	0.025

TABLE 4
SAMPLE LCR TABLE

BOSTON, MASSACHUSETTS

SOLAR SAVINGS FRACTION (%)

TYPE	BASE TEMP	55 F	(3320 DD)							65 F	(5622 DD)						
	LCR	100	70	50	40	30	25	20	15	100	70	50	40	30	25	20	15
SS A1		19	23	28	32	38	42	47	54	15	19	22	25	29	32	36	41
SS A2		24	30	38	43	51	57	63	72	19	25	31	36	42	47	53	61
SS A3		17	21	25	29	33	37	41	47	14	17	20	22	25	27	30	34
SS A4		23	29	37	42	50	55	61	69	19	24	30	34	40	45	50	58
SS A5		19	23	27	30	34	38	42	48	16	18	21	24	27	29	32	36
SS A6		23	30	37	43	50	56	62	71	19	24	30	35	41	46	51	59
SS A7		17	20	23	25	29	31	35	39	14	16	18	20	22	24	26	28
SS A8		22	29	35	41	48	53	59	67	18	23	29	33	39	43	48	55
SS B1		16	20	24	28	33	36	41	48	13	15	19	21	25	27	31	36
SS B2		21	27	34	39	47	52	59	67	16	21	27	32	38	43	48	56
SS B3		15	18	22	25	30	33	37	43	11	14	17	19	22	24	27	31
SS B4		20	26	33	38	45	50	57	65	16	21	26	30	37	41	46	54
SS B5		16	19	22	25	28	31	35	41	13	15	17	19	22	24	26	30
SS B6		20	26	33	38	45	51	57	66	15	20	26	30	37	41	47	54
SS B7		14	17	19	22	25	27	30	35	12	13	15	17	19	20	22	24
SS B8		19	24	31	36	43	48	54	63	15	19	24	29	34	38	44	51
SS C1		14	18	23	27	33	37	42	50	9	12	15	17	21	24	27	32
SS C2		17	23	30	36	43	49	56	65	11	16	21	26	32	36	42	50
SS C3		13	16	20	23	27	30	34	41	9	12	14	16	19	21	23	27
SS C4		16	21	27	32	39	44	50	59	11	15	19	23	29	32	38	45
SS D1		21	27	33	38	45	49	55	63	16	21	25	29	34	38	42	48
SS D2		26	35	44	50	59	65	72	80	20	28	35	41	49	54	61	69
SS D3		20	25	30	34	40	44	49	56	16	20	24	27	31	34	38	43
SS D4		25	33	42	49	57	63	70	78	20	27	34	40	47	52	59	67
SS E1		17	22	28	32	38	42	48	55	11	16	20	23	27	30	34	39
SS E2		22	29	38	44	52	58	65	73	16	22	29	34	41	46	52	61
SS E3		17	20	24	28	32	36	40	46	11	16	19	21	24	26	29	33
SS E4		21	27	35	40	48	53	60	69	16	21	27	32	38	43	48	56

The factor A/A_p simply references S to the projected area rather than to the actual glazing area.

Site shading, if any, can be accounted for in the value of I/Q_h. Reduce the value of I/Q_h as determined from Ref. 2 or 3 by the fraction of sunspace shading in each month.

B. Determining LCR_s. The quantity LCR_s is the load collector ratio of the sunspace (analogous to LCR, which is the load collector ratio of the building). The product of LCR_s and H represent the effect of sunspace heat loss in the SLR correlation [see Eq. (4)]. Values of LCR_s for the 28 sunspace design types are listed in Table 1.

If the sunspace heat loss characteristics differ substantially from those of the basic design types, LCR_s should be recalculated. As a practical matter, most sunspace heat loss occurs through the glazing; thus, the recalculation is probably necessary only when the glazing configuration differs substantially from that of the basic design types. This is the case when the number of glazing layers differs from two and the ratio of glazing area to projected area differs from those in the 28 design types. There may also be other factors that would cause large glazing losses such as a large area of metal mullions with no thermal breaks.

If LCR_s is to be recalculated, refer to Chapter 4 of Ref. 2 for tables and formulas. There is an example in Ref. 3. Note that it is unnecessary to account in LCR_s for a movable insulation R-value other than the basic values of 0 and 9. This is because other R-values are accounted for by an interpolation between results for no movable insulation and R9 movable insulation.

2.3. A Special Correlation Form

The correlation form of Eq. (5) has the advantage of simplicity: there are only two adjustable constants (C and D), and it fits the simulated data set very well with standard deviations ranging between 2.4 and 3.5% (see Refs. 2 and 4). However, caution should be exercised in applying this form for very small values of SLR, say below 0.5. In particular, SSF is overpredicted by a few per cent for some non-night-insulated cases for large values of LCR (greater than about 100). These are cases of small sunspaces on large or poorly insulated buildings.

To improve the accuracy for small SLR, a new correlation form was developed with four, instead of two, adjustable constants. It is

$$SSF = \begin{cases} a + b \times SLR & (SLR < 0.5) \\ 1 - c \exp(-d \times SLR) & (SLR \geq 0.5) \end{cases} \quad (12)$$

SLR is still given by Eq. (4), and the values of LCR_s and H are the same as before. The new constants are a, b, c, and d: they are listed in Table 5.

TABLE 5
SPECIAL CORRELATION CONSTANTS

Type	a	b	c	d
A1	0.0191	0.5160	0.8930	0.4225
A2	0.0154	0.5372	0.9969	0.6621
A3	0.0212	0.4903	0.8803	0.3644
A4	0.0133	0.5258	0.9883	0.6230
A5	0.0601	0.3863	0.9047	0.3838
A6	0.0339	0.4823	1.0237	0.6901
A7	0.0557	0.3690	0.8751	0.2825
A8	0.0316	0.4647	1.0116	0.6358
B1	0.0141	0.5284	0.8976	0.4361
B2	0.0085	0.5634	0.9947	0.6751
B3	0.0109	0.5227	0.8892	0.4003
B4	0.0067	0.5570	0.9929	0.6573
B5	0.0422	0.4097	0.8952	0.3460
B6	0.0216	0.5060	1.0303	0.7016
B7	0.0388	0.3916	0.8830	0.2858
B8	0.0179	0.4980	1.0227	0.6658
C1	0.0022	0.6415	0.9927	0.7654
C2	0.0031	0.6436	1.1219	1.0158
C3	0.0258	0.4763	0.9356	0.4796
C4	0.0145	0.5539	1.0562	0.7984
D1	0.0166	0.5643	0.9728	0.6546
D2	0.0176	0.5671	1.1186	0.9407
D3	0.0541	0.4205	0.9662	0.5453
D4	0.0285	0.5188	1.1038	0.8767
E1	0.0049	0.6114	0.9692	0.6814
E2	0.0073	0.6107	1.1258	0.9868
E3	0.0415	0.4360	0.9369	0.4705
E4	0.0206	0.5330	1.0764	0.8239

3. REMARKS ON ATTACHED GREENHOUSES

Plant production imposes additional constraints on design and operation; two such constraints can be addressed in the context of sunspace SLR methods: light and temperature limits. We discuss below what compromises in the passive solar heating performance, if any, may be required to achieve satisfactory conditions in these respects.

Another issue is whether SLR methods can predict the passive solar heating performance of an attached greenhouse. The question has two aspects: whether typical design and operation parameters of a greenhouse can be accommodated in the SLR method, and whether the effects of the plants themselves can be accounted for. We discuss the former in terms of the parameters related to light and temperature limits, and the latter in terms of the shading of mass by plants and the loss of water vapor by exfiltration.

3.1. Light

Light levels in a sunspace depend on its geometry and interior surface absorptances. We discuss the effect of these parameters on the passive solar heating performance of an attached sunspace.

A. Geometry. It is now well accepted that the glazing in an energy-conserving greenhouse should be primarily on the south (north in the southern hemisphere). East and west glazings reduce the solar heating performance of the sunspace and contribute to summer overheating problems. Nevertheless, small east and west glazings may be desirable to improve the light distribution for plants.

The question remains as to the proper tilt or tilts of the south glazing. Figures 1 and 2 show the dependence of passive solar heating performance in Boston on glazing tilt for two different geometry types: a single glazing plane in Fig. 1; and two glazing planes, a lower vertical one 2/3 the overall sunspace height, and an upper tilted one, in Fig. 2. These are essentially geometry types A and B when the tilts are 50 and 30 degrees, respectively. The curves in Figs. 1 and 2, and the curves in subsequent figures, were generated by a set of annual performance estimates calculated using hour-by-hour computer simulation.

We suppose that the smaller the tilt angle in either of these cases, the better the light distribution for plants. The figures show that there is very little solar heating compromise for low tilts. Indeed, there is no compromise at all except for such

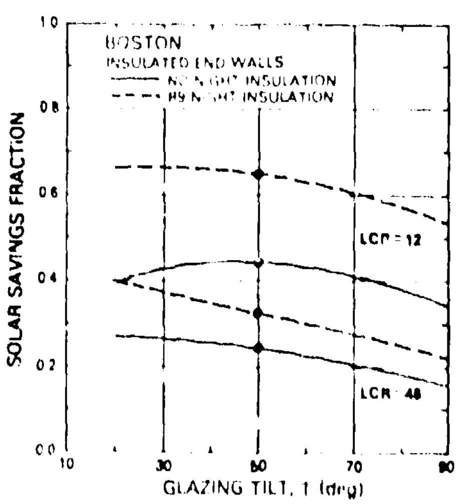

Fig. 1. Annual solar heating performance vs glazing tilt relative to horizontal. At a 50° tilt the systems are design types A1 and A2 (shown by the dots).

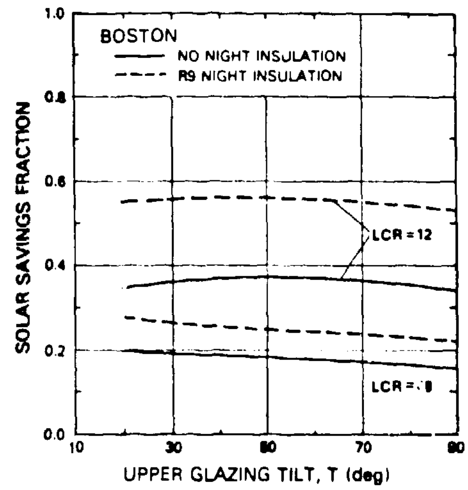

Fig. 2. Annual solar heating performance vs upper glazing tilt relative to horizontal. At a 30° tilt the systems resemble design types B1 and B2.

extremely small values of LCR that they are unlikely to be encountered in practice.

Geometry variations from the 28 basic design types are easily accommodated in the SLR method through the calculation of S and LCR_s as already explained. An alternative is to correct the annual SSF by use of sensitivity curves such as those shown in Figs. 1 and 2. There is a set of graphs like Figs. 1 and 2 for various cities in Ref. 2.

B. Absorptances. Light distribution and passive solar heating performance both depend on the colors (solar absorptances) of the interior surfaces of the sunspace. Figure 3 shows the dependence of passive solar heating performance in Boston on the solar absorptance of the north wall of the sunspace. Very dark (high absorptance) surfaces are seen to give the best solar heating performance, but the north wall in this case is a masonry thermal storage wall (Trombe wall) for which the sensitivity of solar heating performance to color is large because the surface is a thermal storage surface. Still, the sensitivity to color is not very great except for extremely small values of LCR. Similar studies show no significant dependence of solar heating performance on the colors of lightweight walls and ceilings. The weak sensitivity of solar heating performance to surface colors is a consequence of the radiation-trapping behavior of the sunspace structure: light that enters the sunspace strikes several surfaces, on the average, before it is finally reflected back out through the glazing. Some fraction is absorbed each time it strikes a surface so that a large fraction may be eventually absorbed, even if only a small fraction is absorbed at each

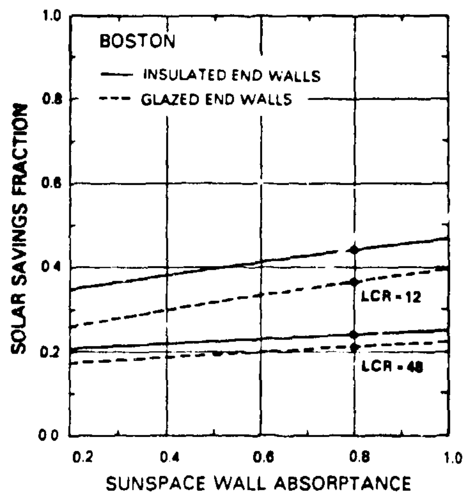

Fig. 3. Annual solar heating performance vs sunspace north wall absorptance. At an absorptance of 0.8, the systems are design types A1 and A3 (shown by the dots).

surface. This effect is most pronounced for deep sunspaces.

We suppose that the lighter the colors (the smaller the absorptances) of interior surfaces, the better the light distribution for plants. It appears that no serious solar heating compromise need be suffe.ed to achieve adequate light distribution.

Color variations from the 2^ basic design types are easily accommodated in the SLR method through the calculation of S, as already discussed. The colors of interior surfaces are accounted for in the absorption factor Abs/T in Eq. (11); there are tables of these factors in Ref. 2. An alternative is to correct the annual SSF by the use of sensitivity curves such as those shown in Fig. 3. There is a set of graphs in Ref. 2 for various sunspace surfaces and cities similar to the graph in Fig. 3.

3.2. Temperature Limits

Temperature limits in the sunspace depend on both design and operation. A primary design parameter affecting temperature limits is heat capacity in the sunspace. Temperature limits may also be controlled by the manner of sunspace operation, namely the use of auxiliary heat and ventilation.

A. Heat Capacity. The effect of heat capacity in the sunspace on solar heating performance and sunspace temperature limits is illustrated for Boston in Figs. 4 and 5. The sunspace heat capacity, or mass, is expressed in Btu/°F ft² of projected area. Figure 4 shows that increased

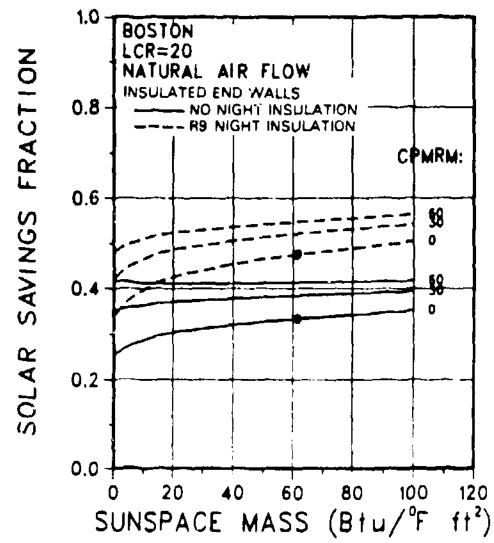

Fig. 4. Annual solar heating performance vs sunspace heat capacity/ft² of projected area in the form of water in containers. (There is also a 6-in.-thick masonry floor.) The parameter CPMRM is the heat capacity in the adjoining building. At a sunspace heat capacity of 62.4 Btu/°F ft² and CPMRM = 0, the systems are design types A5 and A6 (shown by the dots).

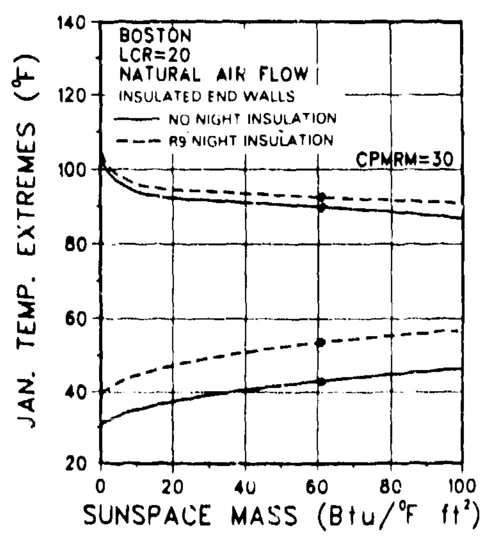

Fig. 5. January temperature extremes in the sunspace vs sunspace heat capacity/ft² of projected area in the form of water in containers. (There is also a 6-in.-thick masonry floor.) The parameter CPMRM is the heat capaci' in the adjoining building. The upper two curves are the maximum sunspace temperatures and the lower two are the minimum sunspace temperatures.

sunspace mass benefits solar heating performance except when there is a large amount of mass in the adjoining building and when there is no movable insulation, in which case the solar heating performance is relatively insensitive to the amount of sunspace mass. Figure 5 shows the dependence of January temperature extremes in the sunspace on the sunspace mass. The upper curves are the maximum temperatures that occurred during January in the typical meteorological year for Boston, and the lower curves are the minimum temperatures. In this case there is no significant compromise required between solar heating performance and moderated temperature extremes: both requirements benefit from increased sunspace mass. More data of this type, and the assumptions that underlie it, are presented in Ref. 5.

Although there is no way of accommodating mass variations in the SLR method itself, curves such as those in Fig. 4 can be used to correct the annual SSF. There is a set of similar graphs for various cities in Ref. 2.

B. Auxiliary Heat. Temperature extremes can also be moderated by the use of ventilation and auxiliary heat in the sunspace. Ventilation is usually a very effective and inexpensive way of controlling winter high temperature extremes, and the solar heating performance of the sunspace is relatively insensitive to the upper temperature limit. On the other hand, the control of low temperature extremes with auxiliary heat amounts to a direct reduction of the solar heating performance. Figure 6 shows the

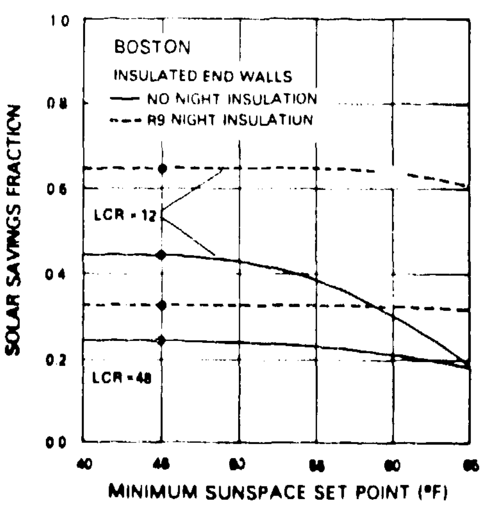

Fig. 6. Annual solar heating performance vs the sunspace auxiliary heat thermostat setpoint temperature. At a 45°F setpoint the systems are design types A1 and A2 (shown by the dots).

effect on the solar heating performance in Boston of the sunspace auxiliary heat setpoint. The effect is significant only above about 50-55°F, and then only for non-night-insulated cases with extremely small LCRs. This simply means that the sunspace temperature would rarely fall below this range in the absence of auxiliary heat because of adequate sunspace mass and relatively low heat loss in the 28 basic design types.

There is no way of accommodating sunspace setpoint variations in the SLR method itself, but curves such as those in Fig. 6 can be used to correct the annual SSF. There is a set of graphs like those in Fig. 6 for various cities in Ref. 2.

3.3. Shading of Mass

We now consider the direct effect of plants on the solar heating performance of a sunspace. One such effect is the shading of thermal storage mass by the leaves. When leaves (or any other lightweight objects) absorb solar radiation, they rapidly heat up. (There are also latent heat transfers as discussed in the next section.) Having no appreciable heat capacity, they rapidly give up their heat to the sunspace air by convection. Thus, plants cause the diversion of some solar energy to the form of heated air that might otherwise have been stored in mass.

Figure 7 shows the effect on the solar heating performance of the fraction of transmitted and reflected solar radiation that is absorbed by lightweight objects. The size of the effect is related to the fraction of solar heating (SSF) achieved by the sunspace. If SSF is small (because of a small sunspace, cloudy climate, etc.), the effect of lightweight absorption is small. Indeed, most of the heated air is useful to satisfy daytime heating needs. But if SSF is large, the solar heating performance is more sensitive to the amount of lightweight absorption because the effectiveness of the thermal storage mass is more important.

There is no way of varying the lightweight absorption fraction in the SLR method itself, but curves such as those in Fig. 7 can be used to correct the annual SSF. There is a set of graphs like those in Fig. 7 for various cities in Ref. 2.

3.4. Water Vapor

Evaporation of water from moist soil and evapotranspiration from plants can comprise a major heat transfer. Heat is transferred from the sensible (that which is sensed as a temperature change) to the latent form at the rate of about 1060 Btu/lb of water or about 8840 Btu/gal. The latent heat is trapped in the water vapor and can be

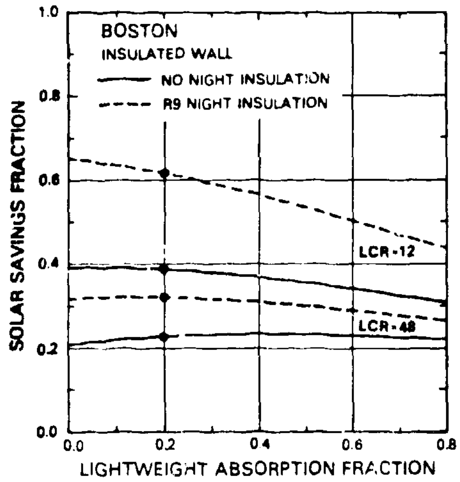

Fig. 7. Annual solar heating performance vs the fraction of solar radiation that is absorbed on lightweight objects within the sunspace after it is transmitted through the glazing and after each internal reflection. At an absorption fraction of 0.2, the systems are design types A5 and A6 (shown by the dots).

recovered only if the vapor recondenses into liquid water. This does not normally happen to a significant extent; instead, the water vapor is mostly lost, carrying the heat with it, through exfiltration to the outdoors.

To convey the potential size of the energy transfer involved, we observe that typical wintertime sunspace solar heat delivery to an adjoining building can be about 50,000-100,000 Btu/ft^2 of projected area. This solar heat would be consumed entirely in the production of water vapor if 5.7-11.3 gal. of water/ft^2 of projected area were used in the greenhouse during the winter. This is the same as about 3-6 gal./day in a 100 ft^2 greenhouse over a 6-month heating season.

It is conjectured that the effect of water vapor transport can be estimated in the SLR method by reducing the value of S by the monthly total latent heat loss/ft^2 of projected area.

4. REFERENCES

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