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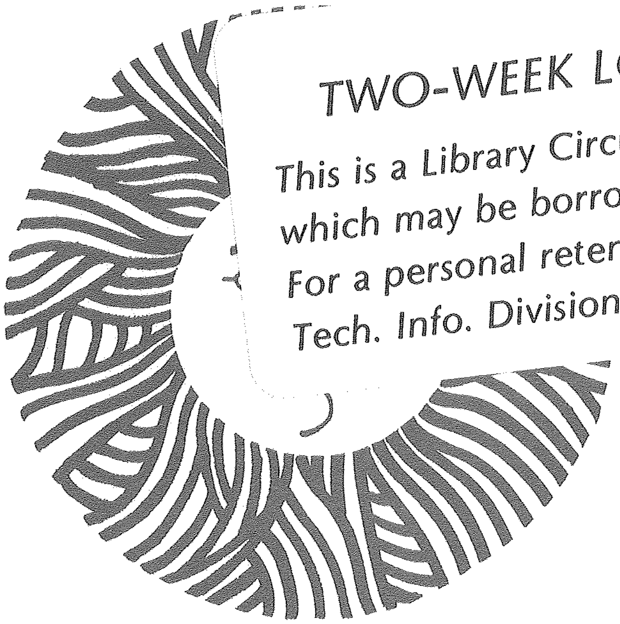

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DISCLAIMER

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ABSTRACT

One important requirement emerging from national and international efforts to shift from our present energy-intensive way of life to an energy conservation mode is the development of standards for assessing and regulating energy use and performance in buildings. This paper describes a life-cycle-cost approach to Building Energy Performance Standards (BEPS) calculated by using DOE-2: The Energy Use Analysis of Buildings Computer Program. The procedure outlined raises important questions that must be answered before the energy budgets devised from this approach can be reliably used as a policy tool. The DOE-2 program was used to calculate the energy consumption in prototype buildings and in their modified versions in which energy conservation measures were effected. The energy use of a modified building with lowest life-cycle-cost determines the energy budget for all buildings of that type. These calculations were based on a number of assumptions that may be controversial. They are contained in the questions listed below, each of which is elaborated in the text of the paper.

<u>Accuracy of the Model</u>. How reliable is the model on which the simulation results are based? Can the results be easily duplicated?

<u>Comparison of the DOE-2 Program With Other Programs</u>. Do other major programs yield the same results as DOE-2? If not, are significant trends reflected in the disagreements? Can builders comply with the energy budget by relying on other programs and simplified methods?

<u>Stability of the Energy Budget</u>. Is the energy budget sensitive to differences in building styles? What impact might such differences have on:

1) Compliance with the recommended budget?
2) Cost effectiveness of conservation measures?

<u>Sensitivity of the Results to Variations in Building Parameters</u>. How does building size affect the selection of appropriate conservation measures and the energy budget? To what extent can changes in building design features be traded off against insulation to comply with an energy budget?

In this paper, buildings are considered "residential buildings"

KEYWORDS

Residential buildings; energy budget; energy use; building energy performance standards; life-cycle-cost; energy use analysis of buildings computer program.

INTRODUCTION

The DOE-2 program (Lokmanhekim, et.al., 1978, 1979) is the latest version in a series of computer programs for hourly energy use analysis of buildings (Lokmanhekim, 1978). It has been developed as an accurate, easy-to-use, state-of-the-art public-domain program, and can be used in two distinct ways in the establishment and enforcement of building energy performance standards. First , the program provides a common measure of energy performance in a building, by allowing the computation of a one-parameter description of the building, the energy budget. This parameter can be used to compare different building designs for checking compliance with the standards. Second, the program can be used as the basis of a life-cycle-cost approach to setting the building energy performance standards. Energy use of a variety of configurations of a prototype building can be computed using DOE-2. By adding some economic assumptions (e.g., cost of each building configuration and present value of the fuel used), one building will be found to have lowest life-cycle-cost. Then, the energy use of that configuration can be used as the energy performance standard.

This paper describes both applications of the program. The second application, the derivation of lowest life-cycle-cost building configurations, is relatively straight forward. However, the first application, comparison of different buildings, raises some complex philosophical issues of equity in enforcing a standard.

METHODOLOGY

Life-Cycle Cost Approach for Setting Building Energy Performance Standards

Energy conservation in buildings can be achieved through either lifestyle or technical changes. Technical conservation measures, such as more insulation or multiple glazing, save energy by investing capital in conservation, with no change in amenities for occupants and no requirements of extra effort. If the capital investments can be amortized by the energy cost savings, then no net losses are incurred by the building owner. The required technical conservation measures are invisible and their cost is repaid to the consumer over the life of the building.

The life-cycle-cost approach allows the calculation of an optimum level of energy conservation investments. For a given set of possible conservation measures, a building is first modelled using a loose base insulation level. Next, one conservation measure is added and the building is modelled again. Costs of the measure are compared with the present value of energy savings due to that measure. Each possible measure is tested, and the one with the highest benefit-to-cost ratio is chosen. To add a second conservation measure, all remaining measures are modelled again, with the first measure already in place; the remaining measure with highest benefit-to-cost ratio is then accepted. This process continues until a measure is found where the costs exceed the benefits. The optimum is then the combination of measures obtained by applying the last measure with benefit-to-cost ratio greater than one. Thus, with this approach, the combination of measures which minimizes life cycle cost to the consumer is selected.

Specifics of the Methodology Assumptions

To calculate energy consumption of a building using the DOE-2 program, one must select one prototype (or several) and determine the energy consumption of that prototype under a set of assumptions concerning construction practice and operational characteristics. In addition, a myriad of other assumptions are needed, both to calculate energy consumption on DOE-2, and to analyze the economics of the results. The key assumptions invole the design of the prototypes , the range of conservation measures to be considered, the building operating conditions, economic data and projections (Levine, et.al., 1979, Goldstein, et.al., 1980).

Each prototype can be adjusted to minimum life-cycle-cost using a set of conservation measures. The result of this exercise is a set of energy budgets for different climates, tied to a set of conservation options (equivalent to prescriptive standards) which produced the budget. A sensitivity study (PNL-3044, 1979) has established that for normal variations in building design and size, for both one-story and two-story prototypes, the energy budget is approximately constant. This near-constancy is necessary for the standard to be equitable; if one style of building has a substantially different budget than another, then the budget for intermediate cases, or for cases not explicitly studied, is likely to be too tight or too loose. The near- constancy of energy budgets is partly fortuitous, and partly a result of assumptions which were made to this end. It is conceivable that for some cases it might be impossible to specify a unit energy budget without creating large inequities.

Results of the Methodology

The results of the life-cycle-cost approach will be a set of energy budgets which correspond to the least-cost configuration of each prototype building. In addition, the DOE-2 program will have produced estimates of heating and cooling energy use. To apply these results to a performance standard, they must be analyzed in terms of the following questions:

How do the Results of Different Prototypes, or Different Variations From a Given Prototype, Compare? To discuss this question, a common measure for energy budgets of different buildings must be used. The most usual and simple approach is to compare the energy budget per unit floor area of building. If this measure is nearly equal for all prototypes and for key variations of each prototype, then the budget can easily be set at that common level. If there is not good agreement, then more thought is needed.

How Are Heating and Cooling Energy Use Estimates Added to Produce A Single Parameter Energy Budget? If heating and cooling are done with different fuels, the energy used for heating and cooling must be added according to some formula. A number of approaches to this issue have been proposed; they all require assigning some weights to a Joule of each type of fuel. It has been shown that a price-weighted energy approach (similar to that proposed by the U.S. Department of Energy) is most consistent with the principles of the life-cycle cost approach.

What are the practical consequences of requiring all residential buildings to conform to the performance standards? Will there be special cases of buildings which will be effectively banned by the standards, or which will behave differently than the prototype? What allowance, if any is, to be made for them?

ISSUES

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 behavioral properties of its occupants. Energy budgets are not energy rations--there is no implication that a building with a design energy budget of 40 GJ/yr will be required to use 40 GJ/yr or less 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 highly on the model used for building simulation and on the assumptions. Frequently, a few apparent minor changes in the model or the assumptions can produce significant changes in the energy budget. But this dependence on model and assumptions is not important, because the budget, since it is not a ration, has no <u>direct</u> physical significance. What is important is not the actual budget number, but the building designs it represents. That is, a budget of 40 GJ/yr really represents the set of all buildings which, when simulated on the model with standard assumptions, result in a prediction of 40 GJ of annual energy use.

There are several apparent paradoxes in setting the budget. Consider the effect of assuming that people set their thermostats lower to save energy. This assumption results in less design energy use, but it also produces lower energy cost savings from conservation measures. This lower energy cost savings frequently results in the last conservation measure becoming non-cost-effective. The resulting cost-minimizing energy budget may still be lower than that in the case where a higher thermostat setting was used, but the standard is weaker because the energy budget represents a building with fewer conservation measures.

<u>Departures of Performance Standards from Life-Cycle-Cost Minimization</u>

Performance standards are different in nature from prescriptive standards in that the objective is to save energy, not necessarily to minimize cost. Either type of standard will both save energy and minimize cost for those buildings which resemble the prototypes. But for buildings which depart significantly from the prototype, the performance standard is met solely on energy-use criteria without regard to cost-minimization.

For example, suppose a building design called for locating all the windows on the north and west elevations, resulting in increased cooling loads as well as increased heating loads. To comply with the prescriptive code, the building would simply require "optimal" insulation levels. But to comply with a performance standard, the insulation (or HVAC systems) would have to go well beyond the optimum to compensate for the energy "wasted" by the desired window orientation. The trade-offs would be solely on the basis of the energy budgets, irrespective of first cost.

The energy budget approach has both advantages and disadvantages in terms of economic efficiency and equity. The disadvantage is that in any individual case it may not result in minimum life-cycle-cost. But the advantage is that it allows the designer more freedom to do something "non-optimally" as long as the energy waste due to such non-optimality is compensated somewhere else in the design. In the long run, the performance standards may also result in lower costs, because innovative technologies may be developed for meeting the energy budget more cheaply.

This flexibility is the major motivating force behind performance standards. Since the objective of the standard is expressed in performance terms and is to save energy rather than money, the variation in a number of energy-related features can be exploited by designers without the need for the policy maker to look at the cost implications of the feature. For example, an architect can alter the floor plan of the structure to provide more south-facing windows and reduce energy use. This option could not be studied by the user of a prescriptive standard, because the costs, and possible loss of amenity, would be different for each individual building design.

Flexibility is maximized by adopting only a few energy budgets. That is, if there are separate budgets for, say, masonry buildings and frame buildings, then the designer is no longer free to trade off construction materials against other features. It has been suggested by different people that separate energy budgets be established for different house shapes, styles, basement types, wall construction, site orientation, fuel and equipment type, window area, etc. Carried to this extreme, the performance standard reverts to a prescriptive standard, since wherever a feature is used to discriminate between buildings, it can no longer be used as a design tradeoff.

Inter-Program Comparisons

One good test to determine the accuracy of the models is to compare simulations of the same building on different computer programs. This is considerably cheaper than actual measurements. There are a number of public-domain computer programs which can calculate heating and cooling loads and energy consumption of a building. If the results of all the programs agree, then their joint prediction is more credible than that of one program alone. If they disagree, the form of discrepancy can often provide insight into the building heat transfer problems, or to possible errors in a program.

The results of DOE-1 and DOE-2 runs were compared with TWOZONE, BLAST, and NBSLD results. The comparisons show generally a good agreement (±10%) between all programs for ordinary buildings in which solar gains are small compared to total heating load (Gadgil, et.al., 1979, 2 papers), (Carroll, 1979).

Comparisons Between Energy Budgets for Different Fuels: Price-Weighted Energy Factors

Great controversy has surrounded the question of how to compare energy budgets for different fuels. Two approaches are commonly used: building boundary energy, and resource energy. The proposed rule on Energy Performance Standards for New Buildings (DOE, 1979) uses a third approach: price-weighted energy factors.

The building boundary energy approach counts the energy content of fuels or electricity as they cross the building boundary.

The resource energy approach is based on the theory that energy budgets are designed to conserve energy resources rather than the amount of processed energy sold, so it counts the original energy needed to produce the energy sold. This approach generally counts gas and oil exactly as is done in building-boundary energy approach, but multiplies the energy content of electricity by a number approximately equal to 3 to account for the thermal efficiency of the power plant.

Proponents of the building boundary energy approach worry that the electric resource use factor of 3 will encourage the use of scarce gas and oil over electricity. But the resource energy proponents insist that the factor of 3 is necessary because electricity is not a primary fuel, and that 1 unit of electricity is worth more than a unit of fuel because it has been converted to a lower entropy form.

A third approach which reduces some of the problem is the price-weighted energy factors 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 (on a life-cycle-cost basis). The price-weighted energy factors method is most consistent with the cost-minimization approach taken in the rest of the performance standard analysis, because it results in energy budgets being directly propotional to life-cycle cost. To implement price-weighted energy factors in a way that provides optimal economic incentives for tradeoffs between different fuels, one should compute the present value of 30 years of saving 1 GJ of fuel per yer. This is given by the product of the uniform present worth factor for the fuel (including the effects of fuel price escalation) times the first year fuel cost. Using the data in PNL-3044, the following weighting factors were obtained: 1.46 for oil, and 3.13 for electricity. These are close but not identical to the Department of Energy's weighting factors (DOE, 1979): 1.22 for oil and 2.79 for electricity.

These factors are numerically close to the resource energy factors, because the economics of electricity production are comparable to the thermo-dynamics: not only does it take 3 Joule of fuel to produce 1 Joule of electricity, but that 1 Joules also costs as much (to the consumer) as 3 Joules of fuel.

Passive Solar Buildings and the Building Energy Performance Standards

There are a number of special problems with implementing passive solar techniques as part of an energy performance standard, from both a political and technical viewpoint.

In terms of policy, passive solar buildings cannot easily be promoted or required by an energy performance standard. This limitation is due in large part to equity considerations (not every building has solar exposure). In addition, the criteria for evaluating passive solar buildings in comparison to "normal" buildings are unclear.

The process of optimizing a passive solar building is more difficult as well, because there are several different definitions of "optimum", particularly in milder climates. The usual definition of optimum is that combination of features which minimizes life-cycle-cost for a given thermostat setting. But passive buildings are often operated in a way that allows large temperature swings -- such as 15°C to 30°C. If two buildings both use the same amount of energy in staying within this range, but one of them almost always stays warmer than 18°C, then this warmer building is closer to optimum. But what if the other requires less heat to stay at 21°C? At the present, the methodology making this determination of the optimum building has not been developed.

Another problem arises in passive solar buildings regarding the modelling of user-operated devices, such as insulated shutters. To what extent should the building modelling assume that the residents will employ the devices? It has been traditional to ignore the effect of any device which is not automatic. This tradition seems unreasonable in that it disallows credit for some very cheap and effective conservation devices; on the other hand, the assumption of 100% reliable operation of these devices is also unrealistic. The issue of exactly how to credit user-operated devices must be resolved before passive solar techniques become part of the energy performance standards.

QUANTITATIVE RESULTS OF THE LIFE-CYCLE COST APPROACH

The results obtained by applying the methodology outlined above are compared to current building practices in Fig. 1. Figure 1 shows heating energy use as a function of degree days. The top curve, labelled U.S. stock, describes the actual fuel sold for space heating per building based on Dole's analysis of 1970 data. The curve labelled HUD current practice, gives the results of DOE-2 simulations of buildings which are typical of 1975 average construction practices by large builders.

The cost-minimizing buildings, as determined by the life-cycle cost approach, are given by the two curves labelled "LBL optimum", at medium (existing) infiltration, and with low infiltration and heat exchangers. The low infiltration measure is cost-effective above about 1500°C degree-days, but will not be used in the 1980 energy budgets chosen by the U.S. Department of Energy, due to inadequate availability of heat exchangers in the U. S. A. By 1985, low infiltration can probably be mandated.

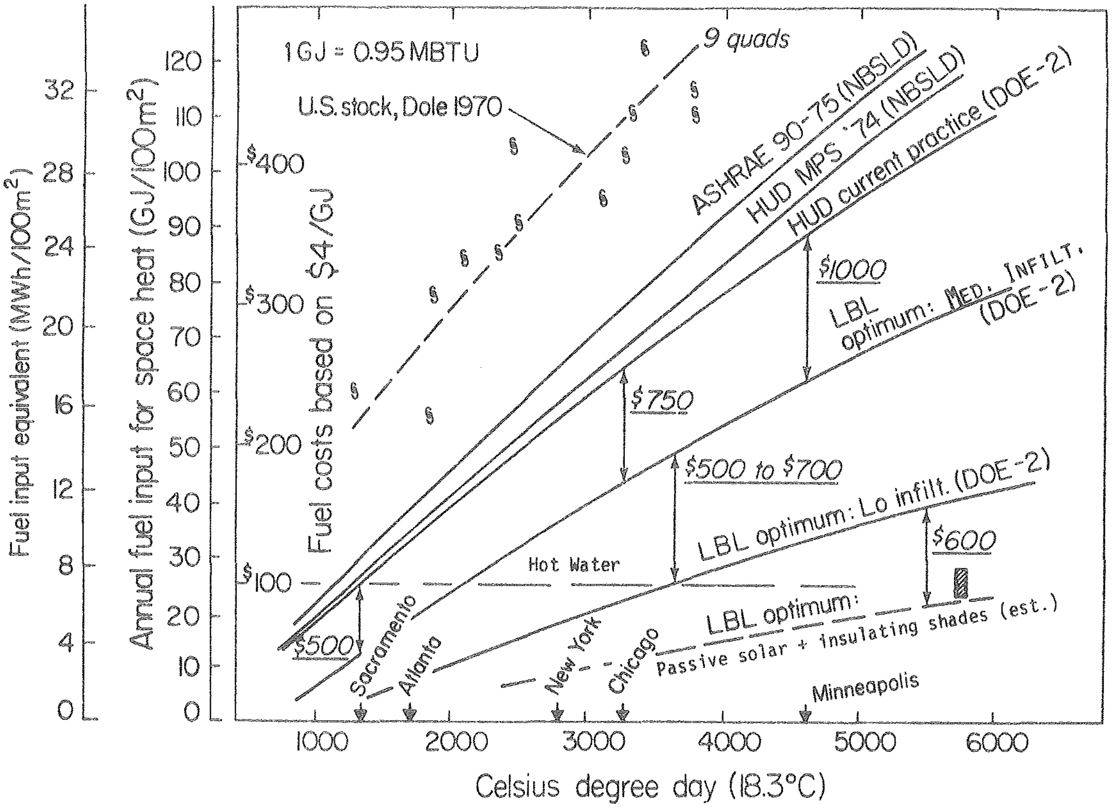

Figure 1. Heating Energy Use A Function of Degree Days For Single Family Residential Buildings in the U.S.A.

The cost-minimizing buildings (LBL optimum at medium infiltration) use substantially more conservation measures than existing buildings and have energy budgets about one-third lower than HUD current practice. Most of the conservation measures studied are cost-effective in most climates; only in the southern-most American climates does the cost curve have a clear minimum.

The lowest line, labelled "Passive Solar and Insulating Shades" shows an interesting option. For example, with another \$400-\$600 investment, space heating can be reduced to about 10 GJ/year in Chicago. 10 GJ (about 1/3 of what an American residential building currently uses for domestic hot water) costs currently about \$50/year. This makes it evident that no need is left for active solar collectors for space heating, although solar domestic hot water remains attractive.

Typical conservation measures used are as follows:

For gas and heat-pump-heated buildings, triple glazing is used in climates as cold as Washington, D.C., and in areas with very large cooling loads, and double glazing is used in all other climates modelled. Typical insulation levels for all but the coldest or most mild climates were R-7 for ceiling and R-3.5 for walls. For the seasonal efficiency of the furnace, 70% is used.

Electric-resistance-heated buildings have tighter conservation measures, but because of the high price of electricity, the energy budget (in units of price-weighted energy factors) is higher for electrically-heated buildings in cool and cold climates than for buildings heated with gas. In the warmest climates, where the cooling load dominates the space conditioning requirements, the energy budgets for the electrically-heated buildings are about equal to or even smaller than for the buildings heated by gas, because extra conservation measures are cost effective with electric heat and these measures save cooling energy along with heating energy (PNL-3044, 1979).

An economic evaluation of electric heating, using heat pumps and using resistance heating, indicates that the heat pump system has lower life-cycle-cost than resistance heating in cool and cold climates, in spite of the higher first cost of the heat pump. In warm climates the comparison is more complex, because cost- minimizing heat pump buildings have less insulation and use about the same amount of energy as resistance-heated houses.

SENSITIVITY ANALYSIS OF RESIDENTIAL ENERGY BUDGETS

The energy budgets of the prototype buildings rely on numerous assumptions. This section describes the effect on the energy budgets of altering key assumptions. Calculations were performed for one-story buildings at the minimum life-cycle-cost.

Results are presented for six assumptions about building design or operation: 1) night setback; 2) insulated shutters; 3) venting (window openings); 4) internal loads; 5) building size; and 6) window area.

Night Setback

The energy budgets were based on a constant thermostat setting of 21.1°C and 25.5°C for heating and cooling respectively and between 21.1°C and 25.5°C the temperature was allowed to float. A possible conservation measure not considered by this procedure is night setback of thermostats to a lower temperature. When this was considered, it was found that night setback may weaken the optimum in moderate and warm climate (Burbank and Atlanta) and increases the energy budget in the warmest climate (Burbank). (The increase occurs because the optimum building with the night setback is so much looser that the energy savings from the night setback are overwhelmed by the extra energy used by being looser.

Insulated Shutters

The sensitivity of the use of insulated (R-1) shutters was tested in four locations: Minneapolis; Washinton, D.C.; Fresno; and Ft. Worth. All cases assume that the shutters were closed from 11 p.m. to 7 a.m. from October through April. The results show that in the coldest climate (Minneapolis) and in a more moderate climate (Washington, D.C.), the heating load is reduced by 6% and 9% respectively. In the warmer climates (Ft. Worth and Fresno), the heating loads are reduced by about 20%. The greater percentage reduction in heating loads in warmer climates occurs because the triple glazing that is used on the nominal case building in Minneapolis and Washington, D.C. reduces the heat losses through windows that could be saved by the shutters.

Venting Through Windows It is assumed that windows in residential buildings are opened when the inside temperature is greater than 25.5°C if the outdoor temperature is lower than indoors. The results show that venting through windows is an effective way of reducing the use of air conditioners. In Minneapolis, Washington, D.C., and Fresno, the electrical energy used for air conditioning is increased by 53%, 40%, and 25% respectively if windows are kept closed at all times.

Internal Loads Changing the internal loads has a smaller effect on the magnitude of the energy budget than it does on the location of the minimun in life-cycle-cost among the conservation options. The heating loads increase when the internal load is halved, and decrease when the internal loads are doubled. Cooling loads increase when internal loads are doubled, and decrease when internal loads are halved.

For Fresno, where the cooling loads are a large fraction of the energy budget, the change in internal loads has little effect on the energy budget. However, doubling the internal loads loosens the optimum. For Chicago, on the other hand, the change in internal loads affects the energy budget: the doubled internal loads case has a smaller energy budget than the case with average internal loads assumptions; the halved internal loads case has a larger energy budget than that of the average case. This result is another indication that the same assumptions used to establish the standards should be used to evaluate compliance.

Building Size

The variation in the energy budget with building size (assuming that window area is 15% of floor area) has been calculated for Chicago, Atlanta, and Fresno. The results show that the energy budget is essentially unchanged (±13% or less) as the size of the house increases from 109 m^2 to 371 m^2. As the size of the building increases, the reduced surface-to-volume ratio indicates a declining heat loss (per unit area of floor) through envelope walls, which means that less heat from external sources is required. But for a larger house, the contribution of internal loads (from people, appliances and lighting) to the total heating requirements declines.

Window Area

The effects on the energy budget of increasing the window area of a building have been calculated for Atlanta and Chicago. The windows are triple glazed in Chicago and double glazed in Atlanta. In all cases an equal window area is placed on all four sides of the building. A linear relationship is found between the loads and window area, with almost equal effects in all cases: increasing the window area by a factor of four (from 10% of floor area to 40% of floor area), increases heating loads by a factor of 1.75 for Chicago, and 2.1 for Atlanta, and cooling loads by a factor of 1.9 for both Chicago and Atlanta. This indicates that the energy budget of a building increases significantly with an increase in window area. From these calcultions, a rough rule of thumb emerges, that is a 1% increase in window area can lead to a 0.5% increase the in energy budget.

The observations apply only to cases in which the window area is distributed equally on all four sides. Other calculations performed on DOE-2 indicate that increasing the glazing area on a south wall tends to decrease the energy budget. Preliminary calculations, in which some passive solar elements were included in the building, indicate the possiblity of significant reductions in the energy budget by increasing south glazing and adding thermal mass to the room. In Minneapolis and Fresno, south glazing was increased from 7.5% to 15% of the floor area in a building, with a higher than average amount of thermal mass, containing either a masonry floor (with tiled floor surface) or masonry interior walls. The energy budget is reduced by 15% and 30% in Minneapolis and Fresno respectively. From this, two conclusions are evident: 1) increasing the area of south glazing does not increase (and is likely to decrease) the energy budget of a building in the U.S., and 2) passive solar techniques can potentially increase the ease of meeting the standards.

CONCLUSION

A methodology has been described by which energy budgets can be set using DOE-2. The level of the budget can be chosen through the use of life-cycle-cost analysis, subject to constraints of technology availability. This has been the approach taken by the U.S. Department of Energy. Assumptions can be chosen which make the budget relatively well-behaved, so that the budget is not strongly affected by building size or shape. If compliance with the performance standard is also established using DOE-2, the budget process is even less dependent on errors or variations in assumptions.

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