POST-INSTALLATION FIELD EVALUATION

Of a Pressure-Equalized Single-Ply Roofing System to Determine Drying Effects on a Moist, Cementitious, Roof Deck

By Warren R. French, P.E., RRC, CCS

A consulting assignment allowed evaluation of moisture content within the lightweight insulating fill on a high-rise commercial building, both before and after roof membrane removal and replacement using a single-ply thermoset roofing system installed in a proprietary pressure-equalized configuration. This type of roof system was selected due to the anticipated wind loads this building would be exposed to, as well as the fact that the manufacturer claims wet insulation can be dried out using this type of installation. A nondestructive nuclear moisture survey was performed prior to the original roof removal, the roof system was then replaced, and the pressure-equalization valves were allowed to function for approximately a year. After about twelve months, another nuclear moisture survey was performed, and the moisture content of the lightweight insulating fill was evaluated for a second time. This paper presents the results of this post-installation roof evaluation and compares the moisture contents of the lightweight insulating fill material both before and after any drying effects that may have occurred due to removal of the built-up roof and application of the pressure-equalized membrane. An attempt is made to analyze and quantify the changes in moisture contents observed, and appropriate comments regarding the effectiveness of this type of design for the stated purpose have been derived.

INTRODUCTION

Moisture in Roofing Insulations

The detrimental effect of the presence of moisture on roofing systems is well known. These effects include physical deterioration of the membrane, reduced service life, and 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 has been a generally recognized axiom 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.

Nondestructive Roof Moisture Surveys

The use of Nondestructive 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 moisture surveys, and capacitance. It is beyond the scope of this article 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. However, it should be understood that thermography uses an infrared imaging device to "read" areas on the roof where thermal anomalies exist. The survey of these thermal anomalies is performed across the roof, and the anomalies are generally assumed to be areas of wet insulation due to the lower thermal resistance (greater heat conductivity) of wet insulation as compared to dry materials. By contrast, nuclear methods and capacitance methods utilize individual meter readings at discreet locations across the roof area, which is usually laid out in a grid spacing from 5 to 10 feet in both directions. The nuclear meter relies upon well-established principles of physics pertaining to the behavior of "fast" neutrons, particularly in an environment with abundant hydrogen, while the capacitance meter works by measuring the relative strength of an electric field as it passes through the roofing materials, with the assumption that there will be greater electrical conductivity in a wet insulation as compared to dry materials.

Nuclear Radioisotope Method

This study utilized nuclear radioisotope methods exclusively for both moisture surveys. Confirming cores of the lightweight insulating fill materials were extracted, subjected to gravimetric testing, and used to correlate the direct meter readings to actual

MOISTURE GAGE DIRECT READINGS - 1997

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
37	29	34	29	32	30	52	50	48	20	24	21	29	34	28
53	59	65	48	27	67	61	53	49	20	21	19	30	40	25
65	77	58	57	50	58	67	48	37	23	28	18	37	25	31
64	58	51	52	67	61	54	18	33	27	20	38	19	21	37
47	78	64	53	55	70	56	50	19	20	19	23	19	38	25
47	75	65	58	55	63	53	38	21	20	17	35	23	24	21
62	70	66	72	62	58	55	40	23	17	24	23	28	34	28
56	70	69	62	61	68	61	50	37	18	17	43	58	27	28
62	77	75	64	67	65	67	54	28	18	20	48	57	57	29
53	72	63	65	67	58	66	48	22	37	51	49	57	61	25
52	62	69	53	69	62	60	53	22	28	28	44	59	28	25
59	56	61	68	61	59	69	21	28	18	31	57	55	38	23
41	54	61	67	51	42	53	45	24	26	51	64	63	51	23
25	53	60	52	39	44	42	41	23	32	49	49	51	47	29
35	66	38	38	50	45	54	34	40	31	41	28	53	31	30
30	51	58	40	24	23	58	30	32	28	32	20	23	44	27
23	46	53	60	55	9	29	24	29	37	24	23	28	33	25
43	46	50	58	50	68	34	71	40	36	27	27	23	21	23
26	48	71	48	54	61	48	53	41	30	27	32	31	37	28
24	66	58	68	67	49	30	47	38	29	22	22	22	32	28
35	58	59	64	60	58	48	53	52	28	25	41	28	30	30
35	65	58	53	63	59	42	44	37	34	30	47	35	23	32
23	46	55	54	54	52	39	45	32	44	28	29	46	33	22
25	27	44	48	46	59	31	66	20	34	30	55	45	63	63
20	38	54	49	65	67	55	70	19	22	25	54	54	45	52
28	19	24	55	60	65	60	58	20	19	32	58	57	51	55
35	25	33	48	63	73	58	39	23	23	28	50	51	38	73
27	28	27	61	62	49	58	55	25	35	30	54	50	48	65
23	28	18	48	63	51	45	45	56	50	58	43	43	72	35
29	28	22	50	48	37	23	48	54	45	65	62	54	50	58
30	22	57	52	55	50	30	38	73	62	60	53	57	53	56
34	39	59	66	67	60	39	35	56	50	47	64	59	61	69
29	42	51		58	65	48	70	59	58	51	60	53	60	68
30	45	58		66	62	59	58	58	46	51	51	56	56	45
29	46	49	52	42		62	76	58	57	46	62	52	61	67
33	56	58	65	45		62	61	46	52	45	64	59	56	61
27	53	52	57	65		53	64	48	49	53	57	52	55	60
40	54	48	51	58		58	56	24	53	44	71	73	62	50
29	45	54	50	61		57	56	49	54	48	64	66	58	60
38	56	57	44	43	53	48	49	52	43	38	57	55	57	50
60	66	58	64	51	56	46	41	39	36	41	58	59	61	63

MAX = 78 MIN = 9 MEAN = 46 STD. DEV. = 15

Figure 1

moisture contents. Correlation results were extrapolated for meter readings occurring between the survey points. 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. See *Figures 2, 5, 7* and *10*. This article presents the results from both surveys conducted in 1997 and 1998, 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. In addition, cores were extracted contemporaneously 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 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.

MOISTURE CONTENT EXTRAPOLATION - 1997

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
10	9	10	8	9	9	14	12	12	8	8	7	9	10	8
15	22	28	12	8	31	24	15	12	8	7	7	9	11	8
28	42	21	20	12	18	31	12	10	8	8	7	10	8	9
27	21	13	14	31	24	16	7	9	8	8	10	7	7	10
12	43	27	15	17	34	18	12	7	8	7	8	7	10	8
12	39	28	21	17	26	15	10	7	8	6	10	8	8	7
25	34	30	36	25	21	17	11	8	6	8	8	8	10	8
18	34	33	25	24	30	24	12	10	7	6	11	21	8	8
25	42	39	27	31	28	31	16	8	7	8	12	20	20	9
15	36	26	28	31	21	30	12	7	10	13	12	20	24	8
14	25	33	15	33	25	23	15	7	8	8	11	22	8	8
22	18	24	32	24	22	33	7	8	6	9	20	17	10	8
11	16	24	31	13	11	15	12	8	8	13	27	26	13	8
8	15	23	14	10	11	11	11	8	9	12	12	13	12	9
10	30	10	10	12	12	16	10	11	9	11	8	15	9	9
9	13	18	11	8	8	21	9	9	8	9	8	8	11	8
8	12	15	23	17	3	9	8	9	10	8	8	8	9	8
11	12	12	21	12	32	10	35	11	10	8	8	8	7	8
8	12	35	12	16	24	12	15	11	9	8	9	9	10	8
8	32	18	32	31	12	9	12	10	9	7	7	7	9	8
10	21	22	27	23	21	12	15	14	8	8	11	8	9	9
10	28	18	15	26	22	11	11	10	10	9	12	10	8	9
8	12	17	16	16	14	10	12	9	11	8	9	12	9	7
8	8	11	12	12	22	9	30	8	10	9	17	12	26	26
8	10	16	12	28	31	17	34	7	7	8	16	16	12	14
8	7	8	17	23	28	23	21	8	7	9	18	20	13	17
10	8	9	12	26	37	21	10	8	8	8	12	13	10	37
8	8	8	24	25	12	18	17	8	10	9	16	12	12	28
8	8	7	12	26	13	12	12	18	12	21	11	11	36	10
9	8	7	12	12	10	8	12	16	12	28	25	16	12	21
9	7	20	14	17	12	9	10	37	25	23	15	20	15	18
10	10	22	30	31	23	10	10	18	12	12	27	22	24	33
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9	12	12	14	11		25	41	22	20	12	25	14	24	31
9	18	18	28	12		25	24	12	14	12	27	22	18	24
8	15	14	20	28		15	27	12	12	15	20	14	17	23
11	16	12	13	21		21	18	8	15	11	35	37	25	12
9	12	16	12	24		20	18	12	16	12	27	30	21	23
10	18	20	11	11	15	12	12	14	11	10	20	17	20	12
23	30	21	27	13	18	12	11	10	10	11	21	22	24	26

MAX = 43 MIN = 3.4 MEAN = 16 STD. DEV. = 8

Figure 4

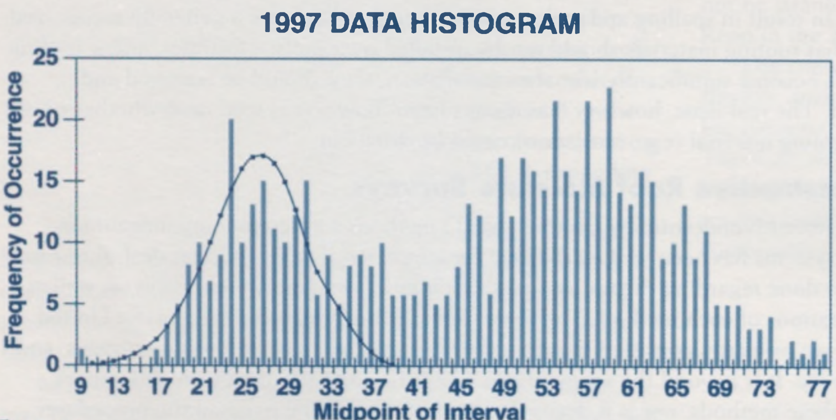

Figure 2

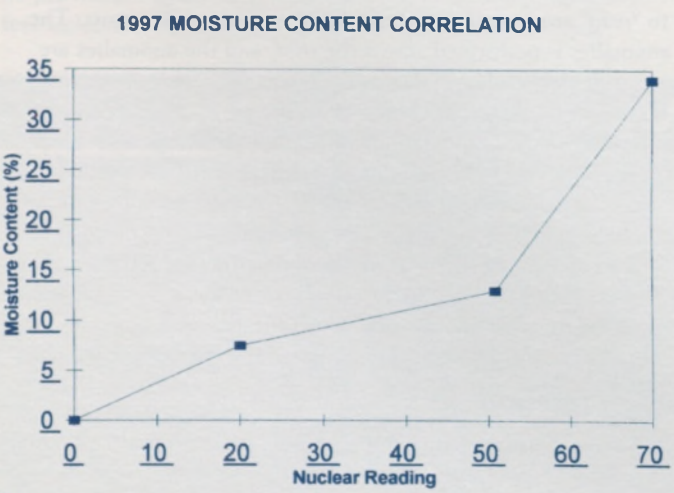

Figure 3

Description of Project

The structure that became the subject of this study is a 43-story high-rise office building in Houston, Texas which was 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 a 3/4″-thick fiberglass insulation, while the penthouse roof had been applied over a layer of 1″-thick wood fiber insulation, installed over a vapor retarder applied directly to the cementitious lightweight insulating fill. The fill 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 design and construction logistics challenges. The latter 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.

Although this building is located in an urban area, it is on the

Left: Lower roof prior to re-roof.

Below: Upper roof after renovation.

southern edge of the downtown district and is fully exposed to the predominant southerly winds common to this locale. Accordingly, the surrounding buildings provide virtually no "shielding" of the wind forces to which this building is exposed. Further, being a coastal environment (approximately 45 miles from the coast of the Gulf of Mexico), the building has been, and would continue to be, periodically subjected to hurricane-force winds also originating from the Texas Gulf Coast. The roof systems on this building had experienced over 35 years of exposure and deterioration, which prompted the owner to initiate replacement by commissioning the services of a roof consultant.

An abbreviated investigation and analysis consisted of a visual survey on both levels and a nondestructive roof moisture survey using nuclear thermalization techniques on the penthouse roof. The results of the original study revealed that the lightweight insulating fill on the penthouse level had incurred significant amounts of moisture throughout most of its surface, which extended down to the concrete deck. Moisture contents of the lightweight fill varied considerably over the roof surface but generally ranged between 8% and 24% of dry weight. The wood fiber insulation at this level was also significantly wet with moisture contents ranging up to 600% by dry weight. Since separate cores and gravimetric analyses were performed for both the wood fiber and lightweight insulating fill, it was believed that the survey produced acceptable results in both situations, although meter readings were undoubtedly skewed by the presence of the extremely wet organic insulation.

Purpose of Study

The purpose of this study was to conduct an independent, objective evaluation of the potential drying effect occurring within the lightweight insulating fill on a pressure-equalized, single-ply roofing system and to assess observed drying rates (if possible).

It should be noted that the author entered into this study slightly dubious that any significant drying would take place within the cementitious deck of this roof system. For at least 14 years, I have 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 conducted in this area

1997 MOISTURE CONTOURS

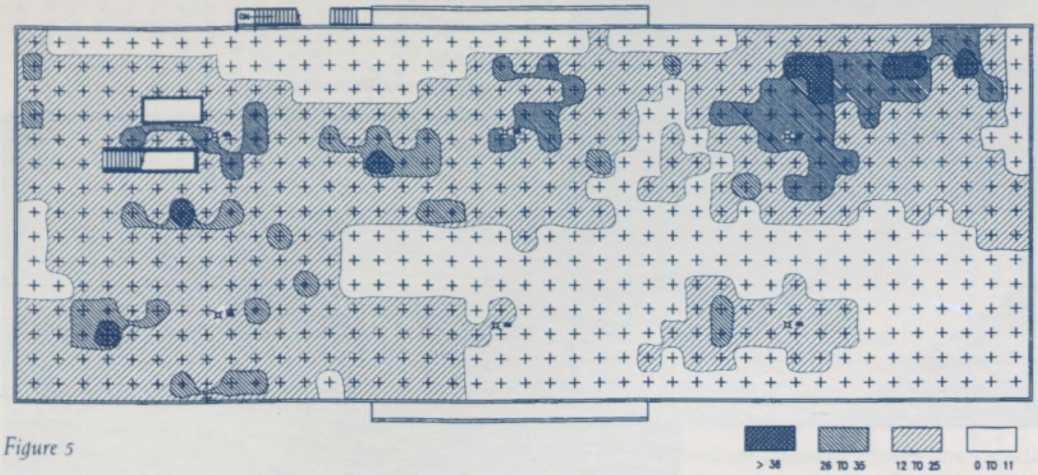

Figure 5

(Tobiasson, 1983). The basic conclusions of Tobiasson's study were that very little drying was achievable, whether by one-way vents, two-way vents, perimeter-edge venting, or 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 wet insulation. 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 roof membrane blow-off without fasteners, it was felt that any drying that might be accomplished would essentially be an unanticipated "bonus" for this roof system.

PROCEDURES AND CHRONOLOGY

Initial Evaluation

The initial study of this roof system 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 30 years, since it was, when constructed, the tallest building in Houston. The roof 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.

Construction Documents and Bidding

Subsequent to the initial evaluation, French Engineering was authorized to develop construction documents for the proposed replacement roof system, and to coordinate with qualified contractors to competitively bid the work. Upon selection of a contractor and award of the re-roofing contract, our firm also provided contract administration services, project management, and periodic on-site inspections of the work.

As previously stated, a pressure-equalized (P.E.), single-ply membrane roof system was selected primarily for its proven track record with respect to the ability of this system to resist high wind uplift. This feature was given high priority due to the exposure of this roof (with no parapet) and in consideration of the hurricane-force winds to which this location could periodically be subjected. Furthermore, an additional design imposed was the ability to resist the anticipated wind uplift using minimal fasteners, which the P.E. system also accommodates since it is essentially "loose-laid" and depends upon the pressure-equalization vents to create a negative pressure (suction) between the roof deck and the underside of the membrane. The desire to eliminate fasteners, or at least minimize them, was due to our recommendation to the owner to retain the lightweight fill, and recognition of the fact that fasteners installed through chronically wet materials would be subject to accelerated corrosion.

As might be expected, the building owner had expressed great aversion to removing the damp, lightweight, insulating fill during design review meetings. In addition, the sheer logistical problems of removing an estimated 2,775 cubic feet (42 tons damp weight) of lightweight fill from a fairly inaccessible roof area located 600 feet in the air were daunting. Also, unless an exterior-mounted construction elevator was erected, all of the debris would have to be transported by hand through a mechanical enclosure, down a stairwell for two floors, then down the service elevator to the loading dock of this fully-operational building. This, in fact, was the route taken for removal of the original built-up membrane and

MOISTURE GAGE DIRECT READINGS - 1998

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
9	14	12	17	19	18	17	19	17	14	14	16	15	15	12
15	12	16	14	14	19	12	13	11	10	12	12	11	15	14
18	18	18	15	11	18	14	14	10	10	10	8	11	9	13
22	23	13	22	16	20	13	12	11	12	10	12	11	11	16
20	25	20	18	18	19	12	12	10	10	11	11	11	10	12
25	23	18	14	17	20	12	11	8	10	11	8	8	8	12
24	19	17	13	14	16	12	11	8	8	10	10	10	12	15
20	17	18	9	12	11	11	12	9	10	10	9	10	18	15
17	14	13	12	11	14	11	12	9	9	9	11	12	13	15
17	14	17	10	11	13	11	10	10	11	12	13	14	12	17
14	9	14	12	11	9	11	9	7	7	10	11	10	10	17
18	10	11	11	18	9	11	11	13	11	13	12	11	9	15
12	9	11	12	9	8	14	14	15	12	13	15	13	11	12
15	14	13	9	8	12	12	17	17	11	10	11	9	11	18
15	12	18	18	12	14	17	20	18	14	8	12	12	11	20
17	14	12	17	17	7	12	18	10	10	10	10	10	12	16
19	14	18	14	15	12	10	10	10	11	8	11	11	18	20
17	14	14	18	13	18	13	14	9	10	11	13	12	13	20
19	12	14	14	14	15	11	12	11	9	10	12	12	12	15
25	13	14	11	12	12	11	14	11	12	12	13	15	12	19
17	12	14	13	12	10	12	13	14	12	14	16	12	12	21
18	11	11	11	11	11	11	11	10	12	13	17	12	11	18
18	9	10	10	10	12	11	12	10	12	11	14	14	12	18
16	11	10	10	12	10	12	12	13	12	12	13	13	15	19
18	11	12	11	12	11	12	14	11	14	13	14	14	15	18
18	12	12	13	14	12	11	13	9	12	12	14	14	14	19
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18	10	10	9	11	8	10	12	14	11	13	11	12	18	17
14	10	10	11	10	11	11	11	10	10	13	9	11	12	18
18	13	10	14	11	11	14	14	11	15	13	13	11	16	18
17	10	17	20	13	13	15	17	14	15	15	11	12	13	19
16	13	15	21	21	15	14	14	14	13	14	10	11	14	17
15	10	13	17	13	17	19	12	13	13	15	15	14	12	15
15	11	18	26	27	27	19	16	14	10	12	17	15	14	18
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15	12	18	22	22		21	18	14	14	15	15	18	12	17
18	12	12	17	27		22	18	15	17	19	22	17	14	19
15	12	10	14	22		22	15	19	17	17	20	13	12	19
17	12	12	16	19	18	21	17	18	12	15	13	11	13	20
18	18	18	15	16	21	22	22	20	21	21	20	17	19	15

MAX = 27 MIN = 7 MEAN = 14 STD. DEV. = 3.7

Figure 6

insulation, but removal of the lightweight insulating fill would have increased the volume of the demolition debris by at least sixfold. Further, the demolition, which would have unavoidably required the use of jackhammers, would have taken place over, and in close proximity to, an exclusive restaurant and club that serves executives in the oil industry. Both of these prospects were unacceptable to the building owner, and they were not completely amenable to the long-term aesthetic problem of having a construction elevator attached to the outside of the building. So, based upon the limited maintenance traffic occurring on the upper roof level, the overall height of this building, and its exposure to anticipated wind forces, as well as the roof renovation logistical problems, the roof system selected for the mechanical penthouse was a 60-mil, ethylene propylene diene monomer (EPDM) membrane installed in a proprietary, pressure-equalized design configuration.

This type of assembly avoided installation of fasteners into the lightweight fill, where concerns related to corrosion and adequacy of uplift resistance would be a problem. In addition, this particular membrane vendor had claimed success in drying out wet insulation using the pressure equalized design and was one of the few suppliers willing to warrant its roof installation over a damp substrate. As a design choice, it was decided not to install the roof in a recover assembly, so the original built-up roof membrane and all wood fiber insulation were removed down to the lightweight insulating fill in order to promote drying of the roof deck material.

Although the mopped vapor retarder was not fully removed, no efforts were made during the tear-off to protect this membrane. The contractor, in fact, was instructed to deliberately disturb the felt plies comprising this membrane before installing the loose-laid, siliconized gypsum sheathing board with fiberglass facers over which the P.E. single-ply membrane was ultimately installed. In keeping with the manufacturer's requirements, the sheathing and insulation were mechanically fastened for about four feet around the roof perimeter, and the EPDM membrane was fully adhered in this area (approximately 14% of the total), while being loose-laid in the field of the roof.

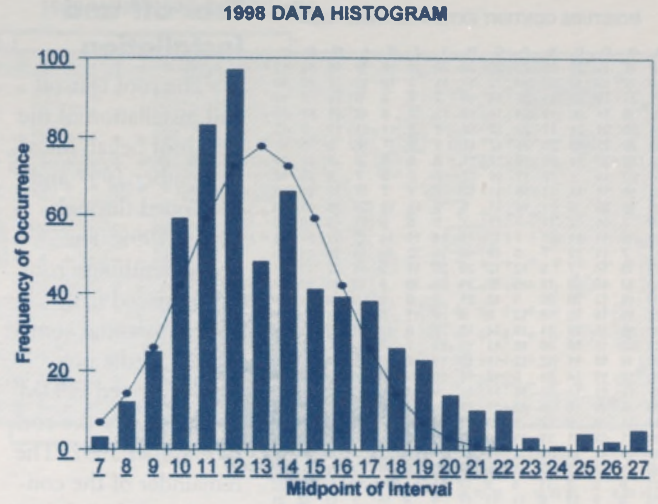

Figure 7

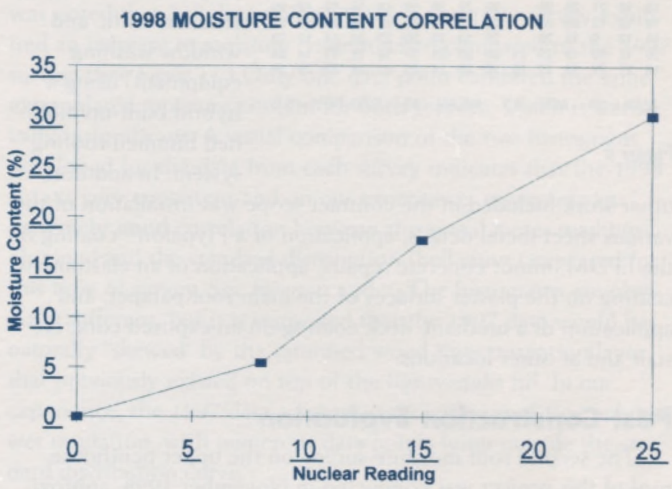

Figure 8

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
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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 9

Tear-off and Installation

The roof tear-off and installation of the new roof began in September 1997 and continued through March 1998. The upper penthouse roof was replaced first, with substantial completion of the pressure-equalized EPDM membrane 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/modified bitumen roofing system. In addition, other work included in the contract scope was installation of the various sheet metal details, application of a Hypalon® coating on the EPDM, minor concrete repairs, application of an elastomeric coating on the plaster surfaces of the main roof parapet, and application of a urethane deck coating on an exposed concrete stair and at other locations.

Post-Construction Evaluation

The second roof moisture survey on the upper penthouse roof of this project was conducted in November 1998, approximately 13 months after installation had been complete. 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 on this roof 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 the gravimetric correlation and extrapolation would provide adequate comparisons for the majority of the roof.

Local Weather Subsequent to Installation

In order to provide a complete evaluation of the P.E. roof system performance with respect to drying, we believe it is pertinent to discuss briefly the local weather that occurred in the Houston area subsequent to installation of the replacement roof. Obviously, it would be anticipated that a similar roof located in Phoenix, Arizona would behave differently (or else exhibit different drying characteristics) than an identical roof located in Seattle, Washington, simply due to the disparity between these two climates with respect to ambient temperature, air humidity, water vapor pressures, etc. Accordingly, it is pertinent to point out that we believe the conditions in Houston for the twelve-month period following installation of the P.E. roof system were excellent for achieving a good drying rate, if in fact that phenomenon is achievable.

During the first quarter of 1998, Houston experienced a winter that was rather mild but otherwise unremarkable with respect to temperature, humidity, and rainfall. However, it should be noted that Houston, and indeed all of Texas, suffered a significant period of drought from about April through August of 1998. In addition, the state recorded a record heat wave, with the City of Dallas reporting over 25 straight days of daily high temperatures above 100 degrees. While the temperatures in Houston were not as dramatic, the city also experienced a long, very dry, very hot summer. This pattern was finally broken in the fall, when, once in September and again in October, there was heavy rainfall and local flooding. Both of these rainfall events were related to the arrival of tropical storms but were not associated with hurricane activity. The remainder of the year returned to a more "normal" weather pattern. The point of this discussion is that during the prime period for anticipated drying of the P.E. roof system (i.e., the summer months), conditions in Houston could not have been better from a weather and environmental standpoint.

TEST RESULTS AND COMPARISONS

1997 Moisture Survey

As previously stated, the 1997 roof moisture survey indicated that the original wood fiber insulation was saturated, with a large majority of the roof area exhibiting moisture contents 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 contents below 25%. (Reference *Figures 1* through *5*.)

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 of the entire roof was 16%, with a standard deviation of 8%. Anderson has previously reported that lightweight insulating fill can exhibit a moisture content of up to 110% when subjected to immersion (1985). In our opinion, the differences in moisture contents 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.

1998 Moisture Survey

The 1998 roof 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 contents 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 insulating fill still exhibited moisture contents ranging from 4.7% to 33%. The mean moisture content throughout the readings of the entire roof was 15%, with a standard deviation of 5.6%. (Reference *Figures 6* through *10*.)

1998 MOISTURE CONTOURS

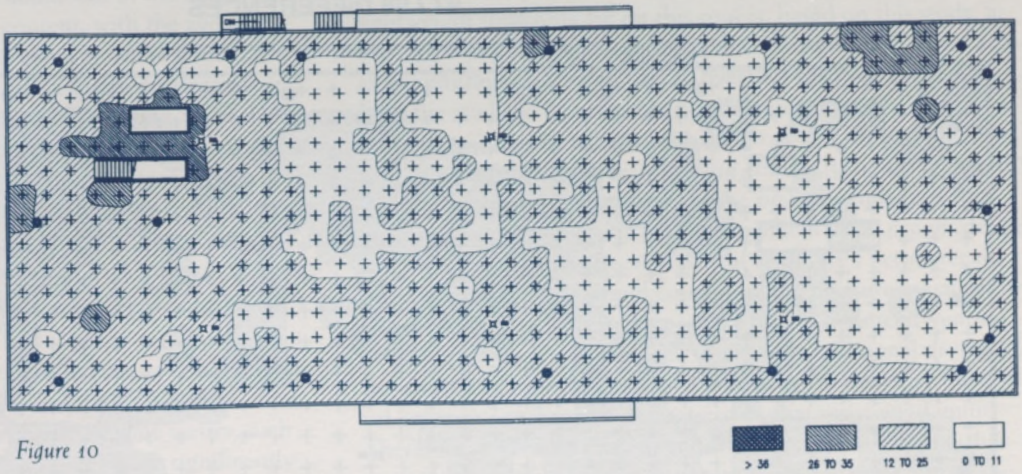

Figure 10

Comparisons and Contrasts

After a year of *in situ* performance, it is significant to point out 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 actually been decreased by ten percentage points by weight (representing an overall reduction of 23%). However, the mean moisture content was reduced by only 1% by weight (a reduction of about 6%). Nevertheless, the standard deviation had been reduced from 8% to 5.6% (a 30% change). From this data, it would be possible to conclude, at first blush, that a respectable amount of drying had taken place during the study period. However, an attempt was made to evaluate the drying rate of this roof at individual grid points. This further analysis yielded some unanticipated and rather surprising results!

Based upon a comparison of our two surveys, it was noted that 289 data points (48%) had decreased in moisture content from 1997 to 1998. However, using our field data on this roof, it was noted that 318 data points (52%) in the 1998 survey exhibited an increase in moisture content when compared to the 1997 survey. (See *Figure 11*.) Only one data point exhibited the same extrapolated moisture content for both surveys, which is statistically insignificant. A visual comparison of the two histograms developed for the data from each survey indicates that the 1998 data is very consistent and, in our experience, represents an extremely good correlation between the actual meter readings obtained and the standard distribution (bell curve) expected for this type of survey. See *Figures 2* and *7*. The histograms are obviously different, but it is suggested that the 1997 data would be naturally "skewed" by the saturated wood fiber insulation layer that previously existed on top of the lightweight fill. In our experience, the 1997 data are consistent with a roof that exhibits wet insulation, with numerous data points lying outside the standard distribution curve.

Further comparison of the data from both surveys indicated that of the 289 points exhibiting a decreased moisture content, the average decrease (or change) at individual grid points was

97 / 98 DIFFERENCES

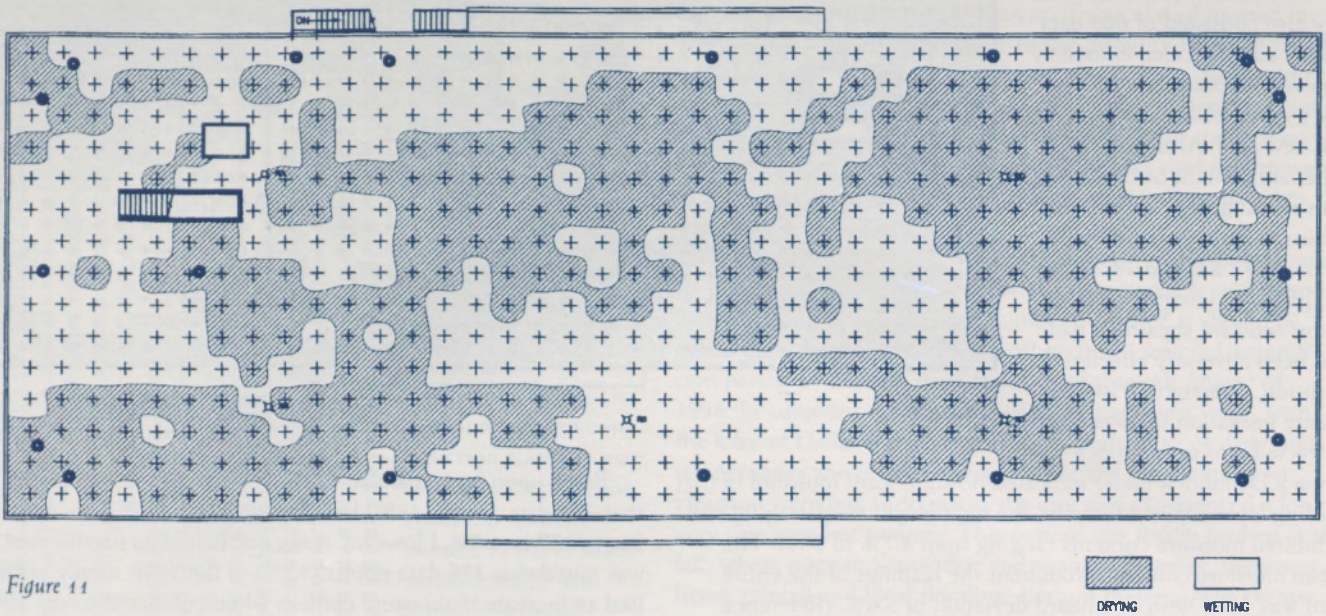

Figure 11

about 32%. By contrast, for those 318 points exhibiting an increase in moisture content, the average increase (or overall change) at each individual grid point was about 61%. So, essentially, it could be said that individual grid point locations on about half of the roof area increased in moisture content and did so by about twice the amount that the other half of the roof decreased. The cause of this observed anomaly is not known but it is somewhat instructive to tabulate the data points with respect to the various ranges, or breakdowns, of moisture contents utilized to draw the moisture contour maps for each survey. Although the break-down divisions are completely arbitrary, using identical breakdowns 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 lightweight insulating fill material. (Reference *Table 1*.)

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

As may be observed in the table above, the number of data points occurring in the two moisture content ranges that were most "wet" decreased in both the highest and next-to-highest range. The number of data points occurring in the lowest, or most "dry" range also decreased significantly; however, the number of data points occurring in the next-to-lowest range overwhelmingly increased. Of the 608 data points, 158 more points (401 total) exhibited moisture contents between 12% and 25% by weight in the second survey as compared to the first survey. According to this analysis, there appeared to be a "centralizing" of a great majority of the data points toward a moisture content range that was on the lower (drier) end of the scale, with the "most dry" points becoming slightly more damp and the "most wet" points becoming significantly drier.

A final evaluation of the two studies indicates that the 1998 survey exhibited apparent "drying" of specific areas such that the one-way pressure-equalization vents tended to be within or on the edge of the closest drying area. Sixteen of the eighteen P.E. vents installed on this roof (89%), when located on the contour map showing change of moisture contents at specific data points, occur adjacent to or within an area exhibiting drying. In our opinion, this is a fairly strong correlation between the location of these vents and the drying observed on this roof.

CONCLUSIONS

Based upon this study, it appeared that the overall moisture content of the lightweight insulating fill at this project had been slightly lowered (about 1%) 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 contents occurring within these materials appeared to have been reduced from 43% to 33%. Where the previous study indicated 14% of the total roof area exhibited moisture contents greater than 25% by weight, the second study indicated only 4% of the total roof area exhibited moisture contents greater than 25%. Based upon the evaluation of this one building, it cannot be stated with confidence whether the apparent drying was due to the P.E. membrane installation or simply due to the removal of the saturated wood fiber layer that had previously overlain the lightweight fill. However, it cannot be denied that the overall patterns and levels of moisture content within the lightweight had "changed" and the apparent change was positive with respect to the amount of moisture observed.

As has been previously noted, about half of the data points exhibited an increase in moisture content, with the average increase being about 61% of the original moisture content. In addition, about half of the data points exhibited a decrease in moisture content, with the average decrease being about 32% of the original moisture content. It should be noted, however, that assuming a dry weight of 26 pounds per cubic foot, a 32% reduction of moisture for a lightweight sample originally having 40% moisture content by weight represents a greater amount of total water (about 3.3 lbsm. H_2O) than a 61% increase of a sample originally having 10% moisture content by weight (about 1.6 lbsm. H_2O).

It was further observed from the differences among our 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 contents between 12% and 25% by weight increased from less than half the roof area (40%) to virtually two-thirds (66%) of the total roof area. This fact appears to indicate a "centralization" or "uniformity" effect for the moisture contents of this roof system. Accordingly, the patterns of drying and the amount of moisture actually removed from the roof appears 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, we would deem the results for this one roof to be essentially "inconclusive" with respect to determining once and for all: (a) whether significant drying may be induced from moist lightweight insulating fill using a P.E. membrane configuration; and (b) what drying rate might be anticipated by this type of design. The reasons for the variability of these results may be due to a number of factors, including one or more of the following:

1. Perhaps one year is an insufficient length of time to satisfactorily observe the drying phenomenon desired.
2. Perhaps roofs with lightweight insulating fill installed over a structural concrete (unvented) roof deck are not good candidates for the drying efforts claimed by the manufacturer for the P.E. roof membranes.
3. Perhaps other types of roof insulations (organic or plastic foam) would lend themselves better to the drying effects claimed.
4. The absence of a more consistent drying pattern on this building may have been due to the fact that the vapor retarder was not fully or consistently removed from all roof areas.

RECOMMENDATIONS

In our opinion, the design 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 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 air 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 circumventing (destroying) the critical pressure-equalization characteristics that resist wind uplift. Therefore, we would recommend that anyone considering this type of roof system be sure to obtain input and advice from the manufacturer for the intended design and that steps be taken to properly install the roofing system in general and the perimeter air seals in particular.

Based upon the current study, it may be prudent and informative to conduct an additional test on this building after more time has elapsed (i.e., perhaps the fall of 2000). This would allow a total of three years since installation, with the cumulative drying potential of three summers to promote the desired effects. In addition, we recommend that additional projects be selected 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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About the Author

Warren R. French is president and founder of French Engineering Inc., Houston, TX. French Engineering specializes in investigation and renovation of building envelopes experiencing moisture problems, including roofing, waterproofing, curtain wall, and condensation issues. He is currently Second Vice President of RCI.

Warren R. French, RRC

Correction

In the June issue of *Interface*, a table in the article by Derek Hodgin, "Wind Failures; Avoiding A Roof Failure Requires an Understanding of Many Factors Other Than Wind Speed," was misplaced. *Table 1* (on page 3) should have been inserted on page 5 after the first paragraph in the second column. The second paragraph should have been deleted, as it is actually part of the table. We regret any confusion this may have caused to the reader.

