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A. O. Desjarlais
T. W. Petrie
J. E. Christian
H. A. McLain
P. W. Childs

Oak Ridge National Laboratory
Energy Division
Building Envelope Research Center

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ABSTRACT

Roof re-cover, the practice of installing a new roof over an existing failed roof, has become commonplace. The 1994 National Roofing Contractors Annual Roofing Survey reported that approximately 33% of current reroofing activity is re-cover. Market trends suggest that re-cover will become an increasingly more popular option.

Moisture in the failed roof complicates the decision whether or not to re-cover and how to do the re-cover if that is the decision. If the roof to be re-covered contains moisture that will not be removed during reroofing, this moisture must be able to escape from the roof system. Otherwise, moisture entrapped in the roofing system may eventually lead to the mechanical failure of fasteners and the roof deck, especially if it is metal.

In 1991, the Oak Ridge National Laboratory (ORNL) surveyed its own roofing inventory and found that 164 buildings or 70% of the laboratory roof area needed reroofing. Because of the high cost of tear off and replacement, an alternative was sought. This paper describes the procedure that we employed to determine the suitability of a particular roof system on a laboratory building for re-covering. The procedure involves the use of field diagnostics, laboratory experiments and numerical simulations that demonstrate that the particular roof type can be re-covered. Furthermore, the building and roof system have been monitored for approximately 16 months after re-cover. The monitoring results are compared to our numerical simulations and demonstrate that the roof system is drying and that the reroofing strategy that we used is cost-effective.

This project is part of a Cooperative Research and Development Agreement (CRADA) between Dow Corning Corporation and the ORNL Building Envelope Research Center with support from Hugh Brooks Industries, 3M Corporation, and the ORNL Plant and Equipment Division.

KEY WORDS

low-slope roof, reroofing, re-cover, moisture, energy conservation, self-drying, heat and mass transfer, energy calculation.

INTRODUCTION

Roof re-cover is a widely practiced form of reroofing that is increasing in popularity (NRCA, 1994). A major reason to reroof is the failure of the existing roof system due to moisture incursion. If the decision is to tear off the old roof, roofing professionals must dispose of the wetted insulation as part of the reroofing job. If the wetted insulation is left in-place and the decision is to re-cover the roof, will the moisture in the failed roofing system be entrapped, eventually leading to the premature failure of the re-cover system? There is a single existing guideline that assists the roofing industry in this decision-making process (NRCA, 1988). This document categorically states that the existing roof must be dry if it is to be re-covered but offers no references or data to support it's position. Knowledgeable roofing professionals have varied opinions on this subject, ranging from "if it's wet, tear it off" to "it will eventually dry, let it stay." Workshops have been held to exclusively address this issue (ORNL, 1994).

The Oak Ridge National Laboratory (ORNL) has 164 buildings that are in need of reroofing; these roofs are typically wet, contain hazardous materials, and include a vapor retarder in their construction (ORNL, 1991). Traditional reroofing practice would require that these roofs be torn off and replaced. Because of the cost of performing a tear off and replacement, a more economic solution was sought. Kyle (1994) demonstrated that re-cover was more cost effective and, as an additional benefit, reduced the total amount of roofing materials that will eventually enter the waste stream.

We investigated the possibility of re-covering a typical ORNL roofing system and have re-covered one campus building as a demonstration project. Our investigation included a thorough on-site study of the condition of the building's existing roofing system, a series of *in-situ*, laboratory and numerical experiments to assess the benefits of proposed modifications to the roofing system, follow-up surveys of the re-covered roof system, and computer simulations to determine the cost-effectiveness of our reroofing procedure if it were done at full cost.

THE BUILDING

We chose a one-story office building at the laboratory for this demonstration project. The building is designated on campus as Building 2518 and houses the central offices for the ORNL Plant and Equipment Division. The building is approximately 1200 m^2 (13,000 ft^2) in area and is constructed on a concrete slab with uninsulated block and brick walls and single-glazed windows.

Figure 1 is a photograph of the building. The building has two different roofs. The north roof has a metal deck, bituminous vapor retarder, 15-mm (0.6-in.) thick fiberglass insulation as 0.61 m ×1.22 m (2 ft ×4 ft) boards butted together, and a four-ply coal tar built-up roof. The hot coal tar flowed between the fiberglass boards during application. This roofing system was installed in 1967 when a 420 m^2 (4500 ft^2) addition was added to the south of the building. The south roof was constructed identical to the north roof except a concrete deck was used. We selected this building because of the small size of the roof, the ease of access, the limited amount of roof-top equipment, and the perceived simplicity of reroofing a building that had a parapet wall. We knew that the roof was very wet because of the number of leaks reported by the building occupants and verified by a preliminary infrared thermographic survey. The engineering report had certified that the roof did not contain any radioactive contamination and the report had ranked the building in the "most urgent" reroofing category. Prior to our selection of this building for our demonstration, the roof on the south addition was torn off and replaced with fiberglass insulation and built-up roof. Therefore, we limited our investigation to the original north roof.

FIELD DIAGNOSTICS

We were interested in determining whether or not the existing roof would dry after it had been re-covered and how much the re-covered roof improved the energy performance of the whole building. Therefore, a series of field measurements was performed, instrumentation was installed in the roof system and building, and samples of the roof system were removed for laboratory testing.

To assess whether or not the roof system would dry, it was essential to accurately determine the initial concentration and distribution of moisture in the existing roof. We performed an infrared scan of the roof system to verify that the roof was indeed wet. We followed up with a neutron gauge (Nuclear densometer) moisture survey. We used the neutron gauge to measure the moisture content of the entire roof on a grid with nodes 1.5 m (5 ft) apart. Figure 2 depicts the results of our initial surveys and shows the equipment that was used to accomplish this task. The infrared survey was qualitatively consistent with the neutron gauge survey. After completing the neutron gauge survey, we studied the results and selected five locations on the roof to span the range from wet to dry. We removed one core sample from each of these locations, dried these cores in a convection oven, and determined the moisture content gravimetrically. A plot relating moisture content of the cores we removed from the roof to the output of the neutron gauge is shown in Figure 3. We linearly regressed the experimental data (correlation coefficient or r^2 of 0.94) and used that relationship to determine the moisture content for each location sampled with the neutron gauge. The total roof system moisture content was determined by an area weighted sum. We computed that the roof system contained approximately 3200 liters (840 gallons) of water and that approximately 40% of the roof area was saturated (contained water in the liquid phase). The bulk of the saturated insulation was located in the central 6 m (20 ft) wide section of the roof. On average, the saturated insulation in this area had a moisture content of approximately 18% by volume (105% by weight).

We were also interested in determining the improvement in the energy efficiency of the roofing system and its impact on the whole building energy performance. To measure these improvements, we installed nine temperature sensors and three heat-flux transducers (HFTs) in the roofing system and the plenum space below the metal deck. The HFTs were installed between the BUR and the fiberglass insulation. Prior to reroofing, 300 mm (12-in) sections of the BUR were cut and removed from the roof. The HFTs were installed on the exposed surface of the fiberglass insulation and the BUR sections were placed over the HFTs and repaired with roofing cement. Two of the HFTs were installed in areas of the roof that were very wet; the third HFT was installed in a dry region. Instrumentation to measure the temperatures of the supply and return air for three air handlers, as well as the air flow rates and the power consumed by these air handlers was installed. We also monitored the whole building electric demand. These data were used to validate a whole building energy simulation that is described later in this paper.

LABORATORY ANALYSES

Since the roof system had a vapor retarder, downward drying could essentially not take place unless we somehow compromised the vapor retarder. To investigate the impact of perforating the vapor retarder and to measure the existing roof's thermal performance, we removed a 1.2 x 1.8 m (4 x 6 ft) section of the roof system (membrane, insulation, vapor retarder, and metal deck) from a dry portion of the roof and brought the section to the laboratory for testing.

A photograph of the roof section that we removed is shown in Figure 4. This section was put into an aluminum frame and, to prevent moisture loss, its edges were sealed with a combination of silicone sealant and polyurethane foam. We installed a calibrated heat flux transducer under the membrane and temperature sensors on the metal deck and membrane. This test panel was installed in a diagnostic panel by suspending the aluminum frame from three load cells. A complete description of the instrumentation used in this experiment is presented by Desjarlais (1994).

The diagnostic panel was positioned in the Large Scale Climate Simulator (Huntley, 1989) for testing. The insertion of the diagnostic platform into the Large Scale Climate Simulator (LSCS) creates two separate chambers, in which the temperature and humidity can be independently controlled. Three experiments were performed on the test panel in which its weight change was monitored. Strips of polyethylene were draped between the test panel and adjacent panels or the edges of the diagnostic platform. They isolated the upper and lower chambers sufficiently while allowing the load cells to accurately follow small weight changes.

For the first experiment, we simulated a Knoxville summer diurnal cycle in the upper (climate) chamber and maintained constant indoor temperature (21°C or 70°F) and relative humidity (50% RH) levels in the lower (guard) chamber. From this experiment, we determined that the "dry" thermal resistance of the roofing system was approximately 0.3 $m^2 \cdot K/W$ (1.8 $h \cdot ft^2 \cdot {}^\circ F/Btu$).

We then removed the test panel from the LSCS and added water amounting to 10% by volume of the insulation. In the second experiment, for the same test conditions as the first, we measured the "wet" thermal resistance of the roofing system to be 0.09 $m^2 \cdot K/W$ (0.5 $h \cdot ft^2 \cdot {}^\circ F/Btu$). By area weighting the "wet" and "dry" R-values, we estimate that the roof system on Building 2518 had an average R-value of 0.2 $m^2 \cdot K/W$ (1.3 $h \cdot ft^2 \cdot {}^\circ F/Btu$).

After the completion of the "wet" thermal performance experiment, we fixed the climate chamber temperature at a constant value of approximately 66°C (150°F) and monitored the output of the load cells. Baseline drying rates were not zero, mostly because we could not perfectly seal the perimeter of the test section in the aluminum frame. We then drilled 33 holes that were 13-mm (0.5-in.) in diameter through the metal deck and vapor retarder. From the steady rate of weight change per unit time before and after the addition of the holes, we calculated the deck permeance. To determine the deck permeance, we measured the weight change using our load cells, measured the interior vapor pressure using temperature and relative humidity sensors installed in the interior chamber below the deck, and assuming that the insulation above the deck is saturated, computed the vapor pressure above the deck by measuring it's temperature and assuming 100% relative humidity. This assumption is defensible; since the test conditions are driving moisture to the deck and the deck is much less permeable than the insulation, water vapor will accumulate and condense at this surface.

The permeance was confirmed by drilling additional holes and repeating the measurements. From this third experiment we concluded that the permeance of the vapor retarder/deck in Building 2518 could be adjusted with the addition of penetrations. Holes 0.3 m (12 in.) on center would yield a permeance of 32 metric perms (0.56 perms) and any desired permeance could be obtained by adjusting the density of the holes.

THE REROOFING

Our CRADA partners supplied the material and labor to prepare the old roof system and install the re-cover roof system. Preparation consisted of pressure washing the dirt and loose aggregate from the BUR. Then, blisters in the BUR were cut open and the areas where the membrane appeared to be loose were mechanically fastened. Holes 13 mm (0.5 in.) in diameter were drilled through the roofing system from above and plugged with cork stoppers from below to reduce the potential for dripping. These holes were approximately 0.6 m (24 in.) on center and were located only in the wet area of the southernmost half of the roof. The northernmost half of the roof system was not drilled. According to our laboratory analyses, the density of the penetrations we used should yield a water vapor permeance of 8.0 metric perms (0.14 perms). We had intended to drill holes at a much higher density but, when the leaking described below started, we became preoccupied with protecting the building interior and did not drill holes to our planned density.

We encountered some leaking into the building immediately after the drilling and the leakage was exacerbated by foot traffic. The effect seemed like wringing out a wet sponge; walking on the roof near a hole compressed the saturated fiberglass insulation and caused appreciable amounts of water to enter the building. We had hoped that the corks in the drilled holes would prevent leakage. They were reasonably successful except we had difficulty sealing the holes that penetrated the metal deck near the ribs. The oblong holes created when the drill hit the ribs would not seal properly with the size of cork stopper we had available.

We installed polyethylene tarpaulins in the plenum space below the drilled area to catch any water leaking into the building. Once the new roof was installed the quantity of water dripping into the building diminished appreciably; after approximately 3 weeks, the dripping stopped entirely. Approximately 110 liters (30 gallons) of water were collected from the tarpaulins. We now believe that some water dripping was inevitable with the amount of water in the old roof. Hedlin (1982) reported that high density fibrous insulation at a 2° (¼:12) slope will drain until it reaches 40% by volume moisture content. Several of the areas that we drilled exceeded this moisture content.

The application of the re-cover roof was initiated on 22 September 1993. Approximately 46 mm (1.8 in.) of HCFC-141b blown polyurethane foam was spray-applied to the roof using a combination of "robot" and manual application[1]. The foam application required two days to complete. Over the next five days, the foam was coated with a base coat, top coat and experimental (white) granules. The roof installation was completed on 28 September. Portions of the foam remained exposed for up to 36 hours prior to receiving any coating.

Specimens of the polyurethane foam were taken to be thin-sliced for accelerated aging experiments. Specimens of the granules applied to the top coat were prepared for solar reflectance measurements. After the roof was re-covered, we marked it with a grid of lines 1.5 m (5 ft) on center and repeated the neutron gauge survey to document changes in the gauge readings for the same moisture content but after the addition of the re-cover roof system. We attempted to measure the moisture content at the same locations that we had surveyed before the reroofing. We correlated these new results to ones from

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[1] The Dow Corning 3-5000 Polyurethane/Silicone Roof System was used along with experimental granules supplied by 3M Corporation.

additional core samples that were gathered and analyzed following the procedures used before the reroofing.

IS THE ROOF DRYING?

We revisited the roof in February 1994, July 1994 and February 1995 (4, 9 and 16 months after the reroofing) and, using the grid marked on the roof as a guide, repeated the neutron gauge moisture survey. We divided the roof system into two zones. The first zone included all of the roof area through which we had not made any penetrations into the vapor retarder (232 neutron gauge measurements) while the second zone included the area where holes had been drilled through the vapor retarder and the deck (65 neutron gauge measurements). We compared the data collected during each survey with the data from the survey immediately after the roof was re-covered. The averages for each zone were used for these comparisons. We noted that, for any individual site, the neutron gauge often suggested that the local moisture content had fluctuated up and down with time. However, when we averaged data for a large number of sites, the fluctuations were eliminated.

In the area where we had not drilled any holes through the vapor retarder, we noted no change in the total moisture content of the roof. Despite the fact that the insulation is saturated in portions of this zone, the intact bituminous vapor retarder essentially prevents moisture vapor from diffusing and water from dripping into the building interior. In the zone where we penetrated the vapor retarder, we measured average reductions in the original moisture content of 6, 17 and 22% by weight for the 4, 9 and 16 month surveys, respectively.

We used a combined heat and mass transfer model (Pedersen [now Rode] 1990) to predict the drying rate of the recovered roof system. Pedersen [now Rode] (1990), Pedersen [now Rode] (1991), Desjarlais (1993a), Desjarlais (1993b) and Kyle (1994) have described, validated and used this model on low-slope roof systems. A comparison of actual drying data and predictions by the model is presented in Figure 5.

The model does not predict any significant seasonal variations in the drying rate of the roofing system. This result is consistent with our expectations because the wetted insulation layer is protected from seasonal temperature fluctuations by the re-cover insulation. We do note that both sets of data measured in the winter/spring season show rates lower than the model predicts while the single set of data gathered in the summer shows drying at a rate higher than predictions. This could be a systematic effect; additional data should settle the issue. Assuming that the measurements scatter randomly above and below the predictions, we find the agreement between measurements and predictions to be exceptional.

THERMAL PERFORMANCE OF THE RE-COVERED ROOF

Using the HFTs and temperature sensors that we mounted in the roof system prior to re-cover, we are able to measure the thermal performance of the roof system *in-situ* and compare it with results of procedures that accelerate the aging of closed cell plastic foams. The techniques that we applied to process the in-situ data and accelerate aging in the laboratory have been reported by Christian (1993). The three HFTs are identified as East, Southwest, and Northwest. Two of these sites, East and Northwest, are located over saturated fiberglass insulation; the Southwest site is located near the parapet wall where the original roof system was dry.

A summary of the in-situ thermal resistance of the entire roofing system before and after re-cover is presented in Figure 6. These data include the thermal resistance of the old roofing system. Prior to re-cover, the sites with wetted insulation show R-values less than 0.2 $m^2 \cdot K/W$ (1.0 $h \cdot ft^2 \cdot {}^\circ F/Btu$) while the dry sites average approximately 0.5 $m^2 \cdot K/W$ (3 $h \cdot ft^2 \cdot {}^\circ F/Btu$). The results from the wetted areas are consistent with our laboratory measurements. However, the *in-situ* dry R-value is appreciably (about 70%) higher than our laboratory result. Since the dry site is near a parapet wall, we suspect that the insulation has not been compressed to the extent of the laboratory specimen and that there is a considerable amount of additional built-up roofing material due to the tie-in with the flashing.

After reroofing, the R-values of the East, Southwest, and Northwest sites increased to 2.8, 2.8 and 1.7 $m^2 \cdot K/W$ (16.0, 16.0 and 9.7 $h \cdot ft^2 \cdot {}^\circ F/Btu$), respectively. The variation in R-value is primarily due to differences in re-cover insulation thickness. We pin-probed the area around each HFT and measured foam thicknesses of 59, 54 and 40 mm (2.3, 2.1 and 1.6 in.), respectively. The slight difference in thickness between the East and Southwest sites is offset by effects of wetness, yielding the same system R-values. The Northwest site is both thin and wet, yielding the lowest system R-value. We also estimated a re-cover insulation thermal resistivity for these three sites based on thermal properties of the recover layers and their thicknesses. The East, Southwest, and Northwest sites had resistivities of 46, 39 and 41 $m \cdot K/W$ (6.7, 5.6 and 5.9 $h \cdot ft^2 \cdot {}^\circ F/Btu\text{-}in$), respectively. They should be the same. The greatest source of uncertainty is the thickness of the insulation over the HFT, which depends on the thickness of the aggregate-covered substrate and how much spray-applied foam was deposited.

We prepared laboratory test specimens from an extra section of foam that was laid down during the reroofing operation. The specimens were cut to a thickness of approximately 10 mm (0.38 in.). The thinner the specimen, the faster it ages thermally (Christian, 1993). We periodically tested the specimens over a period of 180 days at laboratory conditions and, using the scaling procedure, computed the average monthly thermal resistivity for 25-, 51- and 76-mm (1-, 2- and 3-in.) thick foam applications for a 20-year period. The average foam thermal resistivities for a service life of 1, 5, 10 and 20 years are obtained by simply averaging data for the appropriate number of months. The results are presented in Figure 7.

As Figure 7 shows, after a service life of one year, the average thermal resistivities for the three thicknesses are 39.4, 42.0 and 43.3 $m \cdot K/W$ (5.7, 6.1 and 6.2 $h \cdot ft^2 \cdot {}^\circ F/Btu\text{-}in$), respectively. Thicker sections age more slowly because nitrogen and oxygen must diffuse into and the blowing agent must diffuse out through more foam. After a service life of twenty years, the average thermal resistivities for the three thicknesses are more nearly equal: 36.1, 36.8 and 38.1 $m \cdot K/W$ (5.2, 5.3 and 5.5 $h \cdot ft^2 \cdot {}^\circ F/Btu\text{-}in$), respectively. After only three months, the scaling model predicts that the foam should have a thermal resistivity of 40.5 $m \cdot K/W$ (5.8 $h \cdot ft^2 \cdot {}^\circ F/Btu\text{-}in$). After three months of *in-situ* service, we measured a foam thermal resistivity of 41.6 ± 4.2 $m \cdot K/W$ (6.0 ± 0.6 $h \cdot ft^2 \cdot {}^\circ F/Btu\text{-}in$), in good agreement with our laboratory prediction.

WAS THIS RE-COVER COST-EFFECTIVE?

The re-covering of Building 2518 roof increased the R-value of the roofing system and eliminated the leaking problems that had been experienced for several years. If we had to purchase this re-cover, we estimate that the cost would have been approximately \$29.60/m^2 (\$2.75/ft^2) or \$35,400 for the entire building. Would this have been a good investment?

We used the DOE-2.1E Building Energy Analysis Program (LBL 1981, 1993) to determine the energy savings associated with the reroofing. This is an hourly simulation model that has been used extensively for energy analyses of buildings. A comprehensive review of this modelling effort is described by McLain (1995).

Building simulation models use many parameters. The development of the building parameter input file started with a survey that included occupancy, functional areas, office equipment, lighting, envelope construction, HVAC systems, controls and zoning. A candidate model was run and its output compared to measurements. Input parameters were adjusted and the process repeated until there was good agreement. The primary comparison that we used to "calibrate" the simulation was the whole building electric energy consumption. Figure 8 shows the comparison between the measured and predicted electrical energy consumption for Building 2518 for the months of April through December 1994. During swing seasons, the prediction is within 12% of actual consumption while data in the summer months agree within 4%. The variance between the computer simulation and the measurements is partially accounted for by the fact that the simulation does not include the effects of latent heat transfer. Latent heat transfer would accentuate the swing season peak demand and increase energy consumption during this period. A secondary consistency check that we used was the roof heat flux. Figure 9 depicts a comparison between the measured and predicted heat flux for the Southwest (dry) site in April 1994.

To generate annual energy savings, Typical Meteorological Year (TMY) weather data were used. We assumed that the whole building had been re-covered with foam. This assumption does not have a significant impact on the calculations because the south addition, the roof of which was torn-off prior to this project and replaced, has a system with about the same R-value as the foam system. A solar reflectance of 0.18 was assumed for the original roof membrane; we measured a solar reflectance of 0.28 for the new roof membrane/granules. To convert energy savings into cost savings, we assumed the building was heated by a gas furnace that had an annual fuel use efficiency of 65%, assumed a national average cost for natural gas of \$0.017/kWh and a national average cost for electricity of \$0.075/kWh (EIA, 1994).

For the Knoxville TN climate, the cooling energy savings for the reroofed building are about 5.8 MWh (10.3 MBtu) or 10% of the original cooling energy use. Approximately 50 MWh (89 MBtu) or 53% of heating energy is saved. We also simulated the energy savings for re-cover of the same building using TMY weather data for Bismarck ND, Chicago IL, Miami FL and Seattle WA and converted these energy savings into cost savings. These additional cities represent the climate extremes that exist in the continental US. Cost savings for all five cities are presented in Figure 10. The total savings range from \$1.56/m² (\$0.145/ft²) for Bismarck ND to \$0.68/m² (\$0.064/ft²) for Seattle WA. Heating and cooling savings are realized in all climates except for Seattle WA where there is a cooling penalty of \$0.08/m² (\$0.008/ft²) associated with reroofing of the building. Since this office building has a large internal load, the higher R-value of the roof traps relatively more energy generated internally so it must be removed by the cooling system. In swing season climates like Seattle, this increased cooling requirement offsets the benefits of a more thermally resistive roof when cooling requirements increase during the summer months.

To determine if reroofing Building 2518 would have been cost effective at an installation cost of \$29.60/m² (\$2.75/ft²) or \$35,400 for the entire building, we used the life-cycle costing analysis method employed by the U.S. Federal Energy Management Program and the U.S. Department of Defense (NBS

1980). This analysis computes a Savings to Investment Ratio (SIR). This figure of merit is a ratio of the present value of lifetime savings to the initial cost. It is not a simple function but, if the SIR is less than 1, the total return on the investment for reroofing is less than the assumed discount rate. If the SIR is equal to 1, the return equals the discount rate. The desired situation is SIRs greater than 1 to yield returns greater than the discount rate. As a general rule of thumb, SIRs in excess of 2 are considered good investments.

We assumed that the reroofing would have a service life of 25 years, would require recoating every 10 years at a cost of \$11/m² (\$1/ft²) and used a discount rate of 3% for our calculations (Petersen 1994). Based on these assumptions, SIRs of 2, 3 and 4 would yield returns of 5.8, 7.4 and 8.7% or 2.8, 4.4 and 5.7%, respectively, above the discount rate. The SIR was computed as a function of the five climates to account for the different energy savings that climate induced. Net annual maintenance cost savings were varied from \$1.10 to \$5.40/m² (\$0.10 to \$0.50/ft²). Net maintenance cost savings were defined as the difference between the yearly maintenance and repair cost before reroofing and the same costs after reroofing.

The results of the SIR computations are shown in Figure 11. Maintenance costs are the critical issue. Net annual maintenance cost savings of approximately \$3.20/m² (\$0.30/ft²) yield SIRs of approximately 2. If the difference between annual maintenance and repair costs before and after reroofing exceeds this level, the reroofing activity would be financially justified. In the actual building that we reroofed, comparing costs of leaks with the costs to recoat the new roof establishes a net annual maintenance cost savings in excess of \$5.40/m² (\$0.50/ft²). The resulting SIR of 3.3 implies that reroofing Building 2518 would be a very good investment if recoating is the only maintenance required.

We conducted a careful inspection of the roof in March 1995 (16 months after installation) and found no visible defects with the re-cover roof system. We queried the facility manager regarding experience with the roof and confirmed that there have been no occupant complaints since the reroofing. Maintenance seems to have been reduced to the scheduled recoating every 10 years.

CONCLUSIONS

We re-covered the roof of an office building on the campus of Oak Ridge National Laboratory to determine if there was a cost-effective means of reroofing roof systems at ORNL that contained wetted insulation and vapor retarders. We proceeded cautiously, performing extensive field surveys, removing a section of the roof system for laboratory testing, and performing computational simulations to investigate the drying of the roof and the cost-effectiveness of our method. Along the way, we made the following discoveries.

We found qualitative agreement between the moisture survey results generated by infrared thermography and the neutron gauge. Both instruments produced a map that identified the major wetted areas of the roof. Averaging several neutron gauge readings to determine the change in the roof moisture content for a zone and calibrating the neutron gauge data with results of core sampling appears to be reasonably accurate.

To allow us to determine the change in the permeance of the metal deck/vapor retarder as a function of the amount of penetrations, we devised a laboratory procedure using load cells to measure the weight change of the roof section while subjecting it to a temperature (and therefore pressure) gradient. The results were reasonable. This procedure is available to the roofing industry at the ORNL Buildings Technology Center, a national user facility, to determine the permeance of installed decks if a section of the real roof system can be removed or a laboratory test section built to test the real deck in our Large Scale Climate Simulator.

Drilling holes through the roofing system to increase its permeance above zero went reasonably well. If we had been better prepared to deal with the initial water leaks into the building, our plans to have a much higher permeance than we achieved would likely have been realized. With our procedure of increasing permeance by drilling holes, leakage should be expected if the moisture content of the roof system is high (see Hedlin 1982) or if the insulation system is compressible. More accurate placement of the drilled holes to avoid the deck ribs would have reduced leakage and increased the effectiveness of the cork stoppers that we used to try to control the leakage.

This reroofing activity offered a unique modelling opportunity. The heat and mass simulation that we used requires accurate information on the permeance of the deck. In this particular reroofing, we knew what the permeance was because we controlled its value by the density of holes that we drilled into the roof. In most buildings, the permeance of the deck is unknown. This opportunity allowed us to check the agreement between our drying rate simulations and our field data. The agreement to date is exceptional.

We installed temperature sensors and HFTs into the roof prior to re-covering. We utilized this instrumentation to measure the R-values of the wetted roof system, the re-covered roof system, and each component. After three months of *in-situ* testing, the thermal resistivity of the spray applied foam installed on the roof agreed well with the results from the accelerated aging test ongoing concurrently in the laboratory. We used accelerated aging data to compute average or integrated R-values for the insulation material as a function of service life. After twenty years, we predict that the integrated thermal resistivity of the 46-mm (1.8-in.) thick layer of foam applied to the demonstration building will be approximately 36.8 m·K/W (5.3 h·ft^2·°F/Btu-in).

Using a whole building energy analysis program, we computed the energy savings associated with the reroofing. For the actual building that we reroofed, we estimate that there will be a 10 and 50% reduction, respectively, in cooling and heating energy requirements. We converted these savings into cost savings and simulated the building in a series of climates that cover the range of meteorological conditions in the continental U.S. From these simulations, we determined that the cost savings would range from \$1.56/m^2 (\$0.145/ft^2) for Bismarck ND to \$0.68/m^2 (\$0.064/ft^2) for Seattle WA.

We used a life-cycle cost analysis to ascertain if our reroofing activity would be cost-effective at the current cost to install re-cover roofing of the type we used. We discovered that, if the net savings in yearly maintenance and repair costs were greater than about \$3.20/m^2 (\$0.30/ft^2), our reroofing project would be a good investment. Our estimate, based on experience with the roof, including 16 months since the reroofing, is that annual savings for maintenance and repair are more than \$5.40/m^2 (\$0.50/ft^2): the reroofing project would be a very good investment.

We will continue to monitor the drying of the roof system; at some point in the near future, we plan to perforate the metal deck/vapor retarder in the northern half of the building to allow that portion of the roof system to dry.

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FIGURE CAPTIONS

1) Building 2518 at ORNL prior to re-cover.

2) Summary of moisture surveys prior to roof re-cover. Infrared thermography was used to qualitatively assess extent of moisture contamination. We followed up with a neutron gauge survey and quantified these results with sample coring. The instruments we used to perform the surveys are shown below the moisture maps.

3) We correlated the results of the neutron gauge survey with core sampling. These results are linearly regressed and the regression is used to quantify the total roof moisture content.

4) Photograph of the roof section removed from Building 2518.

5) A comparison of the measured drying rate of the re-covered roof and the modelling prediction for the portion of the roof that has a perforated vapor retarder and metal deck.

6) The in-situ thermal resistance of three sites on the roof system before and after re-cover. The east and southwest sites are located where the original insulation is saturated. After reroofing, the R-Values increase appreciably. R-Value data from the northwest site is lower because the thickness of the re-cover insulation is less than the other two sites.

7) Using an accelerated aging laboratory technique, we estimated the integrated R-Value for service lives ranging from 1 to 20 years. The data to perform these calculations required 6 months of actual laboratory aging.

8) Our principal means of calibrating the whole building energy simulation model. Predictions are within 12% and 4% of the measured data during swing and summer seasons, respectively.

9) We used the heat flux data from the HFTs embedded in the roof to calibrate the whole building energy simulation model. A comparison of the measured and predicted heat flux from the southwest HFT for a week in April is presented.

10) Using the whole building simulation model, we predicted the energy (heating and cooling) savings due to reroofing this building. We also predicted the impact on the energy savings if the building had been located in four other climates.

11) A method for determining the cost-effectiveness of the reroofing project is to calculate the Savings-to-Investment Ratio (SIR). This analysis includes energy savings as well as reduced maintenance requirements. We determine the SIR as a function of net roof maintenance cost (pre-reroof cost - post-reroof cost). As examples, net roof maintenance costs ranging from \$0.10 to \$0.50/ft^2 are depicted. An SIR equal to 1 means that the savings obtained from the reroofing is equal to the return that would have been obtained if the money had been deposited in a bank.

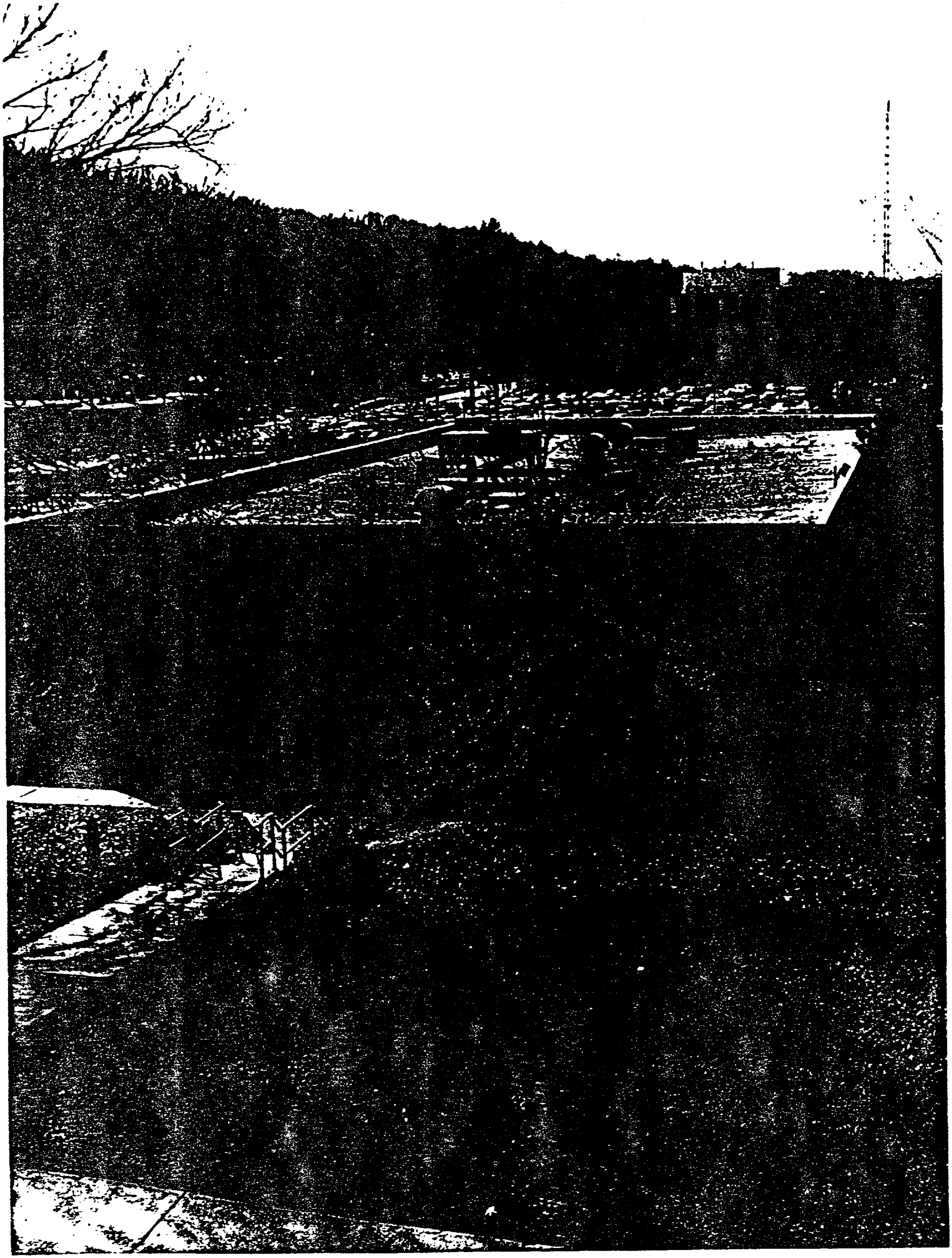


FIGURE 1

Moisture Surveys Indicate Extent of Water Contamination

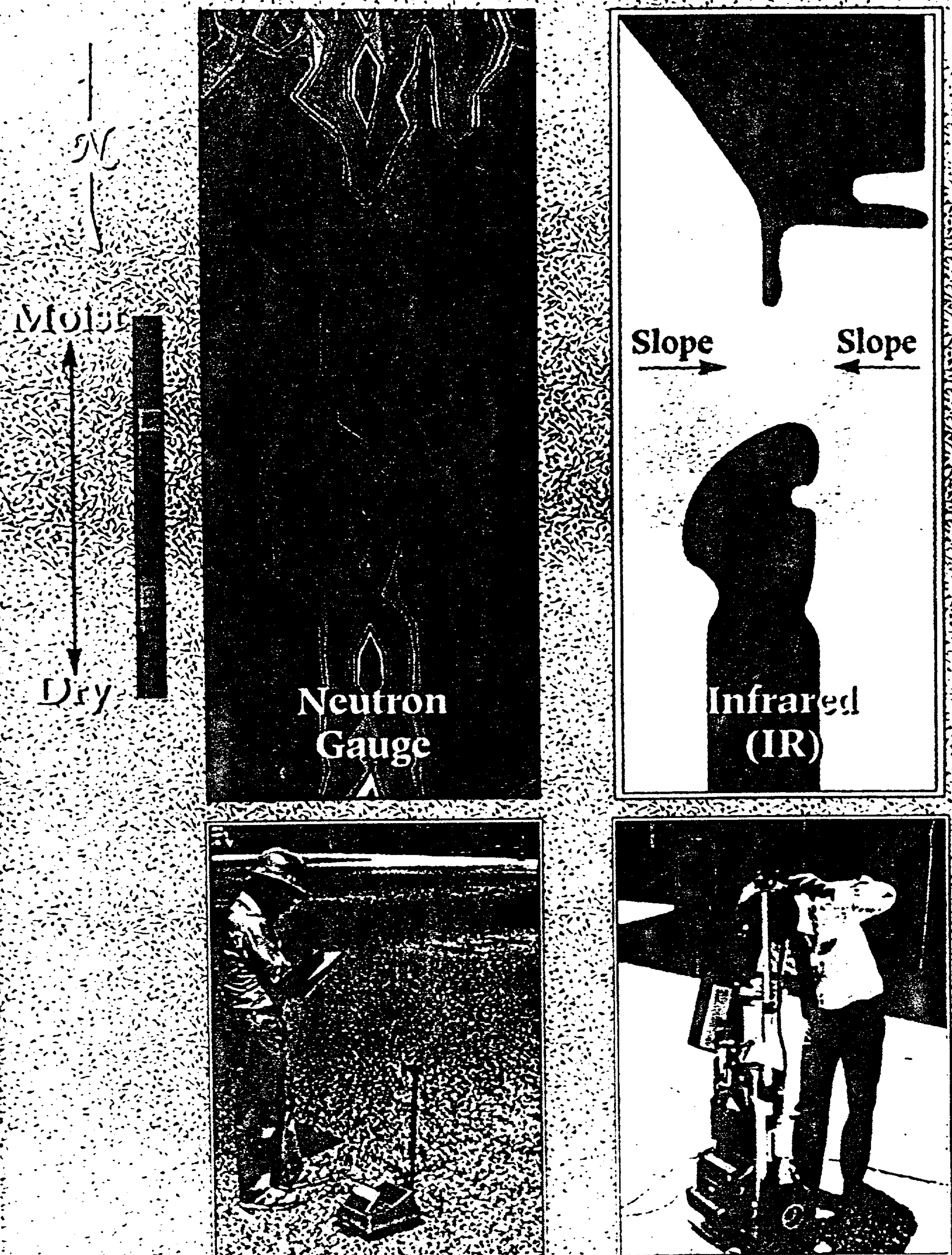
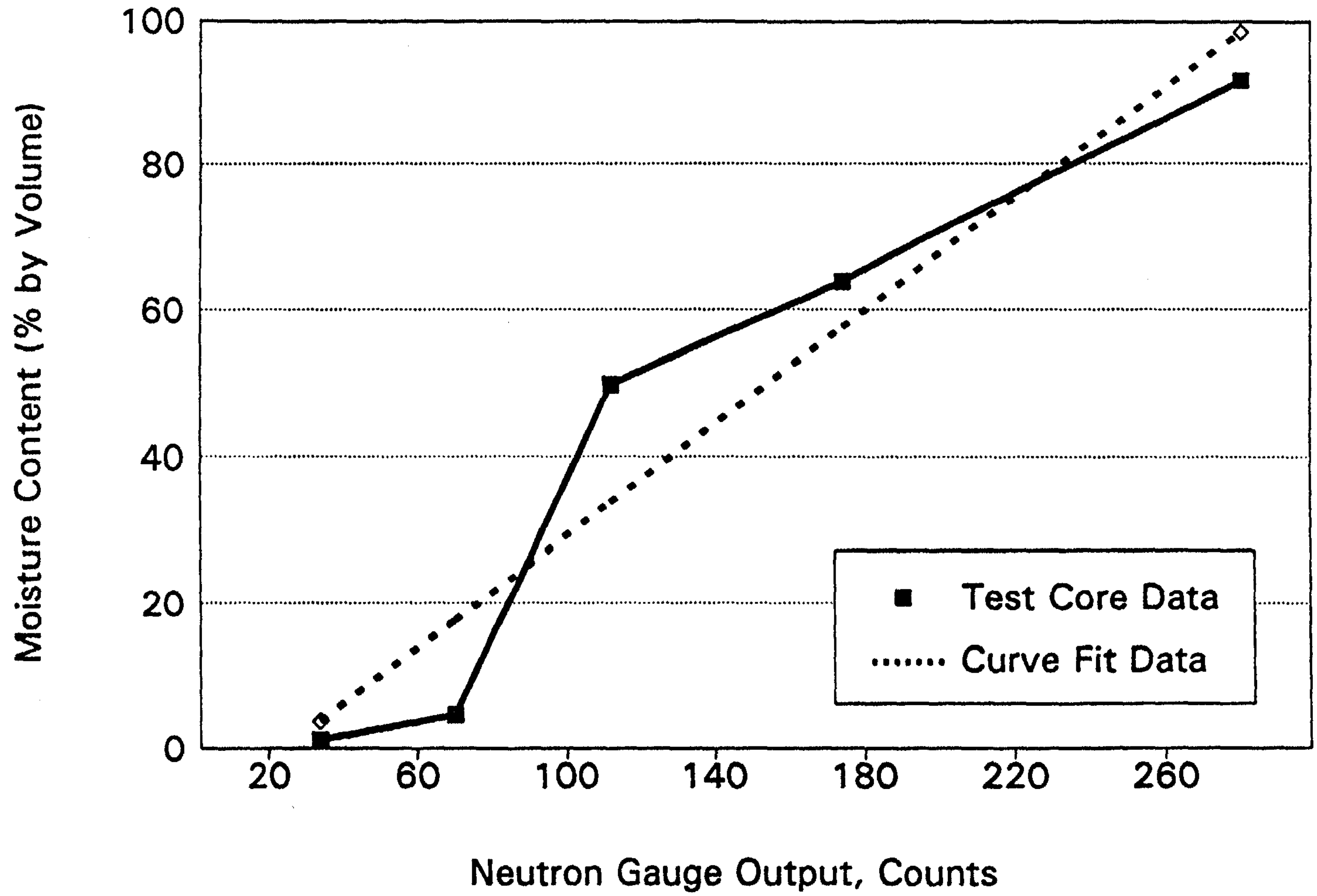


FIGURE 2



Moisture Content (% by Volume)
100
80
60
40
20
0
20
60
100
140
180
220
260
Neutron Gauge Output, Counts
Test Core Data
Curve Fit Data

FIGURE 3

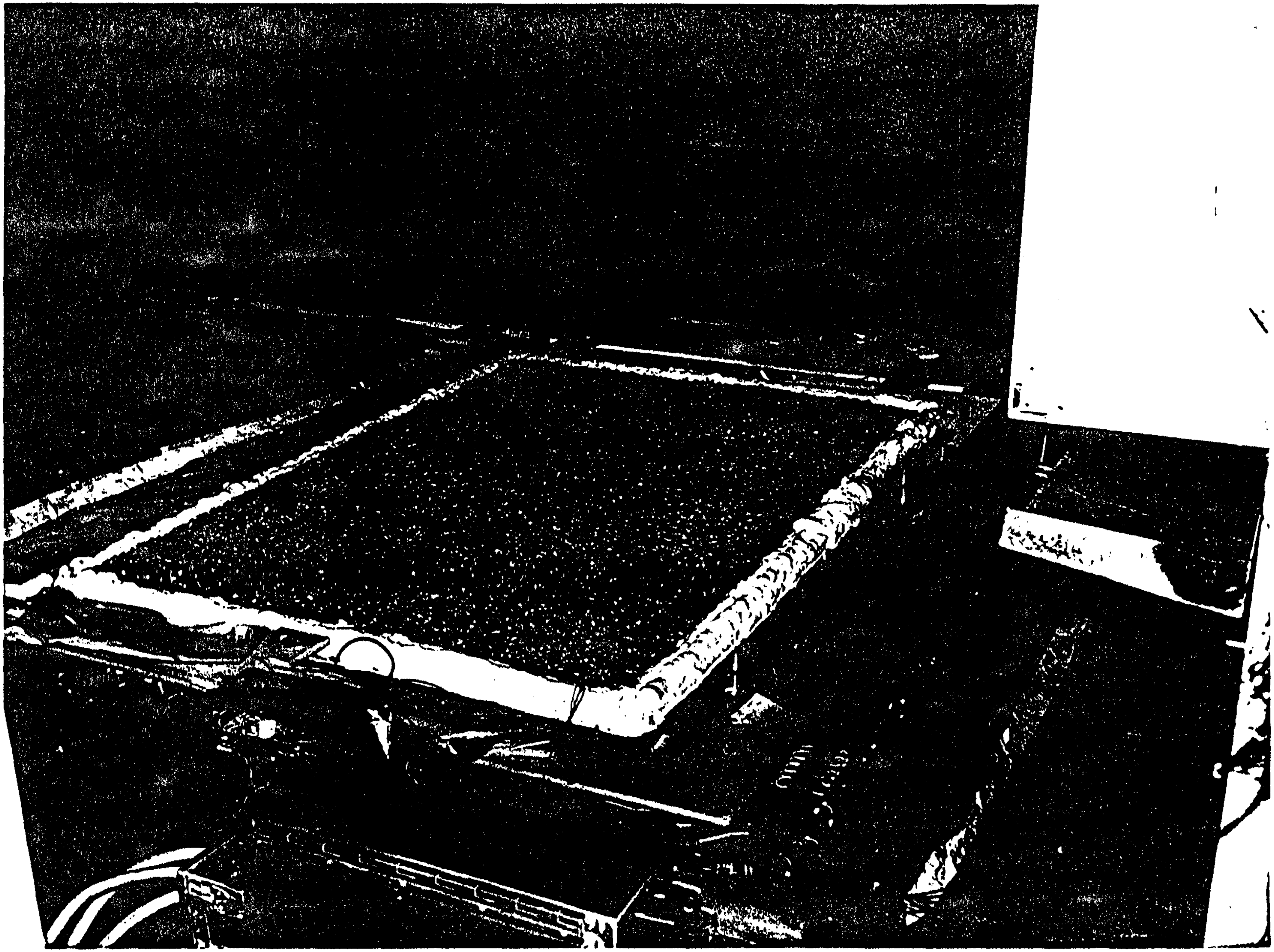
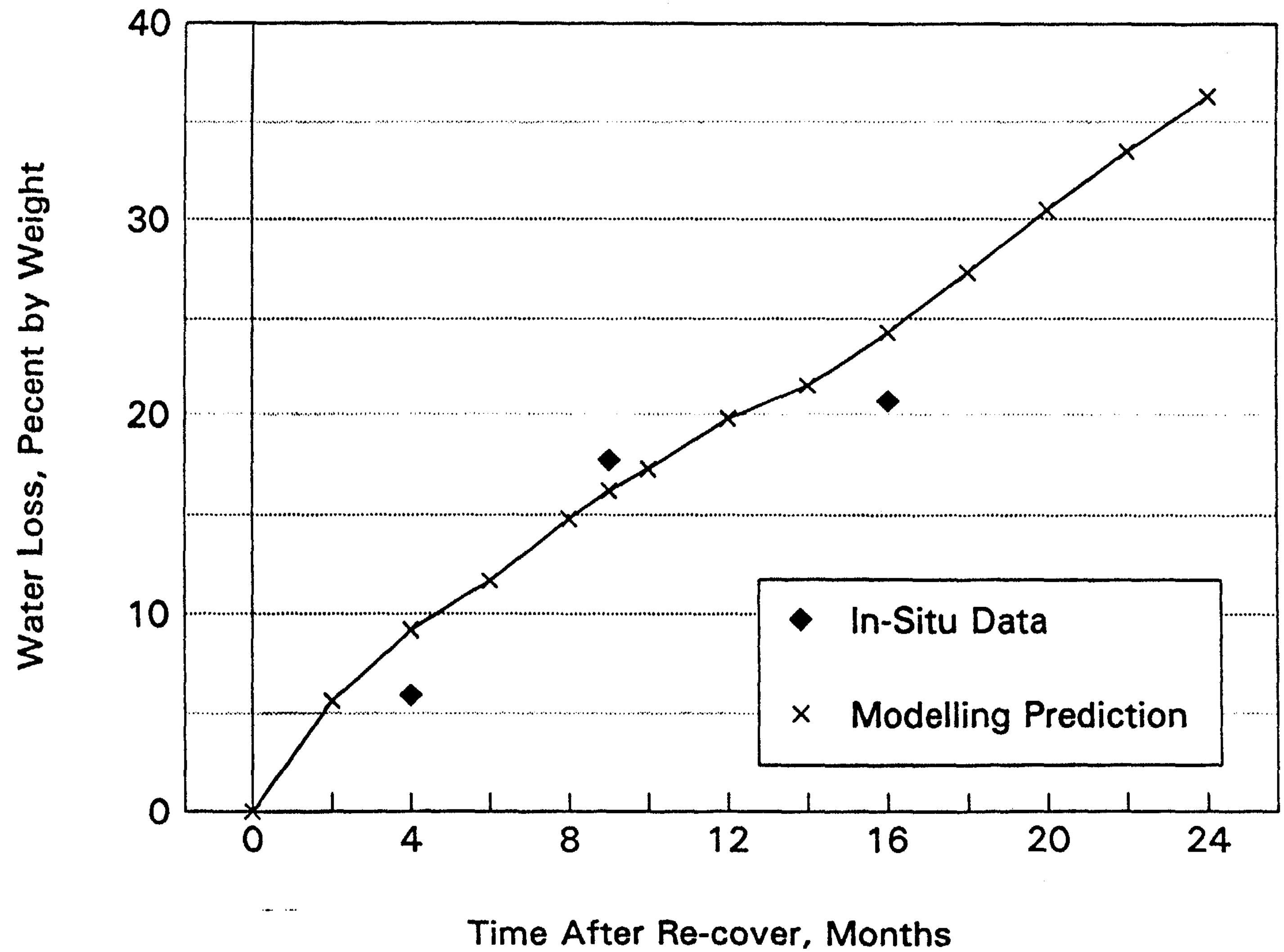
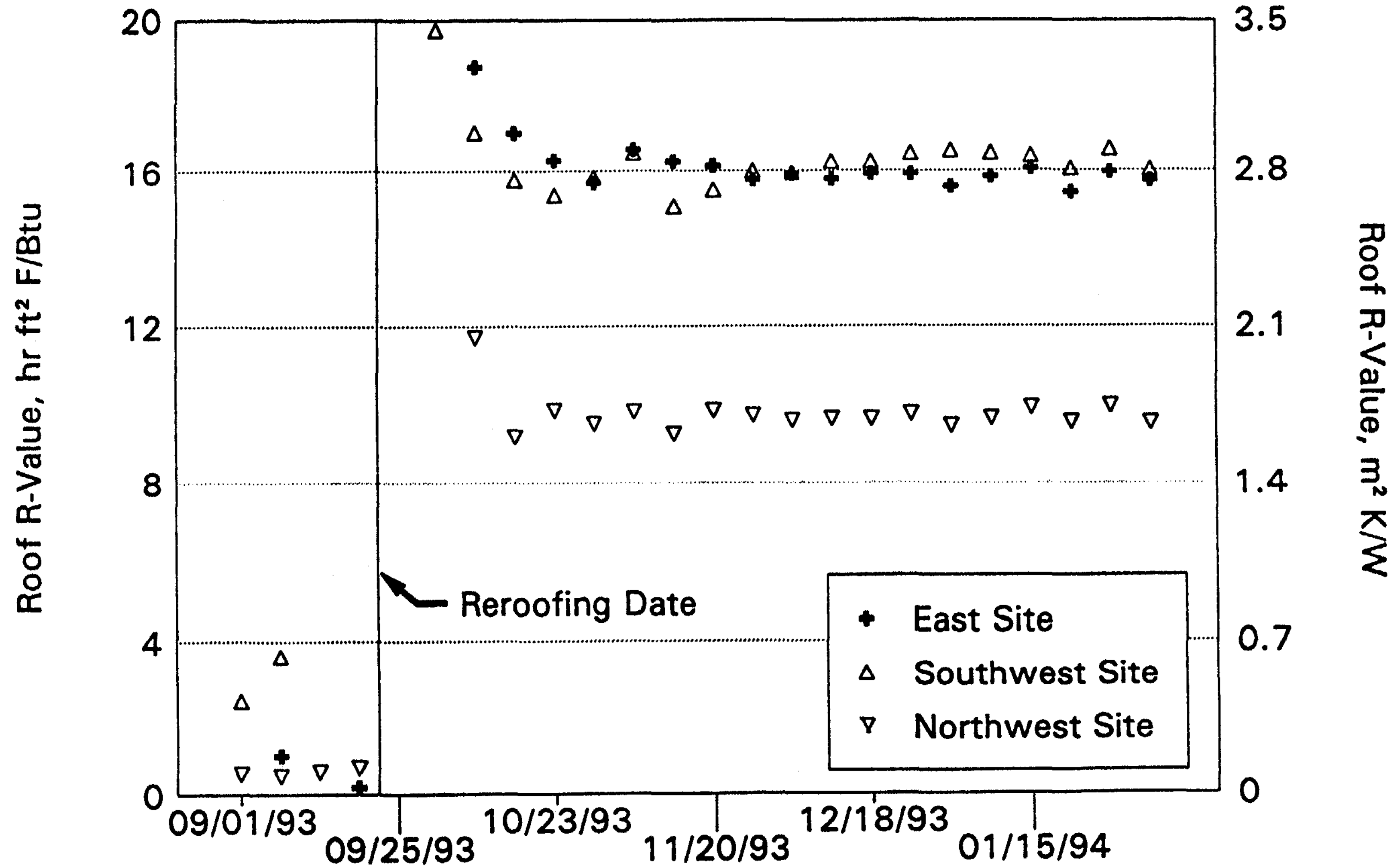


FIGURE 4



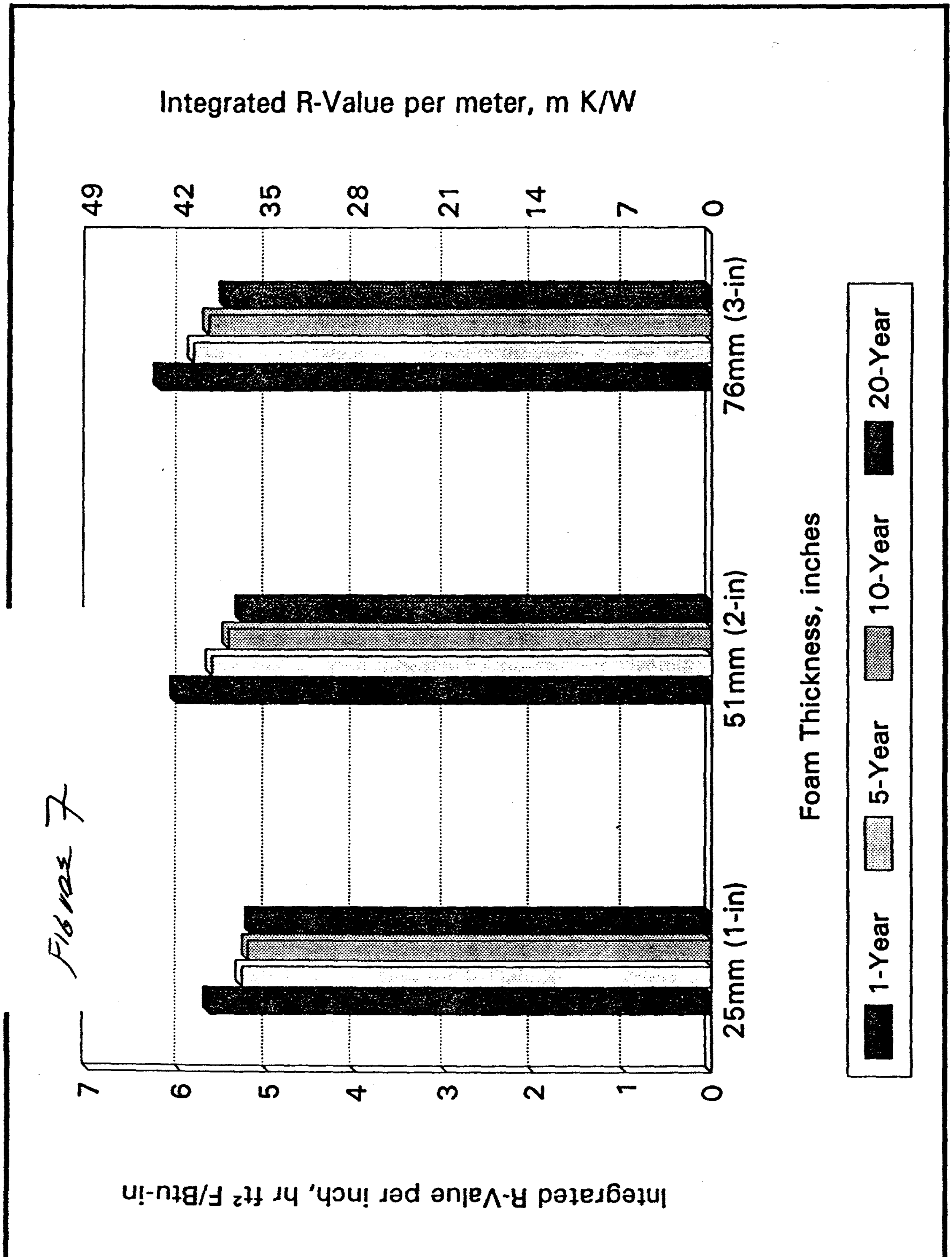
40
30
20
10
0
Water Loss, Pecent by Weight
0
4
8
12
16
20
24
Time After Re-cover, Months
In-Situ Data
Modelling Prediction

FIGURE 5



Roof R-Value, hr ft² F/Btu
20
16
12
8
4
0
Roof R-Value, m² K/W
3.5
2.8
2.1
1.4
0.7
0
09/01/93
09/25/93
10/23/93
11/20/93
12/18/93
01/15/94
Reroofing Date
East Site
Southwest Site
Northwest Site

FIGURE 6



Integrated R-Value per meter, m K/W
0
7
14
21
28
35
42
49
25mm (1-in)
51mm (2-in)
76mm (3-in)
Foam Thickness, inches
0
1
2
3
4
5
6
7
Integrated R-Value per inch, hr ft² F/Btu-in
1-Year
5-Year
10-Year
20-Year

FIGURE 7

FIGURE 8

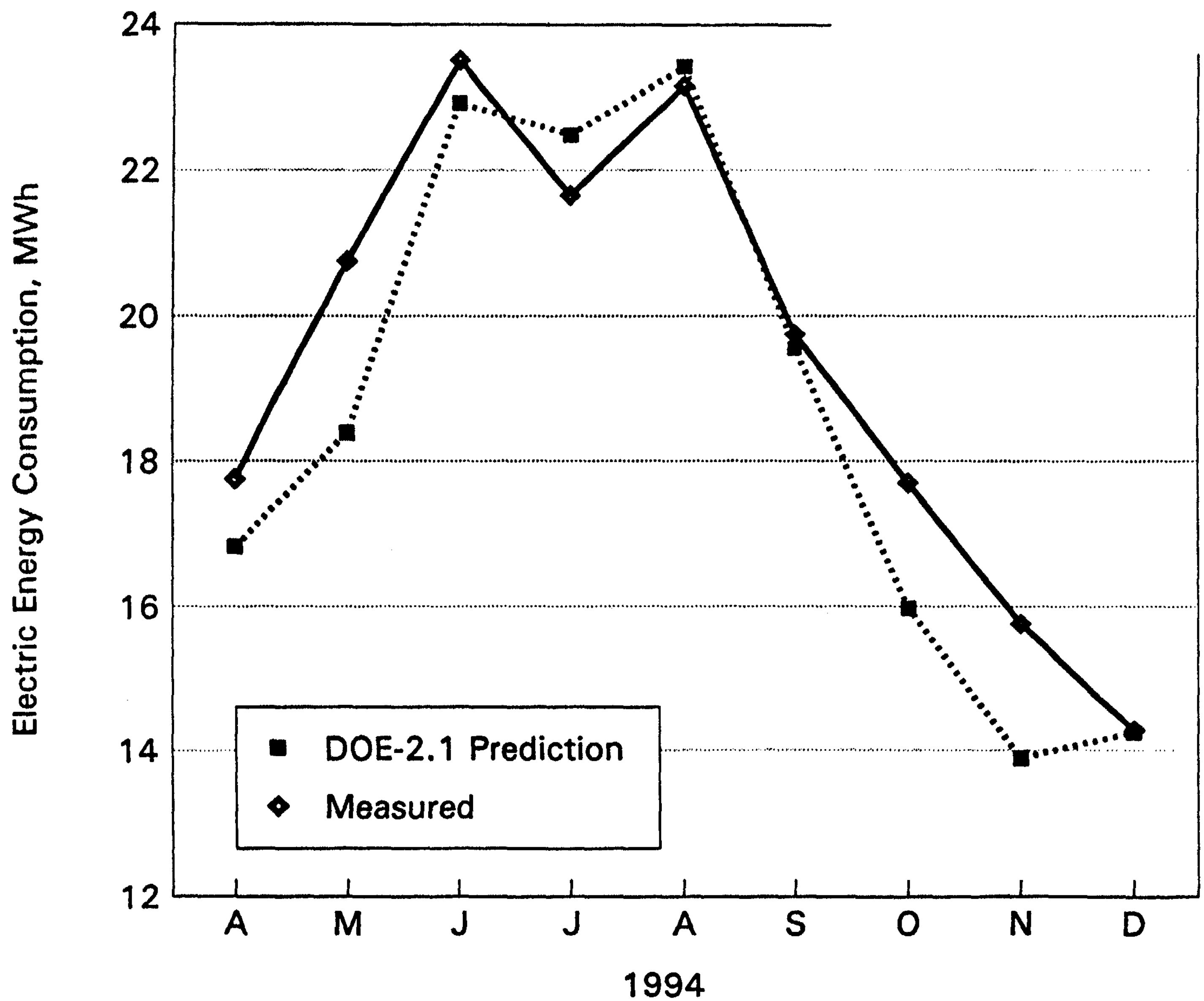
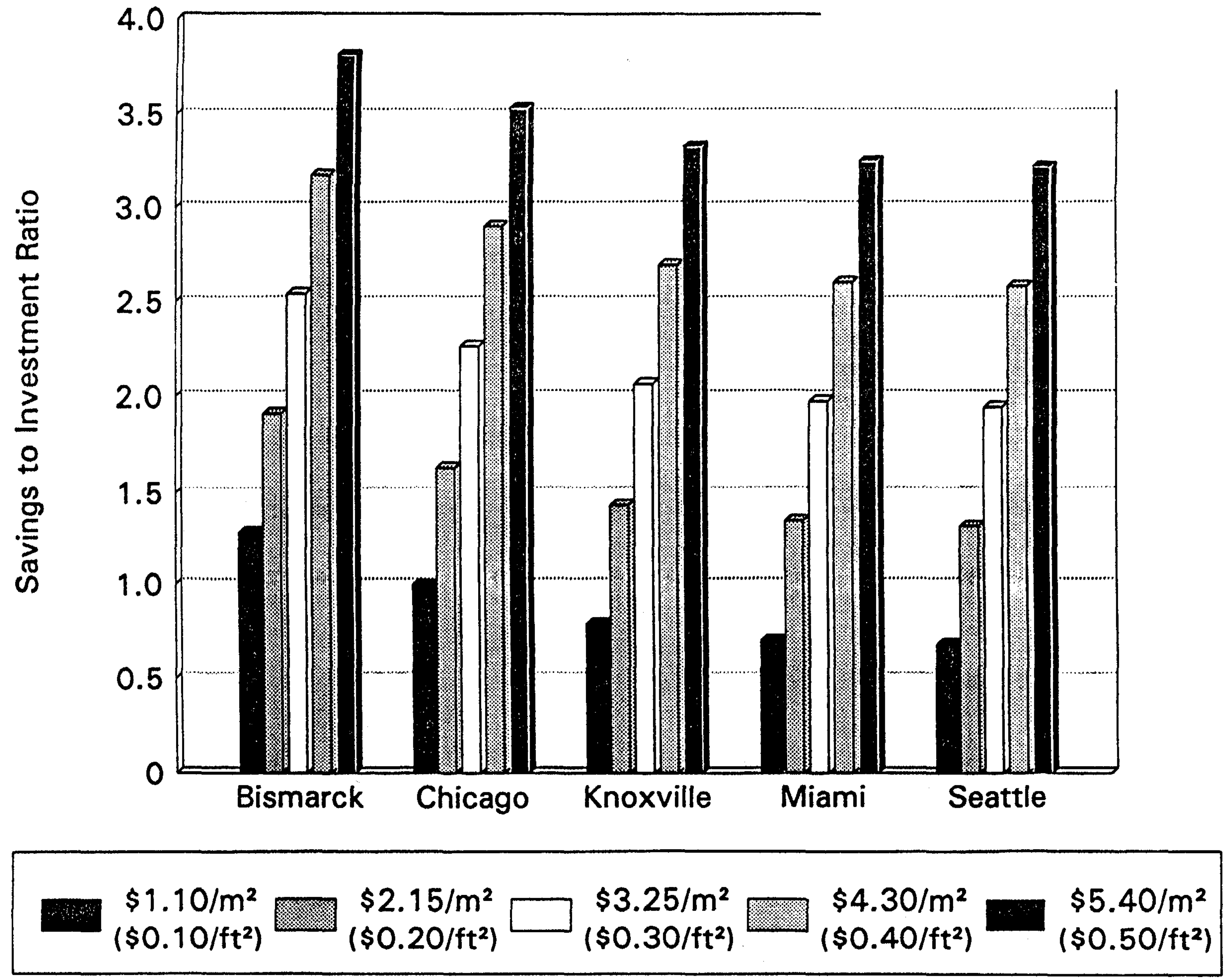

Electric Energy Consumption, MWh
24
22
20
18
16
14
12
A
M
J
J
A
S
O
N
D
1994
DOE-2.1 Prediction
Measured

FIGURE 11


Savings to Investment Ratio
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
Bismarck
Chicago
Knoxville
Miami
Seattle
$1.10/m² ($0.10/ft²)
$2.15/m² ($0.20/ft²)
$3.25/m² ($0.30/ft²)
$4.30/m² ($0.40/ft²)
$5.40/m² ($0.50/ft²)