Life-Cycle Cost Analysis Using Department of Defense Building Energy Standards

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ABSTRACT

The Department of Defense (DOD) has building energy standards that are closely comparable to Department of Energy (DOE) standards. Additionally, the DOD standard recommends energy-conserving design features above and beyond its minimum requirements if they are cost effective. We have examined and compared the life-cycle cost impacts of the DOD and DOE energy standards. We have also developed a methodology for comparing relative life-cycle costs, and for determining what energy performance levels are achievable relative to different life-cycle cost constraints. The methodology thus allows us to ultimately determine economically optimal designs that satisfy the DOD energy standards. The economically optimal designs have the lowest life-cycle cost for a given performance level. These designs thus provide the economic flexibility to incorporate additional energy-conserving design features, compared to standard designs that just satisfy the minimum requirements of the standards. We demonstrate the methodology by quantifying the life-cycle cost impacts of a range of energy-conserving envelope design trade-offs and indicate the corresponding levels of life-cycle cost reduction achievable for common building type developed as part of the U.S. Army Corps of Engineers Standard Design Program.

BACKGROUND

In order to provide a consistent framework for the design of new energy-efficient construction for its building facilities, the Department of Defense (DOD) has developed performance-based building energy standards (Office of the Chief of Engineers 1987) that have been shown in earlier work to lead to energy performance levels approximately comparable to Department of Energy (DOE) building energy standards in most cases (Dumortier and Andersson, n.d.)†. The DOD standard is performance based, and also has related requirements that the design alternatives that can be developed under this flexible approach be evaluated and selected according to their life-cycle cost. Since the energy and economic evaluations can be difficult "in the field," DOD has developed a set of "envelope requirements" that are semi-prescriptive, and that can be applied as alternative requirements. We have developed a method for creating ranges alternative designs that satisfy the DOD performance standard, and that can be used to consistently evaluate the energy and

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† The DOE standards have several alternative compliance paths: prescriptive, system performance, building energy cost, and building energy use. In the comparisons performed here the DOE performance requirements were developed using the prescriptive compliance path, which is easier to use but can lead to more stringent requirements than the performance path.

cost consequences of this "envelope table" (see Table 8-1 of DOD [n.d.]) in light of: (1) the limited tradeoff flexibility they allow; (2) their energy requirements vis-a-vis the more general DOD performance approach; and (3) their economic consequences, expressed as a life-cycle measure that can be easily compared to buildings designed to meet the standards under alternate approaches.

APPROACH

This project was an exploratory effort to develop a straightforward method for evaluating the energy and life-cycle cost of DOD buildings, in various configurations and locations. The methodology was then to be used to generate performance data that could be compared to the DOD "envelope table." We describe below the details of the performance methodology that was developed.

Relation to Earlier LBL/CERL Work

The barracks building that was used in this study was taken from an earlier and related project (Dumortier and Andersson, n.d.) performed by LBL for the U.S. Army Construction Engineering Laboratory (CERL). In 1988, DOD (CERL) was interested in comparing its energy standards to the new ones prescribed by DOE. For a barracks-type building, a prototype was developed that strictly followed DOE prescriptive requirements (U.S. DOE 1989) in terms of the U-values of construction materials, the amount of window area, the ventilation rates, the system type, and other characteristics that are essential for the design of an energy-efficient building.

DOD vs. DOE Standards

The barracks design was one of the buildings for which the prototype following DOE standards was not meeting the DOD design energy targets. In Colorado Springs, CO, the prototype had an energy usage of of 65 kBtu/h, but the DOD design energy target was 50 kBtu/h. In all climates the DOE prototype was using more energy than the level required by DOD. Since the DOD will have to meet or exceed the DOE standards, for this study we decided to use a barracks building that would meet both. (The modifications necessary to provide joint compliance are related to building operational and use assumptions, and are described in detail below.)

Building Configurations Analyzed

A number of building configurations were defined, designed, and analyzed for this study. They fall into three general classes, described below.

Minimal Envelope Building. During development of the method, we found it desirable to define a fundamental base building design against which all other building configurations could be compared for both energy and economic performance. This minimal envelope design has all the characteristics in terms of size and use assumptions as configurations meeting the standard, but differs in the envelope design, and has no insulation in the walls or the roof, and single glazing.

Base Standards Configurations. This class of configurations is designed to jointly meet the DOE and DOD standards. It forms the reference base cases from which the enhanced performance configurations described in the next section are derived. The DOE standard prescribes for each location a U-value for the roof, the wall, and the glazing. The first step was to start from the DOE prototype and suitably modify it to meet the DOD design energy target in each climate. The modifications relate to different operational and use assumptions that are not taken into account by the DOE standards.

- The average installed electrical equipment in a DOD barracks is 0.5 W/ft^2 much lower than the 1.42 W/ft^2 recommended by DOE.

- The heating and cooling systems in a DOD barracks building are turned on and off during heating and cooling seasons. A typical heating season in Colorado Springs is October 15 through May 15. The heating and cooling thermostat setpoints are usually 68 °F and 75 °F. DOE recommendations for the prototype building description are that the building should be heated or cooled whenever it needs it, all year around. The thermostat settings recommended by DOE for heating and cooling are 70 °F and 75 °F.

- The amount of outside air introduced for ventilation in the prototype was based on ASHRAE Standard 62-1981, which led to values somewhat lower than those originally recommended by DOD for their designs.

These modifications brought the DOE prototype into line with the DOD design energy target. In Colorado Springs, CO, the DOE prototype uses 48.5 kBtu/ft^2 with 50.0 kBtu/ft^2 for the DOD design energy target. In Raleigh, NC, it uses 46.2 kBtu/ft^2 with 45.0 kBtu/ft^2 for the DOD design energy target. In San Antonio, TX, it uses 40.9 kBtu/ft^2 with 60.0 kBtu/ft^2 for the DOD design energy target. Finally in Homer, AK, it uses 59.5 kBtu/ft^2 with 60.0 kBtu/ft^2 for DOD design energy target.

The base standards configurations, which thus jointly meet the DOE and DOD requirements, lead to the following envelope design combinations:

Location	Envelope Characterization			Configuration
	Walls	Roofs	Windows	Label
Homer, AK	Wall 4	Roof 4	Window 3	"443"
Colorado Springs, CO	Wall 2	Roof 3	Window 3	"233"
Raleigh, NC	Wall 1	Roof 3	Window 3	"133"
San Antonio, TX	Wall 1	Roof 3	Window 1	"131"

The wall, roof, and window references are described in detail in the following section. Note the variation in configuration as a function of the different climates in each location. We have also introduced the shorthand notation in the last table column to identify configurations where the first of the three digits represents the specific configuration for walls, the second for roofs, and the third for windows, respectively.

Enhanced Envelope Performance Configurations. Finally, we developed a series of design variations that build off of the minimal envelope building, but include designs that go even beyond the base standards buildings in terms of energy conservation behavior. They are meant to bracket the requirements defined in the DOD "Envelope Table."

Based on detailed architectural designs of the barracks building, we chose several variations which represented a wide range of R-values and which would be commonly used in a barracks building design (brick/CMU masonry walls; flat, built-up roofs; and no attics). The following tables list the design variations and their related materials, together with thermal and cost properties.

Insulation			
Design Configuration	Material Description	R-Value	Cost per ft^2
Wall 1	3/4" Polystyrene	4.00	0.73
Wall 2	1.5" Polystyrene	8.10	1.01
Wall 3	2" Polystyrene	10.80	1.23
Wall 4	2" Isocyarunate	14.40	1.10
Wall 5	3" Isocyarunate	21.60	1.51
Wall 6	4" Isocyarunate	28.80	1.89
Roof 1	1" Urethane	6.70	0.78
Roof 2	1.5" Urethane	11.11	0.92
Roof 3	2" Urethane	14.30	1.02
Roof 4	2.5" Urethane	20.00	1.20
Roof 5	3" Urethane	25.00	1.35

Windows				
Design Configuration	Material Description	R-Value	Shade Coefficient	Cost per ft^2
Window 1	1/4" Thick, Clear	1.01	0.95	6.65
Window 2	1/4" Thick, Tinted	0.98	0.71	7.30
Window 3	1/8" Float, 1/4" Air, 1/8" Float Clear	1.59	0.88	11.60
Window 4	1/8" Float, 1/4" Air, 1/8" Float Tinted	1.55	0.67	13.39
Window 5	1/4" Float, 1/2" Air, 1/4" Float Clear	1.69	0.81	15.44
Window 6	1/4" Float, 1/2" Air, 1/4" Float Tinted	1.65	0.51	16.97
Window 7	1/8" Float, 1/4" Air, 1/8" Low E (0.08) Clear	1.85	0.73	12.76
Window 8	1/8" Float, 1/4" Air, 1/8" Low E (0.08) Tinted	1.94	0.60	14.73
Window 9	1/8" Float, 1/4" Air, 1/8", 1/4", 1/8" Clear	2.02	0.79	17.70
Window 10	1/4" Float, 1/2" Air, 1/4", 1/2", 1/4" Clear	2.22	0.70	23.25

Configuration Costs. The material and construction costs were taken from Means (1988). The book provides us with a convenient cost per square foot for materials such as insulation and glazing. Costs include material, labor, and installing contractors' overhead and profits. They do not include premiums for labor or materials or savings that may be realized under certain economic situations. They are given as averages for the United States for 1988. Since the analysis year chosen for the life-cycle cost study was 1989, we used the ratio of the Means 30-city average local cost indexes for 1988 (202.5) and for 1989 (207.1) to determine individual material cost for 1989 from the 1988 data. Costs were also adjusted to each of the four locations by using the following location factors:

Homer, AK	1.31
Colorado Springs, CO	0.94
Raleigh, NC	0.83
San Antonio, TX	0.86

The Means cost data only characterize the insulation materials in terms of their corresponding R-values. For the other thermal characteristics of insulation materials required by BLAST, we used values provided by the BLAST materials library. For the glazing, the only information provided by the Means book was the glass width. The thermal characteristics of the glazing, R-value, and shading coefficient were obtained by using the program Window 3.1 (1988).

HVAC Fan System Design. The standard barracks had both system and plant correctly sized to meet building and system peak heating and cooling loads. However, for each climate the fan system sizing and design was always the same and based on the supply air requirements for the base standards buildings. This was also true for the enhanced performance variations. (In some extreme cases this led to a few hours where the building peak loads could not be met by the fan system, but has essentially no energy consequences.)

Plant Equipment Design. Since boiler and chiller costs could be obtained from Means, for some of the design variations, the redesign induced a reduction/increase of the size of the boiler or of the chiller, which was included as an additional savings/cost in the economic analysis. Chiller resizing was done only for configurations that involved the use of tinted windows, since they significantly reduced the size of the peak cooling loads. Boiler and chiller costs were interpolated from the values in the following table:

Boilers			Chillers		
Type	Capacity (kBtu/hr)	Unit Cost (1989$)	Type	Capacity (kBtu/hr)	Unit Cost (1989$)
Boiler 1	100	1895	Chiller 1	180	12375
Boiler 2	163	2575	Chiller 2	240	13909
Boiler 3	280	3425	Chiller 3	360	16363
Boiler 4	544	6100	Chiller 4	600	23522
Boiler 5	1088	9525	Chiller 5	1200	40908

Climate Selection

A detailed description of the climate analysis and results was developed for an earlier, related project (Dumortier and Andersson 1988) The analysis performed at that time identified the "most representative" climate for each of six CERL regions: region 5 had been dropped out because it only had 2000 military personnel. The selection was based on comparisons to population-weighted means of four key climate variables. The results gave the choice of Homer (Alaska), Colorado Springs, Washington (DC), Raleigh, San Antonio, and El Paso. All of these locations contain between 300,000 and 460,000 personnel, except the coldest (Homer), with about 150,000.

For this study, we restricted ourselves to the use of only four of the six climates defined above: Homer, Colorado Springs, Raleigh and San Antonio. Homer is representative of a really cold climate with no cooling season, Colorado Springs is representative of a cold climate with a cooling season, Raleigh is a mild climate, and San Antonio is a hot climate.

Economic Analysis Methodology

The economic analysis of the various building configurations is straightforward, and consists of determining the life-cycle cost of each of the configurations and directly comparing them. Determining the life-cycle cost requires an estimate of the construction cost and other initial costs for the configuration, and the operation costs related to its energy use (typically, utility bills) over the time period defined as the economic life of the configuration, and any other economic assumptions needed to convert the lifetime stream of energy costs into a present value. Sources of the initial cost estimates have been discussed previously.

Energy costs, their change with time, and the source of other necessary economic assumptions are discussed in the next section. Finally, we simplify the economic analysis by assuming that all initial costs and energy costs can be expressed *relative* to one of the reference building configurations. It can be easily shown that this produces correct *relative* life-cycle costs, which can be used for qualitative ranking and quantitative comparison just as the total building life-cycle costs could. Such a simplification avoids having to cost out the entire building construction cost.

Life-Cycle Cost Analysis — LCCID. The Life Cycle Cost In Design (LCCID) program is an economic analysis computer program tailored to the needs of the Department of Defense. It is intended to be used as a tool in evaluating and ranking design alternatives for new and existing buildings. LCCID incorporates the economic criteria of the Army, Navy, and Air Force for design studies and contains DOE fuel escalation tables. We used LCCID level 35, which incorporates 1988 DOE fuel price escalation tables. The criteria package used was Federal Standard OMB A-94, which assumes a standard discount factor of 10%. The analysis start date was assumed to be January 1989. The analysis period was set at 25 years. The 1988 DOE U.S. national average fuel energy escalation values were used in the analysis (see Table A-1 in Appendix 1). The fuels we considered were electricity and natural gas. LCCID provides 1989 U.S. national average prices of $14.26/MBtu and $2.72/MBtu, respectively. The LCCID program does not provide any information on electric demand costs. We assumed an annual electric demand cost of $0.83/kW of peak electricity per month. (As an artifact to trick LCCID to escalate the electricity demand costs, they were defined as maintenance-repair-custodial costs, which are appropriately escalated.) No other costs than the initial investment costs and the energy costs (including the electric demand cost) were used in the study.

Because we wanted to do sensitivity analyses for a range of variations on these basic economic assumptions, we implemented the basic LCCID calculation methodology in a spreadsheet. Results given by the spreadsheet model were cross-checked with LCCID and were identical in all cases. The advantage of having all results for the four climates defined in only one worksheet was that any change in terms of the energy prices or the economic factors would be immediately reflected in the LCCID column of results for all climates. As compared to using LCCID for doing such parametrics, using the spreadsheet saved a significant amount of time.

Sensitivity Studies. In general, lower initial costs for enhancements, higher fuel costs and cost escalation rates, and lower discount rates tend to favor conservation. We performed an analysis varying these factors to determine whether or not some of them would drive the life-cycle cost of the enhanced configurations significantly lower relative to that of the base standards building, compared to the basic economic assumptions that were used. The specific variations considered were:

(1) Lowering the initial costs by the amount of the architectural fees and contractor overhead (an additional 23% of basic material and labor costs).

(2) Lowering the discount rate from 10% to 7%.

(3) Doubling the fossil fuel price from $2.72/MBtu to $5.44/MBtu.

(4) Raising the electricity price approximately 50% from $14.26/MBtu ($0.042/kWh) to $20.00/MBtu ($0.059/kWh).

(5) Doubling the electricity demand charge from $10/kW-yr to $20/kW-yr.

(6) A simultaneous combination of all of the above variations.

RESULTS

In addition to the performance of the additional envelope design tradeoffs, which are viewed relative to the "base standards" buildings that meet the DOE and DOD standards, it is also instructive to compare the base buildings performance to the even more fundamental "minimal envelope" building benchmark. Note that while the base standards building configuration varies with location, the minimal envelope reference building has the same envelope configuration (but not necessarily the same HVAC equipment sizing) everywhere.

Energy Use

Figure 1a shows for Colorado Springs the total (electricity + fuel) EUI* for the range of configurations described earlier, with the minimal envelope and base standards buildings at the far left as references. As might be expected, all configurations with enhanced envelope performance show significant energy reductions compared to the minimal envelope building. However, in this overall context, two detailed effects can be seen. First, envelope integrity improvements mostly affect fuel use, not electricity. This is true for all four climates analyzed, even including the two hot ones for which cooling is important. Second, essentially all of the energy reduction compared to the minimal envelope building has occurred in the base standards building; only small additional gains (if any) are obtained from additional wall, roof, or window integrity improvements. Figures 1b and 1c show the fuel and electricity EUI components, respectively, with the vertical scale magnified by about 100 to show the fineness of the variations. It is clear that some of the enhanced configurations have either a higher fuel EUI, or electric EUI, or both, compared to the base standards building. Figures 2a through c show plots of the analogous data for the other three climates.

Life-Cycle Cost

With the energy use of the various configurations as reference, we now turn to our primary interest, the life-cycle cost effects of the analyzed configurations. Figures 3 through 6 show the life cycle cost components for the various configurations analyzed in the four climates. All of the life-cycle cost components, as described above, are expressed *relative to the minimal envelope configuration,* as discussed earlier. The three components shown for for each configuration are (1) the positive first cost, which represents the additional investment in conservation; (2) the negative annualized present value of the energy cost, which represents the energy savings achieved; and (3) the net relative life-cycle cost, which is the algebraic sum of the previous two components.

These figures show that the life-cycle cost of the base standards buildings, when viewed in the perspective of the size of the extra first costs and the energy cost savings, is essentially the same as the minimal envelope reference buildings in Colorado Springs and Homer, but are significantly higher in the two mild climates, Raleigh and San Antonio. Additionally, the enhanced envelope configurations almost without exception show life-cycle costs higher than not only the minimal envelope reference, but also the base standards buildings. The figures show that although there are energy cost savings, these savings are either offset by (colder climates) or even significantly dominated by (warm climates) the increased first costs of the conservation enhancements. Thus, it must be concluded that with the economic and energy modeling assumptions used, the configurations specified by the DOE standard are beyond the optimum life-cycle cost. An examination of the details of the initial costs indicate that the high costs of double glazing account for the overall results. Such windows are required by the DOE prescriptive standard, but not necessarily by the DOD performance standard, which only requires that the energy performance meet a certain target. When

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* EUI: Energy Use Index; either component or total energy use, as appropriate, divided by building floor area.

we analyze the window configurations, we should also note that the DOE standard requires any performance simulations to assume that half of the window area is shaded by medium weight drapes (also assumed for the DOD barracks design), which have the effect of reducing the energy savings of any window performance enhancement.

"Intermediate" Configurations

Since the base standards buildings all seem to be beyond the life-cycle cost optimum, not to mention the enhanced envelope performance configurations, we have explored in more detail some configurations "intermediate" in performance between the minimal envelope and base standard buildings for the Colorado Springs climate. These intermediate configurations started with the minimal envelope configuration. Three configurational variations were formed by separately and individually adding the first performance enhancement increment for walls, roofs, and windows, respectively, as described previously. The energy and life-cycle cost performance of each of these three variations was determined, and the one with the lowest life-cycle cost was identified. This enhancement cycle was repeated by forming three new configuration variations based on the "winner" of the previous cycle and identifying the new winner until the energy performance converged to that of the base standards configuration. (For these simulations, equipment sizes were determined for the minimal envelope configuration, and no resizing was done for the intermediate cases.) Figures 7 and 8 show the energy and life-cycle cost, respectively, for the Colorado Springs analysis. Five cycles are shown for the analysis. Figure 7 shows the energy performance, starting from the minimal envelope building and converging to the base standards building. While the base standards building in fact has the best energy performance, it is important to note that by the end of the third enhancement cycle, all configurations closely approach that performance. At the same time, the life-cycle cost (Figure 8) of these intermediate configurations can be considerably lower than the base standards configuration, while yielding essentially the same energy savings. Note in Figure 8 the increasing trend in both the initial cost and the energy cost savings components as performance enhancements are added. Again, it is seen that the high first cost of double-glazed windows has the major impact on net life-cycle cost.

Sensitivity to Economic Assumptions

As a final analysis effort, we explored the effects of changing economic assumptions on the net life-cycle cost of the base standards building. The approach for this analysis was described above.

Figure 9 shows the results of the economic sensitivity studies for Colorado Springs for the three enhanced performance configurations that have the lowest life-cycle cost in the wall, roof, and window categories, respectively. The bar height corresponds to the life-cycle cost of the particular configuration/economic scenario *relative* to the life-cycle cost of the corresponding base standards building with base life-cycle cost assumptions. The six economic scenarios were described above. It is clear that none of these changes, either singly or in combination, significantly alters the result that the enhanced envelope configurations still have a higher life-cycle cost than the base standards building. It also seems clear that essentially no combination of "reasonable" values for these assumptions will qualitatively alter that conclusion.

Consequences for the DOD "Envelope Table"

We examine the requirements of the DOD "envelope table" (Table 8-1 of DOD 4270.1M) in light of the base standards buildings which satisfy both the DOE and DOD energy standards. The requirements comparison is done for both Colorado Springs and San Antonio to determine whether there are climate effects. The table below shows a comparison of the U-value requirements determined from the DOD "envelope table" and the appropriate base standards building configurations for each climate, respectively. The gross wall requirement is the area-weighted overall U-value of the opaque walls and windows together. This is an explicit requirement in the "envelope table," but not in the DOE prescriptive requirements (reflected by the use of parentheses in the table), where the window U-value requirement is explicit. (The Gross Wall requirement can be deduced from the fact that the window/wall ratio is 19% in Colorado Springs and 15% in San Antonio.)

Requirement Source	U-value			
	Walls	Gross Walls	Windows	Roof
Colorado Springs				
"Envelope Table"	.07	.12		.03
Base Standard Bldg ("233")	.09	(.15)	.41	.05
San Antonio				
"Envelope Table"	.15	.23		.05
Base Standard Bldg ("131")	.15	(.28)	.99	.05

It is clearly seen from the table that in both climates the DOD "envelope table" provides the more stringent of the requirements compared to the base standards building, which meets the DOE prescriptive and DOD performance requirements, with the largest discrepancies in the more severe heating climate. Thus the cost effectiveness of the "envelope table" requirements is in question. Our analysis shows that the life-cycle cost of a configuration which approximately satisfies the Colorado Springs "envelope table" requirements ("458") is about $9000 higher than that of the corresponding base standards building, while for San Antonio, the required "envelope table" configuration would be "243," with a $11,400 higher life-cycle cost. At the same time, the base standards building is already so energy efficient that the extra energy savings that result from the performance enhancements required by the "envelope table" are minimal. So the net result of the extra stringency in the "envelope table" is essentially no more energy savings at a significantly higher life-cycle cost.

CONCLUSIONS

We conclude with a series of comments that summarize the most significant outcomes of this work, some of which are specific to the DOD "envelope table," and some of which are more generally related to the relationship between energy use and cost-effectiveness that have been observed in the results.

- The energy saved by the base standard buildings compared to the minimal envelope buildings is primarily in fossil fuels, and is larger in more severe heating climates, ranging from 52% fuel savings in Homer to 18% savings in San Antonio. The electricity savings are all less than 5%, and even go up a few percent in one case (Raleigh).

- On the other hand, the life-cycle costs of the base standard buildings, whose energy-saving configurations were determined by the requirements of the DOE prescriptive standard, are all *greater* than the life-cycle cost of the corresponding Minimal Envelope buildings.

- Analyses of enhanced performance configurations, with additional energy-conserving levels of insulation and window performance, save almost no energy compared to the corresponding base standard configurations, and almost without exception have higher life-cycle costs. Thus, starting from the base standards buildings, there are essentially no additional cost-effective energy savings opportunities.

- An examination of the sensitivity of the above results to a range of alternate economic assumptions does not significantly change the picture provided by the previous two observations, indicating that this result is not simply due to "special" DOD economic circumstances.

- Building designs *intermediate* between the minimal envelope configuration and the base standards buildings can be found with energy savings that are essentially the same as the base standards buildings (within a few percent), but which have significantly lower life-cycle costs.

- The existence of these intermediate designs implies that one can find ways of making design tradeoffs, yet still satisfy the standards, thus introducing some design flexibility. However, even though several (and possibly many) alternate intermediate designs can be found with approximately equivalent energy performance, the life-cycle costs of the alternate designs can differ substantially, so that a cost-effectiveness criterion will always tend to favor one of the equivalent-energy designs over all the others.

- The existence of these intermediate designs also implies that at least the DOE prescriptive requirements may not lead to the most cost-effective designs for the level of energy performance that is achieved. Perhaps the overall design of these prescriptive requirements needs to be reviewed.

- The DOD semi-prescriptive "envelope table" (see Table 8-1 of DOD 4270.1M) has more stringent requirements than either the DOE or DOD energy standards, in both heating and cooling climates. These "envelope table" requirements result in essentially no better energy performance than a building that meets the DOE and DOD standards, but at a significantly higher life-cycle cost. Thought should be given to a reassessment of the requirements in this table, and possibly also to a more fundamental redesign of the table to increase the design tradeoff flexibility that it allows.

ACKNOWLEDGMENTS

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REFERENCES

DOD 4270.1M.

Dumortier, D., and Andersson, B. "A Comparison of existing DOD building energy standards and proposed DOE building energy standards." Berkeley, CA: Lawrence Berkeley Laboratory, Draft Report (no date).

Dumortier, D., and Andersson, B. 1988. "A comparison of existing DOD building energy standards and proposed DOE building energy standards." Berkeley, CA: Lawrence Berkeley Laboratory, LBL-28238, October.

Lawrence Berkeley Laboratory. 1988. "WINDOW 3.1: a PC program for analyzing window thermal performance." LBL-25686, October. Berkeley, CA: Lawrence Berkeley Laboratory.

R.S. Means Company Inc. 1988. Means construction cost data 1988.

Office of the Chief of Engineers, Engineering Division. 1987. "Architectural and engineering instructions: design criteria." Washington, DC.

U.S. DOE. 1989. "Energy conservation voluntary performance standards for commercial and multi-family high rise residential buildings; mandatory for new federal buildings; interim rule." 10 CFR Part 435, Federal Register, January 30. Washington, D.C: US Department of Energy, Office of Conservation and Renewable Energy.

Appendix1: DOE Fuel Price Escalation Factors

DOE Price Escalation Factors		
Year	Electricity	Fuel
1989	-0.29%	2.28%
1990	-1.65%	2.23%
1991	-0.88%	2.91%
1992	-1.33%	3.18%
1993	-0.97%	4.79%
1994	-0.08%	5.88%
1995	0.23%	6.79%
1996	0.38%	5.49%
1997	0.83%	7.12%
1998	1.27%	6.39%
1999	1.40%	4.57%
2000	1.38%	3.91%
2001	0.29%	1.33%
2002	0.29%	1.31%
2003	0.28%	1.29%
2004	0.28%	1.49%
2005	0.28%	1.26%
2006	0.21%	0.62%
2007	0.21%	0.62%
2008	0.21%	0.61%
2009	0.28%	0.81%
2010	0.21%	0.60%
2011	0.21%	0.60%
2012	0.28%	0.60%
2013	0.28%	0.99%

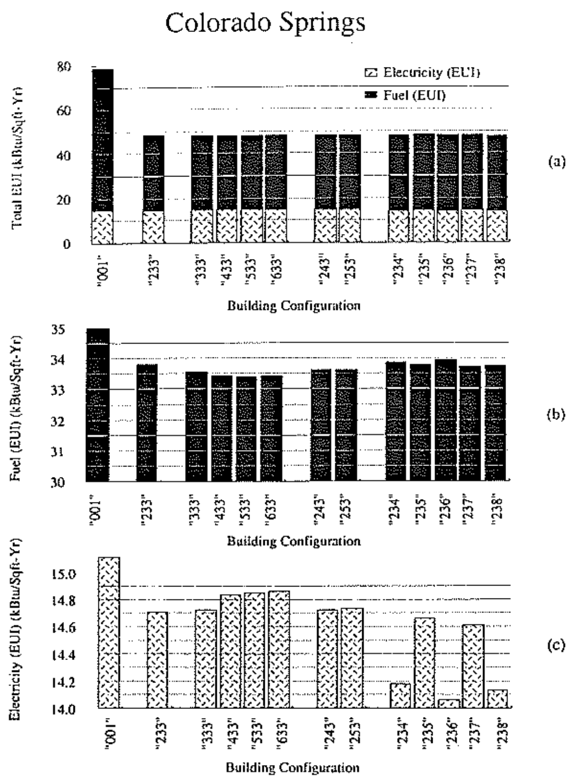

Figure 1. *(a) Total (electricity + fuel) EUI for the enhanced performance configurations for Colorado Springs, with the minimal envelope and base standards buildings at the left as references; (b) and (c) fuel and electricity EUI components, respectively, with the vertical scales magnified by about 100 to show details*

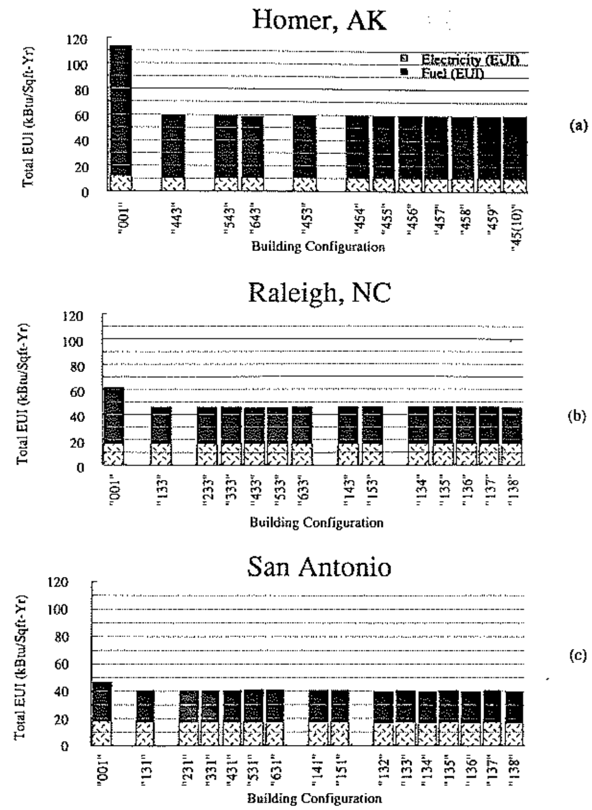

Figure 2. *Total (electricity + fuel) EUI for (a) Homer, (b) Raleigh, and (c) San Antonio*

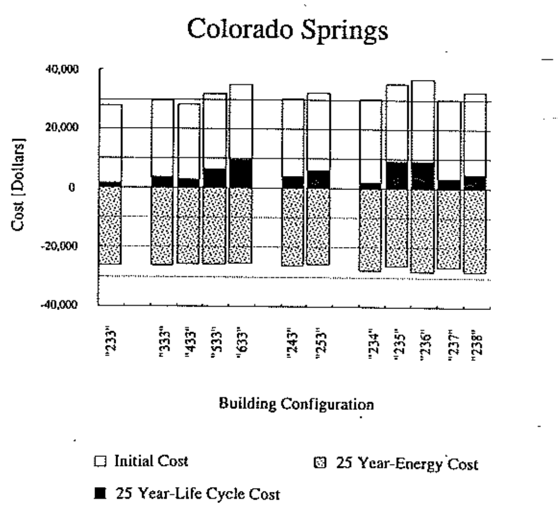

Figure 3. *Life-cycle costs for the configurations shown in Fig. 1 for Colorado Springs. Values are in 1989 $ relative to the minimal envelope configuration.*

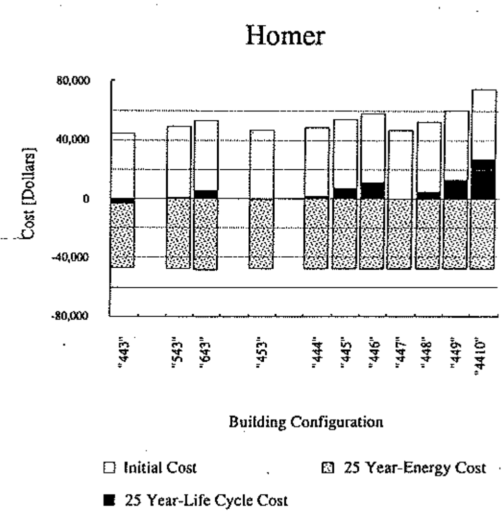

Figure 4. *Life-cycle costs for the configurations shown in Fig. 1 for Homer, AK. Values are in 1989 $ relative to the minimal envelope configuration.*

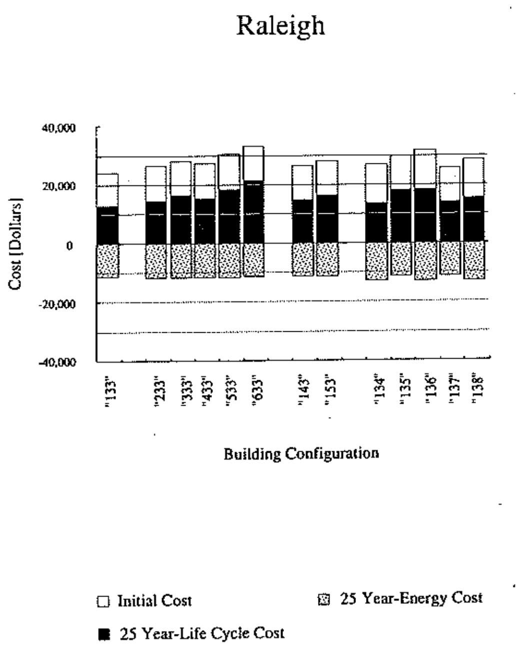

Figure 5. *Life-cycle costs for the configurations shown in Fig. 1 for Raleigh. Values are in 1989 $ relative to the minimal envelope configuration.*

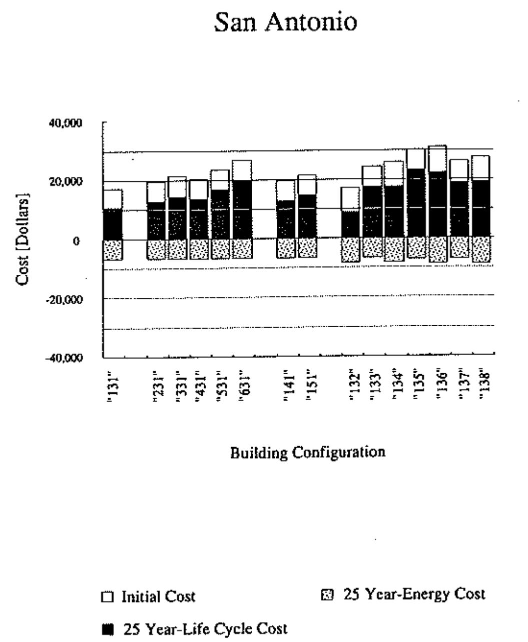

Figure 6. *Life-cycle costs for the configurations shown in Fig. 1 for San Antonio. Values are in 1989 $ relative to the minimal envelope configuration.*

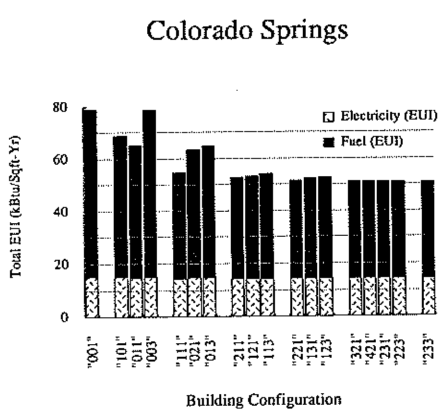

Figure 7. *Total (electricity + fuel) EUI for the "intermediate" configurations for Colorado Springs, with the minimal envelope building at the right and the base standards building at the left as references.*

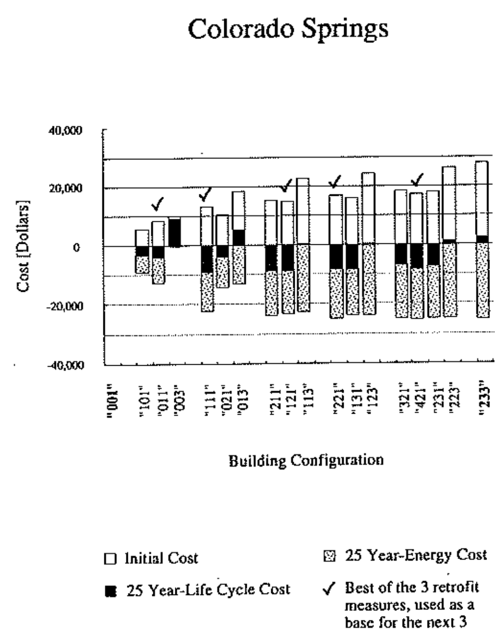

Figure 8. *Life-cycle costs for the "intermediate" configurations shown in Fig. 7 for Colorado Springs. Values are in 1989 $ relative to the minimal envelope configuration.*

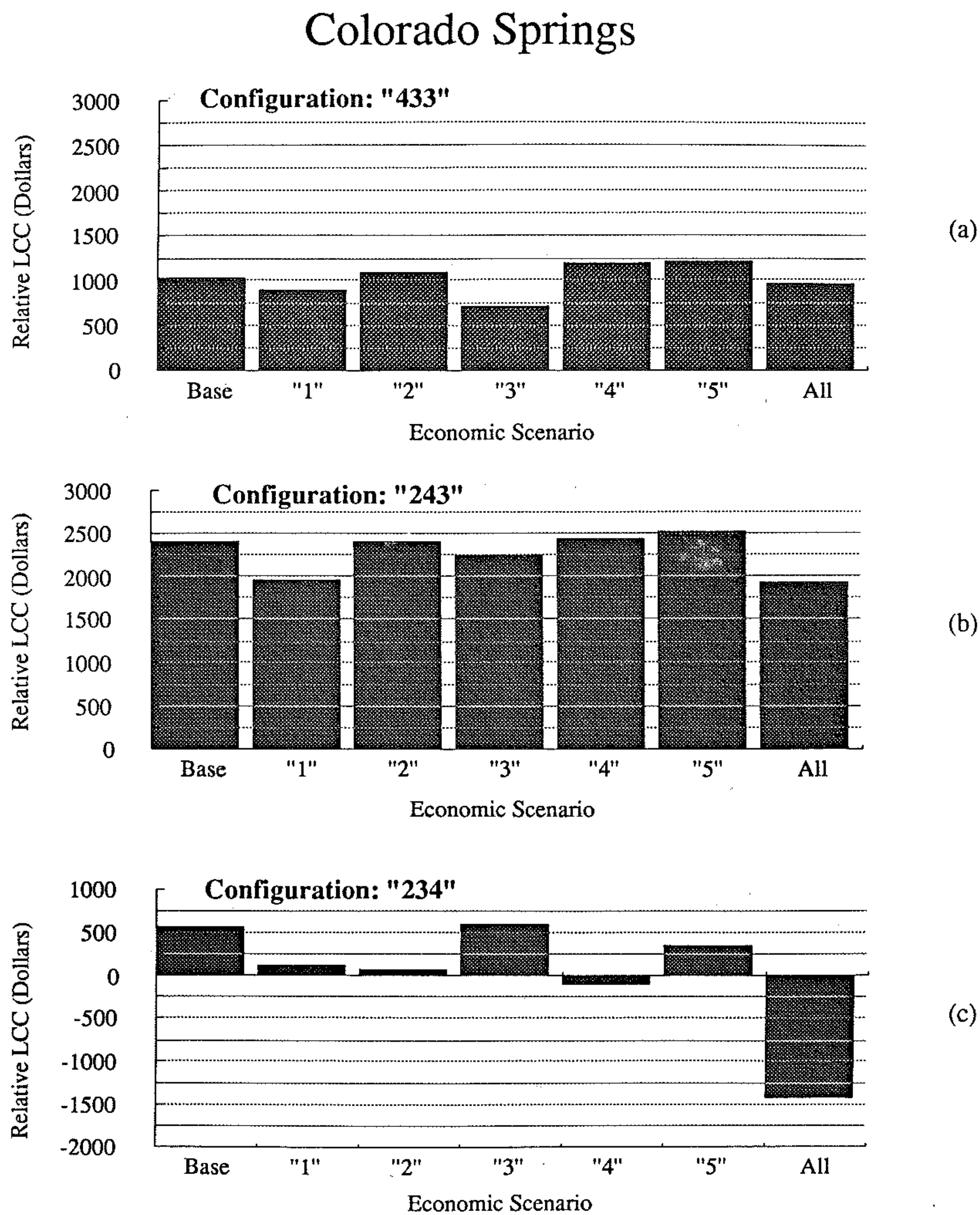

Figure 9. Sensitivity of life-cycle costs for selected configurations for a range of economic scenarios (defined in the text) in Colorado Springs. Values are in 1989 $ relative to the minimal envelope configuration.