EVALUATING THE COST-EFFECTIVENESS OF BUILDING ENVELOPE RETROFITS

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ABSTRACT

As part of a new federal program to promote energy-efficient retrofit of commercial buildings, voluntary private-sector partners evaluate potential envelope retrofits for their buildings. To support this program, a series of simulations of building envelope insulation and fenestration were performed throughout the United States. The DOE-2.1E simulation program was used in a parametric modeling of three building sizes in eight U.S. locations for thousands of combinations of loads, construction, Heating Ventilating and Air Conditioning (HVAC) systems, insulation, and fenestration alternatives—in total, more than 20,000 envelope options. These energy results were combined with upgrade costs to determine cost-effective upgrades based on an existing building envelope.

This paper first describes development of the database of incremental wall and roof insulation and fenestration upgrades. Then, examples of the tabular summaries of energy and economic results are presented. These summaries allow program participants to quickly determine cost-effective wall/roof insulation and fenestration upgrades for a building and location similar to theirs.

INTRODUCTION

A comprehensive approach to energy-efficient retrofits is undertaken through a series of technical stages under a new federal program to promote voluntary private-sector energy-efficiency retrofit of commercial buildings. This technical staging strategy—lighting, building survey and tuneup, load reductions, air distribution systems, and central plant—concentrates measures that reduce loads in the early stages. These load reductions are then included in sizing calculations for replacement heating, ventilating, and air-conditioning (HVAC) equipment in later stages.

In the third stage—load reductions—program participants evaluate and select cost-effective upgrades for internal loads and the building envelope—primarily walls, roofs, and fenestration. To support the envelope retrofit evaluation, a series of simulations of building envelope insulation and fenestration were performed throughout the United States. The intent was to incorporate a database of envelope retrofit simulation results in a simple, user-friendly program (not yet implemented). The program was designed to assist program participants in determining whether there were potential cost-effective building envelope upgrades for their specific building.

The DOE-2.1E simulation program (Winkelmann et al. 1994) was used in a parametric modeling of three prototypical office buildings in eight U.S. locations for thousands of combinations of construction and insulation and fenestration alternatives—in total, more than 20,000 envelope options. The energy results were combined with upgrade costs to demonstrate cost-effective upgrades based on an existing building envelope.

In this paper, the author describes how he defined the series of simulations, presents a sample of the energy and economic results from the simulations of potential insulation upgrade options, and, finally, suggests how the results could be used to determine cost-effective options for upgrading building envelopes.

DEFINITION OF BUILDING SIMULATION COMBINATIONS

The series of simulations were developed to cover a range of climatic, internal load, size, and HVAC system configurations. Three large office building prototypes developed in an earlier work (Crawley 1994) were used for this analysis:

- low-rise office, 48,000 ft^2, 3 floors;
- mid-rise office, 196,000 ft^2, 7 floors; and
- high-rise office, 840,000 ft^2, 20 floors.

Each prototype represents roughly 25% of existing office building stock (EIA 1994). (The approximately 25% of the remaining office buildings are small, single- or two-story offices with packaged HVAC systems. The program focused on larger buildings with central HVAC systems.)

Eight U.S. locations were selected to represent a broad cross section of U.S. climatic conditions and utility rates: Los Angeles, Calif.; Miami, Fla.; Minneapolis,

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Minn.; Omaha, Neb.; Phoenix, Ariz.; San Antonio, Texas; Seattle, Wash.; and Washington, D.C. Weather Year for Energy Calculations (WYEC) weather data (ASHRAE 1985) and actual local utility rates were used for each simulation.

Two internal load levels were included to represent typical existing lighting systems (2.3 W/ft^2) and cost-effective new lighting systems (0.8 W/ft^2). Two HVAC systems were selected to cover the range of potential system efficiency: constant-volume reheat (CV) and inlet vane variable-air-volume reheat (VAV), with and without reducing required airflows through a fan motor pulley changeout.

ENVELOPE UPGRADES

Three sets of independent building envelope upgrades were developed—roof insulation, wall insulation, and fenestration options. These sets of building envelope upgrades were designed to cover the range of potential existing wall and roof conditions (roof insulation condition, thermal insulating value, and color) and fenestration glazing combinations.

For roofs, we varied the insulation thickness (and effective thermal R-value) and roof color (light/dark). We chose to simulate polyurethane insulation (R-6.3/in.) but the results can be transferred to other insulation types by a simple ratio of the new insulation R-value per inch to the R-value per inch of the polyurethane insulation. We varied the insulation thickness in 15 half-in. increments (R-3.2 each) from no insulation to 7 in. (R-44). To simulate the light and dark roof colors, the roof absorptance was varied—20% for light and 90% for dark roof colors. Wall insulation and fenestration remained constant for each location for the set of roof insulation simulations. This produced 30 roof insulation/color combinations.

Similar to the roof simulations, wall insulation thickness was varied in 15 half-in. increments (R-3.2 each) of polyurethane insulation (R-6.3/in.) from no insulation to 7 in. (R-44). The wall color was not changed in the wall simulations. We also varied the percent glazing or fenestration-to-wall ratio (FWR) using 10%, 40%, and 70% glazing. Roof insulation and fenestration remained constant for each location for the set of wall insulation simulations. This yielded 45 wall insulation combinations.

For fenestration, a range of specific glazing was simulated using DOE-2.1E glass type codes. The equivalent U-factors and shading coefficients (SC) for the glazing options are shown in Table 1. Again the FWR was varied, with 10%, 40%, and 70% glazing in the simulations. Wall and roof insulation levels remained constant for each location for the fenestration simulations. This created 30 fenestration combinations.

The combination of building size, HVAC system, location, and internal loads yielded 200 simulations per wall, roof, or fenestration option: three building sizes, four HVAC systems, eight locations, two internal loads, and one base sizing simulation per location. The total number of simulations was 6,000 combinations for roofs, 9,000 for walls, and 6,000 fenestration options—a total of 21,000 DOE-2.1E simulations.

TABLE 1 **Fenestration Options**

Panes	Glazing Color	U-Factor	Shading Coefficient
Single	Clear	0.91	0.84
Single	Gray	0.91	0.83
Single	Green	0.89	0.69
Double	Clear	0.52	0.88
Double	Gray	0.52	0.72
Double	Clear (low-e)	0.51	0.58
Double	Clear (low-e)	0.51	0.55

EVALUATION OF SIMULATION RESULTS

Energy performance and utility costs were extracted automatically from the simulations to create three data bases (roofs, walls, and fenestration). By combining these data with retrofit costs in spreadsheets, cost-benefit results were calculated. The spreadsheets were structured so that users can adjust retrofit costs or change the insulation type to match their specific situation more closely.

In estimating roof and wall insulation retrofit costs, the author assumed that owners would wait until planning a roof replacement or a major rehabilitation of exterior walls before considering increasing insulation levels. This limits retrofit costs to only the cost of installing new insulation (no cost to replace the existing roof or the exterior wall). National average construction cost data bases show installation costs for polyurethane insulation of approximately \$0.60/ft^2 per inch thickness.

For a fan motor pulley changeout (reducing airflow to meet the reduced loads) in the roof simulation set, it was assumed that only the pulley on the top floor would be changed. National average material and installation costs were estimated to be \$250 per fan motor pulley (one per building).

EXAMPLE SIMULATION RESULTS

Tables 2, 3, and 4 present a sample subset of the results for a CV reheat system with fan motor pulley changeout and high lighting levels (2.3 W/ft^2) in Washington, D.C. Table 2 displays results for 1-in. existing roof insulation; Table 3, 1-in. existing wall insulation; and Table 4, single-pane existing glazing.

In the next section, a subset of the energy results from the roof insulation database is presented. Due to the quantity of data, the remainder of the paper concentrates on the roof insulation database results. First, we focus on energy savings results for four locations: Los Angeles, Calif.; Miami, Fla.; Minneapolis, Minn.; and

TABLE 2 Example Results for 1-in. Existing Roof Insulation in Washington, D.C.

Existing Roof		Roof Upgrade Option			Energy and Economic Analyses					
								Annual Energy Savings		
Insulation Thickness, Inches	Roof Color	Add Insulation, Inches	Roof Color	Fan Motor Option	Upgrade Cost, $/ft² Roof Area	Internal Rate of Return, %	Simple Payback Period, Years	$/ft² Roof Area	kWh/ft²	Percentage (%)
1.0	Dark	0.0	Light	Pulley Change Out	$0.00	NA	0.0	$0.24	0.80	2.04
		0.5			$0.30	119	0.8	$0.36	1.39	3.52
		1.0			$0.60	71	1.4	$0.43	1.73	4.39
		1.5			$0.90	52	1.9	$0.47	1.94	4.91
		2.0			$1.20	41	2.4	$0.50	2.11	5.34
		2.5			$1.50	35	2.9	$0.52	2.22	5.63
		3.0			$1.80	29	3.3	$0.54	2.30	5.84
		3.5			$2.10	25	3.8	$0.55	2.37	6.01
		4.0			$2.40	22	4.2	$0.57	2.43	6.17
		4.5			$2.70	20	4.7	$0.58	2.48	6.28
		5.0			$3.00	18	5.1	$0.59	2.52	6.40
		5.5			$3.30	16	5.6	$0.59	2.55	6.47
		6.0			$3.60	14	6.0	$0.60	2.58	6.53

TABLE 3 Example Results for 1-in. Existing Wall Insulation in Washington, D.C.

Existing Wall		Wall Upgrade Option			Energy and Economic Analyses					
								Annual Energy Savings		
Insulation Thickness, Inches	FWR	Add Insulation, Inches	FWR	Fan Motor Option	Upgrade Cost, $/ft² Wall Area	Internal Rate of Return, %	Simple Payback Period, Years	$/ft² Wall Area	kWh/ft²	Percentage (%)
1.0	0.40	0.5	0.40	Pulley Change Out	$0.32	61	1.6	$0.14	0.55	1.54
		1.0			$0.62	50	2.0	$0.23	0.88	2.44
		1.5			$0.92	41	2.4	$0.28	1.08	3.00
		2.0			$1.22	35	2.8	$0.32	1.22	3.40
		2.5			$1.52	31	3.2	$0.35	1.33	3.71
		3.0			$1.82	28	3.5	$0.37	1.42	3.96
		3.5			$2.12	25	3.9	$0.39	1.49	4.15
		4.0			$2.42	22	4.3	$0.41	1.55	4.33
		4.5			$2.72	20	4.7	$0.42	1.61	4.48
		5.0			$3.02	18	5.0	$0.43	1.65	4.60
		5.5			$3.32	17	5.4	$0.45	1.69	4.72
		6.0			$3.62	15	5.7	$0.46	1.73	4.82

TABLE 4 Example Results for Single-Pane Glazing in Washington, D.C.

Existing Fenestration		Fenestration Upgrade Option			Energy and Economic Analyses					
								Annual Energy Savings		
Glazing U-Factor, Color, and SC	FWR	Glazing U-Factor, Color, and SC	FWR	Fan Motor Option	Upgrade Cost, $/ft² Glazing Area	Internal Rate of Return, %	Simple Payback Period, Years	$/ft² Glazing Area	kWh/ft²	Percentage (%)
0.91 Clear 0.84	0.40	0.91 Grey 0.83	0.40	Pulley Change Out	$0.33	10	7.6	$0.02	0.07	0.2
		0.89 Green 0.69			$0.53	151	0.7	$0.39	1.34	3.3
		0.52 Clear 0.88			$1.13	95	1.1	$0.52	2.23	5.5
		0.52 Grey 0.72			$1.33	153	0.7	$0.98	3.86	9.4
		0.51 Low-e 0.58			$2.53	111	0.9	$1.36	5.16	12.6
		0.51 Low-e 0.55			$2.83	104	1.0	$1.42	5.38	13.1

Washington, D.C. Then cost-effectiveness results for Washington, D.C., are used to demonstrate some of the important trends found when examining the sensitivity of the database results to varying HVAC systems, internal loads, and roof colors. Note that the data are well-behaved and predictable (straight, parallel, or slightly curved sets of lines as shown in the figures). The few exceptions are caused by noncontinuous breakpoints in the utility costs.

Figure 1 presents annual energy cost savings in four locations (Los Angeles, Miami, Minneapolis, and Washington, D.C.) for a CV system, changing the roof color from dark to light, fan motor pulley changeout, and high internal loads (lighting power density of 2.3 W/ft^2). The annual energy cost savings are presented in terms of dollars saved per ft^2 of roof area. The bars show the effect of adding ½-in. roof insulation for cases where the existing roof has from 0.0 to 6.5 in. of insulation. As can be seen in all cases, the highest energy cost savings are for the lowest levels of existing roof insulation.

Figure 2 shows similar annual energy cost savings for two lighting power densities (2.3 and 0.8 W/ft^2) and

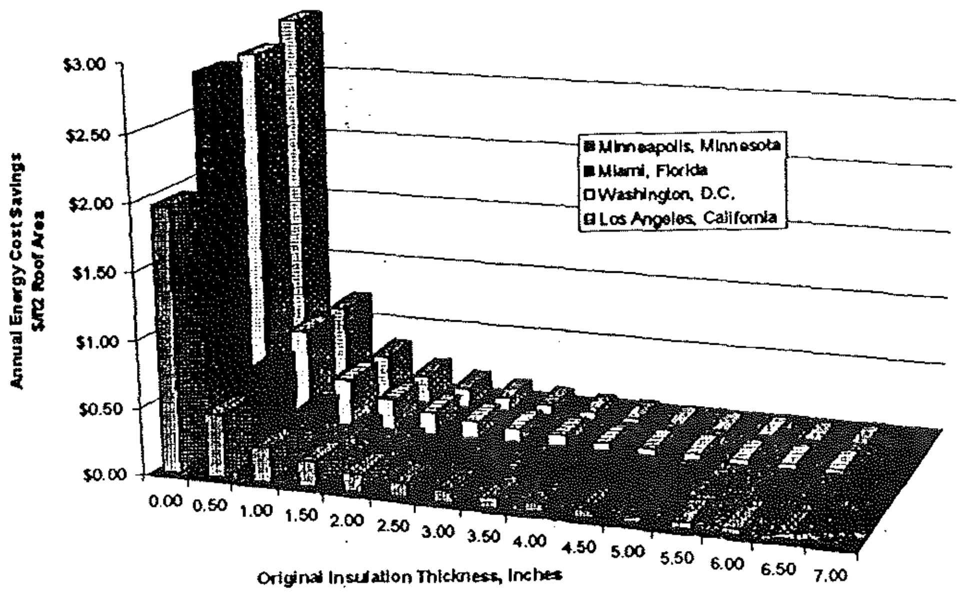

Figure 1 *Annual energy cost savings for adding 1/2-in. roof insulation with CV reheat system and high lighting (2.3 W/ft^2).*

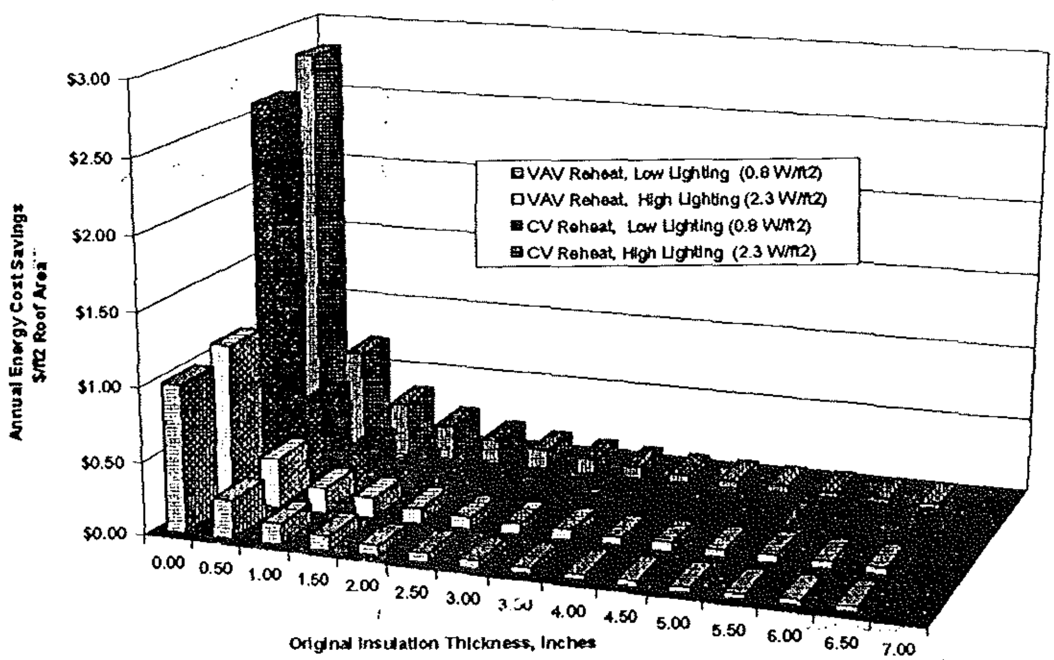

Figure 2 *Annual energy cost savings for adding 1/2-in. roof insulation in Washington, D.C.*

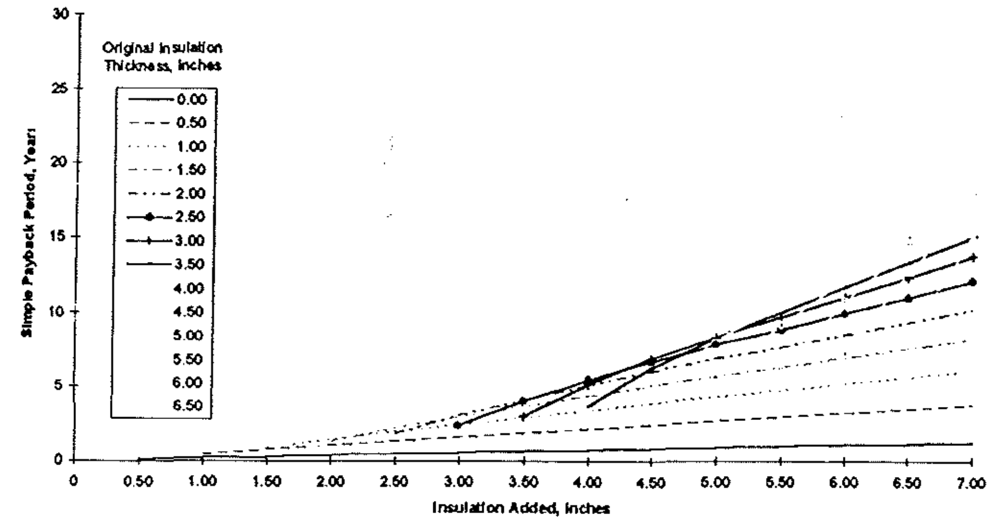

Figure 3a *Cost-effectiveness results for roof insulation upgrades with CV system and high lighting in Washington, D.C.*

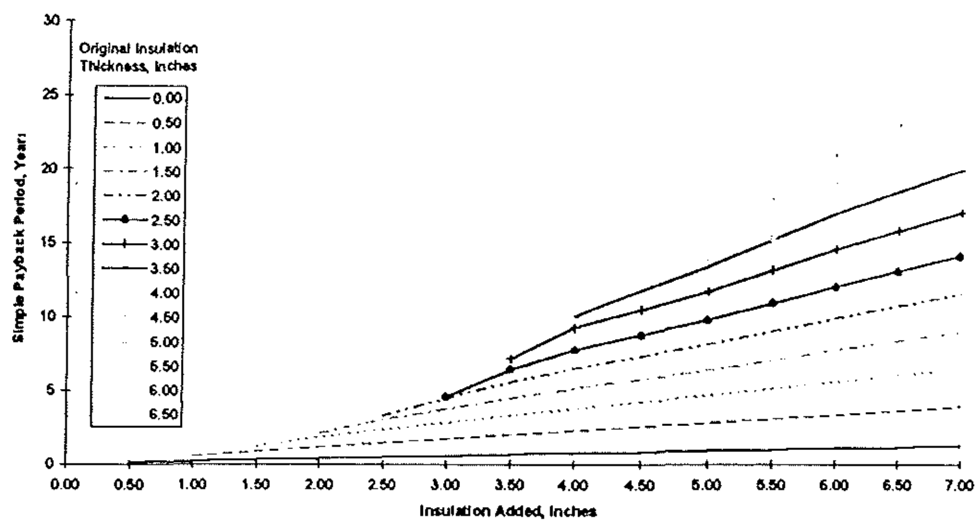

Figure 3b *Cost-effectiveness results for roof insulation upgrades with CV system and low lighting in Washington, D.C.*

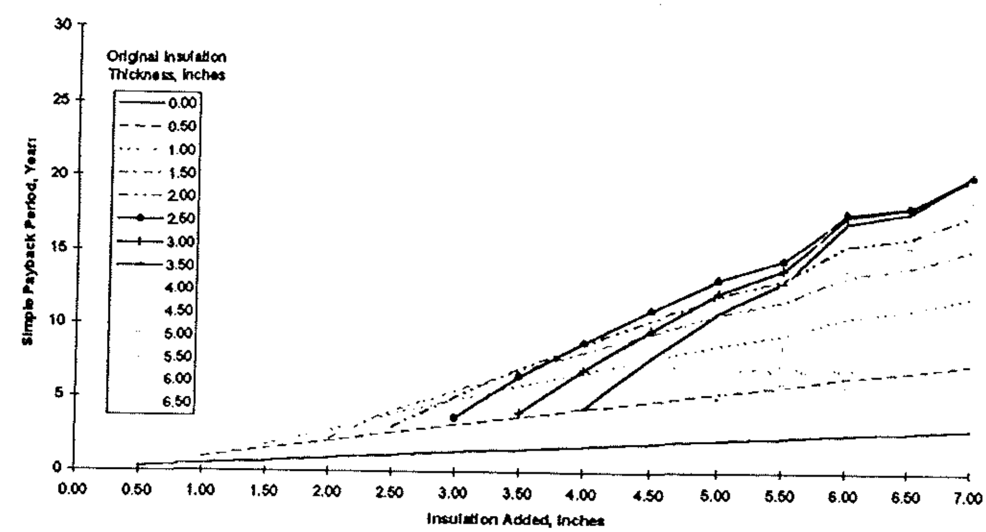

Figure 3c *Cost-effectiveness results for roof insulation upgrades with VAV reheat and high lighting in Washington, D.C.*

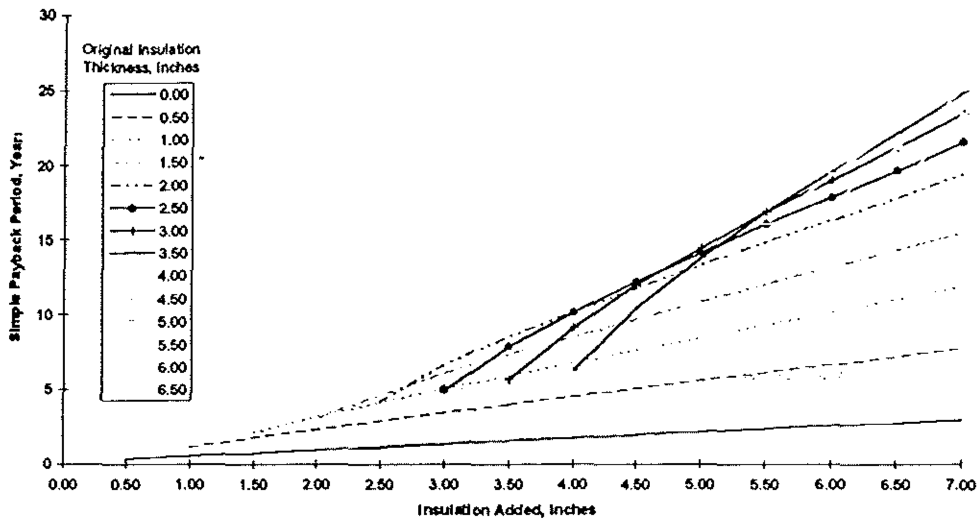

Figure 3d Cost-effectiveness results for roof insulation upgrades with VAV reheat and low lighting in Washington, D.C.

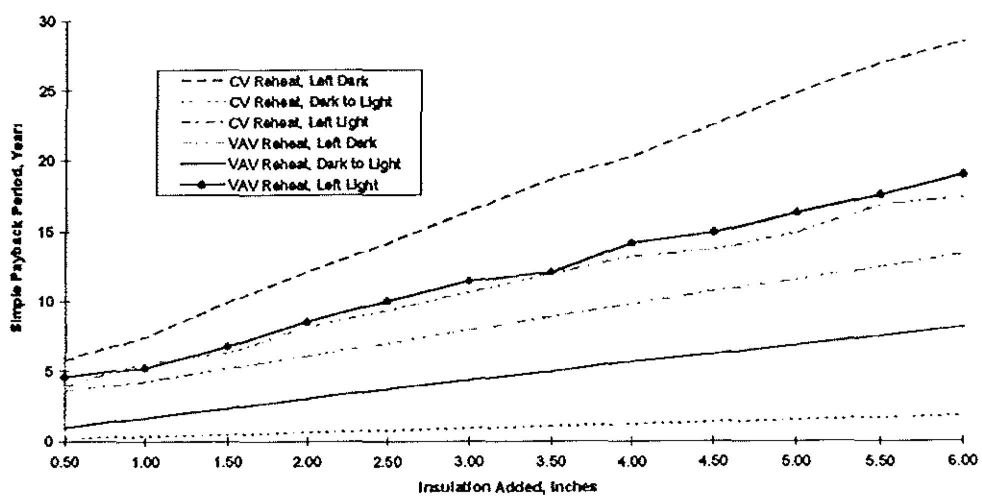

Figure 4 Effect of roof color and system type on roof insulation upgrade cost-effectiveness for Washington, D.C.

two HVAC systems (CV and VAV) in Washington, D.C. The annual energy cost savings for the lower lighting power density are slightly lower than for the higher lighting power density case in Washington, D.C. More significant are the differences in savings between the CV and VAV systems. Because these data are the result of multiple changes to building characteristics, we show impacts of individual changes in characteristics in the following figures.

Figures 3a, 3b, 3c, and 3d present cost-effectiveness results in terms of simple payback period for the same combinations of energy cost savings shown in Figure 2. In all cases, there are significant opportunities for upgrading roof insulation when there is little or no insulation to start with. In most cases, payback periods of less than 10 years are possible for adding additional insulation even when the roof is already heavily insulated.

In Figures 4 through 6, we demonstrate impacts of various building characteristics by using a single starting point for existing roof insulation—1 in. Probably one of the most significant factors in cost-effectiveness is roof color, as shown in Figure 4. An existing dark-colored roof, when changed to a light color, provides the highest predicted savings for both CV and VAV systems. Leaving a roof dark yields the lowest potential savings. If the roof is already a light color, solar gains are already reduced and insulation upgrades are not as effective overall.

In Figure 5, we present the effect of lighting power density on cost-effectiveness for the CV and VAV systems. For Washington, D.C., there is a slightly higher cost-effectiveness for CV systems with the higher level of lighting. In reviewing data for other locations not presented in this paper, internal load level plays only a slight role in cost-effectiveness of roof insulation upgrades. For VAV systems, lighting power density is

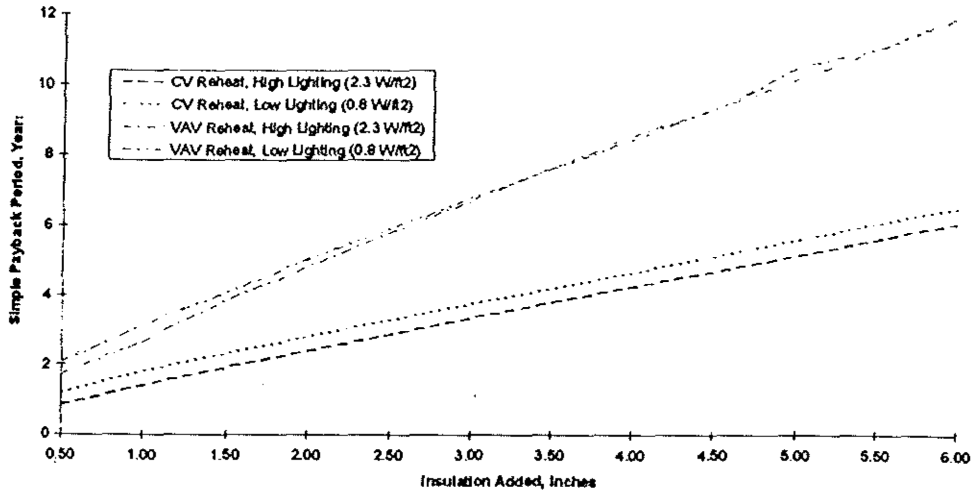

Figure 5 *Effect of internal loads (lighting) and system type on roof insulation upgrade cost-effectiveness for Washington, D.C.*

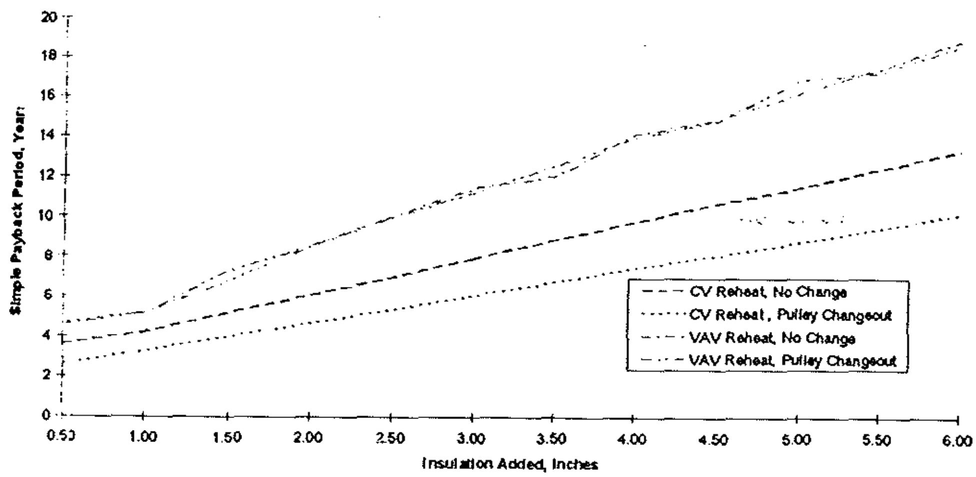

Figure 6 *Effect of fan motor pulley changeout and system type of roof insulation upgrade cost-effectiveness for Washington, D.C.*

even less significant in determining whether insulation upgrades are cost effective. There is little difference between internal load levels.

To single out the effect of reducing airflow to meet the reduced loads through a fan motor pulley changeout, we compare cases with and without the pulley change. Figure 6 compares the two cases (with and without pulley change) for CV and VAV systems. For CV systems, the pulley changeout has significantly lower payback periods, while there is no significant difference between the two cases for VAV systems. VAV systems inherently are more efficient—they automatically reduce supply airflow to meet whatever load is present—changing the pulley does not provide significant advantages.

SUMMARY AND CONCLUSIONS

From this analysis of the data bases of potential roof insulation upgrades, we can draw a number of conclusions.

- It is always cost-effective to add insulation to a roof that has little or no existing insulation (or wet insulation)—up to twice current practice or energy codes. In many cases, it is cost-effective to add insulation even when insulation levels in an existing roof assembly are already significant.
- Changing from a dark- to a light-colored roof provides the most significant savings potential, with the highest savings in locations with high cooling loads. Light-colored roofs actually can increase heating loads in colder locations.
- The level of internal loads plays only a small role in the cost-effectiveness of insulation upgrades.
- HVAC system efficiency plays an important role in the savings equation for insulation upgrades. In a less-efficient CV system, changing out fan motor pulleys to match reduced loads significantly increases the cost-effectiveness of adding insulation (lowest simple payback). This can mean that insula-

tion upgrades that would not be cost effective or even more insulation becomes cost effective.

- For more efficient HVAC systems (VAV system), increased roof insulation is not as cost-effective. In most cases, changing out the fan motor pulley on VAV systems does not significantly improve the cost-effectiveness for added insulation.
- In general, there are greater cost-effective opportunities for roof insulation than for wall insulation or fenestration (and roofs are replaced more frequently than are walls or windows).
- An important conclusion learned from the data bases, but not directly demonstrated in this paper, was that buildings with large internal areas relative to exterior zones have a greater potential for roof insulation upgrades than do externally dominated buildings (low-rise/mid-rise).

These data bases can quickly provide information on the potential cost-effective upgrades for roof insulation, wall insulation, and fenestration options. The simulations were constructed to allow interpolation of results among the building characteristics simulated. The spreadsheets that summarize the cost-effectiveness results facilitate changing basic assumptions—upgrade costs, average utility costs, and insulation type—allowing a user to customize the results to his or her specific building configuration. Once a user determines that potential cost-effective upgrades exist, more detailed engineering analyses can be performed.

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