EVALUATION OF RESIDENTIAL BUILDING ENERGY PERFORMANCE STANDARDS

Levine, M.D.

1979-12-01

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

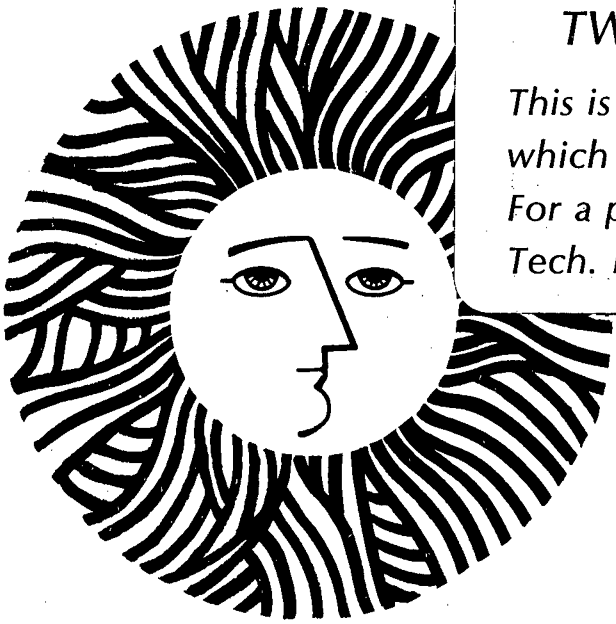
ENERGY & ENVIRONMENT DIVISION

Presented at the Department of Energy/ASHRAE Conference on Thermal Performance of Exterior Envelopes of Buildings, Orlando, FL, December 3-5, 1979

EVALUATION OF RESIDENTIAL BUILDING ENERGY PERFORMANCE STANDARDS

Mark D. Levine, David B. Goldstein,
Metin Lokmanhekim, and Arthur H. Rosenfeld

December 1979



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

DISCLAIMER

LBL-9816

EVALUATION OF RESIDENTIAL BUILDING ENERGY PERFORMANCE STANDARDS

Mark D. Levine, David B. Goldstein,
Metin Lokmanhekim, and Arthur H. Rosenfeld

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720, U.S.A.

ABSTRACT

This paper reports on the development and analysis of energy performance standards for residential buildings in the United States. The approach involves an assessment of the economic costs and benefits of alternative standards and provides quantitative estimates of the reduction of energy use resulting from the implementation of standards. The sensitivities of building energy use to design parameters of buildings--including size, orientation, aspect ratio, basement type, window area, and construction material--are assessed. The DOE-2 Building Energy Utilization Analysis program was used to evaluate the heating and cooling loads of residential buildings. Residential buildings were simulated in ten weather climates using hourly weather data with a variety of energy conservation measures.

A number of key issues relating to the evaluation of building energy performance standards are raised and discussed. These issues include:

- What are alternative methodologies for evaluating building energy standards? How dependent are standards on key economic assumptions of the analysis?
- How can the standards be implemented so that tradeoffs between different energy conservation measures can be made?
- What are the costs and benefits of different approaches to reducing residential building energy consumption?
- What role can reducing infiltration into buildings play in the standards?

- How can the standards be implemented to give appropriate credit for passive solar design?
- How many sets of standards are needed for residential buildings?

I. Introduction

A. Performance Standards

The U. S. Congress designated energy performance standards as a means for reducing the energy use of new buildings. These standards differ from the more conventional "component-based" and prescriptive standards by setting a limit on predicted energy use of the building as a whole rather than specifying the thermal performance of each element of the building separately.

The performance aspect of the standards allows the builder greater flexibility in meeting their requirements, since high performance of one component can be traded off against low performance of another. In spite of this greater flexibility, they are more difficult to implement than prescriptive standards.

This paper discusses the process of applying life-cycle cost analysis to the evaluation of performance standards for residences.

Minimizing life-cycle costs of a building can be accomplished by simulating the energy performance of a prototype building on an energy utilization model under different conditions of thermal integrity. The effect of adding conservation measures to the base house is modeled and, for each measure, a comparison is made between reductions in energy costs over the life of the building and increased investment in energy conservation.

Conservation measures are added in order of decreasing benefit/cost ratio, until the ratio is less than one. The energy budget at this minimum in life-cycle cost is hereafter defined as the Design Energy Budget of a building type.

Energy performance standards can be set by requiring all buildings to achieve the same or better (i.e., lower) energy performance as the cost-minimizing ptototype. If there is a substantial difference in the ability of different types of buildings to meet this performance, different prototypes can be established for each type of building.

The energy budgets derived by this method are abstract numbers (Btu/ft^2 year): additional study is needed to relate these numbers to specific configurations of specific houses (other than the prototype). Sensitivity of the design energy performance of a building to different building parameters must be explored to assume that the energy budgets are realistic for a wide variety or houses.

Many of the key issues revolving around performance standards concern their applicability to different types of houses and the assumptions used to model the energy use and economics of the building.

This report derives energy budgets for residences based on minimizing life-cycle costs of conventional conservation measures to the consumer (home owner). It shows that the houses with conservation measures and energy budgets associated with the minimum in life-cycle costs are relatively insensitive to most variations in house design, so that energy budgets are well-defined and equitable compared to prescriptive standards.

The U.S. Department of Energy has used these budgets and an attendant report 1/ as the basis of the Proposed Rule on Building Energy Performance Standards for Residences, issued in November 1979 2/. Commercial Building Energy Performance Standards (including those for multi-family residential buildings) are based on a statistical methodology developed by the American Institute of Architects Research Corporation 3/.

B. Summary of Results

- *If all new residential buildings incorporate traditional energy conservation measures until the minimum in life cycle cost is achieved, then*

  --a reduction of 30% to 40% in the average energy use for space conditioning (from current building practice) is accomplished,

  --a reduction of 60% to 70% in average energy use for space conditioning (from an average existing house) is obtained,

  --simple payback on conservation investment occurs in 1 to 4 years for electric heat and 3 to 10 years for gas heat, and

  --an increased investment of $0.50 to $1.00 per square foot for a new house is required (i.e., an increase in initial investment of 1 to 2%)

  --the consumer achieves a net saving of $800 to $1500 on the cost of fuel (and conservation) over the life of the house mortgage

- *If the list of available conservation measures is expanded to include reduced air leakage (infiltration) into the house, coupled with mechanical ventilation through a heat exchanger (not yet widely available) and these measures are implemented until the life cycle cost minimum is achieved, then*

  --a reduction of 50% to 60% in average energy use for space conditioning (from current building practice) or 75% to 80% (from an average existing house) is accomplished,

  --an increased investment of $0.75 and $1.50 per square foot for a new house is required, and

  --the net savings is $1500 to $4000 to the consumer.

II. Method of Approach

The approach followed in the analysis of residential space conditioning energy performance standards involves the following steps:

1. Development of Residential Prototypes
2. Selection of Conservation Measures to be Evaluated
3. Description of Standard Building Operating Conditions
4. Development of Economic Data, Projections, and Assumptions
5. Computer Simulation of Building Energy Requirements in Different Climatic Regions

6. Analysis of Life-Cycle Costs of Energy Conservation Measures
7. Sensitivity Analyses on Building Characteristics, Operating Conditions, Conservation Measures, and Economic Parameters
8. Analysis of Impacts of Alternative Energy Budget Levels, in which the Alternative Budget Levels are based on steps 1 through 7

The basis of the analysis method is the use of life-cycle costing. The objective of achieving a minimum in life-cycle costs is a reasonable basis for establishing energy conservation policy because it provides a rational framework for trading off scarce energy resources and other resources (e.g., labor and capital) in achieving a particular goal (in this case, space conditioning in residential buildings) 4/. The acceptance of such an approach can, in our judgment, greatly facilitate the consensus-building that is necessary to establish the major energy conservation elements of a national energy policy. This does not mean that the process of building consensus is necessarily easy or without its divisive aspects. But, the use of an economic approach to energy conservation--and the increasing public awareness of how economics can help resolve issues--can be greatly enhanced by a government decision to use life-cycle costing as one of the major elements of its energy conservation policy.

A. Specifics of Approach and Assumptions

Table 1 contains in summary form the most important elements of the approach. More detailed information on the assumptions used in the analysis is found in reference 5, available from Lawrence Berkeley Laboratory. More detailed information about the results of sensitivity analyses is found in Chapter 4 and appendices A and I of reference 1. We discuss here some of the more important elements of the approach.

Assumptions (based on best available data) are required in all of the areas listed in Table 1: residential prototypes; conservation measures;

TABLE 1. Specific Elements of the Approach to Evaluating the Life-Cycle Cost of Energy Conservation Measures for Single-Family Residential Buildings

Residential Prototypes

- Four designs selected, following Hastings 6/: single story ranch, two story, townhouse, and split level house
- Window area taken to be 15% of floor area for all designs
- Windows equally distributed on all four sides of house (two sides for townhouse)
- Sensitivities of prototypes performed:

  --window area
  --window orientation
  --house size and orientation
  --aspect ratio of house
  --thermal mass of house
  --conservation measures (see below)
  --building operating conditions (see below)

Conservation Measures

- Windows: up to triple glazing (or double glazing plus storm window)
- Exterior wall: up to R-25 (using 2" x 6" studs plus insulating sheathing)
- Ceiling: up to R-38 insulation
- Excludes: exterior wall with double studs (two 2 x 4 or 2 x 8 studs with insulation); ceiling insulation greater than R-38; infiltration reduction (with or without heat recuperator); any conservation measure requiring a change in behavior; other advanced energy conservation technologies

Building Operating Conditions

- Thermostat set points: 70°F for heating; 78° for cooling; no night setback
- Average air infiltration rate: 0.6 air changes per hour
- Average internal loads: 50,000 Btu/day, Highest in early morning (cooking, occupants, lighting) and evenings (cooking, lighting, occupants, TV)
- Natural ventilation: windows open when indoor temperature greater than 78°F and outdoor temperature low enough to cool house to 78° in less than one hour. Non-opening windows considered as a sensitivity case.

TABLE 1. (Concl.)

Economic Data, Projections, and Assumptions

- E.I.A. average energy price projections (Series B)
  - --Gas prices escalate at 2.8% per year above inflation
  - --electricity prices escalate at 1.5% per year above inflation
- Installed cost of Energy conservation measures from N.A.H.B.
- Discount rate chosen to equal cost of borrowed capital for a new house (3% above inflation)
- Possible future changes in assumptions:
  - --marginal energy prices
  - --updated conservation costs
  - --regional prices

Building Energy Simulations

- Use of DOE-2 computer program, checked against TWOZONE and BLAST
- Change in infiltration and ventilation algorithms
- Run for 4 prototypes, about 12 groups of conservation measures per prototype, two ventilation algorithms and 10 cities

building operating conditions; economic data, projections, and assumptions; and building energy simulations. Some of these are discussed below:

1. Prototype Houses

The economic approach to energy budget analysis requires the use of prototype buildings. Cost/benefit analysis cannot be performed in the abstract; instead specific improvements on specific houses must be studied. The prototypes used are described by Hastings 6/; they cover ranch houses, two-story houses, and townhouses. In addition, we modeled a split-level prototype.

The Hastings houses were used in the analysis because they were developed for the purpose of analyzing energy conservation measures, and have for over a year, been subject to public scrutiny and review.

We made several modifications to the basic prototype designs for the purpose of determining energy budgets. Window area was increased from 11% to 15% of floor area to correspond to data on average glass areas in new construction. The windows were distributed uniformly on all four elevations to simulate random orientation. These changes have the effect of loosening the energy budgets such that a typical house could comply, if desired, through universally available conservation measures only, without the requirement of re-orientation (which may not be feasible in many cases).

2. Building Operating Conditions

The conditions used in the analysis were chosen to reflect current usage patterns. This choice was made to limit the scope of the performance standard to changes in building design, with no effect on the lifestyle or preferences of the occupants. If one assumes changed behavior (e.g., lower heating thermostats) then tighter insulation standards produce gains in comfort (temperatures which may float higher than the actual thermostat setting but lower than the desired setting) which cannot be evaluated economically.

Natural ventilation was assumed because the present data, though sparse and not conclusive, suggest that most people do open their windows on cool summer days. Furthermore, the assumption of closed windows would cause passive solar designs (which often rely on natural ventilation) to have higher cooling loads, discouraging the use of passive solar techniques, in conflict with the legislative mandate.

Internal load assumptions were based on average occupancies, appliance ownership, and projected appliance efficiencies. Infiltration rates were calculated using a Coblentz-Achenbach equation with coefficients developed by Stephen R. Petersen 7/. The average, 0.6 in changes per hour, is typical of the averages of measurements made in over 50 houses.

3. Economic Parameters

A discount rate 3% above the inflation rate has been used, based on the approximate cost of capital to the consumer buying a new home. A higher discount rate, such as 10% or 15% above inflation, reduces the number of conservation measures which are cost-effective, particularly in the milder climates; a lower discount rate increases the number of energy conservation measures that are cost effective, particularly in moderate and mild climates.

The 3% rate was chosen for consistency with the cost assumptions: because the conservation measures were evaluated based on cost to the home-buyer (rather than to the builder) and the fuel prices are those appropriate to home-dwellers, not to the Nation, it is consistant to use capital-borrowing costs to the consumer as the discount rate.

Alternately, one might want to re-calculate cost minima using national parameters: marginal fuel prices, increments for environmental degradation and effects on balance of payments and rational security considerations, manufacturing costs for conservation measures, and a social discount rate. Clearly these parameters are more difficult to evaluate than the consumer-oriented parameters. Preliminary results suggest that the use of parameters based on national impacts would result in equal or tougher standards compared with those based on consumer impacts.

B. Comparison with Approach used to Evaluate Commercial Buildings

The American Institute of Architects/Research Corporation (AIA/RC) performed an analysis of commercial buildings that was used by the Department of Energy in much the same way that our research was used in selecting the Design Energy Budgets 3/. The approach taken by AIA/RC differed markedly from that used for single family residential buildings.

A recent book published by Resources for the Future (RFF), "Energy--the Next Twenty Years," 8/ provides an excellent summary and critique of the approach taken to evaluate commercial buildings. We quote:

> "The statute mandating BEPS requires that the standards be applied at the design stage and regulate the energy performance of a building. The government hired the American Institute of Architects Research Corporation (AIA/RC) to collect the data upon which standards would be developed. AIA/RC selected 1,661 buildings designed shortly after the oil embargo, on the somewhat dubious theory that the architects designing those buildings would have put the state of the art of energy conservation in their design stage. Using a proprietary computer program owned by the Edison Electric Institute, the buildings were "modeled" to calculate how many British thermal units per square foot the buildings would use per year. Unfortunately, the researchers did not go back to see whether the buildings as built performed as the computer predicted... A small sample of the original buildings were selected for redesign. Their original architects were given a three day course in energy conservation and told to redesign the building to save more energy. (The redesign instructions included the important limitation that the new building was not to cost any more than the original building. This instruction eliminated most capital improvements to make the redesigned buildings more energy-efficient, except that capital no longer required for large heating and cooling equipment was freed to be used elsewhere in the building.) Interestingly enough, the computer calculations indicated that four out of five of the redesigned buildings were more energy efficient than all but the top fifth of the designs in the original sample. This

> illustrates the power of paying attention to a problem and learning how to deal with it.
>
> Economic calculations have been notably missing in the process. Cost figures for the changes were not made available, and little attention was paid to the question of money, either in the data-gathering phase or in the analysis..."

The commentary above was evidently written by an economist who would have preferred to see standards set on the basis of minimizing life-cycle costs to society, irrespective of whether that required buildings to be constructed at median energy use or at a level below anything currently being built. But in fact there are many practical similarities between the results of the life-cycle costing methodology for residences and those of the statistical approach used for the commercial sector. In both cases, true minimization of life-cycle cost would involve the use of measures (e.g., residential heat exchangers) or techniques (e.g., daylighting in offices or passive solar techniques in residences) not widely available to building designers and builders, but which could lead to large savings in energy beyond those mandated by the energy budgets chosen by DOE. So for both sectors and both methodologies, the energy budgets are on a declining portion of the cost curve - where more conservation would lead to lower costs - but they are running against constraints of DOE's judgment of the capabilities of the industry at the present time.

Nonetheless, the points made by RFF are of considerable importance and we anticipate that the Department of Energy will note them as they continue the research in support of the final rule. The life-cycle costing of commercial building prototypes is not as easy to perform as that for the residential prototypes. However, such an approach has been initiated at AIA/RC and is likely to provide results that are extremely useful for the final BEPS rule.

III. Results of the Life-Cycle Cost Analysis

A. Houses Heated with Gas

Table 2 contains the detailed results obtained by minimizing the life-cycle costs of energy conservation investment and a discounted stream of payments for fuel over the lifetime of the house mortgage, for a house with natural gas heating (assuming a system efficiency of 70 percent) and electric cooling. The first column lists the climatic regions. The second column presents the representative city for which the thermal analysis of the residence was performed. Columns 3 and 4 show the long-term average heating and cooling degree days for each of the cities. The heating degree days are presented with a base of 65°F and, in parentheses, a base of 53°F. The cooling degree days are presented with a base of 65°F and, in parentheses, a base of 68°F. (The 53°F base for heating and 68°F for cooling are included because space heating and cooling loads for a well-insulated house are expected to be more nearly linear with degree days calculated on this basis than for the traditional base of 65°F.)

Column 5 presents the insulation levels and column 6 the number of glazings in the prototype house which minimized life-cycle costs.* These insulation levels would bring most houses into compliance with the energy budgets. Of course, many other configurations would also comply. Triple glazing is used in climates as cold as Washington, D.C., and in areas with very large cooling load, and double glazing is used in all other climates modeled. Typical insulation levels for all but the extreme climates (coldest or mildest) are R-38 ceiling and R-19 walls. Column 7 contains the estimated increase in

---

*For regions in which a crawl space is the common form of basement, the floor insulation levels are noted in Table 2. For unheated full basements, the assumption is made that heat loss-s and gains balance. Slab on grade and basement construction is assumed to have adequate perimeter insulation, as described in reference 1.

Table 2. Results of the life cycle-cost analysis of energy conservation measures for single story houses heated by natural gas and cooled by electricity

1	2	3	4	5			6	7	8	
				Insulation Levels (R-Value)					**Energy Budget**	
Climate Region	Representative City	Heating Degree Days[a]	Cooling Degree Days[a]	**Ceiling**	**Wall**	**Floor**	Number of Glazings	Conservation Investment, $1978	Primary Energy, MBtu/ft^2/yr.	Building Boundary, MBtu/ft^2/yr
1	Minneapolis	8310 (5260)	530 (370)	38	25	--	3	$1,160	66.1	54.5
2	Chicago	6130 (3540)	930 (620)	38	19	--	3	$ 900	42.9	35.0
3	Portland	4790 (1840)	300 (150)	38	19	19	3	$1,050	30.9	25.9
3	Washington, D.C.	4210 (1980)	1420 (1010)	38	19	--	3	$ 900	33.7	22.4
4	Atlanta	3100 (1230)	1590 (1130)	38	19	11	2	$ 900	28.2	18.3
4	Fresno	2650 (770)	1670 (1220)	38	19	--	2	$ 850	31.9	16.1
5	Burbank	1820 (170)[b]	620 (310)[b]	19	11	--	2	$ 380	15.7	7.2
6	Phoenix[c]	1550 (320)	3510 (2960)	38	19	--	3	$1,280	35.8	12.0
6	Houston	1430 (360)	2890 (2240)	30	11	--	2	$ 520	34.4	15.1
7	Ft. Worth[c]	2830 (810)	2590 (2030)	38	19	--	3	$1,280	32.3	15.2

(a) Heating and cooling degree days base 65°F presented; heating degree days base 53°F in parentheses; cooling degree days base 68°F in parentheses.

(b) Degree days for Los Angeles reported.

(c) Under the EIA Medium Price Projections (December 17, 1978) both Phoenix and Ft. Worth would have used double glazing at a conservation investment of $850. Primary energy use was 40.1 and 36.8 MBtu/ft^2/yr for Phoenix and Ft. Worth, respectively.

investment (for all 1176 square foot house) for the conservation measures compared with current investment in conservation in the different climates. (The estimates of current conservation investment are based on an NAHB survey, results of which are contained in Table 3. 9/ Column 8 contains the energy budget at the life-cycle cost minimum, which we have previously defined as the Design Energy Budget of a house. We have expressed these budgets in terms of primary energy use and use at the building boundary.

There are numerous ways that the Design Energy Budgets can be met in the different climates. Table 4, taken from references 2 and 10, illustrates two or three alternative ways of achieving the Design Energy Budgets in three climates.

B. Houses Heated with Electric Resistance

Table 5 summarizes the life-cycle costing results for electric resistance heating. Columns 5 and 6 show the standard insulation and glazing levels that will meet the designed energy budgets of the nominal case: R-38 ceiling and triple glazing insulation is used in all climates except the most mild (Burbank); R-25 wall insulation is used in all climates as cold as or colder than Washington, D.C. and R-19 wall insulation in all other climates. Thus, in all climates except region 1 (Minneapolis), the standard conservation measures for houses using electric resistance heating are stricter than those for natural gas-heated houses. The investment in energy conservation for the electric resistance heated houses reflects the use of tighter measures for all climates except Minneapolis. The increased investment in energy conservation (beyond estimated 1975 current practice) is between $1,160 and $1,433 for the 1176-$ft^2$ wood frame prototype house.

Table 3. Standard energy conservation measures for residential houses constructed in 1975, based on data from the 1977 NAHB survey

City	Standard Practice, 1975			
	C	W	F	Gl(a)
Minneapolis	22	11	--	2
Chicago	19	11	--	2
Portland	19	11	7	2
Washington, D.C.	19	11	--	2
Atlanta	19	11	7	1
Fresno	19	11	--	1
Burbank	19	11	--	1
Phoenix	19	11	--	1
Houston	19	11	--	1
Ft. Worth	19	11	--	1

(a) C = ceiling R-value; W = wall R-value,
F = floor R-value (if applicable);
Gl = number of glazings for all windows.

Table 4. Illustrative ways of meeting the design energy budgets for single family residences in three locations: gas heated homes

Location	Sets of Options
Chicago, IL	1. Average window area and distribution[a]; triple glazing[b]; R-38 ceiling and R-19 wall insulation.
	2. Windows redistributed so that south facing window area increased by 75% and east, west, and north facing window area decreased by 25%; double glazing; R-38 ceiling and R-9 wall insulation.
	3. Active solar domestic water heating system[d]; double glazing; R-38 ceiling and R-11 wall insulation.
Atlanta, GA	1. Average window area and distribution[a]; double glazing; R-38 ceiling, R-19 wall, and R-11 floor[c] insulation.
	2. Windows redistributed so that south facing window area increased by 75% and east, west, and north facing window area decreased by 25%; double glazing; R-30 ceiling, R-11 wall and R-11 floor insulation.
	3. Active solar domestic water heating system[d]; double glazing; R-19 ceiling, R-11 wall and R-7 floor insulation.
Houston, TX	1. Average window area and distribution[a]; double glazing; R-30 ceiling and R-11 wall insulation.
	2. Active solar domestic water heating[d]; R-19 ceiling and R-11 wall insulation.
	3. Other alternatives, such as passive solar design and redistribution of windows, not evaluated for Houston.

NOTES: [a] The average window area is 15% of total floor area. The windows are distributed equally among the exterior walls.

[b] Double glazing plus storm windows can substitute for triple glazing with little change in the Design Energy Consumption of the house.

[c] Floor insulation is noted in Atlanta, Georgia and all other areas where crawl space basements are used.

[d] The active solar domestic water heating is assumed to be sized at 60% of the water heating load in a 1500 square foot house for the purpose of this illustration.

Table 5. Results of the life-cycle cost analysis of energy conservation measures for single story houses heated and cooled by electric heating (other than heat pumps)

1	2	3	4	5			6	7	8	
				Insulation Levels (R-Value)					Electrical Energy Budget	
Climate Region	Representative City	Heating Degree Days[a]	Cooling Degree Days[a]	Ceiling	Wall	Floor	**Number of Glazings**	Conservation Investment, $1978	Primary Energy, MBtu/ft²/yr	Building Boundary, MBtu/ft²/yr
1	Minneapolis	8310 (5260)	530 (370)	38	25	--	3	$1,160	132.2	38.9
2	Chicago	6130 (3540)	930 (620)	38	25	--	3	$1,190	80.0	23.5
3	Portland	4790 (1840)	300 (1010)	38	25	19	3	$1,350	58.5	17.2
3	Washington, D.C.	4210 (1980)	1420 (1010)	38	25	--	3	$1,190	53.7	15.8
4	Atlanta[c]	3100 (1230)	1590 (1130)	38	19	19	3	$1,433	39.6	11.6
4	Fresno	2650 (770)	1670 (1220)	38	19	--	3	$1,280	38.6	11.4
5	Burbank	1820 (170)[b]	620 (310)[b]	30	19	--	2	$ 760	15.1	4.4
6	Phoenix	1550 (320)	3510 (2960)	38	19	--	3	$1,280	38.5	11.3
6	Houston	1430 (360)	2890 (2240)	38	19	--	3	$1,280	33.6	9.9
7	Ft. Worth	2830 (810)	2590 (2030)	38	19	--	3	$1,280	43.0	12.6

(a) Heating and cooling degree days base 65°F presented; heating degree days base 53°F in parentheses; cooling degree days base 68°F in parentheses.
(b) Degree days for Los Angeles reported.
(c) Under the EIA Medium Price Projections (December 17, 1978) Atlanta used R-11 floor insulation for a conservation investment cost of $1,330 and a primary energy budget of 40.7 MBtu/ft²/yr.

C. Houses Heated and Cooled with Heat Pumps

Table 6 summarizes the life-cycle costing results for heating and cooling with an electric heat pump. Column 8 in table 6 presents the seasonal coefficients of performance (COP) of heat pumps in the heating mode in ten climates. These COPs are based on the simulation of available efficient heat pumps in ten climates by the Oak Ridge National Laboratory 11/. The COP for a heat pump is reported as 10% lower than can presently be achieved by commercial models to account for heat losses in the ductwork associated with the heat pump.

Comparison of the Design Energy Budgets for the electric heat pump (column 9 in Table 6) with electric resistance heating (column 8 in Table 5) reveals that the heat pump budget is lower than the electric resistance budget in almost all cases. The heat pump budget is significantly lower in the cool and cold climates. An economic evaluation of electric heating using heat pumps and using resistance heating indicates that the heat pump system has lower life-cycle costs than resistance heating in cool and cold climates, in spite of the higher first costs of the heat pump 12/.

Table 7 illustrates alternative ways of meeting the Design Energy Budgets that were obtained for homes heated and cooled by heat pumps in three climates 2 and 10/.

D. Comparison with Current and Past Energy Conservation Construction Practice

Figure 1 presents a comparison of fuel requirements for space heating using natural gas for a large number of different cases. The upper curve, labeled "U.S. stock, Dole 1970", is the best available estimate of the fuel requirements for space heating the 1970 stock of houses in the United States 13/. The fourth curve from the top labeled "Current Practice (DOE-2)", is our best estimate of the current construction practice in houses built

Table 6. Results of the life-cycle costing analysis of energy conservation measures for single story houses heated and cooled by electric heat pumps

1	2	3	4	5			6	7	8	9	
Climate Region	Representative City	Heating Degree Days[a]	Cooling Degree Days[a]	Insulation Levels (R-Value)			Number of Glazings	Conservation Investment, $1978	Heat Pump Seasonal COP	Electrical Energy Budget	
				Ceiling	Wall	Floor				Primary Energy, MBtu/ft^2/yr	Building Boundary, MBtu/ft^2/yr
1	Minneapolis	8310 (5260)	530 (370)	38	25	--	3	$1,160	1.38	98.3	28.9
2	Chicago	6130 (3540)	930 (620)	38	25	--	3	$1,190	1.52	54.6	16.1
3	Portland	4790 (1840)	300 (1010)	38	19	19	3	$1,050	1.87	34.9	10.3
3	Washington, D.C.	4210 (1980)	1420 (1010)	38	19	--	3	$ 900	1.79	37.7	11.1
4	Atlanta	3100 (1230)	1590 (1130)	38	19	11	3	$1,330	1.82	27.0	7.9
4	Fresno	2650 (770)	1670 (1220)	38	19	--	3	$1,280	2.02	28.6	8.4
5	Burbank	1820 (170)[b]	620 (310)[b]	30	11	--	2	$ 520	2.02	14.6	4.3
6	Phoenix	1550 (320)	3510 (2960)	38	19	--	3	$1,280	1.92	36.0	10.6
6	Houston	1430 (360)	2890 (2240)	38	19	--	3	$1,280	1.83	28.5	8.4
7	Ft. Worth	2830 (810)	2590 (2030)	38	19	--	3	$1,280	1.83	33.9	10.0

(a) Heating and cooling degree days base 65°F presented; heating degree days base 53°F in parentheses; cooling degree days base 68°F in parentheses.

(b) Degree days for Los Angeles reported.

Table 7. Illustrative ways of meeting the design energy budgets for single family residences in three locations: electric heated homes

Location	Sets of Options
Chicago, IL	1. Average window area and distribution[a]; triple glazing[b]; R-38 ceiling and R-25 wall insulation; heating supplied by a heat pump.
	2. Windows redistributed so that south facing window area increased by 36% and east, west, and north facing window area decreased by 12%; triple glazing; R-38 ceiling and R-19 wall insulation; heating supplied by heat pump.
	3. Active solar domestic water heating system[d]; double glazing; R-38 ceiling and R-25 wall insulation; heating supplied by electric resistance.
Atlanta, GA	1. Average window area and distribution[a]; triple glazing[b]; R-38 ceiling, R-19 wall, and R-11 floor[c] insulation; heating supplied by heat pump.
	2. Windows redistributed so that south facing window area increased by 80% and east, west, and north facing window area decreased by 27%; double glazing; R-38 ceiling, R-19 wall and R-11 floor[c] insulation; heating supplied by heat pump.
	3. Active solar domestic water heating system[d]; double glazing; R-30 ceiling, R-19 wall, and R-11 floor[c] insulation; heating supplied by electric resistance.
Houston, TX	1. Average window area and distribution[a]; triple glazing[b]; R-38 ceiling and R-19 wall insulation; heating supplied by heat pump.
	2. Active solar domestic water heating system[d]; R-19 ceiling and R-11 wall insulation.

NOTES: [a] The average window area is 15% of total floor area. The windows are distributed equally among the exterior walls.

[b] Double glazing plus storm windows can substitute for triple glazing with little change in the Design Energy Consumption of the house.

[c] Floor insulation is noted in Atlanta, Georgia and all other areas where crawl space basements are used.

[d] The active solar domestic water heating is assumed to be sized at 60% of the water heating load in a 1500 square foot house for the purpose of this illustration.

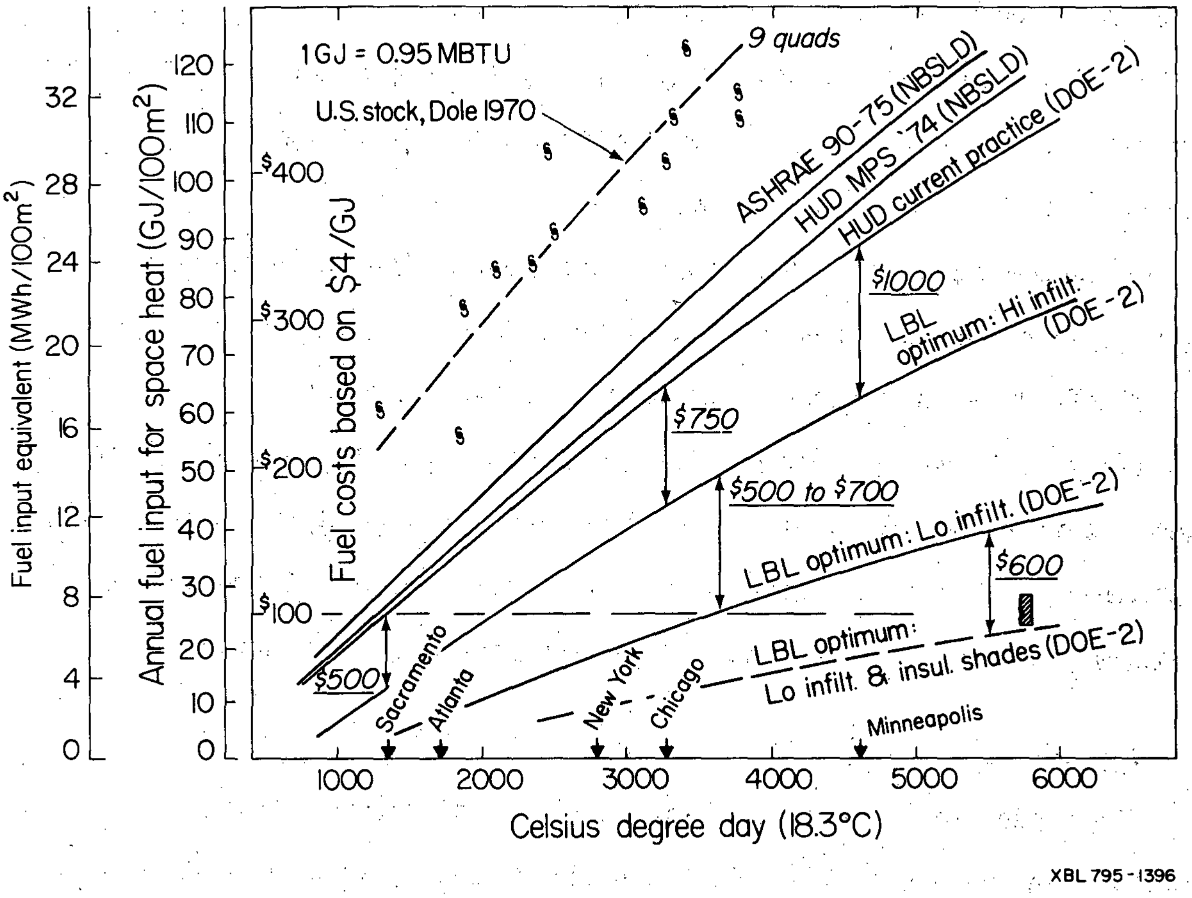


Figure 1. Fuel use for single family residential space heating

after the 1973 oil embargo. This curve is based on survey data for the years 1975 and 1977 and on results of DOE-2 14/ computer calculations performed at LBL 3/.The fifth curve from the top, "labeled LBL optimum medium infiltration," contains the results of life-cycle costing analysis for gas heated houses. The sixth curve, labeled "LBL optimum: low infiltration (DOE-2)", illustrates the energy requirements for a house with infiltration levels reduced from 0.6 to 0.2 air changes per hour. For this case the assumption is made that mechanical ventilation through a heat recuperator restores the outside air exchange rate to 0.6 air changes per hour.

The conclusions from this Figure have been stated in an earlier section of this paper. We note here that the energy savings that can be achieved by cost effective energy conservation measures are enormous. There should be little doubt that U.S. houses can be improved substantially in their thermal performance and that such improvements can save the consumer money. The magnitude of the savings on a national scale are very large and can go a long way toward reducing growth in energy demand in this Nation.

IV. Key Issues

The procedure of using performance standards raises a number of issues of equity and enforceability which are not present with prescriptive standards. Some of these issues revolve around the philosophy of using a performance standard concept, and the objectives of the legislative mandate establishing the standards, (such as the encouragement of renewable energy resources).

Performance standards are a new phenomenon: they are not in wide use anywhere, and even the jurisdictions which have recently established performance standards have had insufficient experience to raise all the important questions. Undoubtedly, the use of nationwide performance standards will spur further debate on issues of fairness and effectiveness of the standards.

option, so that we can evaluate the present value of energy cost savings and compare them with the cost of the measure. Similarly, for compliance with the code, we need to know the relative change in energy consumption of the permit applicant's house compared to that of the prototype house. Again, relative rather than absolute accuracy is important, so long as the same assumptions and simulation models are used in setting and complying with the budget.

The fact that changes in budget level are more important than absolute level explains apparent paradoxes in setting the budget; for example, the fact that lower budget numbers can, under certain circumstances, represent a weaker standard. An example is the effect of assuming that people set their thermostats lower to save energy. This assumption results in a reduction in design energy use, but it also produces smaller energy savings from conservation measures. This reduces the cost effectiveness of the last conservation measure so that it is dropped from the list. The resulting cost-minimizing (i.e., design) energy budget is lower than that in the case where a higher thermostat set point was used, but the standard is weaker because the energy budget represents a house with fewer conservation measures.

Thus, the important result of the energy budget-setting process for residences is the relationship between the budget level and all sets of conservation measures of the house corresponding to it. The energy budget itself has meaning only if rules are provided (prototype descriptions, standard operating conditions, building energy models and accompanying assumptions) to derive the different sets of energy conservation measures consistent with it or to test the compliance of "test" sets of energy conservation measures.

B. Comparisons of Computer Programs to Evaluate Building Energy Use

The cost effectiveness of the energy standards is determined by simulations performed on the DOE-2 building energy analysis model. To what extent can these predictions be relied upon in the real world?

One test for program accuracy is to compare simulations of the same house on different programs. There are a number of public-domain computer programs that model heating and cooling loads of a house. If the results of all the programs agree, then their joint prediction is more credible than that of one program alone. And if they disagree, the form of discrepancy can often provide insight into the building heat transfer problem or to possible errors in the computer programs.

We have compared the results of DOE-1 and DOE-2 with simulations of TWOZONE and BLAST performed at LBL and on NBSLD runs performed at NBS and LBL. The results of several tests show generally good agreement (± 10%) between all programs for ordinary houses in which solar gains are small compared to total heating load 18,19/.

More recent results have considerably reduced the discrepancy between TWOZONE and DOE-2 on cooling loads, and also somewhat lessened the disagreement on heating loads in warm sunny climates. We have also found good agreement between DOE-2, NBSLD, and TWOZONE for masonry buildings 1/.

There continues to be a need for the comparison of the computer results with the energy consumption of a statistical aggregate of residential buildings. Although spot checks, often on test houses, have shown good agreement, the study of a large statistical sample would provide important information about the relationship between the predicted energy budgets and those obtained (or likely to be obtained) in the real world. This information is particularly important in assessing the degree to which BEPS or other energy conservation policy initiatives is likely to result in actual reductions in energy use. We have undertaken some modest work along these lines and we anticipate that DOE will support a more extensive data gathering and analysis program during the implementation of BEPS.

C. Passive Solar Credits

One key argument for the use of performance standards instead of prescriptive standards is the ability of performance standards to credit passive solar techniques. For instance, in a performance standard, a builder can use solar gains from south windows as a way of compensating for extra heat loss through other features (say, extra-large north-facing windows).

Given an evaluation methodology--for example the DOE-2 program and a set of assumptions--the performance standard provides a credit for passive techniques to the extent that the program correctly handles the heat flows in passive systems. Present evidence suggests that DOE-2 shows significant savings potentials from direct-gain passive systems in all climates, although DOE-2 may underestimate these savings. The savings predictions appear to be larger than those in other public-domain programs, such as BLAST, NBSLD, and TWOZONE. Therefore the use of the performance standard methodology will result in credits for passive solar. (It may also, we hope, result in improvements in DOE-2 and other computer programs so that passive solar systems are more accurately simulated.)

To be useful, these credits must be evaluated in simplified form so that they can be used in tradeoff analysis with simple techniques such as design-heat-loss methods, for the majority of builders who will not use DOE-2.

In use, the passive solar buildings will probably use less energy than other buildings which comply with the energy budgets. Passive houses perform better as the thermostat "float" range is increased. The 8°F float band used in the evaluation methodology 2/ is too small to take full advantage of the heat storage in a passive building. However crediting the passive buildings with their full potential savings in use is, in our judgment, not appropriate for several reasons. First, it is inequitable to allow buildings labelled "passive" to take credit for changes in lifestyle (e.g. lower thermostat set points) which are denied to other houses. Second, if larger credits are given, they will be used to trade off passive against lower insulation levels. This reduction in insulation levels will move the passive house away from its own cost optimum. A passive building which used as much energy with widely floating thermostat as a conventional house with conventional thermostat would be a very leaky building. If subsequent occupants tried to heat it to 70°F, they would find it to be much more inefficient than the conventional home!

Optimum passive houses will not necessarily have minimum Design Energy Budgets. A given passive house will probably fall somewhat below the (non-passive) prototype in terms of Design Energy Budget, but will consume substantially less energy in use. Another passive house may have an even lower budget but higher energy use. That is, passive will turn out to be a better way of saving energy than of complying with the budget. But the budget evaluation methodology will assure that a passive house will not use more energy for space conditioning than a conventional house even under conventional operating schedules.

D. Compliance with the Energy Budgets

Energy budgets are derived by running a prototype house description with a set of assumptions through a building simulation model. Compliance can be demonstrated, in principle, by the same procedure: the proposed house design is run through the simulation model with the same set of assumptions, and the resulting energy use determines whether the proposed design complies.

In practice, we expect that very few buildings will use a procedure this complex. Most builders will probably just use the equivalent insulation standards in the optima. When variations are made from the insulation levels the variations are likely to be simple. For example, more window area may be traded against more insulation, or less insulation in one element may trade off against more in another. These tradeoffs can probably be handled by simple design-heat-loss techniques; further analysis of the simulation model results will test this presumption.

More complicated tradeoffs, such as variations in window orientation, shading, and building mass, can be handled by the simulation model. It is desirable to develop simple tradeoff rules based on these simulations.

Other tradeoffs may be beyond the scope of the building model. Changes in landscaping or ground contours to minimize wind pressure on the house can have a large impact on energy use through reductions in infiltration. However, present building simulation models are incapable of computing the magnitude of these effects. The enforcement agency will have to develop appropriate methods for treating these types of measures; otherwise each builder will attempt to use a different method to qualify his particular energy-saving option, and the same measure will be handled inconsistently by different building code officials, resulting in extra analytic work and inequitable treatment of some builders.

This example illustrates one of the problems inherent in a performance standard: the tools for establishing compliance will never be able to model all the newest innovations in design. Code officials are often resistant to innovations where effectiveness cannot be simply and conclusively proved. Since one of the purposes of the performance standard is to foster innovation, there is a need to develop a process whereby the approval of innovations is facilitated. One suggestion is to provide an intermediary to help the innovator obtain approval from the building code official (if appropriate). Another approach could be to have a process to screen innovations to select those that appear both significant (in terms of potential energy savings), widely applicable to many buildings, and sufficiently complex to require careful analysis by DOE. A preliminary analysis in a specified time period could result in approval for all buidlings begun before final results are obtained. Other approaches need be developed to insure the BEPS fosters rather than retards innovative energy conservation techniques in buildings.

E. How Many Energy Budgets are Needed?

The process of life-cycle cost minimization involves altering certain qualities of a house in order to save energy. Inherent in the process is the division of building properties into two classes: those that can be adjusted in the optimization process (e.g. insulation levels and number of glazings) and those that are held fixed (e.g. house shape, house construction). The choice of which items to hold fixed and what values to use for the fixed parameters will affect the level of budget; each different choice will produce a different Design Energy Budget.

There are two approaches to handling a "fixed" parameter. One is to require that all houses comply with a budget derived using one value of that parameter; the other is to derive separate budgets for buildings with different values of the parameter.

The first approach has several advantages. Foremost among them is its flexibility. The reason for using an analytically complex performance standard in place of a simple prescriptive standard is to increase the builder's flexibility

We discuss below some of the issues which have become apparent during the analysis of residential standards.

A. Significance of the Energy Budget

The energy budget provides a means of comparing different designs of buildings in terms of their energy consumption. It is based on a "design" calculation--that is, it is a calculation based on variations in design parameters of the building, rather than on changes in behavior of its occupants. There is no implication that a building with a design energy budget of 40 thousand Btu/sq. ft./yr. will be required to use 40 thousand Btu/sq. ft. annually. The energy budget merely represents the amount of energy the building would be expected to use if operated under standard conditions.

The magnitude of the budget depends on the assumptions incorporated within or used as input to the building energy use simulation model. Frequently, a few apparently minor changes in the assumptions can produce significant changes in the energy budget. This dependence on model assumptions is less important than it may seem: what is important is not the actual budget number but the set or sets of energy conservation measures consistant with a given energy budget. That is, a budget of 40 thousand Btu/sq. ft./yr. really represents the set of all buildings which, when simulated on the building model with standard assumptions, result in a prediction of 40 thousand Btu/sq. ft. of annual energy use. All buildings whose predicted energy use is less than 40 thousand Btu/sq. ft. are considered in compliance with this budget, while buildings with predicted energy use in excess of this budget fail to comply.

We see from this discussion that the <u>absolute</u> accuracy of the model, and the degree of realism of the assumptions, are not nearly as important as the <u>relative</u> accuracy. For the purpose of life-cycle cost modeling, we require accurate predictions of the <u>changes</u> in energy use which result from a conservation in complying by allowing him to trade off non-compliance with prescriptive limits in some areas against overcompliance or design change in others. Setting separate budgets for separate values of some parameter eliminates the builders ability to use that parameter. The single-budget approach (for each weather region) is also much easier to derive and administer, because only one benefit/cost analysis is required and each applicant in a given region has a single target to be hit.

The second approach--different budgets for each value of the fixed parameter--has the advantage of increased fairness and political acceptability. For example, if a certain type of house cannot feasibly comply with a single standard, then a separate standard for that type of house which is set at <u>its own</u> cost minimum will result in greater political acceptability of the standard, and less government interference into people's selection of housing type.

The drawback of the second approach is in its administration. Whenever a criterion is used to differentiate between houses with different energy budgets, some applicant will come in with an intermediate case. For example, if there are separate budgets for one-story and two-story house, how does one treat a case with a 100-ft^2 second-floor room over a 3000-ft^2 first floor? If there are separate standards for gas heat and electric heat, how does one classify an electric heat pump with gas supplementary heat?

There are many possible features for which people have suggested separate energy budgets. These include frame and masonry construction, full basement vs. crawl space or slab floor, two-story houses, one-story houses, split-levels, bi-levels, townhouses, houses with large aspect ratios, houses with large windows areas, sites without solar access, gas-heated or electric resistance-heated houses, houses using heat pumps or oil heat, houses without air-conditioning, houses with evaporative coolers, houses with many bedrooms, houses with special solar features, and other criteria. If all of these suggestions were used, the "performance" nature of the standards would be undermined and setting the standards would involve immense analytic effort.

Resolution of the question of whether separate energy budgets are needed will depend in part on the quantitative difference between the Design Energy Budgets and accompanying sets of energy conservation measures for different values of parameters.

If the selection of the value of a given parameter has little effect on the Design Energy Budget of the building, then one may fix the parameter in question. If, on the other hand, the value of the parameter has a large effect on the Design Energy Budget, then the best decision is not apparent.

For example, our analysis shows that changes in house type, house size, and wall construction (frame or masonry) have only small effects (< 10%) on the energy budget, so that separate budgets may be unnecessary. The difference between heat pump energy budgets and those for gas heat is somewhat larger, with heat pumps 10-20% higher (using price-weighted energy) than gas furnaces in most climates, but over 40% higher in the coldest climates.

F. How Are Energy Budgets for Different Fuels Compared?

Great controversy has surrounded the question of how to compare the energy budgets for different fuels. Two measures are commonly used: building boundary energy and resource energy. This report also discusses a third measure: price-weighted energy.

The building boundary approach counts the energy content of fuels as they cross the building boundary. Oil and gas are counted as the energy content of fuel sold to the building while electricity is counted as the heat content of the electric energy transferred past the electric meter.

The resource (or primary) energy approach is based on the desire to conserve energy resources rather than the amount of processed energy sold. This approach counts the original energy needed to produce the energy sold. Simple applications of this approach, such as that used in the California standards (California Administrative Code Title 24) count gas and oil exactly as is done in building-boundary accounting methods, but multiply the heat content of electricity by 3 to account for the thermal efficiency of the power plant.

Critics of the resource energy approach have argued that it is oversimplified--that to be fair, we must go farther back through the economy and include the efficiency of mining, processing, and transporting fuels, including extraction efficiencies, and that too little is known about the whole process to evaluate the resource use factors (resource energy use per unit building boundary fuel).

Proponents of the building boundary approach also point out that the electric resource use factor of 3 will encourage the use of scarce gas and oil fuels over electricity. But the resource energy proponents insist that the factor of 3 is necessary because electricity isn't a primary fuel, and that one unit of electricity is worth more than a unit of fuel because it has been converted to a lower entropy form.

A third approach that reduces some of the problems is the price-weighted energy method. In this method, one fuel, say gas, is counted at building-boundary levels and other fuels are weighted by their price relative to gas. The price-weighted method is most consistent with the approach of basing energy budgets on life-cycle cost minima taken in the rest of the performance standard analysis, because it results in energy budgets being directly proportional to life-cycle fuel costs. If energy budgets are proportional to fuel costs, then tradeoffs in the building that use an extra price-weighted unit of one fuel in exchange for one less price-weighted unit of another fuel will result in no change in either the energy budget or the fuel costs. Thus, the building designer will be encouraged to make his building design to achieve compliance with the standard in a cost-effective manner if a price-weighting method is used to express the design energy budget of a building.

The price-weighted factors satisfy the objection that the building boundary approach allows the substitution of expensive electricity for cheaper primary fuels. The price-weighting approach also avoids valueing 1 Btu of coal exactly the same as 1 Btu of gas or 1 Btu of oil.

Further, if the government seeks to reduce consumption of a specific fuel, say oil, then it can act as if this fuel had a higher price. This price will affect the energy budget weight, but it will also affect the tradeoffs between use of the fuel and conservation measures. Thus saving a scarce fuel by fuel substitution can be treated on a uniform economic basis with saving the fuel by conservation.

V. Ongoing Research

Continuing analysis addresses a number of specific technical issues involved in the process of standard setting for the energy performance of new single family residential buildings. These include:

- assessment of the effect of jointly setting appliance (including heating and cooling equipment) and building shell energy performance standards
- analysis of the seasonal efficiencies of heating and cooling equipment in different weather regions and in houses with varying amounts of energy conservation
- development of two new single family residential prototypes: single story heated basement; townhouse attached on one side
- continued analysis of the thermal performance of masonry houses

- sensitivity studies of the effects of changing window orientation, size, conservation measures, and internal thermal mass
- assessment of the energy requirements of "zoned" houses in which electric resistance heating is operated on a schedule in which the heat is turned off in selected rooms much of the time
- advanced energy conservation options, including reduced infiltration with a heat recuperator to avoid indoor air quality problems
- comparison of computer calculations of residential building energy requirements with measured data

These technical issues have been selected because they are important to the formulation of a final rule for the Department of Energy Building Energy Performance Standards. The proposed rule, issued in November, 1979, used the results of the analysis of residential life-cycle costs that are presented in this paper. We anticipate that the final rule will also reflect additional knowledge and information gained by the continuing analysis of the issues identified above. Many individuals, including some who are otherwise opposed to the issuance of standards for energy use in buildings, have noted that one of the most important results of the process of developing the standards has been an increased knowledge of the thermal behavior of buildings, the conservation measures that are cost effective in different regions of the Nation, and the holes in our knowledge that are needed to produce better standards in the future. To the extent that the results of the many studies being done for the Department of Energy on the building standards become widely available to the building and design communities, the standards could be effective even without a heroic effort to implement them.

REFERENCES

1. Pacific Northwest Laboratory, Lawrence Berkeley Laboratory, and Oak Ridge National Laboratory, "Economic Analysis of Proposed Building Energy Performance Standards," PNL-3044, September, 1979, (Chapter 4 and appendices A and I by M. D. Levine and D. B. Goldstein).

2. U.S. Department of Energy, "Notice of Proposed Rulemaking for the Building Energy Performance Standards," in press, 1979.

3. American Institute of Architects, "Phase Two Report - for the development of Energy Performance Standards for New Buildings: Commercial and Multi-Family Residential Buildings, 1979.

4. L. J. Schipper, J. Hollander, M. D. Levine, and P. P. Craig, "The National Energy Conservation Policy Act: An Evaluation," Natural Resources Journal, in press, 1979.

5. D. B. Goldstein, M. D. Levine, and J. Mass, "Residential Energy Performance Standards: Methodology and Assumptions," LBL-9110, in press, 1979.

6. S. R. Hastings, "Three Proposed Typical House Designs for Energy Conservation Research," NBSIR, 77-1309, 1977.

7. P. R. Achenbach and C. W. Coblentz, "Field Measurements of Air Infiltration in Ten Electrically Heated Houses," ASHRAE Transactions 69, 1963.

8. Resources for the Future, "Energy: The Next Twenty Years," 1979.

9. National Association of Homebuilders, "A National Survey of Characteristics and Construction Practices for all Types of One Family Houses," 1977.

10. M. D. Levine, D. B. Goldstein, and D. O'Neal, "Residential Energy Performance Standards: Comparison of HUD Minimum Property Standards and DOE's Proposed Standards," LBL-9817, in press, 1979.

11. Dennis O'Neal, personal communication to the authors, August, 1979.

12. See reference 1, Appendix I.

13. A. H. Rosenfeld, W. G. Colborne, C. D. Hollowell, L. J. Schipper, Bo Adamson, M. Cadiergues, Gilles Olive, Bengt Hidemark, G. S. Leighton, H. Ross, N. Milbank, and M. J. Uyttenbroeck, "Building Energy Use Compilation and Analysis (BECA): An International Comparison and Critical Review," LBL-8912, July 1979.

14. M. Lokmanhekim, et. al., "DOE-2: A New State-Of-The-Art Computer Program for the Energy Utilization Analysis of Buildings", presented at the Second International CIB Symposium on Energy Conservation in the Built Environment, Copenhagen, Denmark, May 28 - June 1, 1979.

REFERENCES (cont.)

15. A. J. Gadgil et. al., "TWOZONE User's Manual," LBL-6840, 1978.

16. BLAST - The Buildings Loads Analysis and System Thermodynamics Program, Published by CERL, Technical Report E-153, June 1979.

17. T. Kusuda, NBSLD, Computer Program for Heating and Cooling Loads in Buildings," NBS Build-Science Series 69 (1976).

18. A. Gadgil, D. Goldstein, R. Kammerud, and J. Mass, "Residential Building Simulation Model Comparison Using Several Building Energy Analysis Programs," Proceedings of the Fourth National Passive Solar Conference, Kansis City, Oct. 1979.

19. A. Gadgil, D. Goldstein, and J. Mass, "A Heating and Cooling Loads Comparison of Three Building Simulation Models for Residences: TWOZONE, DOE-1 and NBSLD," Proceedings of the International Conference on Energy Use Management II, Los Angeles, Oct. 1979.

This work was supported by the Conservation/Solar Division of the U. S. Department of Energy under Contract W-7405-ENG-48.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720