Development of a Database of Building Envelope Simulations for Evaluating Building Envelope Retrofits

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ABSTRACT

As part of a new Federal program to promote energyefficient retrofit of commercial buildings, voluntary private-sector partners evaluate potential envelope retrofits for their buildings. To support this program, we performed a series of simulations of building envelope insulation and fenestration throughout the U.S. 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, HVAC system, insulation, and fenestration alternatives--in total, more than 20,000 envelope options. We combined these energy results 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 upgrades 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, so that those load reductions can be included in sizing calculations for replacement HVAC equipment in later stages.

In the third stage, load reductions, program participants evaluate and select cost-effective upgrades for internal loads and building envelope--primarily walls, roofs, and fenestration. To support the envelope retrofit evaluation, we performed a series of simulations of building envelope insulation and fenestration throughout the U.S. 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.

To create the database, we used the DOE-2.1E simulation program (Winkelmann et al. 1994) 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. We then combined these energy results with upgrade costs to demonstrate cost-effective upgrades based on an existing building envelope.

In this paper, we first describe how we defined the series of simulations. Then we present a sample of the energy and economic results from the simulations of potential insulation upgrade options. Finally we suggest how the results could be used to determine cost-effective options for upgrading building envelopes.

DEFINITION OF BUILDING SIMULATION COMBINATIONS

We defined the series of simulations to cover a range of climate, internal load, size, and HVAC system configurations. First, we started with three large office building prototypes we developed in earlier work (Crawley 1994) for use in evaluating energy savings and pollution prevention potential of a staged technical implementation approach:

- low-rise office, 48,000 ft^2, three floors
- mid-rise office, 196,000 ft^2, seven floors
- high-rise office, 840,000 ft^2, 20 floors

These three prototypes each represent roughly 25% of office building stock (EIA 1994). [The approximately 25% remaining office buildings are small, single or two story offices with packaged HVAC systems. The program focused on larger buildings with central HVAC systems.] As in our earlier work, we included two internal load levels to represent typical existing lighting systems (2.3 W/ft^2) and cost-effective new lighting systems (0.8 W/ft^2).

We selected eight U.S. locations to represent a broad cross-section of U.S. climatic conditions and utility rates: Los Angeles, California; Miami, Florida; Minneapolis, Minnesota; Omaha, Nebraska; Phoenix, Arizona; San Antonio, Texas; Seattle, Washington; and Washington, D.C. Weather Year for Energy Calculations weather data (ASHRAE 1985) and actual local utility rates were used for each simulation.

The last step in defining the simulations was to select HVAC systems that would cover the range of potential system efficiency. As in our previous work, we decided to use two different HVAC systems [constant volume reheat (CV) and inlet vane variable air volume reheat (VAV)] with and without reducing required air flows through a fan motor pulley change out.

ENVELOPE UPGRADES

We developed three sets of independent building envelope upgrades--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 fifteen ½-in. increments (R-3.2 each) from no insulation to 7-in. (R-44). To simulate the light and dark roof colors, we varied the roof absorptance--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.

For walls, similar to the roof simulations, we varied the insulation thickness in fifteen ½-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, we simulated a range of specific glazing using DOE-2.1E glass type codes. The equivalent U-values and shading coefficients (SC) for the glazing options are: single clear, 0.91 U-value and 0.84 SC; single gray, 0.91 U-value and 0.83 SC; single green, 0.89 U-value and 0.69 SC; double clear, 0.52 U-value and 0.88 SC; double grey, 0.52 U-value and 0.72 SC; double low-e, 0.51 U-value and 0.58 SC; and double low-e, 0.51 U-value and 0.55 SC. We also varied the FWR, using 10%, 40%, and 70% glazing. 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 option--a total of 21,000 DOE-2.1E simulations.

EVALUATION OF SIMULATION RESULTS

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

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

For a fan motor pulley change out (reducing air flow to meet the reduced loads) in the roof simulation set, we 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

In this section, we present a subset of the energy results from the roof insulation database. Due to the quantity of data (together the three databases comprise approximately 5 gigabytes of data--a spreadsheet for a single location for roofs is more than 3 megabytes), we concentrate on the roof insulation database results for this paper. Table 1 presents a subset of the results for a CV reheat system with fan motor pulley change out, high lighting levels (2.3 W/ft^2), and 1-in. existing roof insulation in Washington, D.C.

First, we focus on energy savings results for four locations: Los Angeles, California; Miami, Florida; Minneapolis, Minnesota; and Washington, D.C. Then we concentrate on cost-effectiveness results for Washington, D.C. to demonstrate some of the important trends we found when examining the sensitivity of the database results to varying HVAC systems, internal loads, and roof color.

Figure 1 presents annual energy cost savings for four locations (Los Angeles, Miami, Minneapolis, and Washington, D.C.). These figures are for a CV system, changing the roof color from dark to light, fan motor pulley change out, 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 bar show the effect of adding ½-in. roof insulation for cases where the existing roof has from none (0.0) to 6.5-in. of insulation. As can be seen in all cases, the highest energy cost savings are for 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 two HVAC systems (CV and VAV) for 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 figures that follow.

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, it can be cost-effective (at payback periods less than 10 years) to add 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. When the existing roof is a dark color (low reflectance) and is changed to a light color, this has the highest savings are possible for both CV and VAV systems. Leaving a roof dark yields the least 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

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

Existing Roof		Roof Upgrade Option			Energy and Economic Analyses					
Insulation Thickness, Inches	Roof Color	Add Insulation, Inches	Roof Color	Fan Motor Option	Upgrade Cost, \$/ft^2 Roof Area	Internal Rate of Return, %	Simple Payback Period, Years	Annual Energy Savings		
								\$/ft^2 Roof Area	kWh/ft^2	%
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%

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-effective of roof insulation upgrades. For VAV systems, lighting power density is even less significant in whether insulation upgrades are cost-effective. There is often almost no difference between internal load levels.

To single out the effect of reducing airflow to meet the reduced loads through a fan motor pulley change out, 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 change out has significantly lower payback periods while there is no significant difference between the two cases for VAV systems. VAV systems are inherently 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 our analysis of the databases 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 color roof provides the most significant savings potential--with highest savings in locations with high cooling loads. Light color roofs can actually increase heating loads in colder locations.

- The level of internal loads plays only a small role in 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 (higher IRR and lower simple payback). Often, the pulley change out can cause more insulation to be cost-effective than would otherwise occur. In many cases, changing the pulley makes an insulation upgrade cost-effective when otherwise it would not be.

- 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.

- Several conclusions learned from the databases, but not demonstrated in this paper: 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). We also found 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 databases 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 between the building characteristics simulated. The spreadsheets which 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 their specific building configuration. Once a user determines that potential cost-effective upgrades exist, more detailed engineering analyses can be performed.

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Figure 1, Annual Energy Cost Savings for Adding 1/2-in. Roof Insulation with Constant Volume Reheat System and High Lighting (2.3 W/ft2)

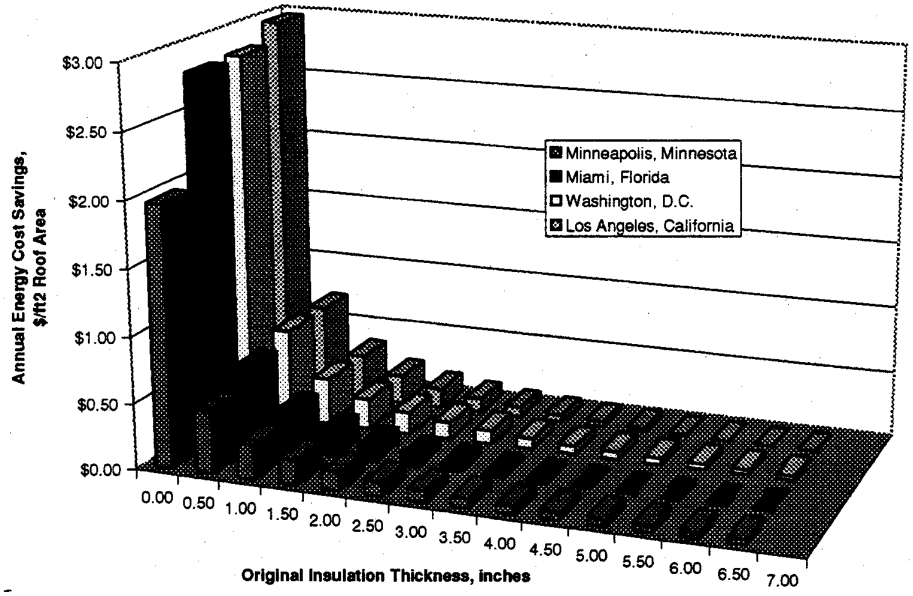

Figure 2, Annual Energy Cost Savings for Adding 1/2-in. Roof Insulation in Washington, DC

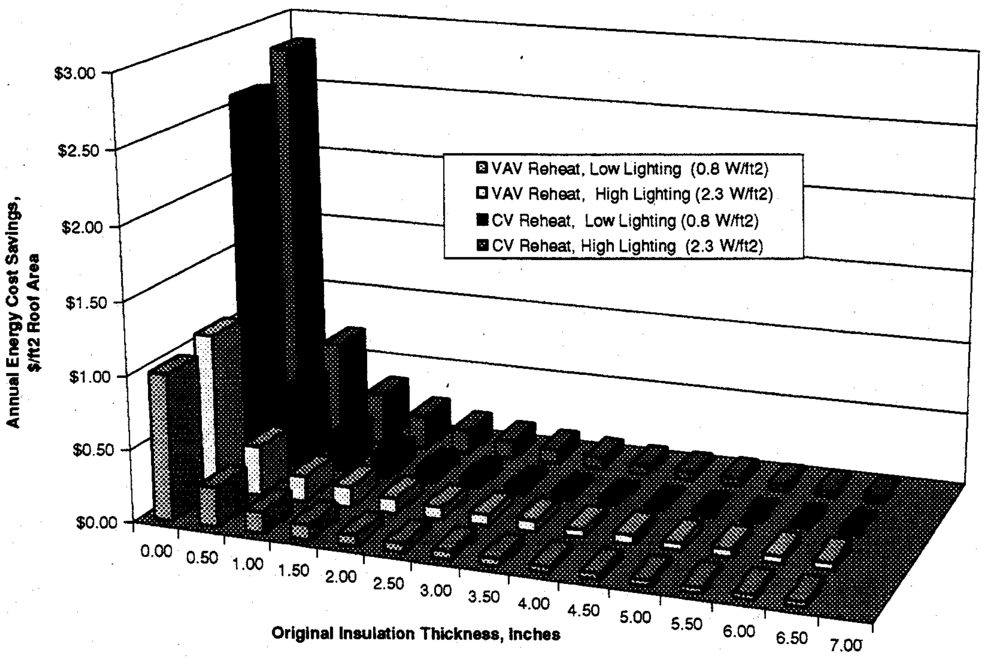

Figure 3a, Cost-Effectiveness Results for Roof Insulation Upgrades with Constant Volume System and High Lighting in Washington, DC

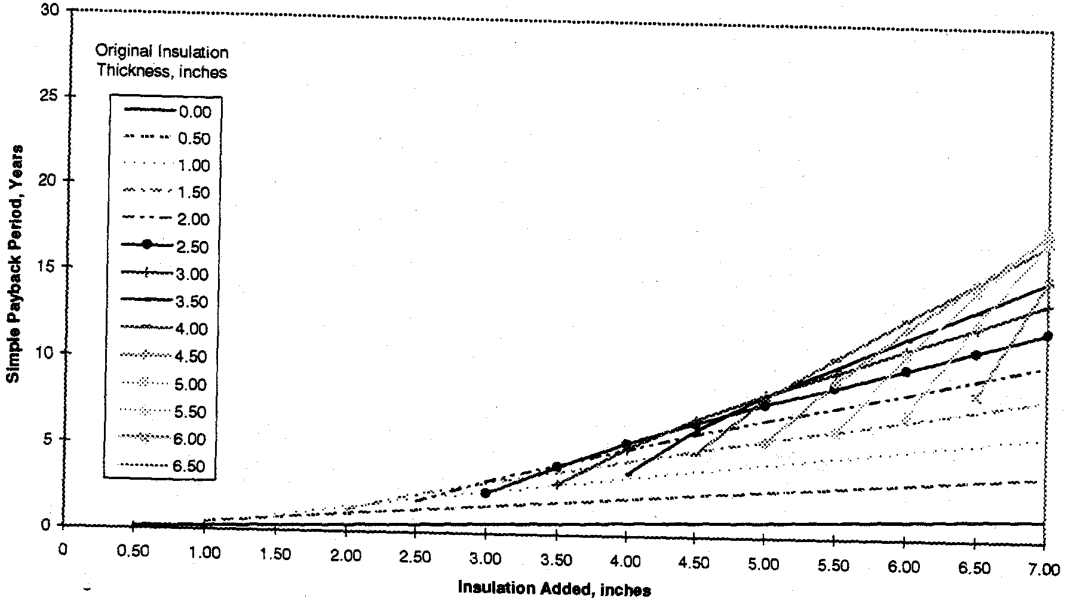

Figure 3b, Cost-Effectiveness Results for Roof Insulation Upgrades with Constant Volume System and Low Lighting in Washington, DC

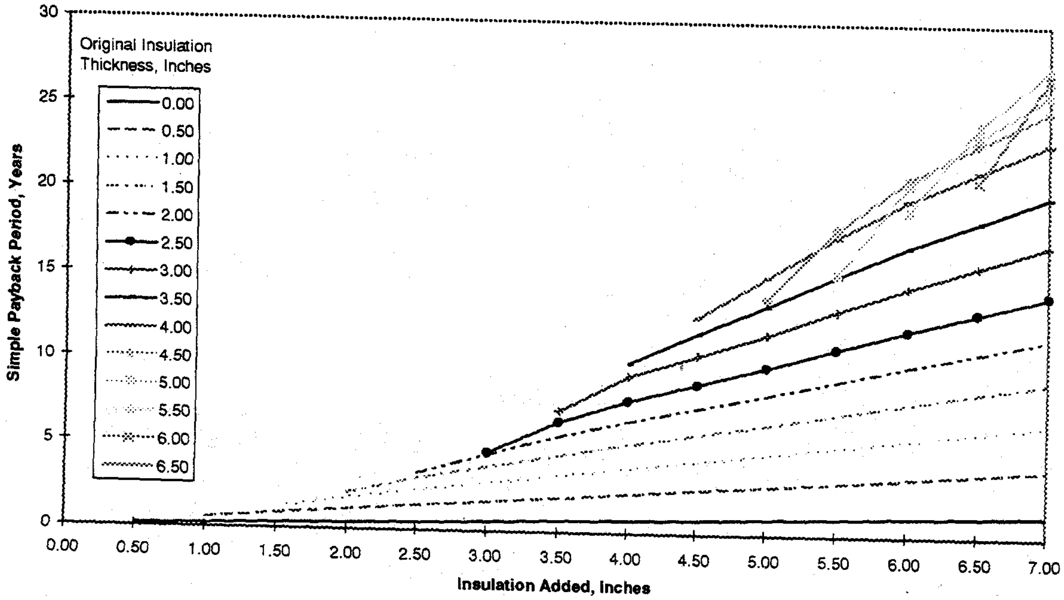

Figure 3c, Cost-Effectiveness Results for Roof Insulation Upgrades with VAV Reheat and High Lighting in Washington, DC

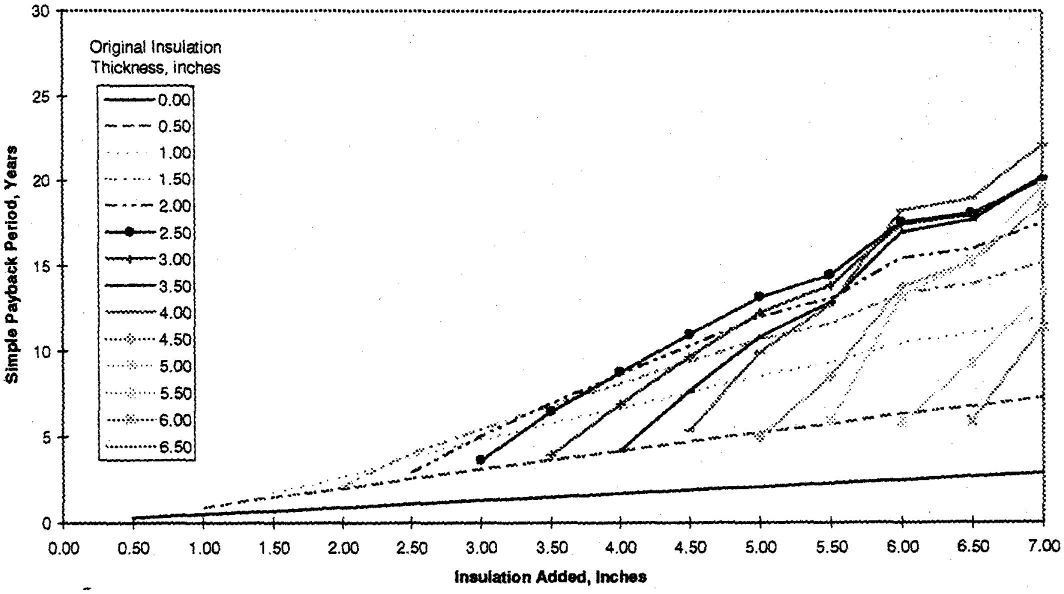

Figure 3d, Cost-Effective Results for Roof Insulation Upgrades with VAV Reheat and Low Lighting in Washington, DC

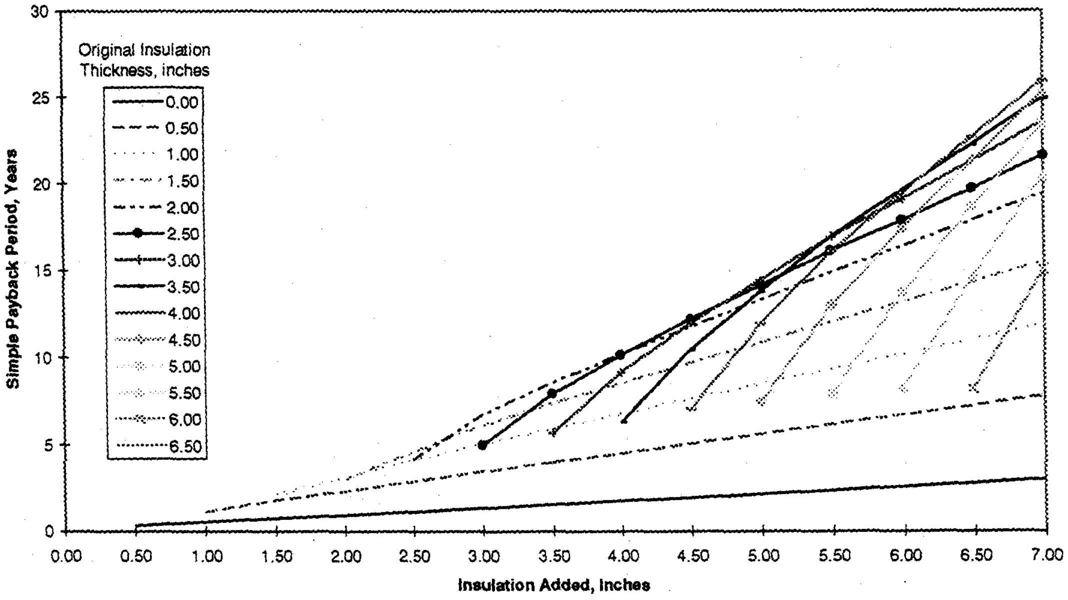

Figure 4, Effect of Roof Color and System Type on Roof Insulation Upgrade Cost-Effectiveness for Washington, DC

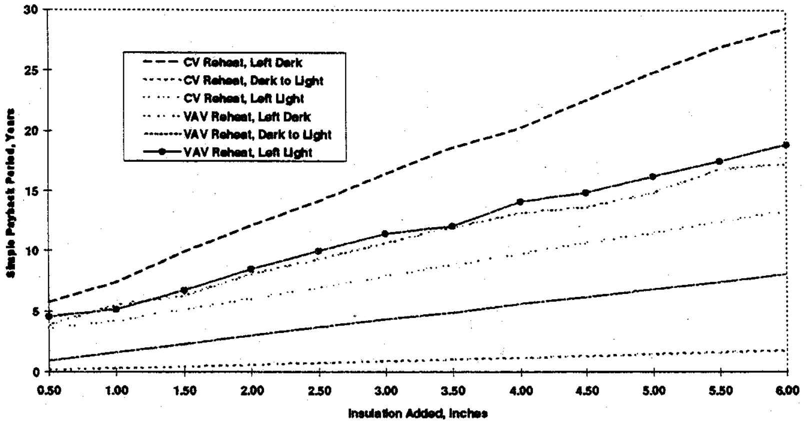

Figure 5, Effect of Internal Loads (Lighting) and System Type on Roof Insulation Upgrade Cost-Effectiveness for Washington, DC

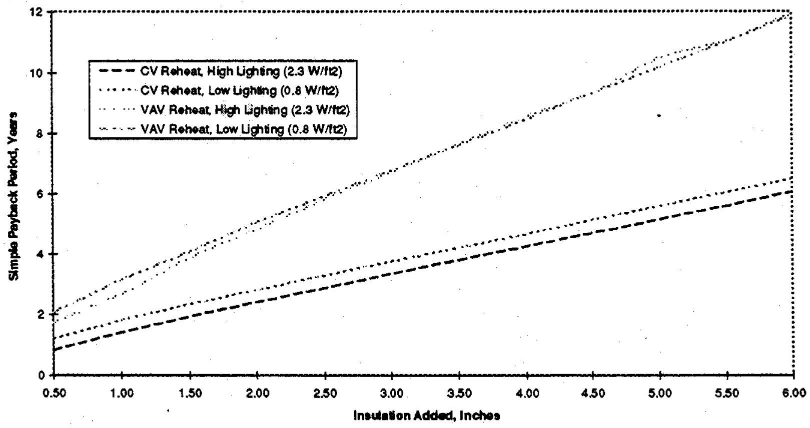

Figure 6, Effect of Fan Motor Pulley Changeout and System Type on Roof Insulation Upgrade Cost-Effectiveness for Washington, DC