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

PART A: SINGLE-FAMILY RESIDENCES

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ABSTRACT

Data on fuel energy used for space heating in single-family residential buildings in the U.S., Canada and Western Europe are compiled, plotted and compared. Three classes of data are presented: (1) calculated data determined by computer simulation or by simplified calculation, (2)

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Part A: Single Family Residences

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INTRODUCTION

This compilation covers three classes of information on single family residences.

(A) Computer Simulations:

The computer simulations are carried out for a selected standard residence in various degree day regions of the United States. Results obtained are: the annual fuel consumption for space heat, and the annual electric consumption for space cooling. The residence is simulated at various levels of insulation and tightness, such as those conforming to current practice, or to various building standards, or to optimized cases. When available, the costs are estimated for moving from the current practice base case to other cases, including the optima. The optimized cases use only building practices which are now available.

The design of houses to take advantage of passive solar heating has not been included in this paper, since these designs are not considered to be common building practice at present. This approach to energy conservation is certainly considered to be very cost effective and a program aimed at providing design information is recommended. The computer simulations did account for solar gains as these affected the energy requirements of the standard house. Also under C below, some of the low energy houses included solar systems, and these systems will be commented on at the appropriate place.

This part of the study, therefore, provides an analysis of energy use for residential heating in various climatic regions (as defined by degree days) for a selected standard small residence. The effects of various insulation and construction standards on the annual heating requirement is shown.

(B) Performance of Current Housing:

This portion of the survey compiles the annual energy consumption for space heating for the general stock of residences in a given country, as well as the consumption for houses built recently according to current practice. This section clearly shows the potential for energy savings through retrofits in existing homes or upgraded construction of new homes. Space heating energy use of actual houses constructed according to current standards may be compared to the computer simulations in order to check on the validity of certain assumptions, as well as to validate the simulated annual consumption from the computer runs.

(C) Performance of Low-Energy Houses:

Many countries and individuals are involved in research programs which are studying the feasibility of special energy conserving ideas. The results of these studies in actual houses provide information about the limits or levels of conservation which are possible with current technology. It is hoped that with documentation and publicity, the most feasible of these new ideas will be quickly accepted by the building industry and then incorporated in national building standards.

Annual Update:

Building technology is evolving rapidly in response to rising energy costs. In the half year during which the material for this paper was assembled, several new homes were conceived and designed. Their projected consumption of energy is very low.

It is anticipated that this survey will be continuously updated as new results become available from various countries. An annual review paper will indicate the progress being made in energy conservation, both with the general housing stock and with new construction. It will then be possible to evaluate the effectiveness of various conservation programs and assist in the development of new incentive programs. This paper provides a format for reporting results on a consistent basis so comparisons can be made.

Forthcoming Compilations: BECA Parts B & C:

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BECA Part B (underway) will cover data and critical reviews of retrofits. BECA Part C will address energy use in commercial buildings.

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II. PRESENTATION OF DATA:

A. COMPUTER SIMULATIONS

Computer simulations of U.S. Houses built according to existing standards as well as the 1980 Building Energy Performance Standards - "BEPS" - are given.

Comparison of 5 Standards and Current Practice (Fig. 1)

Fig. 1 shows the results of six computer simulations on a one-story ranch house having 109m^2 (1176 ft^2) floor area. The house follows the design of S. R. Hastings**1** except for changes as noted.

The curves labelled ASHRAE 90-75 and HUD-MPS.'74 were reported by P.F. Hutchins and E. Hirst**2** based on runs made by S.R. Petersen**3** using the NBSLD program**4**. The indoor temperature was assumed constant at 20^{o}C (68^{o}F) for heating with no night thermostat setback. The runs were made for nine U.S. cities using hourly weather tapes. The cities chosen covered a range of Fahrenheit degree days from 130 to 8316 using traditional 65^{o} base. In all cases oil or gas heat was assumed, and the following relation was applied:

Fuel Energy Input = 1.5 x house space heat load.

This is equivalent to a heating system seasonal efficiency of 67%. In the case of houses with electric resistance heating, the space heat load is nearly equal to the electrical energy input at the house boundary.

In order to be consistent and to hav figures which are directly comparable, the above formula is used for electric resistance heated houses and a sort of equivalent fossil fuel energy input is found. This should not be interpreted as the resource energy used but merely as the fuel input at the house if the heating had been done by the combustion of oil or gas in a system with a seasonal efficiency of 67%. Since the thermal integrity of the house is the principle concern in this paper, the above provides a consistent method for the analysis of houses with electric resistance heating.

The four curves labelled (DOE-2) were based on results generated by Levine et al. **5**, using the DOE-2 program.**7** The indoor temperature was assumed constant at 70°F (21.1°C) for heating, with no night setback, and 78° F (25.6°C) for cooling. The "Hastings Ranch" was slightly modified to provide a window area equal to 15% of the floor area and a full basement was included (rather than the vented crawl space) in those locations where normal construction practice provides a basement. Note that the four curves are merely quadratic fits to heating requirements calculated for 10 cities. The numerical results are given in Ref. **5**, and generally fall within ±10% of these smooth curves.

The curve labelled, "NAHB Current Practice" is based on this same house model constructed and insulated according to NAHB's 1978 established current practice **8** in the respective cities. The curve HUD, MPS '78 is the same house insulated to the levels specified in HUD's 1978 Minimum Property Standards.

The next two curves (labelled OPTIMUM) represent homes designed for minimum life cycle cost, using the economic parameters of Table I. The first curve, labelled "Med. infilt." based the infiltration on the Coblentz-Achenbach equation.**9** Averaged over the nine U.S. cities, this equation gave values of 0.6 air changes per hour (ach) under average conditions of wind and temperature difference, and about one air change per hour under design winter conditions.

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The curve labelled "Lo infilt." represents an energy-equivalent infiltration rate of one-half of the average 0.6 ach just described. This was accomplished by reducing natural infiltration to 0.2 ach by caulking and a continuous vapor barrier and providing fresh air by mechannical ventilation with a heat exchanger. The an air-to-air heat exchanger with an assumed effectiveness of 0.75 provided an air flow of 0.4 air changes per hour, producing a combined total outside air rate of 0.6 air changes per hour under average conditions. This "Lo infilt." conservation option is cost effective above 2200 Celsius (~ 4000^{o} F) degree days under certain assumptions about the cost of the heat exchanger, ductwork and fuel prices.

The low-infiltration/heat-exchanger option is not yet widespread in building practice, but has been proven in actual houses **15** and **16** and is included in this analysis because of its cost effectiveness and the large potential for energy savings.

Costs of Conservation Options (Fig. 2)

The approximate costs of the modifications to move from the current practice curve to the various optimum curves are shown in Fig. 2 for four locations in the United States. The cost data was estimated from reference 10.

Table I summarizes the internal heat gain schedules and economic assumptions which were used. These were specified by the U.S. Department of Energy (DOE) for studies for the 1980 Building Energy Performance Standards (BEPS)**5**.

Table I.

Economic and Energy-Use Assumptions Used in the B.E.P.S. Study**5**.

Interest rates, and fuel price "escalation" rates are in constant dollars, ignoring overall inflation. Thus in a year with 8% inflation, the 3% real interest rate corresponds to a loan at 11% interest.

Economic Assumptions

Real interest rate	3% per year
Gas price (1978)	\$2.85/MBtu [million Btu], i.e. 28.5¢/therm
Gas price escalation	2.9% per year
Electricity price (1978)	\$11.60/MBtu = \$0.04/kWh (enters this discussion for cooling only)
Electricity price escalation	0.7% per year
Economic Lifetime	30 years

Internal Heat Gain Assumptions:

Occupancy: 3.1 persons (average for single-family dwellings)

Appliances: saturations and efficiencies projected to 1981 levels**5**

It is interesting to note, for comparison only, that the fuel used to provide domestic hot water is of the same order of magnitude as that used for space heat in Chicago for the most energy conservative option. This is indicated in Fig. 1.

In order to arrive at the optimum "Med-infilt." curve, a graded sequence of R- values for walls, ceilings, and floors was applied, beginning with the most cost effective items and proceeding to the least cost effective items. Similarly, windows with 1, 2, and 3 glazings were considered. During this sequence, the infiltration formula was never varied. The optimum value was chosen as the point in the sequence which produced the lowest life cycle cost.

Since the low-infiltration/heat-exchanger option departs from current practice, this option was not added until the end, after the high-infiltration optimum was established. The fact that the low infiltration option was treated at the end of the sequence in no way means that it was the least cost effective. The cost of this option, $500-$700, was obtained from reference 15 and Ref. 16. The savings in fuel consumed make this a very cost effective option. Peak power savings are also attractive in hot, humid climates. On a hot, windy afternoon in much of the South and East of the U.S., about one third of the air conditioning capacity is devoted to drying infiltrated air. If a water-permeable heat exchanger is installed, it can be shown **11** to save ~500 Watts of peak electric power. This saves the electric utility a need to invest about $500 in new power plants, and this savings is eventually passed on to the rate-payer, offsetting the initial cost of the low-infiltration/heat-exchanger option. Energy savings are then pure profit for the homeowner.

Optimum Levels of Insulation and Glazing (Fig. 3)

Fig. 3 gives the R-values for the walls, ceilings and floors and the number of glazing layers on windows, all for the optimum medium infiltration case. The costs of all the conservation measures were included in the economic analysis. The R-values shown in Fig. 3 apply to the optimum case when the house is both heated and cooled; i.e., the energy for summer air conditioning is included in the life cycle costing (LCC).

When the LCC is done on the basis of heating only, the optimum values for Minneapolis and Chicago do not change, but for Washington, D.C., the windows are double glazed instead of triple glazed.

Insulating Shades:

Since insulating shades or insulated shutters are available on the market and have been used in some low energy houses, a brief discussion of these follows.

A computer simulation was run on DOE-2 with insulating shades on all windows (window areas equally distributed on four sides). These shades were closed from 11 PM to 7 AM each "winter" night (October through April). These shades were used as additions to the optimum medium infiltration case, which had triple glazing in the colder locations. The savings in annual fuel consumption resulting from the shutters was between 2 and 4 G.J. This saving in fuel could not justify the cost of insulating shades, which was estimated at $4.00 per sq. ft.

On the other hand, if one was designing the house to take advantage of direct solar gain, then double glazing on the south facing windows is desirable instead of triple glazing. Insulating shades or shutters are then cost effective for double glazed windows in both Minneapolis and Chicago. This delicate balance between reducing heat loss and admitting solar energy illustrates the complex economic interactions among various conservation options.

B. NORTH AMERICAN HOUSES (Fig. 4).

Fig. 4 shows measured and calculated fuel consumption of real houses. The optimum curves are replotted from Fig. 1 merely for reference. The curve labelled "U.S. stock 1970" is the result of a comprehensive study by S. H. Dole.**12**

The points labelled NJ (for New Jersey) show the great potential for retrofits as carried out at Twin Rivers by Princeton University. The report by F. W. Sinden**13** shows the energy use for space heating of a townhouse after a retrofit in 1975 and then a "super-retrofit" in 1977. The cost of the retrofit is also shown. The NJ-'73 point indicates the fuel use by the townhouse in its original "as built" condition. For a list of retrofit measures ranked by return on investment, see Ref. **14.**

The rest of the data in Fig. 4 applies to new low-energy houses. At the left, the point labelled CA'77 represents the 1977 California standard for new homes and CA'79 shows the 1979 revision, reducing use of gas to 60% for an added investment of $500**15.** The + labelled MN'78 shows the fuel energy for space heat for the St. Paul, Minnesota, house of D. Robinson.**16** This house is well insulated and sealed and takes advantage of passive solar heating from its south-facing windows. It also makes use of an air-to-air heat exchanger for heat recovery to preheat outside air. This house, MN'78, is close to an economic optimum in its design and is slightly more conservative than the DOE-2 optimum because of the planned use of passive solar heating (Additional south facing window area). The additional costs for energy conserving features beyond the current building practice level in that location were itemized by the owner. These were:

additional insulation	—	$2500
infiltration reduction	--	400
heat exchanger	—	500
assembly and installation	--	<u>200</u>
Total	--	$3600

This total included all materials and labor for th upgrading of this house whih had a floor area of 165 m^2 (1783 $ft.^2$).

The points labelled CAN 79 are from a report by R. S. Dumont, R. W. Besant and G. H. Green,**17** of the University of Saskatchewan, Canada. A one-story bungalow of 100 m^2 floor area and a window area equal to 15% of the floor area was used in the calculations. The base case CAN'79 had insulation levels as required by the current Canadian standard of 1979.

CAN 79 assumes the windows distributed uniformly around the house, while CAN 79-1 is based on all the windows being in the south facing wall. This change from small solar gain to maximum solar gain is a hypothetical case which merely sets the scale of the solar gains that can be achieved from south facing windows. The improvement from CAN 79-1 to CAN 79-2 is due to a tight house (low infiltration) plus an air-to-air heat exchanger. This improvement agrees almost exactly with the DOE-2 values from Fig. 1 at the same degree day location.

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The next step, to CAN 79-3, is achieved by the use of insulated shutters which are closed at night. These shutters are installed over double glazed windows.

The final step, to CAN'79-4, costing $2000 is a high R-value insulation feature, which in fact represents a poor return on investment (4%/year if gas costs $4/MBtu).

The ceilings had $R = 10.6 \frac{m^2\ {}^oC}{W}$ $(60 \frac{hr\ ft^2\ {}^oF}{BTU})$; the walls had $R = 7.3 \frac{m^2\ {}^oC}{W}$ $(41 \frac{hr\ ft^2\ {}^oF}{BTU})$; and the floors had $R = 5.44 \frac{m^2\ {}^oC}{W}$ $(31 \frac{hr\ ft^2\ {}^oF}{BTU})$.

The point CAN'78 represents the Saskatchewan conservative house which was completed in 1977. The house performance was monitored beginning in January 1978. For average year weather conditions the net space heating requirement was determined to be 13.2 G.J.**27** This house had a floor area of 188 m^2 on two stories. Scaling this heating requirement to 100 m^2 of floor area and applying our seasonal heating system efficiency of 2/3, the fuel input would be 10 . G.J./100 m^2.

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This house incorporated a tightly sealed envelope with an air-to-air heat exchanger for ventilation air. The insulation levels were equal to those used in the calculations for point CAN'79-4. Insulating shutters were used on all windows and 11.9 m^2 of window area was south facing and designed for passive solar gain.

Next we present the points labelled CAN'77.

A project near Ottawa, Canada, involved the building of four houses of the same design located on adjacent lots with the same orientation. The initial calculations and description for these houses is provided in a paper by R. L. Quirouette.**18** The point CAN'77 was the reference house built according to the Ontario Building Code of 1975 and consistent with building practice of the area. All houses had 118 m^2 (1248 $ft.^2$) floor area in two stories.

The point CAN'77-1 represents an upgraded house with better insulation. The walls have $R = 3.53 \frac{m^2\,{}^{o}C}{W}$ $(20 \frac{hr\ ft^2\,{}^{o}F}{BTU})$, the ceilings have $R = 5.6 \frac{m^2\,{}^{o}C}{W}$ $(32 \frac{hr\ ft^2\,{}^{o}F}{BTU})$ and on the outside of the foundation walls down to the footings, insulation is applied having $R = 1.32 \frac{m^2\,{}^{o}C}{W}$ $[7.5 \frac{hr\ ft^2\,{}^{o}F}{BTU}]$. This house also had triple glazed windows as well as improved air tightness to reduce infiltration. The added cost of the upgraded house was estimated at \$3000.

The point CAN'77-2 shows an upgraded house identical to CAN 77-1 but equipped with a complete solar heating system. The cost of ths system was given as \$18,000 and was designed to save about 50% of the annual fuel required for space heating in the upgraded house with a conventional heating system.

C. EUROPEAN HOUSES (Fig. 5):

Fig. 5 covers European houses. Again, some familiar U.S. curves are redrawn for comparative purposes.

The French FR'77 "S" and Swedish SW'72 "S" show the residential stock in those countries for the years 1977 and 1972 respectively. The French point Fr.Std.'74 shows the calculated fuel consumption for a house built according to the 1974 standard at an increase in average cost per dwelling of $1500, (i.e., a 3% increase in first cost) to get from pre oil embargo construction of 1972 to the 1974 standard. In the Swedish case the larger average added cost of $3000 to build according to the Swedish Building Norm SBN'75 is shown relative to Swedish stock Cons of 1972.

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Groups of electrically heated houses in Sweden are shown along with the year of construction. The SW'65 "X" shows the average for a group of houses built in 1965 before the concern for energy conservation became evident. The groups of houses built from 1967 to 1974 inclusive, are all about the same level of conservation and are close to the Swedish standard SBN'75.

The straight line labelled "same house in 8 cities" was taken from a paper by R. Bruno and H. Horster.**19** Their calculations were made using a computer simulation of a 150 m^2 floor area, two-story house, constructed according to the Swedish SBN'75. The inside temperature was maintained at 20 °C. They modelled this Swedish standard house in seven cities, four European and three U.S. Solar gain through windows was included in the simulation; however, the windows were closed at night by shutters having $R = 0.67 \frac{m^2\ {}^oC}{W}$ [$3.8 \frac{hrft^2\ {}^oF}{BTU}$] As a result, this simulation gave results of fuel consumption slightly lower than our calculated points from Sweden, e.g. SBN′75. We find it interesting that the SBN′75 house line intercepts zero space heat at 1300 Celsius degree days (2350 F degree day), a climate where average (stock) U.S. houses still need 60 GJ/m^2 (57 MBtu or 570 Therms, costing ~$200/year at U.S. gas prices of $3.50/Mbtu).

The Scottish point X Sc′77 represents a group of Norwegian prefabricated houses erected at Kemnay, near Aberdeen, Scotland. Of the eighteen houses tested and reported, eight were detached houses and 10 were terraced (row) houses. All houses had two stories and had approximately 100 m^2 floor area. Report**20** was prepared by the Electricity Council of London, England. We thank Peter Basnett, one of the authors of this report, for useful information regarding the tests done on these Kemnay houses.

These wooden houses were tightly built with moderate levels of insulation, and including insulation in the floor separating the two stories. The cross indicates the mean value of fuel consumption for 18 houses and the bars above and below represent the standard deviation of the results. The Kemnay houses are electrically heated. Hence, for direct comparison with gas heating systems we have taken the average Kemnay electric use for space heat and multiplied it by 1.5.

A test carried out on one of these detached houses by the Building Research Establishment in East Kilbride, Scotland **25**, showed a slighly higher fuel consumption than the point Sc′77 which represented a group of 18 houses. The result on the single house is shown by point

Sc'76 which had an equivalent fuel consumption for space heat of 22.4 G.J./100 m^2.

Fig. 6 provides an interesting comparison of regulations for the thermal insulation of buildings in the European Economic Community. **21** The ordinate k_m is the overall transmission loss in $\frac{W}{m^2K}$ (infiltration excluded) where the area is the total exterior heat transfer surface area of the building, including basement wall and floor if the basement is heated. The x-axis is the ratio of exterior surface area to inhabitable volume. For the standard bungalow being simulated in this paper, the value of surface to volume ratio falls between 1.1 and 1.4, depending on the presence of a heated basement. It is of interest to note that the Ottawa house, point CAN'77 on Fig. 4, has a surface to volume ratio of 1.26 and a k_m value of 0.36 $\frac{W}{m^2K}$ which corresponds to the "Denmark" curve for single story homes.

The transmission loss accounts for neither additional loss from infiltration, nor solar gains. If the infiltration averages n air changes per hour, then the loss in Watts is

$$W(\text{infil.}) = 0.34\ n\ V\ \Delta T(\text{Watts})$$

and in the units of $k(w/m^2K)$,

$$k(\text{infil.}) = \frac{0.34}{S/V}\ n\ \left(\frac{w}{m^2\ K}\right).$$

where S is the total exterior heat transfer surface area and V is the inhabitable volume. To exhibit the relative importance of infiltration we have plotted k(infil.) for n = 1 ach.

If the infiltration happened to be 1 ach. the energy used to heat this amount of outside air would be equal to the total heat loss by conduction through walls, floors, ceilings, windows and doors of a house built to the standard required for Denmark.

To get an idea of the solar gains in these units, we merely refer to the CAN'79 house at the right of Fig. 4. Here we note that in Saskatchewan, the gain from 50% of the glass area is comparable with the energy difference when changing infiltration by 0.3 ach (from 0.6 to effectively 0.3).

Clearly infiltration losses and solar gains are important terms to be added and subtracted to the transmission loss k_m, and the next generation of building codes must address them.

III. DISCUSSION OF DATA

A. COMPUTER SIMULATIONS:

Fig. 1 clearly illustrates the annual fuel input requirements as a function of degree days for various levels of energy conserving construction practices. The house which was simulated was a one floor ranch house having 109 m^2 (1176 $ft.^2$) floor area. The energy use in all the figures is scaled (proportionately to floor area) to a base of 100 m^2 (1076 ft^2); fairly accurate estimates can be made for larger houses or for houses of different design by multiplying by the appropriate floor area ratio.

Apart from the NJ retrofit boxes in Fig. 4, the cost figures which are given (to get from one level of conservation to the next) apply to new construction. If retrofits are being considered, the costs would, in general, be higher than those shown.

In Fig. 1, the "current practice" curve is about 20% above the MPS'78 curve and about 40% above the LBL Optimum (Med. Infilt.) curve. The construction changes required to meet the MPS 78 and LBL optimum (Med. Infilt.) levels are simple and inexpensive and therefore should be achievable without problems. The significant improvement beyond LBL Optimum (Med. Infilt.) is clearly to reduce infiltration and install mechanical ventilation and an air-to-air heat exchanger.

This low infiltration "package" (including mechanical ventilation and heat exchanger) represents a change in current building practice. Considerable care must be taken during the installation of the plastic vapour barrier sheet on the inside of the insulation. All joints must be sealed and care must be taken to avoid puncturing the vapour barrier. If the house is not tight, the expected energy savings are lost and the air-to-air heat exchanger is pointless. Tests for air tightness have been developed and must be specified as part of a building standard if this low infiltration option is included in a building code. Because of the pre-requisite of reducing natural infiltration to ~ 0.3 ach or less before the effective utilization of a heat exchanger, this option is less likely to be feasible for retrofit than for new construction.

For the retrofit market, it is desirable to identify the heat loss disribution within the building. If, for example, the infiltration rates are above approximately 1 ach then it will likely be cost effective to reduce the infiltration by caulking and other means. If the infiltration rates are below 1 ach, then added insulation levels will be more cost effective.

Limited computer simulation runs were made to consider the use of insulated shades or shutters. Based on a schedule of having the insulating shades drawn during the hours of darkness, it was found that the shades were cost effective over single glazed windows. Over double glazed windows the shades proved to be cost effective at heating Celsius degree days above 3000.

It should also be noted that the simulation runs plotted in Fig. 1 evaluated improvements in the insulation value of the envelope. The lifestyle of the occupants or the comfort levels of the occupants was not affected in any way. If one was willing to consider other conditions and lifestyles then further reductins in fuel heating energy could be attained. For example, lower thermostat settings woul reduce fuel used, night set-back of the thermostat is a fuel saver, more efficient heating systems would prove very effective, and so on.

B. NORTH AMERICAN HOMES (Fig. 4).

Fig. 4 shows the fuel consumed by residential stock in the U.S. in 1970 and test results on four low-energy test houses. The optimum curves have been replotted from Fig. 1 for reference. These houses provide experimental evidence of the levels of fuel consumption which can be achieved with energy conserving features, and also provide validation for the computer simulations.

Retrofit.

The New Jersey townhouse, NJ'77, was the only example of the gains to be achieved by retrofit. Since it was a townhouse, the east and west walls were not outside walls and hence it is not readily comparable to the computer simulations which were for a detached house. Nevertheless, the points are useful to illustrate the savings which can be achieved fairly easily and at relatively low cost.

These retrofits concentrated on reduction of infiltration, reduction of window losses, reduction of ceiling losses and reduction of basement wall losses. Caulking of all obvious cracks and joints and air bypass routes into the attic were carried out, then the house was depressurized and tracer smoke was use to identify leakage points not otherwise readily observable. Insulating shutters were used on south facing windows to reduce night-time heat loss while still allowing solar heat gain during the day. The basement wall was insulated down to floor level and the second floor ceiling was insulated up to R-30.

The caulking and sealing resulted in the average infiltration rate being reduced from 0.6 to 0.3 ach. The indoor air quality is being measured and if more ventilation air is required, then an air-to-air heat exchanger will be installed along with mechanical ventilation.

New Houses

The Minnesota point MN′78 used the low infiltration option with a heat exchanger and it would at first be expected to fall close to the LBL "Lo infilt." line. But the MN′78 house made significant use of passive solar heating, so one would expect the fuel consumption to fall below the DOE-2 prediction. This point appears to validate the computer simulations.

For the Saskatchewan house, the first reduction from CAN 79 which ass ASSUMED THE WINDOWS EQUALLY DISTRIBUTED ON 4 SIDES. ~~utilized no solar gains through windows~~ to CAN 79-1 was achieved by placing all windows in the south-facing wall (thus utilizing maximum passive solar energy). Since that part of Canada is characterized by cold, clear weather, the solar gain may be higher than could be realized in other places. The other conserving features, however, agree well with the DOE-2 simulations. The final step to CAN 78, at a cost of $2000 for more insulation, is not cost effective at present fuel prices based on the economic assumptions outlined in Table I.

One of the Ottawa houses (CAN′77-1) represents the upgraded house which has insulation levels close to the optimum values recommended by the LBL (Med. Infilt.) runs. The assumed Canadian infiltration was slightly below the 0.6 air changes used in the "Med Infilt." DOE-2 curves. The point CAN 77-1 therefore agrees almost exactly with the

DOE-2 simulation after making the small correction for the lower infiltration. The $18,000 solar heating option which reduced the fuel consumption by one-half is shown by point CAN'77-2. It is interesting to note at this point that if one wished to reduce the fuel consumption in a house which was represented by a "base" point such as CAN'77-1 all of the various options should be considered and an economic analysis made for each. The Saskatchewan house (CAN'79-3) gets down to about 25 GJ/100m^2 (for only about $1300 for low infiltration plus shades); the Ottawa house also gets down to 25 GJ/100m^2, but spends 10 times as much to get there.

These two options (low-infilt. and shades) would reduce the annual fuel consumption by about the same amount as the active solar system. The cost of the above options would be approximately $1300, as compared to $18,000 quoted for the active solar system. We conclude that an active solar system in Ottawa is not a cost effective way of providing space heat in a single family residence, because there are alternative ways of reducing the fuel consumption at lower life cycle cost.

C. EUROPEAN HOMES (Fig. 5).

Before discussing Fig. 5 which shows some European data, it is important to consider factors that influence this data causing important variations. Central heating of single family dwellings is close to the saturation point only in the U.S., Canada and Sweden. Room heaters are still common in the U.K. (~ 45% of dwellings 1977), Germany (~ 39% of dwellings 1976) and France (~ 45% of dwellings 1975). Even comparing centrally heated dwellings, economic factors vary greatly. Natural gas, historically inexpensive in only Canada and the U.S., has fallen in cost in the U.K., however heating habits continue to be more spartan in the U.K. than in North America.

For example, in 1978, British practice still called for only 50 mm. of mineral wool in the attic in England, compared with 125 mm. in California, indicating the different habits and economics for insulation in the two countries. Other factors affecting the economic picture also vary. A publication by the German Ministry for Buildings and Land Planning quotes a 1976-77 price of 75 DM/m^2 (about $35.00 at the time) for 100 mm of mineral wool, roughly three times the cost of an equivalent R value in California. As a result, California building standards require higher R values than those in most of Germany.

These examples merely serve as a warning, when one is comparing demand for space heat, technical state of the art, consumption by stock housing between Europe and North America.

Fig. 5 illustrates fuel consumption data for some housing stock, some actual current housing and some energy conservative houses. Once again, curves from Figs. 1 and 4 are redrawn for reference. It can be seen that French stock (FR'77) is worse than U.S. stock, while Swedish stock (SW'72) is better.

Looking at the current standards for new housing, it is clear that the Swedish standard (SBN'75) is comparable with the proposed U.S. standard (LBL-Med-Infil.) and considerably tighter than the French standard (FR.STD.'74).

To illustrate the attractive annual return on investment of these new housing standards we have noted that the new French standard is said to increase the first cost of a \$50,000 house by 3%, i.e., \$1500. But it saves 50 GJ per 100 m^2 house, at a current French residential price for oil of about \$5/GJ, i.e., saves \$250/year. This is a 17% annual return on investment, which can only increase as fuel prices escalate. For Sweden, the same fuel savings (\$250/year) for a \$3000 investment represents an 8% annual return.

Sweden.

The results for groups of homes tested in Sweden are shown by points SW 65 to SW 74. These points represented large groups of single family, detached homes, all electrically heated with the year of construction indicated. According to our plotting convention the electric energy for space heat has been divided by a fictitious furnace efficiency of 2/3. From 1967 on, it is interesting to note that the fuel consumption was very close to that resulting from the SBN'75 building standards.

The computer simulation by Bruno and Horster**12** of a house built according to SBN'75 showed a slightly better performance than some of the calculated and measured Swedish points. In the simulation, night-time shutter use was assumed on all windows and the fuel consumption was therefore slightly lower than the measured Swedish points. Again, the agreement between experimental results and computer simulations was extremely good.

The point SW 79-1 represents calculated fuel consumption for an 8 unit apartment built in Smålands Taberg according to SBN'75. This same apartment was then recalculated with better windows and additional insulation. The point SW 79-2 represents this better insulated building. The insulation level had slightly higher R values than the LBL optimum called for at the 4000 degree day location. The point SW 79-3 is the same building as SW 79-2, except that a greenhouse was added to take advantage of solar heating.

The point SW 74-2 represents a low-energy house built in 1974 in order to test some energy conserving construction features.

The point SW'78 shows test results for an energy conservative house at Ostersund reported by Karl E. Munther.**16**

Scotland.

The point labelled SC-77 represents the prefabricated houses designed by Norwegians and built at Kemnay, near Aberdeen, Scotland. These houses will now be discussed in some detail because they illustrate "zone" heating, an innovation to many Americans. The previous energy conserving features involved more insulation and reduced infiltration. These Scottish houses conserve electricity by heating only the rooms being used at any given time.

The Kemnay homes represent Norwegian current practice; they are reasonably well insulated, double-glazed, and reasonably air-tight (0.6 - 0.9 ach) (conforming to Norwegian standards). The insulation between floors reduces losses when only one floor is heated. Also, oversized electric heaters allow rapid recovery to thermostat set point when a room is to be heated. It is interesting to note that this selective room heating on average achieves the same level of conservation as the strategy of low infiltration with a heat exchanger.

This selective room heating is very dependent on the habits of the occupant. There was also a large variation in the amount of fresh air that each occupant prefers. These factors plus the other normal differences in living habits, caused a large variation in fuel consumed for space heat in this housing project.

The study **20** reported a detached house of 109 m^2 floor area with an annual fuel consumption of 7.4 G.J./100 m^2. The study **25** also gave an annual fuel consumption of 22.4 G.J./100 m^2 using one of the detached houses of floor area 109 m^2. This 3 to 1 variation in space heat energy is large but perhaps typical for those houses where a larger degree of occupant control over the heating is required.

IV. FREE HEATING, FREE COOLING, AND CONTROLS

A. Free Heating

It has been recognized for some time that, for new houses, the base temperature for the heating degree day must be reduced below the value of 18.3 ° C (65° F) if the number of degree days is to correlate well with annual heating requirements. This reduction in base temperature arises as a result of better insulated houses and higher internal loads.

E. Arens and W. Carroll**19**, have shown that the base temperature for the degree day calculation should be 11.5°C (53° F) for the particular house which they analyzed. This "base" is also called the neutral temperature. It is the outside daily average temperature above which no heating is required because internal loads and solar gains provide a "free" temperature rise, ΔT (free), which balances the heat losses and maintains a comfortable indoor temperature.

Table II gives the Δ T (free), and hence the neutral point, for some of the low energy houses discussed in this paper.

Table II. ΔT_{free} and neutral point temperature T^N for several low energy houses.

Houses	ΔT_f (°F)	T^N (°F)
Arens and Carroll**19**	17	53
Sinden**8**	11	52
Kemnay**13**	17	50
Dumont et al.**14**	36	34[a]
Robinson**13**	36	32~~[b]~~

ete "b"

B. Free Cooling and Controls.

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[a] The Saskatchewan Conservation Home is a passive solar design with 11.9 m^2 of south facing glass and a total floor area of 187 m^2.

It is not the purpose of this paper to study system design and control; however, it is obvious that thermostatic control of only the heating system is not going to provide adequate temperature control for energy conservative houses. Heating systems will be operating a smaller percentage of the time, and some cooling by outside air will be needed for a considerable amount of time during the year.

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We show calculated load characteristics of an energy efficient house in Fig. 7. It has been It has been assumed that use will be made of passive solar energy from south facing windows, and therefore an inside temperature float band from 70° F to 78° F has been permitted. This will permit heat storage within the house in walls, furniture, etc. Free cooling, using outside air, will operate when inside temperature is between 75° F and 78° F with the temperature maintained at 75° F if possible. This so-called "free cooling" is achieved by using a "whole-house" fan. The use of such a fan combined with planned window opening achieves very effective cooling**23**. This has been shown even for outdoor temperatures of 28°C (82°F). 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 78°F (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 regions having moderate summer climates (the northern half of the U.S.

In terms of outside temperatures, it can be seen that the heating system will operate at outside temperatures below 50° F. Free cooling with outside air will be used between 55° F and 75°F, and if available, mechanical cooling will be used when the outside temperature exceeds 75°F.

TABLE III. Fan Capacities for an Energy-Efficient Residence of Volume 250 m^3.

	ach[a]	m^3/hr.	cfm
Mechanical Vent/H.X.	0.4	100	60
Furnace (for winter heating)		340	200[c]
Chiller (for summer cooling)		680	400[c]
Whole House Fan[b]	<=50	<=10,000	<=5900

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[a] Nominal Volume = Floor Area ($100 m^2$) x Height (2.5 m) = 250 m^3

[b] Multispeed fan, e.g., 2000, 4000, 6000 cfm

[c] Two speed Central HVAC fan. Note that energy-efficient homes need fans hat are 3/5 smaller than those used in current practise.

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To look at the operating time for each of the three modes, the temperature histogram for central New Jersey was considered. It was determined that the heating system would operate about 3371 hours yearly, representing about 38% of the year. The "float" or "free cooling" mode between 50° F and 75° F would be required about 45% of the year. The air conditioning mode would account for 17% of the year. Thermostatic control of a free-cooling outside-air system is obviously a necessary feature.

The strategy for control of the whole-house fan has normally been based on outdoor temperature. In some cases, however, when outdoor humidity is very high, higher than indoor humidity, the use of the whole house fan may indirectly put a heavier load on the air conditioning system when that system is brought into operation. This problem is probably rare and perhaps confined to certain climatic regions; however, it should be considered when further research is done in the area of "whole-house" fans.

V. INDOOR AIR QUALITY:

P
SP

Indoor air quality in single family residential buildings has not been a matter of concern in the past. Natural ventilation rates (infiltration) of abou 0.75 ach and higher apparently have been sufficient to control the build-up of pollutants. Since tight constructin and hence reduced natural ventilation is now being proposed as one means of conserving energy, the whole matter of indoor air quality becomes very important.

P

Concentrations of familiar pollutants such as formaldehyde, combustion products and radon soon reach undesirable levels. in very tight houses. For this reason, the computer simulatins quoted in this paper have maintained ventilation rates not less than 0.6 ach. This figure was an arbitrary choice in the absence of reliable data.

The LBL Building Envelopes and Ventilation program is monitoring the correlation between reduced ventilation and increased indoor concentration of pollutants. It is expected that future drafts of BECA will present more information and references in this important area.

In this draft we present two recent figures on indoor radon concentratin. Figure 8 shows radon levels outdoors, in conventional homes, in "tight" houses, and in a Florida development built on land which is rich in phosphates.

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 <u>Working Level</u> (WL) is defined as 100 nCi/m^3 of radon (in equilibrium with its first four radioactive daughters), and U.S. uranium miners must receive less than 5 WL - months/year. At lower levels of 1-10 nCi/m^3, where there are no epidemiological data, we can only invoke some form of the linear dose-response hypothesis. Although crude, we can gain some insight by comparing lung cancer rates from radon and from cigarettes; we then come up with the rule of thumb that 1 nCi/m^3 represents a risk of the same order of magnitude as smoking one cigarette/day.

Figure 9 is a scatter plot of radon levels vs. natural infiltration rates for 14 houses which we have measured. The figure indicates that as we reduce infiltration, to save energy, we should replace it with mechanical ventilation and a heat exchanger, to preserve indoor air quality.

VI. CONCLUSIONS AND RECOMMENDATIONS:

Conclusions

1. Computer simulations have been run on a standard single family dwelling and various energy conserving features have been analyzed. The computer simulations have proven to be a valuable tool for the evaluation of the various energy conserving options. Savings in space-heating fuel of about 1/3 could be achieved if current practice housing was upgraded to the "LBL optimum: med. infilt." Using this as a new base, a further 40% could be saved if construction was upgraded to the "Lo infilt." curve and the air-to-air heat exchanger was utilized for heat recovery from exhaust air.

Put differently, savings of approximately 60% can be achieved in new houses compared to current practice, using only proven procedures, all of which are cost effective. Figures 1 through 5 show that it is cost effective today to reduce fuel required for space heat in new homes to the level *now* required for domestic hot water.

2. Saving via *retrofit* is more expensive than in new construction but the N.J. (squares shown on Fig. 4) clearly indicate that intelligent retrofit yields excellent return on investment and the savings can be accomplished nationwide in a few years instead of 100.

3. Comparison of the calculated results and the actual measured performance of various energy conservative houses adds credibility to the computer simulation runs. The real houses have also shown the cost effectiveness of the energy conservative construction features which have been examined in this paper. It can also be concluded that the building standards being developed by various countries are still very modest and have not gone as far as they might go with energy saving ideas. While the reasons for this are beyond the scope of this paper (low energy prices, high interest rates, resistance to change) the spread of the data suggests a great potential for energy conservation.

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Five Options

There appear to be five options that can play a significant role in reducing the fuel required for space heating.

(a) Reduction of transmission losses by better insulation; (this is the only one of the five that is already widely recognized).

(b) Reduction of energy required by making use of Free heating (passive solar) and free cooling (thermal storage) ~~should be recognized and used more widely~~.

(c) Reduction of infiltration from 1 ach to perhaps 0.2 ach. This saves heating energy in winter and peak power in summer. But until the minimum level of fresh air is required for health and comfort is known, forced ventilation through a heat exchanger will be needed.

(d) Reduction of window losses by using Insulating shutters or shades ~~could become more common and cheaper and become cost effective for energy saving~~.

(e) Reduction of fuel required by improving Heating system efficiencies. ~~must be improved.~~ ~~but~~ Costs of these improvements should be compared with those associated with improved building integrity for the same level of saving.

Recommendations:

(a) The reduction of infiltration along with controlled ventilation through a heat exchanger saves energy, is very cost effective and requires no new technology or change in life style. This feature should be included now in building standards with a target date for implementation of say 1982. This approach, which is now used for fuel economy in the auto industry, would give the building industry time to respond to new energy conserving ideas.

(b) The next major saving in fuel for heating can be accomplished by emphasizing passive solar design in residences. It is recommended that the production of design manuals for passive solar residences should be given high priority. Credits in new building standards could be given for shouth facing windows particularly when the energy can be distributed and stored. These windows should be shaded in summer.

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SP.

(c) Studies of indoor air quality for health and comfort are required so that acceptable levels of fresh air can be established. If it is found that some homes can be safe and comfortable with 0.25 ach, then perhaps the heat exchanger can be eliminated.

(d) The present emphasis of building standards on the reduction of transmission losses takes buildings about half way to the ultimate target of pleasant, unpolluted, cost effective, low energy houses. Building standards should be revised regularly as more information, equipment and experience become available. Governments must not only support continuing studies of energy efficiency in buildings, but should promulgate long range target standards to stimulate the production of better materials and equipment. Given a guaranteed future market, industry should respond with increased research, development, and re-tooling. Government incentives for innovative low-energy features would further speed this process.

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Appendix A, not yet ready, will be a printout of our data base for each country.

Appendix B, will show fits to individual low-energy homes.

Appendix C follows.