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D. CLARIDGE
D. SIMMS

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David E. Claridge
David A. Simms
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

ABSTRACT

The Solar Energy Research Institute (SERI) sponsored the Denver Metro Solar Homebuilders Program in cooperation with the Department of Energy and Western SUN. The auxiliary heating requirements for 11 of the passive solar homes were calculated using SLR or SUNCAT-2.4 with a standard set of basic assumptions. The analysis shows that seven of the homes should use less than half as much heating fuel as typical houses recently built in the area; two should use about half; and two should use about two-thirds or more. Comparing these results with performance estimates provided by design consultants shows numerous large discrepancies. These differences can be attributed largely to specific differences in assumptions in every case but one.

1. INTRODUCTION

Twelve mainstream builders in the Denver Metro area ranging in size from the Friis Development Group, which built six homes during 1979, to U.S. Home Corporation, which built 1,490 homes in the Denver area during 1979, constructed speculatively-built passive homes with design assistance from SERI during 1980-81. It was crucial that each builder be confident that their design would appeal to their market as well as save energy, so specific energy-use goals were not part of the program. Each builder worked with an experienced solar design consultant who provided architectural services and thermal analysis of the options considered. More details on the assistance provided, the market success of the homes, and the incremental costs of the energy features are provided in separate papers (1,2). This paper examines the predicted thermal performance of these houses, and later papers will report the results of monitoring, which SERI has begun.

The average gas-heated house built in the Denver area during 1977-78 used 220 kJ/m^2-DD$_C$ (DD$_C$ = Celsius degree-day) during 1978 (3) of which 140-160 kJ/m^2-DD$_C$ was for heating. When considering the efficiency of furnaces and distribution systems, this indicates a typical heating load of 80-100 kJ/m^2-DD$_C$ (4-5 Btu/ ft^2-DD$_F$ (where DD$_F$ = Fahrenheit degree-day). The heating load estimates provided by the design consultants for the Denver Metro homes average 46 kJ/m^2-DD$_C$ (3.1 Btu/ft^2-DD$_F$). This is about half the load of the typical new house. However, two of the houses are predicted to have loads near 100 kJ/m^2-DD$_C$ (4 Btu/ft^2-DD$_F$).

Examining the performance calculations provided by the design consultants showed a considerable range in key assumptions such as thermostat setting and air infiltration rates. This paper provides auxiliary heating load estimates based on standard assumptions and investigates the specific impact of the differing assumptions used by the consultants.

2. DESIGN TOOLS USED

Seven of the design consultants used the Solar Load Ratio (SLR) method developed at Los Alamos National Laboratory (5). Two used proprietary programs, and one adapted ASHRAE steady-state techniques.

The tools used in the analysis for this paper were SUNCAT-2.4, developed at the National Center for Appropriate Technology (6), and an automated version of the SLR method (7). The houses with thermal storage capacity near 920 kJ/m^2-K (45 Btu/°F-ft^2) of glazing and/or Trombe walls were analyzed with SLR. Houses with other mass levels or rock bed storage were analyzed with SUNCAT-2.4.

3. STANDARD ASSUMPTIONS

Table 1 shows the standard assumptions used in the analysis. The consultants assumed widely varying thermostat set points, air infiltration rates, and levels of internal heat generation. The heating set point of 18.3°C (65°F) shown in Table 1 corresponds to the weighted average Denver area daytime thermostat setting of 18.6°C (65.5°F) and nighttime setting of 17.2°C (63.1°F) found in the latest Residential Energy Use Survey conducted by the Public Service Company of Colorado (the local utility)(8). This average is used since SLR and

SUNCAT do not allow explicit night setback. An air infiltration rate of 0.6 air changes per hour (ACH) corresponds to a typical value for new houses as determined for the BEPS program (9). Internal heat generation of 55.9 MJ/day (53,000 Btu/day) was used (9).

Other assumptions used were standard values incorporated in the SLR method (5) and were used for the SUNCAT runs to facilitate comparison with SLR. All of the houses are in the Denver metropolitan area, though some are as far away as Boulder, but none are located in the mountains, so Denver weather was used.

4. SIMULATION RESULTS AND COMPARISONS

Table 2 shows characteristics of the homes analyzed and the auxiliary heating loads calculated by the consultants and by using the assumptions of Table 1. Note that these are auxiliary heating loads, not fuel consumption. Good gas heating installations have seasonal efficiencies of 60%-70%. Several cases show large discrepancies between the two load calculations. Five of these are examined below.

The house built by the Alpert Corporation is a split-level, direct-gain house that includes some clerestories. It has a small unfinished basement area that was unheated. Table 3 shows that using the consultants' assumptions for set point, internal gains, and BLC account for most of the difference in predicted loads. The consultant estimate does not consider the solar gain from nonsouth glazing, which accounts for an additional difference of 2.7 GJ (2.6 MBtu). The final difference of 5.3 GJ (5 MBtu) represents fair but not outstanding agreement.

The consultant for the house built by the Friis Development Group provided an extremely low estimate of 3.1 GJ (2.9 MBtu) auxiliary load (Table 4) for this house with a modest amount of direct gain aperture. Our estimate is 21.6 GJ (20.5 MBtu). The consultant's estimate (based on use of the code QUICKEE) contained two large but offsetting differences in assumptions: he assumed internal gains of 127.1 MJ/day (120,500 Btu/day) and a BLC of 19.4 MJ/DD_C (10,194 Btu/DD_F). The documentation provided with the estimate did not allow us to identify other differences in assumptions, and we have not yet identified the reasons for the 21.5 GJ (20.4 MBtu) discrepancy.

The Klaus Daily Corporation built 12 townhouses, each with a two-story, mass-backed sunspace and an actively-charged, passively-discharged rockbed under the slab floor on the north side of the unit. A middle unit with no east-west wall losses is considered in Table 5, which shows the consultant's estimate of auxiliary load to be 13.2 GJ (12.5 MBtu). SUNCAT-2.4 predicted 2.1 GJ (2.0 MBtu) using the standard assumptions. However, disconnecting the rockbed, increasing the set point to 20°C (68°F), the internal gains to 63.3 MJ/day

Table 1. STANDARD ASSUMPTIONS USED FOR THERMAL ANALYSIS OF DENVER METRO HOMES

Direct southern exposure.

No shading of solar apertures except overhangs where applicable

Heating set point of 18.3°C (65°F)

Infiltration rate of 0.6 ACH

Internal heat generation of 55.9 MJ/day (53,000 Btu/day)

Ground reflectance of 0.3

Double glazing
$U = 3.1$ W/m^2-K (0.55 Btu/ft^2-hr-°F)
$T = 0.747$ at normal incidence

Nonmass absorptance of 0.2 (radiation that heats air directly)

Mass absorption of 1.0 for Trombe walls and 0.8 for direct gain

No radiation lost through windows—cavity albedo of 0.0

Night insulation (when used) in place 1700-0800 for Trombe walls, 1700-0700 for direct gain.

Masonry and concrete properties:
conductivity of 0.012 W/m-K (1.0 Btu/ft-hr-°F)
density of 2400 kg/m^3 (150 lb/ft^3)
specific heat of 840 J/kg-K (0.2 Btu/lb-°F)

Typical Denver weather used

(60,000 Btu/day), and the BLC to 10.3 MJ/DD_C (5445 Btu/DD_F) resulted in a SUNCAT prediction of 14.1 GJ (13.4 MBtu).

The house built by U.S. Home incorporates a 12-in. concrete Trombe wall with a selective absorber. The consultant's estimate of 40.9 GJ (38.8 MBtu) auxiliary load is over twice as large as the estimate of 14.7 GJ (13.9 MBtu) based on use of the standard assumptions. The major factors leading to the higher estimate were using a set point of 21.2°C (70.2°F), a BLC of 18.5 MJ/DD_C (9762 Btu/DD_F), and failure to include the basement portion of the Trombe wall (Table 6). Smaller differences were because of an internal gain of 64.8 MJ/day (61,440 Btu/day) and a ground reflectivity of 0.2.

The house built by Walden Homes has the largest discrepancy between the two load estimates (Table 7) and showed relatively poor performance based on the consultant's estimate. This house uses direct gain in both the main living level and the basement with an actively-charged rockbox for additional storage. The familiar differences due to different set point, internal gain, BLC assumptions, and a small difference in the window takeoff are present, but the major difference is related to the amount of basement mass that is thermally effective. The SUNCAT-2.4 load estimate of 21.5 GJ (20.4 MBtu) assumes that all of the basement mass is in the same zone as the direct gain aperture. This provides a mass level of 2960 kJ/m^2-K (145 Btu/°F-ft^2) of glazing—much greater than the 920 kJ/m^2-K (45 Btu/°F-ft^2) assumed in SLR. Some of this mass may not be effective. If the building mass is reduced to 695 kJ/K-m^2 (34 Btu/°F-ft^2) of glazing [near the SLR assumption of 920 kJ/K-m^2 (45 Btu/°F-ft^2) of glazing], there is a difference of 9.2 GJ (8.7 MBtu) between the consultant's and the SUNCAT estimates. Removal of remaining basement mass increases the load estimate to 55.9 GJ (53.0 MBtu).

The differences in BLCs in Tables 3-7 are primarily due to use of different infiltration rates, but some small differences reflect the practice of different engineers in calculating BLCs.

The discrepancies between the consultants' estimates and those using the standard assumptions for the remaining houses can be explained similarly. Note that the house built by Heritage Construction includes 16.6 m^2 (9 ft^2) of vertical air collectors and both estimates include rather optimistic assumptions for the collector performance. Additional parametric investigation of its expected load is planned.

All of these houses are now being monitored by SERI using microprocessor data loggers developed for the Class B Passive Monitoring Program, and comparison of the measured performance with the model predictions is planned for next year.

5. CONCLUSIONS

Modeling 11 of the homes built in the Denver Metro Program using SLR or SUNCAT-2.4 with a standard set of operating assumptions indicates that they should have heating loads ranging from 5-81 kJ/m^2-DD_C (0.3-4.0 Btu/ft^2-DD_F) with an average load of 36 kJ/m^2-DD_C (1.8-2.2 Btu/ft^2-DD_F). This is less than half the 80-100 kJ/m^2-DD_C (4-5 Btu/ft^2-DD_F) typical of new houses built in the Denver

Table 3. BASIC CHARACTERISTICS AND MODELING RESULTS FOR THE HOME BUILT BY THE ALPERT CORPORATION

Heating Loads Using SUNCAT-2.4 GJ (MBtu)	Assumptions Used (Changes are Cumulative)
14.8 (14.0)	Standard assumptions
26.0 (19.0)	20 C (68° F) set point
19.1 (18.1)	63.3 MJ/day (60,000 Btu/day) internal gain
28.9 (27.4)	16.4 MJ/DD_C (8632 Btu/DD_F) BLC
31.6 (30.0)	Remove solar gain from E-W glazing
36.9 (35.0)	Consultants' estimate using SLR

Table 4. BASIC CHARACTERISTICS AND MODELING RESULTS FOR THE HOME BUILT BY THE FRIIS DEVELOPMENT GROUP

Heating Loads Using SUNCAT-2.4 GJ (MBtu)	Assumptions Used (Changes are Cumulative)
21.6 (20.5)	Standard assumptions
13.1 (12.4)	127 MJ/day (120,500 Btu/day) internal gain
24.6 (23.3)	19.4 MJ/DD_C (10,194 Btu/DD_F) BLC
3.1 (2.9)	Consultants' estimate using QUICKEE

Table 2. PREDICTED AUXILIARY HEATING LOADS OF DENVER METRO HOUSES

Builder	Size m^2(ft^2)	BLC MJ/DD_C (Btu/DD_F)	South Glass m^2(ft^2)	Estimated Auxiliary Heating Load: Consultant			Estimated Auxiliary Heating Load: Standard Assumptions		
				GJ/yr	(MBtu/yr)	kJ/m^2-DD_C	GJ/yr	(MBtu/yr)	kJ/m^2-DD_C
Alpert	161 (1730)	14.0 (7365)	15.0 (162)	36.9	(35.0)	69	14.8	(14.0)	27
Arnold	223 (2400)	27.5 (14490)	24.6 (265)	75.1	(71.2)	101	60.6	(57.4)	81
Friis	129 (1386)	14.7 (7737)	14.0 (150)*	3.1	(2.9)	7	27.9	(26.4)	65
Ferguson	297 (3200)	33.4 (17603)	46.8 (505)	31.8	(30.1)	32	48.1	(45.6)	48
Heritage	214 (2300)	14.0 (7394)	30.6 (330)**	0.0	(0.0)	0	3.7	(3.5)	5
Klaus Daily	121 (1300)	7.7 (4029)	17.7 (191)	13.2	(12.5)	33	2.1	(2.0)	5
Kurowski	177 (1900)	22.0 (11594)	27.4 (295)*	21.7	(20.6)	37	31.5	(29.9)	53
Tradition	142 (1530)	13.1 (6884)	15.5 (167)	Not available			15.6	(14.8)	33
Unique	300 (3230)	25.5 (13454)	39.1 (421)	22.2	(21.0)	22	20.7	(19.6)	21
U.S. Home	186 (2000)	16.3 (8587)	32.7 (352)*	40.9	(38.8)	66	14.7	(13.9)	24
Walden	176 (1890)	18.2 (9574)	26.1 (282)	57.4	(54.4)	98	21.5	(20.4)	37

*Includes Trombe wall area.

**Includes vertical air collector.

area in 1977-78. Hence, the program appears to have achieved its goal of inducing the participating builders to build more efficient houses.

The large discrepancies between the load estimates prepared by the design consultants and those based on the standard assumptions of Table 1 were adequately explained based on the different assumptions used in every case except one.

In the three cases where the consultant estimated loads with SLR and we used SUNCAT-2.4, some differences were observed after assumptions were made comparable, but agreement was clearly adequate for design purposes.

6. ACKNOWLEDGMENTS

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Table 5. BASIC CHARACTERISTICS AND MODELING RESULTS FOR MIDDLE UNIT TOWNHOUSE BUILT BY THE KLAUS DAILY CORPORATION

Heating Loads Using SLR GJ (MBtu)	Assumptions Used (Changes are Cumulative)
2.1 (2.0)	Standard assumptions
5.3 (5.0)	Remove rock bed
8.1 (7.7)	20 C (68° F) set point
7.4 (7.0)	63.3 MJ/day (60,000 Btu/day) internal gain
14.1 (13.4)	10.3 MJ/DD_C (5445 Btu/DD_F) BLC
13.2 (12.5)	Consultants' estimate using SLR

(7) McLenon, Rodney. 1981 Residential Energy Use Survey, Public Service Company of Colorado, Denver, CO, to be published.

(8) U.S. DOE, "Energy Budget Levels Selection," DOE/CS-0119, November 1979, pp. C-12 through C-19.

Table 6. BASIC CHARACTERISTICS AND MODELING RESULTS FOR HOUSE BUILT BY U.S. HOME CORPORATION

Heating Loads Using SLR GJ (MBtu)	Assumptions Used (Changes are Cumulative)
14.7 (13.9)	Standard assumptions
22.6 (21.4)	21.2 C (70.2 °F) set point
21.2 (20.1)	64.8 MJ/day (61,440 Btu/day) internal gain
28.2 (26.7)	18.5 MJ/DD_C (9762 Btu/DD_F)
35.8 (33.9)	Remove 9.3 m^2 (100 ft^2) Trombe wall omitted by consultant
36.9 (35.0)	Decrease ground reflectivity to 0.2
40.9 (38.8)	Consultants' estimate using SLR

Table 7. BASIC CHARACTERISTICS AND MODELING RESULTS FOR THE HOME BUILT BY WALDEN HOMES

Heating Loads Using SUNCAT-2.4 GJ (MBtu)	Assumptions Used (Changes are Cumulative)
21.5 (20.4)	Standard assumptions
28.3 (26.8)	20 C (68° F) set point
27.1 (25.7)	63.3 MJ/day (60,000 Btu/day) internal gain
36.9 (35.0)	21.3 MJ/DD_C (11215 Btu/DD_F) BLC
36.1 (34.2)	Increase direct gain area to 30.4 m^2 (327 ft^2)
38.0 (36.0)	Remove rock box
48.2 (45.7)	Reduce mass to 700 kJ/m^2-K (34 Btu/ft^2-°F)
55.9 (53.0)	Reduce mass to 290 kJ/m^2-K (14 Btu/ft^2-°F)
57.4 (54.4)	Consultants' estimate using SLR

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