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ABSTRACT

In the Building Energy-Use Compilation and Analysis (BECA) project, Part A (New homes), we have analyzed 215 submetered, energy-efficient residential buildings (including 7 small multi-family buildings comprising 68 single-family units). We compare the energy use of these buildings, normalized to an indoor temperature of 20°C. The average thermal integrity of these buildings is 53 kJ/m^{2}DDC. Only 29 buildings have submetering adequate to permit normalizing space heating loads for both indoor temperature and internal gains. The average "standard" thermal integrity of these 29 buildings is 46 kJ/m^{2}DDC. These compare favorably to U.S. 1979 building practice of 100 kJ/m^{2}DDC and U.S. Stock at 180 kJ/m^{2}DDC. We have data on the added first cost of conservation measures for 92 buildings. Of these buildings, the only homes that have costs of conserved energy below current energy costs are those with superinsulation, either alone or combined with low-aperture, passive-solar design. We continue to collect data and solicit the reader's participation.

1. INTRODUCTION

In BECA,[3] Part A (BECA-A) from which this paper is derived, we focus on space heating, which is by far the largest energy end-use in most new residential buildings. We have collected data on low-energy homes throughout North America and Europe, which include active-solar, passive-solar, superinsulated, and earth-sheltered dwellings (and many combining these techniques). The data consist of submetered energy consumption, inside and outside temperatures, number of occupants, and the associated costs of the conservation measures. For those buildings that reported submetered heating only we present annual energy use normalized to standard indoor temperature. For a subset of homes with submetered heating, appliances, and hot water, we normalize the data to reflect "standard" internal gains, and inside temperature.

In this paper we compare 215 buildings--276 units in total--on the basis of annual energy savings and cost of conservation. We discuss the effect of internal gains on performance measures and introduce a method to normalize the heating load to "standard" conditions. We emphasize the importance of normalization to compare building performance accurately, and present the standard heating loads compared with simulations, current building practice, and the national building stock.

2. DEFINITIONS

We have divided the homes into the following five primary categories: active solar, passive solar, hybrid solar, earth sheltered, and superinsulated. The concepts of active solar and earth sheltering are self-evident, but with superinsulation, passive solar and hybrid solar the definitions become hazy. We have defined superinsulated homes as

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[3] The BECA series is available from the Energy Efficient Buildings program, LBL (Lawrence Berkeley Laboratory), and includes:
Part A = New residential buildings (from which this paper is derived)
Part B = Retrofit residential buildings
Part C = Commercial buildings
Part D = Appliance energy use
Part V = Validation of computer programs

those in which insulation is a major conservation measure, and have allowed passive solar homes to include those with a majority of the glazing on the south. Hybrid solar is passive solar with fans to distribute the hot air. In practice we find that many of our 215 buildings combine several of these features, we designate these active solar/superinsulated, passive solar/superinsulated and "multi-strategy."

The "additional cost of conservation" is defined as the cost for conservation or solar measures above conventional construction costs. The figures we present were derived by the builders or researchers from whom we received data by summing up the added costs incurred (i.e., extra insulation, alternative framing, or solar collectors) and subtracting avoided costs (as in downsizing or eliminating the furnace).

3. BASIC ENVELOPE PERFORMANCE: METHODOLOGY

In order to compare the energy performance of different buildings we must normalize for differences in internal gains and thermostat settings. In this section we present the method for correcting indoor thermostat settings to a standard 20°C during the heating season, and for extrapolating part-year data to a full heating season. First, we estimate the building load coefficient, k. From this we derive the annual heating load, AQ, which is the annual thermal energy delivered to the house by the heating system at 20°C indoor temperature. The data we work with consist of submetered heating fuel, E, (including gas, oil and electricity), measured outdoor temperature, T_{out}, and indoor temperature, T_{in}. The measurements are typically for month-long periods and there are between five months and four years of data per house.

We have excluded all buildings heated with wood because of large uncertainties in stove and fireplace efficiencies, energy content of wood, and amount of wood burned. However, future improvements in wood heat monitoring techniques may allow such houses to be analyzed.

For any monitoring period,[4] the basic equation for the heat balance across a building envelope is

$$Q_{loss} = Q_{furn} + Q_{int} + Q_{sol}, \quad \text{(MJ)} \qquad [1]$$

where

Q_{loss} = total heat loss from the home,

Q_{furn} = thermal energy delivered to the home by the furnace or other heating system,

Q_{int} = internal gains from people, appliance and hot water, and

Q_{sol} = solar gains.

We can readily calculate Q_{furn} for each metered period:

$$Q_{furn} = E_{furn}\,\eta_{furn}, \qquad [2]$$

where

E_{furn} = energy consumed by the heating system during each monitored period, and

η_{furn} = furnace efficiency (or COP in the case of a heat pump) for each metered period.

The input to the furnace, E_{furn}, is always a measured value. η_{furn} is 1.0 for electric resistance heat (most of our homes). For the other homes η_{furn} is measured or we use default values. Hybrid solar and active solar collectors typically use a small amount of electricity for pumps and fans. We include these parasitic losses in Q_{furn}. However, solar gains are treated separately as discussed below.

For each building we must estimate the balance temperature and the overall heat loss coefficient. The balance temp, T_{bal}, is the temperature below which the furnace turns on. The overall heat loss coefficient, k, includes both conduction and infiltration losses over a given time.

To estimate T_{bal} and k we define the following:

$$Q_{free} = Q_{int} + Q_{sol}. \qquad [3]$$

Then the heat delivered to the home is given by

$$Q_{furn} = Q_{loss} - Q_{free} \qquad [4a]$$

$$= k\left[T_{in} - T_{out}\right] - Q_{free} \qquad [4b]$$

$$= k\left[\left(T_{in} - \frac{Q_{free}}{k}\right) - T_{out}\right]. \qquad [4c]$$

Defining T_{bal} as follows:

$$T_{bal} = T_{in} - \frac{Q_{free}}{k}, \qquad [5]$$

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[4] The instantaneous heat balance equation also includes a storage term. We exclude this term, since for monitoring periods of a week or more its average value is zero.

we see that

$$Q_{furn} = k\left[T_{bal} - T_{out}\right]. \qquad [6]$$

If each house had the same thermostat setting T_{in} every month of the heating season, we would immediately perform a least squares fit to Eq. 6, and determine k and T_{bal}. In practice, T_{in} can vary by ~3°C from month to month. As can be seen in Eq. 5, a change in T_{in} will result in an equal change in T_{bal}. We can therefore get a better fit if we add a correction term (for each month) to Eq. 6. The correction term, δ, is defined as:

$$\delta = 20^{\circ}C - T_{in}. \qquad [7]$$

This choice of δ normalizes each house to an indoor temperature setting of 20°C, at the same time as it corrects for variation in T_{in}. We now fit the corrected equation;

$$Q_{furn} = k\left[T'_{bal} - T_{out} + \delta\right]. \qquad [8]$$

where

$$T'_{bal} = T_{bal} \text{ for } T_{in} = 20^{\circ}C.$$

Using Eq. 8 we perform an ordinary least squares regression of Q_{furn} against T_{out}. From the regression we obtain the estimated values for T'_{bal} and k. Typical values of T'_{bal} are 10-15°C (Table 2. Column T) and typical R^2-values for the fit are between 0.8 and 0.95 (Table 2. Column S).

Note that in the calculation of AQ, solar gains contribute to the free heat, Q_{free}. An increased Q_{free}, lowers the balance temperature, and thereby reduces AQ. This procedure insures that in subsequent economic calculations solar gains are credited for displacing heating energy.

With our estimated value of k we can now calculate the temperature-adjusted monthly heat demand, Q'_{furn}, corrected to $T_{in} = 20^{\circ}C$;

$$Q'_{furn} = k\left[T'_{bal} - T_{out}\right]. \qquad [9]$$

Thus, AQ, the annual heating load (for T_{in} = 20°C), is the sum of the monthly Q'_{furn}.

$$AQ = \frac{1}{Y}\left[\sum_{m=1}^{n} Q'_{furn}(m)\right] \qquad [10]$$

where

AQ = annual heating load,

m = month,

n = number of months in metered period,

Y = number of years (always in integral numbers).

For incomplete heating seasons we extrapolate the annual heating load from available months. Thus, Q'_{furn} for the missing months is derived using k and T'_{bal} from the fit, and the average outdoor temperature, T_{out}, from each missing month.

For some homes we have only annual data. The analysis above is then impossible, therefore, we report no fit. Instead we use an approximation technique to estimate AQ (also adjusted as above to T_{in} = 20°C) (Ribot, Ingersoll and Rosenfeld, June 1982). In this approximation procedure we use a degree day ratio to extrapolate to annual performance (when months are missing), and to normalize indoor temperature.

4. STANDARDIZED PERFORMANCE: CORRECTING INTERNAL GAINS

Heating-energy consumption for a building may be described with the following basic heat-balance equation (combining eqs. 1 and 2):

$$E_{furn}\eta_{furn} = Q_{furn} \qquad [11]$$

$$= Q_{loss} - Q_{int} - Q_{sol}$$

By adjusting eq. 6,

$$Q_{furn} = k\left[T_{bal} - T_{out}\right]$$

to a standard inside temperature, we have been able to obtain an estimate of Q'_{furn} which is corrected for differences in occupants' thermostat settings. The correction also allowed us to extract the parameters k and T'_{bal}. We have not yet considered the two remaining terms in eq. [11], Q_{int} and Q_{sol}. In principle, Q_{sol} should be corrected to its long term, local average value, to correct for year to year fluctuations. However, because solar and insolation data is scarce and gains are difficult to estimate, we have left Q_{sol} unadjusted. This does not introduce a significant error into the results since, for a given site, variation of insolation from year to year is small.

Variations in internal gains, however, can cause large variations in heating loads, even among homes with identical shells and furnaces. Internal gains, Q_{int}, for the surveyed houses are presented in column W of Table 2. The average internal gains were 35 GJ/year [33 MBtu/yr],[5] but ranged from 15 -

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[5] 1 MBtu = 1.054 GJ. M is used to represent 10^6 in both British and SI units throughout this paper.

60 GJ/year (compared to a typical annual heating load of 50 GJ). Since internal gains during the heating season can be as large as 150% of the heating load, considerable error will result if internal gains are not properly included.

However, correcting the heating use for variations in internal gain requires submetered data on hot water use, appliance energy use, and number of occupants, in addition to the indoor temperature and submetered heating use. In our sample, these data are available for only 29 buildings. For this subset of houses we can correct the heating energy for both indoor temperature and internal gains. We use the same standard inside temperature as before, and use an algorithm (presented in appendix A) for calculating standard internal gains. $\overline{Q}_{int}$ (note that the bar, " — ", will be used with any parameter which is calculated using the standard internal gain). $\overline{Q}_{int}$ is typically 32 GJ/yr (~1 kW).[6]

To normalize for internal gains we first calculate the new balance temperature for the house with internal gain = $\overline{Q}_{int}$ (analogous to Eqs. 4 and 5):

$$\overline{T}'_{bal} = T'_{bal} + \left[\frac{Q_{int} - \overline{Q}_{int}}{k}\right] \qquad [12]$$

where

$\overline{T}'_{bal}$ = standard balance temperature (corrected for T_{in} = 20°C and $Q_{int} = \overline{Q}_{int}$), and

$\overline{Q}_{int}$ = standard internal gains.

The "standard annual heating load" (SAQ) is then calculated as follows (analogous to Eqs. 9 and 10):

$$\overline{Q}'_{furn} = k(\overline{T}'_{bal} - T_{out}) \qquad [13]$$

$$SAQ = \frac{1}{Y}\left[\sum_{m=1}^{n} \overline{Q}'_{furn}(m)\right] \qquad [14]$$

where

$\overline{Q}'_{furn}$ = heating load normalized for internal gains and indoor temperature, and

SAQ = standard annual heating load.

This procedure is equivalent to subtracting the difference between standard and actual internal gains ($\overline{Q}'_{int} - Q_{int}$) from the heating energy for each metered period.

Since T_{in} was normalized to 20°C in calculating T'_{bal}, SAQ is now corrected for both internal gains and indoor temperature. For example, consider a house with a reported heating load, an 18° indoor temperature, and internal loads of 40 GJ/year. After adjusting to the standard indoor temperature (20°), the AQ will be several percent higher than the reported heating load. After standardizing the internal gains to 32 GJ/year, the SAQ will be roughly 8 GJ greater than the AQ.

5. RESULTS

Using the methodology outlined in sections 3 through 5, we calculated adjusted annual heating load, AQ, for each building, and standard heating load, SAQ, for the subset of 29 buildings with more detailed metering. In Figs. 1 and 2 we show the thermal performance of the buildings on a degree day scale. Table 2 provides additional details. We also present an economic analysis based on AQ and added cost of conservation.

5.1 Adjusted Annual Performance

Figure 1 is a scatter plot of thermal intensity (adjusted annual heating load per unit area, AQ/m^2) versus degree-days for 215 buildings (including 7 small low-rise apartment houses). The points are all identified by category of conservation measure, and by the identification number for each home (or group of homes). Building characteristics and performance data can be found in Tables 1 and 2 respectively.[7] Below we present a general comparison of the thermal performance of building types.

A summary of the data in Fig. 1. is presented in Table 3. For each building type we show the average "thermal integrity," TI, which is the AQ divided by floor area and degree days. In this sample superinsulated homes show the best thermal performance with TI = 32, followed by passive solar, TI = 36, and then earth sheltered homes, TI = 50. Superinsulated/passive homes are next in rank, with TI = 52, however, it should be noted, that the average for this group of 172 homes, is dominated by two large groups. The superinsulated/passive average is composed of 144 MHFA homes, TI = 54, (#77 in Table 2), 27 Saskatoon homes, TI = 39, (#27 - 55 in Table 2), and the one Pasqua (#1) house, TI = 17. The MHFA group consists of passive solar, passive/superinsulated, and superinsulated homes; we include it in the passive/superinsulated average since we have not yet entered these sub-groups into our

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[6] An internal gain of ~1 kW is in common use among researchers as the U.S. average (California Energy Commission, April 1981, and Oak Ridge National Laboratory, December 1978).

[7] 1Btu/ft^{2}DDF = 20.4 kJ/m^2/DDC

data base (further discussion of the breakdown of the MHFA Homes will be found in Section 6.3). At the bottom of the ranking are active solar and active/superinsulated, with TI = 76 and 83 respectively (multi-family buildings not included). Note that the 7 multi-family buildings are active solar, with average TI = 102. When included in the average with the single-family homes, the multi-family buildings bring the active solar average up to TI = 90. Note that TI is merely a measure of thermal performance and is not the sole basis for making economic comparisons between houses.

5.2 Standard Annual Performance

Figure 2 shows standard thermal intensity for the 29 homes which we compared using standard internal gains and indoor temperature. Here we compare the homes with 1) the Building Energy Performance Guidelines (BEPG, 1981) for residential buildings,[8] 2) new building practice (NAHB, 1979) (Ingersoll, 1981), and 3) the national building stock (NIECS, 1980).[9] The BEPG and NAHB curves were calculated using the same internal gain and thermostat setting as above. The NAHB curve is derived from simulations based on NAHB 1979 Home Builders Survey data. The NAHB curve is probably somewhat below the actual thermal intensities of new U.S. building practice, due to discrepancies in reporting and tabulation. Furthermore, the NAHB survey only included NAHB builders; average U.S. building practice may, therefore, be different.

Figure 2 displays the tremendous potential for conservation in U.S. buildings. Dividing each point by the heating degree-days, we find the mean standard thermal integrity, STI, of our energy-efficient homes is 45 kJ/m^{2}DDC compared with STI = 180 for the national building stock and STI = 100 for current building practice.[10] The lowest STI = 8 (one of the SERI homes), which is about one-twentieth of the U.S. average, and one-tenth of current U.S. (NAHB) building practice. The average standard thermal integrities, broken down by building type, are presented in Table 4. Earth-sheltered, and passive/superinsulated entries have been omitted since only one building was represented in each.

5.3 Economic Analysis

Energy conservation savings can only be interpreted in the context of their costs; it is trivial to build a home that needs no auxiliary heat if cost is not a concern. In this section we compare our sample homes to each other and to current building practice on the basis of added costs and energy savings.

Figure 3 shows annual energy savings as a function of the added cost of conservation for the 92 buildings for which we have cost data. Annual energy savings is the difference between the NAHB "new building practice" line (see figures 1 and 2) and the thermal intensity of each home. (We base our economic analysis on AQ, annual heating load, rather than SAQ, standard annual heating load, since we have been able to standardize too few buildings (only 29) to draw any meaningful conclusions.) Since the NAHB current practice line is likely to be a conservative estimate of "baseline" energy use, actual savings are probably somewhat greater than shown.

The reference lines (drawn from the origin) represent the boundary of conservation cost-effectiveness using recent U.S. average residential energy prices for electricity (7.2¢/kWh) and gas (56¢/therm) (Monthly Energy Review, October 1982). The slope was calculated as follows. Since conservation investments for new residential buildings are typically "one-time," we convert the future stream of energy purchases for 30 years (the assumed amortization period for an energy-saving feature in a new home) to a single present value assuming a 3% or a 6% real interest rate (thus the two boundary lines for electricity and two for gas). The cost of conserved energy for the conservation measure is less than that of purchased energy (i.e. the measure is cost-effective) if the data point lies above the purchased energy line.

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[8] BEPG was developed at LBL as an extension of the research on the federal Building Energy Performance Standards (BEPS, 1979) (Ingersoll, 1981).

[9] Note that the lowest three curves of Figure 2 have a reasonable shape, but the "stock" curve (NIECS) is straight line. This is due to the fact that we have not yet plotted NIECS points for many locations and fitted a curve to them. Instead we took the U.S. average intensity and average degree-days calculated from the NIECS data and simply drew a straight line through the origin and through that point. We will provide a curve in the next edition of BECA-A (Meyers, March 1981).

[10] The "average" thermal integrities associated with the NAHB and BEPG curves are the slopes of lines constrained to the origin which best approximate these curves.

Figure 3 provides the basis for comparing the relative merit of the homes. Comparing the electric homes to the electric reference lines and gas-heated homes to the gas reference lines we can see the following general patterns. The 3 active solar homes in our sample are certainly far from cost effective; despite an incremental cost of \$80-90/m^2, one home used more electricity than conventional construction (i.e.—showed "negative savings"), and the other two saved only one-third to one-half the energy that would have been necessary to meet a cost-effectiveness criterion. The results are not so clear for homes with passive solar, superinsulation, and combinations of the two. All of the individual superinsulated homes shown in Fig. 3 are clearly cost-effective. The EWEB group of 9 superinsulated homes is cost effective on the average, with only one home with CCE above that of purchased energy. The 27 Saskatoon passive/superinsulated homes are all clearly cost-effective regardless of which fuel they use, because their CCE's are well below either gas or electric prices. For the 144 MHFA homes, though the range is large, the distribution of homes within this range is not random. This group consists of 144 single-family homes, all with high insulation levels but with greatly varying south aperture (south-glazing area)—mostly direct gain. Curiously, the investment in insulation was approximately the same for the homes with high south aperture as it was for those with low south aperture. Within this group the homes with lower south aperture are cost effective with respect to both electricity and gas prices, while on the average, those with higher south glazing aperture cost more and conserved less energy (Hutchinson and Nelson, 1983). A few of the SERI passive solar homes are cost effective; however, on the average their cost of conserved energy is above that of purchased energy (Swisher, 1982). Superinsulation is the only clearly cost-effective conservation measure in our limited sample of homes. Passive/superinsulation is also cost effective in some regions. Some of the passive solar homes are marginally cost effective; in general, however, they are not. Active solar houses in this sample are clearly too expensive.

6. SUMMARY AND CONCLUSION

In this paper we compared the thermal and economic performance of superinsulated, passive-solar, active-solar, and several different "multi-strategy" homes. Of 215 buildings in our data base, 92 had data on additional first cost and 29 were monitored in enough detail to normalize for both indoor temperature and internal gains. We have compared the homes by building type, heating performance, and added cost for conservation and solar measures.

Table 3 summarizes our findings on thermal performance. We found that active-solar buildings used the most heating energy, 76 kJ/m^{2}DDC [3.8 Btu/ft^{2}DDF] for single family, and 102 [5.0] for multi-family dwellings. Homes with superinsulation, or passive solar and superinsulation combined, consumed considerably less — 32 [1.6] and 52 [2.6] respectively.

We have introduced a method to normalize for occupant effects on measured thermal performance, by substituting a standard internal gain and indoor temperature. In Table 4 we compare our "standardized" buildings with U.S. building stock data, current building practice, and with building energy performance guidelines (BEPG). On a scale where U.S. building stock averages 180 kJ/m^{2}DDC [8.9 Btu/ft^{2}DDF], current practice is 100 [5.0], and BEPG are 66 [3.3] (high infiltration) and 45 [2.2] (low infiltration), solar and conservation buildings average 46 [2.3] (ranging from 8 [0.5] to 130 [6.4]).

We used the cost of conserved energy (CCE) to judge each conservation measure's cost effectiveness. A measure is cost effective if its CCE is less than the price of the energy it displaces. We observed that homes employing either superinsulation or a combination of superinsulation and passive solar (with low south glazing) typically have CCEs well below that of purchased energy. The average CCE for passive solar homes is above that of purchased energy. In our sample the CCEs for active solar homes are far above that of purchased energy. In summary, superinsulation and superinsulation used in combination with moderate south glass area are the only cost-effective measures to have been demonstrated in our data sample.

We continue to collect data, and encourage the participation of our readers.

7. ACKNOWLEDGMENTS

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Table 1. Input Data

A ID NO.	B SITE NAME	C LOCATION	D NO. OF BLDG	E NO. OF METERED UNIT PER BLDG	F FUEL/SYSTEM TYPE (SEE KEY) SPACE HEAT 1	SPACE HEAT 2	HOT WATER	COOLING	G YR. BUILT	H HEATED FLOOR AREA PER UNIT (m^2)	I SOUTH GLAZ. AREA PER UNIT (m^2)	J NO. OF GLAZINGS; SOUTH	J-1 E,W,N	K R-WALL (SI)	K-1 R-CEIL (SI)	K-2 R-FLOO (SI)	L INFILTRATION (AC/H)	M HOW INF. MEASURED (SEE KEY)	N CONSERVATION MEASURES (SEE KEY)	O ADDED COST OF CONS. 1981 $	P NO. OF OCCUPANT PER UNIT
1	PASQUA	REGINA SA CANADA	1	1	ER		ER		80	247	8			7.0	9.2	1.8	.13		HI X	8637	4
2	HUD-EER I	MT. AIRY MD	1	1	EH	ER	ER	C	77	117	14	3	3	3.2	6.8		.19		I	5429	4
3	PHELPS	LERNA IL	1	1	ER		ER		79	160	3	3	3	6.9	8.9	5.3			I	2281	2
4	EWEB-A	EUGENE OR	1	1	EH		ER		77	107		2	2	3.4	6.8	3.4	.36	B	I	3454	2
5	EWEB-B	EUGENE OR	1	1	ER		ER		77	107		2	2	3.4	6.8	3.4	.30	B	I	1961	4
6	EWEB-C	EUGENE OR	1	1	ER		ER		77	102		2	2	3.4	6.8	3.4	.26	B	I	1866	5
7	EWEB-D	EUGENE OR	1	1	ER		ER		77	102		2	2	3.4	6.8	3.4	.21	B	I	1866	4
8	EWEB-E	EUGENE OR	1	1	ER		ER		77	107		2	2	3.4	6.8	3.4	.16	B	I	1968	2
9	EWEB-F	EUGENE OR	1	1	ER		ER		77	102		2	2	3.4	6.8	3.4	.12	B	I	1866	2
11	EWEB-H	EUGENE OR	1	1	ER		ER		77	83		2	2	3.4	6.8	3.4	.37	B	I	1527	1
12	EWEB-I	EUGENE OR	1	1	ER		ER		77	83		2	2	3.4	6.8	3.4	.30	B	I	1527	1
13	EWEB-J	EUGENE OR	1	1	EH		ER		77	133		2	2	3.4	6.8	3.4	.22	B	I	3936	2
14	ACORN	CONCORD MA	1	1	ER	EA	ER		75	130	9	1	1	2.3	3.4				A I	11333	0
15	LYNN-SDG+E	SAN DIEGO CA	1	1	ER	EA	ER	C	76	185		2	2	2.0	3.4				A	17311	5
17	LA VIGNE	CAMANO ISLAND WA	1	1	ER		ER		76	142	19	2		2.2	3.4				E IP	0	2
18	SASK.CONS	REGINA SA CANADA	1	1	ER	EA	ER		77	188	11	2	2	7.3	10.6		.60	T	A IP	4010	0
20	USC CAMDEN	CAMDEN STATE PARK MN	1	1	ER	EP	ER		79	167				3.6	4.5				EH		3
21	USC SEWARD	MINNEAPOLIS MN	1	1	ER		ER		79	98				2.7	3.6				E		1
23	USC WILLMA	WILLMAR MN	1	1	ER		ER		79	195				3.6	3.6	0.			E		3
24	CENTOFTE	CENTOFTE DENMARK	1	1	OB	EA	OB		78	133		2	2	1.3	1.7				A		4
25	GREVE	GREVE DENMARK	1	1	OB	EA	OB		78	108	16	3	3	3.7	3.4	2.5			A		4
26	FJARAS	FJARAS SWEDEN	1	1	ER	EA	ER		79	160	15	3	3	7.1	9.1	8.3	.20		AD I		3
27	BOURGOIN W	BOURGOIN FRANCE	1	6	ER	EA	ER		77	95		2	2	2.3	2.4	1.8			A		4
28	BOURGOIN E	BOURGOIN FRANCE	1	6	ER	EA	ER		77	95		2	2	2.3	2.4	1.8			A		4
29	SASK A1	SASKATOON SA CANADA	1	1	ER		ER		80	179				5.1	10.6	0.	1.70	B	IP	3412	1
30	SASK B1	SASKATOON SA CANADA	1	1	ER		ER		79	199				7.8	10.6	3.5	2.20	B	IP	4886	2
31	SASK B3	SASKATOON SA CANADA	1	1	GB		ER		79	300				7.9	10.6	0.	1.50	B	IP	4653	3
32	SASK B5	SASKATOON SA CANADA	1	1	GB		GB		79	306				7.0	12.3	1.3	.60	B	IP	4653	4
33	SASK B6	SASKATOON SA CANADA	1	1	ER		ER		78	287				7.0	10.6	5.3	1.00	B	IP	4037	4
34	SASK B7	SASKATOON SA CANADA	1	1	ER		ER		80	164				5.3	8.8	0.	2.20	B	IP	3412	2
35	SASK D1	SASKATOON SA CANADA	1	1	GB		GB		80	284				6.3	7.0	0.			IP	4265	2
36	SASK F1	SASKATOON SA CANADA	1	1	GB		GB		80	297				5.1	7.0	0.	1.60	B	IP	4265	3
37	SASK C2	SASKATOON SA CANADA	1	1	ER		ER		79	218				7.8	4.7	0.			IP	3722	3
38	SASK C3	SASKATOON SA CANADA	1	1	GB		GB		79	265		2	2	5.3	10.6	0.		B	IP	4653	2
39	SASK G4	SASKATOON SA CANADA	1	1	ER		ER		79	241				7.8	10.6	4.9			IP	3722	2
40	SASK C5	SASKATOON SA CANADA	1	1	ER		ER		79	297				7.0	10.6	1.8	1.40	B	IP	3722	2
41	SA H1 BEST	SASKATOON SA CANADA	1	1	ER		ER		79	225				5.3	8.8	0.	1.70	B	IP	3722	2
42	SASK K3	SASKATOON SA CANADA	1	1	ER		ER		80	210				5.3	8.8	0.			IP	3412	4
43	SASK L2	SASKATOON SA CANADA	1	1	ER		ER		78	163		2	2	6.3	10.6	0.			IP	4037	1
44	SASK L6	SASKATOON SA CANADA	1	1	GB		GB		80	226				5.3	8.8	0.	2.50	B	IP	4265	2
45	SASK R1	SASKATOON SA CANADA	1	1	GB		GB		79	217		2	2	4.8	7.0	0.			IP	4653	4
46	SASK S1	SASKATOON SA CANADA	1	1	ER		ER		79	167				6.4	10.6	3.5			IP	3722	1
47	SASK S2	SASKATOON SA CANADA	1	1	ER		ER		79	328				5.3	8.8	0.			IP	3722	4
48	SASK T1	SASKATOON SA CANADA	1	1	ER		ER		80	250				10.6	10.6	4.9	.80	B	IP	3412	1
49	SASK V1	SASKATOON SA CANADA	1	1	ER		ER		79	495				5.3	8.8	0.	2.50	B	IP	3722	2
50	SASK W1	SASKATOON SA CANADA	1	1	GB		GB		80	212				4.9					IP	4463	4
51	SASK W4	SASKATOON SA CANADA	1	1	ER		ER		78	242				7.8	10.6	0.	1.30	B	IP	4037	5
52	SASK AA2	SASKATOON SA CANADA	1	1	ER		ER		80	219				5.3	8.8	0.	2.30	B	IP	3570	0
53	SASK AA3	SASKATOON SA CANADA	1	1	ER		ER		79	200				5.3	8.8	0.	1.60	B	IP	3722	0
54	SASK AA4	SASKATOON SA CANADA	1	1	ER		ER		79	204				5.3	8.8	0.			IP	3722	4
55	SASK AA5	SASKATOON SA CANADA	1	1	ER		ER		79	200				5.3	8.8	0.	2.80	B	IP	3722	2
58	ROUSSET	MARSEILLE FRANCE	1	16	EH	EA	[illegible]		76	91	0	1	1	1.8	1.7	1.6			A	7621	3
60	CARCASSONE	CARCASSONNE FRANCE	4	10	ER	EA	ER		77	90		1	1						A		3
61	LE HAVRE	LE HAVRE FRANCE	1	1	ER	A	ER		76	116									A		4
63	SUNCATCHER	DAVIS CA	1	1	GB		A	N	77	150	12	2	2	3.4	5.3		.75		P		3
67	ARAMON	MONTPELLIER FRANCE	1	1	ER		ER		75	150									A		5
68	EINDHOVEN	EINDHOVEN NETHERLAND	1	1	GB	EA	GB		78	220	9	2	2	2.5	2.5	2.0			A		4
70	MILTON KEY	BRADVILLE ENGLAND	1	1	GB	EA	ER		74	85									A		3
71	ZOETERME 3	THE HAGUE NETHERLAND	1	1	GB	EA	ER		78	130	12	2	2	1.7	2.7	1.4	.60		A I		3
72	ZOETERME 4	THE HAGUE NETHERLAND	1	1	GB	EA	ER		78	130	12	2	2	1.7	2.7	1.4	.60		A I		2
73	ZOETERME10	THE HAGUE NETHERLAND	1	1	GB	EA	ER		78	130	12	2	2	1.7	2.7	1.4	.60		A I		2
74	ZOETERME 2	THE HAGUE NETHERLAND	1	1	GB	EA	ER		78	130	12	2	2	1.7	2.7	1.4	.60		A I		4
75	BRADVILLE	BRADVILLE ENGLAND	1	1	GB	EA	ER		74	85	8	1	1	1.2	1.8	.6	1.00		A		4
76	SERI	DENVER CO	5	1					80	For details see Swisher, '82 (for #76) and Hutchinson, '82 (for #77).									P		
77	MHFA	MINNESOTA	144	1					81										IP		

KEY TO TABLE 1: INPUT DATA

Column F: Fuel/System Type

space heat 1 = primary (purchased)
space heating type and fuel
space heat 2 = secondary space heating
type and fuel
hot water = fuel and type

fuel (first letter)	type (second letter)
G gas	B burner
O oil	H heat pump
E electricity	R resistance
	A active solar

cooling (if applicable)
C central
N other

Column M: How Infiltration Is Measured
B blower door
T tracer gas

Column N: Conservation Measures

A active solar
D double envelope
E earth-sheltered
H hybrid solar
I superinsulated
P passive solar
X air-to-air heat exchanger

Table 2. Results

A	Q	R	S	T	U	U-1	U-2	V	V-1	V-2	W	X	Y	Z	A
ID NO.	-K-[a] (W/K)	NO. OF PO-INTS IN FIT	R SQU	BALANCE TEMP. T-SUB-B (C)	-AQ- ANNUAL HEATING LOAD (GJ)	THERMAL INTENS. (10^7J/ SQM)	THERMAL INTEG. (KJ/SQM DD-C)	-SAQ- STD. ANNUAL HEATING LOAD (GJ)	STD. THERMAL INTENS. (10^7J/ SQM)	STD. THERMAL INTEG. (KJ/SQM DD-C)	AVERAGE ANNUAL INTER-NAL FREE HEAT (GJ)	ANNUAL HEATING DEGREE-DAYS (18.3C)	DEFAULT VALUES (SEE KEY)	ANNUAL SOLAR RAD. (MJ/ SQM)	ID NO.
*****	*****	****	***	*******	*******	*******	*******	*******	*******	*******	*******	*******	*********		
1	88.8	8	.96	8.6	24.1	9.8	17.1	37.0	15.0	26.3	55.7	5700	L R	5100	1
2	111.6	8	.46	11.6	14.2	12.1	40.8	12.2	10.3	34.9	25.9	2953	V E		2
3	65.9	7	.84	12.7	11.1	6.9	21.4	8.1	5.1	15.7	26.9	3233	VRT		3
4	276.5	19	.49	9.4	13.9	13.0	46.4	19.5	18.1	64.9	41.7	2795	LVRTE I	4671	4
5	96.9	26	.84	14.1	13.2	12.3	43.8	22.4	20.9	74.6	42.1	2795	LVRT I	4671	5
6	90.2	18	.87	10.9	6.6	6.5	23.1	23.6	23.1	82.5	52.8	2795	LVRT I	4671	6
7	118.9	24	.80	11.6	10.3	10.1	36.1	13.7	13.4	47.8	35.3	2795	LVRT I	4671	7
8	71.0	8	.94	11.9	6.1	5.7	20.7	5.5	5.1	18.8	29.1	2734	P VRT	4671	8
9	48.8	7	.83	11.3	3.6	3.6	13.0	4.9	4.8	17.7	32.1	2734	P VRT	4671	9
11	80.3	8	.97	12.3	7.4	8.8	32.3	4.8	5.7	20.8	23.9	2734	P VRT	4671	11
12	100.7	9	.72	11.5	7.8	9.3	34.0	8.1	9.6	35.2	29.5	2734	P VRT	4671	12
13	184.0	5	.97	11.5	14.3	10.7	39.2	24.4	18.2	66.7	47.1	2734	P VRTE	4671	13
14	308.6	11	.91	11.0	48.0	36.9	109.3	34.7	26.7	79.0	0.	3379	LVRT	4579	14
15	161.5	7	.59	16.3	5.0	2.7	32.2	19.7	10.6	128.1	59.1	827	I	6857	15
17					11.1	7.8	26.9					2894		4370	17
18	105.6	6	.95	8.4	33.2	17.7	28.1	17.5	9.3	14.8	0.	6284	LVRT I	5100	18
20	165.4	4	.94	8.5	27.7	16.5	38.2	22.9	13.7	31.6	24.0	4332	PLVRT I	4851	20
21	156.5	5	.89	7.8	24.2	24.6	57.5					4283	P I	4851	21
23	168.7	4	.88	10.7	35.0	17.9	41.4	32.2	16.5	38.1	29.5	4332	PLVRT I	4851	23
24	307.4	24	.93	15.0	57.9	43.6	139.5					3122	E	3690	24
25	199.4	23	.84	11.9	31.5	29.2	83.3					3499	E	3690	25
26	111.7	12	.78	11.8	19.6	12.2	31.7					3855		3690	26
27	146.5	25	.78	15.2	21.7	22.7	91.9	13.6	14.3	57.8	14.7	2473	R	5041	27
28	131.7	26	.90	15.7	21.0	22.0	89.4	14.5	15.2	61.8	18.4	2461	R	5041	28
29					48.9	27.3	52.3					5216		5000	29
30					41.6	20.9	40.1					5216		5000	30
31					61.5	20.5	39.3					5216	E	5000	31
32					37.9	12.4	23.8					5216	E	5000	32
33					36.7	12.8	24.5					5216		5000	33
34					26.2	16.0	30.7					5216		5000	34
35					52.1	18.3	35.2					5216	E	5000	35
36					80.7	27.2	52.1					5216	E	5000	36
37					37.3	17.1	32.8					5216		5000	37
38					72.0	27.2	52.1					5216	E	5000	38
39					36.9	15.3	29.3					5216		5000	39
40					45.1	15.2	29.1					5216		5000	40
41					33.3	14.8	28.4					5216		5000	41
42					41.8	19.9	38.2					5216	P	5000	42
43					74.2	45.5	87.2					5216		5000	43
44					32.1	14.2	27.2					5216	E I	5000	44
45					64.9	29.9	57.3					5216	E	5000	45
46					43.9	26.3	50.4					5216		5000	46
47					68.9	21.0	40.3					5216		5000	47
48					39.8	15.9	30.5					5216		5000	48
49					76.2	15.4	29.5					5216		5000	49
50					42.3	20.0	38.2					5216	E	5000	50
51					45.7	18.9	36.2					5216		5000	51
52					48.0	21.9	42.0					5216		5000	52
53					40.2	20.1	38.5					5216		5000	53
54					35.3	17.3	33.2					5216		5000	54
55					38.0	19.0	36.4					5216		5000	55
58	59.2	8	.80	16.1	7.9	8.6	40.0					2151		5753	58
60	155.7	8	.93	16.9	23.1	25.4	124.6					2040		4296	60
61	280.3	8	.86	12.4	26.1	22.5	79.2					2838			61
63	185.1	8	.68	16.0	16.5	11.0	72.3					1518	P E	5562	63
67	385.6	8	.89	14.4	29.7	19.8	111.3					1781			67
68	479.7	8	.55	10.8	42.8	19.5	62.1	51.9	23.6	75.3	51.7	3136	LVR E	3412	68
70	179.6	16	.76	10.6	15.7	18.4	63.5	23.9	28.2	97.0	44.3	2903	LVR E		70
71	240.9	9	.94	11.9	25.2	19.4	68.3	21.6	16.6	58.3	24.6	2844	L R E	3510	71
72	266.4	11	.94	13.3	34.9	26.8	94.9	28.2	21.7	76.6	19.6	2829	L R E	3510	72
73	365.5	8	.91	10.4	28.6	22.0	77.9					2829	E	3510	73
74	233.5	7	.92	11.8	21.8	16.7	66.2	20.1	15.5	61.3	27.8	2529	L R E	3510	74
75	90.2	12	.58	12.4	9.6	11.3	42.9	6.7	7.9	29.9	23.4	2635	R	3446	75
76						9.5	28.4		9.7	29.0		2342			76
77						24.4	54.3					4500			77

[a] For those homes where k could not be calculated, AQ and SAQ were calculated with an approximation method. See Ribot et al., "Monitored Superinsulated and Solar Houses in North America: A Compilation and Economic Analysis," PASSIVE '82, the National Passive Solar Conference, Knoxville, TN, September 1982.

KEY TO TABLE 2: RESULTS

Column Y: Defaulted Values

P number of occupants
L water heater location
V water heater volume
R water heater insulation R-value
T water heater thermostat setting
E furnace efficiency
I inside temperature

(for default values see Appendix B)

Table 3. Adjusted Thermal Integrity.* Thermal integrity for 215 low-energy buildings normalized to an inside temperature of 20°C.

Building Type	Number of Buildings	Thermal Integrity	
		kJ/m^{2}DDC	Btu/ft^{2}DDF
AVERAGE	208 [215]	52 [53]	2.5 [2.6]
Passive/Superinsulated	172	52	2.5
Active Solar	7 [14]	76 [90]	3.8 [4.4]
Superinsulated	11	32	1.6
Passive Solar	6	36	1.8
Active/Superinsulated	5	83	4.1
Earth-Sheltered	2	50	2.4
Other	4	31	1.5
Multi-family (all active solar)	--- [7]	--- [102]	--- [5.0]

*Numbers in brackets include multi-family and single-family buildings. All other numbers are for single-family homes only.

Table 4. Standard Thermal Integrity.* Thermal integrity for 46 buildings normalized to an inside temperature of 20°C and internal gains of ~32 GJ/yr.

Building Type	Number of Buildings	Standard Thermal Integrity	
		kJ/m^{2}DDC	Btu/ft^{2}DDF
AVERAGE	27 [29]	45 [46]	2.2 [2.3]
Active Solar	4 [6]	83 [75]	4.1 [3.7]
Superinsulated	11	44	2.1
Passive Solar	5	29	1.4
Active/Superinsulated	4	68	1.9
U.S. Building Stock	---	180	8.9
New Building Practice	---	100	5.0
BEPG**	---	66 (45)	3.3 (2.3)

*Numbers in brackets include multi-family and single-family buildings. All other numbers are for single-family homes only.

**Numbers in parentheses are for low infiltration model.

APPENDIX A: INTERNAL GAINS

In this appendix we present the method by which we estimate internal gains. We estimate "actual internal gains, Q_{int}, and standard internal gains, $\overline{Q}_{int}$, for each house with sufficient data. First we present our procedure for estimating Q_{int}, and then we present our method for scaling $\overline{Q}_{int}$.

Internal gains, Q_{int}, are defined as the thermal energy generated inside the building shell other than that specifically for heating.

$$Q_{int} = Q_p + Q_a + Q_w$$

where

Q_p = gains from people,

Q_a = gains from appliances, and

Q_w = gains from water heating system.

We calculate Q_p, Q_a, and Q_w for each home as follows:

1) People: Gains from people equal 7.6 MJ/person-day. This is 88 W per person, for 16 hours per day (Sonderegger et al., 1982).

2) Appliances: Q_A is equal to the total appliance energy consumption minus 80% of the dryer energy use. Dryer energy use is calculated as a function of the number of people:

$$Q_D = (3.6 \text{ MJ/person-day})(0.8)$$

$$= 33 \text{ W/person}$$

where Q_D is dryer energy that does not heat the home, and 0.8 is average dryer efficiency (Usibelli, 1980). (2) energy from latent heat is not counted as gains, since any latent heat is lost via evaporation and infiltration.

3) Hot water: Gains from the water heating system are calculated from water heating energy consumption, tank volume, tank insulation, tank location, set temperature, and heating type (i.e. gas or electric).

$$Q_w = SL + 0.05(\eta_w E_w - SL)$$

$$= 0.95\,S\,L - 0.05\eta_w E_w$$

where

S = standby losses,

L = location factor (fraction of standby losses which enter the conditioned space) (Sonderegger et al., 1980),

E_w = water heater energy consumption,

η_w = efficiency (1.0 for electric, and 0.7 for gas) (Clear and Goldstein, 1980).

0.05 is the fraction of the energy which is assumed to enter the house via conduction from pipes and drains. No latent gains are included since they are only temporary (they are offset by evaporation into dry infiltrating air).

Standby losses are calculated as follows:

$$S = \left[\frac{1}{R_T + R_I}\right]\left[1.25V^{2/3}\right]\left[T_{set} - T_L\right],$$

where

S = standby losses,

R_T = average DHW tank R-value,

R_I = added tank insulation R-value,

V = volume (1.25 is a shape factor),

T_{set} = set temperature, and

T_L = location dependent room temperature (a function of outside or inside temperature depending on location).

To calculate standard internal gains, $\overline{Q}_{int}$, we scale gains from people, $\overline{Q}_p$, and lighting, $\overline{Q}_L$, by conditioned floor area, and add them to a fixed internal gain from all other appliances, $\overline{Q}_{other}$.

$$\overline{Q}_{int} = \overline{Q}_{other} + \overline{Q}_p + \overline{Q}_L$$

where

$\overline{Q}_{other}$ = 0.061 GJ/day,

≡ internal gains from appliances and hot water,

$\overline{Q}_p$ = (0.02 people/m^2) Q_p

= 0.00052 GJ/m^2-day, and

$\overline{Q}_L$ = 0.00013 GJ/m^2-day.

The figure of 0.02 people/m^2 in $\overline{Q}_p$, is explained in appendix B; the figures are derived from BEPS (Ingersoll et al., 1981).

APPENDIX B: DEFAULTS

Below we present the values for defaults used in our analysis. The homes for which defaults were used are flagged in Table 2 (Column y) and the quantities defaulted are indicated.

1. (P) Number of occupants = 0.02 people/m^2. This was derived by dividing the U.S. population by the number of homes and by the average floor area of U.S. homes.

2. (L) Water heater location = living space (Sonderegger _et al._, 1982).

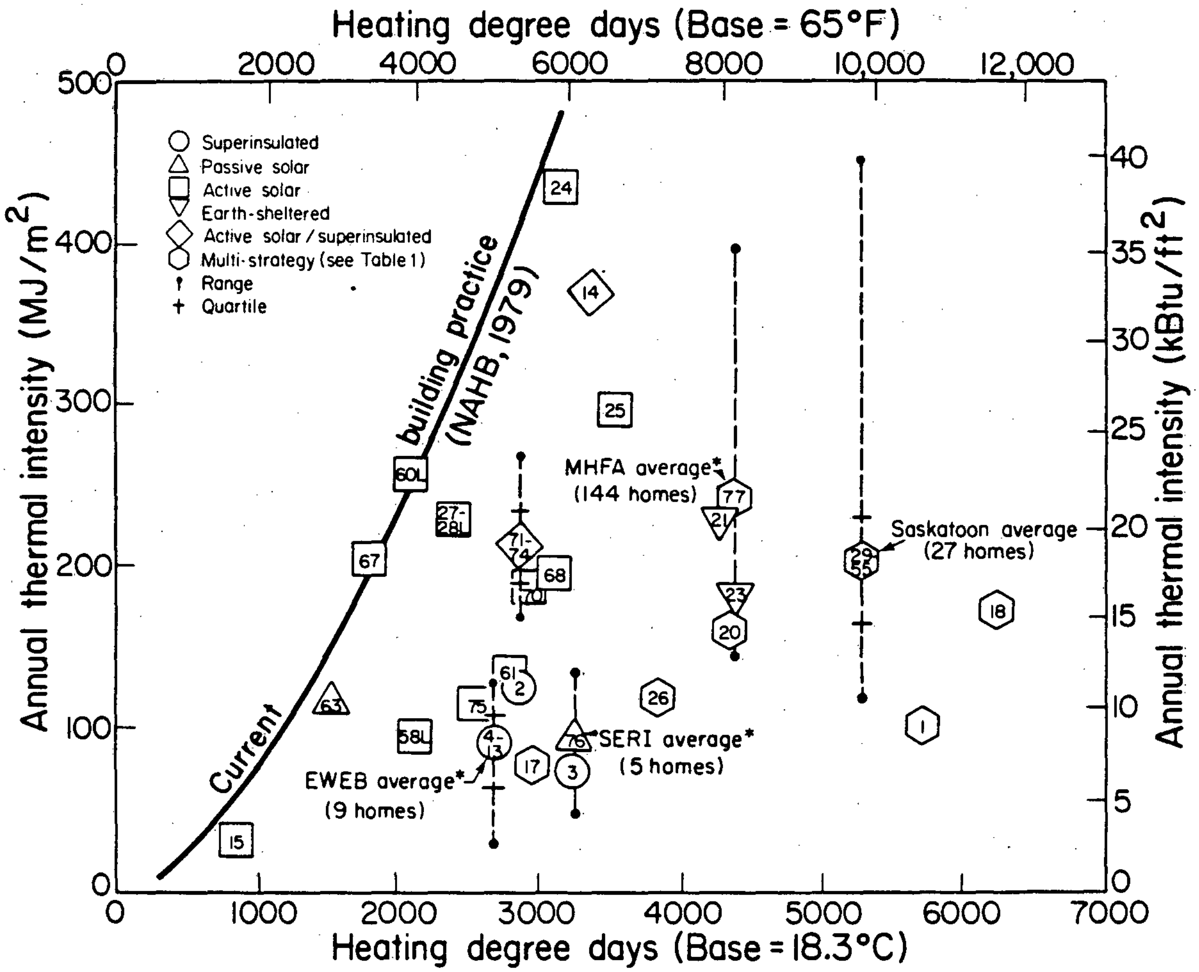
3. (V) Water heater volume = 150 liters = 40 gallons (Clear and Goldstein, 1980).

4. (R) Water heater tank insulation R_{SI} = 1.6, $R_{British}$ = 9 (Clear and Goldstein, 1980).

5. (T) Hot water set temperature = 60° C = 140° F (Sonderegger _et al._, 1982).

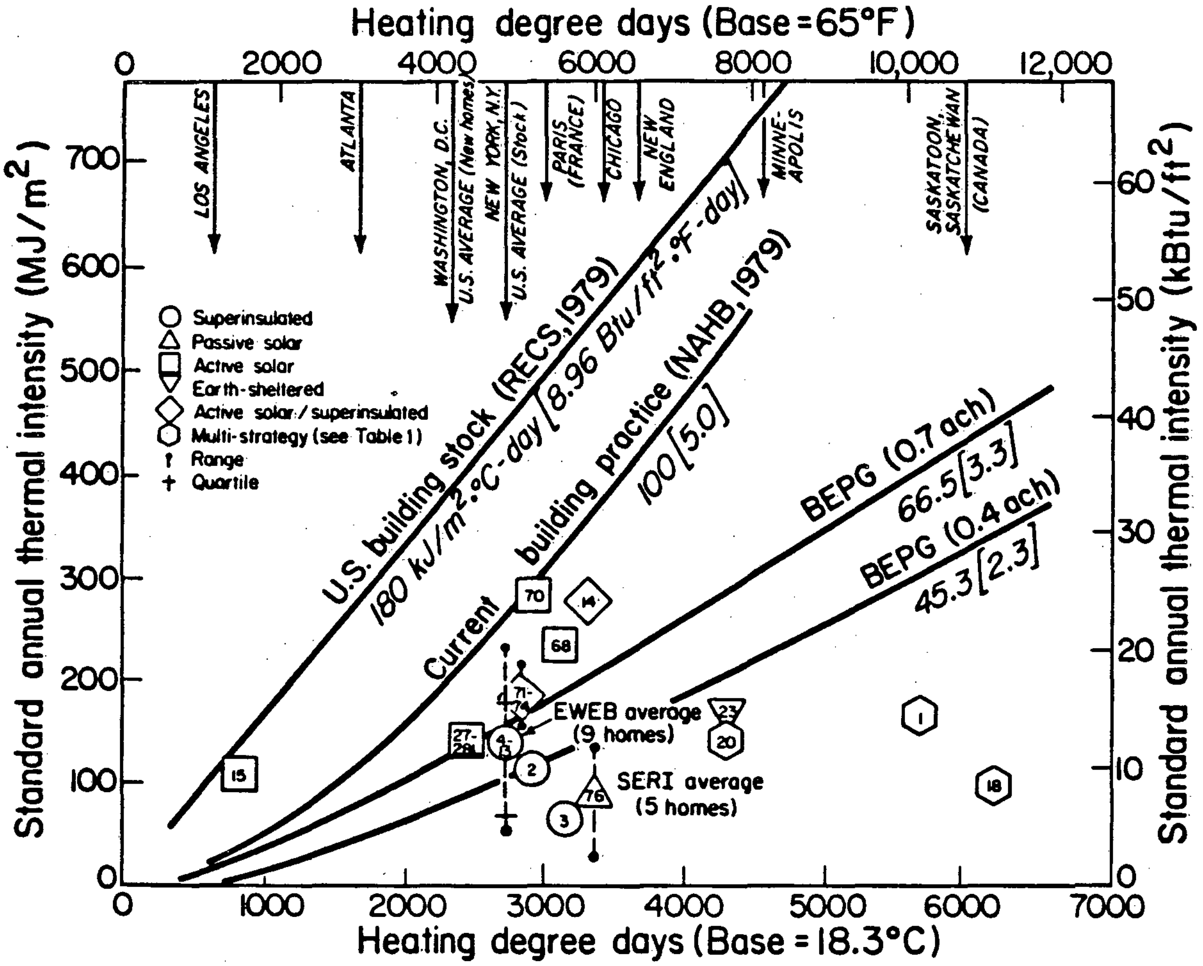
6. (E) Space heating efficiency, N_{furn}: gas burner = 0.7 (assuming new furnaces in new homes). Heat pump COPs are generated as a function of heating degree-days for each metered period (Ingersoll _et al._, 1981). Electric resistance N_{furn} = 1.0.

7. (I) Inside temperature = 20° C = 68° F (Sonderegger _et al._, 1982).



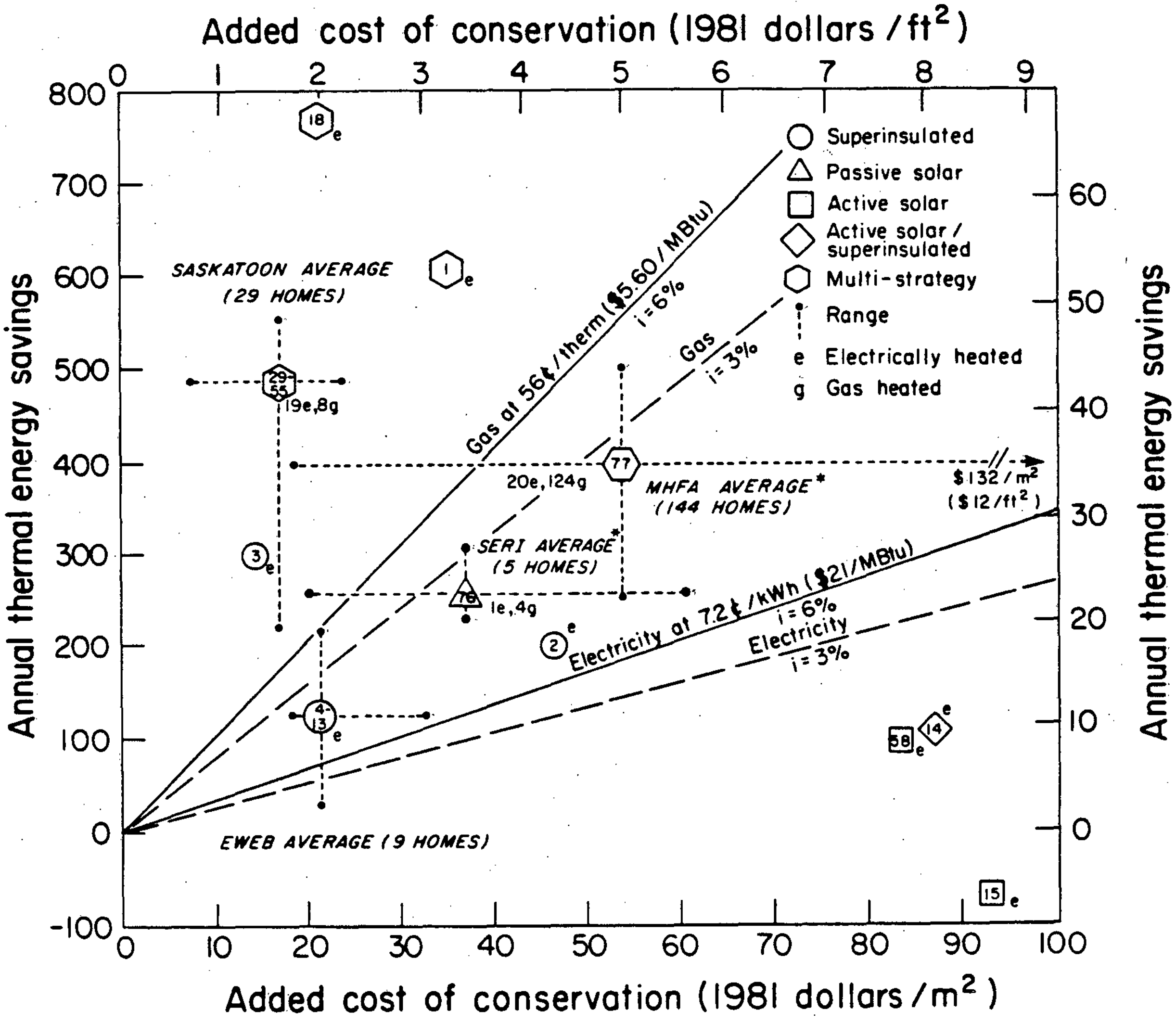
XBL 827 – 958

Figure 1. Scatter plot of annual heating load/m^2 vs. climate for 27 points representing 215 submetered energy-efficient new buildings. The solid curve is NAHB based 1979 survey of U.S. building practice, described in text.



XBL 827 – 956

Figure 2. Twenty-nine building scatter plot of "standardized" thermal intensity vs. climate. The various comparison curves are defined in the text. The average thermal intensity per degree-day for our 29 buildings is 46 kJ/m^2 DDC, or half of the current building practice.



XBL 8211-7301

Figure 3. Ninety-two building scatter plot of annual energy savings vs. added first cost of conservation and solar features. The energy savings represent the difference between the home's annual thermal intensity and the current building practice line of Figs. 1 and 2. The reference lines drawn from the origin represent the boundary of conservation cost-effectiveness against recent U.S. average residential energy prices for electricity (7.2¢/kWh) and gas (56¢/therm). Since conservation is typically a "one time" investment, the future stream of energy savings for 30 years are converted to a single present value, assuming 6% or 3% real interest rate. The home is cost effective if its point lies above the reference line in question.

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