MEASURED PERFORMANCE OF SUPERINSULATED HOMES IN MONTANA: SECOND REPORT

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ABSTRACT

Five all-electric superinsulated homes are being monitored in Eastern Montana. For each home, over a year's worth of hourly data on seventeen channels has been collected.

The energy performance of these homes is consistent with expectations, and can be summarized as follows:

1. Average annual 1985 space heat for three occupied homes in Great Falls was 5207 kWh (2.17 kWh/Sqft) in a year with 8218 base 65 degree days. The heating system provided about 34% of the total heating load, while internal gains provided about 53% and passive solar gains provided about 13%.

2. Space heat consumption varies by almost 2 to 1 between sites due to different levels of internal and solar gains, and different thermostat settings.

3. Average annual 1985 electric use of the three occupied homes was 20,077 kWh, of which 26% was space heat, 17% was water heat, 4% was dryer, and 53% was "Other" which includes everything else.

INTRODUCTION

Recent approaches to low-energy housing, especially in the Pacific Northwest, favor high levels of insulation in combination with predominantly south facing glass. In these superinsulated homes, internal and solar gains are expected to offset much of the space heating requirements. To evaluate actual field performance of these structures and to assess occupant satisfaction, five superinsulated homes are being monitored in eastern Montana. This paper is the second in a series which summarize the measured data and performance of these homes. [1]

The five homes were built in the late summer and fall of 1984 and have been monitored since January of 1985. Three sites have been continuously occupied, one has had short unoccupied periods, and one is an unoccupied control unit. The homes are virtually identical two story structures with full basements, with a total floor area of approximately 2400 square feet. Each is equipped with electric baseboard heating units with separate thermostats in each room and air-to-air heat exchangers.

Seventeen channels of data are recorded hourly. At each site, ambient air temperature and south vertical solar radiation are measured along with five indoor air temperatures. Monitored electricity consumption includes upstairs heat, basement heat, water heat, dryer consumption, and a house total. On the air-to-air heat exchanger the supply and exhaust air temperatures are measured along with the percent on-time of the supply and exhaust fans. Data summarized on a daily and monthly basis is available from the National Center for Appropriate Technology in Butte, Montana.

DESCRIPTION OF HOMES AND OCCUPANTS

The five homes were all built according to the same set of plans with some deviations. Insulation in the building components includes R-50 ceilings, R-40 walls on the north, east, and west, R-26 walls on the south, R-12 doors, R-19 on the basement walls, and R-8 under the basement slab. Windows are either triple glazed or low-E double, with 35.7 square feet on the south wall and 13.8 square feet on each of the north, east, and west walls. There is also a continuous polyethylene air-vapor barrier and mechanical ventilation with an air-to-air heat exchanger.

Deviations from the plan do exist. Sites 1 and 5 are oriented up to 30 degrees from true south. Sites 2 and 3 use standard double glazing on some of the windows, and window areas and orientations were altered on every home. Sites 4 and 5 have attached garages, and Site 1 has a hot tub in the basement. Sites 1, 2, and 3 are located in Great Falls, Site 4 is in Lewistown, and Site 5 is in Billings.

Site 1 is occupied by a small working family. A retired couple lives at Site 2 and they are typically home during the day. Site 3 is a family of four including two working parents so the home is empty during most of the daylight hours. Several renters have occupied Site 4, and each has operated the home in a different manner. Site 5 was unoccupied until March of 1986.

PERFORMANCE RESULTS

The measured performance of the homes is presented in the tables and graphs. Annual data summaries for the three occupied homes in Great Falls during the year 1985 are in Table 1. Space heat for the year averaged 5207 kWh, or about one quarter of the total house consumption. The end use Other averaged 10,569 kWh for the three sites, representing 53 percent of the total load. Note that while ambient temperature and solar radiation varied little between the sites, there is a difference of almost 2 to 1 in the annual space heating consumption. A graphical depiction of the 1985 electrical consumption at the three sites is in Figure 1 and the weather data and upstairs temperatures for the same period are shown in Figure 2. The data for the calendar year has been folded and is represented as July through June to better see the space heating data. Note that the heating season is confined to only about five months, November through March. A large proportion of the space heating consumption occurs during short periods of continued cold.

Table 2 gives monthly electricity consumption for the five sites during the 1985-86 heating season to date, November through February. There was a small amount of heating in October, but after November 1 heating has occurred essentially uninterrupted. It also shows the interior temperatures, hot water consumption, and weather conditions for the same period. Daily space heat, indoor temperatures, and base 65 F degree days for the period are depicted graphically in Figure 3. Much of the performance variation in space heating between the homes can be explained by comparing the temperatures and Other consumption found in the measured data. It is also of interest to compare data from the occupied sites with that from Site 5, which is unoccupied. Figure 4 shows average daily end-use profiles for each of the five homes during this period, which highlight the variation in the way the occupants operate their homes.

DIFFERENCES IN SPACE HEAT BETWEEN HOMES

A comparison between the three occupied Great Falls sites for the year 1985 shows almost a 2 to 1 difference in measured space heat consumption with almost identical weather conditions. For the 1985-86 heating season, sites show an even greater spread, especially when including unoccupied Site 5 in the comparison. There are several reasons for the difference.

One reason is the levels of internal gains. While space heat consumption is quite different, the sum of space heat and Other consumption is less different, and removes a good deal of the variation between homes.

Thermostat setpoints also contribute to house-to-house variation in space heat consumption. During the spring of 1985, the occupants at Sites 1 and 2 kept their homes much colder than those at Site 3, and their space heating consumption was much lower. Occupants at all sites except for Site 3 also tend to maintain different temperatures in the different rooms of the house, sometimes with temperature differentials of 10 to 15 F between rooms.

For instance, the basement at Site 2 was essentially unheated for most of spring 1985 and stayed about 6 F below the upstairs temperature. This tends to reduce the actual heated area by a factor of almost 2. However, in the fall of 1985, the basement was heated to temperatures consistent with the rest of the home.

SUNDAY SIMULATION RESULTS

In order to make a projection of annual space heat requirements in the early stages of the project, we adjusted the input parameters of the SUNDAY daily simulation model to match the January 1985 space heat use averaged across the three occupied homes. The inputs used were:

Thermostat Setpoint	65	F
Building UA	263	BTU/Sqft-F-h
Heat Storage	6000	BTU/F
Internal Gains	4500	BTU/h
South Glass	54.8	Sqft
North Glass	8.8	Sqft
East Glass	14.3	Sqft
West Glass	23.1	Sqft
Shade Factor	.7	

Predicted annual space heating energy was 4509 kWh using Great Falls TMY weather data, compared with the measured average of 5207 kWh for the three Great Falls sites. The TMY weather year has 7598 base 65 degree days compared with a measured 8218 averaged across sites.

Use of actual weather data with the same assumptions yielded a predicted annual space heating energy of 5253 kWh, within 0.8% of the measured result. However, deviations in single months reached as high as 400 kWh in November. This may be due to the presence of the basement, which loses much of its heat to the surrounding soil where temperature fluctuations lag those of ambient.

The simulations provided an estimate of the contributions of various heat sources toward meeting the overall thermal load:

Internal Gains	7999 kWh	53%
Heating System	5253 kWh	34%
Passive Solar	1991 kWh	13%
Total Heating	15243 kWh	100%

The simulation model also allows estimates of the sensitivity of annual space heat to changes in the parameters and climate. For the Great Falls climate and with no internal gains, the space heat load would increase to 12080 kWh and the solar contribution to 21%. About 42% of a reduction in annual internal gains will appear as an increase in space heat. A one degree F change in average thermostat setting will cause a 4% change in annual space heat. With the inputs listed above, space heat in Seattle, Washington would have been only 1200 kWh.

It should be emphasized that these space heat projections result from an empirical estimation of the model parameters. The combination of parameters used gives reasonable agreement with the monthly measured data for the three homes occupied throughout the year. The predictions were also in agreement with the unoccupied control home. This does not imply that the parameters (UA, setpoint, gains, etc.) are correct.

The presence of multiple thermostats, leading to large room-to-room temperature variations, changes in thermostat settings over time, vacations and vacancies, variations in internal and solar gains across homes, between rooms, and over time, variations in the use and settings of the air-to-air heat exchangers, and the thermal flywheel effect of the basements combined with the concentration of space heat into short cold spells makes it difficult to predict space heat for individual homes or specific months.

ACKNOWLEDGEMENTS

This paper reports on work which was funded in part by the State of Montana, Department of Natural Resources and Conservation, Energy Division and managed by the National Center for Appropriate Technology in Butte, Montana. The authors gratefully acknowledge the cooperation of the occupants which makes the project possible. Michael Kennedy of Ecotope, Inc. developed the software for interrogation of the data loggers and has archived the weekly data.

REFERENCES

1. Palmiter, L. and Hanford, J. 1985 "Measured Performance of Three Superinsulated Homes in Montana," Conservation in Buildings: Northwest Perspective Conference Proceedings. National Center For Appropriate Technology, Butte, MT.

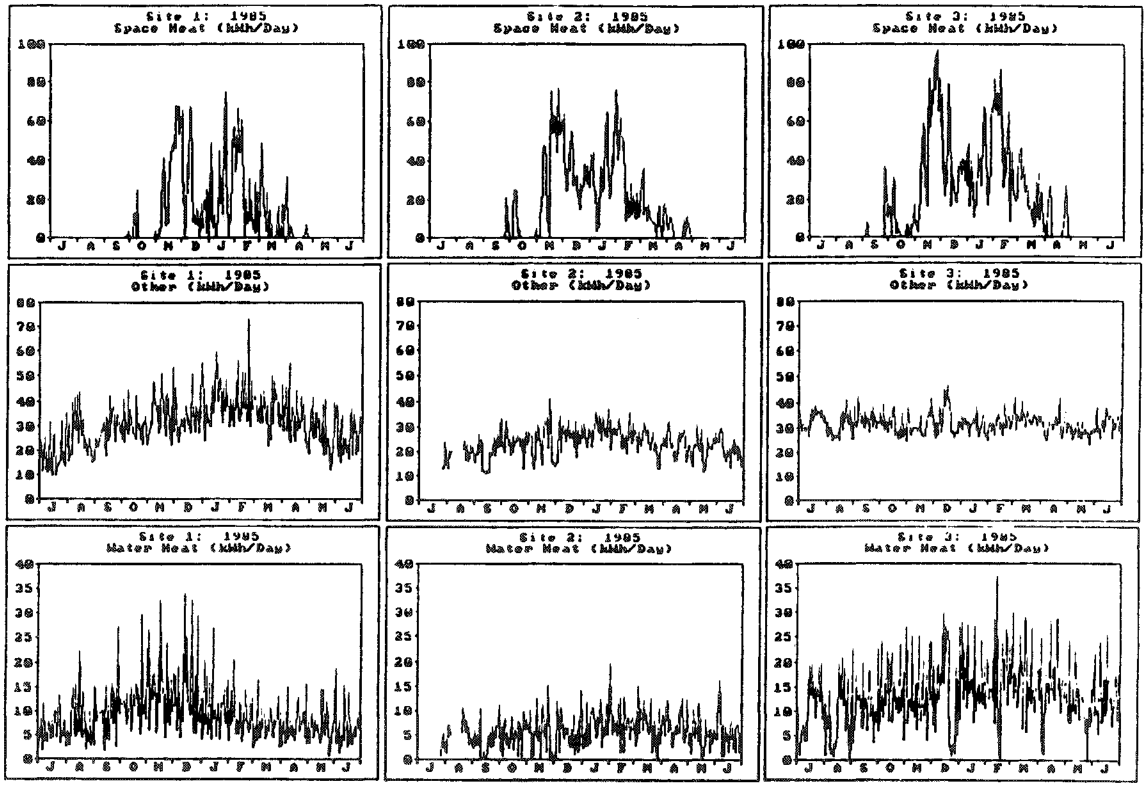

FIG. 1. DAILY ELECTRICAL END USE FOR 3 SITES IN GREAT FALLS DURING 1985.
The time scale in each plot has been arranged to run from July through June. The first row shows space heat usage. The bulk of space heat usage (81 to 87%) occurs during Nov. through Feb. The number of days with nonzero space heat ranged from 172 to 215. Much of the space heat was used during two prolonged cold snaps in Nov. and Feb. The second row shows the consumption of Other. The generally high level and spiky appearance of the Other for Site 1 reflects hot tub use. The strong seasonal variation may also be due to tub use. Site 3 shows a typical pattern while Site 2 shows seasonal variation. The bottom row shows water heat usage. This is the best indicator of occupancy. Vacations and weekend trips are evident at both Sites 2 and 3, while Site 3 shows typically greater water heat use on weekends due to clothes washing. Water heat shows a strong seasonal variation at all sites due to variation in mains temperatures. Residuals from a fit of water heat KWH to Gallons were used to estimate a mains temperature variation of about 25 F peak to peak. Note the large day-to-day variation in water heat.

Table 1. 1985 Annual Data Summaries for Three Sites in Great Falls, MT

Electricity Consumption (kWh)	Site 1		Site 2		Site 3		Average	
Upstairs Heat	1579	8%	2389	15%	2770	11%	2246	11%
Basement Heat	2279	11%	2639	17%	3965	16%	2961	15%
Total Heat	3858	19%	5028	32%	6735	28%	5207	26%
Dryer	1226	6%	308	2%	903	4%	812	4%
Water	3436	17%	2150	13%	4882	20%	3489	17%
Other	11576	58%	8441	53%	11689	48%	10569	53%
Total Appliance	16238	81%	10899	68%	17474	72%	14870	74%
House Total	20096	100%	15927	100%	24209	100%	20077	100%
Hot Water Use (Gal/Day)	41.7		37.5		76.1		51.8	
Vertical Solar (Btu/Sqft-Day)	936		994		943		958	
Heating Degree Days (F-Day)	8101		8435		8117		8218	
Space Heating								
kWh/Sqft	1.61		2.10		2.81		2.17	
Btu/Sqft-Degree-Day	.68		.85		1.18		.90	

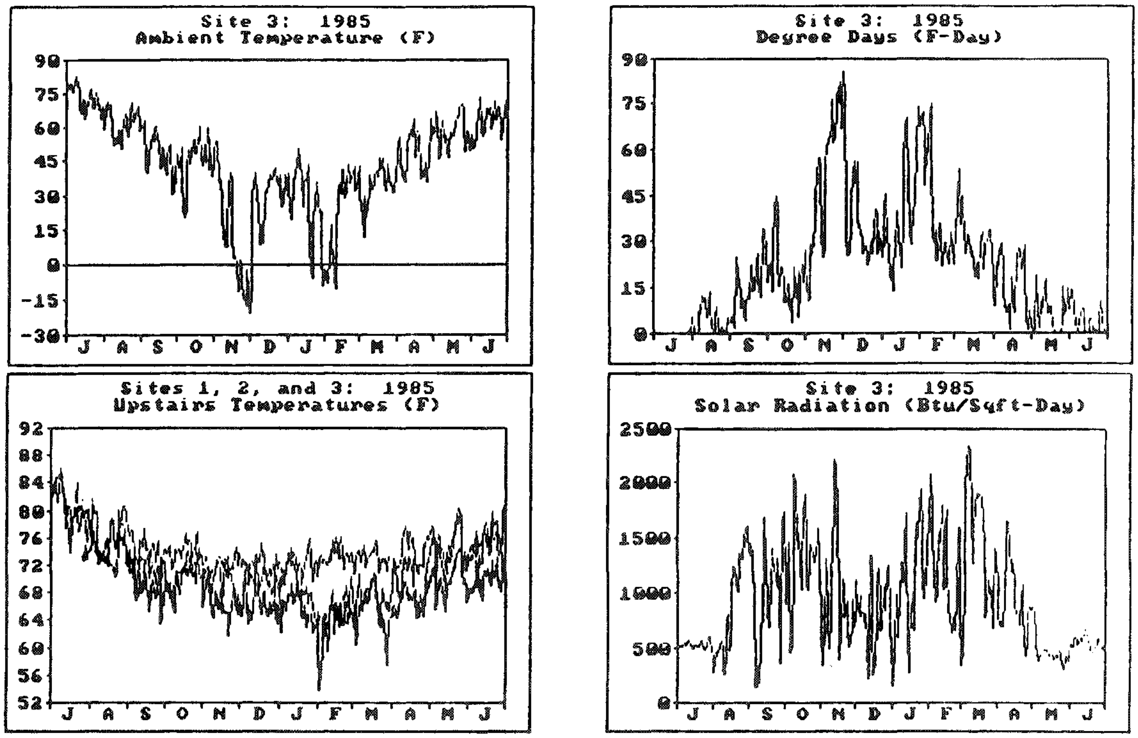

FIG. 2. DAILY AMBIENT CONDITIONS AND INTERIOR TEMPERATURES DURING 1985.
The upper left plot shows ambient dry-bulb temperature for Site 3, while the upper right plot shows base 65 degree days. Both plots are dominated by two prolonged cold spells in Nov. and Feb. Daily average temperatures range from 87 to -20 F. The lower right plot shows daily total south vertical solar radiation. Because solar radiation shows extreme day to day variation the data were smoothed with weights (.25,.5,.25) to better show the main features. The two peaks during Oct. and late Feb. are due to the solar geometry at this latitude. The roof overhang totally shades direct radiation during May through mid-Aug. Thus the summer values consist only of diffuse radiation. This helps prevent overheating in the summer. The lower left plot shows average daily upstairs temperature at Sites 1,2 and 3. The temperatures range from 86 to 54 with large differences between sites.

Table 2. Data Summaries for All Sites, November 1985 through February 1986

Electricity Consumption (kWh)	Site 1	Site 2	Site 3	Site 4	Site 5
Upstairs Heat	1385	1584	2211	3104	3533
Basement Heat	1606	2825	2751	1548	3669
Total Heat	2991	4409	4962	4652	7202
Dryer	499	103	294	671	0
Water	1633	710	1912	1441	17
Other	4344	3158	3898	1975	492
Total Appliance	6476	3971	6104	4087	509
House Total	9467	8380	11066	8739	7711
Temperatures (F)					
Bedroom 1	65.6	68.1	72.2	69.5	66.6
Bedroom 2	65.5	70.0	71.1	68.1	67.0
Bedroom 3	68.1	70.8	71.7	68.6	68.2
Dining Room	66.7	72.5	73.3	67.3	68.0
Basement	66.3	71.9	70.0	60.7	66.2
Average House	66.5	70.7	71.7	66.8	67.2
Ambient	25.9	24.7	25.8	24.2	26.3
Average Delta	40.6	46.0	45.9	42.6	40.9
Hot Water (Gal/Day)	57.0	34.6	71.2	49.0	.3
Vertical Solar (Btu/Sqft-Day)	926	871	963	942	781
Heating Degree Days (F-Day)	4693	4835	4701	4900	4639

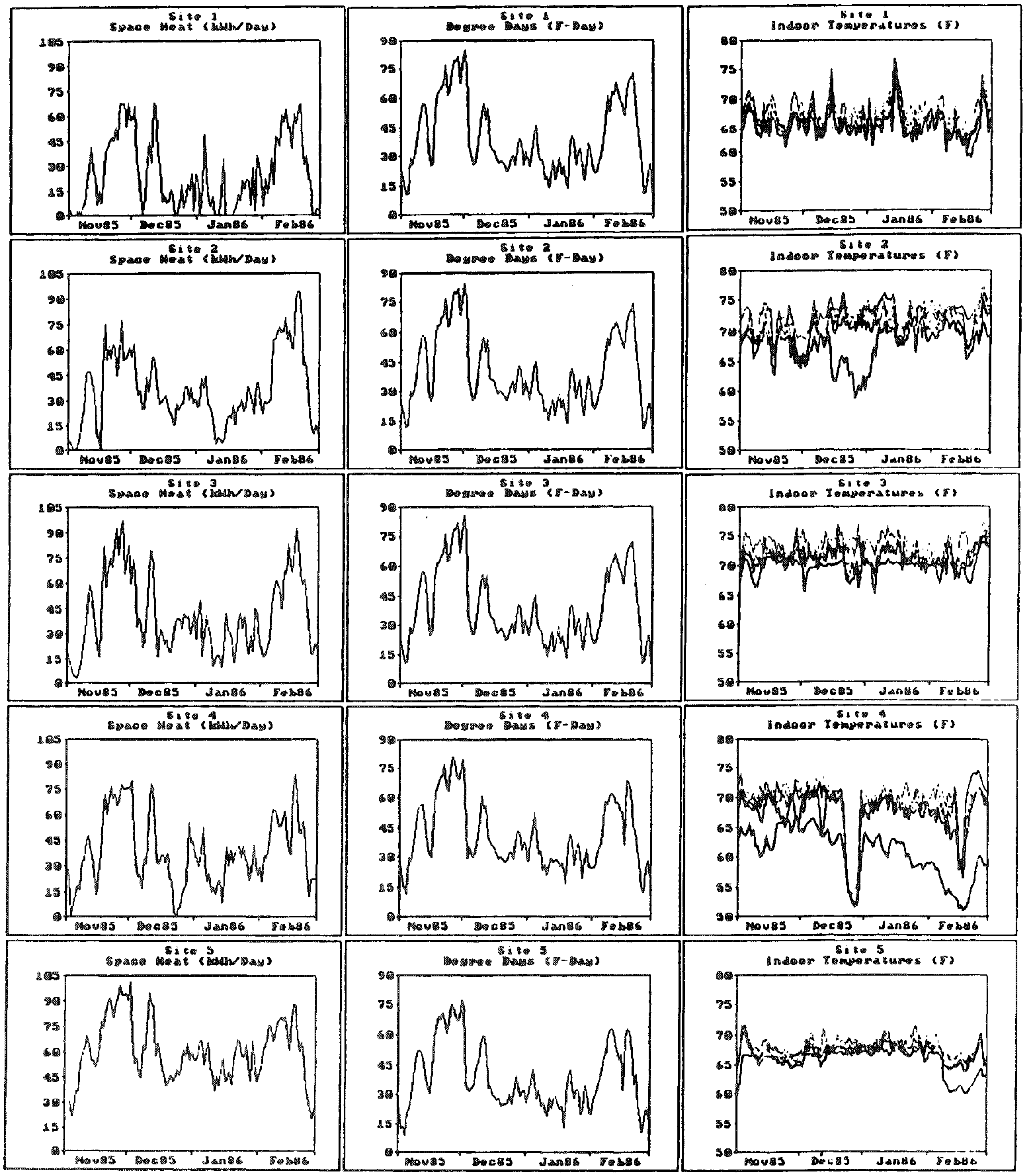

FIG. 3. THERMAL PERFORMANCE AT ALL 5 SITES FOR THE 1985-1986 HEATING SEASON.
The middle column shows base 65 degree days for each site. There is very close agreement in general pattern at all five sites although they are separated by as much as 180 airline miles. The daily space heat use shown in the left column tracks the corresponding degree days fairly well in terms of broad peaks and dips. The heating load at Site 5 is significantly larger because the site was unoccupied. The right column shows the five inside temperatures for each of the sites. Site 1 is typically between 65 and 70 F with occasional excursions to 75 F. Site 2 shows temperatures generally between 70 and 75 F. The low temperature in Dec. is due to reduced thermostat setting in one of the bedrooms. A drop in all temperatures during a vacation in Nov. is also evident. Site 3 shows the most consistent thermostat behavior of the occupied sites, with temperatures between 70 and 75. At Site 4 the basement is about 65 in Nov. while the upstairs temperatures are between 68 and 72. The low temperatures in Dec. occurred during a one week vacancy between renters. The basement heat was then turned off. There is a short vacancy again in late Feb. Site 5 was unoccupied during the period and shows very steady interior temperatures until Feb. when the basement thermostat was reduced. Concentration of heating loads in brief cold snaps combined with occupant variation in thermostat behavior and vacancy causes great difficulty in prediction and comparison of space heat loads.

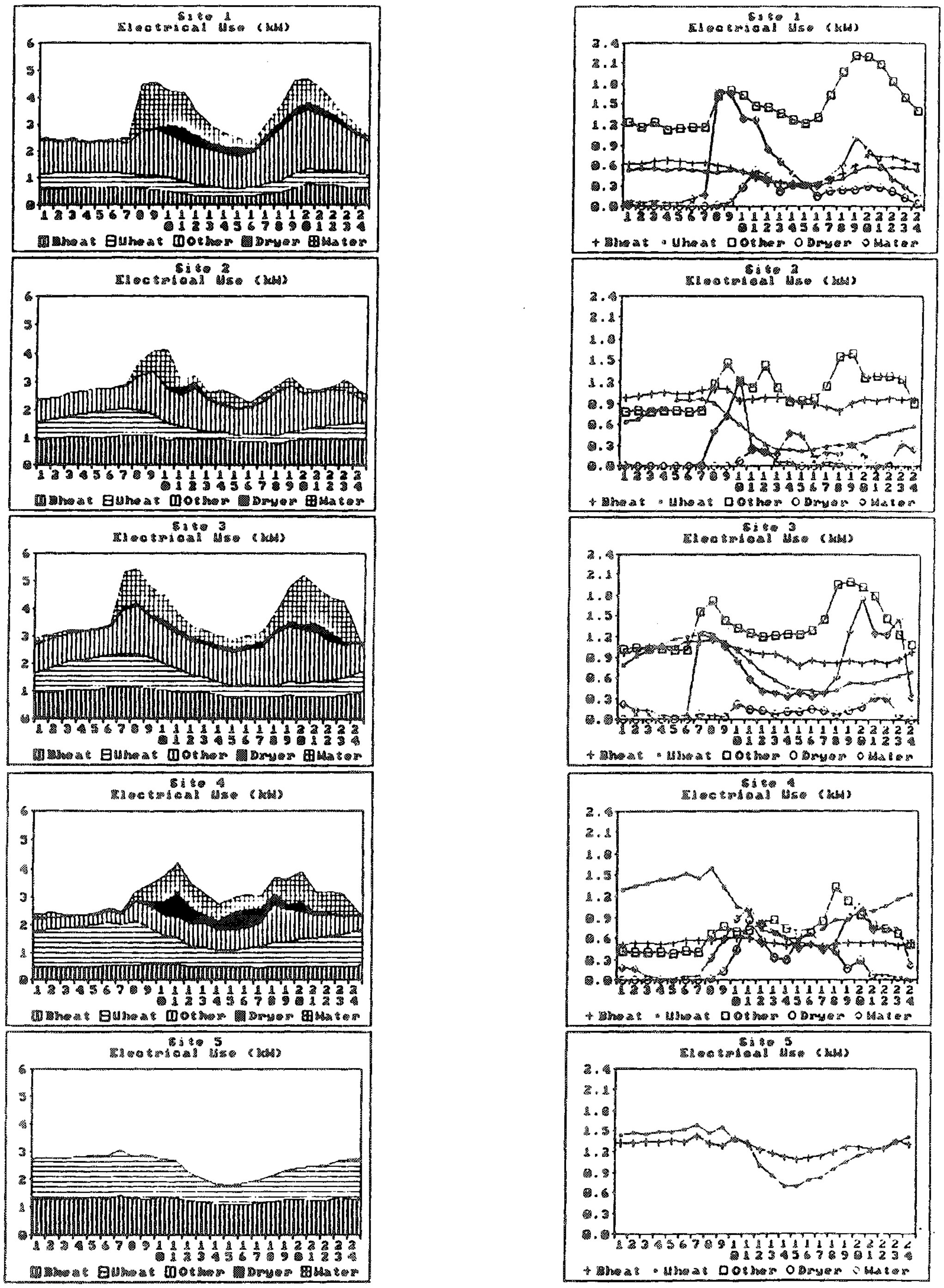

FIG. 4. END-USE PROFILES BY HOUR OF DAY FOR 1985-86 HEATING SEASON.
The left column shows the cumulative end-use consumption with Heat at the bottom followed by Other. The right column shows the individual end-use patterns each plotted at the same scale. At each of the occupied sites, the total consumption shows two peaks, one in the morning and one in the evening. The relative magnitudes, shape, and timing of these peaks varies from site to site. Site 2 is occupied by a retired couple who are home days, and shows a small peak at lunch time. Other is the largest load at all sites except Site 4. Upstairs space heat at Site 4 is large because the basement is unheated and the level of internal gains is low. The sum of Heat and Other at 6 AM is similar at all sites. The basement heat is nearly constant, while the upstairs heat shows a solar effect during the day. The large evening peak in Other at Site 1 is partially due to use of the hot tub.