{ TC "'CHAPTER FOUR: BUILDING ENVELOPE"' \l 1 **}**CHAPTER **FOUR**

BUILDING ENVELOPE

Computer simulations were used to simulate the effects of building envelope changes on the energy use of the office and retail buildings. The envelope changes studied here are those most frequently required by building codes - the addition of insulation to walls, roofs and foundations. This thesis focuses on the building envelope changes required by ASHRAE Standard 90.1. Other parts of the standard pertaining to equipment efficiencies or lighting power densities were considered outside the scope of this research. Both prescriptive and performance compliance methods of the standard are considered.

4.1 Energy Savings from ASHRAE Standard 90.1 - Prescriptive Method{ TC "4.1 Energy Savings from ASHRAE Standard 90.1 - Prescriptive Method" \l 2 }

The prescriptive method of ASHRAE Standard 90.1 was developed to provide a simple method for demonstrating compliance. The method relies on tables that list limiting values of building envelope characteristics such as maximum percent fenestration, wall U-value, and window U-value. The user calculates a number of parameters from their proposed building design, and then checks whether they lie within the limits set by the Standard.

If a proposed building design does not fall within the limits set in the prescriptive tables, the designer may have more than one way to bring the design into compliance. For example, if the building's percent fenestration exceeds the limit set by the standard, several things about the building design could be changed to bring it into compliance. Shading devices could be added to the windows, other windows with higher shading coefficients could be used, or perimeter daylighting controls could be added. Any of these changes may bring the building design into compliance.

For some building components there is no flexibility in meeting the prescriptive standard. The standard for roof insulation, for example, is effectively set at a particular level for each climate region. U-values for below-grade walls, walls adjacent to unconditioned spaces, and floors over unconditioned spaces are also set at determined levels for each climate zone.

One feature of the calculations prescribed by the standard is a correction for thermal bridging in wall and roofs. In previous compliance calculations required in Wisconsin, the effective resistance in a wall was simply found from the sum of the resistances of the layers in a wall. The ASHRAE Standard now requires that equivalent resistance be corrected by a factor that accounts for the passage of heat through parallel paths in building layers. The method is a way to approximate the decreased overall resistance of a wall or roof caused by heat bypassing insulation through structural elements such as wood or metal studs.

The effect of adding the thermal bridging correction factor is significant. For some types of wall constructions, the effective R-value of wall insulation may be decreased by 60% by adding the corrections in the standard. The standard will thus require much more insulation for a particular design than it otherwise would without considering thermal bridging. For this reason, correcting for thermal bridging may be a significant enforcement issue for new building codes based on the ASHRAE standard. If those charged with enforcing the standard choose to overlook the detailed calculations of the R-values in walls and roofs, it could greatly impact the stringency of the standard.

The design of the two buildings were checked for compliance with the prescriptive criteria of ASHRAE Standard 90.1. The methods prescribed by the standard were used to determine relevant parameters pertaining to the thermal characteristics of the building. The buildings, as they were constructed, were checked for compliance using the tables for Madison, Wisconsin (Table 8A-33 in the Standard). The building models were then modified to reflect changes required to meet Standard 90.1 and computer simulations were used to estimate the energy savings associated with changes to the building envelope. The economic impacts of these building envelope changes were then assessed, based on the energy and equipment cost savings.

A number of assumptions were made in the analysis pertaining to the costs of equipment and construction. All the construction costs were taken from Means Building Construction Cost Data (Means, 1995). Means data were used to determine the incremental cost of adding insulation. The incremental costs were determined from the cost differences between different insulation thicknesses, divided by the added thickness. For example, if 3 inch thick insulation was \$0.50/sf and 6 inch thick insulation was \$0.80/sf the incremental cost would be \$0.30/sf divided by 3 inches or \$0.10/sf-inch. The costs used were those for total cost of installed items, including material, labor, overhead and profit. An average over all of the data available were used for each type of insulation. The incremental costs found from the Means data are shown in the table below.

Item	**Incremental Cost [$ / sf-inch]**	**Basis**
Wall Insulation	0.060	Fiberglass Batt
Roof Insulation	0.27	Expanded Polystyrene
Perimeter Insulation	0.13	Polystyrene bead board

Table 4.1 Incremental costs for insulation based on Means data.**{** TC "Table 4.1 Incremental costs for insulation based on Means data." \l 6 **}**

Means data were also used to estimate the capital cost savings that might be achieved by downsizing heating and cooling equipment. The cooling size of the unit was used to estimate the savings associated with resizing equipment. The costs were estimated from the Means Mechanical Cost Data (Means, 1995) for multizone, rooftop air conditioners with electric cooling, gas heat, and economizers. A regression was performed on the costs of the units as a function of the cooling size. The data indicated a incremental cost of $890 per ton of cooling capacity.

The ASHRAE prescriptive standard was also used to find recommended insulation levels for four other locations around the U.S.. Because the buildings were designed for Madison, the insulation levels that were in the buildings would not make a suitable base case for comparison in locations such as Miami and Phoenix. The levels set by the standard were used as the base case for comparison in locations outside of Madison. In these locations computer simulations were used to establish the base case energy use.

4.1.1 Prescriptive Compliance for Retail Building{ TC "4.1.1 Prescriptive Compliance for Retail Building" \l 3 }

The retail building did not pass the prescriptive criteria of Standard 90.1. It failed in the areas of roof, wall and perimeter insulation but the windows passed the prescriptive criteria. The ways in which the building failed to meet the standard are summarized in the table below.

	As Built R-value		ASHRAE Required R-value	
Building Component	(hrft^{2}F)/Btu	(m^2 K)/W	(hrft^{2}F)/Btu	(m^2 K)/W
Sales area wall insulation	9.6	1.7	13.9	2.4
Stock area wall insulation	3.1	0.55	13.9	2.4
Suspended roof insulation	15.7	2.8	22.2	3.9
Roof deck insulation	13.9	2.4	22.2	3.9
Perimeter insulation	5.0	0.88	8	1.4

Table 4.2 Required measures to pass prescriptive criteria - retail building{ TC "Table 4.2 Required measures to pass prescriptive criteria - retail building" \l 6 }, Madison, Wisconsin. R-values shown are for entire wall assembly.

Although the ASHRAE standard offers some flexibility in meeting the prescriptive criteria, for the case study building, the only way to pass the criteria of the standard was to add insulation to the walls, roof and slab perimeter.

To determine compliance for windows in the building requires the calculation of a number of factors relating to the building construction and loads. The internal load density is estimated based on lighting, equipment, and occupancy loads in the building and is given in units of W/sf. A projection factor is determined for windows that are shaded by overhangs. The projection factor is a measurement of how windows are shaded in the building. These two factors, and the shading coefficient of the glass are used to determine the allowed window to wall ratio for the building.

The retail building had standard double-pane windows, with no overhangs. The maximum percent of fenestration was determined for the retail building using the window U-value, internal load density, projection factor and shading factor. There was so little fenestration in the case study building that, for any of the windows listed in the tables, the building was below the maximum allowable percent of window area.

Because the building failed compliance only with respect to the building envelope insulation, the remainder of the analysis will focus on the areas of wall, roof and perimeter insulation.

The simulations of the retail building were used to estimate the energy savings that might have been achieved had the building been constructed to meet the prescriptive version of Standard 90.1. The inputs to the building model were changed to match the requirements of the code, and the simulations were conducted again. Average utility costs for Wisconsin were used to estimate the cost savings associated with each of the changes to the building envelope. Flat rates of $0.058/kWh and $0.43/therm were used for electricity and natural gas prices respectively. The energy and utility cost savings of these measures relative to the building as it was constructed, are shown in Table 4.3 below. The energy and cost savings are put on a per square foot basis so that they might more easily be compared to other buildings.

Compliance Measure	Annual Electricity Use [$/sf]	Savings [%]	Annual Nat Gas Use [$/sf]	Savings [%]	Cooling Peak Load [W/sf]	Savings [%]
As Constructed	0.802		0.098		3.6	
With Added Wall Insulation	0.801	0.2%	0.067	30.9%	3.4	5.2%
With Added Roof Insulation	0.799	0.4%	0.087	10.7%	3.3	7.0%
With Added Perimeter Insulation	0.802	0.0%	0.097	0.7%	3.6	0.0%
In Compliance with Std 90.1	0.798	0.5%	0.056	42.4%	3.2	12.2%

Table 4.3 Savings from compliance with prescriptive criteria - retail building**{** TC "Table 4.3 Savings from compliance with prescriptive criteria - retail building" \l 6 **}**, Madison, Wisconsin.

The results indicate that the energy savings from compliance to the Standard in the retail building are primarily found in the heating loads of the building. Significant energy savings - up to 42% savings for full code compliance - were found in the natural gas consumption in the building. There was very little decrease in the cooling energy use, i.e. the electricity use, of the building.

Significant savings were also found in the peak cooling loads of the building. Peak cooling load savings of 12% were found for compliance to all of the measures required by the prescriptive standard.

The economic impact of code compliance was also estimated. A simple payback period was calculated for each of the measures required by the ASHRAE Standard. The first costs associated with each measure were taken to be the sum of the cost of added insulation minus any equipment savings resulting from downsizing equipment. The equipment size savings were found from the decrease in peak cooling load associated with each measure. The difference in peak load was multiplied by the incremental equipment cost ($890/ton) to find the equipment cost savings. The simple payback was then calculated as the first costs divided by the annual savings. The results of this analysis are shown in the table below.

Compliance Measure	Annual Utility Savings [$/sf]	Equipment Cost Savings [$/sf]	Added Insulation Cost [$/sf]	Simple Payback [yr]
With Added Wall Insulation	0.032	0.082	0.033	0
With Added Roof Insulation	0.014	0.111	0.444	23.8
With Added Perimeter Insulation	0.001	0.000	0.003	4.7
In Compliance with Std 90.1	0.046	0.193	0.480	6.3

Table 4.4 Economic summary of code compliance - retail building**{** TC "Table 4.4 Economic summary of code compliance - retail building" \l 6 **}**, Madison, Wisconsin.

The overall impact of the measures required by Standard 90.1 would be a positive one for building owners that pay their own utility bills. Compliance with all of the measures required by the standard would have a payback period of 6.3 years. Equipment sizing savings, however, is important to the economic impact of the measures. If equipment savings are not included in the analysis, the payback for compliance to all the measures increases to 10 years. Equipment size savings are also responsible for the instant payback of wall insulation. The cost of adding wall insulation is more than offset by the equipment savings achieved.

4.1.2 Prescriptive Compliance for Case Study Office Building{ TC "4.1.2 Prescriptive Compliance for Case Study Office Building" \l 3 }

The office building did not pass all the requirements of the prescriptive standard of ASHRAE 90.1 It failed in the areas of wall and roof insulation. The ways in which the office building failed to meet the prescriptive criteria are summarized in the table below.

Building Component	As-built R-value		ASHRAE Required R-value	
	(hrft^{2}F)/Btu	(m^2 K)/W	(hrft^{2}F)/Btu	(m^{2}K)/W
Wall insulation	13.0	2.3	15.4	2.7
Sloped roof insulation	17.5	3.1	22.2	3.9
Flat roof insulation	14.0	2.5	22.2	3.9

Table 4.5 Required measures to pass prescriptive criteria - office building**{** TC "Table 4.5 Required measures to pass prescriptive criteria - office building" \l 6 **}**, Madison, Wisconsin. R-values shown are for entire wall assembly.

As in the retail building, the prescriptive standard offered no real flexibility in how requirements could be met. The only way to pass was to add insulation to the walls, roof and slab perimeter.

The office building simulations were used to estimate the energy savings that might have been achieved had the building been constructed to meet the prescriptive version of Standard 90.1. The inputs to the building model were changed to match the requirements of the code, and the simulations were conducted again. The same average utility costs for Wisconsin were used to estimate the cost savings associated with each of the changes to the building envelope. The energy and utility cost savings of these measures relative to the building as it was constructed, are shown in Table 4.6 below. The energy and cost savings are put on a per square foot basis so that they might more easily be compared to other buildings.

Compliance Measure	Annual Electricity Use [$/sf]	Savings [%]	Annual Nat Gas Use [$/sf]	Savings [%]	Cooling Peak Load [W/sf]	Savings [%]
As Constructed	0.730		0.156		4.2	
With Added Wall Insulation	0.729	0.2%	0.155	0.9%	4.2	0.4%
With Added Roof Insulation	0.718	1.6%	0.148	4.9%	4.0	4.1%
In Compliance with Std 90.1	0.717	1.8%	0.147	5.8%	4.0	4.5%

Table 4.6 Energy savings from compliance to prescriptive standard - office building**{** TC "Table 4.6 Energy savings from compliance to prescriptive standard - office building" \l 6 **}**, Madison, Wisconsin.

Greater electricity savings were found to result from compliance to the ASHRAE standard in the office building than in the retail building. Electricity savings ranged from 0.2 to 1.8% in the office building. Natural gas savings ranged from 0.9 to 5.8%. In this building, these savings cannot be easily separated into heating and cooling load savings because of the type of HVAC system employed in the building. Heat pumps are used in the office building so electricity savings may result from either decreased heating or cooling loads.

The office building also showed a significant decrease in peak cooling loads for compliance to the standard. Adding roof insulation had the greatest effect on peak loads, resulting in a decrease in peak cooling load of 4.1%.

The economic impact of code compliance was also found for the office building. A simple payback period was calculated using the same method as for the retail building. The results of this analysis are shown in the table below.

Compliance Measure	Annual Utility Savings [$/sf]	Equipment Cost Savings [$/sf]	Added Insulation Cost [$/sf]	Simple Payback [yr]
With Added Wall Insulation	0.003	0.008	0.025	6.4
With Added Roof Insulation	0.019	0.085	0.254	8.7
In Compliance with Std 90.1	0.022	0.093	0.278	8.4

Table 4.7 Economic summary of code compliance - office building**{** TC "Table 4.7 Economic summary of code compliance - office building" \l 6 **}**, Madison, Wisconsin.

As in the retail building, the measures required by the ASHRAE standard for the office building would have been economically beneficial for the building owners (assuming they would have paid the utility bills in the building). Each of the measures required by the code had a payback period of less than 9 years - less time than might be expected for the owners to occupy the building.

Equipment savings play a significant role in the cost savings associated with the building envelop measures. The equipment savings ranging from roughly 3 to 4 times the annual utility bill savings. Had these savings not been included in the analysis, the overall payback period for all of the measures would have increased to 12.6 years.

4.2 Energy Savings from ASHRAE Standard 90.1 Performance Method{ TC "4.2 Energy Savings from ASHRAE Standard 90.1 Performance Method" \l 2 }

The performance method offers building designers more flexibility in meeting the requirements of Standard 90.1 To demonstrate compliance, one uses ENVSTD, a computer program that comes with the standard. The program takes the thermal characteristics of the building as inputs, and uses regression equations to determine an estimate of the annual heating and cooling loads developed by the building. If these loads are within the limits set for the climate zone, the building passes. The same building characteristics used as inputs for the prescriptive method were used as inputs for the performance method.

4.2.1 Performance-Based Compliance for Retail Building{ TC "4.2.1 Performance-Based Compliance for Retail Building" \l 3 }

The ENVSTD computer program was used to determine compliance for the retail building with the performance criteria of the standard.

The retail building passed the wall and window sections of the standard within ENVSTD. The wall insulation in the building, which had failed the prescriptive criteria, passed the performance criteria. The building failed, however, in areas of roof and perimeter insulation. The standard for roof and perimeter insulation within ENVSTD is exactly the same as the prescriptive standard. These parts of ENVSTD are not really performance-based at all; the program only verifies that the users inputs meet prescriptive criteria.

The required changes to the original design to meet Standard 90.1, using the performance-based criteria, are that the roof and perimeter insulation be increased. The R-values for the insulation are exactly the same as those found using the prescriptive criteria, and are shown in Table 4.2.

The building envelope changes required to pass the performance standard are a subset of those required by the prescriptive criteria. The energy savings for increased roof and perimeter insulation are the same as those found previously for the prescriptive criteria and are shown in Table 4.3.

As mentioned in the documentation of Standard 90.1, the prescriptive standard is more stringent that the performance-based criteria. The case study of this building demonstrates that this definitely is the case. A designer choosing to meet the prescriptive standard might have specified much more insulation in the walls than was necessary to meet the performance standard. Although using the prescriptive standard may offer more energy savings, it may also add significant costs in the construction of the building.

4.2.2 Performance-Based Compliance for Office Building{ TC "4.2.2

Performance-Based Compliance for Office Building" \l 3 }

The ENVSTD computer program was also used to determine compliance for the office building with the performance criteria of the standard.

The office building passed the wall and window portions of the standard within ENVSTD. The wall insulation in the building, which had failed the prescriptive criteria, passed the performance criteria. The building failed, however, with respect to the roof insulation. The standard for roof insulation within ENVSTD is exactly the same as the prescriptive standard.

The required changes to the office building design, using the performance-based criteria, is that the roof insulation be increased. The R-values for the insulation are exactly the same as those found using the prescriptive criteria, and are shown in Table 4.5.

Within the performance-based portion of the ENVSTD program, there are three sets of criteria, corresponding to buildings having heating only, cooling only, or both heating and cooling. The criterion for buildings with heating and cooling is that the sum of the loads found separately for heating and cooling must be lower than the sum of the separate criteria for heating and cooling loads. Thus a building may fail one of the criteria, yet pass when both heating and cooling are considered. This was the case with the office building. It passed the cooling criterion but failed the heating criterion.

As in the retail building, the building envelope changes required for the office building to pass the performance standard are a subset of those required by the prescriptive criteria. The energy savings for increased roof and perimeter insulation are the same as those found previously for the prescriptive criteria and are shown in Table 4.6.

The office building case study demonstrates again that the prescriptive criteria are more stringent than the performance criteria of the standard.

4.3 Optimal Levels of Insulation{ TC "4.3 Optimal Levels of Insulation" \l 2 }

An analysis was conducted to determine those levels of wall, roof and perimeter insulation that would be optimal for the two buildings. The computer models were run parametrically, varying only one parameter at a time to determine the effect on heating and cooling energy use over the course of a year. Different levels were simulated for the wall, roof and perimeter insulation for both the office and retail buildings.

Optimal was defined in this analysis as the most cost effective level of insulation over the lifetime of the building. The cost effectiveness was calculated using the life-cycle cost analysis method described in the next section.

Many of the assumptions going into the life cycle cost analysis depend on the analyst's perspective. The two perspectives of interest in this study are those of the building owner or tenant, who is paying the utility bills, and a societal perspective. When considering the building owner's perspective the costs and benefits considered in the analysis are only those realized by the owner. In considering a societal perspective, other external considerations may be taken into account. For example, a societal perspective may account for environmental factors that may have costs or benefits for society that are not directly born by the building owner. A more efficiently run building may decrease power plant emissions, leading to better air quality for society in general. Although it is a benefit for society, it may not directly benefit the owner of the building in such a way that they would consider it in their analysis of costs and benefits associated with efficiency measures.

The economic assumptions made in this analysis also depend on the perspective. For example, from a building owners point of view, a reasonable time line of the analysis of the building may be 10 to 20 years. If the building is not cost effective over this time span, it may be for him or her, a bad investment. However, from a societal perspective it may make sense to use a longer life time for the analysis. The building, regardless of who owns it, will continue to require energy resources for heating, cooling and lighting for 50 to 100 years. Thus from a societal perspective it makes sense to use a longer planning horizon.

A societal perspective was probably taken in developing Standard 90.1. One of the purposes of building codes is to protect the interests of society in general. Sometimes the interests of society take precedent over those of the individual building owners. For example, building owners may be required to provide access for disabled persons, although it may not be profitable in the short term for them to do so. In the same way, the standard may require levels of insulation beyond what is cost-effective for the owners and tenants, so that the energy needs of future generations may be protected.

The optimization analysis was conducted using a variety of locations and economic assumptions. Some of these assumptions depend on perspective, others depend only on local conditions such as cost of insulation or costs for electricity and natural gas. Results are provided for a wide variety of cases to determine the sensitivity of the analysis to those assumptions.

4.3.1 Method{ TC "4.3.1 Method" \l 3 }

The life cycle cost analysis was conducted based on a method developed by Duffie and Beckman (Duffie, 1991). The method uses two factors to determine life cycle costs. The first factor, P_1 is used as a multiplier for the costs or savings that occur on an annual basis. It is the ratio of life cycle fuel cost savings to the first-year fuel cost savings, and is corrected to account for the present worth of future costs and savings. The second factor, P_2, is used as a multiplier for the one-time costs associated with a project. It is defined as the ratio of the life cycle expenditures incurred because of the capital investment to the initial investment. These two factors can be represented in the following equations.

$$P_1 = \left(1 - C\bar{t}\right) PWF\left(N_e, i_f, d\right) \tag{4.1}$$

$$\begin{aligned} P_2 = {} & D + (1-D)\frac{PWF(N_{min}, O, d)}{PWF(N_L, 0, m)} \\ & - \bar{t}(1-D)\left[PWF(N_{min}, m, d)\left(m - \frac{1}{PWF(N_L, 0, m)} \right) + \frac{PWF(N_{min}, O, d)}{PWF(N_L, 0, m)} \right] \\ & + M_s(1 - C\bar{t}) \cdot PWF(N_e, i, d) + pV(1 - \bar{t}) \cdot PWF(N_e, i, d) \\ & - \frac{C\bar{t}}{N_D} PWF(N'_{min}, 0, d) - \frac{R_v}{(1+d)^{N_e}}(1 - C\bar{t}) \end{aligned} \tag{4.2}$$

The present worth function is defined as:

$$PWF(N, i, d) = \sum_{j=1}^{N} \frac{(1+i)^{j-1}}{(1+d)^{j}} \tag{4.3}$$

And the terms in the equations are defined as:

C = 1 if business, 0 if residence

D = Ratio of down payment to initial investment

d = Discount rate

i = General inflation rate

i_F = Fuel inflation rate

m = Annual mortgage interest rate

M_s = Ratio of first year miscellaneous costs to initial investment

N_D = Depreciation lifetime in years

N_e = Period of economic analysis

N_L = Term of Loan

N_{min} = Years over which mortgage payments contribute to the analysis

N'_{min} = Years over which depreciation contributes to the analysis

$\bar{t}$ = Effective income tax rate

p = Property tax rate based on assessed value

R_v = Ratio of resale value at end of period of analysis to initial investment

V = Ratio of assessed valuation in first year to the initial investment

Using these two factors, the overall life-cycle savings of a particular option are found using the following equation.

$$LCS = P_1 \cdot (F_{ANN,0} - F_{ANN}) + P_2 \cdot (E_0 - E) \tag{4.4}$$

Where these terms are defined as:

LCS = Life cycle savings, relative to base case building

$F_{ANN,0}$ = Annual fuel costs of base case building

F_{ANN} = Annual fuel costs of option to be considered

E_0 = First costs (equipment) of base case building

E = First costs of option to be considered

The annual fuel costs were determined from the overall fuel requirements of the building as estimated by the building model. The equipment costs were determined from the added or reduced costs of insulation and cooling equipment required for each option considered.

The energy bills for the buildings were determined by multiplying the energy consumed, either electricity or natural gas, by a simple flat rate. The electricity rates used were adjusted to include typical electricity demand charges for commercial customers. The demand charges were not, however, added in on a monthly basis as is usually done in billing by utilities. Several comparisons were made between fees that would have been assessed using the estimated demand charges, and billing using the estimated monthly demand, and a monthly demand charge. The difference between the energy bills calculated using the two methods was less than 3% for each of the months during the year, and summed to a difference of less than 0.5% over the course of the entire year. Therefore, it was concluded that the estimated demand charges would be sufficient for calculating the energy bills of the two buildings.

4.3.2 Assumptions{ TC "4.3.2 Assumptions" \l 3 }

The base economic assumptions in this thesis were chosen to represent the perspective of the building owner or tenant. These assumptions are summarized in the table below.

Parameter	Value	Notes
D	20 %	Down payment
d	12 %	Discount rate
i	3 %	Inflation rate
i_F	5 %	Fuel inflation
m	8 %	Mortgage rate
N_D	39 yr	According to IRS
N_e	20 yr	Term of analysis
N_L	20 yr	Term of loan
p	2 %	Property tax (annual)
$\bar{t}$	40 %	Income tax
M_s	0	Assume no misc. costs
V	1	Assume assessed value equal to cost
R_v	1	Assume no resale value

Table 4.8 Economic variables - base case assumptions.**{** TC "Table 4.8 Economic variables - base case assumptions." \l 6 **}**

Some of these parameters would be quite different if one were taking a societal perspective in the analysis. For example, the discount rate from a societal perspective is much lower. Typical values are around 8% for public planning and policy decisions. Also a societal perspective tends to consider longer time spans for consideration. A period of 40 to 50 years, more on the order of the true lifetime of the building, might be used in determining the life cycle costs from this perspective.

The estimates for the costs of added insulation and equipment savings were the same as those used in section 4.1 for finding the economic impacts of compliance with Std 90.1. The equipment cost savings were taken to be $890/ton of cooling capacity. The incremental cost of insulation is the same as that shown in Table 4.1.

Utility prices used in the analysis were taken from the most recently available survey of electricity and natural gas prices for commercial customers in Energy User News (EUN, 1995). The electricity price for each of the five locations studied was taken to be the simple average of the prices listed for all the utilities in that state. For natural gas prices the state-wide estimate from EUN was used without adjustment. The utility prices assumptions used in the analysis are summarized in the table below.

State	Electricity [¢/kWh]	Natural Gas [$/therm]
Arizona	9.3	0.54
District of Columbia	8.2	0.61
Florida	6.2	0.52
Washington	4.1	0.50
Wisconsin	5.8	0.43

Table 4.9 Electricity and natural gas prices used in the analysis (EUN, 1995).**{** TC "Table 4.9 Electricity and natural gas prices used in the analysis (EUN, 1995)." \l 6 **}** Electricity prices include average demand charges.

In the optimization analysis, the corresponding utility rate was used for each location. The electricity prices from EUN include average demand charges found from dividing the total revenue by the total kWh sold to commercial customers at each utility.

4.3.3 Results of Insulation Optimization{ TC "4.3.3 Results of Insulation Optimization" \l 3 }

For each of the two buildings, simulations were run parametrically, varying the level of wall, roof and perimeter insulation over a wide range of values. The life-cycle savings per unit floor space was then found for each case. The base case in each of the runs was defined as the lowest level of insulation that would meet the requirements of the prescriptive version of Standard 90.1. This process was repeated over five locations around the U.S. and with both the retail and office buildings.

Wall Insulation

The optimization was first conducted on the wall insulation in the retail building. The results for Madison, Wisconsin are shown in the figure below.

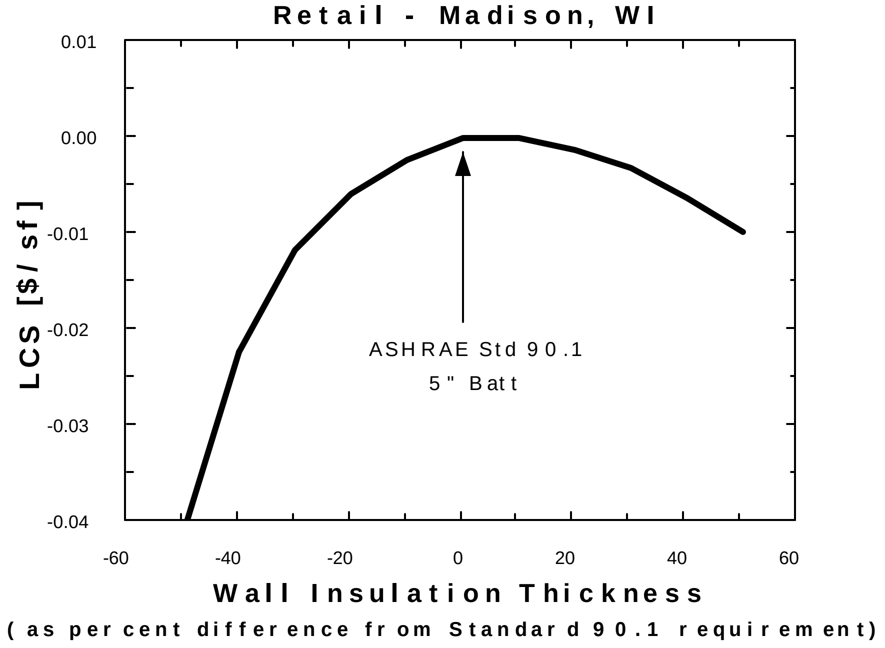

Figure 4.1 Wall insulation optimization - retail building, Madison, Wisconsin.{ TC "Figure 4.1 Wall insulation optimization - retail building, Madison, Wisconsin." \l 5 }

Figure 4.1 shows the life-cycle costs per square foot of floor area, for a range of wall insulation thicknesses. The plot passes through the point 0,0 by definition. The base case wall insulation is defined having the same thickness as was required by the standard, and is taken as having zero life-cycle savings. Points on the graph that have negative life-cycle savings are more expensive over the lifetime of the building than the base case. Points that have positive life-cycle savings represent options that would offer savings over the base case level of insulation required by the ASHRAE standard. The best option in each case is that which maximizes life-cycle savings.

The shape of the graph is typical for life-cycle savings analyses and actually represents the summation of two competing effects. As wall insulation thickness is added, the construction costs (first costs) of the building increase. Adding insulation also increases the thermal performance of the building, causing annual operating costs to decrease. The maximum life-cycle savings occurs at the point where the combination of first costs and annual costs is at an optimum, resulting in the best trade-off between first costs and operating costs.

The results show that for the Madison retail building, the level of wall insulation required by the standard is very nearly that which would have given the maximum life-cycle savings. The maximum level of life-cycle savings occurs at a level of insulation 5% greater than that required by the code.

An analysis was conducted to determine how sensitive the optimal level of insulation was to the assumptions made in the analysis. Figure 4.2 shows how the optimal level of insulation would have been affected by changes in the assumptions used in the analysis. Each point on the graph represents the optimal level of insulation for a given set of assumptions. The center point of the graph, where each of the lines cross represents the optimal insulation value given the base case assumptions. In the base case the optimal insulation level was 5% greater than the amount required by the ASHRAE Standard. Each line shows how the optimal level of insulation would have changed in response to a change in one of the assumptions, with all the other values held constant. The variables examined in the sensitivity analysis are shown at the right in the figure and were varied over a range of ±100%. The values in parenthesis are the base case assumptions for each variable.

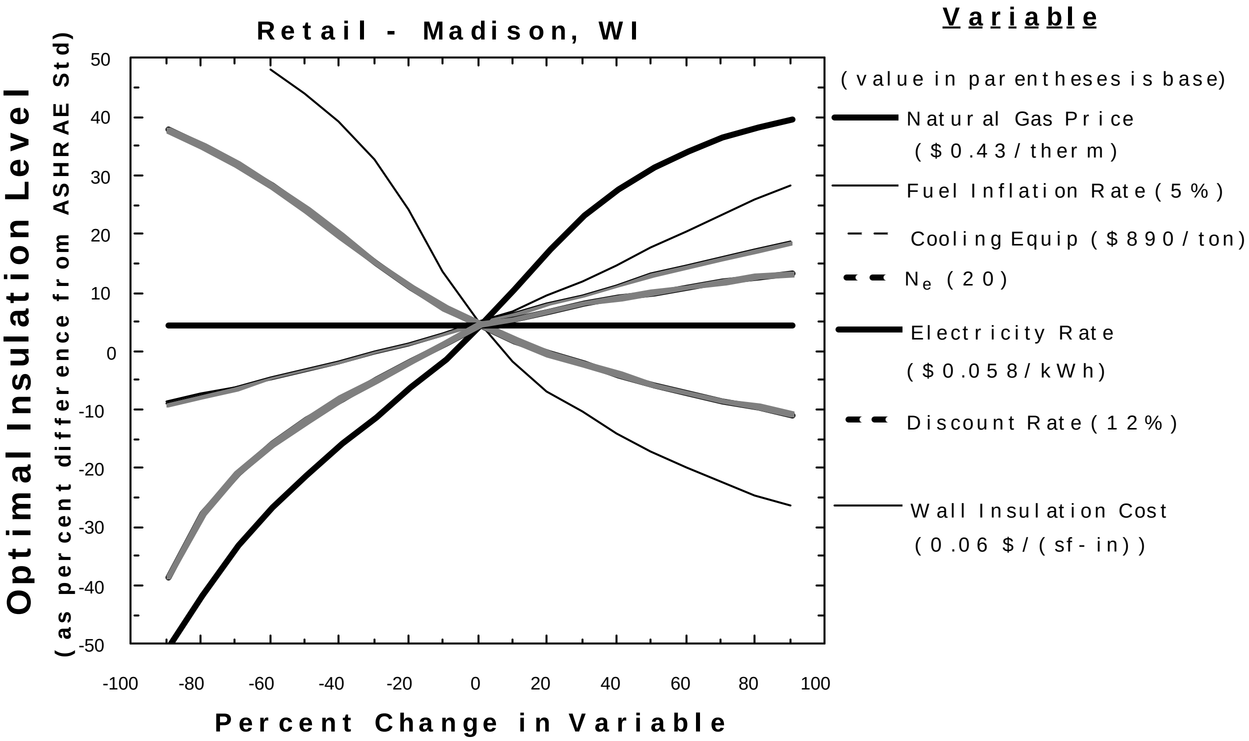

Figure 4.2 Wall insulation sensitivity analysis - retail building{ TC "Figure 4.2 Wall insulation sensitivity analysis - retail building" \l 5 }, Madison, Wisconsin.

The analysis shows that the determination of the optimal level of wall insulation in the retail building is the most sensitive to the assumptions of wall insulation cost and natural gas price. The curves for these two variables are the steepest, therefore changes in their assumed values would cause the greatest change in the optimal level of insulation found in the analysis. Changes in the electricity price had no effect on the optimum value because virtually all of the energy savings due to wall insulation resulted in only decreased heating loads and therefore decreased only the natural gas use in the building.

The wall insulation was varied for the retail building model at four other locations in the U.S.. The results of these simulations are shown in Figures 4.3 through 4.6. In Miami and Phoenix, there was no insulation required by the standard so results are plotted for the absolute level of insulation, rather than a percentage of that required by Standard 90.1.

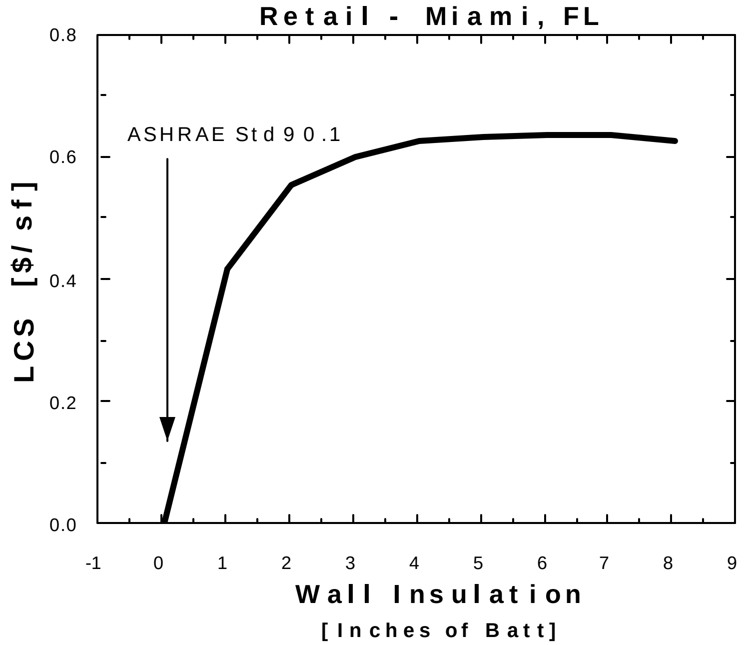

Figure 4.3 Wall insulation optimization - retail building, Miami, Florida.**{** TC "Figure 4.3 Wall insulation optimization - retail building, Miami, Florida." \l 5 **}**

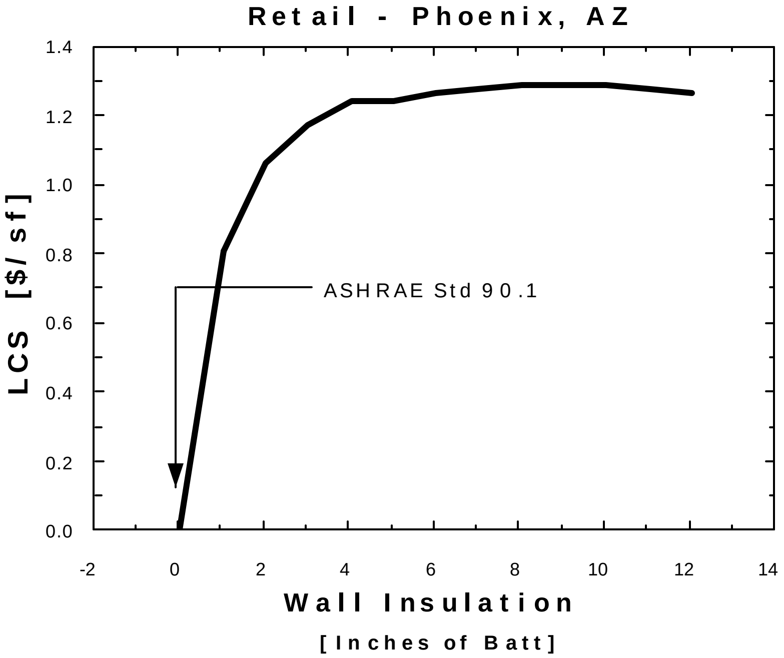

Figure 4.4 Wall insulation optimization - retail building, Phoenix, Arizona.**{** TC "Figure 4.4 Wall insulation optimization - retail building, Phoenix, Arizona." \l 5 **}**

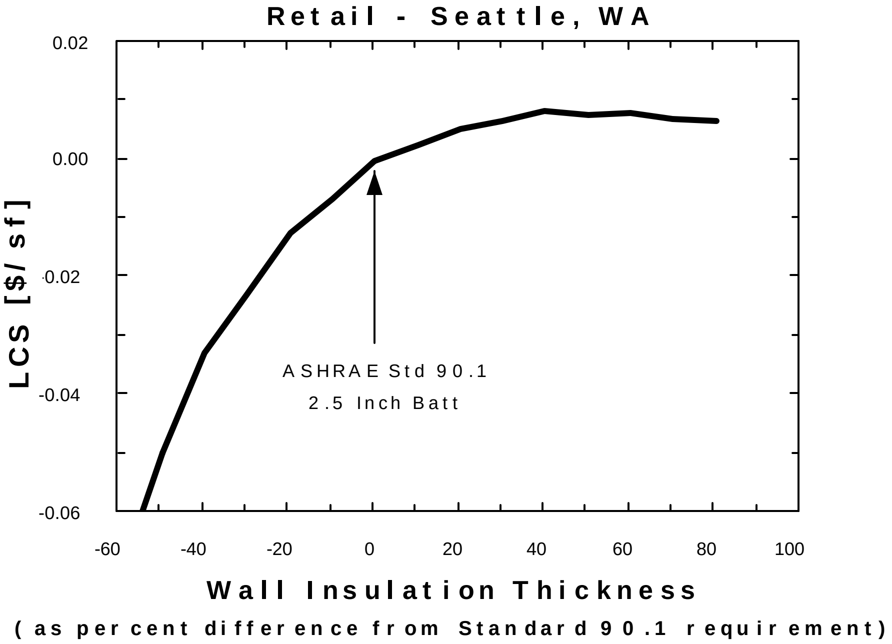

Figure 4.5 Wall insulation optimization - retail building, Seattle, Washington.**{** TC "Figure 4.5 Wall insulation optimization - retail building, Seattle, Washington." \l 5 **}**

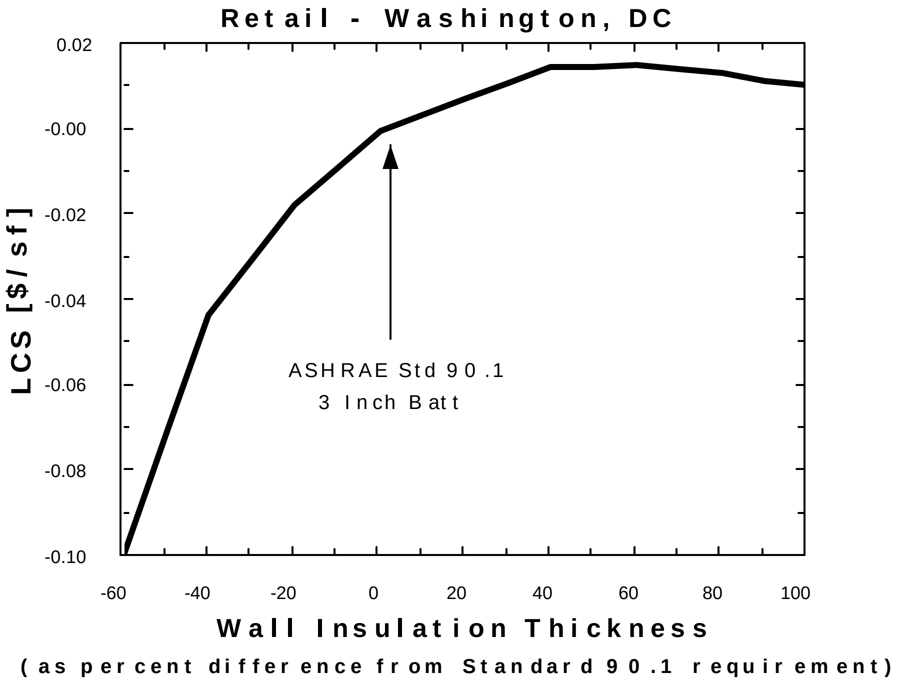

Figure 4.6 Wall insulation optimization - retail building, Washington, DC.**{** TC "Figure 4.6 Wall insulation optimization - retail building, Washington, DC." \l 5 **}**

The results for the retail building in Miami and Phoenix indicate that the ASHRAE Standard requires a level of wall insulation much less than what would be economically optimal. For both of these locations, no wall insulation would have been required by the prescriptive standard. However, the maximum life-cycle savings was found for 6 inches of batt in Miami and 9 inches of batt in Phoenix. The driving variable in these cases was found to be the savings resulting from down-sizing cooling equipment.

The level of insulation required by the prescriptive standard in Seattle and Washington DC was also less than the optimal level found in the analysis. The results indicate that the wall insulation should be 40% thicker in Seattle and 60% thicker in Washington DC to achieve the optimal life-cycle savings.

A life-cycle cost analysis was also conducted for the wall insulation in the office building model. The results for Madison are shown in Figure 4.7 below.

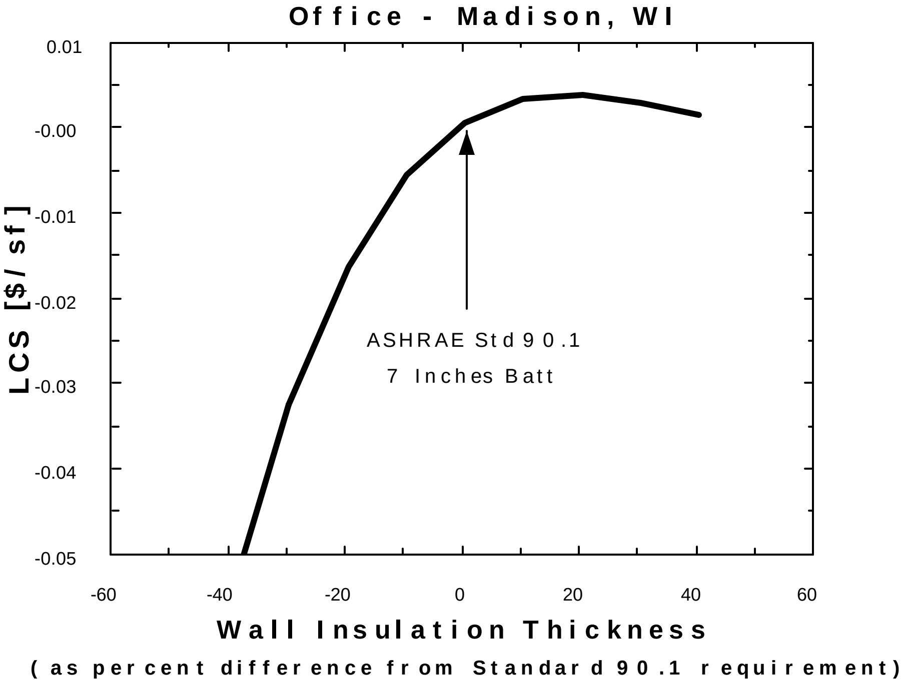

Figure 4.7 Wall insulation optimization - office building, Madison, Wisconsin.**{** TC "Figure 4.7 Wall insulation optimization - office building, Madison, Wisconsin." \l 5 **}**

The level of insulation required by the standard is less than the optimal amount for the Madison office building. The life-cycle savings are achieved at a level of wall insulation 16% greater than that required by the standard.

A sensitivity analysis was conducted on the optimization of the office-building wall insulation. The results of this analysis are shown in Figure 4.8. As in the sensitivity analysis for the retail building, each line on the graph represents how the optimal level of insulation would have been effected by a change in one of the assumptions in the analysis. The assumptions that were varied are listed on the graph. The value in parenthesis next to each is the base case assumption.

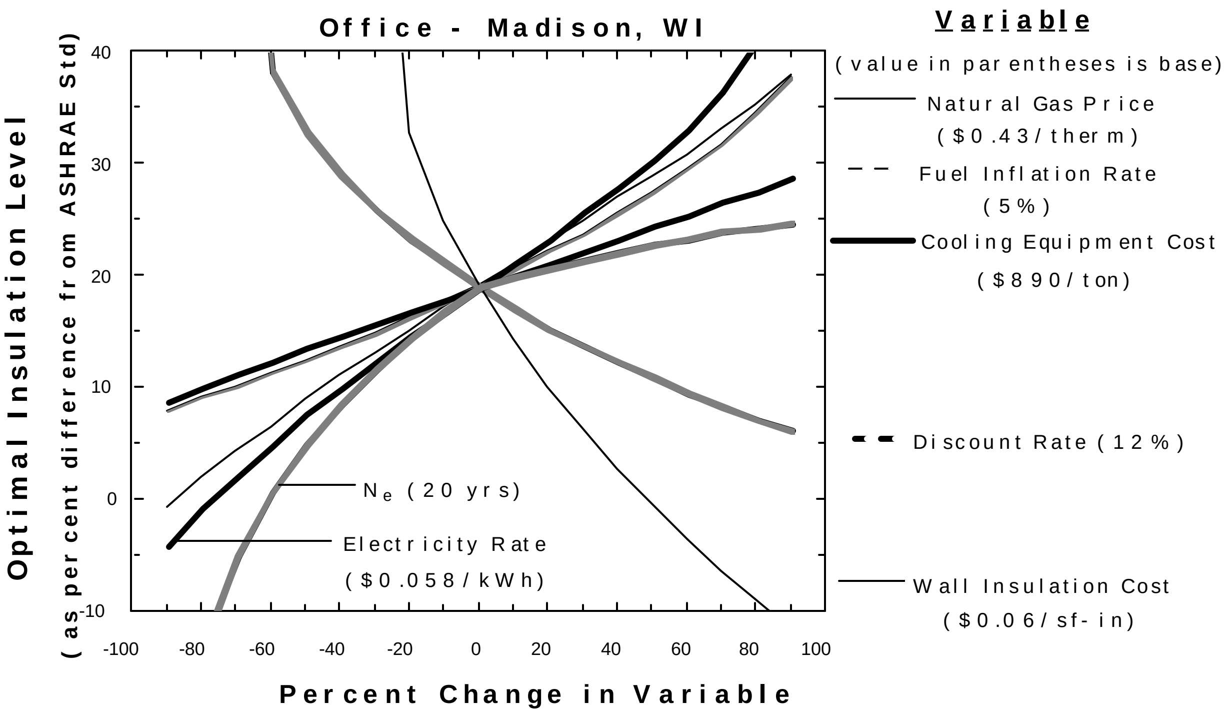

Figure 4.8 Wall insulation sensitivity - office building, Madison, Wisconsin.**{** TC "Figure 4.8 Wall insulation sensitivity - office building, Madison, Wisconsin." \l 5 **}**

As in the retail building, the office building results are the most sensitive to the assumption of the cost of insulation. The results also show sensitivity with respect to the assumptions of discount rate, electricity price and natural gas price.

The process was repeated for wall insulation in the office building model in four other locations in the U.S.. The results of these simulations are shown in Figures 4.9 through 4.12.

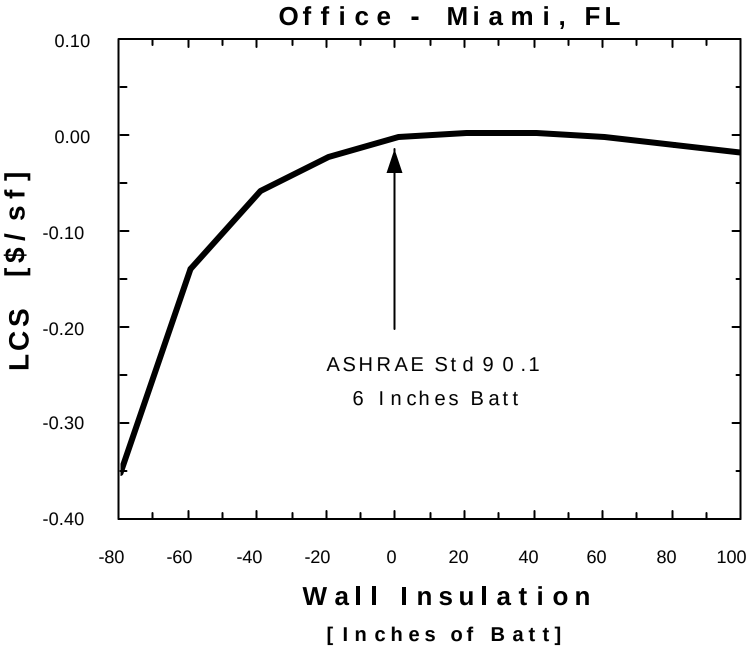

Figure 4.9 Wall insulation optimization - office building, Miami, Florida.**{** TC "Figure 4.9 Wall insulation optimization - office building, Miami, Florida." \l 5 **}**

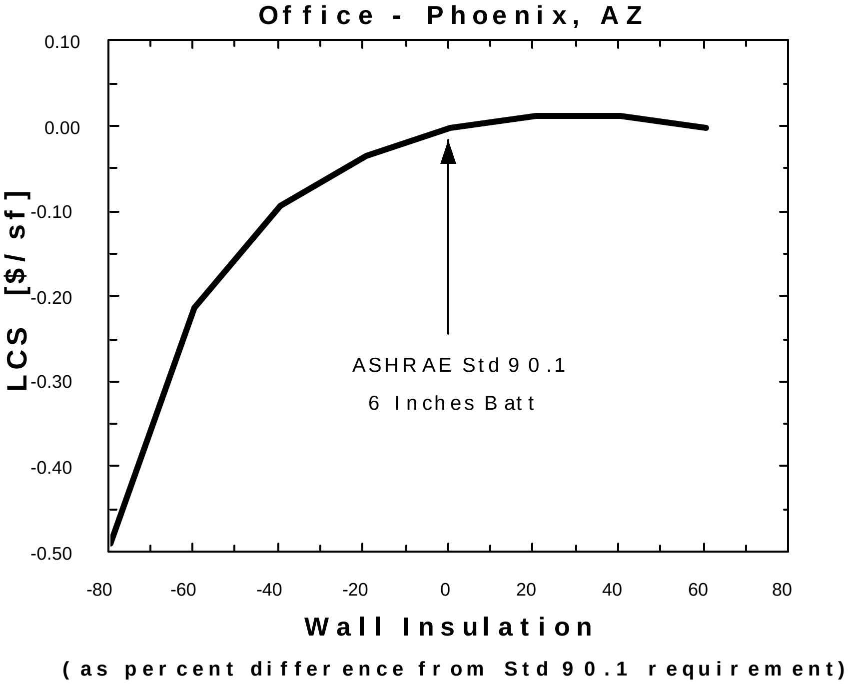

Figure 4.10 Wall insulation optimization - office building, Phoenix, Arizona.**{** TC "Figure 4.10 Wall insulation optimization - office building, Phoenix, Arizona." \l 5 **}**

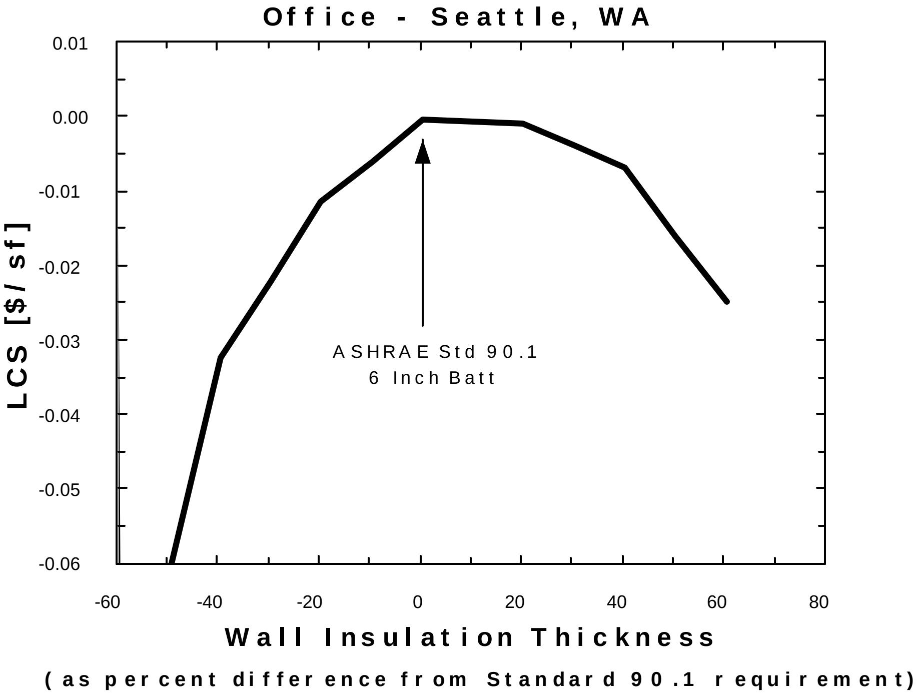

Figure 4.11 Wall insulation optimization - office building, Seattle, Washington.{ TC "Figure 4.11 Wall insulation optimization - office building, Seattle, Washington." \l 5 }

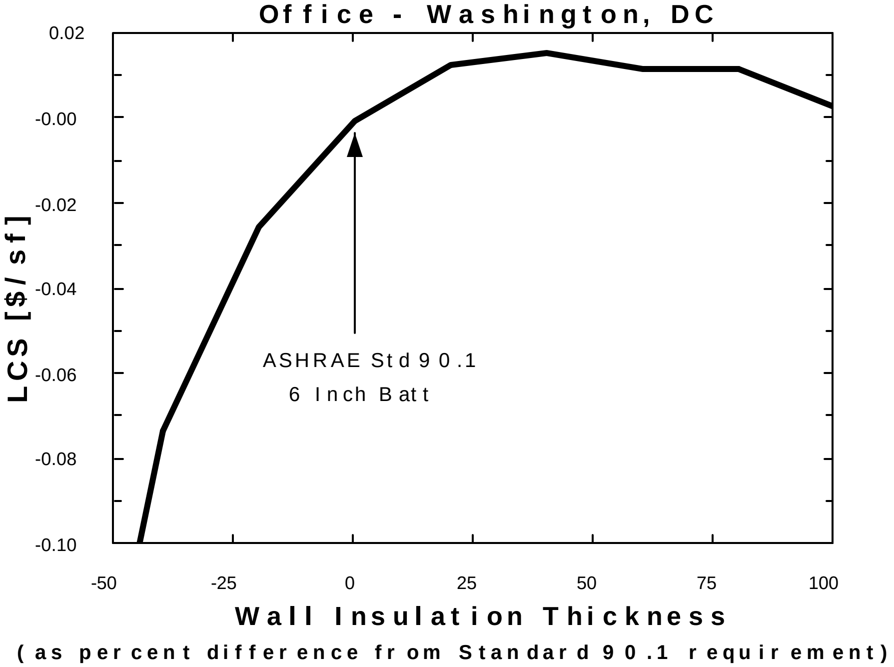

Figure 4.12 Wall insulation optimization - office building, Washington, DC.**{** TC "Figure 4.12 Wall insulation optimization - office building, Washington, DC." \l 5 **}**

The results of the simulations indicate that for Miami, Phoenix and Washington DC, the level of wall insulation required by Standard 90.1 is less than the optimal by about 40%. The level of wall insulation required by the standard for Seattle was the optimal amount found in the simulations.

Figure 4.13 below summarizes the comparison between optimal wall insulation level and the level recommended by ASHRAE. The plot shows the R-value of the optimal insulation level versus the ASHRAE required R-value for wall insulation for each of the cases studied. Had the ASHRAE required amount and the optimal found in the analysis been the same, they would lie on the 45 diagonal line shown on the graph. Points lying above this line indicate instances where the optimal was greater than the ASHRAE requirement and points lying below the line represent instances where the ASHRAE requirement was greater than the optimal.

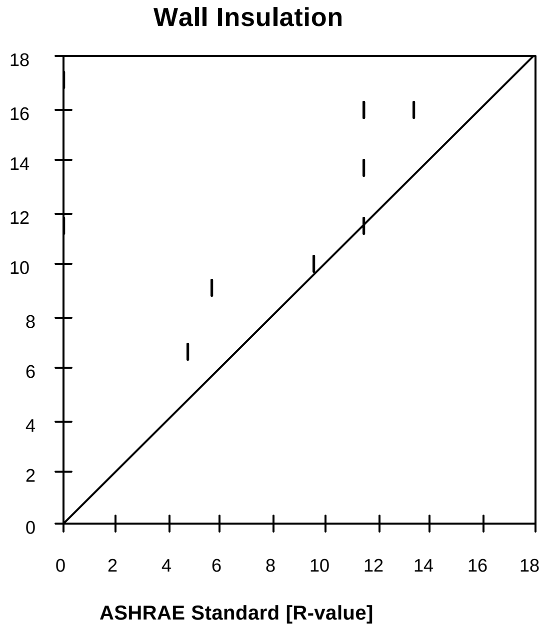

Figure 4.13 Comparison of optimal wall insulation to ASHRAE Standard 90.1**{** TC "Figure 4.13 Comparison of optimal wall insulation to ASHRAE Standard 90.1" \l 5 **}**

In almost all of the cases studied, the optimal R-value for wall insulation was greater than the amount required by the ASHRAE standard.

Roof Insulation

The simulations were used to find the optimal level of roof insulation in the two buildings. Again the amount of insulation required by the prescriptive version of the ASHRAE Standard was used to define the base level for the analysis. The results for the retail building in Madison are shown in Figure 4.14 below.

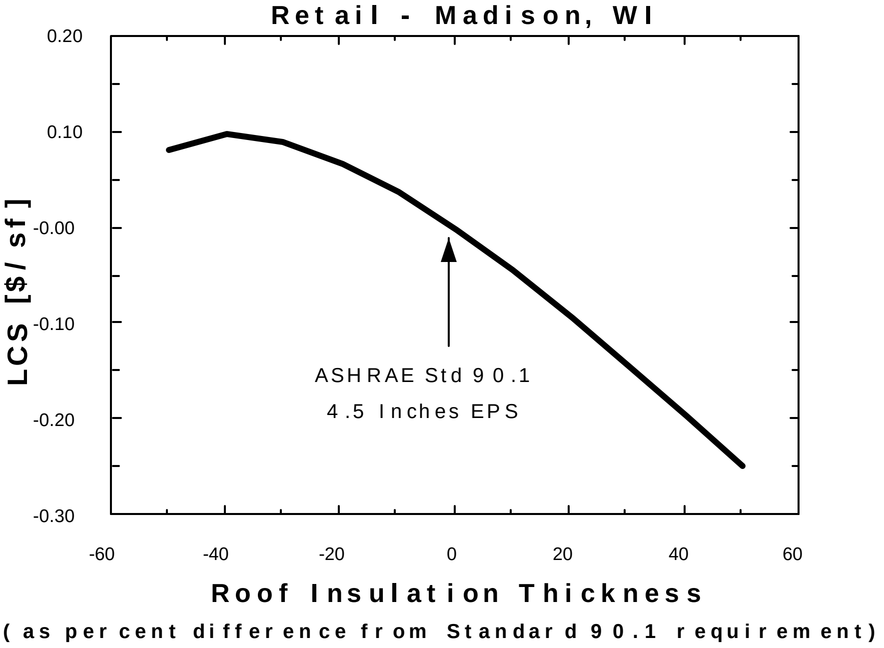

Figure 4.14 Roof insulation optimization - retail building, Madison, Wisconsin.**{** TC "Figure 4.14 Roof insulation optimization - retail building, Madison, Wisconsin." \l 5 **}**

The level of roof insulation that optimizes life-cycle savings was found to be well below the amount required by the ASHRAE standard for the Madison retail building. The optimal level was found to be 40% less than that required by the standard.

An analysis was conducted to test the sensitivity of the conclusions to changes in the assumptions of key variables in the analysis. Figure 4.15 shows the results of this sensitivity analysis.

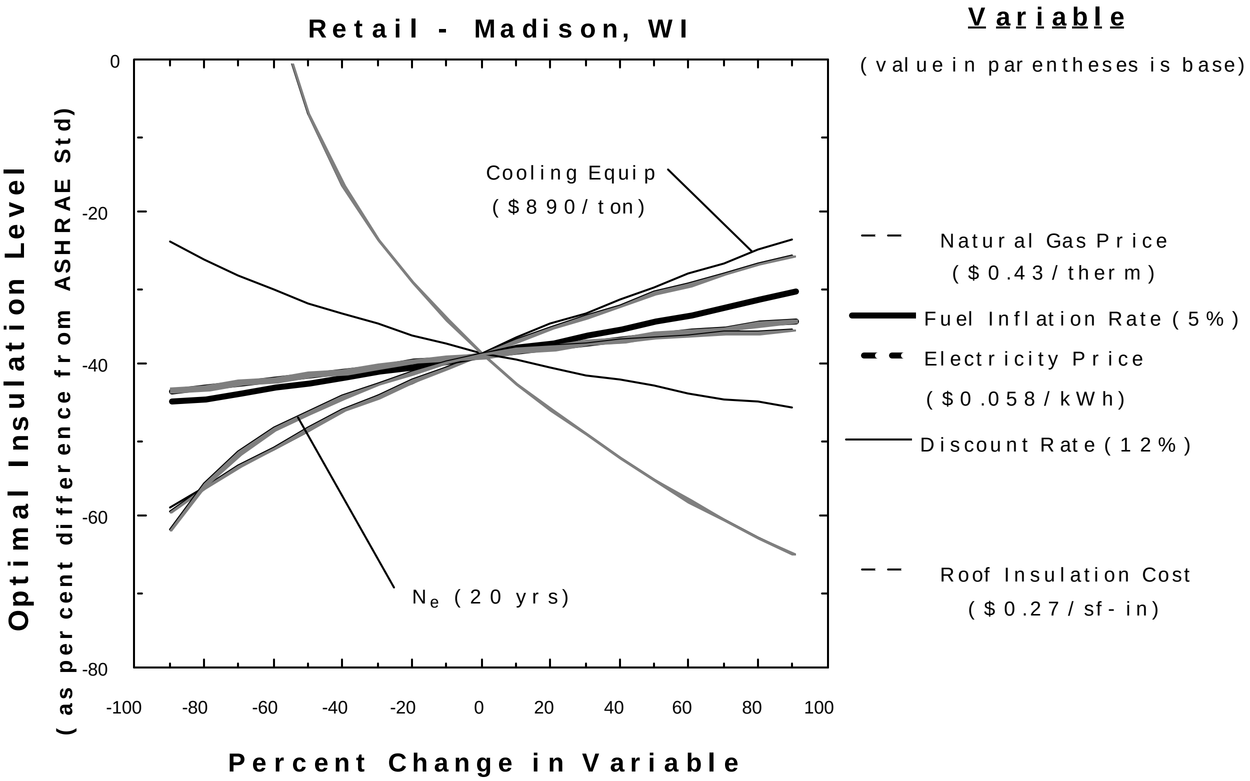

Figure 4.15 Roof insulation sensitivity - retail building, Madison, Wisconsin.{ TC "Figure 4.15 Roof insulation sensitivity - retail building, Madison, Wisconsin." \l 5 }

The optimization of roof insulation in the Madison retail building shows the greatest sensitivity to variations in roof insulation cost. This case shows a broader peak in the maximum life-cycle savings than that found in the optimization of wall insulation. Changes in assumptions of all variables except insulation cost result in small deviations in the resultant level of optimal insulation.

The life-cycle savings was also found as a function of roof insulation level for four other locations in the U.S.. The results of those analyses follow in Figures 4.15 through 4.18.

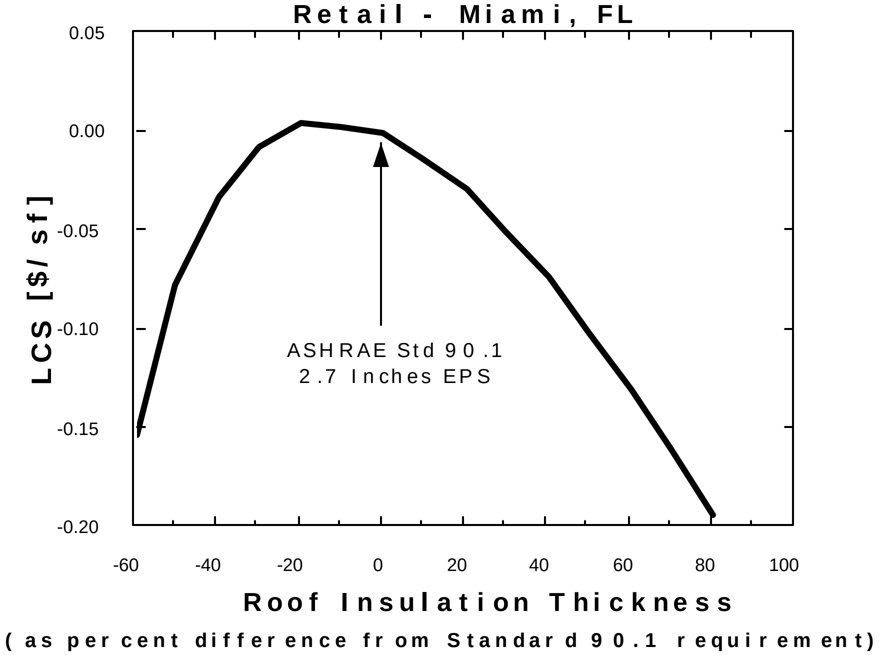

Figure 4.16 Roof insulation optimization - retail building, Miami, Florida.{ TC "Figure 4.16 Roof insulation optimization - retail building, Miami, Florida." \l 5 }

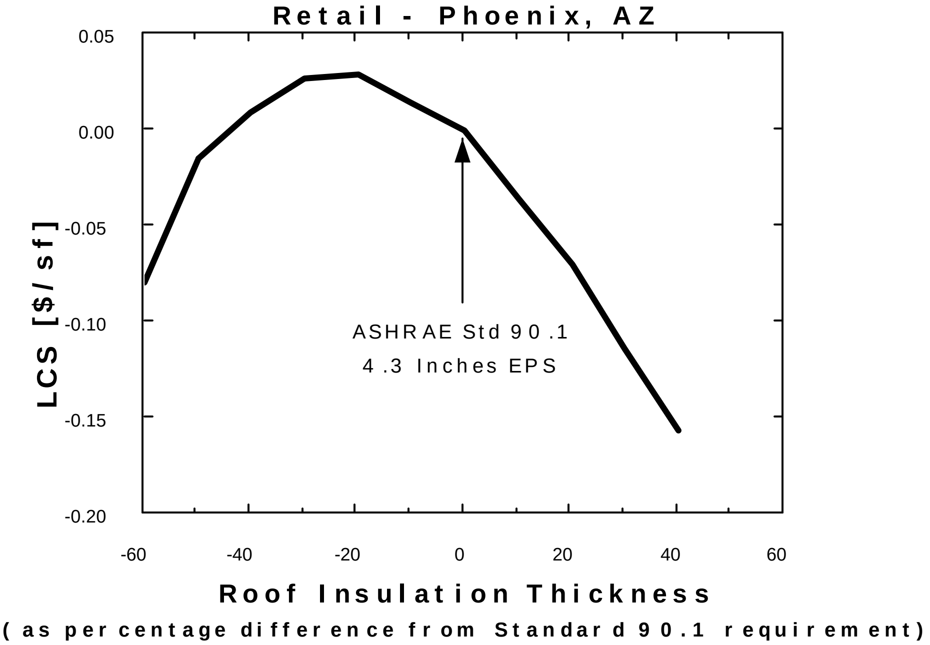

Figure 4.17 Roof insulation optimization - retail building, Phoenix, Arizona.{ TC "Figure 4.17 Roof insulation optimization - retail building, Phoenix, Arizona." \l 5 }

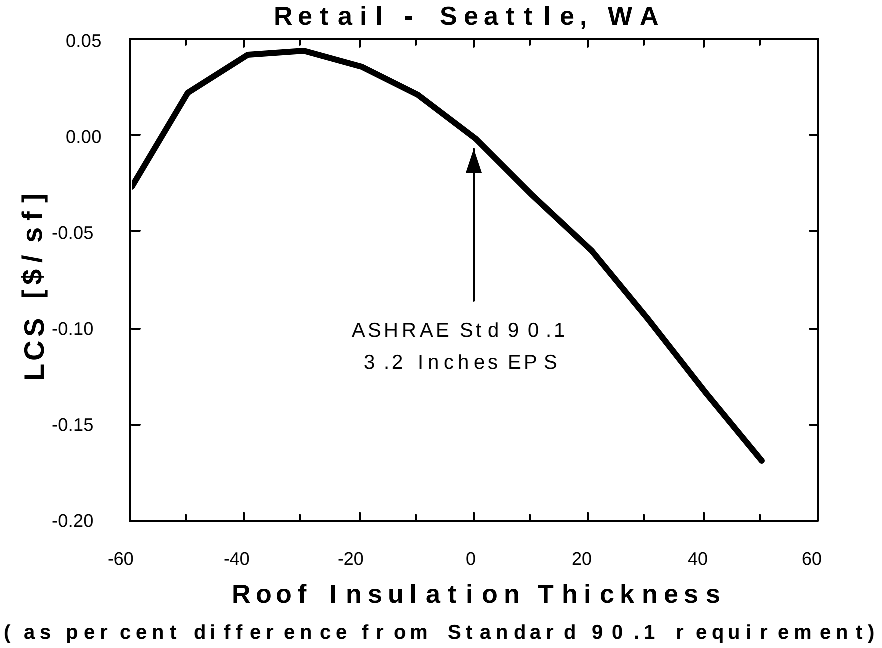

Figure 4.18 Roof insulation optimization - retail building, Seattle, Washington.**{** TC "Figure 4.18 Roof insulation optimization - retail building, Seattle, Washington." \l 5 **}**

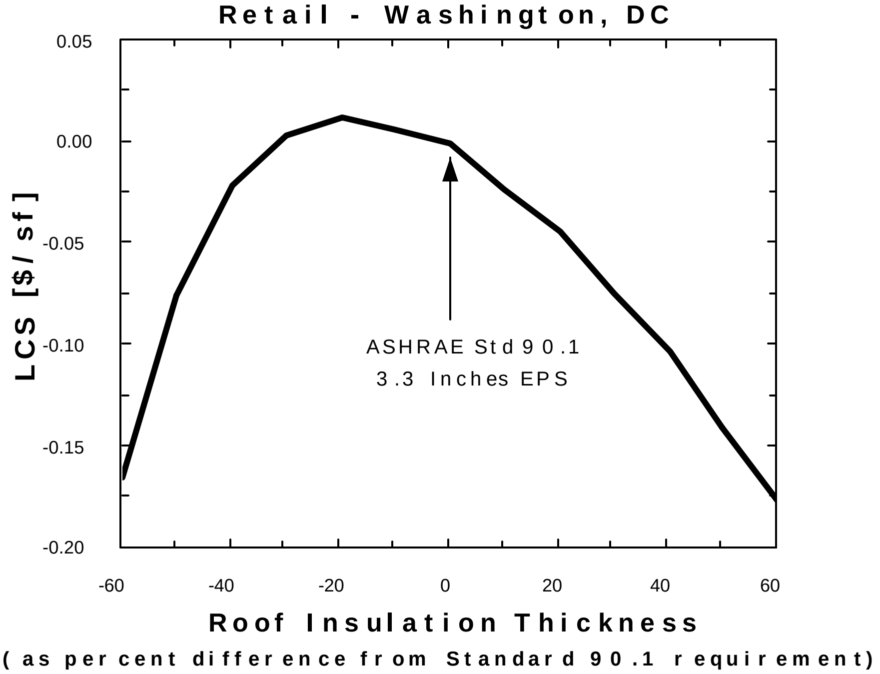

Figure 4.19 Roof insulation optimization - retail building, Washington, DC.**{** TC "Figure 4.19 Roof insulation optimization - retail building, Washington, DC." \l 5 **}**

In each location, the optimal level of roof insulation found for the retail building was less than that required by the prescriptive version of ASHRAE Standard 90.1. In each of the five cases tested, the optimal level was 20 to 40% less than the required amount.

The life-cycle cost analysis was conducted for the office building in Madison, Wisconsin. The results of the analysis are shown below in Figure 4.20.

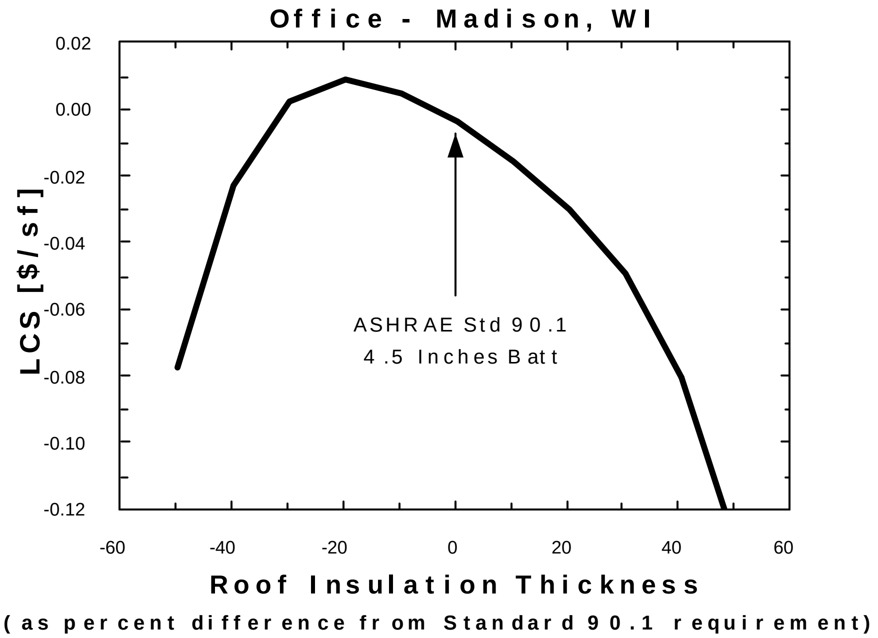

Figure 4.20 Roof insulation optimization - office building, Madison, Wisconsin.{ TC "Figure 4.20 Roof insulation optimization - office building, Madison, Wisconsin." \l 5 }

Analysis on the roof insulation in the Madison office building indicates that the optimal level of insulation is 20% less than that required by the prescriptive version of the standard.

A sensitivity analysis was conducted to assess how this result might change if some of the key assumptions in the analysis were changed. The results of the sensitivity analysis on the roof insulation level in the Madison office building are shown below in Figure 4.21.

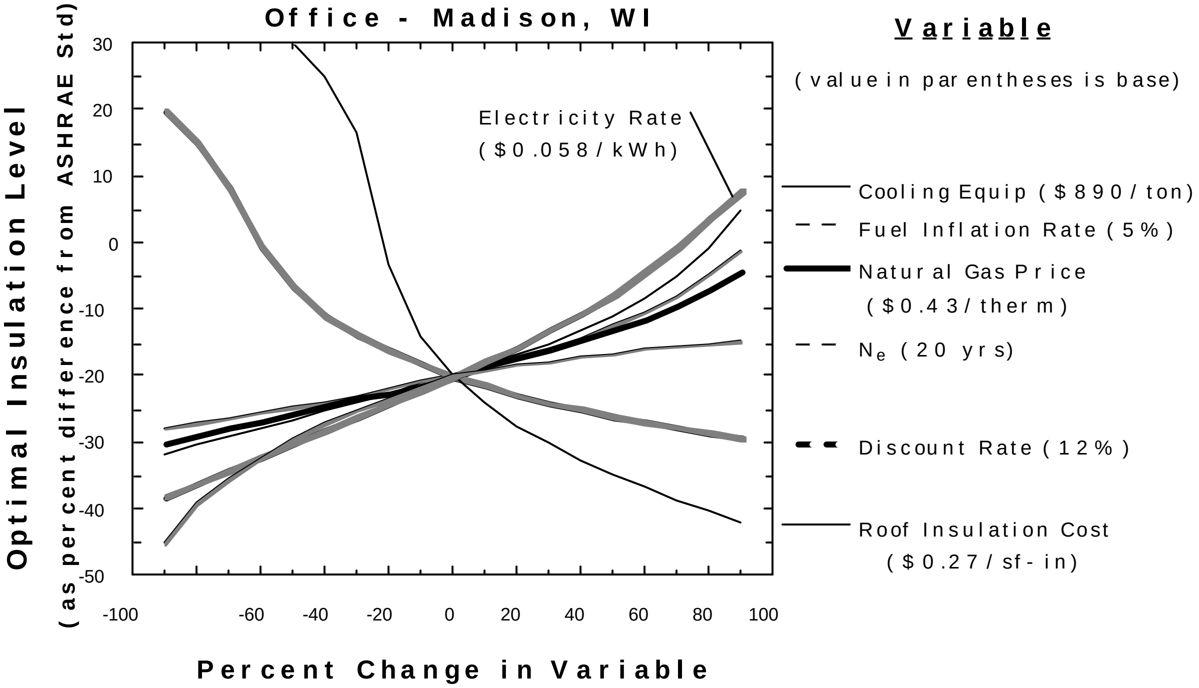

Figure 4.21 Roof insulation sensitivity - office building, Madison, Wisconsin.**{** TC "Figure 4.21 Roof insulation sensitivity - office building, Madison, Wisconsin." \l 5 **}**

The optimal level of roof insulation in the Madison office building was the most sensitive to changes in the assumption of roof insulation cost. This sensitivity was also asymmetrical - a *decrease* in the estimated roof insulation cost would cause a greater change in the resulting optimal roof insulation level than an *increase* in insulation cost of the same size.

The optimal level of roof insulation in the office building was also found for four other locations. The results of these analyses follow in Figures 4.22 through 4.25.

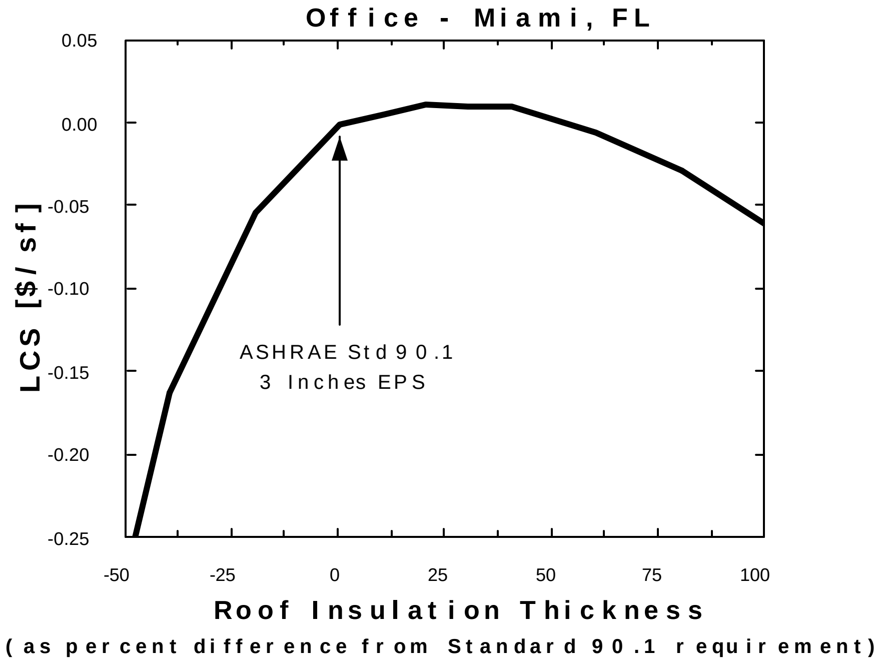

Figure 4.22 Roof insulation optimization - office building, Miami, Florida.**{** TC "Figure 4.22 Roof insulation optimization - office building, Miami, Florida." \l 5 **}**

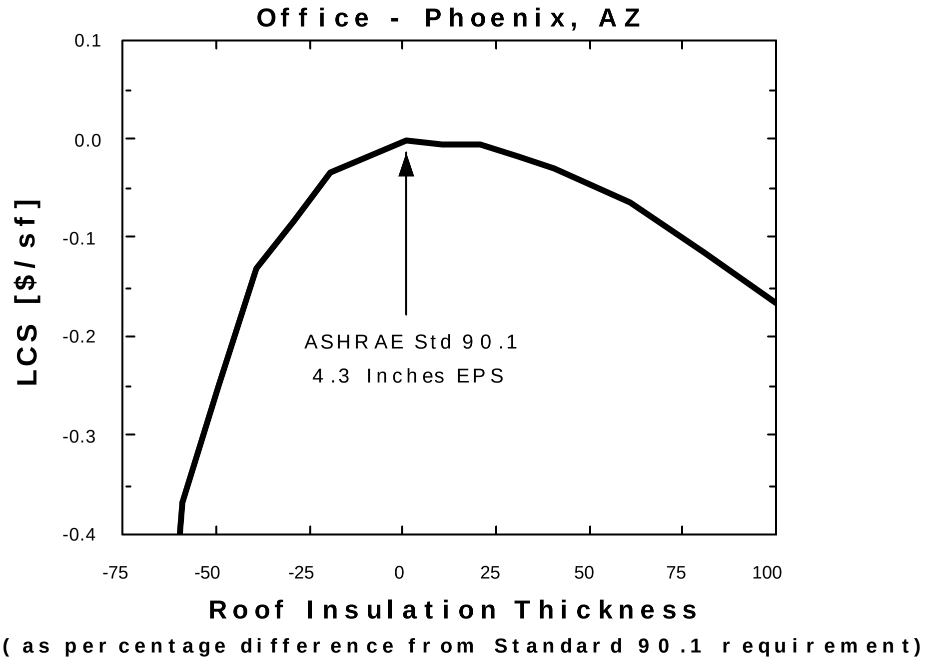

Figure 4.23 Roof insulation optimization - office building, Phoenix, Arizona.{ TC "Figure 4.23 Roof insulation optimization - office building, Phoenix, Arizona." \l 5 }

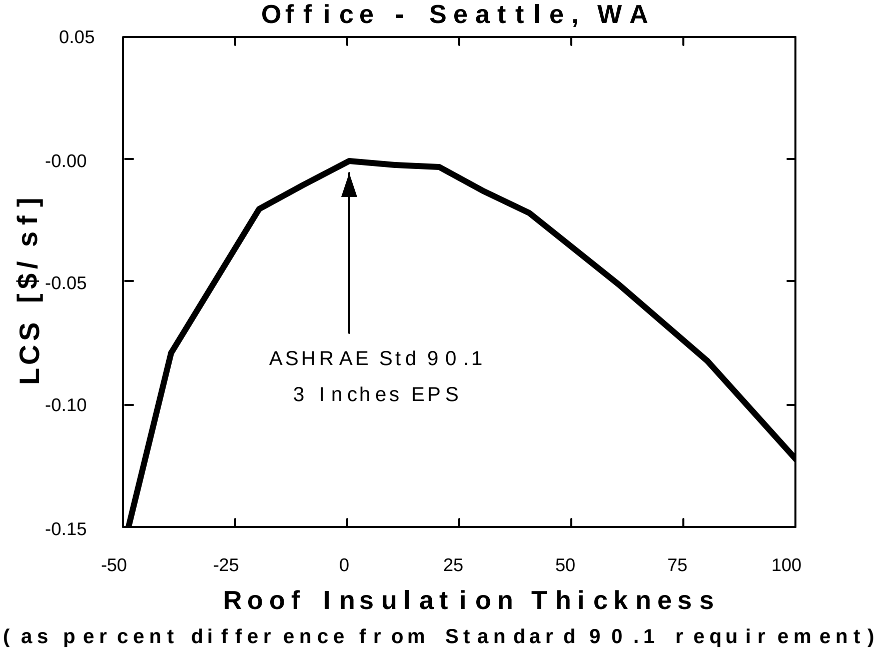

Figure 4.24 Roof insulation optimization - office building, Seattle, Washington.{ TC "Figure 4.24 Roof insulation optimization - office building, Seattle, Washington." \l 5 }

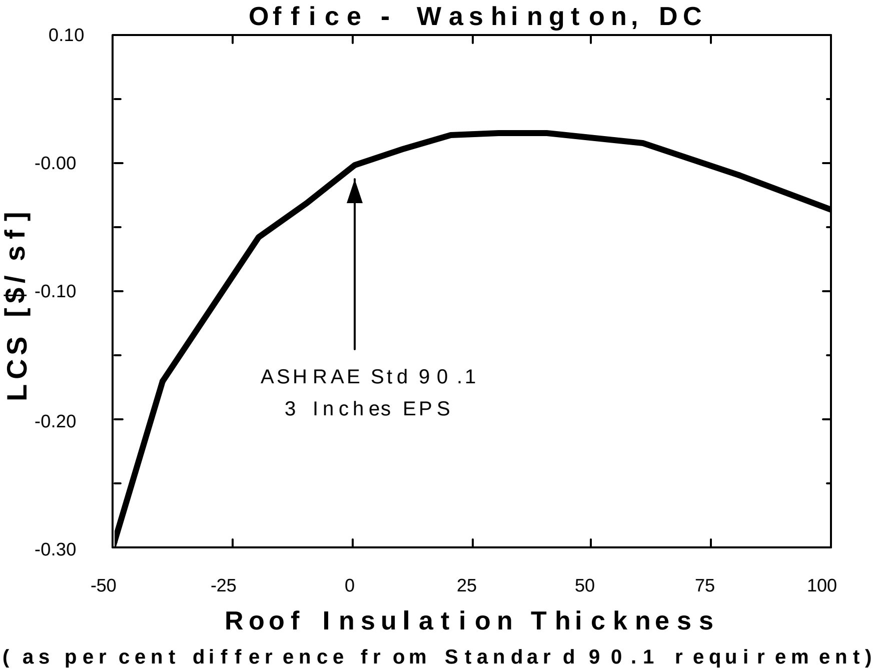

Figure 4.25 Roof insulation optimization - office building, Washington, DC.**{** TC "Figure 4.25 Roof insulation optimization - office building, Washington, DC." \l 5 **}**

The results of the office building roof-insulation analysis show that in Phoenix and Seattle the life-cycle savings method resulted in an optimal level of roof insulation the same as required by the ASHRAE standard. In Miami and Washington DC, however, the optimal level was found to 20% greater than that required by the standard.

Figure 4.26 below summarizes the comparison between the optimal roof insulation level and the level recommended by ASHRAE. The plot shows the R-value of the optimal insulation level versus the ASHRAE required R-value for roof insulation for each of the cases studied. The diagonal line represents where the points would lie if the ASHRAE level where equal to the optimal level found by maximizing life-cycle savings.

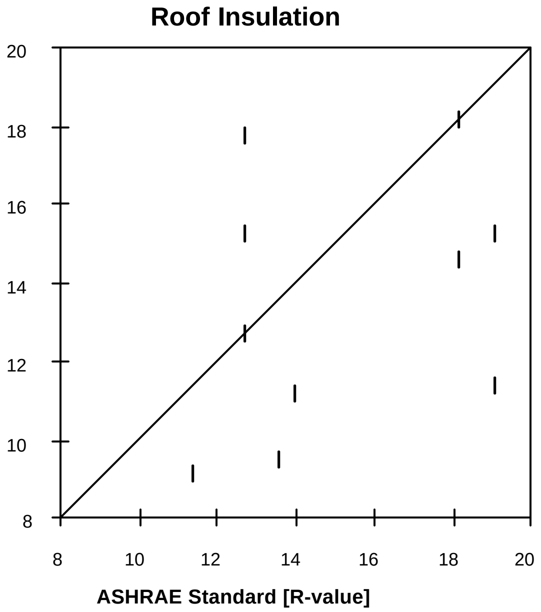

Figure 4.26 Comparison of optimal roof insulation to ASHRAE Standard 90.1.**{** TC "Figure 4.26 Comparison of optimal roof insulation to ASHRAE Standard 90.1." \l 5 **}**

Perimeter Insulation

A life-cycle cost analysis was also carried out to determine the optimal level of perimeter insulation for the retail and office buildings. This analysis was only conducted for the three locations (Madison, Seattle and Washington DC) where perimeter insulation was required by the ASHRAE standard.

The analysis was also limited to only a few cases of perimeter insulation at each location. The slab loss models required a great deal of modeling time - both in terms of computer processing time and model development. Therefore the slab loss models were run for only four cases at each location. The four cases were; 1) no insulation, 2) 1" EPS, 3) 1.5" EPS and 4) 3" EPS. The 1" and 1.5" cases were modeled because they represented the "as-constructed" level of insulation at the retail and office sites respectively.

The results of the life-cycle cost analysis for the retail and office building perimeter insulation are shown below in Figure 4.27 through 4.32. The life-cycle savings curves appear less smooth because each is made up of only four points - the four cases of insulation listed above.

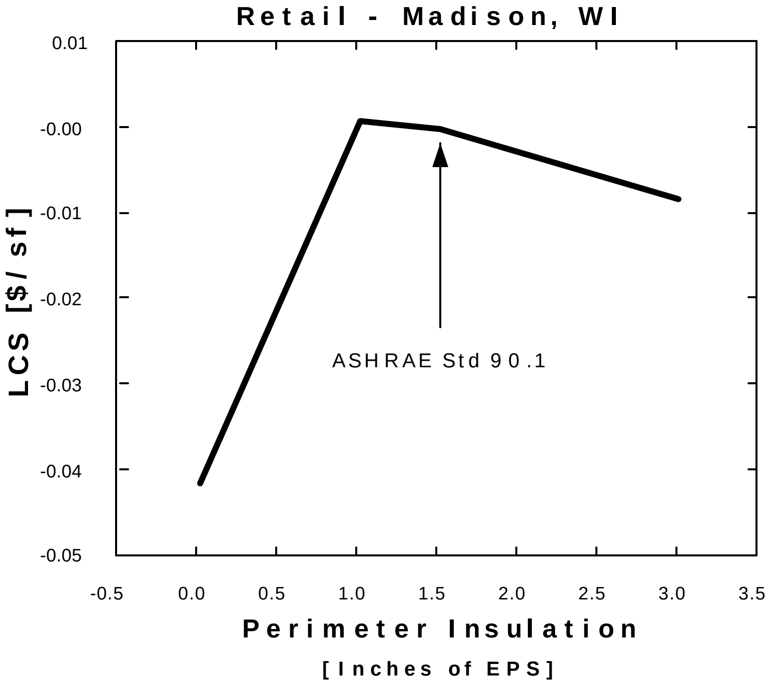

Figure 4.27 Perimeter insulation optimization - retail building, Madison.{ TC "Figure 4.27 Perimeter insulation optimization - retail building, Madison." \l 5 }

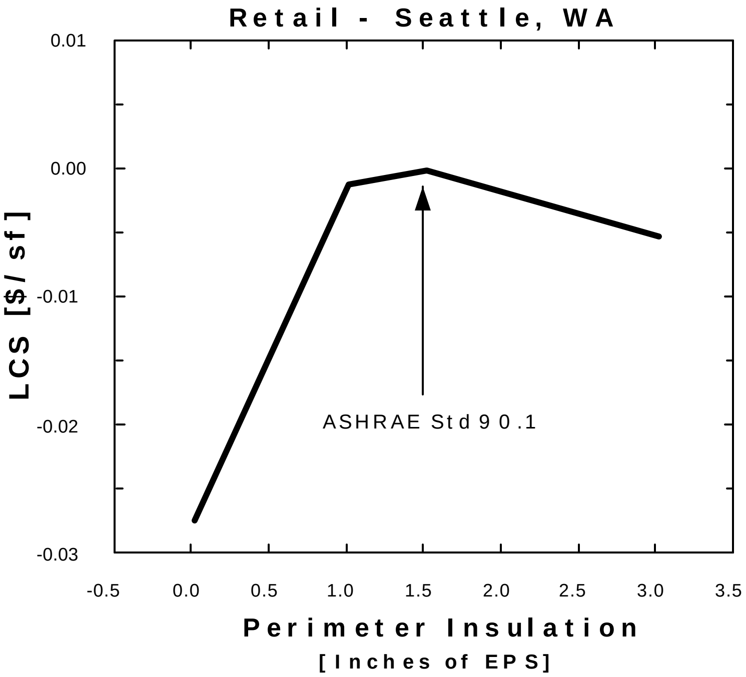

Figure 4.28 Perimeter insulation optimization - retail building, Seattle.{ TC "Figure 4.28 Perimeter insulation optimization - retail building, Seattle." \l 5 }

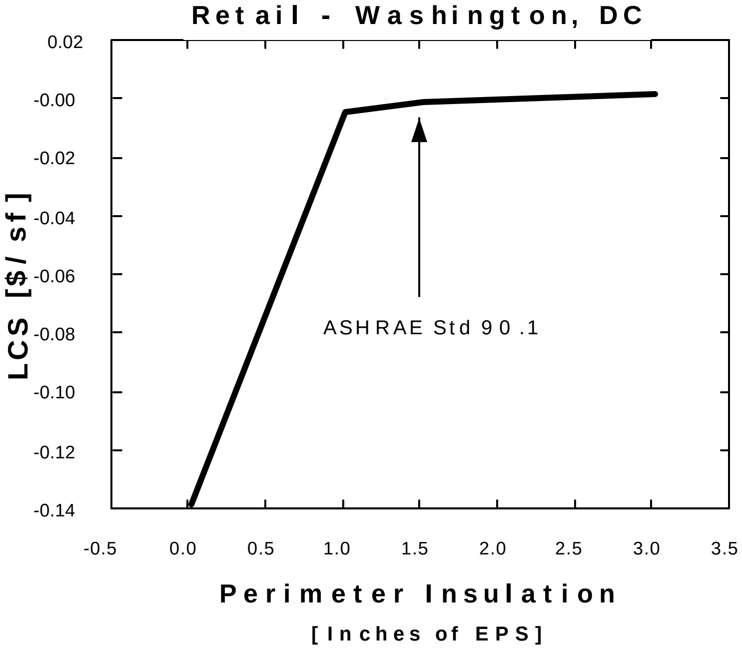

Figure 4.29 Perimeter insulation optimization - retail building, Washington.{ TC "Figure 4.29 Perimeter insulation optimization - retail building, Washington." \l 5 }

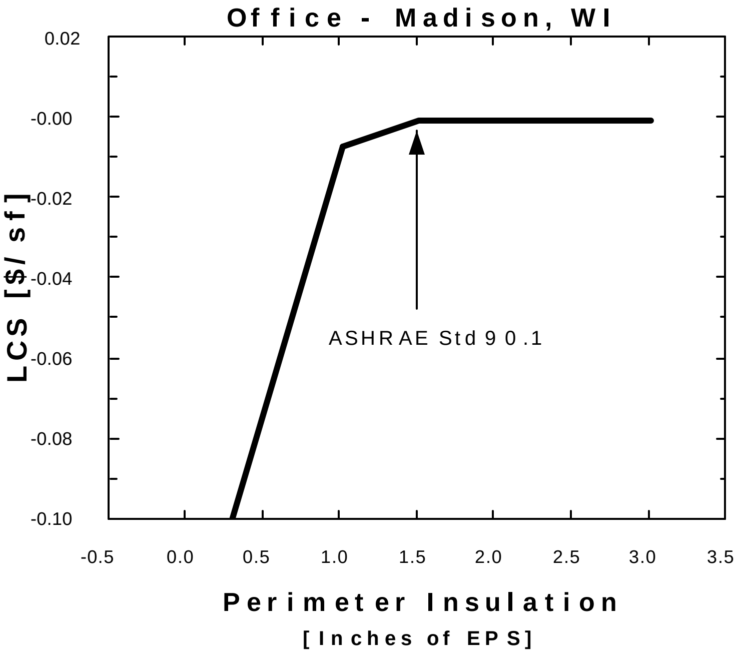

Figure 4.30 Perimeter insulation optimization - office building, Madison.**{** TC "Figure 4.30 Perimeter insulation optimization - office building, Madison." \l 5 **}**

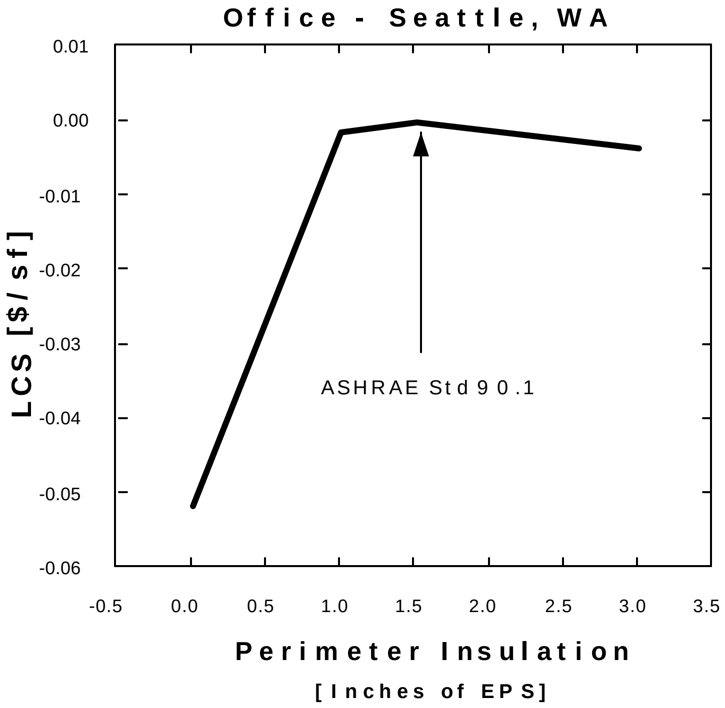

Figure 4.31 Perimeter insulation optimization - office building, Seattle.**{** TC "Figure 4.31 Perimeter insulation optimization - office building, Seattle." \l 5 **}**

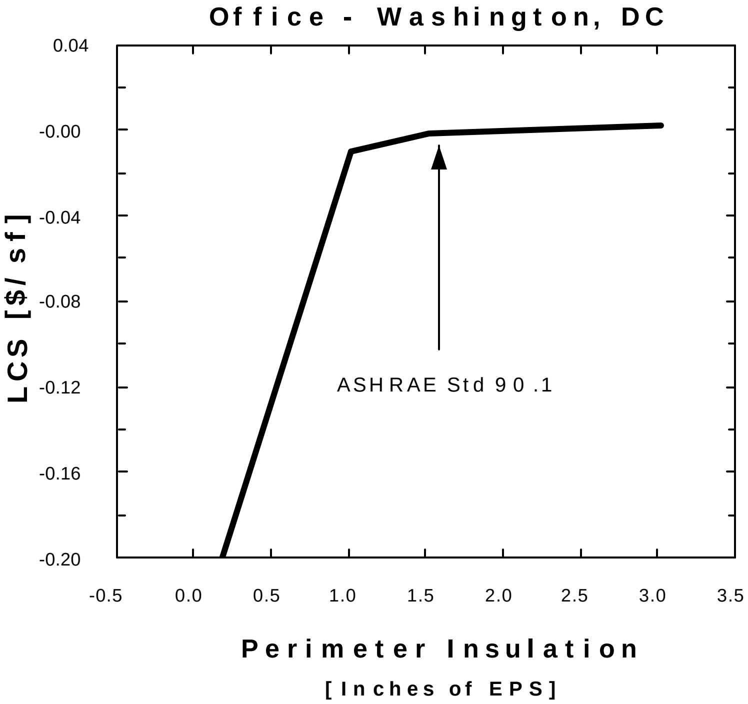

Figure 4.32 Perimeter insulation optimization - office building, Washington.{ TC "Figure 4.32 Perimeter insulation optimization - office building, Washington." \l 5 }

In most cases the level of perimeter insulation required by the standard was the same or close to the optimal level of insulation according the life-cycle cost analysis. In each of the six cases the peaks in the life-cycle cost curves were very broad, indicating very little difference among the three levels of insulation tested. Only the case with no insulation showed a significant decline in life-cycle savings.

4.4 Conclusions{ TC "4.4 Conclusions" \l 2 }

Computer simulations were used to assess the energy and cost savings associated with different levels of wall, roof and perimeter insulation. The energy savings that could be expected by meeting both the prescriptive and performance versions of ASHRAE Standard 90.1 were found. A life-cycle cost approach was used to find the optimal levels of insulation, using the prescriptive version of the ASHRAE standard as a base.

The life-cycle cost analysis was conducted based on assumptions derived from a building owners perspective. A number of these assumptions would have been different had the cost analysis been conducted using a different point of view, such as a societal perspective. Because a societal perspective was probably used to develop the ASHRAE standard, the levels of insulation required by the standard may be different than what was found to be optimal from a building owners point of view.

The prescriptive version of the ASHRAE standard was found to be more stringent for wall insulation than the performance version of the code. This agrees with the description of the two versions in ASHRAE's documentation for the standard. However, the level of insulation for the roof and building perimeter were the same for both versions.

The ENVSTD program was used to check compliance with the performance version of Standard 90.1. For buildings that use both mechanical heating and cooling, the program uses the sum of estimated heating and cooling loads as the criterion for whether the building envelope passes or fails the code. This method implicitly weights the heating and cooling loads equally. For many buildings, however, the cost of fuel for heating (usually natural gas) is much less than the cost of fuel used for cooling (usually electricity). A better method might include a factor that includes the cost of fuel in the analysis so that the code is more in line with what is economically beneficial.

A better method might be found for considering both the heating and cooling criteria in the performance method of the standard. Currently the criterion for buildings with heating and cooling is that the sum of the loads found separately for heating and cooling must be lower than the sum of the separate criteria for heating and cooling loads. The implicit assumption in ENVSTD is that the two should be given equal weight. Some consideration might be given to the relative length of the heating and cooling seasons, or the costs of heating and cooling equipment and fuels.

The energy and cost savings resulting from meeting the prescriptive version of the standard were found to be significant. Natural gas savings ranged from 1 to 31%, and electricity savings ranged from 0 to 2% for individual measures. Overall compliance to the standard resulting in energy savings up to 42% for natural gas and 2% for electricity. Peak cooling loads were also decreased from 5 to 12% due to meeting all measures required by the standard.

The results of the optimization analysis indicate that levels of wall insulation greater than those required by ASHRAE Standard 90.1 would be beneficial to building owners. In eight of the ten cases tested, the life-cycle savings were maximized by a level of wall insulation greater than that required by the standard. The difference between the optimal and the required amount were most striking in the cases of the retail building in Phoenix and Miami. In those cases the standard had no requirement for wall insulation, but the optimum level was found to be over six inches of batt insulation.

The results of the optimization analysis for roof insulation are less conclusive. The results from the retail building analysis indicate that the roof insulation specified by the standard is consistently greater than the optimal level. In the office building simulations, however, the results are mixed, with the standard in some cases specifying greater than the optimal amount of insulation and in other cases less than, or equal to the optimal amount. If one standard is to be used for all building types, then no strong conclusion can be drawn about how close the current standard is to the optimal for all buildings.

The level of insulation set by the standard for perimeter insulation is close to the optimal level in each of the cases studied. In those cases where the optimal differed from the required amount the life cycle-cost curves were very broad - indicating little difference in life-cycle savings among the insulation levels tested.

Sensitivity analyses were conducted on the wall and roof insulation optimization for both retail and office buildings. The cost assumptions made for wall and roof insulation were found to be the most influential variables in the determination of optimum insulation levels. Furthermore, the sensitivity to these variables was often asymmetric with a decrease in insulation cost causing a greater change in the results than an increase in insulation cost. The discount rate was found to be the second-most influential variable in the optimization. This variable is particularly significant in that it is one of the primary variables that would change if the life-cycle cost analysis were to be conducted using a societal viewpoint rather than the perspective of the building owner.

Of the variables having any influence on the optimization, the period of the analysis, and the fuel inflation rate had the least effect. The assumptions for down payment, mortgage rate, property tax rate, income tax rate had virtually no effect on the optimal insulation values.