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Ribot, J.C.

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To be presented at the International Conference on Earth Sheltered Buildings, Sydney, Australia, August 1-10, 1983

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April 1983

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To be presented at the 1983 International Conference on Earth Sheltered Buildings, Sydney, Australia, August, 1983.

SUMMARY OF INTERNATIONAL DATA ON MONITORED LOW-ENERGY HOUSES: A COMPILATION AND ECONOMIC ANALYSIS

Jesse C. Ribot, Arthur H. Rosenfeld, Françoise Flouquet,* and Wolfgang Lührsen**

Energy Efficient Buildings Program
Lawrence Berkeley Laboratory
University of California
Berkeley CA 94720 USA

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* Visiting Researcher at LBL March--September 1982, current address is Dr. Françoise Flouquet, Ave. 'des Martyrs, BP166X Centre de Tri, 38042 Grenoble, Cedex, France.

** Visiting Researcher at LBL March 1982--March 1983, current address is Nondweg 108, 2111 Königsmoor, Germany.

SUMMARY OF INTERNATIONAL DATA ON MONITORED LOW-ENERGY HOUSES: A COMPILATION AND ECONOMIC ANALYSIS

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^2DDC. These compare favorably to U.S. 1979 building practice of 100 kJ/m^2DDC and U.S. Stock at 180 kJ/m^2DDC. We have data on the added first cost of conservation measures for 202 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.

INTRODUCTION

In BECA,[1] 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. The data consist of submetered heating energy consumption, inside and outside temperatures, number of occupants, building descriptions, and the associated costs of the conservation measures.

In this paper we compare 215 buildings--276 units in total--on the basis of annual energy savings and cost of conservation, and present the heating loads compared with simulations, current building practice, and the national building stock. This paper is a summary of the current BECA-A analysis. For a more detailed analysis and building descriptions see Ribot, Rosenfeld, Flouquet, and Lührsen, April 1983.

DEFINITIONS

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[1] 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

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 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. Since 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).

ENVELOPE PERFORMANCE: METHODOLOGY

To compare the energy performance of different buildings we normalize for differences in thermostat settings and, where possible, internal gains. A description of the latter is beyond the scope of this paper (see Ribot, Rosenfeld, Flouquet and Lührsen, April 1983). In this section we present the method for correcting indoor thermostat settings to a standard $20^{o}C$ 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 $20^{o}C$ 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, the basic equation for the heat balance across a building envelope is

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

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 outside 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:

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

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, Θ, is

defined as:

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

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

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

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 $T_{in} = 20^{\circ}C$), 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 $T_{in} = 20^{\circ}C$) (Ribot, Ingersoll and Rosenfeld, June 1982). In this approximation procedure we use a degree day ratio to extrapolate to annual performance

and normalize indoor temperature.

RESULTS

Using the methodology outlined above, we calculated adjusted annual heating load, AQ, for each building. In Fig. 1 we show the thermal performance of the buildings on a degree day scale. We also present an economic analysis based on AQ and added cost of conservation, illustrated in Fig. 2.

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). The current building practice curve is based on the National Association of Home Builders (NAHB) home builders survey (Ingersoll, 1981), and is discussed below.

A summary of the data in Fig. 1. is presented in Table 1. 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 kJ/m^2DDC, followed by passive solar, TI = 36, and then earth sheltered homes, TI = 50.[2] 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, 27 Saskatoon homes, TI = 39, and the one Pasqua 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 subgroups into our data base (further discussion of the breakdown of the MHFA homes will be found below. 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.

In table 1 we also compare the homes with 1) the Building Energy Performance Guidelines (BEPG, 1981) for residential buildings,[3] 2) new building practice (NAHB, 1979) (Ingersoll, 1981), and 3) the national building stock (NIECS, 1980). The BEPG and NAHB curves were calculated using 20°C thermostat setting and U.S. average internal gains (Ingersoll et al., forthcoming). Note that the NAHB curve is derived from simulations based on survey data that only included NAHB builders; average U.S. building practice may, therefore, be different. We find the mean

[2] $1 Btu/ft^2DDF = 20.4\ kJ/m^2DDC$

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

thermal integrity of our energy-efficient homes is less than one-third of the U.S. stock and about one-half of the NAHB new building practice. This points to a tremendous potential for conservation. Note that TI is merely a measure of thermal performance and is not the sole basis for comparing houses.

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 2 shows annual energy savings as a function of the added cost of conservation for the 202 buildings for which we have cost data. Annual energy savings is the difference between the NAHB "new building practice" line (see figure 1) and the thermal intensity of each home.

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 measure is cost-effective if the data point lies above the purchased energy line.

Figure 2 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"). 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. 2 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.

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, 202 had data on additional first cost. We have compared the homes by building type, heating performance, and added cost for conservation and solar measures.

Table 1 summarizes our findings on thermal performance. In Table 1 we compare our 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^2DDC [8.9 Btu/ft^2DDF] and current practice is 100 [5.0], solar and conservation buildings average 52 [2.5], with superinsulated homes at 32 [1.6].

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.

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Table 1. 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^2DDC	Btu/ft^2DDF
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]
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.

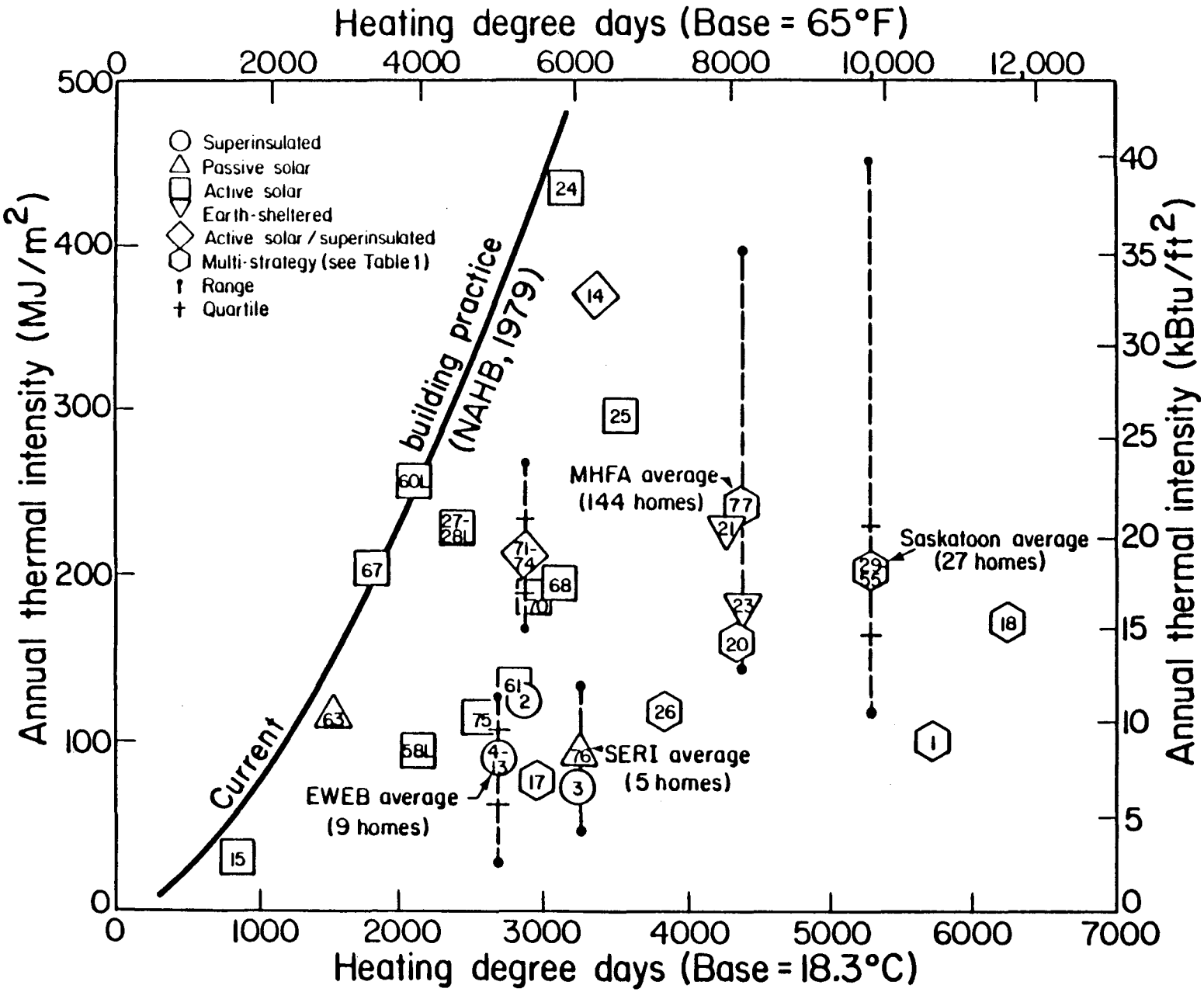

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Figure 1. Scatter plot of annual heating load/m^2 vs. climate for 27 points representing 215 submetered energy-efficient new buildings. The solid curve is NAHB based 1979 survey of U.S. building practice, described in text.

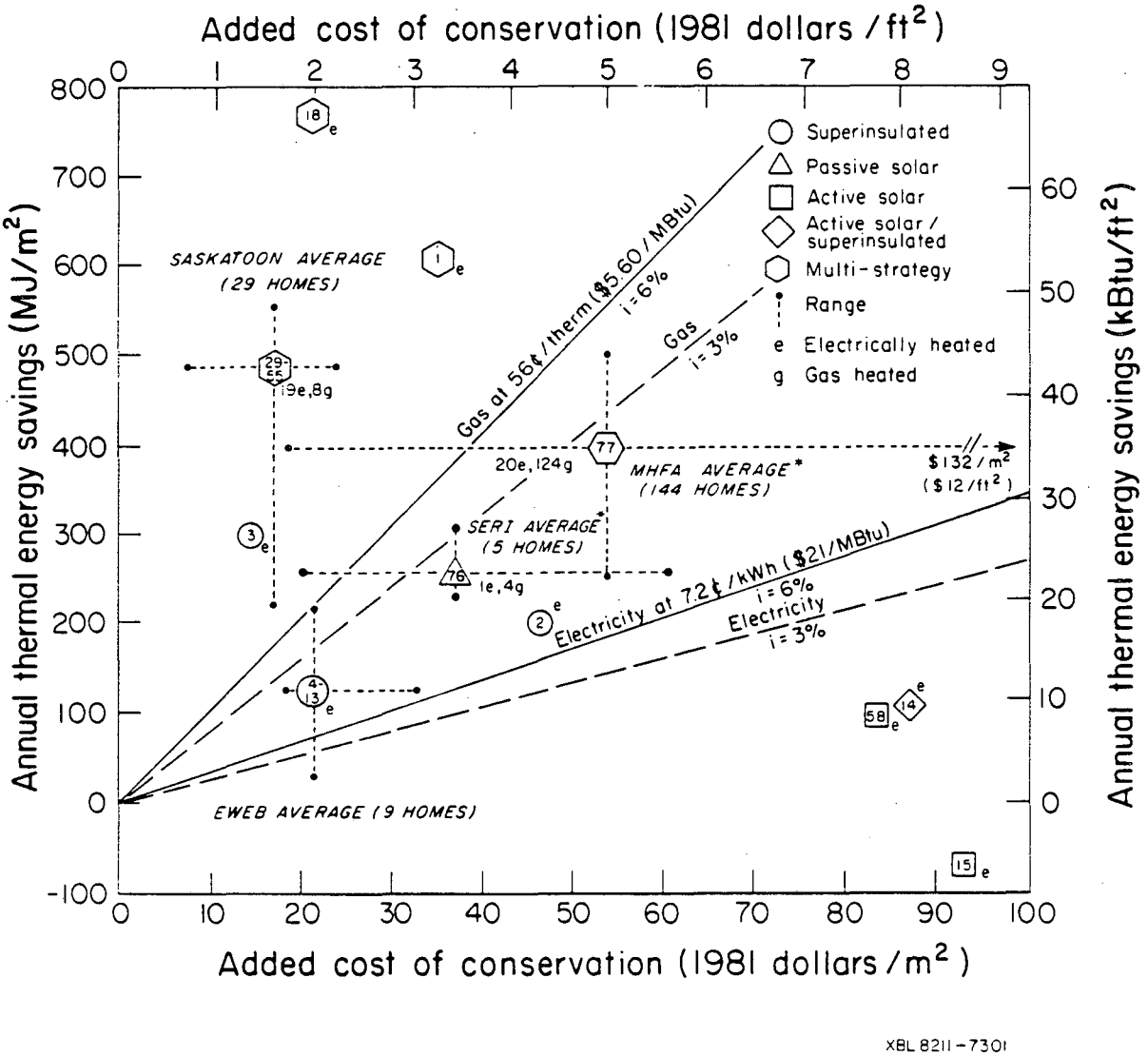

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Figure 2. Two-hundred-two building scatter plot of annual energy savings vs. added first cost of conservation and solar features. The energy savings represent the difference between the home's annual thermal intensity and the current building practice line of Fig. 1 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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