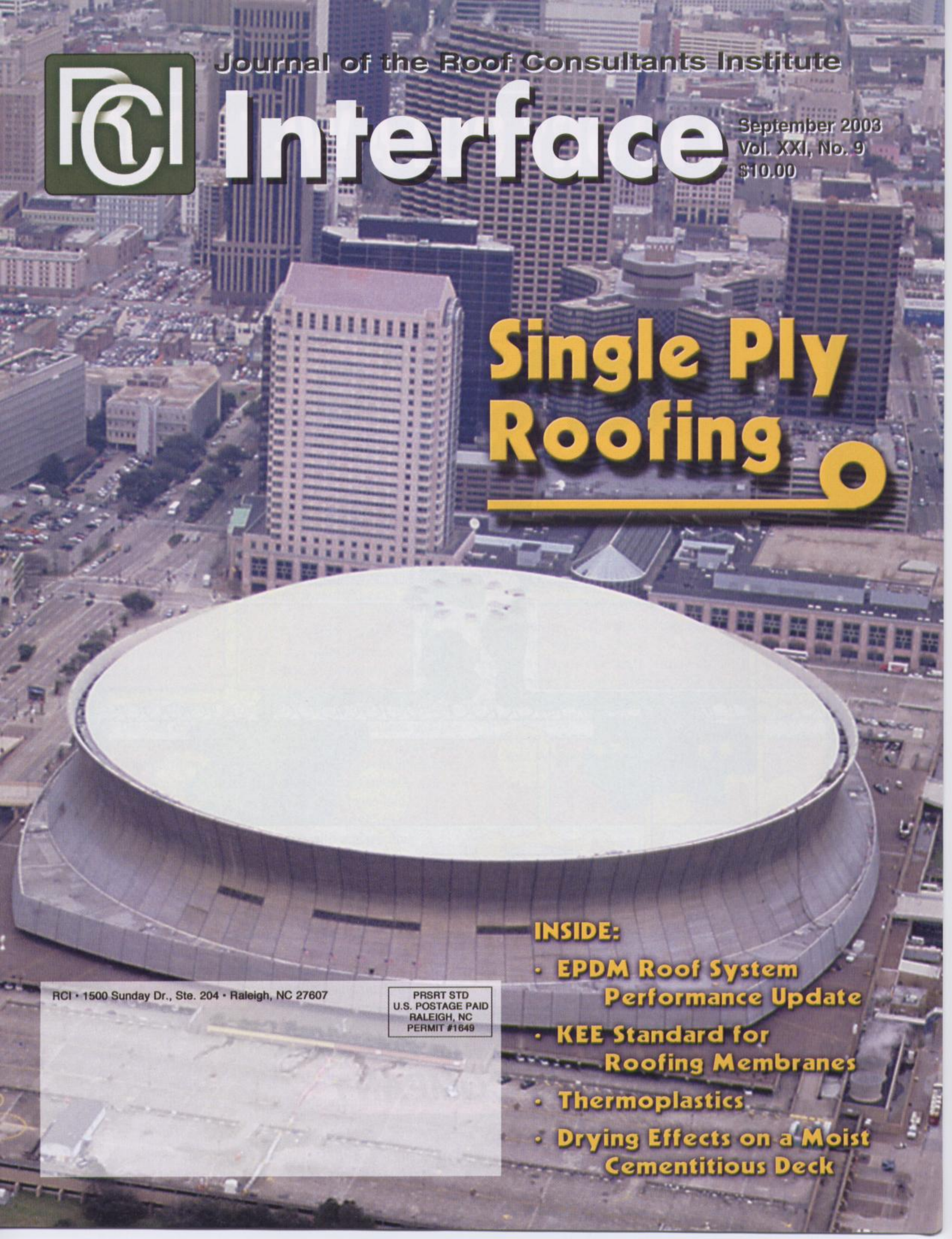

Journal of the Roof Consultants Institute
RCI Interface
September 2003
Vol. XXI, No. 9
$10.00

Single Ply Roofing

INSIDE:

- EPDM Roof System Performance Update
- KEE Standard for Roofing Membranes
- Thermoplastics
- Drying Effects on a Moist Cementitious Deck

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A FOLLOW-UP STUDY

Further Evaluation of a Pressure-Equalized Single-Ply Roofing System to Determine Drying Effects on a Moist Cementitious Roof Deck

By Warren R. French, PE, RRC, CCS, FRCI

ABSTRACT

At the 1999 RCI International Convention in Charlotte, North Carolina, a paper was presented on the study of a high-rise building that was re-roofed over an existing, wet, lightweight insulating concrete deck. The paper was subsequently published in the August 1999 issue of *Interface* journal. The subject of that study was the 15,760 s.f. penthouse roof of a 43-story office building located in downtown Houston, Texas, originally constructed in 1961. The height of this roof is 602 feet above surrounding grade, and the roof level terminates in a metal-edge perimeter. The building is periodically subjected to hurricane-force winds. The system selected for the roof replacement was a pressure-equalized (P.E.) ethylene propylene diene monomer (EPDM) membrane installed in a loose-laid configuration with appropriate pressure-equalization vents in accordance with the manufacturer's requirements.

The majority of the penthouse roof has been loose-laid over a 1-1/2" layer of isocyanurate insulation and a 5/8" layer of siliconized gypsum roof sheathing with a glass fiber facer, installed over the damp, lightweight fill, which ranges in depth from approximately 8" at roof perimeters to 4" at interior drains. As is recommended by the roof manufacturer, the perimeter four feet of insulation and roof deck sheathing were mechanically fastened through the lightweight fill and into the structural concrete deck.

Our previous study related the results of the initial (1997) non-destructive roof moisture survey using nuclear methods with a follow-up study conducted in November of 1998, approximately thirteen months after completion of the P.E. membrane system. During the original moisture survey, moisture content varied considerably over the roof surface, but generally ranged between 8% and 43% of dry weight for the lightweight insulating fill. In addition, approximately 86% of the total area exhibited moisture content that was less than 25% by dry weight, which we consider to be a threshold value.

The 1998 moisture survey exhibited moisture content ranging between 4.7% and 33% of dry weight, with approximately 96% of the total area exhibiting moisture content that was less than 25% by dry weight. The most surprising result of a comparison between the two surveys was *not* that approximately half the data points on the 5' by 5' grid had decreased in moisture content, but that about half of the data points had *increased* in moisture content for no apparent reason. Even so, a large majority of the roof locations (about two-thirds of the total area) occurred in the 12% to 25% moisture content range. This represented an increase in the data points occurring in this range of about 65% over the previous study. Although the results of the previous study were considered to be "inconclusive" with respect to drying effects of the P.E. roof system, there was no doubt that the overall trend of

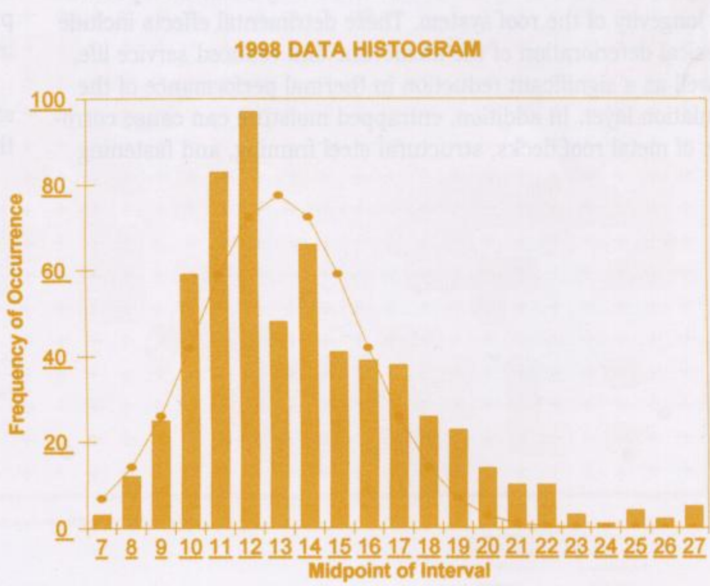

Figure 1

MOISTURE CONTENT EXTRAPOLATION - 1998

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
7	16	12	20	23	23	20	23	20	16	16	19	18	18	12
18	12	19	16	16	23	12	14	11	9	12	12	11	18	16
21	21	19	18	11	21	16	16	9	9	9	5	11	7	14
26	28	14	26	19	24	14	12	11	12	9	12	11	11	19
24	30	24	21	21	23	12	12	9	9	11	11	11	9	12
30	28	21	16	20	24	12	11	5	9	11	5	5	5	12
29	23	20	14	16	19	12	11	5	5	9	9	9	12	18
24	20	19	7	12	11	11	12	7	9	9	7	9	19	18
20	16	14	12	11	16	11	12	7	7	7	11	12	14	18
20	16	20	9	11	14	11	9	9	11	12	14	16	12	20
16	7	16	12	11	7	11	7	5	5	9	11	9	9	20
19	9	11	11	21	7	11	11	14	11	14	12	11	7	18
12	7	11	12	7	5	16	16	18	12	14	18	14	11	12
18	16	14	7	5	12	12	20	20	11	9	11	7	11	21
18	12	19	19	12	16	20	24	21	16	5	12	12	11	24
20	16	12	20	20	5	12	21	9	9	9	9	9	12	19
23	16	19	16	18	12	9	9	9	11	5	11	11	19	24
20	16	16	19	14	19	14	16	7	9	11	14	12	14	24
23	12	16	16	16	18	11	12	11	7	9	12	12	12	18
30	14	16	11	12	12	11	16	11	12	12	14	18	12	23
20	12	16	14	12	9	12	14	16	12	16	19	12	12	25
19	11	11	11	11	11	11	11	9	12	14	20	12	11	21
19	7	9	9	9	12	11	12	9	12	11	16	16	12	21
19	11	9	9	12	9	12	12	14	12	12	14	14	18	23
19	11	12	11	12	11	12	16	11	16	14	16	16	18	21
19	12	12	14	16	12	11	14	7	12	12	16	16	16	23
19	11	7	11	12	11	9	11	11	9	16	12	18	19	23
21	9	9	7	11	5	9	12	16	11	14	11	12	19	20
16	9	9	11	9	11	11	11	9	9	14	7	11	12	21
19	14	9	16	11	11	16	16	11	18	14	14	11	19	21
20	9	20	24	14	14	18	20	16	18	18	11	12	14	23
19	14	18	25	25	18	16	16	16	14	16	9	11	16	20
18	9	14		14	20	23	12	14	14	18	18	16	12	18
18	11	21		33	33	23	19	16	9	12	20	18	16	21
19	12	33	31	31		25	23	14	14	19	19	11	19	23
12	7	28	33	30		25	21	12	12	19	16	16	9	20
18	12	21	26	26		25	21	16	16	18	18	19	12	20
19	12	12	20	33		26	21	18	20	23	26	20	16	23
18	12	9	16	26		26	18	23	20	20	24	14	12	23
20	12	12	19	23	21	25	20	21	12	18	14	11	14	24
19	21	21	18	19	25	26	26	24	25	25	24	20	23	18

MAX = 33 MIN = 4.7 MEAN = 15 STD. DEV. = 5.6

Figure 2

moisture content changes within the lightweight insulating concrete fill were favorable.

This article will present the results of a *third* non-destructive moisture survey conducted on this project during 2003, with a comparison of the relative moisture content of the lightweight fill material after approximately six years of service. Since the one-year period of the previous study was deemed too short for definite conclusions related to drying effects, this follow-up study would be able to fully ascertain the potential benefits of this type of roof system in reducing insulation moisture. Attempts will be made to quantify the amount of drying and associated drying rates, if possible, and appropriate comments regarding the implications of these findings on overall roof selection and design will be developed.

INTRODUCTION

Moisture in Roofing Insulations

For many years, it has been somewhat axiomatic in the roofing industry that the presence of moisture within a compact roofing system is detrimental — sometimes fatally so with respect to the longevity of the roof system. These detrimental effects include physical deterioration of the membrane and reduced service life, as well as a significant reduction in thermal performance of the insulation layer. In addition, entrapped moisture can cause corrosion of metal roof decks, structural steel framing, and fastening systems, as well as corrosion of steel reinforcing within concrete roof decks, which can result in spalling and scaling.

Accordingly, it is generally accepted that roofing materials should not be installed over moist substrates, and if roofing materials become significantly wet after installation, they should be removed and replaced. The real issue, however, has always been "how wet is wet?" and whether or not a wet roofing material (e.g., insulation) could be dried out. This article will present the results of a six-year study conducted on the referenced building. Initial results obtained from the 1997 and 1998 studies at this project have been previously presented.[1]

Non-Destructive Roof Moisture Surveys

The use of Non-Destructive Testing (NDT) methods for determining moisture in roofing systems has been well established for a number of years. A great deal of research has been done regarding the use and methodology of such moisture surveys, as well as the limitations of each method. The three methods historically utilized in the United States have primarily consisted of infrared thermography, nuclear isotope thermalization, and capacitance. It is beyond the scope of this paper to discuss in depth the differences among these methods, nor is it deemed necessary to describe in detail the procedures for each type of survey.

Nuclear Radioisotope Method

For all three moisture surveys, this study utilized nuclear radioisotope (thermalization) methods exclusively. Confirming cores of the lightweight insulating fill were extracted each time, subjected to gravimetric testing, and used to correlate the direct meter readings to actual moisture content by extrapolating the correlation results for meter readings occurring between the survey points taken and analyzed. For each survey, an appropriate statistical analysis of the survey data was performed in accordance with the manufacturer's recommended procedure, as well as in keeping with recognized industry standards (RCI, 1986). The moisture survey data, correlations, statistical analysis, and graphic representation of these results are generally provided by the use of graphs and a map of the roof surface, which typically depicts contours of the measured moisture content. This paper presents the results from the two most recent surveys conducted in 1998 and 2003, and refers to both in this manner.

It should be noted that an attempt was made to utilize the same grid spacing and configuration for both surveys; however, the 2003 survey was conducted with one additional column and

1998 MOISTURE CONTOURS

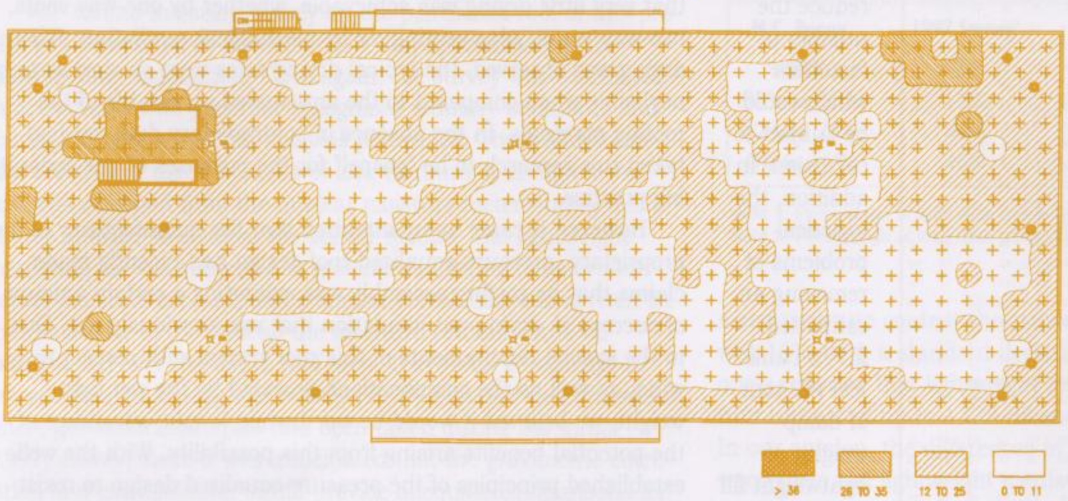

Figure 3

one additional row, resulting in a greater number of overall data points. For the comparison of data point rates of drying, the extra row and column were disregarded. As with the prior two surveys, cores of the roof insulation and cementitious fill were extracted concurrently with each survey at essentially a common low meter reading, a high meter reading, and a reading occurring generally in the middle of the two extremes. Gravimetric analysis involves determining the actual moisture content of the sample by weighing the sample and drying it in a laboratory oven until a constant weight is reached. With this information, the moisture content of the sample may be derived as a percentage of dry weight and used in the correlation to extrapolate results to the entire roof.

Description of Project

The subject of this study is a 43-story high-rise office building located in Houston, Texas, originally constructed in 1961 with a built-up roof system installed at the main roof level, as well as on a 15,760 s.f. mechanical penthouse above the main roof. The building footprint is a simple rectangle, and approximate heights of the main roof and penthouse roof above the surrounding grade are 587' and 602', respectively. In addition, the main roof consists of approximately 13,400 s.f. and is somewhat protected by a four-foot-high parapet; however, perimeters of the penthouse roof terminate into a metal edge condition on all four sides. The main roof was originally installed over 3/4" fiberglass insulation, while the penthouse roof was applied over a layer of 1" wood fiber insulation installed over a vapor retarder applied directly to the lightweight insulating fill, which ranged in depth from approximately 8" at roof perimeters to 4" at interior drains.

As with many high-rise buildings, implementation of the roof renovation project presented a number of different challenges with respect to design, as well as actual construction logistics. These included limited access, negligible staging locations, constraints imposed by building occupancy and management, and the physical aspects of mobilizing manpower and material from the ground to roof level. The previous article outlined the primary reasons for selecting a pressure-equalized, single-ply, membrane roof system. In summary, these reasons were the extreme winds associated with a high-rise building located in a hurricane-prone region and

97 / 98 DIFFERENCES

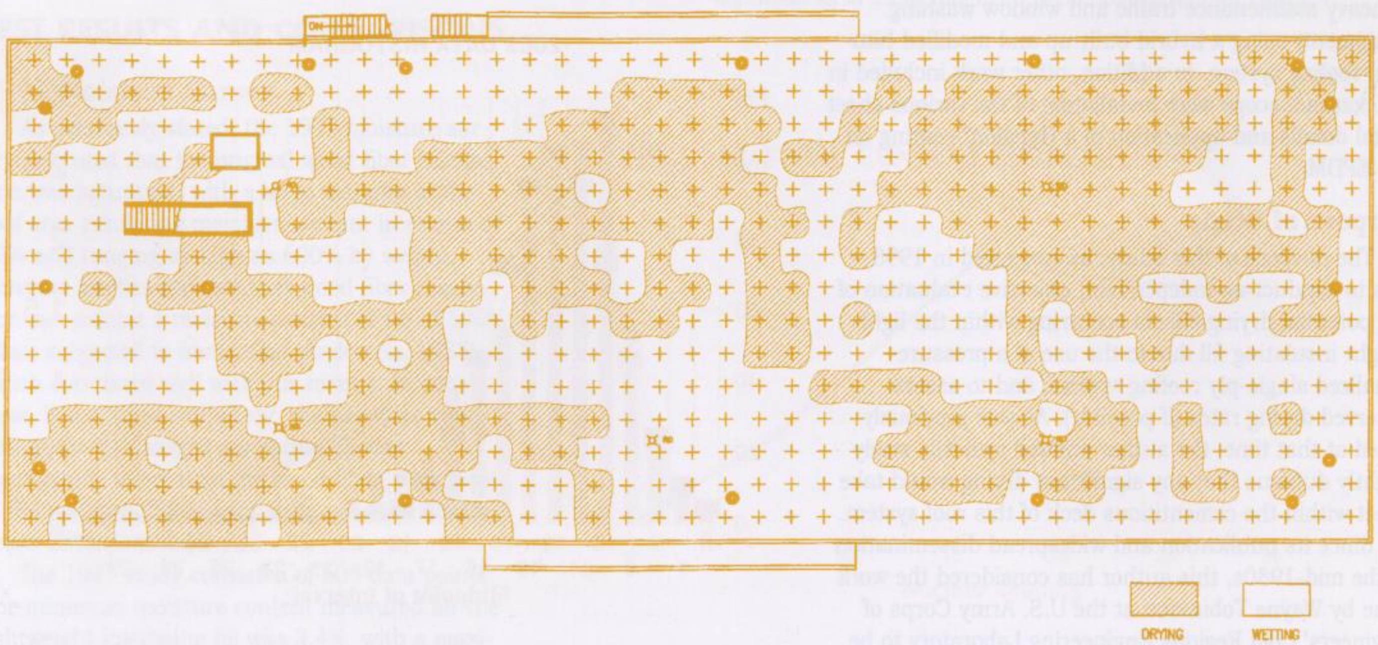

Figure 4

MOISTURE GAUGE DIRECT READINGS - 2002 SURVEY

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	
16	16	15	14	16	14	15	12	12	12	15	14	13	15	17	13	1
17	13	14	17	12	14	10	13	9	11	12	11	10	12	13	15	2
19	17	14	13	12	13	14	12	12	11	9	9	10	10	12	14	3
16	16	14	12	13	15	12	13	11	10	10	11	11	10	11	14	4
19	16	16	12	12	13	11	10	9	8	10	9	10	12	9	14	5
20	16	11	10	13	14	11	9	8	7	8	10	8	9	10	14	6
15	13	12	10	11	10	11	9	8	8	9	10	9	9	10	16	7
15	12	13	12	10	9	13	10	8	11	11	9	12	9	12	14	8
14	11	10	10	9	9	12	11	9	11	8	13	12	13	14	15	9
14	11	10	10	11	10	10	9	8	8	10	10	11	10	13	17	10
14	10	10	8	12	10	11	9	8	9	13	12	10	10	10	13	11
15	10	10	11	11	11	9	9	11	11	11	12	11	10	11	14	12
11	9	8	11	8	10	10	10	13	9	12	10	11	12	12	15	13
16	13	10	7	9	13	12	12	13	13	12	10	10	11	14	17	14
12	10	12	14	11	8	12	14	15	12	8	9	11	10	11	15	15
16	11	12	11	12	7	11	11	11	13	11	9	10	11	12	15	16
15	14	12	13	12	13	11	11	12	13	9	10	14	15	13	19	17
16	13	12	11	13	18	12	13	10	9	12	13	13	13	12	18	18
13	13	13	11	12	11	10	11	10	9	12	10	12	13	11	16	19
15	10	11	10	10	11	10	12	13	10	13	13	13	14	13	18	20
19	11	13	10	10	10	10	12	13	10	12	12	15	13	13	22	21
14	10	9	12	11	10	10	9	8	11	11	12	12	12	10	17	22
12	9	11	11	13	12	11	14	10	9	13	10	15	15	12	15	23
14	9	10	10	9	10	12	10	12	11	12	11	11	12	13	15	24
15	13	10	11	12	13	12	10	10	12	14	9	12	12	13	14	25
13	10	10	12	10	10	10	11	9	11	11	11	10	13	13	14	26
15	11	9	9	12	8	10	8	11	10	13	11	11	13	11	13	27
14	11	10	6	9	9	9	8	8	9	13	9	11	14	13	16	28
13	11	11	10	11	10	10	12	9	10	14	9	12	13	14	16	29
15	13	10	13	11	10	10	10	10	11	10	12	10	14	13	17	30
15	10	13	13	13	10	18	10	10	11	12	11	10	10	13	16	31
15	12	16	18	20	27	22	13	11	12	11	10	10	10	15	19	32
13	11	12	13	14	15	30	11	12	8	10	12	11	11	12	14	33
14	11	19	19	23	22	17	14	10	9	11	15	12	13	11	13	34
14	12	23	16	19		15	13	11	10	12	11	11	12	11	13	35
15	11	20	15	16		16	14	7	11	9	11	12	8	10	16	36
15	11	17	18	15		17	14	11	12	14	9	10	10	12	19	37
17	14	10	11	22		18	18	11	12	16	16	15	12	16	17	38
15	13	10	8	18	16	17	14	13	11	12	12	12	12	11	15	39
16	13	12	12	14	13	16	16	14	13	11	12	12	13	18	17	40
14	11	10	11	13	13	16	15	15	14	13	16	14	15	17	16	41
16	16	18	16	16	20	19	18	20	19	22	19	18	15	17	17	42

Figure 5

a desire to reduce the number of fasteners which could be subject to corrosion. In addition, the logistical problems of removing an estimated 2,775 cubic feet (42 tons of damp weight) of lightweight fill from a fairly inaccessible roof area located 600 feet in the air were daunting. Furthermore, the manufacturer was willing to provide a full system warranty despite acknowledgement of the existing moist cementitious deck fill.

The roof tear-off and installation of the new roof began in September of 1997 and continued through March of 1998. The upper penthouse roof was replaced first, with substantial completion of the pressure-equalized EPDM membrane occurring by the end of October 1997. The remainder of the construction schedule was utilized to replace the main roof (which is subject to heavy maintenance traffic and window washing equipment) using a hybrid built-up and modified bitumen roofing system. In addition, other work included in the contract scope were installation of the various sheet metal details and application of a Hypalon® coating on the EPDM.

Purpose of Study

The purpose of this study, as conceived in 1998, was to conduct an independent, objective evaluation of the potential drying effects occurring within the lightweight insulating fill due to the use of a pressure-equalized single-ply roofing system, and to assess observed drying rates (if possible). As was previously noted at that time, the author entered into this study slightly dubious that any significant drying would take effect within the cementitious deck of this roof system.

Since its publication and widespread dissemination in the mid-1980s, this author has considered the work done by Wayne Tobiasson at the U.S. Army Corps of Engineers' Cold Regions Engineering Laboratory to be the most definitive work previously conducted in this area (Tobiasson, 1983). The basic conclusions of that paper were that very little drying was achievable, whether by one-way vents, two-way vents, edge venting, or by mechanical ventilation. Where drying was observed, the typical drying rates were so slow as to be negligible when compared to the anticipated service life of the roofing materials. In the absence of contradictory data, we had taken this research to be "gospel" for the purposes of our consulting practice.

However, it came to my attention that the manufacturer of the proprietary, pressure-equalized roof design had recently made claims that its roofing assembly was exhibiting a certain amount of success in drying out insulation that was previously wet. Due to the special requirements of this roof system with respect to wind, as well as the complications provided by the wet lightweight, we believed it would be worthwhile to take advantage of the potential benefits arising from this possibility. With the well-established principles of the pressure-equalized design to resist membrane blow-off without fasteners, it was felt that any drying that might be accomplished would essentially be an unanticipated "bonus" for this system.

PROCEDURES AND CHRONOLOGY

Initial Evaluation

The initial study of this roof and the associated nuclear moisture survey conducted in early 1997 were performed as part of the normal consulting services provided by our firm for a large international oil and gas company. The subject building represents a significant regional office for this company and has been a Houston landmark for over thirty years, since it was, when constructed, the tallest building in Houston. The moisture survey was conducted in accordance with generally recognized industry standards and the analysis was presented to the building owner in order to assist in the re-roof decision. The information obtained from the original survey was also utilized during the design and detailing of the proposed replacement roof system.

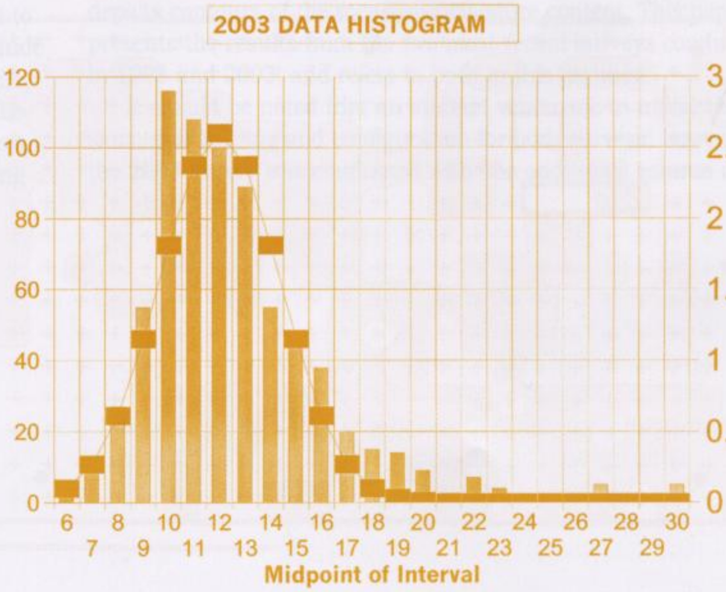

Figure 6

Post-Construction Evaluation in 1998

The second moisture survey on the penthouse roof of this project was conducted in November of 1998, approximately 13 months after installation. Once again, the survey was conducted in accordance with generally recognized industry standards and the appropriate statistical analysis performed. Three additional roof cores were taken at areas of low, medium, and high meter readings obtained from the nuclear moisture meter during the survey in order to confirm the survey results. The lightweight insulating fill was subjected to gravimetric testing to determine actual moisture content, and a similar correlation was derived for the remainder of the data so the moisture content could be extrapolated over the entire roof area. There was no attempt to extract samples during this survey (1998) from the exact locations where gravimetric samples had been taken during the initial (1997) survey, since it was anticipated that the gravimetric correlation and extrapolation would provide adequate comparisons for the majority of the roof.

Post-Construction Evaluation in 2003

The third moisture survey on the upper penthouse roof of this project was conducted in January of 2003, approximately five years and three months after installation had been completed. Once again, the survey was conducted in accordance with generally recognized industry standards and the appropriate statistical analysis was performed. Three additional roof cores were taken at areas of low, medium, and high meter readings obtained from the nuclear moisture meter during the survey in order to confirm the survey results. The lightweight insulating fill was subjected to gravimetric testing to determine actual moisture content, and a similar correlation was derived for the remainder of the data so the moisture content could be extrapolated over the entire roof area. There was no attempt to extract samples during the most recent survey (2003) from the exact locations where gravimetric samples had been taken during the second (1998) survey, since it was anticipated that the gravimetric correlation and extrapolation would provide adequate comparisons for the majority of the roof.

TEST RESULTS AND COMPARISONS

1997 Moisture Survey

As previously stated, the 1997 moisture survey indicated that the original wood fiber insulation was saturated, with a large majority of the roof area exhibiting moisture content in excess of 30% and ranging as high as 600% by weight. Previous studies indicate that wood fiber insulation can exhibit a moisture content of up to 580% when subjected to immersion (Anderson, 1985), which correlated well with our results. In contrast, based upon our study, the moisture content of the lightweight insulating fill was significantly lower than the wood fiber, with most of the roof area (86%) exhibiting moisture content below 25%. (See *Table 1.)*

The 1997 study consisted of 608 data points. The minimum moisture content measured for the lightweight insulating fill was 3.4%, with a maximum moisture content of 43% by weight. The mean moisture content throughout the readings on the entire roof was 16%, with a standard deviation of 8%. Anderson has previously reported that lightweight insulating fill will exhibit a moisture content of up to 110% when subjected to immersion (1985). In our opinion, the differences in moisture content between the wood fiber and lightweight insulating fill during the 1997 survey are due to the relative densities and absorption properties of these two materials, as well as the fact that the vapor retarder may have served as a water barrier between the wood fiber and the lightweight fill, restricting the amount of water actually getting into the cementitious layer.

Table 1: Comparison of Data Point Changes

M.C. Range	1997 Survey[1]	1998 Survey[1]	Group Change[2]
>36%	2%	0%	2% Decrease
26% to 35%	12%	4%	8% Decrease
12% to 25%	40%	66%	26% Increase
0% to 11%	46%	30%	16% Decrease

Note 1: Percentage of total data points with moisture contents in specific ranges
Note 2: Percentage of total data points changing within each specific range

1998 Moisture Survey

The 1998 moisture survey also consisted of 608 data points and indicated extremely consistent conditions within the gypsum sheathing layer of the new roof. Although the moisture content of these materials was slightly elevated, with moisture content ranging between 17.8% and 18.2% by weight, the integrity of the water-resistant sheathing had not been adversely affected. In addition, although no isocyanurate insulation samples were extracted, moisture probes using a Delmhorst meter indicated no significant moisture in that roofing layer either. However, the lightweight fill still exhibited moisture content ranging from 4.7% to 33%. The mean moisture content throughout the entire roof was 15%, with a standard deviation of 5.6%. Reference *Figures 1* through *3*. A comparison of the wetting and drying that had occurred as of 1998 has been presented herein as *Figure 4*.

2003 MOISTURE CONTENT CORRELATION

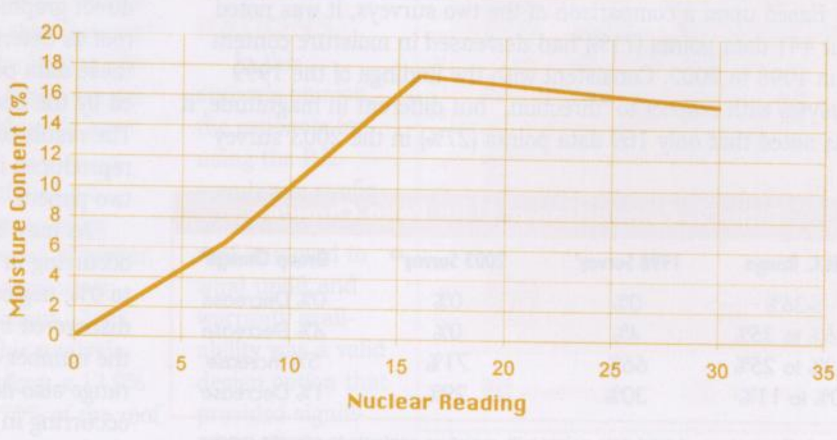

Figure 7

2003 Moisture Survey

The 2003 moisture survey consisted of 667 data points and indicated consistent results, based on the statistical analysis. During the 2003 survey, samples of the isocyanurate insulation were extracted concurrent with the lightweight insulating fill. The isocyanurate exhibited moisture content ranging between 20.0% and 171.4% by weight, with the highest moisture absorption occurring at a location where an active roof leak was found. More importantly, the lightweight fill exhibited moisture content ranging from 5.4% to just 17.4%. The mean moisture content throughout the roof was down to 12.6%, with a standard deviation of only 2.8%. See *Figures 5* through *8*.

Comparisons and Contrasts

After an additional five years of *in-situ* performance, it was surprising to observe that the *maximum* moisture content measured within the lightweight insulating fill (by extrapolation of the nuclear moisture meter readings and correlation with the gravimetric analysis of confirming cores) had decreased an additional *fifteen percentage points* by weight (representing an overall reduction of 47%). This would represent a total reduction in the maximum moisture content from 43% in 1997 to 17.4% in 2003 (a reduction of about 60% overall). At the same time, the mean moisture content was reduced by almost 2-1/2% by weight, from 15% in 1998 to just 12.6% in 2003 (a reduction of about 16% for the last 5 years). Furthermore, the *standard deviation* had been reduced from 5.6% to 2.8% (a 49% change). This "narrowing" of the standard deviation indicates that the uniformity and consistency of the moisture content within the insulating fill is increasing. Reference *Tables 2* through *4*.

From this data, one could conclude that a respectable amount of drying has taken place during the study period. As was observed in the 1999 paper, there were some rather unique phenomena observed within this roof with respect to the fact that there are some points that have increased in moisture content (as observed in the minimum moisture contents between 1998 and 2003 rising from 4.7% to 5.4%), as well as some data points that decreased in moisture content. These phenomena continued to be exhibited by this roof over the last five years.

Based upon a comparison of the two surveys, it was noted that 441 data points (71%) had *decreased* in moisture content from 1998 to 2002. Consistent with the findings of the 1999 analysis with respect to "direction," but different in magnitude, it was noted that only 169 data points (27%) in the 2003 survey

Table 2: Comparison of Data Point Changes

M.C. Range	1998 Survey[1]	2003 Survey[1,3]	Group Change[2]
>36%	0%	0%	0% Decrease
26% to 35%	4%	0%	4% Decrease
12% to 25%	66%	71%	5% Increase
0% to 11%	30%	29%	1% Decrease

Note 1: Percentage of total data points with moisture contents in specific ranges
Note 2: Percentage of total data points changing within each specific range
Note 3: Two data points at known leak points within the roof were discarded

Table 3: Comparison of M.C. Characteristics

Characteristic	1998 Survey	2002 Survey	Change	Percentage
Maximum	33%	17.4%	-15.6 pts.	-47%
Minimum	4.7%	5.4%	+0.7 pts.	+15%
Mean	15.0%	12.6%	-2.4 pts.	-16%
Standard Deviation	5.6%	2.8%	-2.8 pts.	-49%

Table 4: Comparison of M.C. Characteristics

Characteristic	1997 Survey	2002 Survey	Change	Percentage
Maximum	43%	17.4%	-25.6 pts.	-60%
Minimum	3.4%	5.4%	+2.0 pts.	+59%
Mean	16.0%	12.6%	-3.4 pts.	-21%
Standard Deviation	8.0%	2.8%	-5.2 pts.	-65%

exhibited an *increase* in moisture content when compared to the 1998 survey. This compares to 318 data points (52%) from the 1998 survey that exhibited an increase. This would indicate that the number of points getting "wetter" is decreasing or "slowing down." A visual comparison of the two histograms developed for the data from the 1998 and 2002 surveys indicates that the 2002 data is even more "standard" than the previous 1998 data. This statistical analysis represents an extremely good correlation between the actual meter readings obtained and the standard distribution (bell curve) expected for this type of survey. See *Figure 6*. In our experience, the histogram for the 2003 survey represents a normal distribution that one would expect to see on a relatively dry roof, with only minor variations.

Further comparison of the data from both surveys indicated that of the 441 points exhibiting decreased moisture content, the *average decrease* or change at each grid point was about 13.9%. By contrast, for those 318 points exhibiting an increase in moisture content, the *average increase* or overall change at each grid point was about 10.3%. So, essentially, it could be said that individual grid point locations on 71% of the roof area *increased* in moisture content and did so by about *40% more* than the amount that the other 29% of the roof decreased.

As observed within the 1999 paper, it is instructive to tabulate the data points with respect to the various ranges or break-down, of moisture content utilized to draw the moisture contour maps for each survey. Although the break-down divisions are completely arbitrary, using identical break-downs for both surveys allows a direct graphical comparison of the moisture contours within the roof as determined by the two surveys. In addition, tabulating these data points allows another measure of the *changes* exhibited by the insulating fill material. Reference *Table 2* of this report. The result comparison between the 1997 and 1998 surveys is reproduced in order to allow a convenient comparison between the two papers.

As may be observed in *Table 2*, the number of data points occurring in the 26% to 35% range went from 4% (about 26 total) to 0%, neglecting the two data points that occurred at roof leaks discovered by the moisture survey during this study. Once again, the number of data points occurring in the lowest, or most "dry" range also decreased slightly (1%), and the number of data points occurring in the next-to-lowest range increased by 5% (about 33 total). Of the 667 data points in the new study, 474 total points (71%) exhibited moisture contents between 12% and 25% by weight in the third survey. This analysis appeared to confirm the "centralizing" of the data points toward a moisture content range on the lower (drier) end of the scale. In contrast to the earlier study, only a small portion (1%, or 7 total) of the "most dry" points (0% to 11% moisture content) became more damp, whereas in the previous study, there was a 16% decrease in that moisture range. Reference *Tables 3* and *4*.

MOISTURE CONTENT CORRELATION - 2003 SURVEY

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
17	17	16	15	17	15	16	12	12	12	16	15	14	16	17	14
17	14	15	17	12	15	10	14	9	11	12	11	10	12	14	16
17	17	15	14	12	14	15	12	12	11	9	9	10	10	12	15
17	17	15	12	14	16	12	14	11	10	10	11	11	10	11	15
17	17	17	12	12	14	11	10	9	8	10	9	10	12	9	15
17	17	11	10	14	15	11	9	8	6	8	10	8	9	10	15
16	14	12	10	11	10	11	9	8	8	9	10	9	9	10	17
16	12	14	12	10	9	14	10	8	11	11	9	12	9	12	15
15	11	10	10	9	9	12	11	9	11	8	14	12	14	15	16
15	11	10	10	11	10	10	9	8	8	10	10	11	10	14	17
15	10	10	8	12	10	11	9	8	9	14	12	10	10	10	14
16	10	10	11	11	11	9	9	11	11	11	12	11	10	11	15
11	9	8	11	8	10	10	10	14	9	12	10	11	12	12	16
17	14	10	6	9	14	12	12	14	14	12	10	10	11	15	17
12	10	12	15	11	8	12	15	16	12	8	9	11	10	11	16
17	11	12	11	12	6	11	11	11	14	11	9	10	11	12	16
16	15	12	14	12	14	11	11	12	14	9	10	15	16	14	17
17	14	12	11	14	17	12	14	10	9	12	14	14	14	12	17
14	14	14	11	12	11	10	11	10	9	12	10	12	14	11	17
16	10	11	10	10	11	10	12	14	10	14	14	14	15	14	17
17	11	14	10	10	10	10	12	14	10	12	12	16	14	14	17
15	10	9	12	11	10	10	9	8	11	11	12	12	12	10	17
12	9	11	11	14	12	11	15	10	9	14	10	16	16	12	16
15	9	10	10	9	10	12	10	12	11	12	11	11	12	14	16
16	14	10	11	12	14	12	10	10	12	15	9	12	12	14	15
14	10	10	12	10	10	10	11	9	11	11	11	10	14	14	15
16	11	9	9	12	8	10	8	11	10	14	11	11	14	11	14
15	11	10	5	9	9	9	8	8	9	14	9	11	15	14	17
14	11	11	10	11	10	10	12	9	10	15	9	12	14	15	17
16	14	10	14	11	10	10	10	10	11	10	12	10	15	14	17
16	10	14	14	14	10	17	10	10	11	12	11	10	10	14	17
16	12	17	17	17	16	17	14	11	12	11	10	10	10	16	17
14	11	12	14	15	16	15	11	12	8	10	12	11	11	12	15
15	11	17	17	16	17	17	15	10	9	11	16	12	14	11	14
15	12	16	17	17		16	14	11	10	12	11	11	12	11	14
16	11		16	17		17	15	6	11	9	11	12	8	10	17
16	11	17	17	16		17	15	11	12	15	9	10	10	12	17
17	15	10	11	17		17	17	11	12	17	17	16	12	17	17
16	14	10	8	17	17	17	15	14	11	12	12	12	12	11	16
17	14	12	12	15	14	17	17	15	14	11	12	12	14	17	17
15	11	10	11	14	14	17	16	16	15	14	17	15	16	17	17
17	17	17	17	17	17	17	17	17	17	17	17	17	16	17	17

Figure 8

CONCLUSIONS

Based upon this study, it appeared that the *overall* average moisture content of the lightweight insulating fill had been lowered by about 3.4% since 1997 after removal of the old built-up roof and installation of the pressure-equalized single-ply roofing membrane. In addition, the upper extreme range of moisture content occurring within these materials appears to have been reduced from 43% to 17.4%. Where the initial 1997 study indicated 14% of the total roof area exhibited moisture content greater than 25% by weight, the second study indicated only 4% of the total roof area exhibited moisture content in that range, and the current study indicates that there were *no data points* or portions of the roof that exceeded 25% moisture content by weight. Based upon the evaluation of this one building, it appears that the overall patterns and levels of moisture content within the lightweight have improved, with certain portions of the roof no longer as wet as they were and the overall average moisture significantly lowered (by about 21%).

As previously noted, 29% of the data points exhibited an *increase* in moisture content, with the average increase being about 10.3% greater than the original moisture content. However, 71% of the data points exhibited an unmistakable *decrease* in moisture content, with the average decrease being about 13.9% less than the original moisture content. Based on this analysis and assuming a dry weight of 26 pounds per cubic foot, a 13.9% reduction of moisture for lightweight samples over 70% of the roof originally having 19% moisture content by weight represents a *greater amount* of total water (about 5,977 lbs.-m [pounds mass] H_2O) than a 10.3% increase of a sample originally having 5% moisture content by weight over 30% of the roof area (about 283 lbs.-m H_2O).

It was further observed (from the differences between the data for each survey) that the wettest areas of the roof became drier and the driest areas of the roof generally became wetter, such that the lower middle range of moisture readings significantly increased in quantity overall. In fact, the number of data points exhibiting moisture content between 12% and 25% by weight increased from less than half the roof area in 1997 (40%) to virtually three-fourths (71%) of the total roof area. This fact appears to indicate that the "centralization" or "uniformity" effect for the moisture contents of this roof system has continued over the past five years. Accordingly, the patterns of drying and the amount of moisture actually removed from the roof appear to be the result of a very complex process that is not easily categorized by this one example and does not behave in a linear fashion at any particular point on the roof.

Based upon this study, it would seem that the results for this roof exhibit fairly strong evidence for significant drying that may be induced from moist lightweight insulating fill using a P.E. membrane configuration. In addition, although the drying rate is not overwhelming, there is no doubt that the general trend is toward a drier roof with presumably beneficial effects on overall performance and longevity.

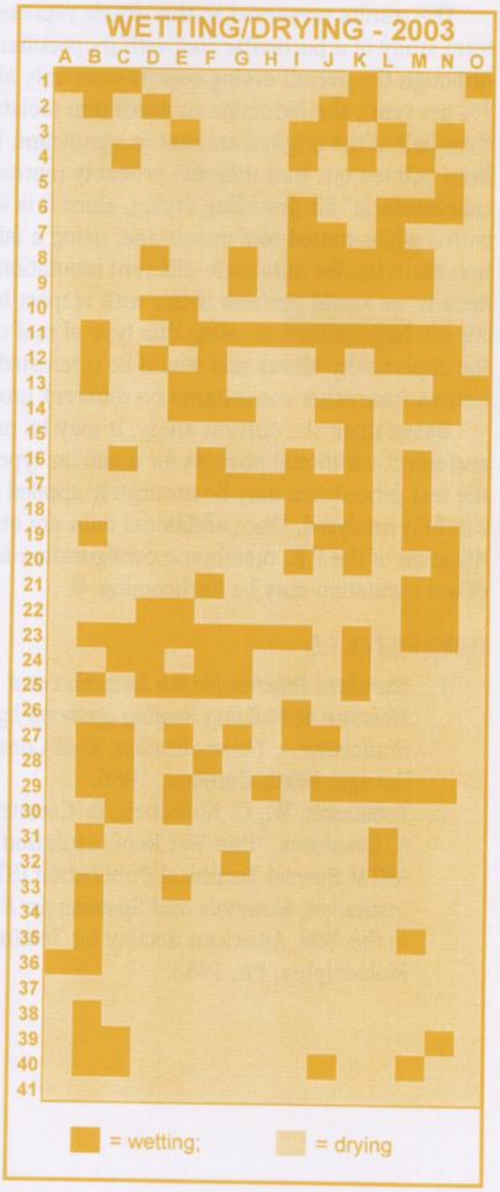

Figure 9

RECOMMENDATIONS

In this author's opinion, the rationale for using the P.E. membrane configuration for this roof in regard to wind uplift and warranty availability was a valid design option that provided significant benefits to the building owner with respect to renovation costs, job site logistics, and inconvenience to the building occupants. In addition, it may be claimed that moisture content of the lightweight insulating fill on this roof is, based on this study, at least "trending" in the desired direction of drying out, if not actually exhibiting acceptable drying overall. However, the results from the study of this one roof are not definitive enough, in our opinion, to promote selection or design of this roof configuration based solely on potential drying effects. It should be noted that the successful performance of the pressure-equalized roof membrane configuration is highly dependent upon proper design and installation of an effective seal at the roof perimeter to avoid air leakage that would counteract the pressure-equalization efforts. Accordingly, it is not possible to add perimeter venting or underside "holes" in the deck to promote additional drying for these types of roofs without violating the critical pressure-equalization characteristics that resist wind uplift. Therefore, we would recommend that anyone considering this type of system be sure to obtain input and advice from the manufacturer for the intended design and that steps be taken to properly install the roof in general and the perimeter air seals in particular.

The results presented in this article represent a fairly long-term study of a particular roof with its peculiar characteristics. Although the overall drying results were only about 5% total (or 1% per year), the reduction in maximum moisture content to less than half of the original amount is significant. In addition, it has been pointed out that this roof probably represents the "worst case scenario" for providing drying, since it is a concrete deck with a white-coated roof membrane, using a fairly dense insulation material. We anticipate different insulation materials and deck types would perform better with respect to drying capability. We will look forward to using this type of roof configuration when the opportunity allows and would be interested in hearing of experiences from other consultants on different projects.

Based upon the current study, it may be prudent to obtain and select additional projects for a similar type of study, where the test procedures may be accurately applied and the results carefully analyzed. Once additional data are obtained, further justification of the P.E. membrane configuration for promoting drying of wet insulation may be forthcoming. ■

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ACKNOWLEDGMENTS

The author would like to acknowledge the continuing assistance and contribution of Tom Kelly and the roof membrane manufacturer, 2001 Roofing Systems, as well as the assistance and contribution of Jim Dorsey, project manager for the roofing contractor, Texas Coatings Applications & Waterproofing, Inc.

FOOTNOTE

1. French, Warren R., "Post-Installation Field Evaluation of a Pressure-Equalized Single-Ply Roofing System to Determine Drying Effects on a Moist, Cementitious Roof Deck," *Interface,* August 1999, p. 3.

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