# AN OFFICE BUILDING USED AS A FEDERAL TEST BED FOR ENERGY-EFFICIENT ROOFS

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## ABSTRACT

*The energy-savings benefits of re-covering the roof of an existing federal office building with a sprayed polyurethane foam system are documented. The building is a 12,880-ft$^2$ (1,197-m$^2$), one-story masonry structure located at a national laboratory. Prior to re-covering, the roof had a thin fiberglass insulation layer that had become partially soaked because of water leakage through the failed built-up roof membrane. The average R-value for this roof measured at 2 h·ft$^2$·°F/Btu (0.3 m$^2$·K/W). After re-covering the roof, it measured at 13 h·ft$^2$·°F/Btu (2.3 m$^2$·K/W).*

*The building itself is being used as a test bed to document the benefits of a number of energy-efficiency improvements. As such, it was instrumented to measure the half-hourly energy consumption of the whole building and of the individual rooftop air conditioners, the roof heat fluxes, and the interior air and roof temperatures. These data were used to evaluate the energy effectiveness of the roof re-covering action.*

*The energy savings analysis was done using the DOE-2.1E building simulation program, which was calibrated to match the measured data. The roof re-covering led to around 10% cooling energy savings and around 50% heating energy savings. The resulting energy cost reductions alone are not sufficient to justify re-covered roofs for buildings having high internal loads, such as the building investigated here. However, the energy savings do contribute significantly to the measure's savings-to-investment ratio (SIR). A \$0.30/ft$^2$ annual maintenance savings leads to an SIR of 1.4. Adding the energy cost savings for a building at Knoxville, Tennessee, for example, increases the SIR to 2.0. The building internal loads, the plenum spaces, and the use of air economizers were found to be important parameters for the savings that are realized.*

## BACKGROUND AND OBJECTIVE

The research program of the Office of Building Technologies, within the Energy Efficiency and Renewable Energy Program of the U.S. Department of Energy, has directed its efforts over the past several years to advancing the capabilities for improved energy-efficiency technologies in residential and commercial buildings. In March 1994, President Clinton signed an executive order designed to meet and exceed the provisions of the Energy Policy Act of 1992. The policy act mandated that the energy consumption in federal buildings be reduced 20% from 1985 levels by the year 2000. The executive order exceeds that goal and states that the federal building energy use will be cut by 30% over 1985 levels by the year 2005 (FEMP 1994).

As part of these overall energy conservation goals, an existing federal building is being used to evaluate selected energy-efficiency improvements. It is a 12,880-ft$^2$, one-story office building. The original building was constructed in the early 1950s, and an addition to the building was constructed in the mid-1960s. It is now occupied by about 50 people and has a small auditorium and conference room.

Energy-efficiency improvements for the building's roof and lighting were implemented during 1993 and 1994. The roof of the building addition was replaced in August 1993, and the roof of the original part of the building was re-covered in September 1993. In March 1994, the building's fluorescent light fixtures were upgraded to use high-efficiency bulbs and ballasts. A third measure, a new chiller/ice storage system, was designed, and much of the equipment had been installed at the time this paper was written (May 1995). To help analyze the effectiveness of the measures, the building was instrumented to record the temperatures and heat fluxes in the roof, the circulating air temperatures at the air handlers, and the electrical energy consumption of the individual air handlers and for the whole building. Weather data were also collected at the site.

This study focused on the roof re-covering measure. This project was conducted under a Cooperative Research and Development Agreement (CRADA) between the lab and a U.S. corporation. Part of this agreement was an evaluation of the energy savings due to the higher levels of roof insulation. Therefore, the objective

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of the study undertaken for this paper was to evaluate the energy effectiveness of the re-covered roof using the DOE-2.1E building simulation program, calibrated using the available measured building data. The objective also included using the calibrated program as a tool to evaluate the effects of the building's operating parameters and the climate on the re-covered roof's energy savings.

## BUILDING DESCRIPTION

The office building addressed in this study is a 12,880-ft$^2$ (1,197-m$^2$), one-story structure designated as building 2518. The front of the building faces 34 degrees west of north. It is built on a concrete slab, and the exterior walls are concrete block with a red brick face. The walls are uninsulated, and the windows have single-pane glass glazing.

Figure 1 is a simple sketch of the building plan. The north, original part of the building was constructed in the early 1950s, and it has a floor area of 8,400 ft$^2$ (780 m$^2$), or 65% of the total area. The south addition was constructed in the middle 1960s, and its floor area is 4,480 ft$^2$ (416 m$^2$), or 35% of the total area. The roofs on the two parts of the building are different. The roof on the original part of the building is a low-slope built-up roof (BUR) supported on a steel deck that is 15.7 ft (4.8 m) above the floor. The roof on the building addition is a flat BUR supported on a concrete deck located 12 ft (3.6 m) above the floor. Details of the roofs' construction and renovation are discussed in the next section.

Most of the building is used for offices that have acoustic tile ceilings suspended 9 ft (2.7 m) above the floor. A small auditorium occupies the northwest corner of the building, and it has a ceiling height of 10.5 ft (3.2 m). This results in plenums about 6.7 ft (2 m) high in the north part and 3 ft (0.9 m) high in the south part of the building. Most of the interior walls in the building extend from the floor to the roof deck, so air communication between the individual plenums over the conditioned spaces is limited. The building interior is illuminated by recessed fluorescent lights, and it was assumed in the analysis that 10% of the lighting heat is deposited in the plenums.

Five packaged rooftop air-conditioning units are used for space cooling. They are labeled AHR1 through AHR5 in Figure 1 and are located over the building corridors. The evaporators and circulating air fans are located in the corridor plenums. All the air handlers are constant-volume systems, and the conditioned air is supplied from the air handlers to the occupied spaces through duct networks. The circulating air is returned to the air handlers through ducts, the building corridors, or the plenums. Table 1 is a summary of the building air handler data: cooling capacities, location and function of the area being conditioned, type of circulating air return, and whether the unit is operated continuously or shut down nights and weekends. The circulating air that is identified in the table as returning directly to the air handlers flows from the work areas through the corridors and ceiling air grilles to the air handlers. There are no air economizers; the make-up air for the air removed by the exhaust fans is drawn through shielded grilles mounted on the exterior walls and the roof.

Plant steam is used to heat the circulating air during the winter. Several of the offices have electric baseboard and portable space heaters to supplement this heat source.

About 50 people work in the building offices from 7:00 a.m. to 3:30 p.m. during weekdays, except for holidays. In addition, up to 65 people occupy the building conference room and auditorium at various times during the week, including nights and weekends. The air

***TABLE 1*** **Building 2518 Air Handler Data**

| Air Handler No. | Rated Cooling Capacity (tons)[a] | Air Distribution System Location | Type of Circulating Air Return | Normal Type of Operation |
|---|---|---|---|---|
| 1 | 10 | NW auditorium and conference room | Duct | Continuous |
| 2 | 5 | N small office suite | Plenum | Continuous |
| 3 | 22 | NE offices | Direct | Off nights and weekends |
| 4 | 7.5 | SE offices | Direct | Off nights and weekends |
| 5 | 10 | SW offices | Direct | Off nights and weekends |

[a] 1 ton = 3.53 kW

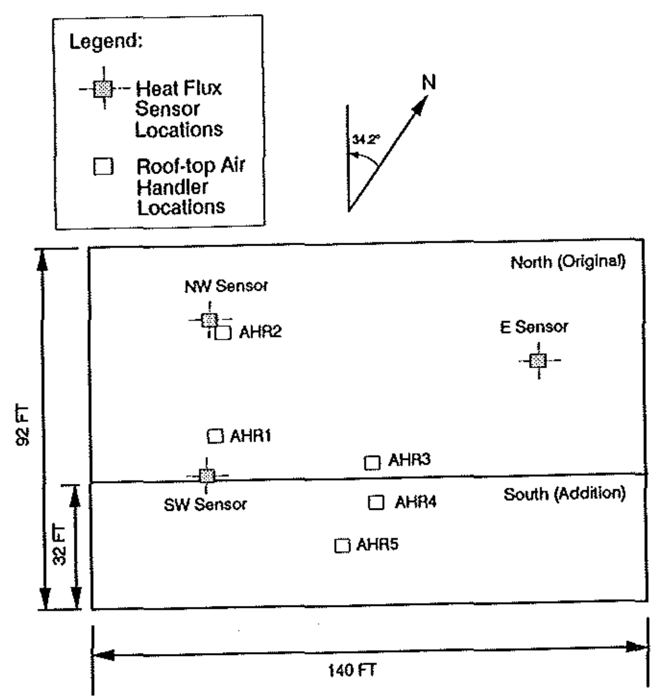


***Figure 1*** *Schematic plan for building 2518.*

handlers for most of the office areas are operated from 4:00 a.m. to 6:00 p.m. Mondays and from 6:00 a.m. to 6:00 p.m. Tuesdays through Fridays. They are shut down nights and weekends. The remaining two air handlers—serving the conference room, auditorium, and a small group of adjacent offices—operate continuously.

Before March 1994, the estimated lighting power level was about 2.2 $W/ft^2$ (24 $W/m^2$). The lighting fixtures were retrofitted with efficient bulbs and ballasts, which reduced the lighting power density to about 0.75 $W/ft^2$ (8.1 $W/m^2$). The power density for computers and other office equipment remained at about 1.3 $W/ft^2$ (14 $W/m^2$).

## ROOF IMPROVEMENTS

The roofs of the north (original) and the south (addition) parts of the building are different. Details of the two roofs and their improvements are discussed below. Both roofs were considered in the analysis because of the thermal interactions between the two parts of the building.[1]

The existing roof on a steel deck over the northern part of the building was re-covered with a spray-applied polyurethane (PUR) foam and a silicone top coat. The original roof was a BUR topped by gravel ballast. The steel deck was covered with a felt layer and 5/8 in. (16 mm) thick fiberglass insulation boards. Over the years, the BUR membrane failed and water soaked into about 40% of the insulation. Before applying the foam layer, a 4-ft by 6-ft (1.2-m by 1.8-m) section of the roof was removed and tested in a climate simulator. In the dry condition, the overall R-value of the section was measured at 2.8 $h \cdot ft^2 \cdot °F/Btu$ (0.48 $m^2 \cdot K/W$). In the wet condition, it was measured at 0.5 $h \cdot ft^2 \cdot °F/Btu$ (0.09 $m^2 \cdot K/W$). From these values, it was estimated that the average R-value of the existing roof was 1.8 $h \cdot ft^2 \cdot °F/Btu$ (0.32 $m^2 \cdot K/W$).

Prior to re-covering the north roof, it was pressure washed to remove loose roof gravel and any other debris. Blisters in the PUR were cut open and areas where the membrane appeared to be loose were mechanically fastened. The PUR was then sprayed on the roof and it immediately foamed, forming an insulation layer with a thickness in the range of 1.5 in. to 2.1 in. (38 to 51 mm). The estimated overall average thickness is 1.84 in. (46.7 mm). The thermal resistivity of the foam was measured to be 6.25 $h \cdot ft^2 \cdot °F/Btu \cdot in.$ (43 $m \cdot K/W$), which results in an average overall R-value of 13.2 $h \cdot ft^2 \cdot °F/Btu$ (2.32 $m^2 \cdot K/W$). A silicone top coating, together with the whitest reflective granules available at the time of installation, was applied over the polyurethane foam. The solar reflectance of this coating was measured to be 0.28 using a commercial solar reflectometer.

The original roof system on the southern part of the building was installed on a concrete deck. The deck was covered by felt and 5/8 in. (16 mm) fiberglass roof insulation boards. The insulation was covered by BUR and gravel ballast. This BUR membrane was severely cracked and the fiberglass insulation was soaked. The R-value of the original south roof was not known, but it was probably low because of the wet insulation. This roof was replaced with a new roof having 2-in. (51 mm) fiberglas insulation, which leads to an estimated R-value of 8 $h \cdot ft^2 \cdot °F/Btu$ (1.4 $m^2 \cdot K/W$). For the calibration of the analytical model, the solar reflectance of the crushed marble cover was assumed to be 0.35 (Reagan and Acklam 1979).

## DEVELOPMENT OF A CALIBRATED SIMULATION MODEL

The simulation model selected to evaluate the energy savings for the roof re-covering measure was the DOE-2.1E Building Energy Analysis Program (LBL 1981, 1993). This is an hourly simulation model that has been used extensively for energy analyses of buildings. The program uses a transfer function method to calculate the dynamic thermal behavior of the building.

Building simulation models, such as DOE-2.1E, are functions of many parameters that must be adjusted to predict the true physical behavior of the building. The selection of the most appropriate input data parameters, or "calibration," of the model is strongly dependent on the user's knowledge and experience. These models are approximations of the true physical behavior, and in this project, extensive test data were used to gain confidence in the model.

The calibration of the DOE-2.1E model was done for the building as it was actually renovated, having a re-covered roof on the north part and a new roof on the south part. The calibration was done for the period of April through December 1994, which was after the roof and lighting improvements were implemented. Collection of the whole-building electricity consumption data every half hour was begun in March 1994. Collection of the electricity consumption data by each of the five rooftop air handlers, including the air circulation fan energy, every half hour was started in June 1994. Because this study was a research effort, a large amount (several weeks) of time was devoted to develop a well-calibrated model.

The development of the input data files for the model started with a building survey that included data for occupancy; functional areas; office equipment; lighting systems; envelope construction; heating, ventilating, and air-conditioning (HVAC) systems; controls; and zoning. The model was then run and the results were

[1] For the calibration of the DOE-2.1E model, both roof constructions were used. However, to evaluate the impacts of re-covering the roof, it was assumed that both parts of the building had the same BUR roof systems and that they were both re-covered. Part of the reason for doing this was that the R-value of the south roof before it was replaced was unknown.

compared with the experimental data collected at the building. The input parameters were adjusted, and the process was repeated until there was a reasonably good match between the simulations and the building data.

The data base for the building was large. Thermocouples and heat flux sensors were embedded in the roof at three locations shown in Figure 1. The original fiberglass roof insulation is dry at the southwest sensor location but is very wet at the two other locations. A thermocouple was located below the roof at each of the three locations to measure the plenum temperatures. Air handler units 1, 2, and 3 were instrumented to measure the temperatures of the supply and return air. Circulating airflow rates for each of these three units were measured using pitot tube and hot-wire anemometer traverses. Measurements of the flow rates by the two methods were in good agreement. The operating power level of the circulation air fan for each of the five air handlers was also measured.

Site meteorological data were collected each half hour at the laboratory's roof thermal research apparatus, located within one-fourth mile of the building. These data were used as the weather data for the calibration of the DOE-2.1E model. The data included ambient air temperature and humidity, wind speed and direction, and the total horizontal solar energy.

Plots of the daily total electrical energy load profiles were of help in developing the building activity (internal load) profiles and the HVAC system operating schedules. These plots generally agreed with the office equipment and lighting loads estimated by inspection of the offices, together with measured energy consumptions for a typical lighting fixture and a typical computer workstation. During nights, weekends, and holidays, it was estimated that about 10% of interior lights were left on. Many of the personal computers in this building are left on during the unoccupied hours, which results in about a 50% office equipment load at these times.

For all the DOE-2.1E calculations, it was assumed that the R-value of the dropped ceiling tile separating the conditioned spaces and the plenums is 1 h·ft$^2$·°F/Btu (0.18 m$^2$·K/W), compared to the reference value of 1.89 h·ft$^2$·°F/Btu (0.33 m$^2$·K/W) (ASHRAE 1993), to allow for some interchange of air between the conditioned spaces and the unconditioned plenums.

On a monthly basis, the agreement between predicted and measured electrical energy consumption for 1994 is reasonably good, as shown in Figure 2. During June through September and December, the agreement is within 5%. For May, October, and November, the agreement is within 12%. A number of factors could contribute to these differences. Among these are different air conditioner performance curves than assumed in the calculations and the use of individual electric space heaters in some of the offices. Pursuit of these factors had reached diminishing returns for the resources available for this study, and the model was judged sufficiently accurate for evaluating the impacts of the roof re-covering measure.

A second check on the model calibration was a comparison of the measured heat fluxes and the model's prediction of heat fluxes through the roof. The east roof heat flux sensor is located over a dead-air space plenum above a group of offices. The air handler (identified as unit 3) for these offices operates only on weekdays. The other two sensors are located over a common plenum above a corridor on the west side of the building. Air handler units 1 and 2 are both located in this common plenum, and they operate all of the time. The north part of the building has a 3 ft (0.9 m) high parapet at the perimeter of the roof for the north part of the building. This parapet shades the southwest flux sensor most of the time. (The shading was factored into the analytical model.) The sprayed PUR foam thickness was measured at each flux sensor and was found to be 2.12 in. (53.8 mm) at the southwest sensor, 1.56 in. (39.6 mm) at the northwest sensor, and 2.37 in. (60.2 mm) at the east sensor. These values were used in the DOE-2.1E simulations for flux comparisons.

Figure 3 presents the comparisons at the locations of the three heat flux sensors for the week of April 10-17, 1994. The comparisons for Sunday, April 10, 1994, were not included, since measured temperature data suggested that all the air handlers were shut down that day. Figure 4 presents the comparisons at the locations of the southwest

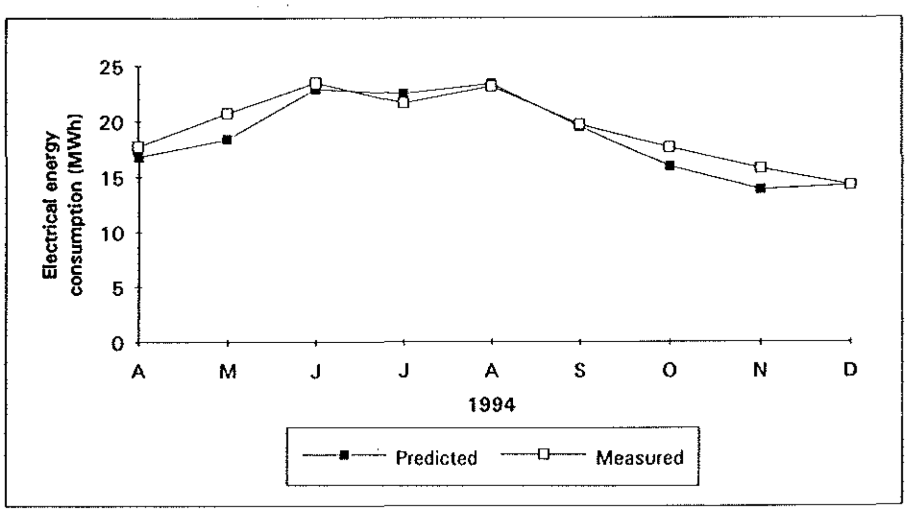


*Figure 2 Comparison of predicted and measured monthly electrical energy consumption for building 2518.*

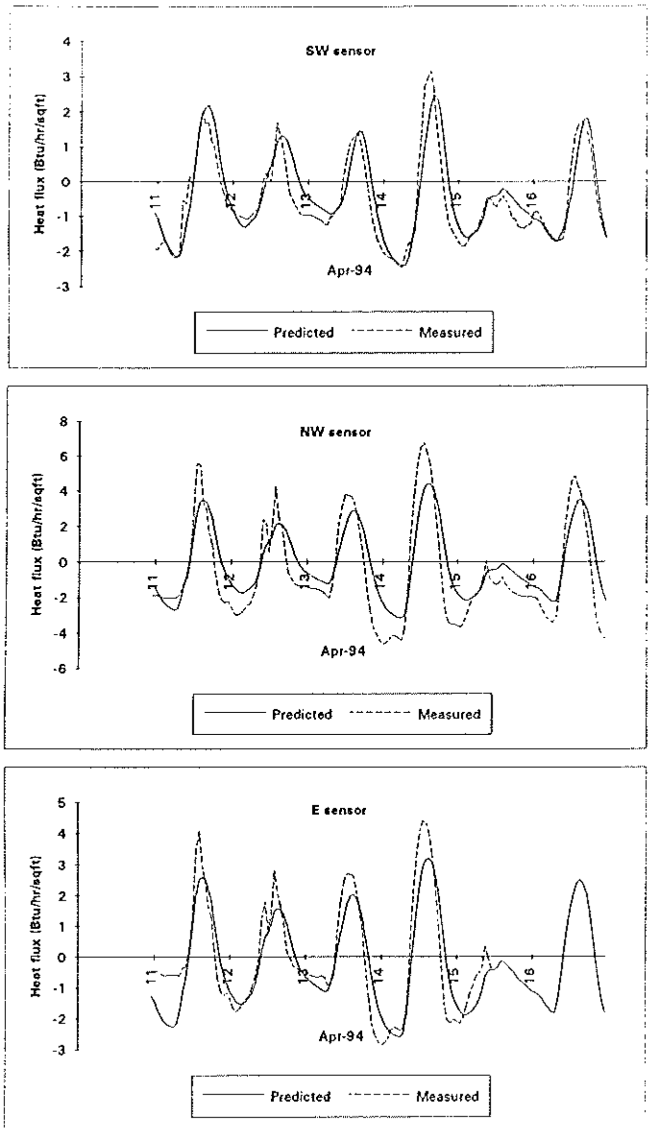


***Figure 3*** *Comparison of predicted and measured roof heat fluxes for building 2518 during April 10-17, 1994.*

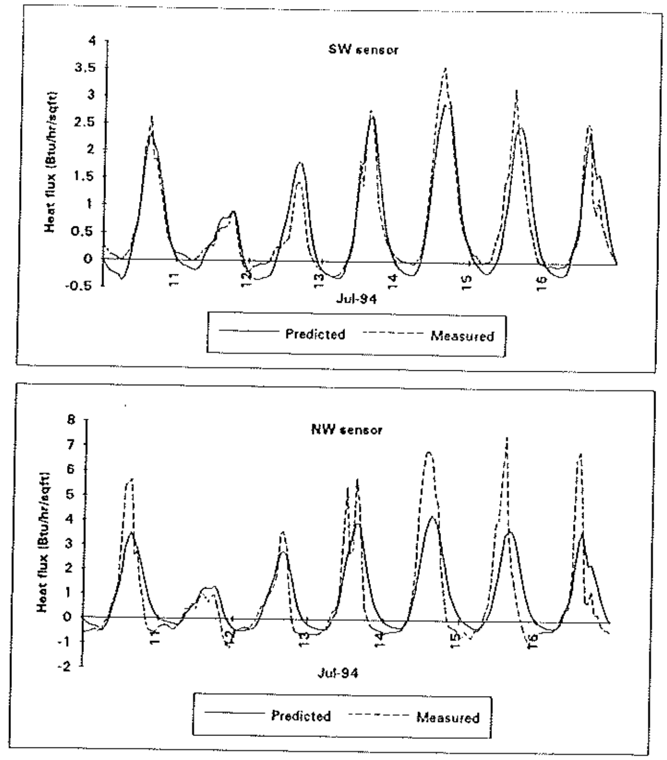


***Figure 4*** *Comparison of predicted and measured roof heat fluxes for building 2518 during July 10-17, 1994.*

***TABLE 2*** **Time-Integrated Values of Building 2518 Roof Heat Fluxes Presented in Figures 3 and 4 (Btu/ft²)**

| Time Period | Roof Sensor Location | | |
|---|---|---|---|
| | SW | NW | E |
| April 11-16 | | | (April 12-14) |
| Predicted | −56.9 | −16.6 | −7.7 |
| Measured | −77.8 | −92.4 | 8.3 |
| July 10-16 | | | |
| Predicted | 106.7 | 159.1 | |
| Measured | 107.7 | 150.9 | |

and northwest flux sensors for the week of July 10-17, 1994. The data logger for the east flux sensor failed April 15, 1994, and was still off-line in July. The agreement at the southwest (SW) sensors, where the original fiberglass insulation is dry, is good. But at the northwest (NW) and east (E) sensors, the effects of the wet fiberglass insulation are evident. The measured heat flux profiles have higher peaks and valleys than in the predicted profiles.

The DOE-2.1E program uses conductive heat transfer functions to calculate the heat flow through the walls. Including the movement and the heat of condensation of the moisture within the fiberglass layer results in heat flux profiles having higher peaks and valleys (Pedersen and Courville 1991). A rough estimate of the net effect of this was done by integrating the flux profiles. These integrated values are listed in Table 2. In July, the net effect on the energy use is small. In April, when the space-conditioning energy requirements are lower, the integrated values from the wet roof result in higher measured heating energy consumption.

## ENERGY SAVINGS ANALYSIS

The calibrated DOE-2.1E model was used to estimate the annual energy savings that would be realized by re-covering the roof of building 2518. For this evaluation, the original roof systems for the entire building were assumed to be re-covered with a 1.84-in. (46.7-mm) PUR foam layer. This modification was made because the thermal properties of the original roof on the south part of the building were unknown and the authors felt that the evaluation would be more meaningful if it was done for the whole building.

The only difference between the roofs on the two parts of the building as modified for the energy-savings analysis is that the north roof system is supported by a steel deck and the south roof system is supported by a concrete deck. The R-values of the original roofs were 1.7 h·ft$^2$·°F/Btu (0.30 m$^2$·K/W) and 1.9 h·ft$^2$·°F/Btu (0.32 m$^2$·K/W) for the north and south parts, respectively, because of the difference of the thermal resistivities of the steel and concrete. The R-values of the re-covered roofs were 13.2 h·ft$^2$·°F/Btu (2.32 m$^2$·K/W) and 13.4 h·ft$^2$·°F/Btu (2.37 m$^2$·K/W) for the north and south parts, respectively. The assumed solar reflectance of the original roof was 0.18 and that for the re-covered roof was the measured 0.28.

The energy-savings calculation using the roof physical data listed above is defined in this paper as the *base case*. The re-covered roof parameters, building internal loads, and the HVAC systems configuration and operation were then changed and additional calculations were made to estimate the effects of these parameters on the energy savings of the re-covered roof. The building was assumed to be located near the Knoxville, Tennessee, airport, and the typical meteorological year (TMY) weather data for this location were used for this set of calculations.

Additional energy-savings calculations were then made for the building at other locations to estimate the effect of the climate on the energy savings. TMY weather data were used at all of the selected locations. The selected climates and their heating degree-days (HDD) for this comparison were those for Bismarck, North Dakota (9,044 HDD), Chicago, Illinois (6,497 HDD), Knoxville, Tennessee (3,695 HDD), Miami, Florida (206 HDD), and Seattle, Washington (4,650 HDD) (USAF 1978).

## Building Parameter Impacts

The impacts of the building parameters on the annual energy savings that would be realized by re-covering the roof with a PUR foam layer are summarized in Tables 3 and 4a.

**Base-Case Re-Covered Roof** The cooling energy savings for the re-covered roof building assumed for the base case is about 5,900 kWh, or about 10% of the original cooling energy consumption. About 53%—89 MBtu (26 MWh)—of the heating energy is saved. Clearly, the magnitude of the heating energy savings is much greater than that of the cooling energy savings.

**Re-Covered Roof Reflectivity Impacts** Increasing the roof reflectivity to 0.7 increases the cooling energy savings another 4,100 kWh to a total of 16% cooling energy savings. Decreasing the reflectivity to 0.05 reduces the cooling savings 2,100 kWh to a total of 6%. The effect of the reflectivity on heating is in the opposite direction, with 4% less (than 53%) savings for the higher reflectivity and 1% more (than 53%) savings for the lower reflectivity.

**Re-Covered Roof R-Value Impacts** The effect of the variations in the re-covered roof PUR thickness (1.5 to 2.0 in. [38 to 51 mm]), compared to the 1.84 in. (46.7 mm) base case, on the building's annual energy consumption is small. The difference between the cooling energy savings for these two PUR thicknesses is less than 0.5%. The heating energy savings are 50% for the 1.5-in. (38-mm) thickness and 54% for the 2-in. (51-mm) thickness.

**Internal Load Impacts** The impacts of the internal loads are very pronounced. This was first demonstrated by increasing the lighting power density to the pre-retrofit value of 2.2 W/ft$^2$ (24 W/m$^2$) instead of the present value of 0.75 W/ft$^2$ (8.1 W/m$^2$). This internal load

**TABLE 3 Effect of Selected Parameters on Building 2518 Annual Cooling Energy Savings by Re-Covering Roof with 1.84 in. (47 mm) PUR Foam—Knoxville, Tenn., TMY Weather Electricity Rate = $0.06/kWh**

| | Cooling Energy Before (kWh) | Cooling Energy After (kWh) | Cooling Energy Savings (kWh) | Cooling Energy Cost Savings ($) | Cooling Energy and Cost Savings (%) |
|---|---|---|---|---|---|
| Base-case re-covered roof* | 60,694 | 54,818 | 5,876 | 352 | 9.7 |
| Re-covered roof reflectance = 0.7 | 60,694 | 50,715 | 9,979 | 599 | 16.4 |
| Re-covered roof reflectance = 0.05 | 60,694 | 56,970 | 3,724 | 223 | 6.1 |
| 1.5 in. (38 mm) PUR foam | 60,694 | 54,836 | 5,858 | 351 | 9.7 |
| 2 in. (51 mm) PUR foam | 60,694 | 54,824 | 5,870 | 352 | 9.7 |
| Original lighting | 73,624 | 71,000 | 2,624 | 157 | 3.6 |
| Computers off nights and weekend | 53,538 | 45,278 | 8,260 | 496 | 15.4 |
| Plenum returns | 65,279 | 55,355 | 9,924 | 595 | 15.2 |
| Economizers | 54,042 | 45,466 | 8,576 | 515 | 15.9 |
| Economizers, cptr off nights and weekend | 48,127 | 38,702 | 9,425 | 566 | 19.6 |
| All air handlers off nights and weekend | 55,269 | 51,062 | 4,207 | 252 | 7.6 |
| All air handlers on all time | 84,406 | 77,707 | 11,699 | 701 | 13.1 |

*Base-case roof parameters for building as modified for energy-savings evaluation purposes (see text):
Original wet roof, North roof R = 1.7 (RSI = 0.30), South roof R = 1.9 (RSI = 0.34), Reflectance = 0.18
Re-covered roof, North roof R = 13.2 (RSI = 2.32), South roof R = 13.4 (RSI = 2.37), Reflectance = 0.28

*TABLE 4a* **Effect of Selected Parameters on Building 2518 Annual Heating Energy Savings by Re-Covering Roof with 1.84 in. (47 mm) PUR Foam—Knoxville, Tenn., TMY Weather**

| | Steam Heating Energy Before (MBtu) | Steam Heating Energy After (MBtu) | Steam Heating Energy Savings (MBtu) | Electric Heating Energy Before (MBtu) | Electric Heating Energy After (MBtu) | Electric Heating Energy Savings (MBtu) | Total Heating Energy Before (MBtu) | Total Heating Energy After (MBtu) | Total Heating Energy Savings (MBtu) | Total Heating Energy Savings (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Base-case re-covered roof* | 144.4 | 59.9 | 84.5 | 7,528 | 6,072 | 1,456 | 49,837 | 23,623 | 26,241 | 52.6 |
| Re-covered roof reflectance = 0.7 | 144.4 | 65.9 | 78.5 | 7,328 | 6,242 | 1,286 | 49,837 | 25,551 | 24,286 | 48.7 |
| Re-covered roof reflectance = 0.05 | 144.4 | 57.1 | 87.3 | 7,328 | 5,988 | 1,540 | 49,837 | 22,718 | 27,195 | 54.4 |
| 1.5 in. (38 mm) PUR foam | 144.4 | 64.7 | 79.7 | 7,528 | 6,202 | 1,326 | 49,837 | 25,159 | 24,678 | 49.5 |
| 2 in. (51 mm) PUR foam | 144.4 | 58.2 | 86.2 | 7,528 | 6,029 | 1,499 | 49,837 | 23,082 | 26,756 | 53.7 |
| Original lighting | 109.3 | 39.7 | 69.6 | 6,191 | 5,051 | 1,140 | 38,216 | 16,683 | 21,533 | 56.3 |
| Computers off nights and weekend | 178.7 | 89.1 | 89.6 | 7,786 | 6,524 | 1,262 | 60,145 | 32,630 | 27,515 | 45.7 |
| Plenum returns | 192.4 | 71.0 | 121.4 | 7,791 | 6,046 | 1,925 | 64,344 | 26,849 | 37,495 | 58.3 |
| Economizers | 143.8 | 59.5 | 84.3 | 7,549 | 6,071 | 1,478 | 49,682 | 23,504 | 26,178 | 52.7 |
| Economizers, cmptr off nights and weekend | 178.3 | 88.3 | 90.0 | 7,815 | 6,543 | 1,272 | 60,057 | 32,415 | 27,642 | 46.0 |
| All air handlers off nights and weekend | 110.0 | 46.5 | 63.5 | 16,744 | 6,180 | 1,436 | 39,846 | 19,804 | 20,041 | 50.3 |
| All air handlers on all time | 152.9 | 66.8 | 86.1 | 16,744 | 11,644 | 5,100 | 62,544 | 31,216 | 30,327 | 49.3 |

*Base-case roof parameters for building as modified for energy-savings evaluation purposes (see text):
Before: Original wet roof, North roof R = 1.7 (RSI = 0.30), South roof R = 1.9 (RSI = 0.34), Reflectance = 0.18
After: Re-covered roof, North roof R = 13.2 (RSI = 2.32), South roof R = 13.4 (RSI = 2.37), Reflectance = 0.28

*TABLE 4b* **Effect of Selected Parameters on Building 2518 Annual Heating Cost Savings by Re-Covering Roof with 1.84 in. (47 mm) PUR Foam—Knoxville, Tenn., TMY Weather Electricity Rate = $0.06/kWh, Steam Supply Rate = $10/MBtu ($0.034/kWh)**

| | Steam Heating Cost Savings ($) | Steam Heating Cost Savings (%) | Electric Heating Cost Savings ($) | Electric Heating Cost Savings (%) | Total Heating Cost Savings ($) | Total Heating Cost Savings (%) |
|---|---|---|---|---|---|---|
| Base-case re-covered roof* | 845 | 58.5 | 87 | 19.3 | 932 | 49.2 |
| Re-covered roof reflectance = 0.7 | 785 | 54.4 | 77 | 17.1 | 862 | 45.5 |
| Re-covered roof reflectance = 0.05 | 873 | 60.5 | 92 | 20.5 | 965 | 50.9 |
| 1.5 in. (38 mm) PUR foam | 797 | 55.2 | 80 | 17.6 | 877 | 46.2 |
| 2 in. (51 mm) PUR foam | 862 | 59.7 | 90 | 19.9 | 952 | 50.2 |
| Original lighting | 696 | 63.7 | 68 | 18.4 | 764 | 52.2 |
| Computers off nights and weekend | 896 | 50.1 | 76 | 16.2 | 972 | 43.1 |
| Plenum returns | 1214 | 63.1 | 116 | 24.2 | 1330 | 55.3 |
| Economizers | 843 | 58.6 | 89 | 19.6 | 932 | 49.3 |
| Economizers, comptr off nights and WE | 900 | 50.5 | 76 | 16.3 | 976 | 43.4 |
| All air handlers off nights and weekend | 635 | 57.7 | 86 | 18.9 | 721 | 46.3 |
| All air handlers on all time | 861 | 56.3 | 306 | 30.5 | 1167 | 46.1 |

*Base-case roof parameters for building as modified for energy-savings evaluation purposes (see text):
Before: Original wet roof, North roof R = 1.7 (RSI = 0.30), South roof R = 1.9 (RSI = 0.34), Reflectance = 0.18
After: Re-covered roof, North roof R = 13.2 (RSI = 2.32), South roof R = 13.4 (RSI = 2.37), Reflectance = 0.28

increase added 53,000 kWh to the annual lighting electricity consumption and 13,000 kWh to the cooling energy consumption before the roof was re-covered. But the cooling energy savings associated with re-covering the roof for this case are lower than for the base case—2,600 kWh (or 4%) compared to 5,900 kWh (or 10%). The added thermal resistance of the PUR foam layer leads to more heat being retained when ambient conditions allow direct dissipation of the heat to the atmosphere. The additional internal load for the original lighting case exacerbates this effect. Of course, the added internal load reduces the building heating energy requirements, but the percentage heating energy savings is 3% greater (than 53%) when adding the re-covered roof insulation.

Decreasing the internal loads has the opposite effect. This is demonstrated by assuming that all the building office equipment is turned off nights, weekends, and holidays. (As stated above, only part of the equipment is turned off such that the equipment load is about 50% of the full load during the nonworking hours.) Turning the equipment off decreases the equipment energy consumption by 40,000 kWh and the cooling energy consumption by 7,000 kWh. The re-covered roof PUR insulation is more effective for this case, saving 8,300 kWh, or 15% of the cooling energy. However, the heating energy consumption is higher than for the base case, but the percentage heating energy savings is 7% lower (than 53%) when adding the re-covered roof insulation.

**Plenum Returns** Most of the plenums above the conditioned space in building 2518 are essentially dead air spaces, although there is some air communication between them and the offices through the small cracks and other imperfections in the suspended ceiling tile system. The dead air spaces result in added resistance for the transfer of heat through the roofs, but the cracks decrease this extra amount. Many buildings use plenum returns for their air handlers, which leads to greater contact between the circulating air and the roofs. Assuming that building 2518 has plenum returns would significantly increase the energy consumption for the building with the original roofs. The added re-covered roof insulation with plenum returns results in about 15% cooling energy and 58% heating energy savings.

**Addition of Economizers** Much of the cooling energy consumption during the spring and fall could be eliminated by using air economizers. They use outside air temperature or air enthalpy controls to modulate the amounts of outside air brought into the circulating air systems. When the outside air is cooler or has a lower enthalpy than the air in the conditioned space, it can be used for space cooling. This cuts down the air conditioner compressor's energy requirements. However, economizers for small rooftop air conditioners had not been commonly used and, when used, maintenance had often left much to be desired.

To evaluate the effect of the economizers in this study, the calculations assumed that they were activated at outdoor air temperatures below 68°F. (Economizers often use air enthalpy controls, but the differences between temperature-controlled and enthalpy-controlled economizers for evaluating the re-covered roof energy savings are very small.) In addition to saving about 6,000 kWh cooling energy by using the economizers, another 8,600 kWh, or 16%, of the cooling energy would be saved by re-covering the roof. Adding economizers and turning off the office equipment on nights and weekends would save about 12,000 kWh cooling energy plus another 9,400 kWh by re-covering the roof, or a total of 20% energy savings. The impact of the economizers on the heating energy is negligible.

**HVAC Systems Operating Schedules** Two of the building's air handlers are operated continuously and the other three are shut down on nights and weekends (Table 1). Calculations were made to see the effect of the extremes of operating all units continuously or shutting down all units during nights and weekends. Continuous operation, of course, leads to much greater energy consumption. The added roof insulation saves about 13% of the cooling energy. Total shutdown nights and weekends leads to about a 10% reduction in the cooling energy consumption, and the added re-covered roof insulation saves about 8% of the cooling energy. About half of the heating energy is saved for both cases.

## Climate Impacts

The effect of the building climate on the energy-saving effectiveness of the re-covered roof was calculated using TMY weather data for Bismarck, North Dakota, Chicago, Illinois, Miami, Florida, and Seattle, Washington for comparison to Knoxville, Tennessee. These calculations were done for three building configurations: (1) using the base-case building as modified to evaluate the re-covered roof energy savings (representing an energy-efficient building), (2) using the base-case building with the old inefficient light fixtures to estimate the effect of a higher internal load (representing a building that is not energy efficient), and (3) using the base-case building having HVAC system economizers (representing a very energy efficient building). The results are listed in Tables 5 and 6. For the reader's convenience, the savings were

***TABLE 5*** **Effect of Climate on Building 2518 Annual Cooling Energy Savings by Re-Covering Roof with 1.84 in. (47 mm) PUR Foam*—Electricity Rate = 0.075/kWh**

| Location | Cooling Energy Before (kWh) | Cooling Energy After (kWh) | Cooling Energy Savings (kWh) | Cooling Energy Cost Savings ($) | Cooling Energy and Cost Savings (%) |
|---|---|---|---|---|---|
| Base Case (Energy Efficient) | | | | | |
| Bismarck | 30,373 | 28,206 | 2,167 | 163 | 7.1 |
| Chicago | 43,731 | 40,237 | 3,494 | 262 | 8.0 |
| Knoxville | 60,694 | 54,818 | 5,876 | 439 | 9.6 |
| Miami | 130,281 | 115,963 | 14,318 | 1,074 | 11.0 |
| Seattle | 22,548 | 23,903 | −1,355 | −102 | −6.0 |
| Increased Internal Loads (Old Lights-Not Energy Efficient) | | | | | |
| Bismarck | 38,517 | 38,794 | −277 | −27 | −0.7 |
| Chicago | 54,167 | 53,171 | 996 | 75 | 1.8 |
| Knoxville | 73,624 | 71,000 | 2,624 | 197 | 3.6 |
| Miami | 148,401 | 135,415 | 12,986 | 974 | 8.8 |
| Seattle | 32,833 | 38,356 | −5,523 | −414 | −16.8 |
| Addition of Economizers (Very Energy Efficient) | | | | | |
| Bismarck | 2,948 | 21,118 | 3,830 | 287 | 15.4 |
| Chicago | 37,745 | 32,443 | 5,302 | 398 | 14.0 |
| Knoxville | 54,042 | 45,466 | 8,576 | 643 | 15.9 |
| Miami | 127,308 | 112,205 | 15,103 | 1,133 | 11.9 |
| Seattle | 11,770 | 9,461 | 2,309 | 173 | 19.6 |

*Base-case roof parameters for building as modified for energy-savings evaluation purposes (see text):
Before: Original wet roof, North roof R = 1.7 (RSI = 0.30), South roof R = 1.9 (RSI = 0.34), Reflectance = 0.18
After: Re-covered roof, North roof R = 13.2 (RSI = 2.32), South roof R = 13.4 (RSI = 2.37), Reflectance = 0.28

*TABLE 6* Effect of Climate on Building 2518 Annual Heating Energy Savings by Re-Covering Roof with 1.84 in. (47 mm) PUR Foam*—Natural Gas Rate = $5.00/MBtu ($0.017/kWh)

| Location | Heating Energy Before (MBtu) | Heating Energy After (MBtu) | Heating Energy Savings (MBtu) | Heating Energy Before (kWh) | Heating Energy After (kWh) | Heating Energy Savings (kWh) | Heating Cost Savings ($) | Heating Energy and Cost Savings (%) |
|---|---|---|---|---|---|---|---|---|
| | | | | Base-Case (Lights (Energy Efficient) | | | | |
| Bismarck | 867.2 | 525.8 | 341.4 | 254,096 | 154,072 | 100,025 | 1,707 | 39.4 |
| Chicago | 539.4 | 308.0 | 231.4 | 158,038 | 90,243 | 67,795 | 1,157 | 42.9 |
| Knoxville | 261.7 | 124.0 | 137.7 | 76,672 | 36,343 | 40,329 | 688 | 52.6 |
| Miami | 3.1 | 1.1 | 2.0 | 902 | 316 | 586 | 10 | 65.0 |
| Seattle | 373.7 | 189.4 | 184.3 | 109,491 | 55,489 | 54,002 | 922 | 49.3 |
| | | | | Increased Internal Loads (Old Lights-Not Energy Efficient) | | | | |
| Bismarck | 748.6 | 423.4 | 325.2 | 219,342 | 124,051 | 95,292 | 1,626 | 43.4 |
| Chicago | 448.6 | 235.8 | 212.8 | 131,443 | 69,102 | 62,341 | 1,064 | 47.4 |
| Knoxville | 200.5 | 87.5 | 112.9 | 58,735 | 25,649 | 33,086 | 565 | 56.3 |
| Miami | 3.1 | 2.0 | 1.1 | 902 | 316 | 316 | 5 | 35.0 |
| Seattle | 286.3 | 133.4 | 152.9 | 83,887 | 39,081 | 44,806 | 765 | 53.4 |
| | | | | Addition of Economizers (Very Energy Efficient) | | | | |
| Bismarck | 865.2 | 524.5 | 340.8 | 253,510 | 153,666 | 99,844 | 1,704 | 39.4 |
| Chicago | 539.2 | 308.2 | 231.1 | 157,993 | 90,288 | 67,705 | 1,155 | 42.9 |
| Knoxville | 260.9 | 123.4 | 137.5 | 76,450 | 36,151 | 40,298 | 688 | 52.7 |
| Miami | 3.1 | 1.1 | 2.0 | 902 | 316 | 586 | 10 | 65.0 |
| Seattle | 372.0 | 187.2 | 184.8 | 108,995 | 54,858 | 54,137 | 924 | 49.7 |

*Base-case roof parameters for building as modified for energy-savings evaluation purposes (see text):
Before: Original wet roof, North roof R = 1.7 (RSI = 0.30), South roof R = 1.9 (RSI = 0.34), Reflectance = 0.18
After: Re-covered roof, North roof R = 13.2 (RSI = 2.32), South roof R = 13.4 (RSI = 2.37), Reflectance = 0.28
Assumed annual average heating system efficiency = 0.65

*TABLE 7* Building 2518 Annual Energy Savings by Re-Covering the Roof with 1.84 in. PUR per ft$^2$ Roof Area*—Electricity Rate = $0.075/kWh, Natural Gas Rate = $5.00/MBtu ($0.017/kWh)

| Location | Cooling Energy Savings (kWh/ft$^2$) | Cooling Energy Savings ($/ft$^2$) | Heating Energy Savings (kBtu/ft$^2$) | Heating Energy Savings (kWh/ft$^2$) | Heating Energy Savings ($/ft$^2$) | Total Energy Cost Savings ($/ft$^2$) | Total Energy Cost Savings (%) |
|---|---|---|---|---|---|---|---|
| | | | | Base Case (Energy Efficient) | | | |
| Bismarck ND | 0.1682 | 0.0126 | 26.51 | 7.766 | 0.1325 | 0.1451 | 28.3 |
| Chicago IL | 0.2713 | 0.0203 | 17.96 | 5.264 | 0.0898 | 0.1102 | 23.7 |
| Knoxville TN | 0.4562 | 0.0342 | 10.69 | 3.132 | 0.0535 | 0.0877 | 19.3 |
| Miami FL | 1.1116 | 0.0834 | 0.16 | 0.045 | 0.0008 | 0.0841 | 11.1 |
| Seattle WA | −0.1052 | −0.0079 | 14.31 | 4.193 | 0.0715 | 0.0637 | 23.0 |
| | | | | Increased Internal Loads (Old Lights-Not Energy Efficient) | | | |
| Bismarck ND | −0.0215 | −0.0016 | 25.25 | 7.398 | 0.1263 | 0.1246 | 24.2 |
| Chicago IL | 0.0773 | 0.0058 | 16.52 | 4.840 | 0.0826 | 0.0884 | 18.1 |
| Knoxville TN | 0.2037 | 0.0153 | 8.77 | 2.569 | 0.0438 | 0.0591 | 11.7 |
| Miami FL | 1.0082 | 0.0756 | 0.08 | 0.024 | 0.0004 | 0.0760 | 8.8 |
| Seattle WA | −0.4288 | −0.0322 | 11.87 | 3.479 | 0.0594 | 0.0272 | 9.0 |
| | | | | Addition of Economizers (Very Energy Efficient) | | | |
| Bismarck ND | 0.2974 | 0.0223 | 26.46 | 7.752 | 0.1323 | 0.1546 | 32.1 |
| Chicago IL | 0.4166 | 0.0309 | 17.94 | 5.257 | 0.0897 | 0.1206 | 28.1 |
| Knoxville TN | 0.6658 | 0.0499 | 10.68 | 3.129 | 0.0534 | 0.1033 | 24.8 |
| Miami FL | 1.1726 | 0.0879 | 0.16 | 0.045 | 0.0008 | 0.0887 | 11.9 |
| Seattle WA | 0.1793 | 0.0134 | 14.35 | 4.203 | 0.0717 | 0.0852 | 40.0 |

*Building roof area = 12,880 ft$^2$ (1197 m$^2$)
1 ft$^2$ = 0.0929 m$^2$

translated to a per-square-foot basis and summarized in Table 7. No changes in the building use or envelope construction, including the amount of insulation, were assumed at any of the locations.

**Base-Case (Energy Efficient) Building** For the base-case building as configured to evaluate the re-covered roof energy savings, the cooling energy savings due to the re-covered PUR insulation are in the range of 7% to 11% for four of the climates. The greatest savings, of about 14,300 kWh, are for Miami. Seattle requires 1,400 kWh more energy due to the greater retention of the internal load energy during early spring and late fall. The heating energy savings are in the range of 40% to 50%. The greatest heating energy savings are about 220 MBtu for Bismarck. Miami has about 65% heating energy savings, but its annual heating energy consumption is very small.

**Increased Internal Loads (Old Lights, Not Energy Efficient Building)** The effect of increasing the internal loads on the re-covered roof's annual savings was calculated by assuming that the old, inefficient lighting fixtures were used. The cooling energy requirements are higher because of the 53,000 kWh of additional energy that was used for the lights. The cooling energy savings are lower than for the base case because of greater quantities of heat that cannot be dissipated through the more highly insulated roof during the early spring and late fall. Bismarck and Seattle now require more cooling energy. The cooling energy savings for the remaining locations are reduced 1,500 to 2,500 kWh. The heating energy requirements are lower for this situation, but the percentage savings increased on average only 4% to a range of 43% to 53%, except for Miami.

**Addition of Economizers (Very Energy Efficient Building** Air economizers can help to increase the cooling energy savings since they mitigate the effect of the added insulation trapping the heat generated internally when ambient air conditions favor direct dissipation of heat to the atmosphere. Assuming that the economizer is activated at outside air temperatures below 68°F (20°C), the air conditioner energy requirements are reduced and the cooling energy savings associated with the re-covered roof PUR insulation are greater. For Seattle, the energy savings increase from about −1,400 kWh to about 2,300 kWh. The benefit of the economizer in Miami is small. For the remaining three locations, the energy savings increase from 7% to 10% to 14% to 16%. The impact of the economizers on the heating energy consumption is negligible for all the climates.

## COST SAVINGS ANALYSIS

### Costs and Assumptions

A typical cost for re-covering the roof with a sprayed PUR foam system is about $2.75/ft$^2$ ($29.60/m$^2$), which leads to a $35,420 cost to recover the total 12,880 ft$^2$ (1,197 m$^2$) of building roof area. This cost includes a 10-year warranty on the outer silicone roof membrane. The cost of installing a new membrane is about $1.00/ft$^2$ ($10.76/m$^2$) (Brooks 1995).

Two sets of utility costs were used in the economic evaluation of the re-covered roof system. The first was for the building located at the laboratory using Knoxville, Tennessee, TMY weather data, where the effects of the selected parameters were evaluated. Here, the lab's utility rates of $0.06/kWh for electricity and $10/MBtu ($0.034/kWh) for central plant steam were used (MacDonald 1995). The second set, used for evaluating the energy cost savings for the nation as a whole, was the national average rates of $0.075/kWh for electricity and $5.00/MBtu ($0.017/kWh) for natural gas (EIA 1994).

There are a number of figures of merit that are used for evaluating the benefit-to-cost ratio of a measure (Ruegg 1987). An elementary figure of merit is the simple payback time (SPT), which is the time required to break even when re-covering the initial investment cost. The shortcoming of this method is that it ignores the cost of money and energy escalation rates.

A more realistic approach is to evaluate a life-cycle cost over the economic life of a measure. This approach is used by the Federal Energy Management Program (FEMP). A 25-year economic life is generally used by FEMP (Ruegg 1987), and this was the value used for the re-covered roof evaluation.

The figure of merit usually used by FEMP to rank the cost-effectiveness of a measure is the savings-to-investment ratio (SIR). The SIR is defined as a ratio having a numerator of the reduction of the energy costs, plus any decreases or increases in nonfuel, maintenance, and repair costs, and a denominator of the investment cost, plus any increases or decreases in the salvage and replacement costs. All quantities in this ratio are expressed in terms of the present value (PV) over the economic life of the measure (Ruegg 1987). An SIR of greater than 1 is required for the savings to be greater than the discount rate. The greater the SIR, the greater the return. For example, assuming that the economic life of the investment is 25 years and there are no salvage or replacement costs or savings, an SIR of 2 represents a total return of 2.8% plus the discount rate. An SIR equal to 3 leads to a 4.4% additional return, and an SIR equal to 4 leads to a 5.7% additional return.

The PV of a quantity adjusts the future savings or expenditures to account for the opportunity cost of money (discount rate). Discount factors, which are simple multipliers determined using discount formulas with the discount rate as the independent variable, are often used to calculate the PV savings or costs. Details of these formulas are given by Ruegg (1987).

The federal government updates the discount factors used by FEMP each year. For this study, the 1995 discount factors were used (Peterson 1994). The 1995 factors are based on a 3% real discount rate and U.S. Department of Energy fuel escalation rates. These factors are in constant dollars, which do not include the general inflation rate.

## Cost Savings

The annual energy cost savings realized by re-covering the entire building roof at the laboratory are listed in Tables 3 and 4b. For the evaluation base-case re-covered roof, the annual energy cost savings for the cooling and heating energy are $352 and $932, respectively. This translates into a 27.6-year SPT, meaning that the re-covered roof is not cost-effective based only on energy savings. However, there were large maintenance savings associated with the re-covered roof. The cost of maintaining the roof for the last three years prior to re-covering was about $0.75/ft$^2$ ($8.07/m$^2$), or $9,660 for the whole building (Shamblin 1995). The addition of this cost reduction lowers the payback time to 3.2 years.

Figure 5 is a plot of the annual energy cost savings per square foot of roof area that are listed in Tables 3 and 4b. Most of the savings are due to the reduction in the building's heating demand. The dead-air plenums above the conditioned-space ceilings were significant in lowering the energy savings. If there was greater contact between the circulating air and the roofs, such as using plenum returns, there would be greater energy savings. Also, high internal loads in the building tend to reduce the energy savings associated with the re-covered roof.

The energy-saving SIRs for the selected cases are shown in Figure 5. It is 0.673 for the evaluation base case, which is less than 1. It increases to around 1 if all the air handlers are operating continuously or plenum returns are used for the circulating air. The effect of the internal loads is apparent. Using the old inefficient lights decreases the SIR to 0.486 and turning off all the computers at night increases it to 0.766. As will be seen later, the major reason for re-covering roofs is maintenance savings. Assuming a $0.75 annual maintenance savings and allowing for the installation of a new silicone outer roof membrane every 10 years, the SIR for the evaluation base-case roof increases to 4.949.

## National Average Cost Savings

For calculating heating cost savings for the nation as a whole, it was assumed that the building was heated by a hot water boiler having an annual fuel use efficiency (AFUE) of 0.65. The annual energy cost savings using these assumptions for the five selected climates are listed in Tables 5 and 6. For the reader's convenience, these costs are converted per unit of roof area, listed in Table 7 and plotted in Figure 6.

For the re-covered roof for the energy evaluation base-case building, the annual energy cost savings are in the range of $820 (Seattle) to $1,869 (Bismarck), as shown in Tables 5 and 6. SPTs for these savings are 43.2 and 19.0 years, respectively. For Knoxville, these values are $1,126 and 31.5 years. The building with higher internal loads (old, inefficient lights) would have lower energy cost savings and longer payback times, while the opposite behavior would be true for a building with lower internal loads (Figure 6).

These calculations show, for the building located at the national laboratory, that energy cost saving by itself is not sufficient to justify re-covering the roof. Other savings, such as the reduction in maintenance costs, must be added to economically justify this action. If the re-covered roof has a $0.40/ft$^2$ ($4.31/m$^2$) annual maintenance cost savings, the SPT for the base-case building would be reduced to a range of 5.0 to 5.9 years.

The energy-savings-only SIRs for the re-covered roof in different climates are shown in Figure 6. Except for Bismarck, the SIRs are less than 1. They are lower at all locations for the building with higher internal loads, but they are higher for buildings that have economizers because, when ambient air conditions are favorable, they allow displacement of the hot inside air with cooler outside air.

Roof maintenance (to stop roof water leakage) cost saving is a primary reason to replace or recover an existing roof. The SIRs for annual roof maintenance savings in the range of $0.10 to $0.70 per ft$^2$ are listed in Table 8. Included in the table are the PV of the annual roof maintenance savings and the PV of the cost of replacing the outer silicone roof membrane every 10 years. The net roof maintenance SIR for a $0.30 annual maintenance

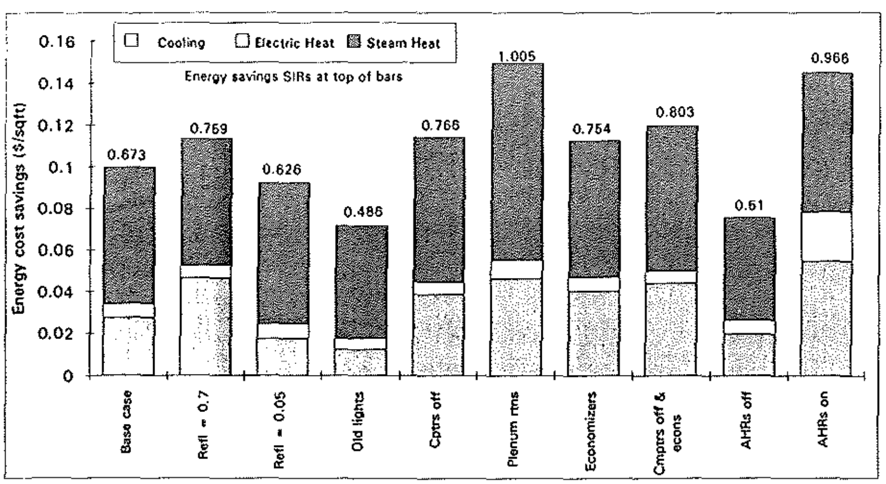


***Figure 5*** *Re-covered roof energy cost savings for building 2518 (as modified for energy-savings evaluation) (Knoxville TMY weather data).*

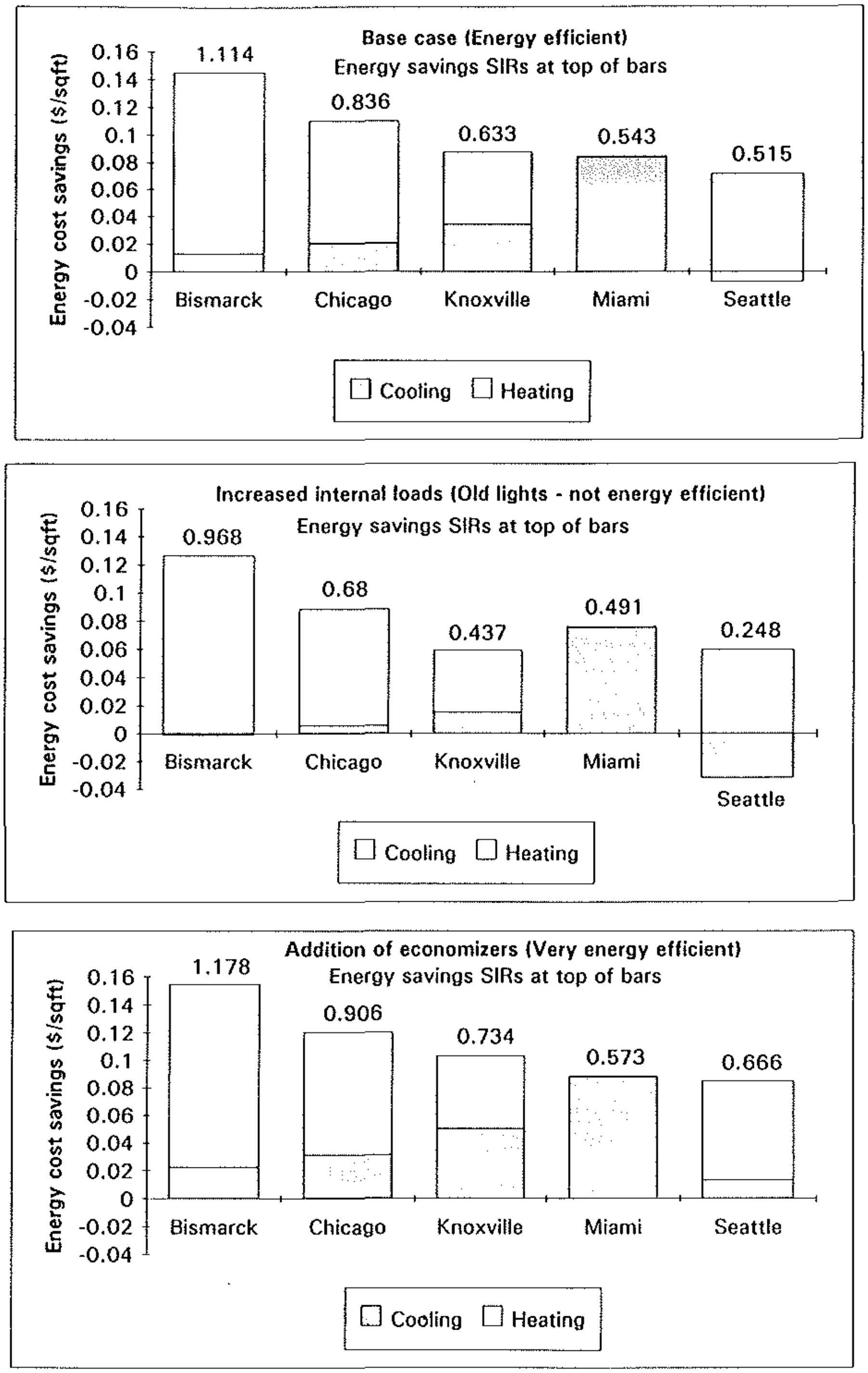


***Figure 6*** *Re-covered roof energy cost savings for building 2518 (as modified for energy-savings evaluation) at selected locations.*

cost savings is 1.43, and that for a $0.40 annual maintenance cost savings is 2.06.

The maintenance and the energy-cost-savings SIRs are linearly additive. Figure 7 shows a series of bar charts for the two SIR components and their sums. It can be seen that the energy savings do make the SIRs for the re-covered roofs more attractive. For a $0.30 annual maintenance savings in the Knoxville climate, the energy saving increases the SIR from 1.4 to around 2. For a $0.40 annual maintenance savings, it is increased from 2.1 to around 2.7.

## CONCLUSIONS

The application of the DOE-2.1E model to simulate building 2518 energy consumption for the evaluation of energy conservation measures was successful. A good match between the predicted and measured building energy behaviors was obtained. The effort to arrive at a match suitable for research purposes was considerable (several weeks). The calibrated model was used to calculate the energy savings realized by re-covering the building roof with the sprayed PUR system. The instrumented building and the model can be used to predict the impacts of other energy-efficiency improvements, thus becoming a prototype building for the evaluation of other energy-saving measures.

Except for Miami, the heating energy savings realized by re-covering the roof with a sprayed PUR system are much greater than the cooling energy savings. In general, the heating energy savings are around 50% and the cooling energy savings are around 10%. These reductions are not sufficient alone to justify re-covering roofs of buildings having high internal loads, such as building 2518. The primary motivation for this action is the reduction of maintenance costs to prevent leaks. However, the energy savings add significantly to the SIR. A $0.30/ft^2$ annual maintenance savings leads to an SIR of 1.4. Adding the energy cost savings for the building at Knoxville increases the SIR to 2.0.

The greatest energy savings are for the building located in heating-dominated climates. The building's internal loads and plenums were found to be very important in the amount of energy that is saved. If the plenums are nearly dead air spaces, as for building 2518, the energy-savings benefits of the re-covered roofs are lower than for buildings with plenums, which allow greater contact of the circulating air with the roof.

*TABLE 8* **Maintenance Savings-To-Investment Ratios (SIRs) for Building 2518 Recovered Roof.* Initial Recovered Roof Cost = $2.75/ft² ($29.60/m²). Recovered Roof Membrance Replacement Cost = $1.00 ft² (10.76 m²) at 10 yr Intervals.**

| Annual Roof Maint. Cost Savings ($/ft²) | PV of Annual Roof Maint. Cost Savings ($/ft²) | PV of Roof Membrane Replacement Costs ($/ft²) | PV of Net Roof Maint. Cost Savings ($/ft²) | Roof Maint. SIR |
|---|---|---|---|---|
| 0.10 | 1.74 | −1.30 | 0.44 | 0.161 |
| 0.20 | 3.48 | −1.30 | 2.18 | 0.794 |
| 0.30 | 5.22 | −1.30 | 3.93 | 1.427 |
| 0.40 | 6.96 | −1.30 | 5.67 | 2.060 |
| 0.50 | 8.71 | −1.30 | 7.41 | 2.694 |
| 0.60 | 10.45 | −1.30 | 9.15 | 3.327 |
| 0.70 | 12.19 | −1.30 | 10.89 | 3.960 |

*Based on FEMP 1995 Uniform Present Value discount factors.[a]
(3% discount rate and U.S. Department of Energy projected fuel escalation rates.)
Assumed recovered roof economic life = 25 yrs

[a]Peterson, S.R. 1994. Energy price Indices and Discount Factors for Life-Cycle Cost Analysis 1995, National Institute of Standards and Technology, NISTIR-3273-9 (Revised 10/94).

Air economizers can help to increase the cooling energy savings since they mitigate the effect of the added insulation trapping the heat generated internally when ambient air conditions favor direct dissipation of heat to the atmosphere.

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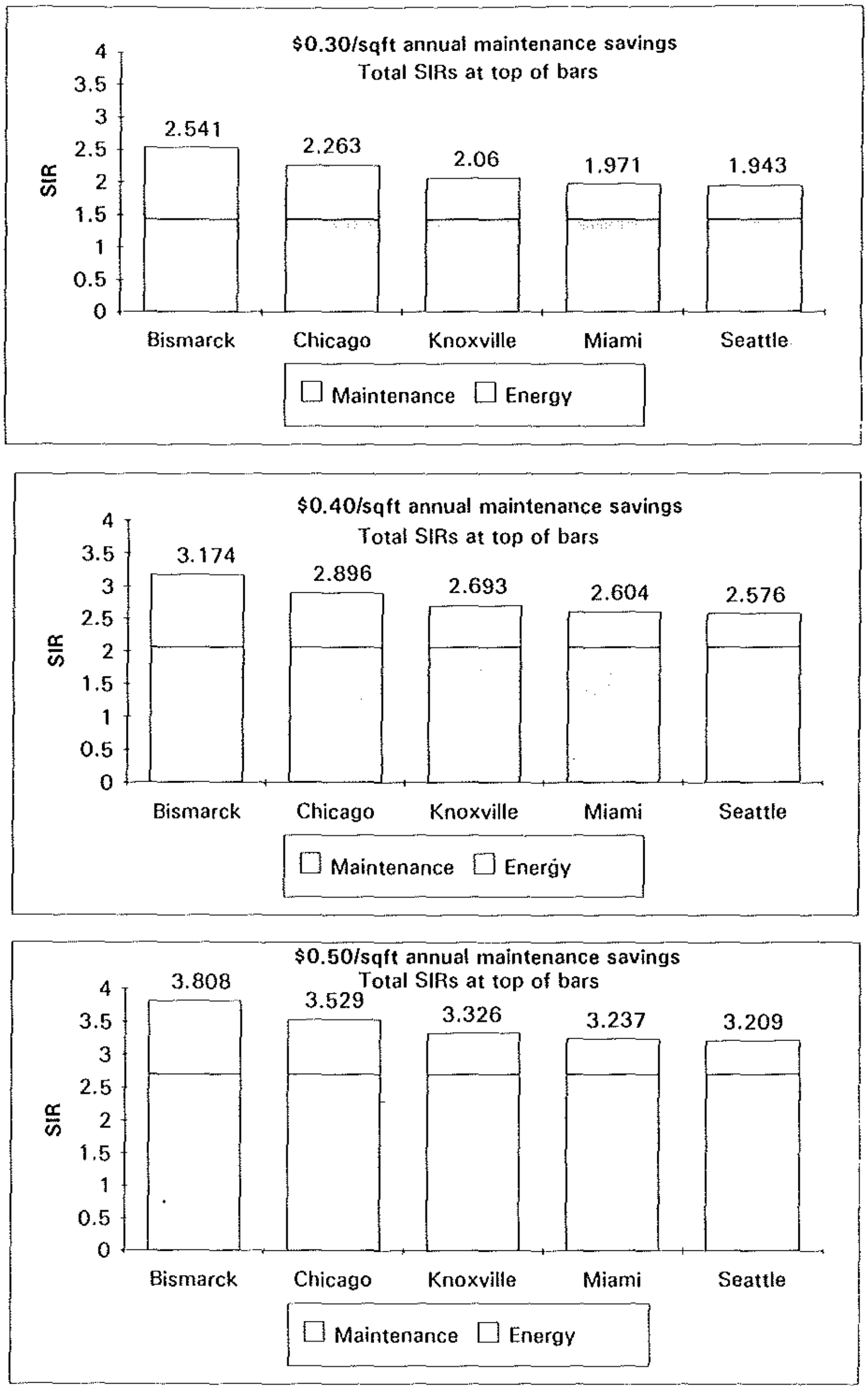


***Figure 7*** *Re-covered roof energy cost-savings SIRs for building 2518 (as modified for energy-savings evaluation) at selected locations.*