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BUILDING ENERGY USE COMPILATION AND ANALYSIS (BECA) AN INTERNATIONAL COMPARISON AND CRITICAL REVIEW. PART A: NEW RESIDENTIAL BUILDINGS

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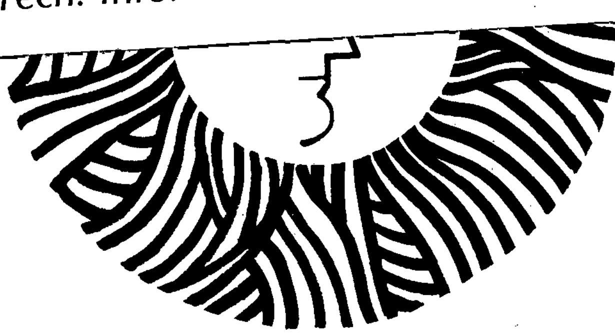

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Building Energy Use Compilation and Analysis (BECA)
An International Comparison and Critical Review

PART A: NEW RESIDENTIAL BUILDINGS*

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*In preparation also are Part B: Residential Retrofit and Part C: Commercial Buildings.

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ABSTRACT

The potential for energy conservation in space heating of new residential buildings is characterized using results from computer analysis, and from a survey of low-energy houses. Simulations of the energy requirements of a prototypical house in the United States at different levels of conservation have shown that much higher levels of conservation than those presently employed in new houses result in minimum life-cycle cost. Measurements taken in actual houses indicate that very low space heating energy requirements -- comparable to that now used for domestic water heating -- can be achieved in new houses by attention to insulation, infiltration, and solar-design principles. We conclude that building standards should be made more stringent to hasten the adoption of cost-effective conservation measures.

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I. INTRODUCTION

The construction of a new building commits society to a long-term expenditure of energy resources. Unlike an inefficient stock of automobiles or appliances, which can be replaced relatively quickly, buildings continue to consume energy for decades after their construction. "Retrofitting" what the original builder neglected is possible, but in the long run it is easier and cheaper to construct a building with an eye toward its future energy requirements.

In the United States, new housing is being added to the stock at a rate of some two million units per year. The growth rate of new housing in Europe is lower; in all countries, however, conservation in new buildings represents an important source of energy savings that will continue to yield returns long into the future.

Most countries where space conditioning is a major energy demand have devised regulatory standards to ensure that new buildings meet minimal levels of energy efficiency. In most cases, however, these standards do not approach the technical and economic potential for conservation that both research and practice have shown to exist. To encourage the development of adequate standards and speed the adoption of energy-conserving building practices, it is imperative that reliable information on actual energy consumption in buildings be available.

In this paper we present findings from our initial efforts to systematically collect and analyze data on energy use in residential buildings in North America and Western Europe. Our focus is on space heating, by far the largest energy end use in today's residential buildings. The data presented comprise: 1) Computer simulations of energy use in a prototypical house incorporating differing levels of conservation, 2) Energy consumption of existing housing stock, and 3) Measured energy consumption of houses that exhibit very low energy use. Most of the low-energy houses were constructed by innovative builders operating in the housing market. They are tangible evidence of the extraordinary potential for reducing energy use by intelligent design and careful construction.

Throughout this paper, we present building energy requirements in terms of fuel energy input, which we define as:

$$\text{Fuel energy input} = \frac{\text{House space heat load}}{\text{Heating system efficiency}}$$

Although many new houses are now built with electric heating systems, (including most of the low-energy houses in our sample) the use of this convention facilitates easier comparison of new houses with existing housing stock, which is primarily gas- or oil-heated in both North America (~80%) and Europe (90%+ in most countries).

The design and construction of low energy buildings raises many topics that have not been major concerns in the past. The relationship between building energy conservation and indoor air quality, for example, is one of great importance, and has been given intensive study by

Lawrence Berkeley Laboratory's (LBL) Building Ventilation and Indoor Air Quality group, whose research findings are reported here. Heating and cooling of energy efficient buildings is another field where new ideas are evolving, and we discuss how "free" heating -- the use of solar and internal heat gains -- natural cooling, and appropriate system design can save energy.

Building technology is evolving rapidly in response to rising energy costs. It is anticipated that this survey will be continuously updated as new results become available. New special topics of importance will also be reviewed in each update. Collecting significant amounts of quality data is a difficult task. We invite contributions from all interested parties.

Note: Copies of this paper (text or figures) with English units are available from Lawrence Berkeley Laboratory.

II. COMPUTER SIMULATIONS

Energy Conservation in a Prototypical U.S. House

A simulation of the energy requirements for heating a small (109 m^2) one-story house built with increasing levels of conservation is presented in Figure 1 for nine different climates. The simulations are based on the Hastings ranch-style house, a prototype developed by the National Bureau of Standards for the purpose of analyzing energy conservation measures.[1]

The curves labeled "ASHRAE 90-75" and "HUD-MPS '74", based on runs made with the NBSLD computer program,[2,3] represent the energy use of the Hastings house built to comply with two guidelines formulated in the mid-1970s. The runs used hourly weather tapes for nine U.S. cities representing a range of climatic conditions. The indoor temperature was assumed constant at 20 ^{o}C with no night thermostat setback. In plotting the "ASHRAE" and "HUD" curves, a furnace efficiency of 70% was used.

The three lower curves in Figure 1 are based on results generated by Levine, et al as part of LBL's work on proposed Building Energy Performance Standards (BEPS).[4,5] The LBL analysis, which used the DOE-2 computer program,*[6] assumed a constant indoor temperature of 21 ^{o}C for heating, with no night thermostat setback.** Fuel inputs for heating were calculated assuming a furnace efficiency of 70%, a value corresponding to the seasonal efficiency of furnaces with pilotless ignition, insulated and well-sealed ducts, using outside air for combustion. The basic Hastings house design was slightly modified to provide a window area equal to 15% of the floor area, with the windows equally distributed among all four walls. (This ratio corresponds to national averages; in the unmodified Hastings house, window area is 12% of floor area.) Following local building practice in the cities studied, the house was modeled with either a slab-on-grade foundation, a crawlspace (below an insulated floor), or a full basement. Heat gains to the basement from heating equipment and other appliances were assumed to approximately balance heat losses through the insulated basement walls.

Internal heat gain was modeled with the assumption of 3.2 occupants (the average for single-family dwellings), with appliances corresponding to saturation levels and efficiencies projected for 1981. These internal gains were modeled on an hourly basis, with a total daily contribution of 55.9 MJ, or an average of 650 watts. DOE-2 calculates solar heat gain through the windows and on the walls and roof from data on sun

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*Comparison of DOE-2 results with those from NBSLD shows generally good agreement for conventional buildings in which solar gains are small compared with total heating load.[7]

**The conditions used in the analysis reflect current usage patterns. The standard pertains to the thermal quality of the building and not to occupant behavior; it is recognized that some occupants may set thermostats below this level, further decreasing energy consumption.

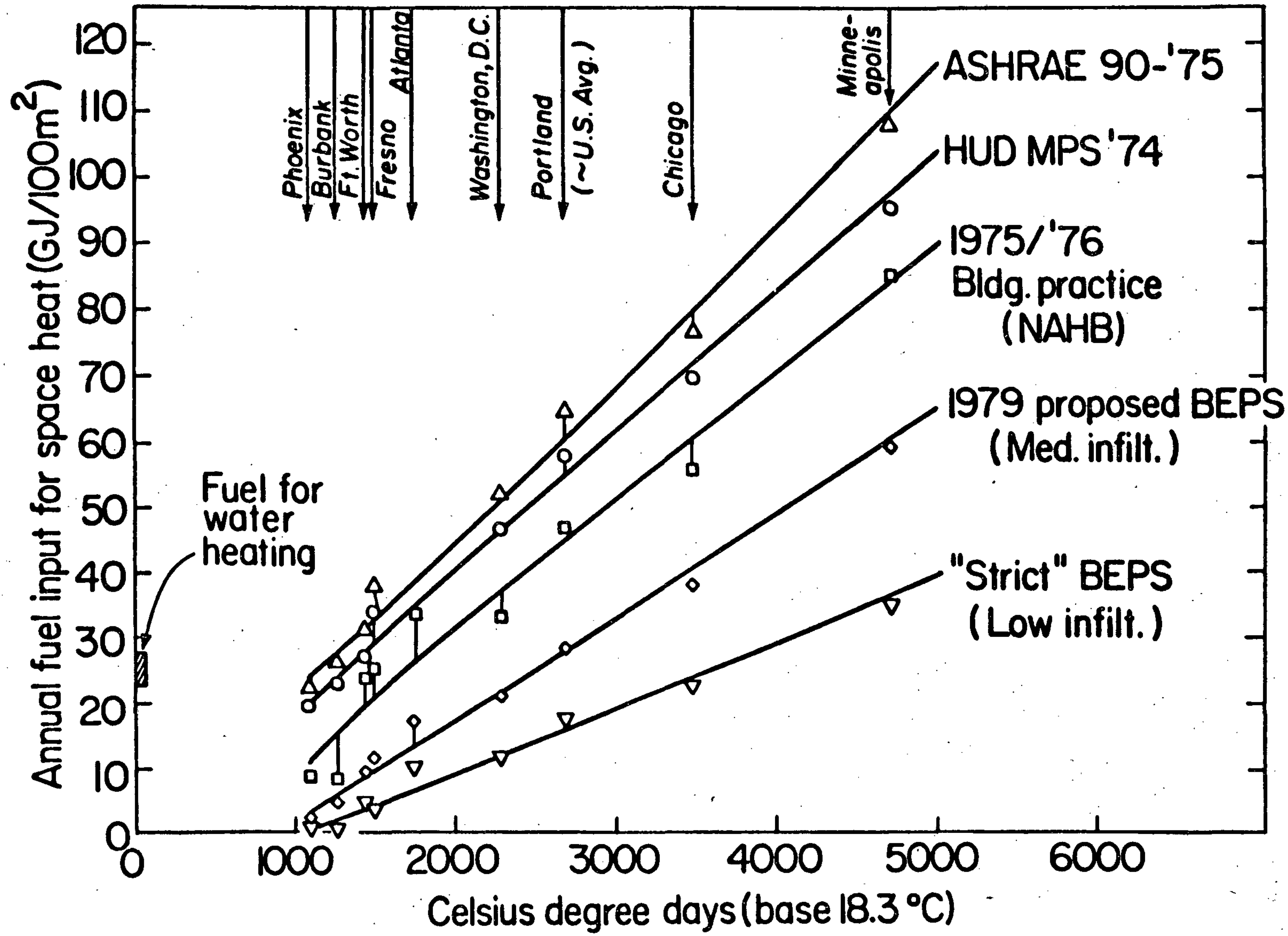

Fig. 1. Annual fuel input for space heat for a one-story house (based on computer simulations for selected U.S. climates) scaled to a floor area of 100 m^2. Note: Population-weighted average U.S. climate has 2646 degree-days; however, weighted for the location of new housing construction, the average is 2333 degree-days. (1 GJ/100 m^2 = 0.88 MBtu/1000 ft^2; 1000 Celsuis degree-days = 1800 Fahrenheit degree-days).

angle, cloud cover, cloud type, and statistical correlations.

The data presented in Figure 1 show how fuel requirements decrease as one adds insulation and extra window glazing layers. The curve labeled "1975/76 Building Practice" represents the Hastings house with insulation and glazing corresponding to average building practice in the respective cities as reported in a 1977 survey by the National Association of Home Builders(NAHB).[8] In most parts of the United States this entails ceiling insulation of R-3.4 (R-19), wall insulation of R-1.9 (R-11), and, in northern climates, double-glazed windows. A more recent survey indicates that many builders have responded to the energy situation by incorporating energy conservation in new construction.[9] From 1976 to 1977 the percentage of new homes with R-2.3-2.5 (R-13-14) in exterior walls increased from 21% to 46%, and houses with ceiling insulation of R-5.3 (R-30) or more rose from 3% to 28%.

The lower two "BEPS" curves in Figure 1 represent the fuel requirements for heating the Hastings house modified by the addition of conservation measures designed to achieve minimum life cycle cost for gas heating. The economic analysis conducted by Levine's group (see Table 1) used a 3% real discount rate and a real gas price escalation rate of 2.8% per year. For a house with electric resistance heating, the equivalent fuel energy input would be somewhat lower since electricity is more expensive and therefore allows cost-effective use of a larger conservation investment.

To arrive at the optimum level of conservation investment, a sequence of discrete R-values for walls, ceilings, and floors was applied, beginning with the most cost-effective items and proceeding to the least cost-effective. Windows with single, double, and triple glazing were considered in similar fashion. During this sequence the infiltration rate was never varied. The optimum level of conservation for each location was chosen as the point in the sequence at which the cost of adding a conservation measure was estimated to be greater than the benefit achieved from reduced fuel costs.*

The curve labeled "1979 proposed BEPS (Med. infilt.)" depicts fuel requirements of the Hastings house assuming an infiltration rate of 0.6 air changes per hour (ach). This "medium" infiltration case corresponds to good construction practice -- tight-fitting windows and doors and normal caulking -- and is consistent with infiltration measurements made by LBL in over 50 houses throughout the U.S.[11] This infiltration rate refers to average conditions of wind and temperature, and corresponds to a rate of about 1 ach under design winter conditions.

The curve labeled "Strict BEPS (Lo infilt.)" shows that reducing natural infiltration to 0.2 ach can greatly reduce energy consumption. The insulation and glazing levels are the same here as in the medium infiltration case for almost all cities. Tightening a house to this level generally involves caulking the sill plates and electrical and

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*For a detailed discussion of the methodology used in the BEPS analysis, see Goldstein, et al.[10]

Table I. Economic assumptions in BEPS analysis

Discount rate (real)[a]	3%/yr
Gas price (1978)[b]	$2.85/Mbtu
Gas price escalation (real)	2.8%/yr
Electricity price (1978)	$0.037/kWh
Electricity escalation (real)	1.5%/yr
Economic lifetime[c]	30 yrs

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[a] In a year with general price inflation of 8%, a 3% real interest rate corresponds to a mortgage at 11% interest, the approximate cost of capital to a consumer buying a new house.

[b] Fuel prices and escalation rates are based on April, 1979 projections of the U.S. Energy Information Administration. The given 1978 gas price corresponds to a price of $3.36/MBtu in 1980 $; the actual Jan. 1980 average price of residential natural gas was $3.55/MBtu.

[c] The lifetime of a typical home mortgage; since many conservation improvements remain effective longer than 30 years, this assumption actually undervalues conservation.

plumbing penetrations to the outside, installing and weatherstripping tight-fitting doors and windows, and attaching a polyethlyene air-vapor barrier to the walls and ceiling. To compensate for this reduction in natural ventilation, additional fresh air is provided by a mechanical ventilation system equipped with an air-to-air heat exchanger, which recovers 75% of the heat from the exhaust air and transfers it to the incoming supply. In the simulations, the air flow provided by the heat exchanger was assumed to be 0.4 ach, producing a total air exchange rate of 0.6 ach under average conditions, but a thermal load equivalent of only 0.3 ach.

Although such low-infiltration construction and the use of heat exchangers are not yet common in U.S. building practice, their effectiveness has been demonstrated under real conditions in severe climates. Many of the houses described in this paper (Section III) have infiltration rates well below 0.2 ach. When a house is this tight it is possible to maintain adequate ventilation with a relatively small heat exchanger. If a house is not tight, on the other hand, the expected energy savings are lost and the heat exchanger is pointless. Residential heat exchangers are widely available in Japan and Europe, and are now entering the North American market.

Costs of Building Improvements

The proposed BEPS yield an average energy savings of 30% to 40% over 1975/76 building practice. The approximate cost of the modifications involved in the shift from 1975/76 practice to BEPS, along with optimum insulation and window glazing levels, are shown in Figure 2 for several locations.* It is interesting to note that the conservation measures that produce minimum life-cycle do not vary greatly across the country. The increased investment for a typical new house to comply with BEPS is about $10.00/m^2. (The BEPS analysis based its cost assumptions for conservation measures on a 1977 study performed by the NAHB Research Foundation.[12] The costs were figured on a national basis, but regional variations are fairly small.) For a Washington, D.C. house built to comply with BEPS, the cost of conserved resource energy (including energy for air conditioning) is about $3/GJ, or $18 per barrel of oil equivalent.**

For low-infiltration houses that employ heat exchangers, space heating fuel consumption can be reduced by an additional 20% to 30% compared with levels (simulated) for 1975/76 new houses. The cost of the low-

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*This paper deals principally with space heating; in determining the conservation option with minimum life-cycle cost, the BEPS analysis also took into account energy used for cooling. When the life-cycle cost analysis is done on the basis of space heating alone, windows in Washington, D.C. are optimized with double rather than triple glazing.

**Cost of conserved energy = Annualized cost of conservation investment/annual energy savings; this calculation assumes a capital recovery rate of 5%/year, corresponding to a 3%/year real interest rate and a 30-year lifetime for the building improvements.

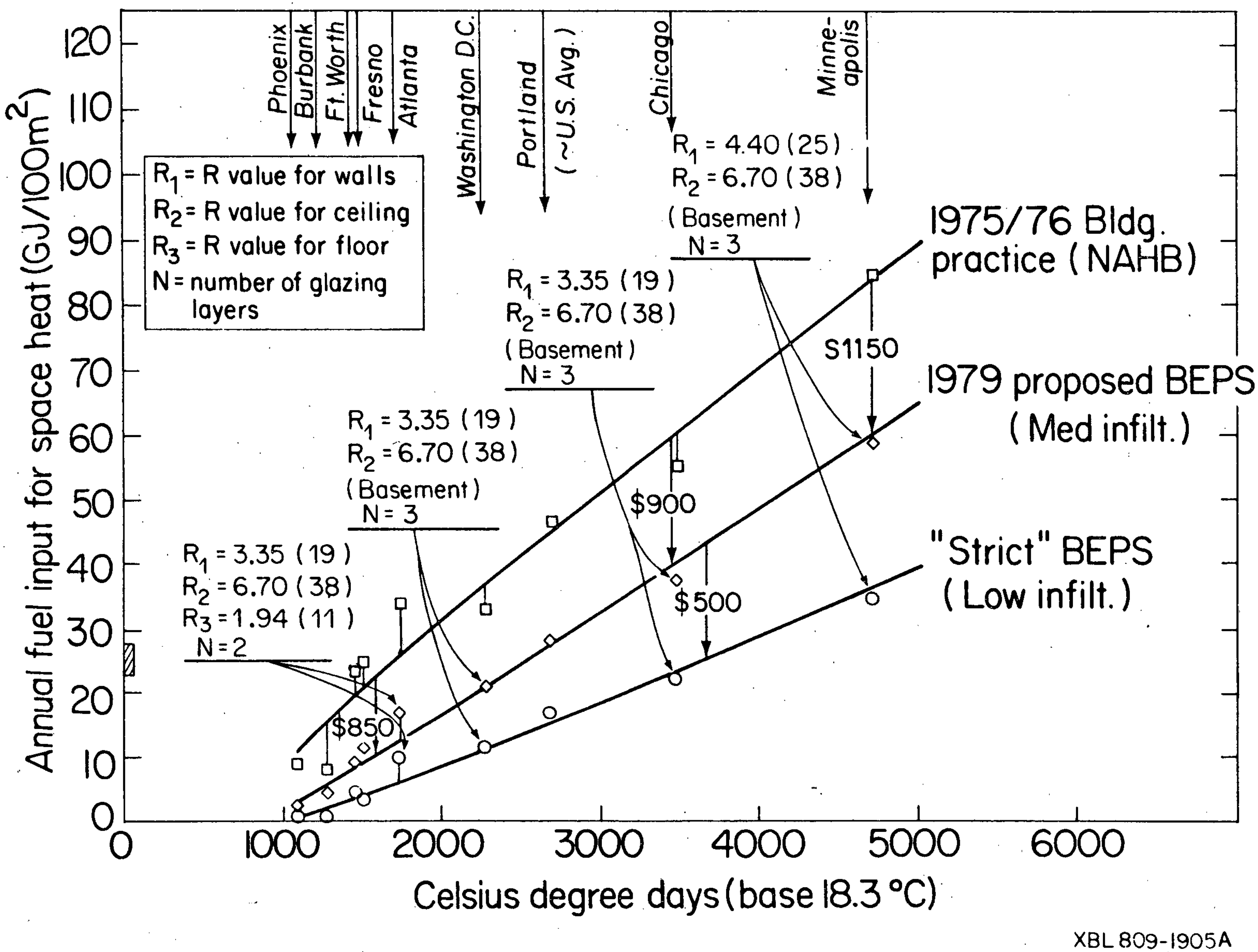

Fig. 2. Insulation and glazing levels for minimum life-cycle cost for gas heating, along with cost in 1978 \$ to upgrade a small new house from 1975/76 building practice to BEPS optima. R-values for insulation are given in m^2-°C/W, with equivalent English units in parentheses. Where a basement is present, no floor insulation was used.

infiltration measures used in the BEPS analysis was $200 for small houses, with another $300 added for an air-to-air heat exchanger. Residential heat exchangers currently range in price from $200 - $1000, but as their use increases, they should cost about as much or slightly less than a large window air conditioner ($150-$300). More recent estimates of the total initial cost of the low infiltration/ heat exchanger package for new average-size houses range from $700 to $1000. A cost-benefit analysis conducted by Roseme, et al indicates that the use of mechanical ventilation with heat exchangers in tight houses is cost-effective for climates like Minneapolis, Chicago, and Washington, D.C., whether oil, gas, or electric heating is used.[13] In addition, water-permeable air-to-air heat exchangers can produce peak power savings in hot, humid climates, where a large portion of air-conditioning energy is spent for removing water vapor from the air. This kind of operation can reduce peak power needs by about 500 watts, thus saving the utility a capital investment of ~$500 in new electric generating capacity.

III. NORTH AMERICAN HOUSES

Although spot comparisons between energy-use values obtained by computer simulation and those measured in actual buildings have shown good agreement, to validate the potential for energy conservation in new houses demands accurate information on energy use in real buildings. Although many houses have been built that use much less energy than BEPS would require, reliable data on their actual energy consumption are relatively scarce. In this section we present data for some 20 low-energy houses whose energy consumption has been very well or acceptably well validated. These houses (plotted in Figure 3) illustrate that space-heating fuel requirements can be reduced to as low as 25 GJ/100 m^2 even in very cold climates, and still lower -- ~10 GJ/100 m^2 -- in climates close to the U.S. average.* At this level, energy demand for space heating is equivalent to or less than the average energy now used for domestic water heating. Before presenting data on low-energy houses, we consider the energy consumption of the existing housing stock -- a useful yardstick for looking at the magnitude of energy savings possible in new houses.

Existing Housing Stock

United States. Most of the 80 million dwellings in the U.S. were built during an era of cheap energy. It is not surprising, then, that their energy-efficiency is low. The points in Figure 3 labeled "U.S. Stock" illustrate the state of existing housing in the U.S. The points labeled "D" come from Dole,[14] who used 1970 residential gas consumption figures to estimate average space heating demand in nine regions of the United States. Fuel consumption ranges from 300 kJ/m^2-DD in the Mountain region to 490 kJ/m^2-DD in the West South Central region. [Note: 20 kJ/m^2-DD($^\circ$C) is about 1 Btu/ft^2-DD($^\circ$F)]. The other points were derived from the 1978 Gas Househeating Survey of the American Gas Association and depict the average gas consumption per customer for space heating as reported by over 70 utilities. (We assumed an average floor area of 125 m^2 per unit to plot the points, an estimate based on a recent survey conducted for the U.S. Department of Energy).[15] The large scatter in the data is striking. Housing in similar climates appears to use very different amounts of energy for space heating. Taking the average of the 70 points yields a normalized fuel consumption of 300 kJ/m^2-DD, a 15-20% decrease from the 1970 average. (The 1970 and 1978 data include multiple-family dwellings, which comprise about one-fourth of today's U.S. housing stock. The curve would be somewhat higher if only single-family dwellings were plotted).

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*To provide a consistent method for comparing the thermal integrity of houses that use electric heating and those that use fossil fuels, we divide the space heating load of electrically-heated homes by 0.7, the efficiency of a hypothetical gas furnace. The resulting consumption should not be interpreted as the resource energy use, but rather as the fuel input at the house if the heating had been done by the combustion of gas in a relatively efficient furnace.

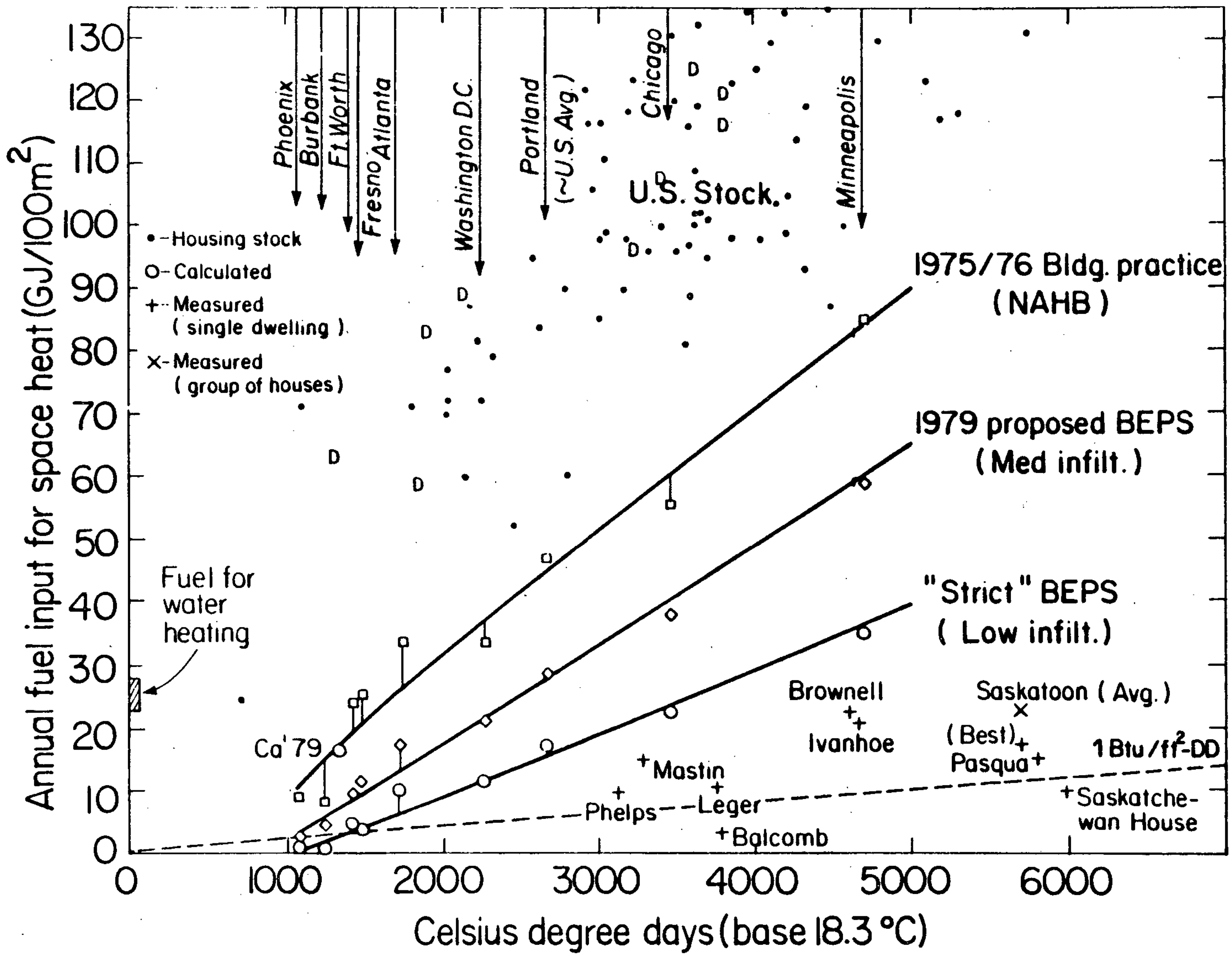

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Fig. 3. Annual fuel input for space heating of low-energy houses compared with existing U.S. housing stock, recent building practice, and proposed standards. Net cost of the conservation features incorporated in these houses ranges from several hundred to several thousand dollars. Note: the points plotted for the Mastin and Brownell houses are estimates based on part-year measurements; the point labelled "(Best)" refers to the house in the Saskatoon group with the lowest energy consumption. (1 GJ/100 m^2 = 0.88 MBtu/1000 ft^2; 1000 ^oC-days = 1800 ^oF-days).

Canada. Canada has far fewer housing units than the United States (~8 million), but the thermal characteristics of Canadian housing are similar to the U.S. stock. Results derived from a report by Scanada Consultants show that fuel requirements for space heating of Canadian houses average about 310 kJ/m^2-DD per unit.*[16] Apartments, which comprise 25% of the Canadian housing stock in Scanada's breakdown, average about 220 kJ/m^2-DD per unit. Thus, the average Canadian energy consumption for all housing units appears to be slightly less than the U.S. average. Energy consumption of Canadian housing also exhibits much less regional variation than U.S. stock. Fuel requirements range from 300 kJ/m^2-DD in Quebec to 360 kJ/m^2-DD in Newfoundland; all other provincial averages are 325 kJ/m^2-DD or below.

New Houses: The Potential for Energy Savings

As evident from Figure 3, U.S. houses built in the mid- to late-1970s ("1975/76 Bldg. practice") are roughly twice as energy-efficient as the existing housing stock. Actual ("Ca '79") and proposed building standards ("BEPS") for new houses represent a three- to four-fold reduction in space heating energy requirements from existing housing stock. The low-energy houses in our sample are well below these levels. The space heating fuel requirements of the low-energy houses fall in the range of 30-45 kJ/m^2-DD, almost an order of magnitude lower than the U.S. stock. Several houses in the sample have space heat loads that reach what can be considered a milestone number for North Americans: 1 Btu/ft^2-DD(^oF)!

A comparison of space heating fuel requirements between a number of actual and simulated houses is given in Table 2. The low-energy houses fall below the BEPS levels (even the low infiltration BEPS curve) for two main reasons. First, the BEPS analysis included only those conservation measures that are now in common use. The highest level considered for attic insulation was R-6.7 (R-30); for the walls, R-4.2 (R-24) insulation was the most stringent measure considered. Second, the window area in the Hastings house used in the BEPS study was distributed equally on all sides, whereas in the low-energy houses it is generally concentrated in the south wall to utilize solar gain and minimize thermal losses through east, west, and north windows.

Physical and heating characteristics of the houses in our sample are given in Appendix B. The low-energy houses encompass two general building styles that have evolved as a response to the energy shortages and higher prices of the 1970s. Two of the houses incorporate traditional passive solar concepts: large areas of south-facing glazing, and thermal storage to retain solar gains and control temperature swings. The other houses also utilize solar gain, but their south-side window area is generally less than 10% of the floor area, and they use little or no extra thermal mass. Instead, they sharply reduce heat loss through the building envelope by heavy insulation and attention to control of

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*We estimate fuel input assuming a heating efficiency of 62%. Average degree-days is 4500(^oC). All figures are approximate.

Table II. Space-heating fuel requirements[a]

	KJ/m^2-DD(°C)	Btu/ft^2-DD(°F)
Surveys and Simulations		
U.S. Stock, 1970 (Dole)	300	15
ASHRAE 90-75[b]	219	10.7
HUD MPS '74[b]	197	9.6
1976/76 Bldg. practice[b]	140	6.8
1979 proposed BEPS[b]	89	4.4
"Strict" BEPS (Lo infilt.)[b]	48	2.3
Measured Houses[c]		
Leger	27	1.3
Phelps	31	1.1
Pasqua	26	1.3
Saskatoon (avg.)	40	2.0
Saskatoon (best)	30	1.4
Balcomb	12	0.7
Saskatchewan	17	0.8
Ivanhoe	44	2.2
Brownell	48	2.4
Mastin	30-59	1.5-3.0

[a] Fuel equivalent, calculated assuming a heating system efficiency of 0.7; except for U.S. stock and Leger house, which are fuel-heated.

[b] Hastings house simulated for Washington, D.C. [2359 DD(°C)]

[c] These are only approximate measures for comparing the thermal integrity of actual houses. Dividing energy consumption by the floor area of the house and the number of degree-days for that area accounts for only two of the variables that affect consumption. Occupant behavior (thermostat setting, etc.) and other climatic factors (solar insolation, wind) strongly affect the energy consumption of a particular house. Also, the floor area to be used is sometimes ambiguous when, for example, a basement or attached greenhouse is present. (Among the measured houses, floor area for Pasqua, Ivanhoe, Mastin, Brownell, and seven of the 11 Saskatoon houses includes basement area; for Balcomb and Mastin, floor area includes an attached greenhouse).

infiltration. These so-called "superinsulated" houses are able to satisfy two-thirds or more of their space heating needs with only solar and internal heat gains even in climates where winter insolation is low.[17]

Although some observers view the two styles as reflecting differing design philosophies*, local climatic conditions help determine the most effective low-energy design for a given place. The Balcomb House,[18] located in sunny New Mexico, has the lowest space heating demand of the houses (less than 10 kJ/m^2-DD) although it is not heavily insulated. Under winter insolation conditions typical of most of the northern U.S., its auxiliary heating requirements would be a good bit higher.

<u>Low-Energy Houses: United States</u>. The prototype for many of the superinsulated low-energy houses built in the U.S. is the Illinois Lo-Cal House design, developed by Schick, et al at the University of Illinois.[19] Suitable in climates of 2500 DD(°C) or more, the Lo-Cal design combines solar orientation with heavy insulation and low infiltration.

Several Lo-Cal houses have been built in the northern United States. The Phelps House in Illinois has verified the energy-efficiency of the Lo-Cal design. From December 1979 to June 1980 it used only 2584 kWh for space heating -- even though the inside temperature was kept around 20 °C. Insulation levels in the 160 m^2 Phelps House are high: R-10.6+ (R-60+) of cellulose in the ceiling, R-7+ (R-40+) in the walls, and R-5.6 (R-32) over a vented crawl space. The "double-framed" wall construction,* a key feature of the Lo-Cal design, provides a large cavity for continuous blowing of cellulose insulation down from the top of the wall. The staggered-stud construction used for the double wall also eliminates heat conduction at the wood framing. South-facing window area is only 4.2 m^2, or 38% of the total window area -- all of which is triple-glazed. The north side of the house is buffered by an unheated garage. A polyethylene vapor barrier installed on the room side of the inner wall prevents migration of internally-generated moisture into the insulation while also retarding infiltration. Conventional procedures and materials were used in construction of the house.

The Leger House located in northern Massachusetts, is also based on the Lo-Cal design, but incorporates several variations.[20] Insulation is provided at difficult places -- headers, sills, foundation walls -- and styrofoam is used in place of plywood as a sheathing material. Care was taken to make the house as air-tight as possible. Other than doors and

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*Passive solar homes featuring large amounts of glass area for solar energy collection have greater interaction with the surrounding environment. Unlike many passive solar homes, the appearance of superinsulated (or "micro-energy", as some prefer) houses is conventional, a point some credit to their favor.

*The outside wall consists of two separate 4 cm x 8.3 cm (2 in. by 4 in.) wood frames, set 61 cm (24 in.) on center. The gap between them is 8.9 cm (3.5 in.) in the Phelps House, less in other Lo-Cal houses, depending on the amount of insulation desired.

windows, there is only one penetration (a bathroom vent) in the polyethylene vapor barrier. Openings into the outer wall for electrical wiring and plumbing were also avoided. Although no special attention was given to installation of the vapor barrier, air leakage measured under 50 pascals pressure was only 2 ach.* A small Mitsubishi air-to-air heat exchanger is used to provide ventilation.

The Ivanhoe House in Minnesota is an early example of the solar/superinsulated (or "tight solar") approach.[21] The house is very tight: measured infiltration at 50 pascals is only 1.8 ach.[22] A heat-pipe heat exchanger provides additional ventilation. Thermal resistance is provided by R-10.6 (R-60) cellulose insulation in the ceiling, R-5.3 (R-30) fiberglass in the walls (above grade), and R-1.4 (R-8) on the slab below the basement. Half of the house's 16.7 m^2 window area faces south. These windows are double-glazed with an insulating Venetian shade between the panes.

In the Brownell House, located in upper New York State, high thermal integrity has been achieved with a different technique: a continuous insulation envelope made of 10.2 cm of high quality polyisocyanurate rigid foam insulation. A vapor barrier reduces infiltration to about 0.15 ach. South-facing glass area (23.2 m^2) is 11% of the floor area -- somewhat more than in typical superinsulated designs. The fuel input indicated for the Brownell House in Figure 3 is based on calculations whose general accuracy has been validated by Brookhaven National Laboratory measurements.[23]

The Mastin House of Rhode Island and the Balcomb House are more typical of passive solar design. The Mastin House incorporates a large area of south-facing glass (48.3 m^2) into a unique double envelope design. A 20-cm continuous airspace separates the outer north wall and roof from an inner wall. Both inner and outer walls are insulated. Air warmed in an integral south-side greenhouse is free to circulate in a convective loop up to the attic, between the two shells, and then down to a sub-basement space. The effectiveness of this design in actual operation is uncertain. Infiltration and transmission through the double envelope are certainly low, but the additional wall may not be the most cost-effective method of achieving this result. Still, preliminary results from Brookhaven monitoring indicate that the house needs little auxiliary heat to maintain a comfortable temperature. The point plotted for the Mastin House in Figure 3 is the median of a range of values measured under varying conditions of solar insolation. Other houses built on the double envelope concept reportedly have smaller auxiliary heating requirements.

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* It is difficult to make a direct correlation between infiltration measured at 50 pascals pressure and natural infiltration, because the two pressure regimes produce different air flow characteristics. In tight houses, a rough estimate of natural infiltration can be made by dividing the infiltration rate at 50 pascals by a factor of 20.

The Balcomb House is a highly successful example of New Mexico solar architecture. It uses an adobe mass wall to store heat collected in a solar greenhouse. The useful solar heat averaged over the heating season is 301 MJ/day, corresponding to 88% of the net space-heating load. A fan-forced rock storage bed located below the floor slab has also been shown to be an important element of its thermal system. Infiltration losses are estimated at 0.33 ach.

Low-Energy Houses: Canada. Up to 200 superinsulated low-energy houses have been built across Canada.[24] The forerunner of these efforts is the Saskatchewan Conservation House.[25] Constructed in 1977 in Regina, Saskatchewan, the Saskatchewan Conservation House was designed by University of Saskatchewan researchers as a demonstration of low-energy building principles. In this extremely cold climate (6000 DD[^{o}C]), the net space heating load for the 188 m^2 house was calculated from measured data to be only 13.2 GJ. Its 30 cm double wall of 5 x 15 cm ("2 by 6") studs is filled with fiberglass insulation to provide a thermal resistance of R-7.3 (R-40); the ceiling, insulated with cellulose fiber, has an effective thermal resistance of R-10.6 (R-60). A well-sealed and caulked vapor barrier contributes to a very low infiltration rate, measured by tracer gas technique at less than 0.05 ach. An air-to-air heat exchanger incorporating plastic sheeting as the heat transfer surface provides an air exchange rate of up to 0.8 ach.

Several homebuilders in Saskatchewan have transferred the energy-conserving characteristics of this demonstration house to the housing market. Dumont, et al monitored the energy consumption of a number of low-energy houses built in Saskatoon, Saskatchewan.[26] Space-heating energy consumption was not measured directly; rather it was calculated by subtracting the non-heating baseload from total energy consumption. The point labeled "Saskatoon (Avg.)" in Figure 3 represents the mean fuel energy equivalent for 11 of these low-energy houses. The space heating load of these houses, most of which are electrically-heated, falls in the range of 12 to 24 GJ/100 m^2. The energy consumption of four other houses measured even lower, but they supplemented electric heating with an unknown quantity of wood.

Insulation levels in the Saskatoon houses are approximately three times the prevailing local standard: wall insulation ranges from R-5.3 to R-7.9 (R-30 to R-45), ceiling levels from R-8.8 to R-12.3 (R-50 to R-70). All of the 11 houses incorporate a caulked 0.15 mm (6 mil) vapor barrier and an air-to-air heat exchanger. Infiltration at 50 pascals pressure has been measured at a very low 1.0-1.5 ach. Heat exchanger air-flow rates of about 40 liter/sec (80 cfm) are typical. Many of the units release fresh air to the basement and extract house air from the bathroom. In outside temperature conditions of -20 ^{o}C the heat exchanger will raise the temperature of the incoming outside air to about +10 ^{o}C. South window area is generally equal to about 6% of the total floor area, which includes a basement in many cases. Some of the houses incorporate thermal storage components such as a small Trombe wall.

The Pasqua House is one of 15 low-energy houses built by a private firm in Regina, Saskatchewan.[27] Like the Saskatchewan Conservation House, it has a 30-cm thick double-frame wall with an insulation value of R-7 (R-40). Windows are sealed thermal-pane units with thermal shutter systems over all windows. With a polyethylene vapor barrier and the special procedures used to seal doors, windows, electric boxes, floor headers, etc., the natural infiltration rate is reduced to about 0.13 ach. Containerized water is situated in a remote insulated room for thermal storage. Although not carefully analyzed, the Pasqua House appears to need no auxiliary heating until outdoor temperatures drop below -5 to -10 ^{o}C under conditions of bright sunshine, and below 0 to 5 ^{o}C under cloudy conditions.

Cost of Achieving Low-Energy Performance

Comparing the cost of low-energy houses to a conventional house is difficult, because building a low-energy house is not simply a matter of adding insulation, window glazing, or a solar greenhouse to a conventional design. Costs also depend on particular design features that may not be strictly related to energy-efficiency. It appears, however, that houses with very low energy requirements <u>can be</u> built at a cost that approaches that of conventional construction, as long as heat losses are so low that a furnace and central air distribution system are not required. Many low-energy houses use baseboard heaters and/or a wood stove for their total space heating needs. The savings gained from this step can be subtracted from the additional investment in insulation, glazing, or thermal mass to yield a corrected net cost. For the Leger House, for example, which had a fuel heating cost of only $40 in 1979, the net cost for conservation features was less than $1000, and perhaps much lower. Other practitioners estimate that low-energy features add from $1500 to $5000 to the cost of an average size new house. Even at the high end of the range, the low -energy investment is marginally attractive: for one of the Saskatchewan houses, the added construction cost for conservation is 7% to 8%, which translates to a cost of conserved electricity of about $0.06/kWh -- below the marginal cost of electricity in many places (this assumes a 5%/year capital recovery rate spread over 30 years, with a house built to prevailing standards as the base case). For other low-energy houses, the cost of conservation appears to be competitive with average prices of fuel and electricity.

IV. EUROPEAN HOUSES

In this section we present data on energy use for space heating in housing stock and individual houses in several Western European countries, as well as a comparison of regulations for thermal insulation in new housing.

When contrasting North American and European demand for space heat, it is important to consider factors unique to the European setting. Central heating of single-family dwellings, for example, is close to saturation only in the U.S., Canada, and Sweden. Room heaters are still common in the United Kingdom (~45% of dwellings as of 1977), Germany (39% of dwellings as of 1976), and France (45% of dwellings as of 1975). Even when comparing centrally heated dwellings, economic factors vary greatly. Natural gas, historically inexpensive only in Canada and the U.S., has fallen in cost in the U.K., but heating habits continue to be more spartan there than in North America. Milbank reports that the average winter indoor temperature (all rooms) in British homes is only about 12 °C.*

As fuel price differ between North America and Europe, so do the costs of conservation measures. The German Ministry for Buildings and Land Planning quotes a 1976/77 price of 75 DM (about $35 at the time) for 100 mm of mineral wool, roughly three times the cost of insulation with an equivalent R-value in California. As a result, California building standards require higher R-values than those in most of West Germany -- even though German winters are more severe.

Contrasts: France and Sweden

Housing stock. A major effort to collect and analyze data on residential energy use in Western Europe is presently underway at LBL (see Schipper and Ketoff).[28] In Figure 4 we present data on space-heating energy consumption in two countries with very different energy-use patterns -- France and Sweden -- along with familiar U.S. curves. The point labeled "Fr '77" depicts the average fuel consumption of centrally heated French housing stock. If apartments are included, the average consumption drops by about 25%, which brings it to the approximate level of the U.S. stock. Swedish housing stock ("Sw '77"), almost all of which is all of which is centrally heated, is considerably more efficient.

*In areas where indoor temperatures are kept low, improving the thermal integrity of the dwelling allows a more comfortable indoor temperature and/or the heating of more rooms. Such houses often achieve only half of the predicted fuel savings, but the amenity gain is also a tangible benefit.

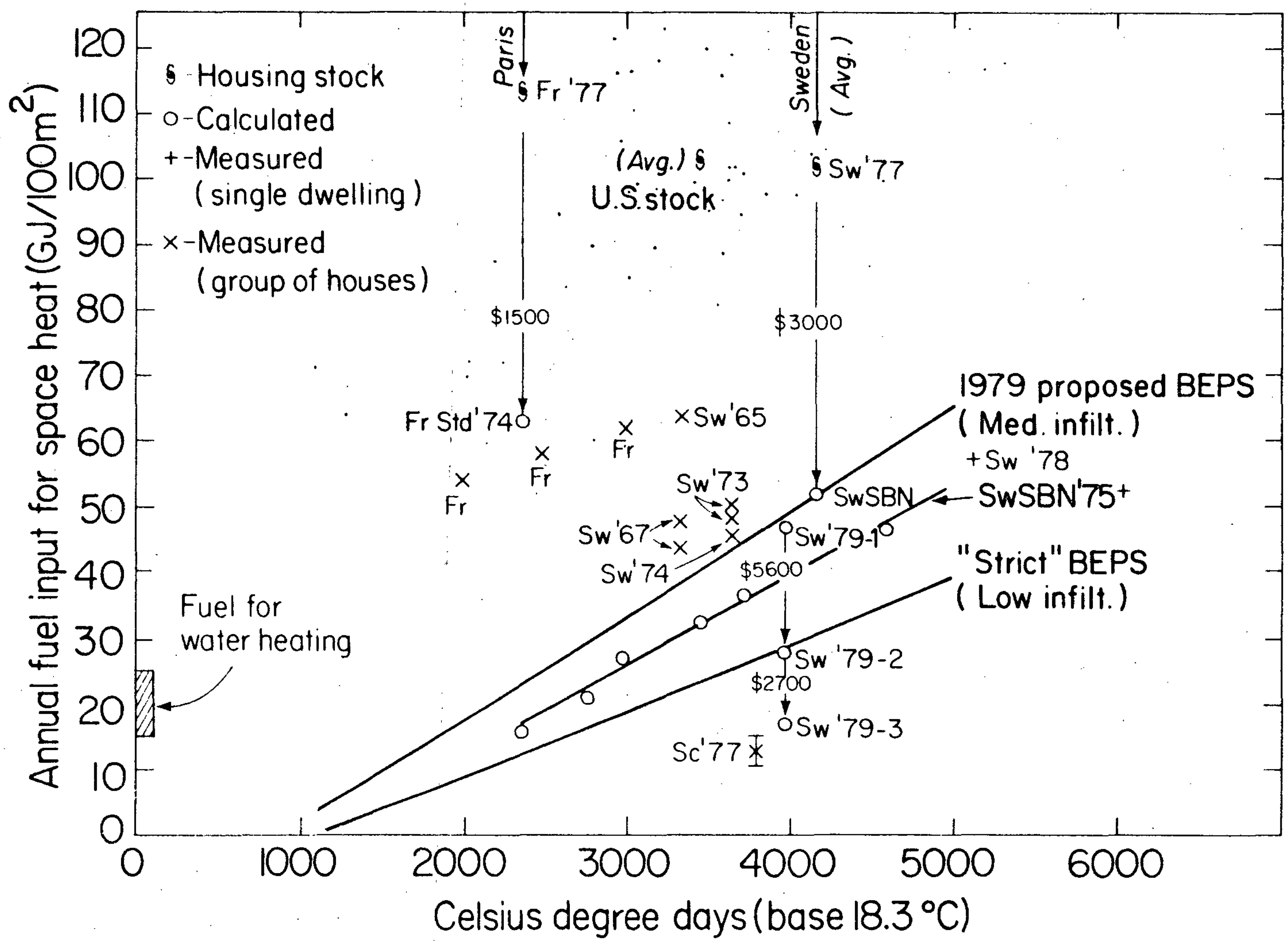

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Fig. 4. Annual fuel input for space heating for European houses. Shown are French and Swedish centrally-heated housing stock (Fr '77 and Sw '77), calculated points for French and Swedish standards (Fr Std '74 and Sw SBN), and groups of measured houses in France (Fr), Sweden (Sw), and Scotland (Sc). U.S. stock and proposed standards are shown for comparison.

Building standards. The 1974 French building norm for detached houses ("Fr Std '74") represents a considerable improvement over the French stock. The 1974 standard requires an average cost per dwelling of about $1500 -- a 3% increase in initial cost from early 1970s construction practice. The 1975 Swedish Building Norm ("Sw SBN") is comparable to the proposed U.S. Building Energy Performance Standards, and is substantially tighter than the French standard. The average additional cost to build according to SBN '75 is approximately $3000.

The curve labeled "Sw SBN '75+" shows the results of a computer simulation of a 150 m^2 two-story house constructed to comply with the 1975 Swedish standard.[29] The same house was modeled in four European and three U.S. cities with the inside temperature maintained at 20 C. In all cases, solar gain through windows was included and insulating shutters of R-0.67 (R-3.8) were used at night. As a result, the fuel consumption in this simulation is slightly lower than the calculated point for SBN '75, which does not assume insulating shutters.

Measured houses. Swedish building practice was relatively energy-efficient even before the rise in oil prices. Test results from large groups of single-family-detached ,electrically-heated homes ("Sw '65, 67, 73, 74") suggest that many new houses were near the 1975 SBN from 1967 on (numbers indicate the year of construction). It is interesting to note that the measured fuel consumption of the 1967 houses is very close to the consumption of 1974 post-embargo houses. Test results for an energy-conserving house built in the colder climate of Ostersund ("Sw '78") revealed that fuel consumption was somewhat lower than calculated requirements of a house built to SBN '75.[30]

The fuel consumption for an 8-unit apartment building in Smalands Taberg ("Sw '79-1") constructed according to SBN '75 was calculated to be about 46 GJ/100 m^2. Fuel requirements were then recalculated with better windows and insulation levels slightly higher than those called for by the proposed U.S. BEPS ("Sw '79-2"). A further reduction in space heating fuel input was accomplished with the addition of a greenhouse to take advantage of solar gain ("Sw '79-3").

Olive reports data for over 40 electrically heated houses in France, located in a diversity of French climates. The three points labeled "Fr" in Figure 4 represent the average (fuel equivalent) heating demand for houses in climates with 1750-2250, 2250-2750, and 2750-3250 DD(°C), respectively. The measurement period was the 1971-72 heating season.

As an illustration of how heating practices affect energy use, we present measurements of a group of well-insulated prefabricated houses erected at Kemnay in northeastern Scotland ("Sc '77").[31] Ten of the 18 monitored Kemnay houses, all of which are electrically heated, two-story structures of about 100 m^2, are terraced (row) houses; this feature partially accounts for the low average energy consumption of the group. Test results reported by Milbank and Anderson indicate that space-heating electricity use for one of the detached houses was 4440 kWh -- over 75% higher than the estimated group average.[32]

Windows in the Kemnay houses are only double-glazed and the houses are only reasonably air-tight (0.6-0.9 ach). The low energy consumption for space heating is largely attributable to the use of "zone heating", which conserves energy by heating only the rooms in use. To permit zone heating, the floor between the two stories is insulated. The energy consumed in houses with zone heating is very dependent on the occupants' habits. Records of indoor temperatures in the Kemnay houses show that the average whole-house temperature was very low in most cases, indicating that the occupants took care to heat only those rooms in use.

European Regulations for Insulation

A comparison of regulations for the thermal insulation of residential buildings in the European Economic Community is shown in Figure 5.[33] Unlike the proposed U.S. standard (BEPS), which considers infiltration and solar and internal gains in the calculation of an "energy budget" for the building, most European regulations (as well as the ASHRAE guideline now commonly used in the United States) tend to consider only transmission losses of the building's outer shell. Typically, European countries specify a maximum loss in W/ΔT, per sq. meter of the building's total exterior heat-transfer area [A (tot)], thereby effectively specifying a maximum U-value [$_m$]. France specifies the same maximum load in W/ΔT, but per cubic meter of heated space. France also includes infilration in its building standards (assumed with mchanical ventilation to be one air-change per hour), as does Sweden, which specifies a maximum value for natural infiltration of about 0.3 ach (with additional ventilation provided mechanically).

The maximum mean transmission loss [U_m], averaged over the total exterior heat-transfer area of the building (includng the basement walls and floor if the basement is heated), is shown in Figure 5, plotted aganst the volume-to-surface area ratio of the building. For ease in comparison, the various regulations have been plotted as straight lines. These lines are explained as follows:
Consider a rectangular building with overall dimensions of length L, depth D, and height H. (For the purpose of this comparison we assume that the ceiling is flat and that the ground floor is fully exposed to the outside air). The volume of heated space V is then

$$V = X \times B \times H \text{ (meter}^3) \tag{1}$$

and the total heat-transfer area A(tot) is

$$A(tot) = 2\left[(L \times B) \times H \, (L + B)\right] (m^2) \tag{2}$$

The glazed area is assumed to be a fraction of α of the total floor area A(floor) = n L x B, where n is the number of floors (i.e., n = H/h, where h is the space between floors). The window area is then

$$A \text{ (window)} = \alpha \frac{H}{h} L \times B = \frac{\alpha}{h} V \; (m^2); \tag{3}$$

If U_g is the transmittance of the glazing, and U_{mo} for that of the opaque wall which it replaces, the extra heat loss (glazing minus wall)

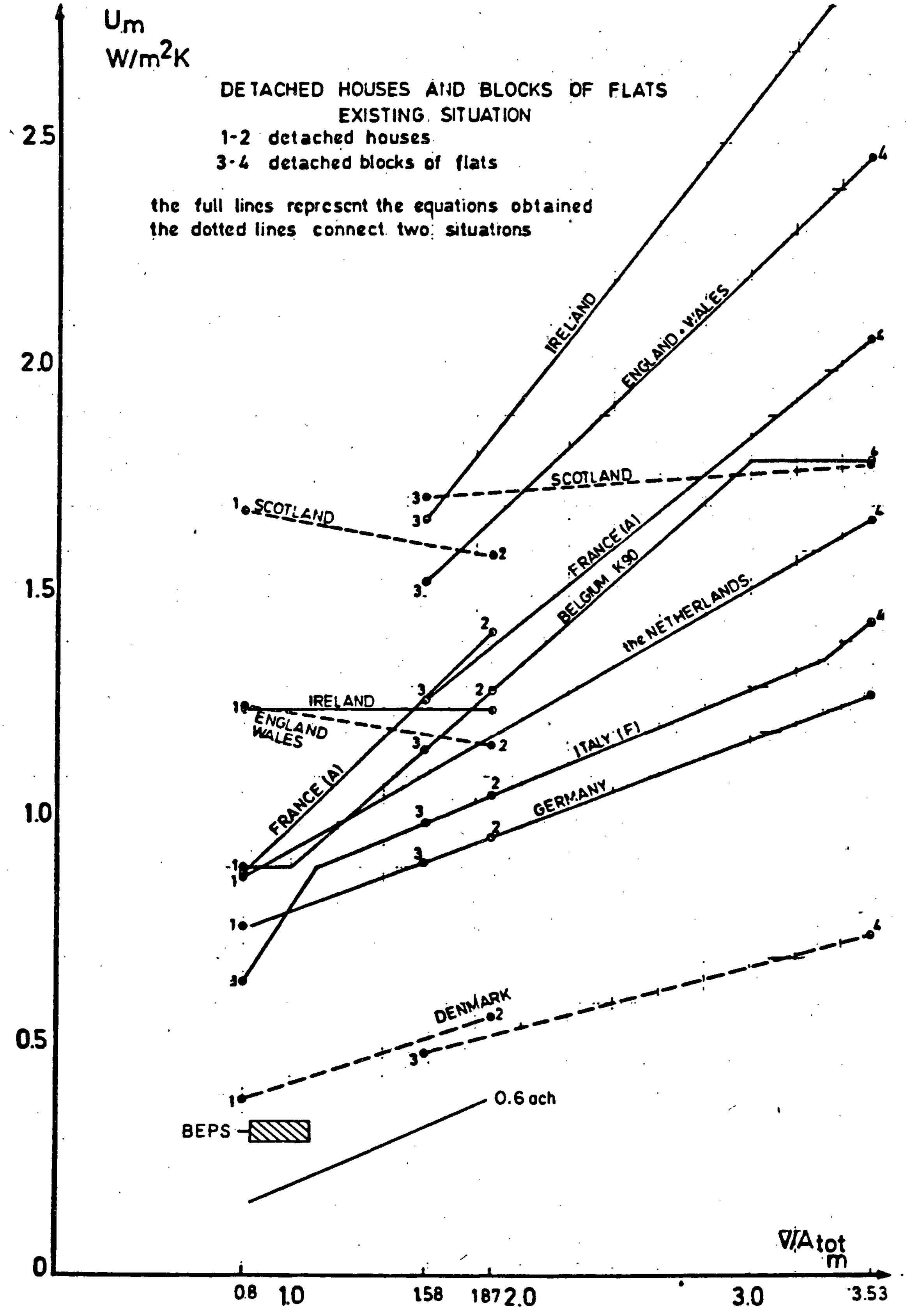

Fig. 5. Requirements for thermal insulation in the European Economic Community. Proposed U.S. standard (BEPS) is also shown along with equivalent heat loss for average infiltration.

is then

$$q \text{ (windows)} = \alpha \frac{H}{h} V (U_g - U_m) \Delta T \quad \text{(watts)} \tag{4}$$

and the effective extra U-value due to windows is

$$U \text{ (windows)} = \alpha \frac{H}{h} (U_g - U_w) \frac{t}{A_{tot}} (W/m^2 k). \tag{5}$$

Note that in a plot of U_m vs. V/A(tot), it is the window term (5), and not the wall term (6), which contributes to the rise in U_m as V/A increases. (Note further that in reality the window area is proportonal to n(B x L), where n is the discrete number of floors, not the smooth quantity n = V/h). The slope with increasing n or V/A arises because the fraction of floorspace [A(floor)/A(tot)] increases linearly with building dimensions. For a single-story detached house, A(floor)/A(tot) approaches n/2. Thus, if windows tend to be a constant fraction α of the floor area, their fraction of the total surface area grows like n or V/A.

The average transmittance for the opaque walls can be expressed as

$$H (L + V) U_w \; U(\text{opaque}) = \frac{(L \times B) (U_c + U_f)}{A_{tot}} \tag{6}$$

wnere U_c = U(ceiling), U_f = U(floor), U_w = U(walls), and U(opaque) = the average over the whole area A(tot). Note that U(opaque) does not depend explicitly on V/A.

To illustrate the importance of infiltration as a contributor to a building's overall heat loss, we express infiltration as an effective transmittance. If ach = the average infiltration in air changes per hour, the thermal load due to infiltration is

$$0.34 \times ach \times V \times \Delta T, \quad \text{(Watts)} \tag{7}$$

and the equivalent U-value is

$$U(\text{infil}) = 0.34 \times ach \times V/A \text{ (tot)} \frac{\text{watts}}{m^2 \; k} \tag{8}$$

We have plotted a sloping line for 0.6 ach, the approximate average infiltration of U.S. houses built in the last five years, which is also the value used in the calculation of the proposed U.S. standard. If the infiltration happed to be 1 ach, the energy used to heat the incoming outside air would be as large as the total heat loss by conduction through walls, ceiling, floors, and windows of a house built to the standards of Denmark.

For comparison with proposed standards in the U.S., we plot the average U-value of a small house built to comply with BEPS. (Although in Figure 5 the V/A for detached houses ranges from 0.8 to 1.87, the single-story Hastings house used in the BEPS analysis has a V/A value of

0.82, and a two-story house with the same floor area has a V/A of only 1.1). We see that the U-values for the proposed U.S. standard are quite stringent -- comparable with that for Denmark -- and well below other EEC standards. The Swedish standard SBN -75 (not plotted in Figure 5) is also comparable with BEPS.

V. ENERGY EFFICIENT BUILDINGS: SPECIAL TOPICS

Indoor Air Quality

Indoor air quality in residential buildings has not been given much attention until recently. Natural ventilation rates (primarily infiltration) of about 0.75 ach and higher apparently have been sufficient to control the build-up of pollutants other than cigarette smoke to below noticable levels.* Since tight construction (and hence reduced natural ventilation) is an important means of conserving energy, the whole matter of indoor air quality becomes more critical.

Concentrations of indoor pollutants such as formaldehyde, carbon monoxide, nitrogen dioxide, and radon may reach undesirable levels in a very tight house. The health effects of this circumstance are uncertain: actual pollutant concentrations in a building depend on the sources of pollution as well as ventilation, and further, the effect of continuous exposure to low levels of indoor pollutants on health is not well understood. The computer simulations quoted in this paper have maintained air exchange rates not less than 0.6 ach, a level comparable to ventilation rates in present housing.

The LBL Building Ventilation and Indoor Quality program is studying the correlation between reduced infiltration and increased indoor concentration of pollutants. Sources of indoor air pollution may vary greatly in strength from one location to the next. The air in a typical home in an area with large radon sources, for example, can easily have a higher radon concentration than a tight home in an area with small sources. Figure 6 is a scatter plot of radon levels vs. natural infiltration rates as measured in 16 houses around the U.S., most of which incorporated specific features to achieve low infiltration rates.[35] Ventilation rates in these houses ranged from 1.05 to 0.04 ach; corresponding radon concentrations were found to range from 0.6 to 22 nCi/m^3.** In one tightly built house, a mechanical ventilation system with an air-to-air heat exchanger was installed. Figure 7 shows how increased ventilation reduced radon daughter concentrations.[36] Only with ventilation

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*Ongoing studies indicate, however, that indoor radon may already cause a significant fraction of the lung cancer rate.[34]

**For those who want to relate 1 nCi/m^3 (nano-Curie per cubic meter) to more familiar units or hazards, we mention the "Working Level" Standard for miners, and the cigarette. One Working Level (WL) is defined as 100 nCi/m^3 of radon (in equilibrium with its first four radioactive daughters); U.S. uranium miners may receive no more than four WL-months/year. At lower levels of 1-10 nCi/m^3, where there are no epidemiological data, we can gain some insight by comparing hypothetical lung cancer rates from radon and from cigarettes; assuming linear dose-response, we then come up with the crude estimate that 1 nCi/m^3 represents a risk of the same order of magnitude as smoking one cigarette/day.

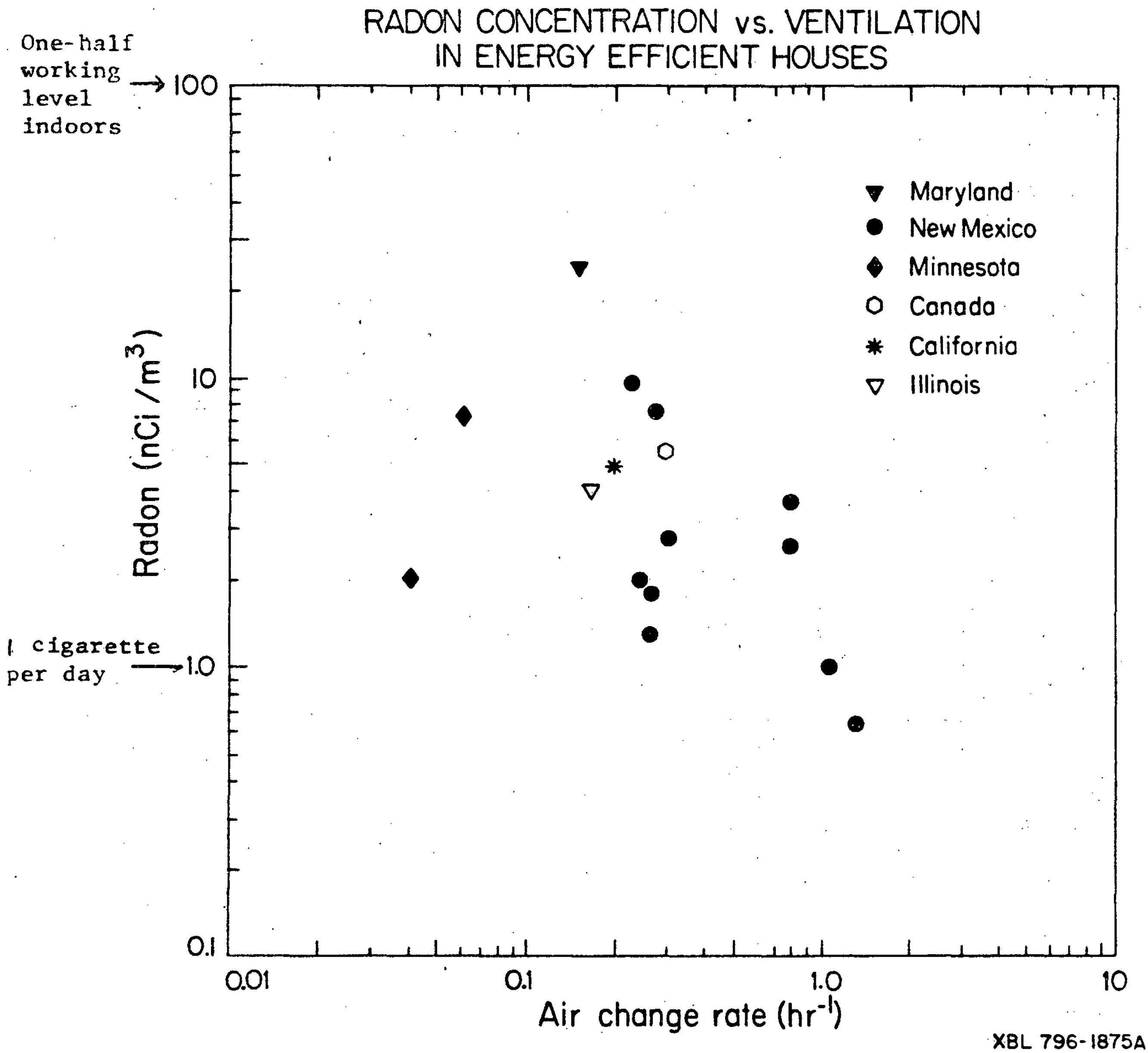

Fig. 6. Radon concentration vs. minimum ventilation in energy-efficient houses. Data were taken over a two-hour morning period in which the house is closed and had been closed overnight (i.e., no open windows, no exhaust fans running, etc.). Hence, they represent minimum air-change rates and maximum concentration of indoor contaminants.

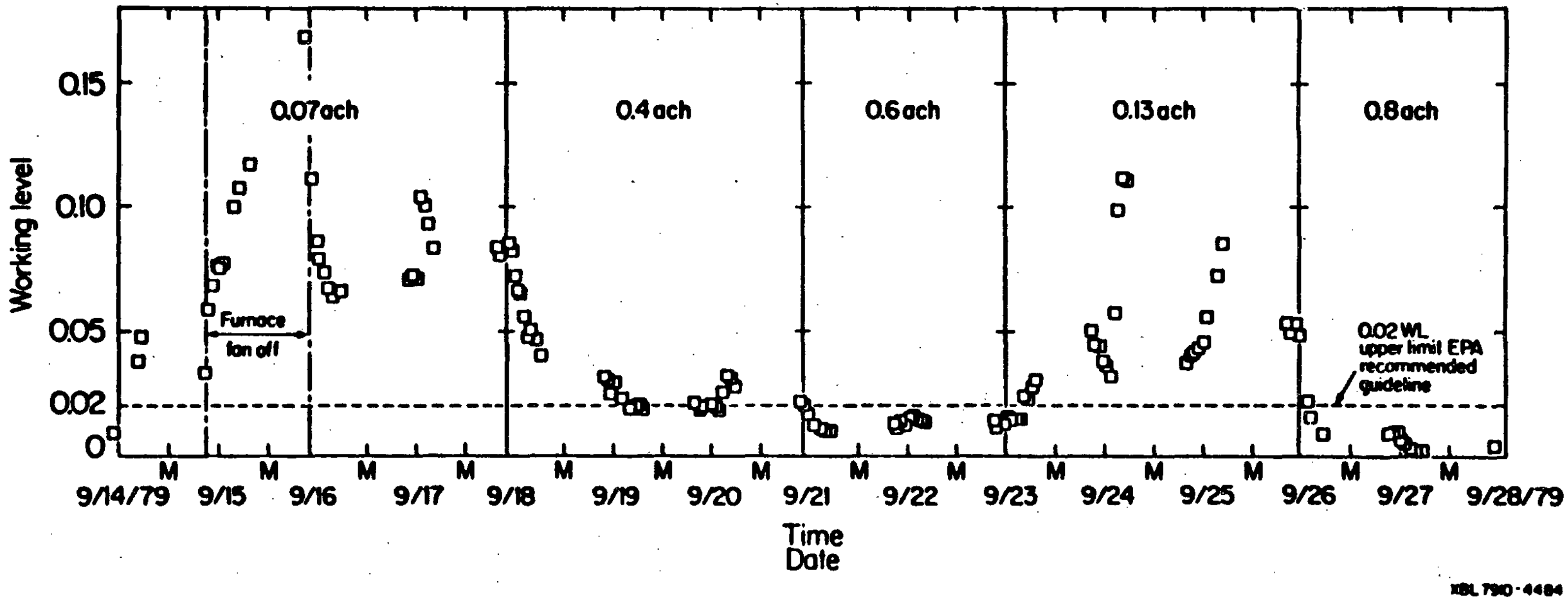

Fig. 7. Radon-daughter working level (WL) in an energy-efficient house, plotted as a function of time for five different ventilation rates. The ventilation conditions were changed every 2-4 days by adjusting the flow through the heat exchanger. The 0.02 WL EPA guideline applies to homes in Florida built on land reclaimed from phosphate mining and high in radium concentration.

rates of 0.6 ach or higher do radon daughter levels drop below the guideline recommended by the Environmental Protection Agency for indoor concentrations for a group of Florida houses built on land reclaimed from phosphate mining. (The house monitored in the study, however, is in an area which appears to have abnormally intense sources of radon).

From preliminary research findings, it appears that properly designed mechanical ventilation systems with air-to-air heat exchangers can maintain acceptable air quality as well as energy efficiency.

System Design for Energy-Efficient Houses

In an energy efficient house, internal and solar heat gains can replace much of the energy conventionally provided by mechanical heating and cooling systems. This changed set of demands has important implications for the design and use of heating, cooling, and ventilation systems.

Free heating and cooling. Degree-days are typically used as a reference for calculating the space-heating load of a building. In theory the degree-day base temperature should equal the "balance point" or "neutral" temperature of the building: the outdoor temperature above which the heating system is not required.* It has long been recognized that the conventional 18.3 °C (65 °F) base is too high for moderately well-insulated houses. Arens and Carroll have shown that using a base of 11.7 °C (53 °F) provides excellent correlation with the simulated (NBSLD) annual heating requirements of the Hastings House designed to meet the ASHRAE 90-75 standard.[37] [R-3.4 (R-19) ceiling insulation, R-1.9 (R-11) wall insulation, and single glazing suffice to meet the standard in an average U.S. climate]. Even with such modest levels of insulation, internal loads and solar gains provide a "free" temperature rise which balances heat losses to maintain a comfortable indoor temperature.

In well-insulated, solar-oriented houses, free heat can maintain indoor comfort when outdoor temperatures are at or even below freezing. Thus, the period when auxiliary heating is necessary is considerably shortened. This characteristic has a negative effect on the economics of active solar space heating, since the active system is required only during those times when it operates least efficiently (when ambient temperatures are very low). The "neutral" temperature and free temperature rise for several low-energy houses are given in the table below.

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*Free heating is a dynamic process and involves daily temperature swings; the "neutral" temperature is an average. The exact value depends on the size of the swing occupants consider acceptable.

"Neutral" Temperature (T_N) and Free Temperature Rise (ΔT_f) - ^oC		
	T_N	ΔT_f
Ivanhoe	0	20
Saskatchewan House	1	20
Pasqua (cloudy)	0-5	15-20
(sunny)	-5 to -10	25-30
Kemnay	10	9.4
Twin Rivers[38]	11	9

It is not the purpose of this paper to make a detailed study of system design and control; however, it is obvious that conventional thermostatic control is inadequate for energy-efficient houses. Heating systems will be operating a smaller percentage of the time, and outside air can be used for cooling for much of the year.

The calculated load characteristics of an energy -efficient house are shown in Figure 8. The calculation assumes that use will be made of passive solar gains through south-facing windows for space heating and that adequate thermal storage is present in the building structure and furniture. An inside temperature float band from 21 ^oC to 26 ^oC has been permitted. Free cooling using outside air operates when the inside temperature is between 24 ^oC and 26 ^oC, with the temperature maintained at 24 ^oC if possible. This so-called "free cooling" is achieved by opening windows and using a "whole-house" fan. The use of such a fan combined with planned window opening can achieve effective cooling even when outdoor temperatures are 28 ^oC.[39] By cooling the structure at night, the thermal mass helps to maintain comfort conditions after outdoor temperature rises to uncomfortable levels. (Of course, when the indoor temperature rises to 26 ^oC or higher, one can close the windows and resort to air conditioning.) Since a whole-house fan uses about one-tenth of the energy of a central air conditioner, significant savings can be achieved in energy for space cooling.

In the particular house analyzed, the heating system will operate when ambient temperatures drop below 10 ^oC, and free cooling with outside air will be used when the ambient is 24 ^oC and below. Mechanical cooling would be used when the outside temperature exceeds 24 ^oC. Using a temperature histogram for central New Jersey, it was determined that the heating system would operate about 3371 hours yearly, or 38% of the year. No mechanical heating or cooling would be required about 45% of the year. The air conditioning system would be operated for 17% of the year. Thermostatic control of a free-cooling outside-air system is obviously an attractive consideration.*

<u>System design</u>. A typical energy-efficient house might have a total design heating load of about 3.5 kW (12,000 Btu/hr), which is comparable to the load of the living room alone in an average house. The fan capacities for a central heating and cooling system can be three to five times smaller than today's conventional installations.

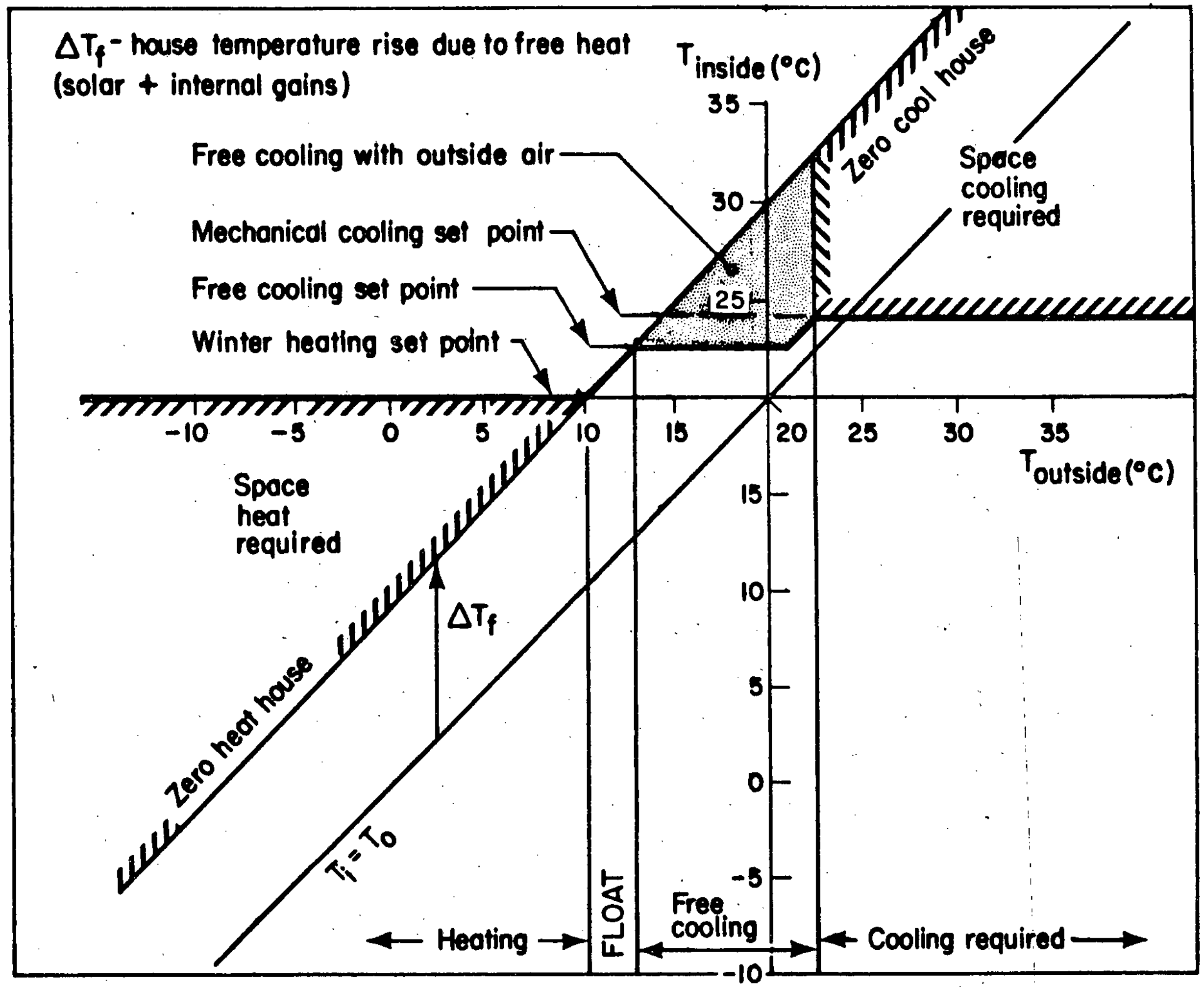

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Fig. 8. A plot of inside temperature versus outside temperature for a representative low energy house. The zero-heat/zero-cool line shows the inside house temperature with the house closed (no windows or doors open) but with the normal internal loads plus solar gains. The regions of space heating, cooling with outside air, and cooling with mechanical refrigeration are shown. The free cooling "set point" can be managed by the occupants' control of open windows or by a whole house fan controlled by a thermostat. The cooling set-point of 23°C might apply to an occupied house in the heating season; however, on a summer night the set point would be lower (≃ 15°C) to store coolth for the next day.

Fan Capacities for an Energy-Efficient Residence (volume 250 m^3)	ach	m^3/hr	cfm
Mechanical ventilation with heat exchanger	0.4	100	60
Furnace (for winter heating)[a]		340	200
Chiller (for summer cooling)[a]		680	400
Whole-house Fan (at maximum setting)[b]	50	10,000	6,000

[a] Two-speed central HVAC fan.
[b] Multispeed fan, e.g., 2000, 4000, 6000 cfm

Since space heating in low-energy houses requires roughly the same amount of energy as domestic water heating, it may be possible to integrate these heating functions into the same appliance. The Leger house, for example, uses the gas water heater to also supply heat to a baseboard radiator. It appears that small, high efficiency furnaces and heat pumps are likely to become integral parts of future HVAC systems.

VI. CONCLUSIONS

1. Computer simulations for a single-family dwelling indicate that, on the average, a 50-60% savings in energy required for space heating can be achieved in new houses by incorporating proven, cost-effective energy-conserving measures. These measures can reduce the fuel required for space heating in new houses to the level now required for domestic hot water.

2. Measured performance of actual energy-efficient houses adds credibility to the computer predictions, and suggests that much greater energy savings can be gained in new houses than result from application of present standards. The fuel requirements of many of the low-energy houses studied are almost ten times less than the average energy use of the existing U.S. housing stock, for example, and are well below proposed U.S. Building Energy Performance Standards.

3. Five cost-effective options that can play a significant role in reducing the energy required for space heating and cooling are:

(a) Reducing transmission losses by better insulation (the only one of the five options that is widely recognized),

(b) Reducing heat losses through windows by using triple glazing, and in some cases, insulating window devices,

(c) Reducing natural infiltration (to about 0.2 ach or less) while maintaining good indoor air quality by supplying mechanical ventilation with an air-to-air heat exchanger,

(d) Reducing energy requirements by making controlled use of free heating (passive solar with thermal storage) and free cooling (whole-house fan),

(e) Reducing energy requirements by improving heating system design as well as efficiency.

The present emphasis of building standards on the reduction of transmission losses takes buildings only about half-way to the potential target of constructing comfortable, unpolluted, energy-efficient houses. It is important that building standards not lag too far behind proven cost-effective technical innovations. For example, reducing infiltration is an important conservation measure, and the intention to include this option in future standards should be announced early to give the building industry time to respond. In addition to supporting continuing studies of energy efficiency in buildings, governments should promulgate long-range target standards to stimulate the production of better materials and equipment. Given a guaranteed future market, industry can be expected to respond with increased research, development, and retooling. Government incentives to the building industry for adopting innovative low-energy features would further speed this process.

VII. ACKNOWLEDGEMENTS

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Appendix A. Window Insulation

In a well-insulated house, effective movable insulation can substantially reduce thermal losses from single- and double-glazed windows.[40] Analysis with DOE-2 indicates, however, that triple glazing without shutters is the most cost-effective window treatment in most parts of the U.S. If windows on all sides are treated equally, computer simulations show that using shutters of R-0.9 (5) at night over double glazing results in slightly higher fuel input than triple glazing alone for Minneapolis, and about the same fuel requirements in Washington, D.C. With shutters at $4/ft^2, this option is $350 more expensive than triple glazing for a house like the Hastings house.

In some locations, however, double-glazing plus window insulation for south-facing windows may be desirable. A definitive comparison of the relative cost-effectiveness of this option and triple glazing for south-facing windows is difficult, since performance and cost of insulating window devices vary widely.[41] Professionally installed shades and shutters may cost $5-$15/ ft^2, while the extra cost of triple glazing is only about $2.50/ft^2. It is possible, however, that window insulation can be used at little or no incremental cost. Thermal draperies, for example, may be no more expensive than ordinary custom draperies. Still, the balance between reducing heat loss and admitting solar energy is delicate, and the preferred design depends on the magnitude of local solar insolation, the time pattern of shutter use, as well as the relative costs of glazing and window insulation.

Table B1. Physical Characteristics

		Leger Mass.	Phelps Illinois	Ivanhoe Minn.	Balcomb New Mex.	Brownell New York	Mastin Rhode Is.	Pasqua Saskatch.	Saskatoon Saskatch.	Sask. House Saskatch.
Floor area	m^2	112	160	166	214	214	242	247	297	187
-No. of storeys		1	1	2	2	1 1/2	2	1 1/2	1	2
-Basement area	m^2	112	0	?	0	?	92	84	yes	0
Glazing area	m^2	14.2	11.2	16.7	53.3	36.0	52.8	18.7		13.8
-South-facing	m^2	9.2	4.2	8.4	37.0	23.2	48.5			11.9
-S. glazing/fl. area		8%	3%	5%	17%	11%	20%			6%
-Glazing layers		3/2	3	3/2	2	2	2	2	3	3/2
-Window insulation		no	no	so.	no	no	no	all	no	all
Insulation										
-Ceiling	m^2-$^oC/W$	7.1	8.8	10.6		6.9	3.4/1.9	9.2	10.6	10.6
-Walls, above grade	m^2-$^oC/W$	7.6	7.1	5.3		6.4	3.4/1.9	7.0	7.0	7.3
-Walls, below grade	m^2-$^oC/W$		1.2	2.8	--		2.2/1.9	1.3-4.8	4.2	--
-Floor	m^2-$^oC/W$		5.3	1.4			1.9	1.8	1.8	5.3
Vapor barrier		yes	yes	yes	yes	yes	no	yes	yes	yes
Infiltration	ach	0.13/2.5		0.12/1.8	0.3	~0.15		0.13		0.05
Heat exchanger		yes	no	yes	no	no	no	yes	yes	yes
Cost of conservation features (net)	$	0-1000	1000-2000	3500		5000-7000		7000-8000	3000-4500	4000

<u>Table Notes:</u>

Floor area -- includes basement for Ivanhoe, Brownell, Mastin, Pasqua, and Saskatoon; includes attached greenhouse for Balcomb and Mastin
Number of storeys -- above grade
Glazing layers -- some houses have double-glazing on south windows and triple-glazing on others
Window insulation -- "so." means used on south windows, "al" means used on all windows
Insulation -- two numbers are given for Mastin, which is a "double envelope" design (inner and outer walls form the shell); the first number refers to the outer wall, the second to the inner wall
Infiltration -- where two numbers are given, the second refers to meassurement at 50 pascals pressure; others are based on tracer gas measurements (Ivanhoe, Saskatchewan) or estimates
Cost of conservation features (net) -- additional cost for conservation features (compared to standard practice) net of avoided costs for HVAC equipment

Table B2. Heating Characteristics

		Leger Mass.	Phelps Illinois	Ivanhoe Minn.	Balcomb New Mex.	Brownell New York	Mastin Rhode Is.	Pasqua Saskatch.	Saskatoon Saskatch.	Sask. House Saskatch.
Degree-days	°C	3760	3100	4665	3795	4610	3300	5810	5700	6000
Insulation (annual,horiz.)	GJ/m^2	4.9	5.4	5.3	7.8	4.6	5.2	5.1	5.1	5.1
Indoor temp-day	°C	18	20	19	18			20		20
Indoor temp-night	°C	16	20	17	18		20	15		
Heating system		baseboard	baseboard	stove/ furnace	stove/ baseboard	stove	baseboard	furnace	furnace	solar
Heating energy (monitored)	GJ	11.5	9.3	~24	2.9/3.7	--	--	25.9	35.9	13.2
- period covered		1/79-12/79	12/79-5/80	10/78-4/79	11/78-4/79	--	--	3/79-2/80	11/79-4/80	10/78-4/79
- fuel		gas	elec	elec	wood/elec	wood	wood/elec	elec	elec	elec
- cost	$	39	130	~270				170		
Annual consumption	GJ	11.5	10.7	24	6.6	33 (est.)	17-33 (est.)	26	35.9	13.2
Consumption index	kJ/m^2°C									
- actual		27.3	21.6	31	8.1	33	21-41	18.0	21.2	11.7
- fuel equiv.		27.3	30.9	44	11.6	48	30-59	25.8	30.3	16.8

Table Notes:

Degree-days -- base 18.3 °C, annual
Insulation -- average from nearest weather station reporting solar insulation
Heating energy -- Consumption for space heating sub-metered for Leger, Phelps, Balcomb, and Pasqua; calculated from monitored operating time of electric furnace for Ivanhoe; calculated by subtracting non-heating load from total electric consumption for Saskatoon; calculated for average year conditions from total electric consumption for Saskatchewan House (with no input from active solar system); for Balcomb, first number is electric, second is delivered heat (est.) from a fireplace and wood stove
Period covered -- inclusive
Annual consumption -- corresponds with monitored consumption for Leger, Ivanhoe, Balcomb, Pasqua, Saskatoon, and Saskatchewan House; estimated from monitored consumption for Phelps; estimated from performance tests by Brookhaven National Laboratory for Brownell and Mastin
Consumption index (fuel equivalent) -- space-heating load/0.7 (hypothetical furnace efficiency), except for Leger, which is fuel-heated

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