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Moisture in the Roofs of Cold Storage Buildings

Wayne Tobiasson and Alan Greatorex

November 1998

Abstract: The low-slope roofs of 10 cold storage buildings in the Dallas area were examined visually and thermographically from above and below. Cores were taken to verify infrared findings, and 12- × 12-in. (30- × 30-cm) specimens of many of the insulations were removed for laboratory studies of their thermal properties. Insulations included fibrous glass, fiberboard, perlite, wood fiber, expanded and extruded polystyrene, isocyanurate, and phenolic. Areas of wet insulation were found in 8 of the 10 roofs. Some wetness was due to leaks caused by flaws in the roofing membranes and their flashings, but some was associated with infiltration of warm, moist outside air at roof–wall intersections without effective air seals. Of all the insulations examined, permeable fibrous glass was the most susceptible to wetting by air infiltration. Sustained one-way vapor drive, the sealing-in of moisture at the base of insulation in roofs of cold storage buildings by freezing, and the limited opportunities for drying wet insulation in such roofs provide incentives to use insulation that is very resistant to wetting. Its very low rate of moisture gain by vapor diffusion and its resistance to wetting in the presence of freeze–thaw cycles make extruded polystyrene insulation particularly appealing for use in the roofs of cold storage buildings.

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PREFACE

This report was prepared by Wayne Tobiasson (ret.), Research Civil Engineer, and Alan Greatorex, Civil Engineering Technician, Civil Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory.

The work was conducted as a Cooperative Research and Development Agreement (CRDA) between CRREL and Owens Corning. A CRREL and Owens Corning team investigated 10 different roofs in Dallas and Arlington, Texas, during the week of 16 September 1996. The field team consisted of Wayne Tobiasson and Alan Greatorex of CRREL and David Beatty and William Harris of Owens Corning. The roofs were on cold storage buildings owned by United States Cold Storage Inc. (USCS). Everardo Criado, Chief Engineer of the Dallas and Arlington installations for USCS was our on-site point of contact. Javier Hernandez assisted us in Dallas and Antonio Monsivars assisted us in Arlington. Seyforth Roofing Company Inc. (SRC) of Dallas, Texas, patched all membrane cuts. Michael Zwick was our point of contact with SRC. They were selected by USCS.

The authors thank Charles Korhonen and Byron Young of CRREL for technically reviewing the manuscript of this report.

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Moisture in the Roofs of Cold Storage Buildings

WAYNE TOBIASSON AND ALAN GREATOREX

INTRODUCTION

Several kinds of roofing systems of cold storage buildings (i.e., freezers and coolers) were inspected and sampled for entrapped moisture. The information collected was used to develop maintenance, repair, and replacement recommendations for these roofs. That information was also used to develop recommendations for improving the design of freezer and cooler roofs.

The following tasks were performed:

- Nighttime on-the-roof infrared roof moisture surveys (Tobiasson and Korhonen 1985) (Fig. 1).
- Daytime indoor infrared roof moisture surveys.
- Visual inspections of the membranes and their flashings.
- Core sampling of membranes and insulations and subsequent gravimetric measurement of the moisture content of those cores.
- Removal of 12- × 12-in. (30- ×30-cm) specimens of the various insulations for laboratory determination of the following properties:
  1. Dry density
  2. Moisture content
  3. Thermal resistance—as obtained
  4. Thermal resistance—after drying.

The 2-in.- (5-cm-) diam. cores were analyzed at CRREL. The 12- × 12-in. (30- × 30–cm) specimens were analyzed at Owens Corning.

INFRARED SURVEYS

Temperatures varied from daytime highs of 88°F (31°C) to nighttime lows of 62°F (17°C). The humidity was high, and a few showers were encountered that required us to halt coring and cutting operations and nighttime infrared surveys. However, not enough rain fell to prevent the surfaces of these roofs from drying out during the heat of the day.

In a prior study where we used an infrared scanner to find wet insulation in a ballasted roof over refrigerated spaces (Tobiasson and Greatorex 1994), numerous core samples revealed that the infrared scanner missed large areas of wet insulation deep in the roof. Indoor-outdoor temperature *differentials* were slightly less than the 27°F (15°C) minimum, then specified in ASTM C1153 (ASTM 1990). As a result, we recommended increasing that minimum to 32°F (18°C). The current version of C1153 contains that recommendation.

The indoor–outdoor temperature differentials for these Texas roofs were much greater than either of these minimums. We probably found most of the wet areas in these freezer roofs, but some questions remain and additional core samples are needed to verify some of our findings.

The large indoor–outdoor temperature differences present during these surveys tended to cause the top surface of the roof to be cooler (i.e., darker in the thermal image) where wet insulation was present. However, when the wet insulation was located near the top of the roof, a significant amount of solar energy was stored in it during the day. At night this "hot water bottle" of energy kept the surface of the roof there hotter (i.e., brighter in the thermogram) than at areas containing dry insulation. Thus, the nature of the thermal anomaly (i.e., hot / bright or cold / dark) changed with the type of insulation present, the amount of moisture it contained, and how deep in the roof the moisture was located.

The infrared surveys conducted within the freezers always detected bright (i.e., hot) thermal anomalies where wet insulation was present in the roof, since both effects (i.e., loss of insulating ability upon wetting and enhanced storage of solar energy in wet insulation) tend to warm that side of the roof.

THE ROOFS

A plan view of the seven roofs in Dallas (roofs D1–D7) is shown in Figure 2. The temperatures

Figure 1. Conducting nighttime on-the-roof infrared roof moisture surveys. We found it quite valuable to observe the roof from as high a vantage point as possible.

under those roofs are shown on that figure as are the locations of all cores and cuts made on them. Roofs D1–D6 are interconnected by lower roofs not shown in Figure 2. Figure 3 contains similar information for the three roofs in Arlington (roofs A1–A3).

All roofs except D5 have a loose-laid ballasted EPDM membrane. Roof D5 contains a loose-laid ballasted Hypalon membrane. All Dallas roofs except D7 contain an old bituminous built-up membrane below. The new membranes were added because the old ones were problematic. The old membrane is directly below the Hypalon membrane on roof D5. It is separated from the EPDM membrane on roof D6 by half an inch (1.3 cm) of wood fiber insulation and by 2 in. of expanded polystyrene insulation on roofs D1–D4. No old membranes exist within the three Arlington roofs. A number of different insulations exist within these roofs: expanded polystyrene (EPS), extruded polystyrene (XPS), isocyanurate (ISO), phenolic (PHE), perlite (PER) fibrous glass (FGL) and wood fiber (WOF).

Detailed information on each roof is presented in the sections that follow.

ROOF D1

This roof consists of a ballasted EPDM membrane, expanded polystyrene insulation (2 in.), an old bituminous built-up membrane, fibrous glass

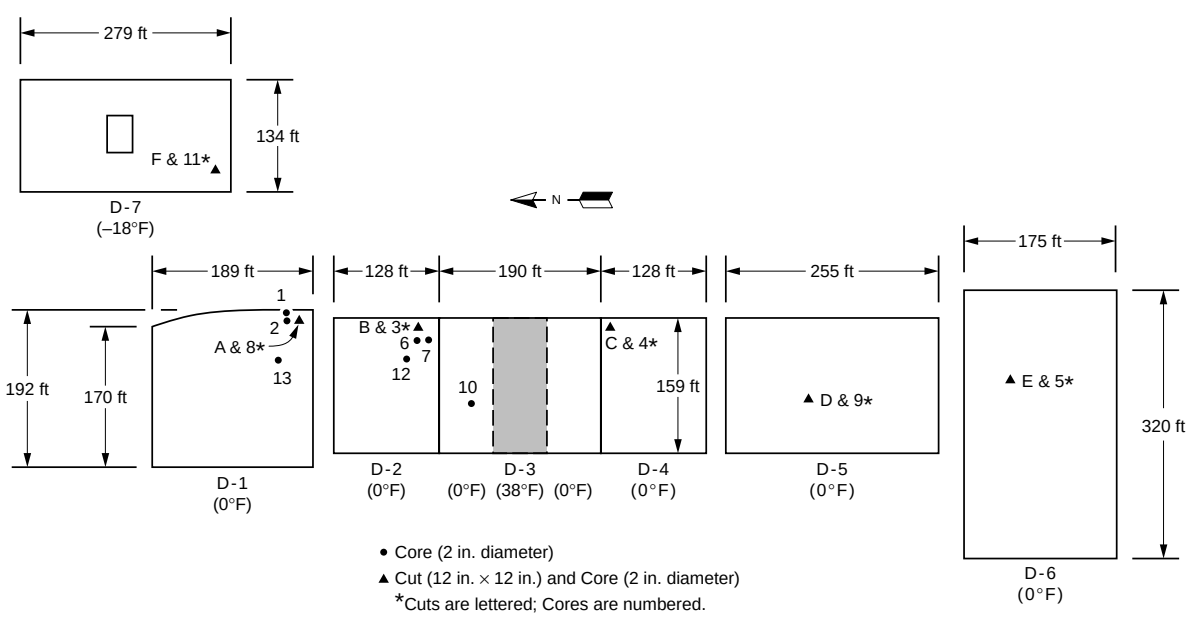

Figure 2. Plan view of the seven roofs examined in Dallas, Texas.

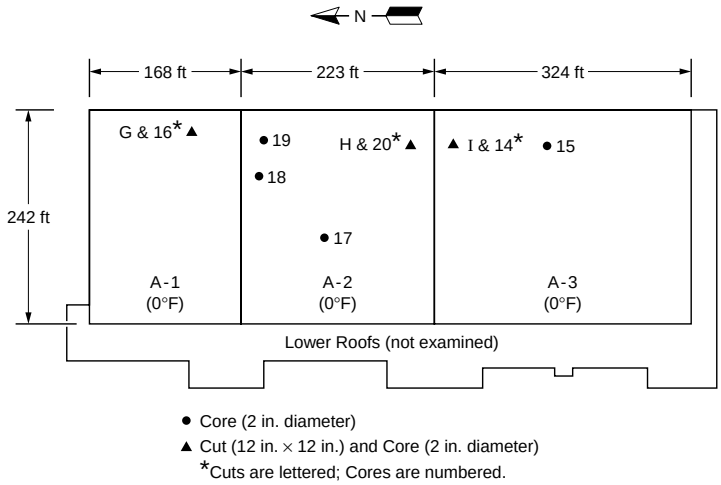

Figure 3. Plan view of the three roofs examined in Arlington, Texas.

insulation (7 in. [17.8 cm]) and a concrete deck. The temperature of the freezer below this roof was 0°F (–18°C).

The daytime visual inspection revealed that ballast scour by wind existed in the northwest corner (Fig. 4); a portion of the north edge metal was depressed below the level of the membrane (Fig. 5); and a failed patch (Fig. 6) existed along the north edge 115 ft (35 m) from the northwest corner.

The nighttime on-the-roof infrared survey uncovered only a small area of brightness (Fig. 7) at the failed patch shown in Figure 6. Finger probing into the flaw revealed that wet insulation existed directly below. A large cancer of wet insulation had not developed in this area, because little water drains across it and none ponds there. This flaw was patched by SRC in conjunction with our other work.

Bright areas were also detected by the infrared scanner in the southeast corner of this roof. Core samples 1, 2, and 8 and roof cut A were taken in this area (Fig. 2). Table 1 presents all core sample findings for this roof. The bottom 1 to 3 in. (2.5 to 7.6 cm) of fibrous glass insulation in this area was frozen "solid" (i.e., it was full of ice). Figure 8 shows the two areas of cleaned membrane where

Figure 4. Ballast scour in the northeast corner of roof D1.

Figure 5. Depressed edge along a portion of the north side of roof D1, looking west.

Figure 6. Failed patch along the north edge of roof D1, looking NW.

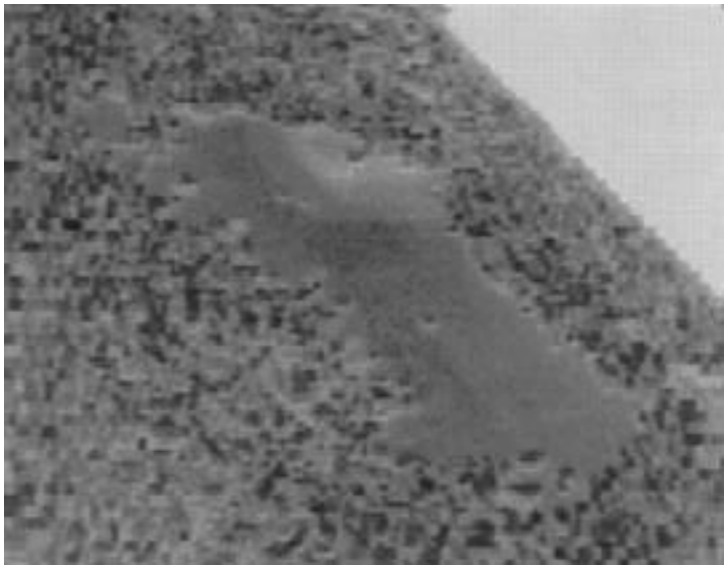

Figure 7. Thermal image (thermogram) of the failed patch shown in Figure 6, looking NW.

Table 1. Core sample findings for roof D1.

Core	*Insulation*	*Thickness (in.)*	*Moisture content (% of dry weight)*	*TRR (%)*	*Status*
1	EPS	0.87	0	100	dry
1	EPS	2	8	99	dry
1	FGL	2.5	25	88	dry
1	FGL(frozen)	1	455	16	**WET**
2	EPS	2	0	100	dry
2	FGL	2	0	100	dry
2	FGL	2	0	100	dry
2	FGL(frozen)	3	295	25	**WET**
8	EPS	2	2	100	dry
8	FGL	2	0	100	dry
8	FGL	2	1	99	dry
8	FGL	1	1	99	dry
8	FGL(frozen)	1	407	18	**WET**
13	EPS	2	1	100	dry
13	FGL	2	0	100	dry
13	FGL	2	0	100	dry
13	FGL	2	0	100	dry

Notes:
EPS = expanded polystyrene
FGL = fibrous glass
Samples are tabulated above as they are positioned in the roof from top to bottom.
Core 1: Taken near edge of roof where additional EPS was present as a tapered edge strip. Additional frozen fibrous glass existed below the portion sampled. It was probably about 3.5 in. thick.
Core 13: All of this sample was recovered down to the concrete deck and no frozen material was present. The thickness of fibrous glass does not add up to 7 in. This is probably due to the compression it experiences upon sampling.

Figure 8. Southeast corner of roof D1 showing areas cleaned for cores 1 and 2 and a larger area being prepared for core 8 and cut A, looking SE.

Table 2. Roof cut A, test results.

Insulation	*Thickness (in.)*	*Density (lb/ft³)*	*Moisture content (% of dry weight)*	*Thermal resistance*		*TRR (%)*
				As received	*After drying*	
EPS	2	1.0	14.7	7.2	7.4	97
FGL	2	8.0	2.6	7.9	8.1	98
FGL	3	6.0	14.8	3.9	10.9	36

Notes:
Thermal resistance units are $ft^2 \cdot hr \cdot °F/BTU$.
TRR = (as-received thermal resistance × 100) / after-drying thermal resistance.
An additional 1-in. layer of frozen FGL existed below the two layers sampled. It was full of ice and could not be removed intact for testing. Core 8 sampled this material. It had lost most of its insulating ability.

cores 1 and 2 were subsequently taken. The individual is marking the area where core 8 and cut A were taken. Core 13, taken nearby where shown in Figure 2, was outside this bright (wet) area. All insulation was dry where core 13 was taken. Thus it appears that only a small area of wet (frozen) fibrous glass insulation is present in the southeast corner of this roof. No obvious flaw was uncovered that could be held responsible for this problem. It is likely that the flaw was in the old membrane, and the wetness has been present since the old bituminous built-up membrane was overlaid with additional insulation and a ballasted EPDM membrane. Because this moisture is located deep in the roof, not near its top, the thermal anomaly should have been dark not bright. Since it was bright, something else is happening here. One possibility is that moist, warm air is infiltrating into this portion of the roof below the old membrane.

Figure 2 shows where 12- × 12-in. roof cut A was made. Results of tests run on the components of that cut are presented in Table 2. Core 8 was taken at the same place as cut A. Both found the expanded polystyrene insulation and the upper layer of fibrous glass insulation to be dry. However, the lower layer of fibrous glass obtained in cut A contained considerably more moisture than the similar layer in core 8 (14.8% vs. 1% by weight). In all likelihood, some of the wet fibrous glass below was collected in the cut while it was all left behind in the core. Prior CRREL studies (Tobiasson et al. 1991) indicate that fibrous glass with a moisture content of 14.8% by weight would have about 93% of its dry insulating ability (i.e., it would have a Thermal Resistance Ratio [TRR] of 93%). However, the TRR obtained by measuring the insulating ability of these fibrous glass specimens before and after drying them was only 36%. Differing test conditions (steady state in the prior CRREL studies and somewhat transient in these studies), and the ease with which moisture moves about in fibrous glass insulation explain the difference.

Infrared roof moisture surveys were also conducted from within this freezer. Figure 9 is a general view of the interior showing the deck of precast concrete double-tee beams. Figure 10 presents

Figure 9. Interior view of the freezer below roof D1, which has a precast concrete deck.

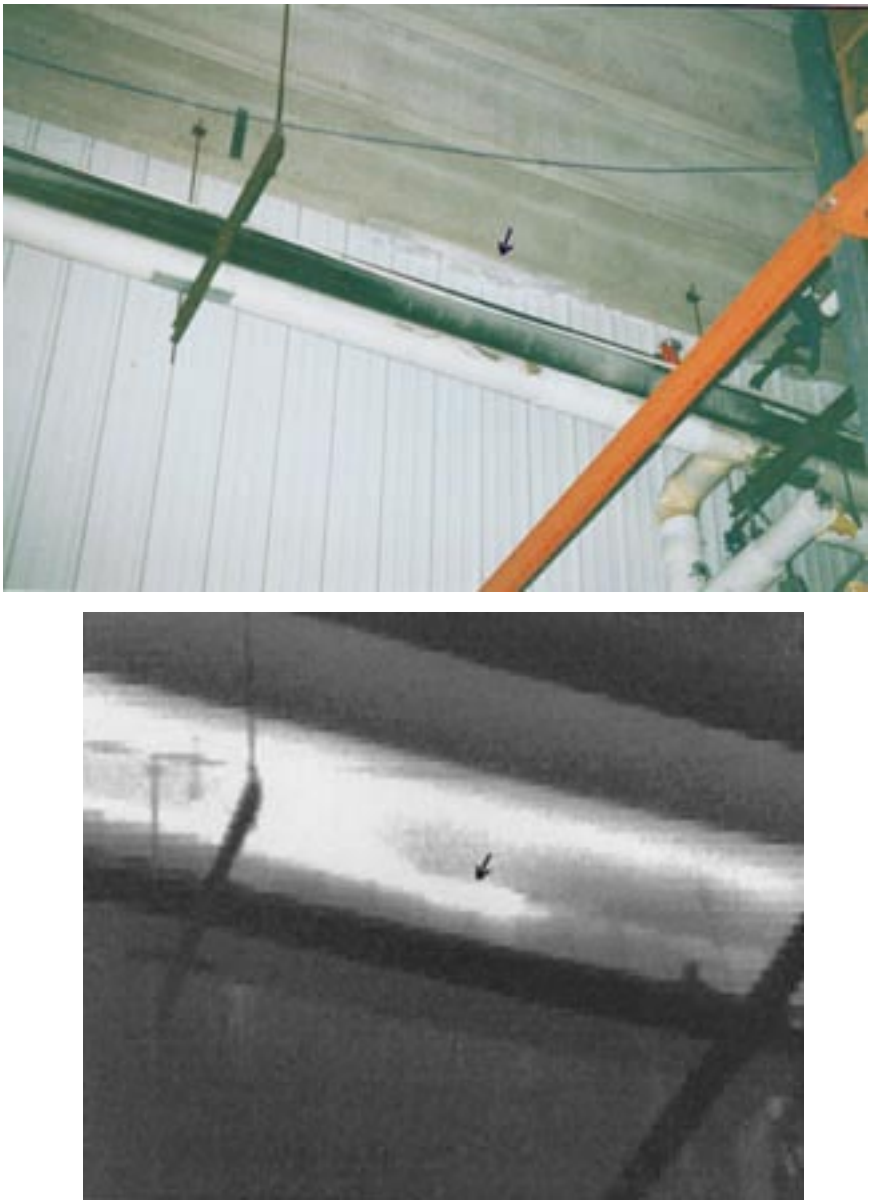

Figure 10. Photograph and thermogram from within the D1 freezer, showing ice and air infiltration where the roof and wall join.

a photograph and a thermogram of the area along the north side of the building where the roof and wall join. Ice is visible in the photograph and the bright thermal image indicates that warm outdoor air is leaking into the freezer along this seam. Figure 11 shows similar images taken of the northeast corner. Frost has accumulated there as warm outdoor air infiltrates into the freezer. Figures 10 and 11 indicate that air infiltration is occurring along the roof-wall intersection. The next time this freezer is warmed up, it may be appropriate to take steps to seal this joint. Spraying it with polyurethane foam may be worth considering. Warming this freezer could also be used to melt the ice in the fibrous glass insulation. The meltwater would probably leak out of the roof between the concrete double-tees, thereby drying out the wet fibrous glass insulation and recovering much of its lost insulating ability.

Most of the waterproofing membrane on this roof is in good condition. It may be wise to revise the north edge of this roof to eliminate the problem shown in Figure 5. It may also be appropriate to replace the stone ballast with roof pavers in the

Figure 11. Photograph and thermogram from within the D1 freezer showing frost, ice, and air infiltration in the northeast corner of the D1 freezer where the two walls and roof join.

northeast and northwest corners, and perhaps all along the north edge, to prevent ballast scour there. Pavers are more stable in high winds.

ROOF D2

This roof consists of a ballasted EPDM membrane, expanded polystyrene insulation (2 in.), an old bituminous built-up membrane, fibrous glass insulation (7 in.), and a concrete deck. The temperature of the freezer below this roof was 0°F.

The daytime visual inspection revealed no roofing defects. During the nighttime on-the-roof infrared survey, large bright thermal anomalies were detected in the southeast corner. A few marks were made with orange spray paint there to define the general extent of these bright areas. Figure 12 shows a photograph and a thermogram of this corner of the roof. Figure 13 shows a photograph and a thermogram of a small rhombic anomaly also in this general area. That wet area is also visible at

Figure 12. Photograph and thermogram of the southeast corner of roof D2, looking SE. The bright area on the thermogram defines where wet EPS insulation exists below the EPDM membrane.

the right edge of Figure 12. Table 3 presents all core sample findings for this roof and Table 4 presents findings for cut B. Cut B and core 3 were taken at about the same place but far enough apart to experience significant differences in moisture. The EPS insulation *above* the old membrane was wet at three of the four places sampled. Solar energy stored in the wet EPS caused this surface to be warmer there when we surveyed it. The new EPDM membrane probably is (or was) flawed here. No obvious flaws (or patches) were detected but some must be present. The ballast would have to be moved aside in this area to find them. If flaws are not found and eliminated, the amount of wet EPS insulation in this roof can be expected to increase. We also detected a small (2-ft [0.6-m] square) semibright area about 8 ft (2.4 m) in from the northwest corner of this roof. It was marked with spray paint. No obvious flaw was present there. Since that area was not very bright, we expect that the EPS insulation is dry but some frozen fibrous glass insulation is present below the old bituminous membrane.

The upper couple of inches of fibrous glass insulation were dry over the entire roof but, in 2 of the 4 places sampled; the lower 2 to 5 in. (5 to 13 cm) of that insulation was full of ice. At cores 3 and 6, where both the EPS and a portion of the fibrous glass were wet, the roof had lost about half of its insulating ability. All these problems are within a 40-×40-ft (12.2-× 12.2–m) area at the southeast corner of this roof. Currently, as evidenced

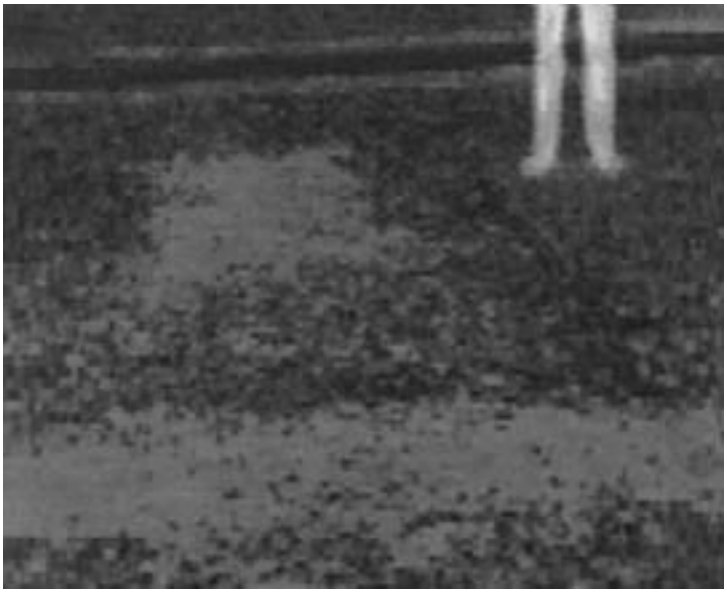

Figure 13. Photograph and thermogram taken near the area shown in Figure 12, looking south.

by core 12, most of the insulation in this roof is dry.

Leaving the wet insulation in this roof not only reduces its insulating ability but it also accelerates its rate of deterioration. It would be expensive to remove and replace all wet EPS insulation, but this option should be considered since this insulation cannot can be dried out in place. The bituminous membrane below prevents downward drying.

If this freezer is allowed to warm up and remain warm for a few days, the ice in the fibrous glass insulation will melt. The meltwater would probably run down between the seams in the concrete deck. In this way, it should be possible to somewhat dry that insulation.

A photograph and thermogram of the east end of the expansion joint that forms the south end of roof D2 are shown in Figure 14. The insulation did not feel soft (i.e., wet) within the bright area of the thermogram. This and other evidence suggests that this warmth was caused by air infiltration from the edge of the roof. As stated for roof D1, if

Table 3. Core sample findings for roof D2.

Core	*Insulation*	*Thickness (in.)*	*Moisture content (% of dry weight)*	*TRR (%)*	*Status*
3	EPS	2	430	69	**WET**
3	FGL	2	0	100	dry
3	FGL(frozen)	2	406	18	**WET**
6	EPS	2	568	62	**WET**
6	FGL	2	0	100	dry
6	FGL	3	0	100	dry
6	FGL(frozen)	2	429	16	**WET**
7	EPS	2	1010	41	**WET**
7	FGL	2.5	0	100	dry
7	FGL	2.5	1	99	dry
7	FGL	2	0	100	dry
12	EPS	2	2	100	dry
12	FGL	2	0	100	dry
12	FGL	2	0	100	dry
12	FGL	2	1	99	dry

Notes:
Core 3: An additional 3-in. layer of frozen fibrous glass insulation was present below the bottom of this core. It also had lost most of its insulating ability.
Cores 7 and 12: No frozen fibrous glass insulation here. It was all dry.

Table 4. Roof cut B, test results.

Insulation	*Thickness (in.)*	*Density (lb/ft^3)*	*Moisture content (% of dry weight)*	*Thermal resistance*		*TRR (%)*
				As received	*After drying*	
EPS	2	1.0	3337	1.8	7.1	25
FGL	2	8.6	9.0	7.0	7.5	93
FGL	2	5.6	1.1	10.1	9.9	102

Notes:
An additional 3-in. layer of frozen FGL existed below the two layers sampled. It was full of ice and could not be removed intact for testing. Core 6 sampled similar material that had lost most of its insulating ability.

and when this freezer is warmed up, such air infiltration paths should be blocked.

The wet and dry thermal resistance measurements made of cut B (Table 4) indicate that the EPS insulation there had only about 25% of its dry insulating ability. At adjacent core 3, the EPS contained much less moisture (430% by weight vs. 3337% at cut B) and had about 69% of its insulating ability (Table 3). By either measurements the EPS was quite wet and had lost a significant portion of its insulating ability.

ROOF D3

This roof consists of a ballasted EPDM membrane, expanded polystyrene insulation (2 in.), an old bituminous built-up membrane, fibrous glass insulation (7 in.), and a concrete deck. As shown in Figure 2, the middle third of this roof is over a 38°F (3°C) cooler and the rest is over 0°F freezers. Roof D3 is separated from roofs D2 and D4 by expansion joints. The one at D2 is visible just behind the individual in Figure 13. It is also shown in Fig-

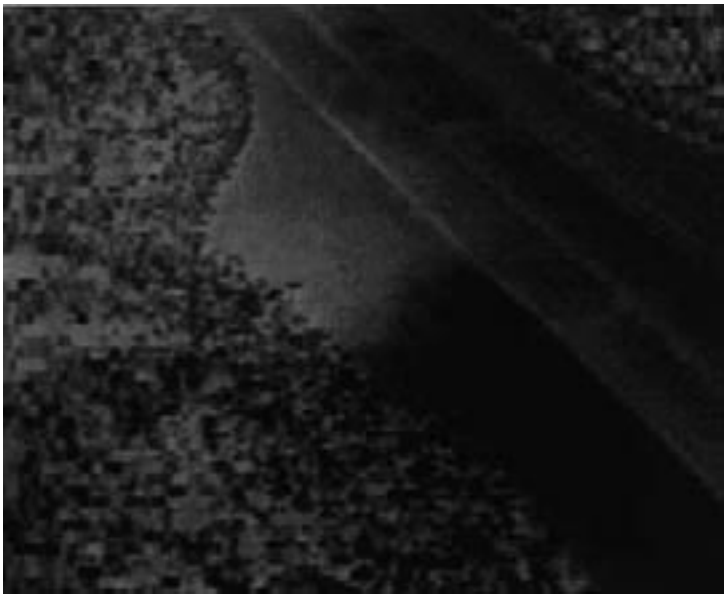

Figure 14. Photograph and thermogram of the east end of the expansion joint at the southeast corner of roof D2. The intense brightness on the thermogram is probably due to air infiltration, not wet insulation.

ure 14. Figure 15 shows it again along with the bright thermal image that extends from it onto this roof. A few orange spray painted marks were made on the roof to indicate where this bright 2-ft-wide, 52-ft-long (0.6- × 16-m) strip is located. It is parallel to and about 50 ft (15.2 m) from the east edge of this roof. We did not core the roof in this area, so we do not know for sure if it contains wet insulation. Our uncertainty is due to differences in ballast color in this area, which are also, in part, responsible for the bright thermal images. The owner may wish to investigate this further to determine if wet EPS or wet fibrous glass is present since, as stated for roofs D1 and D2, moisture in each insulation should be responded to in a different way. If the EPS is wet, the EPDM membrane

Figure 15. Roof D3, looking south from the expansion joint that separates it from roof D2. The bright area on the thermogram may indicate the presence of wet insulation.

should be inspected closely with the goal of finding the flaw(s) where water bypassed the waterproofing system.

The western half of this roof contained numerous parallel bands of brightness when viewed with the infrared scanner. Figure 16 shows a photograph and thermogram of three such bands. They were all caused by differences in the ballast. All bright areas correspond to bands of dark ballast as can be seen in the Figure 16 photograph. Core 10, the only sample taken on this roof, was taken in one of the bright areas to verify that all the brightness was caused by dark ballast. Its location is shown in Figure 2. Table 5 presents the information obtained at core 10. It verified that these bright bands were *not* moisture related.

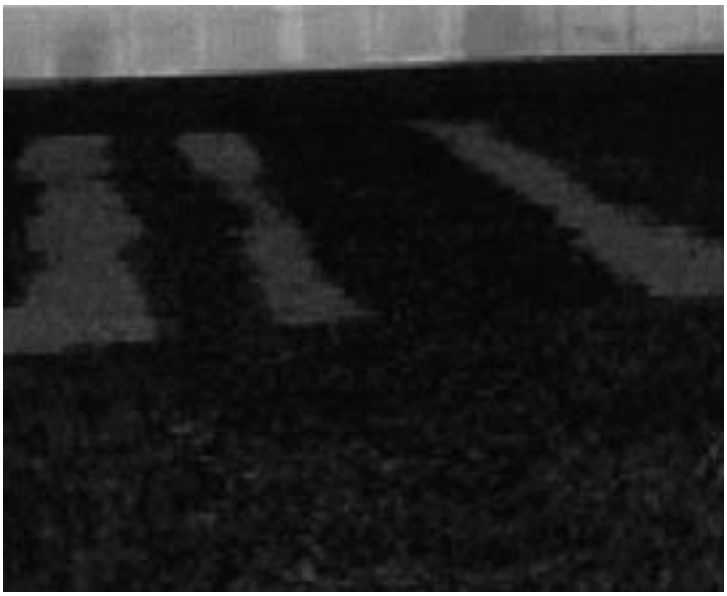

Figure 16. Roof D3, looking west. The bright bands on the thermogram are due to dark ballast in those areas as shown in the photograph. Core 10, taken in one of the bright bands, verified that the brightness is not due to wet insulation.

Table 5. Core sample findings for roof D3.

Core	*Insulation*	*Thickness (in.)*	*Moisture content (% of dry weight)*	*TRR (%)*	*Status*
10	EPS	2	0	100	dry
10	FGL	2	0	100	dry
10	FGL	3	0	100	dry
10	FGL	2	1	99	dry

Figure 17. General view of roof D4 looking towards downtown Dallas (i.e., about southeast).

ROOF D4

This roof consists of a ballasted EPDM membrane, expanded polystyrene insulation (2 in.), an old bituminous built-up membrane, fibrous glass insulation (7 in.), and a concrete deck. The temperature of the freezer below this roof was 0°F. A general view of this roof is shown in Figure 17. There were no bright or dark thermal anomalies on it. However, the infrared survey done within the freezer revealed extra brightness within a few feet (about a meter) of the northeast corner of this roof. That brightness was similar to that shown for roof D1 in Figure 11. We expect that it was caused by air infiltration not wet insulation. Core 4 and cut C were taken in this area to verify our suspicions. Core 4 findings are presented in Table 6 and cut C findings in Table 7. At core 4, a thin (1/4-in.- [6-mm-] thick) layer of frozen fibrous glass insulation was present on the concrete deck, but the rest of the insulation was dry. When cut C was taken, we noticed that there was a lot of frost in the fibrous glass near an insulation seam but little frost in the middle of the insulation board. Finding frost, not ice, suggests that moist outdoor air infiltrating into the freezer in this area has deposited some of its moisture within the insulation. Some moisture has also entered the freezer and has frosted the roof–wall intersection in this area, similar to that shown in Figure 11.

ROOF D5

This roof consists of a ballasted Hypalon membrane, a thin slip sheet, a thin, old mineral sur-

Table 6. Core sample findings for roof D4.

Core	*Insulation*	*Thickness (in.)*	*Moisture content (% of dry weight)*	*TRR (%)*	*Status*
4	EPS	2	1	100	dry
4	FGL	2	0	100	dry
4	FGL	2.5	0	100	dry
4	FGL	1.75	0	100	dry
4	FGL(frozen)	0.25	357	20	**WET**

Table 7. Roof cut C, test results.

Insulation	Thickness (in.)	Density (lb/ft^3)	Moisture content (% of dry weight)	Thermal resistance: As received	Thermal resistance: After drying	TRR (%)
EPS	2	1.1	0	7.2	7.2	100
FGL	2	8.4	0.7	7.4	7.4	100

Notes:
About 5 in. of FGL was present below this. The lower 1/2 in. was frozen to the deck and the rest broke apart into small pieces during sampling, so it was not retained for testing. Core 4 sampled this material.

faced bituminous built-up membrane, perlite insulation (3 in. [7.6 cm]), fibrous glass insulation (5 in. [12.7 cm]), and a concrete deck. The temperature of the freezer below this roof was 0°F.

The Hypalon was not well installed and numerous wrinkles are present as shown in Figure 18. There is one bare spot on the roof where ballast does not protect the Hypalon. It is shown in Figure 19. The membrane is also wrinkled there. There were no bright or dark thermal anomalies on this roof. Core 9 and cut D were taken near the center of this roof where shown in Figure 2. Figure 20 shows the amount of dirt present on the Hypalon membrane. A considerable amount of effort was needed to clean the membrane so that it could be cut and patched properly. Figure 21 shows the cut made when taking cut D. That hole was backfilled with dry insulation before the membrane was patched. Table 8 presents findings of core 9 and Table 9 presents findings of cut D. The perlite is essentially dry and has retained most of its insulating ability. Portions of the fibrous glass insulation are wet, and that moisture has reduced its insulating ability. The lack of well-defined thermal anomalies suggests that this level of wetness is present over most of the roof.

No flaws were evident on this roof. It would take a more detailed investigation to determine how the fibrous glass insulation became wet without wetting the thick layer of perlite insulation above. The fact that the perlite is dry suggests that the moisture in the fibrous glass was there before the Hypalon membrane was installed over the original bituminous built-up membrane. It also

Figure 18. Raised edge of roof D5 showing wrinkled Hypalon.

Figure 19. Bare area on roof D5, looking southwest.

Figure 20. Cleaning the roof D5 Hypalon membrane before making cut D.

suggests that this moisture, which is located quite some distance from the perimeter of the roof, may have been introduced by air infiltration, not by leaks in the waterproofing membrane.

If this freezer is ever warmed up and allowed to remain warm for a few days, some of the ice in the fibrous glass insulation would melt and, in all likelihood, drip down into the freezer, thereby recovering some of the insulating ability of the fibrous glass. However, moisture in the upper layer of fibrous glass insulation cannot be expected to drain and dry this way.

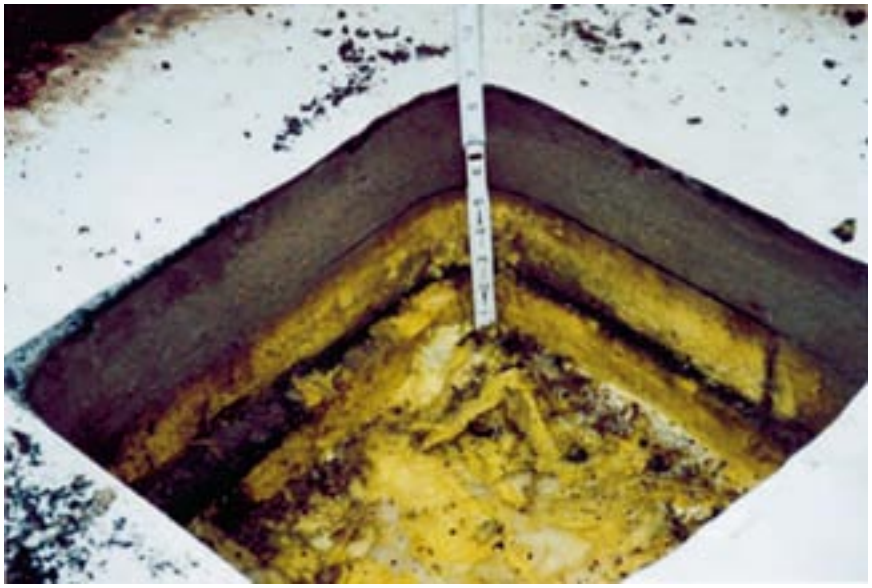

Figure 21. Cut D on roof D5 showing layers of perlite and fibrous glass insulation.

Table 8. Core sample findings for roof D5.

Core	*Insulation*	*Thickness (in.)*	*Moisture content (% of dry weight)*	*TRR (%)*	*Status*
9	PER	3	1	98	dry
9	FGL	2	0	100	dry
9	FGL	0.25	327	22	**WET**
9	FGL	1.75	8	96	dry

Notes:
PER = perlite.
The 0.25 in. thick layer of FGL was the bottom of the top layer of FGL. The facer below allowed water to accumulate here.
Another 0.25 in. of FGL was present below the 1.75-in. FGL listed above. A sample of it was taken when cut D was made. It had a moisture content of 966% and a TRR of 10%; thus it was also **WET**.

Table 9. Roof cut D, test results.

Insulation	*Thickness (in.)*	*Density (lb/ft^3)*	*Moisture content (% of dry weight)*	*Thermal resistance*		*TRR (%)*
				As received	*After drying*	
PER	3	9.9	5.8	6.1	6.9	88
FGL	2	4.9	68.5	6.0	11.7	51

Notes:
Two more inches of fibrous glass were present below the insulations listed above. The bottom of this layer contained ice and was frozen to the roof deck. Its condition is discussed in the Table 8 notes.

Figure 22. Hole where core 5 was taken and where cut E is being taken on roof D6.

ROOF D6

This roof consists of a ballasted EPDM membrane, wood fiber insulation (0.5 in. [1.3 cm]), an old mineral-surfaced bituminous built-up membrane, perlite insulation (1 in.), expanded polystyrene insulation (10 in. [25.4 cm]), and a concrete deck.

The temperature of the freezer below this roof was 0°F.

No signs of entrapped moisture were detected during the infrared surveys of this roof. During the visual inspection, no membrane or flashing defects were noticed. Core 5 and cut E were taken where shown in Figure 2. Figure 22 shows cut E being taken where core 5 had been taken. Figure 23 shows the wall of the cut E hole. Table 10 presents findings for core 5 and Table 11 presents findings for cut E. All three types of insulation at this location were dry.

This roof is in excellent condition.

ROOF D7

This roof consists of a ballasted EPDM membrane, expanded polystyrene insulation (12 in. [30.5 cm]), perlite insulation (1 in.), and a steel deck. The temperature of the freezer below this roof was –18°F (–28°C).

Figure 23. Cut E on roof D6 showing layers of wood fiber, perlite, and expanded polystyrene insulation.

Table 10. Core sample findings for roof D6.

Core	*Insulation*	*Thickness (in.)*	*Moisture content (% of dry weight)*	*TRR (%)*	*Status*
5	WOF	—	4	91	dry
5	PER	1	1	98	dry
5	EPS	5	0	100	dry
5	EPS	5	1	100	dry

Notes:
WOF = wood fiber

Table 11. Roof cut E, test results.

Insulation	*Thickness (in.)*	*Density (lb/ft³)*	*Moisture content (% of dry weight)*	*Thermal resistance*		*TRR (%)*
				As received	*After drying*	
EPS	5	1.0	0	15.1	15.0	101
EPS	5	1.0	0	14.9	14.9	100

Notes:
The 0.5-in. wood fiber and 1-in. perlite insulations above the EPS fell apart when this sample was taken. Table 10 indicates that they were dry at adjacent core 5.

The thermal image of this roof was uniformly bright except for a dark (cold) band that started along the south side of the penthouse and ran west to the west side of the roof. This band is shown in Figure 24, which is a mosaic of three thermograms. The visual inspection revealed that cold water from refrigeration equipment at the penthouse was draining across the roof and causing this thermal anomaly. The uniform nature of the thermal image over the rest of this roof suggested that there was no wet insulation in cut I or that it was uniformly wet. As shown in Table 12, core 11, taken where shown in Figure 2, determined that the bottom 6-in. (15.2-cm) layer of expanded polystyrene (EPS) insulation was quite wet. The water and ice in it had reduced its insulating ability to about 65% of its original value. The 1-in.-thick layer of perlite insulation below was also wet and had only about half of its original insulating ability. These two layers of frozen insulation could not be removed in big enough pieces for testing when cut F was taken. Figure 25 shows cut F in progress. Table 13 presents test results for the EPS insulation removed from cut F.

Figure 24. Thermogram showing the cold band caused by movement of cold water from refrigeration equipment across roof D7, looking north.

Table 12. Core sample findings for roof D7.

Core	*Insulation*	*Thickness (in.)*	*Moisture content (% of dry weight)*	*TRR (%)*	*Status*
11	EPS	6	2	100	dry
11	EPS	6	508	65	**WET**
11	PER (frozen)	1	116	54	**WET**

Notes:
The upper layer of EPS was damp on its bottom.
The lower layer of EPS was mostly frozen.

The thermal image of the entire roof, being of a uniform tone, suggests that the lower layer of EPS insulation is wet over the entire roof. If this is true, that is indeed unfortunate since this is a relatively new roof. Additional samples should be taken to determine the full extent of wet insulation in this roof.

We were not able to determine the source of the moisture found in this roof. Thermographically, there were no brighter or darker areas of the type that point to the membrane and flashing flaws through which moisture is currently gaining access. Since vapor drive is downward year-round for a freezer in Texas, we do not think this is a condensation problem. We speculate that enough moisture has entered at membrane or flashing flaws on occasion in the past to create several inches of hydrostatic pressure in the vertical seams between the 13-in.- (33-cm-) high "pile" of insulation boards in this roof. That moisture froze at its base, allowing the water above to spread laterally within the roof along the vertical seams and horizontal surfaces between boards. In the process, the continuous downward vapor drive forced that moisture into the perlite and EPS insulations

The samples taken on this roof were near its perimeter. It is possible that air infiltration at inadequate seals between the roof and walls allowed moisture into this area, or that the amount of wet insulation diminished gradually with increasing distance from the perimeter. These possibilities further support the need for additional samples.

It takes quite some time to dry out most wet insulations, particularly cellular plastic insulations

Figure 25. Taking cut F on roof D7. The lower layer of EPS was "full" of ice and frozen to the deck. A 12- ×12-in. sample of it could not be obtained.

Table 13. Roof cut F, test results.

Insulation	*Thickness (in.)*	*Density (lb/ft³)*	*Moisture content (% of dry weight)*	*Thermal resistance*		*TRR (%)*
				As received	*After drying*	
EPS	3	0.8	0	11.0	11.1	99
EPS	3	0.9	2.2	10.6	10.6	100

Notes:
The two 3-in.-thick layers of EPS tested were cut from a 6-in.-thick layer of EPS insulation. Another 6-in.-thick layer of EPS was present below. It was very wet, fell apart, and could not be sampled. Core 11, taken at this location, indicates that it had only 65% of its insulating ability. A 1-in.-thick layer of perlite insulation was present below the EPS. It was frozen to the deck. Core 11 indicates that it was quite wet and had only 54% of its insulating ability.

such as EPS. Fibrous glass insulation can be an exception. It wets fast but, on occasion, it can dry out rapidly. It is probably impractical to try to dry out the wet perlite and EPS insulations in this roof. If further studies indicate that much of this roof contains wet insulation, the economic impact of having lost, perhaps, a third of this roof's insulating ability to wet insulation should be determined.

ROOF A1

This roof consists of a ballasted EPDM membrane, extruded polystyrene insulation (6 in.), isocyanurate insulation (3 in.), and a steel deck. The temperature of the freezer below this roof was 0°F.

The daytime visual inspection uncovered no signs of membrane or flashing distress on this roof. The nighttime on-the-roof infrared survey uncovered only one cold (dark) line where nothing existed visually on the roof. Those thermal and visual images are shown in Figure 26. The dark line was found to be a flush expansion joint hidden below the ballast. The findings of core 16 are presented in Table 14 and the findings of cut G are presented in Table 15. Their locations are shown in Figure 3. No wet insulation was found. Figure 27 shows the hole made when taking cut G. As shown in that figure, no rust existed on the steel deck.

This roof is in excellent condition.

ROOF A2

This roof consists of a ballasted EPDM membrane, phenolic insulation (6 in.), and a steel deck. On the north it is bounded by a higher wall and, on the south, by an expansion joint that separates it from roof A3. Two large penthouses are present on this roof. Ballast has been moved aside in a few places in what appear to be searches to stop leaks. This includes a portion of the expansion joint where this roof joins roof A3. That area is shown in Figure 28. At least one patch has been made in that area. The temperature of the freezer below this roof was 0°F.

The on-the-roof nighttime roof moisture survey uncovered several dark anomalies on this roof. The thermogram shown in Figure 28 suggests that some moisture may exist directly under the membrane at the patch.

Figure 29 shows another area of disturbed ballast. While they cannot be seen in the Figure 29 thermogram, we could see the outlines of individual insulation boards during the survey. The spray painted lines on the photograph mark some such outlines. The dot on the photograph is where core 18 was taken. Figure 30 shows a portion of the phenolic insulation core taken here. Findings from the four cores taken on this roof are presented in Table 16. Core 18 contained wet phenolic insulation. Perhaps moisture entered the roofing system at the place where a patch had already been made (just above the dot in the Figure 29 photograph). However, it is also possible that other flaws exist in this area.

Figure 31 shows a thermally dark area to the west of the west penthouse on this roof. The photograph and the thermogram were taken from roof A1, which is about 9 ft (2.7 m) higher. Core 17 was taken in the middle of that dark area. As indicated in Table 16, core 17 contained wet phenolic insulation. We did not remove ballast in this area to search for the membrane flaw through which that

Figure 26. Photograph and thermogram of roof A1, looking west. The dark line in the thermogram is a hidden expansion joint.

Table 14. Core sample findings for roof A1.

Core	*Insulation*	*Thickness (in.)*	*Moisture content (% of dry weight)*	*TRR (%)*	*Status*
16	XPS	3	1	100	dry
16	XPS	3	1	100	dry
16	ISO	3	1	100	dry

Notes:
ISO = isocyanurate

Table 15. Roof cut G, test results.

Insulation	*Thickness (in.)*	*Density (lb/ft^3)*	*Moisture content (% of dry weight)*	*Thermal resistance*		*TRR (%)*
				As received	*After drying*	
XPS	3	2.0	0.8	14.0	14.4	97
XPS	3	2.0	0.0	14.6	14.8	99
ISO	3	2.3	2.0	19.0	19.4	98

Notes:
Steel deck contains a small amount of rust.
Core 16 was taken at this location.

Figure 27. Hole made in roof A1 when taking cut G. No rust existed on the steel deck.

Figure 28. Photograph and thermogram of the expansion joint that separates roofs A2 and A3, looking a little south of east. The bright spot on the thermogram suggests that wet insulation exists below the patch.

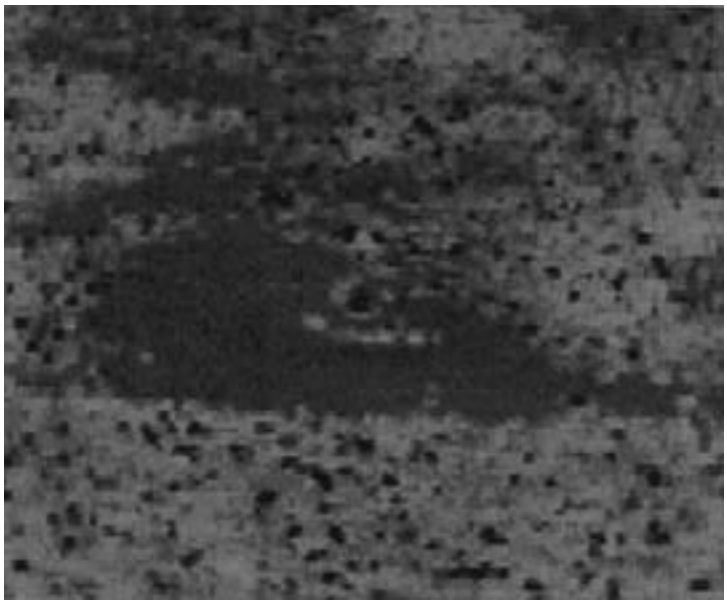

Figure 29. Photograph and thermogram of disturbed ballast on roof A2, looking north. The spray painted lines outline some insulation boards and the dot is where core 18 would soon be taken. Insulation was wet there.

Figure 30. Upper layer of phenolic insulation at core 18.

Table 16. Core sample findings for roof A2.

Core	*Insulation*	*Thickness (in.)*	*Moisture content (% of dry weight)*	*TRR (%)*	*Status*
17	PHE	3	2542	near zero	**WET**
17	PHE (frozen)	3	546	25	**WET**
18	PHE	3	61	68	**WET**
18	PHE (frozen)	3	326	37	**WET**
19	PHE	3	2844	near zero	**WET**
19	PHE (frozen)	3	1962	near zero	**WET**
20	PHE	3	4	96	dry
20	PHE	3	8	92	dry

Notes:
The TRR of the three samples with moisture contents in excess of 1000%, calculate to less than zero using information in Tobiasson et al. (1991). Their actual thermal resistivity is probably close to that of ice (i.e., about 0.06 $ft^2 \cdot hr \cdot °F/BTU \cdot in.$). Since the thermal resistivity of dry phenolic is about 10 $ft^2 \cdot hr \cdot °F/BTU \cdot in.$, their TRRs, using the value of ice, are about 1%.

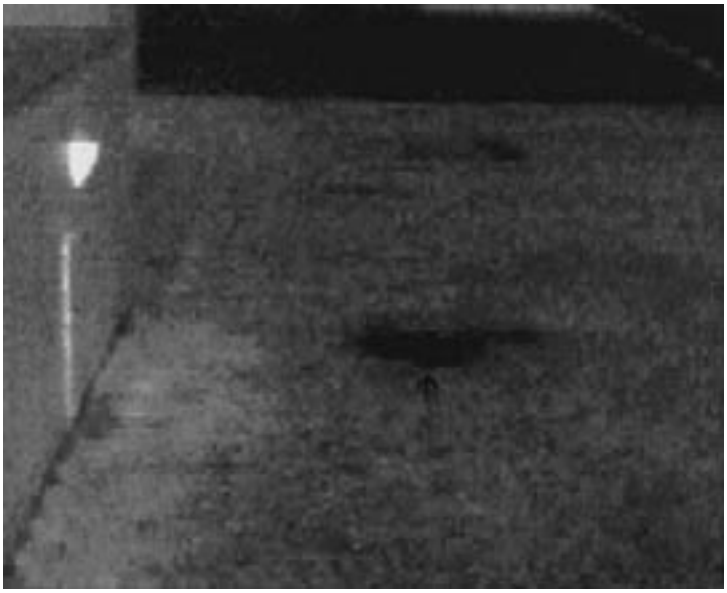

Figure 31. Photograph and thermogram of a strong thermal anomaly on roof A2, looking south. Core 17, taken here, found wet insulation.

moisture entered the roof. We expect that a search will find it within a 4-ft radius of the patch we made in the membrane where core 17 was taken.

Figure 32 shows a photograph and thermogram where core 19 was taken. When the ballast was moved aside to take core 19, it was noticed that there was a lot of fine-grained soil on the membrane. As that soil was moved aside, a 1-in.-long slit was found in the membrane (Fig. 33 and 34). It explains why insulation in this area is wet. We took core 19 at the slit so that the patch made to seal the core hole would also cover the slit.

Core 20 and cut H were taken where shown in Figure 3. Figure 35 shows cut H being taken. Findings of cut H are presented in Table 17. The phenolic insulation contained only a little moisture, which reduced its insulating ability by only a few percent. The steel deck below contained a small amount of rust.

The acid released by phenolic insulation when

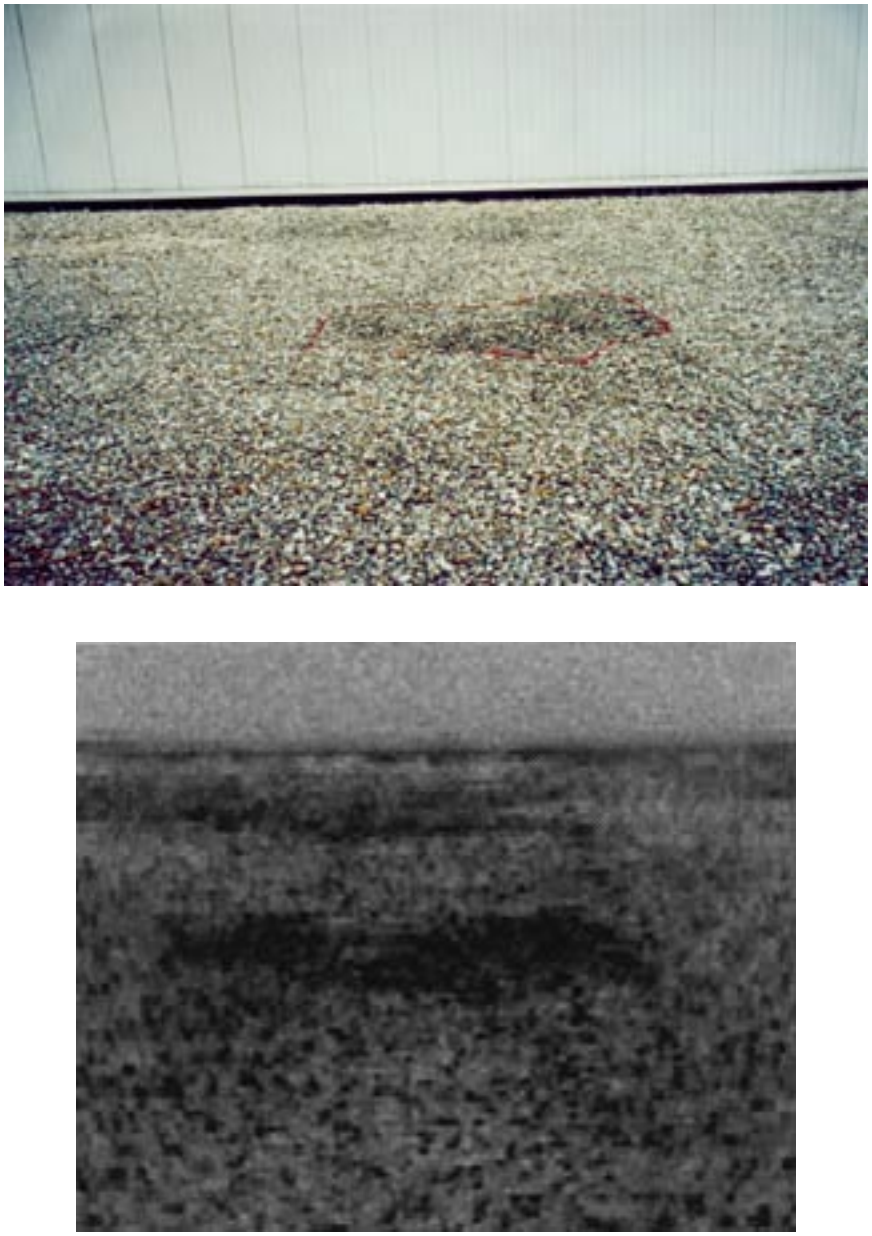

Figure 32. Photograph and thermogram of another strong thermal anomaly on roof A2, looking north. Core 19, taken here, found wet insulation.

Figure 33. Ballast contained a lot of fine soil where core 19 was taken. Note the membrane slit at the upper end of the pencil.

Figure 34. The membrane slit shown in Figure 33 after cleaning the membrane.

Figure 35. Cut H on roof A2. A small amount of rust was present in the flutes of the steel deck.

it becomes wet has caused serious rusting of steel decks in conventional buildings. The removal of phenolic insulation from the roofing market because of this problem attests to its very serious consequences. The much retarded rate of this chemical reaction at low temperatures has saved the steel deck on this freezer from being ruined. However since some rusting is occurring, *the wet phenolic insulation in this roof must be considered a very serious problem that requires attention*. The manufacturer of this insulation should be determined and contacted. It may be possible to obtain some financial assistance without the need to take legal action.

ROOF A3

This roof consists of a ballasted EPDM membrane, perlite insulation (0.75 in. [1.9 cm]), expanded polystyrene insulation (12 in.), perlite insulation (0.75 in.), and a steel deck. The temperature of the freezer below this roof was 0°F. Like adjacent roof A2 this roof contains some areas of disturbed ballast that appear to be related to searches for leaks. One such area is shown in the photograph and thermogram of Figure 36, which shows water ponded along the west edge of this roof. The dark area on the thermogram is much bigger than the area of bare membrane where the

Table 17. Roof cut H, test results.

Insulation	*Thickness (in.)*	*Density (lb/ft³)*	*Moisture content (% of dry weight)*	*Thermal resistance*		*TRR (%)*
				As received	*After drying*	
PHE	3	2.9	2.8	23.0	24.4	94
PHE	3	2.8	5.2	21.8	23.4	93

Notes:
Steel deck contains a small amount of rust.
Core 20 was taken at this location.

Figure 36. Photograph and thermogram of bare membrane and ponded water along the west side of roof A3, looking SW.

thermal image is bright due to extra solar energy absorbed by the exposed black EPDM. Wet insulation may exist in this area.

Figure 37 presents a photograph and thermogram of a thermal anomaly present along the north side of the east penthouse, with the west penthouse visible in the background. The brightest portion of the thermogram is the patched bare area visible in the photograph. Extra solar energy absorption, in part, explains that brightness. However, a medium bright area extends out beyond the bare area in the thermogram. This area was outlined in spray paint as shown in the photograph. Core 15 was taken in the bright area where "15" has been marked on the photograph.

Table 18 presents findings from the two cores taken on this roof, and Table 19 presents findings from cut I that was taken adjacent to core 14. Their locations are shown in Figure 3.

Wet insulation was present from the top to the

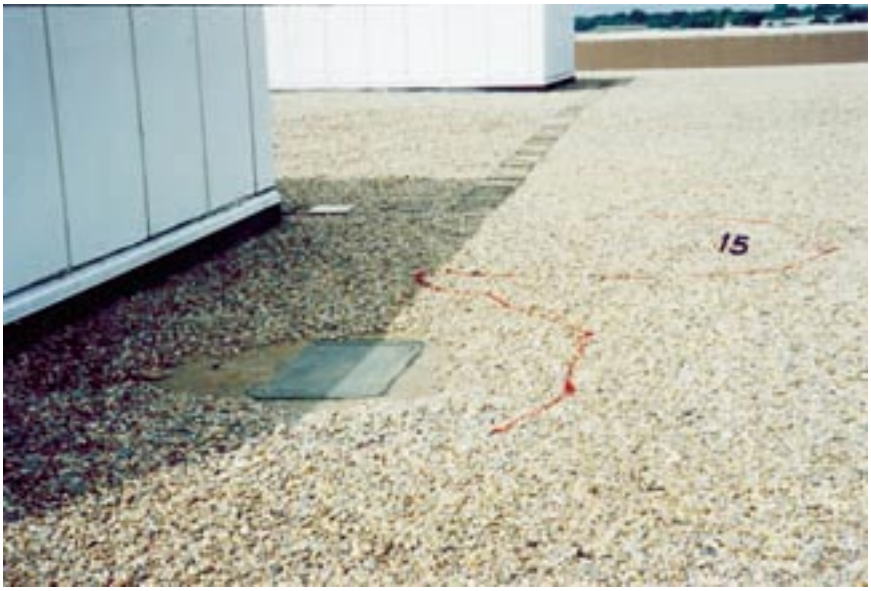

Figure 37. Photograph and thermogram of an area of wet insulation that extends out beyond a patched bare area on the north side of the east penthouse on roof A3, looking a little south of west. Core 15 was taken at the "15."

bottom of the roof at core 15. Perhaps the patch shown in Figure 37 eliminated the flaw that allowed water to enter the roof in that area.

All other thermal anomalies noticed on this roof were the result of bare membrane or piles of gravel. However, core 14 and cut I were taken in an area that thermally represented the rest of the roof. While most of the insulation there was dry, the lower layer of perlite that rested on the steel deck was quite wet and the deck was covered with rust as shown in Figure 38. It is not possible to say with assurance that the entire steel deck is rusted badly but that possibility exists. Because of the amount of rusting at this location, additional cuts should be made to determine the extent of this problem. It may be necessary to replace all or portions of this roof deck.

Table 18. Core sample findings for roof A3.

Core	*Insulation*	*Thickness (in.)*	*Moisture content (% of dry weight)*	*TRR (%)*	*Status*
14	PER	3/4	1	98	dry
14	EPS	4	0	100	dry
14	EPS	4	1	100	dry
14	EPS	4	0	100	dry
14	PER (frozen)	3/4	244	37	**WET**
15	PER	3/4	431	20	**WET**
15	EPS	4	718	54	**WET**
15	EPS	4	1170	35	**WET**
15	EPS	4	1566	23	**WET**
15	PER (frozen)	3/4	194	43	**WET**

Notes:
Core 14: Deck is rusted badly. Lower perlite could not be sampled by coring. It was obtained from the edge of cut I which was taken in the same place.
Core 15: Deck could not be examined for rusting. Some of the EPS was also frozen.

Table 19. Roof cut I, test results.

Insulation	*Thickness (in.)*	*Density (lb/ft^3)*	*Moisture content (% of dry weight)*	*Thermal resistance*		*TRR (%)*
				As received	*After drying*	
PER	3/4	10.1	3.0	2.4	2.0	120
EPS	4	1.2	0	15.3	15.2	101
EPS	4	1.0	0	14.6	14.6	100
EPS	4	1.0	0	14.9	14.9	100
PER	3/4	10.3	136.0	1.4	2.0	70

Notes:
Steel deck is covered with serious rust.
Core 14 was taken at this location.

Figure 38. Hole made when taking core 14 and cut I. The bottom layer of perlite on the steel deck was wet and the steel was badly rusted.

FINDINGS AND RECOMMENDATIONS

A number of roof-specific findings and recommendations are presented in the body of this report where each roof is discussed. Visually, these roofs appear to be in good condition, but thermographically, eight of the ten are suffering some moisture related problems.

On-the-roof infrared roof moisture surveys were found to be more informative than indoor infrared roof moisture surveys because shelving, goods, piping, and such, block indoor views of the roof. Nonetheless, the indoor infrared surveys and indoor visual inspections were quite valuable supplements to the on-the-roof surveys and inspections. The indoor work showed us that air infiltration is occurring at places along roof–wall intersections.

Air infiltration at these intersections is apparently bringing moisture into the roofs and into the freezers themselves. Permeable fibrous glass insulation does not resist air infiltration very well, and thus of all the insulations encountered, it is the most susceptible to moisture gain by air movement.

The adverse effects of air infiltration on the performance of roofs of freezers and coolers deserves further study.

We found more wet insulation in these roofs than we expected. Eight of the ten contain some wet insulation and therefore have lost a portion of their insulating ability. Fortunately, only a portion of each roof, not the entire roof, contains wet insulation, except for D7, all of which may contain wet insulation. Unfortunately in most cases, cost-effective, easy, reliable ways of removing this moisture are not available. Knowing that, we feel it is wise to select more moisture resistant insulations for such roofs.

Some of the moisture we found was in the "old" insulation of roofs that have been re-covered with a new waterproofing membrane without removing wet insulation. We found areas of wet fibrous glass insulation in roofs D1, D2, D4, and D5. We expect that a small amount is present in roof D3 also. It is likely that flaws in the original bituminous built-up membrane allowed water to enter the "old" fibrous glass insulation. It was easy for that water to move laterally in that material. As a result, cancers of wet fibrous glass insulation remain in those roofs. Some of that moisture is in the form of ice. While fibrous glass insulation may be able to be dried out (by warming up the freezers), the rapid growth of wet insulation makes it somewhat ill-suited for use in freezers and coolers where vapor drive and air movement are both usually inward.

We found wet expanded polystyrene (EPS) insulation in two roofs (D7 and A3) that had not been re-covered with a new waterproofing membrane. Additional investigations are needed to determine the total amount of wet EPS in each roof. We know of no way to dry out that insulation, in place, even by warming up the freezers below.

In four of the roofs, EPS insulation was placed over the old bituminous membrane in conjunction with adding a new EPDM waterproofing membrane above. In one and perhaps two of those roofs, some of that "new" EPS insulation has become wet. Flaws in the flashings and membrane of the new EPDM waterproofing system allowed water to gain access to that insulation. Fortunately, only a small portion of that insulation is wet but, unfortunately, there is no way to dry out that material in place.

Roof D6 (one of the two problem-free roofs in this study) contains EPS insulation and it is dry. The new waterproofing membrane on this roof suggests that some problems occurred in the past. Perhaps past moisture has thawed and drained away during defrosting of this freezer. Perhaps, deep in this roof, some moisture still exists that we were unable to detect. Perhaps the new waterproofing membrane was not needed.

Roof A1 (the other problem-free roof in this study) contained extruded polystyrene and isocyanurate insulation. The watertight EPDM membrane, not these insulations, deserve the credit for that.

Roof A3 has wet EPS insulation and a badly rusted steel deck that should be examined in detail.

Roof A2 contains wet phenolic insulation that is capable of destroying a warm steel deck in a few months. Since the A2 steel deck is cold, its rate of deterioration is slow but it is progressing. Plans should be made to remove the phenolic insulation from this roof.

As long as the roof membrane and its flashings keep water and moist air away from the insulation in roofs of freezers and coolers, any insulation will stay dry and perform well.

Most freezers and coolers are subjected to intense inward vapor drive and air infiltration for their entire lives. If a permeable insulation such as fibrous glass is to be used, it is most important to seal the roof against air infiltration.

Water that gains access to the roof insulation of a freezer at flaws in the waterproofing system, and moist air that gains access at air gaps at the perimeter and at penetrations, freezes in place. This ice adversely affects the insulating ability of the roof. Ice conducts heat about four times as fast as water, so the loss in insulating ability is quite dramatic for freezers where much of the moisture in their roofs is in the form of ice.

Ice that accumulates in the roof insulation of a freezer acts as a dam, allowing additional moisture to accumulate above as ice or, in the upper, warmer portions of the roof, as water. Seasonal variations in outdoor temperatures do not promote drying of this moisture. The year-round tendency is to promote wetting. Thus, there is incentive to use a very moisture-resistant insulation in the roofs of freezers and, for the same reason but to a lesser degree, in the roofs of coolers. The two most moisture-resistant roof insulations are cellular glass and extruded polystyrene. However, since cellular glass insulation can be destroyed in short order by freeze-thaw cycles in the presence of moisture (Tobiasson et al. 1997), the only currently available roof insulation that can offer much improved moisture resistance in the roofs of freezers and coolers is extruded polystyrene.

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The low-slope roofs of 10 cold storage buildings in the Dallas area were examined visually and thermographically from above and below. Cores were taken to verify infrared findings, and 12- × 12-in. (30- × 30-cm) specimens of many of the insulations were removed for laboratory studies of their thermal properties. Insulations included fibrous glass, fiberboard, perlite, wood fiber, expanded and extruded polystyrene, isocyanurate, and phenolic. Areas of wet insulation were found in 8 of the 10 roofs. Some wetness was due to leaks caused by flaws in the roofing membranes and their flashings, but some was associated with infiltration of warm, moist outside air at roof–wall intersections without effective air seals. Of all the insulations examined, permeable fibrous glass was the most susceptible to wetting by air infiltration. Sustained one-way vapor drive, the sealing-in of moisture at the base of insulation in roofs of cold storage buildings by freezing, and the limited opportunities for drying wet insulation in such roofs provide incentives to use insulation that is very resistant to wetting. Its very low rate of moisture gain by vapor diffusion and its resistance to wetting in the presence of freeze–thaw cycles make extruded polystyrene insulation particularly appealing for use in the roofs of cold storage buildings.

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