Feature

Case Study: Thermal Contraction of a PVC Membrane and EPS Insulated Roof Assembly in Alaska's North Slope Borough

Figure 1. *Overview of the building (looking northeast).*

Figure 2. *East elevation.*

By Grace Wong, AIA, PE, LEED AP BD+C; and Christian Gorry, RRC, RRO, PE

SINGLE-PLY POLYVINYL CHLORIDE (PVC) roof membranes have been in use in the US and Canada since the 1970s and remain a popular choice for low-slope roof coverings, making up an estimated 5–10% of the global low-slope roofing market.[1] Expanded polystyrene (EPS) rigid insulation has been in use in the roofing industry for at least as long.[2] Whereas we found extensive testing data and best practice recommendations for the installation of PVC and EPS in low-slope roof assemblies, we did not find widely accepted practices on their installation in arctic and subarctic climates where winter temperatures can dip to -40°F (-40°C). Our findings from a forensic study of a large low-slope PVC and EPS roof assembly installed in Alaska's North Slope Borough suggest specifications that perform adequately in most other climate zones may require an additional level of oversight during design and installation to prevent assembly shrinkage and premature failure.

BACKGROUND

We investigated the failure of a low-slope PVC roof assembly in Deadhorse, Alaska, in 2018. Deadhorse is a small town in Alaska's

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North Slope Borough and exists primarily to service the oil industry that operates in Prudhoe Bay. It is a place with short summers and long winters where everything, including building construction, has an added degree of complication and something as routine as material delivery may have an outsized impact if limited to delivery by barge and a three-month roofing season. The roof assembly was installed on a one-story steel-framed industrial building with premanufactured insulated exterior wall panels (**Figs. 1** through **4**). The building was substantially complete in the fall of 2015, and the owner first discovered roof edge failures in the spring of 2017. Failures identified at that time included the perimeter membrane, prefinished metal roof edge flashing, and wood curb below visibly peeling off, as well as water entry at the exterior wall-to-roof interface.

INVESTIGATION OBSERVATIONS

Field Investigation—Roof Survey

We performed a visual survey of the roof assembly from the interior and exterior and noted that the roof membrane at each corner of the building was wrinkled in a diagonal pattern that pointed toward the corners (**Fig. 5**). Membrane adhesion to the cover board generally appeared intact, but we noted "excess" or wrinkled membrane at several locations at the cover board joints where the membrane was not adhered (**Fig. 6**).

From a lift and from the roof, we observed that the top edge of the roof curb had rotated up and back toward the building and failed along the entire roof perimeter (**Figs. 7** and **8**). The wood-framed curb was constructed from four pieces of 2 x 6 (38 x 140 mm) and 3 x 6 (64 x 140 mm) dimensional lumber attached with 0.130 in. (3.3 mm) nails in two rows spaced alternately at approximately 8 in. (203 mm) on center (**Figs. 9** and **10**). The top plate of the wall appeared to be intact and had not been displaced. The failure of the roof edge at all four elevations was clearly visible and appeared to be the most severe at the center of each elevation (**Figs. 11–13**).

Roof Openings

We created two openings into the roof. The first opening was made at the north elevation, approximately in the center of the building, and the second opening was made at the south elevation, toward the southwest corner. **Figure 14** shows the existing roof assembly observed during our investigation, which was in general agreement with the construction documents.

Figure 3. *Overview of roof (looking northeast)*

Figure 4. *The plant interior.*

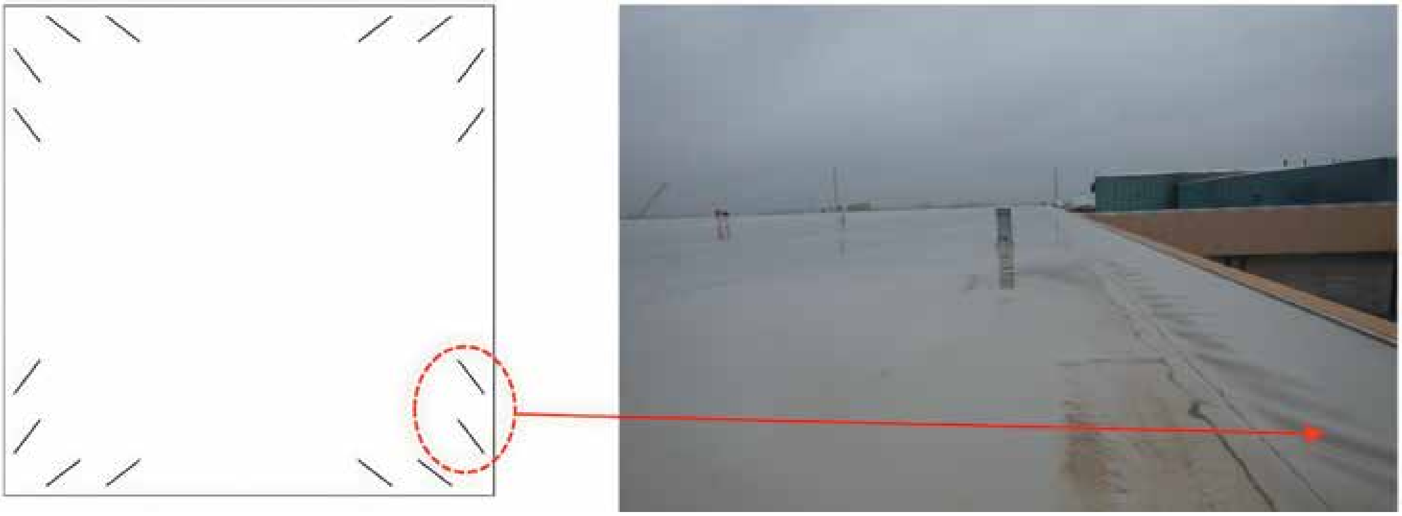

Figure 5. *Roof plan and a related photo of the shear pattern observed at the roof corners.*

Figure 6. *Ridges of unadhered membrane at panel joint.*

The membrane appeared to be pulling away from the roof edge at all elevations and toward the center of the roof.

At each opening, we noted the components and attachment methods described in the roofing submittal issued during construction appeared to be present. Also, the adhesion between the roof membrane and cover board and between layers of rigid insulation appeared to be intact. At both openings, there was an approximate 2 in. (51 mm) gap between the edge of the insulation and the inside face of curb (**Figs. 15** and **16**).

Membrane fasteners and washers were present beneath the membrane flashing and spaced in general conformance with the roof membrane manufacturer's recommendations (that is, 12 in. [305 mm] on center). However, at both openings, roofing screws appeared to have been displaced (**Figs. 17** and **18**); they were not plumb and had begun to tear through the insulation. In addition, the roof membrane appeared deformed around the head of one of the screws (Fig. 16).

Underneath the vapor retarder, the roof deck remained tight to the wall and generally intact. The thickness of the PVC roof membrane measured 72 mils.

ANALYSIS

From our brief analysis of the as-built documents, we concluded that the appropriate wind uplift design loads were used for the area, type, and time of construction. Therefore, we would not expect the roof curb fasteners to fail in wind uplift. Indeed, the observed failures were relatively consistent on all elevations and not aligned with expected wind directions. In addition, the observed failures were generally inconsistent with the pull-out behavior we would expect to see from a wind uplift failure.

Another possible cause of fastener pullout at the roof curb might be movement of the structure such as repetitive movement in the roof deck due to load-deflection response. However, we observed from as-built drawings that the metal pan roof decking ran exclusively in the north/south direction (**Fig. 19**). The ribs of the metal decking were significantly stronger in one direction than the other. If the damage were caused by structural deflection, we would expect the damage to be different in the two primary directions. That was not the case, as we observed that the damage was consistent on all four elevations. Also, roof deck and adjacent structural components exposed during the exploratory investigation, and as observed from the exposed ceiling below, remained in-place, planar, and displayed no signs of distress. Therefore, we ruled out structural movement as a possible cause.

A third possible cause of the observed pull-out failure might be stress imparted by the roof

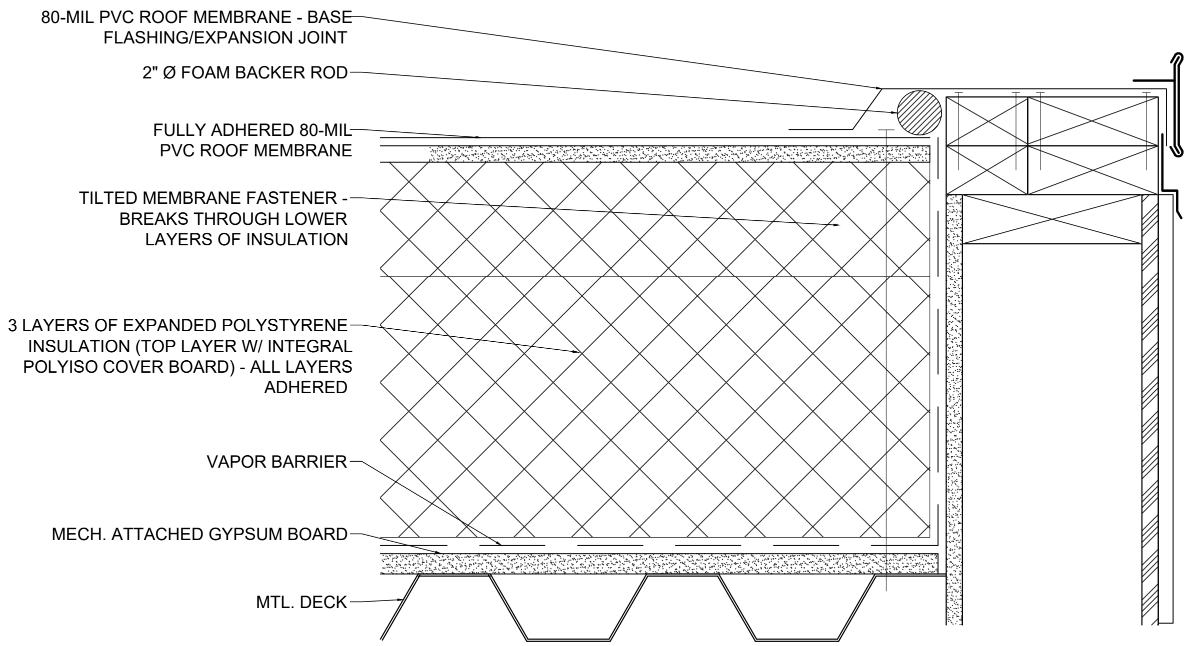

Figure 7. *Roof assembly at a failed roof edge–as designed.*

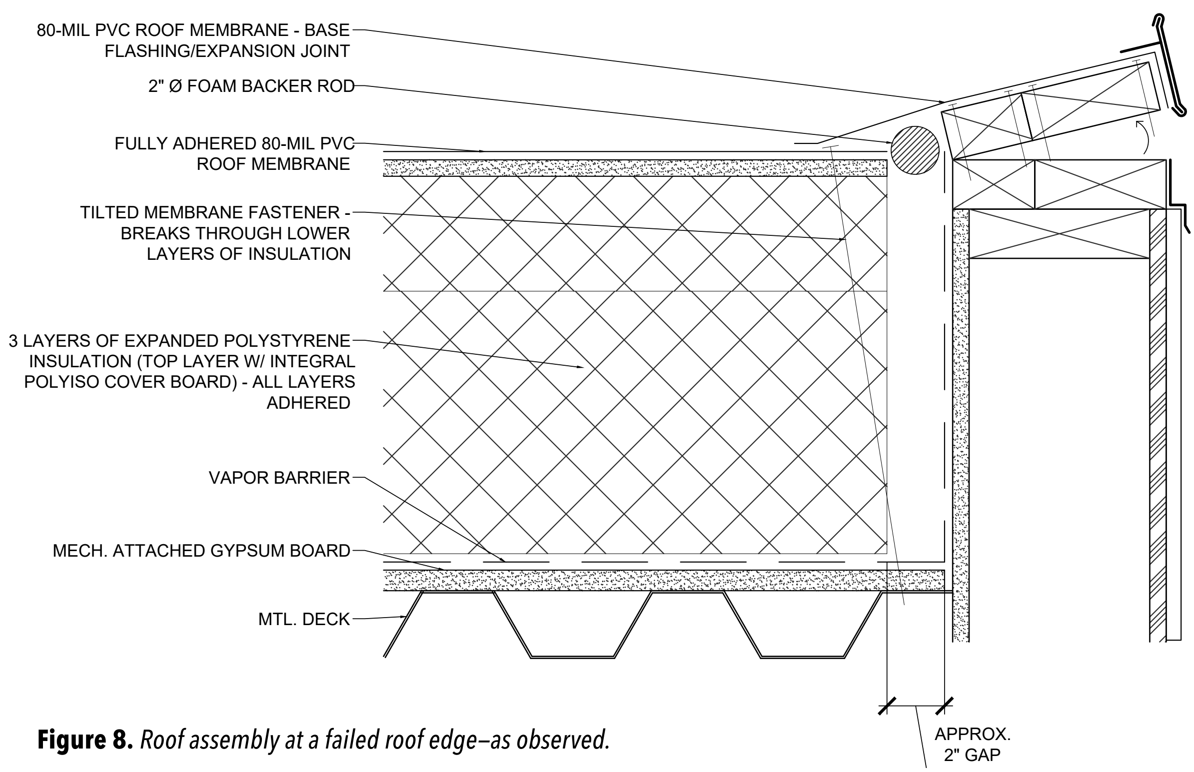

Figure 8. *Roof assembly at a failed roof edge–as observed.*

membrane itself. We suspect this was the case because the pattern of wrinkles on the roof was strongly correlated with patterns of uniformly and concentrically applied tensile stress on the roof membrane on a square-shaped roof (Fig. 5). The membrane appeared to be pulling away from the roof edge at all elevations and toward the center of the roof. The built-up wood roof curb was attached with 0.130 in. (3.3 mm) × 3½ in. (89 mm) nails at approximately 8 in. (200 mm) on center—staggered, providing an uplift resistance of 78 lb/ft (115 kg/m). This amount of resistance was adequate to resist the design wind uplift demand but less than that recommended by the Single Ply Roofing Industry (SPRI). Per ANSI/SPRI/FM 443/ES-1, *Wind Design Standards for Edge Systems Used with Low Slope Roof* Systems,[3] "Nailers should be . . . secured to structural components of the building by corrosion-resistant means sufficient to resist a vertical load of 200 lb/ft (300 kg/m) or the design load, whichever is greater."

As part of our analysis, we compared the breaking strength of the PVC membrane to the anchorage capacity of the wood curb. Basically, we wondered if the PVC membrane had the capacity to pry back the wood curb before failing. The breaking strength for Type III reinforced PVC membrane required by ASTM D4434, *Standard Specification for Poly(Vinyl Chloride)*

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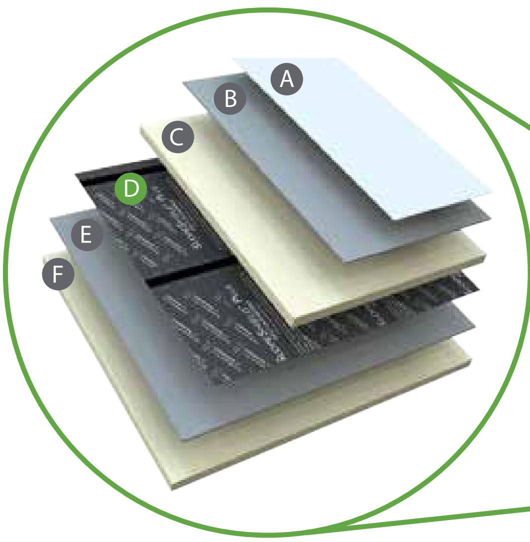

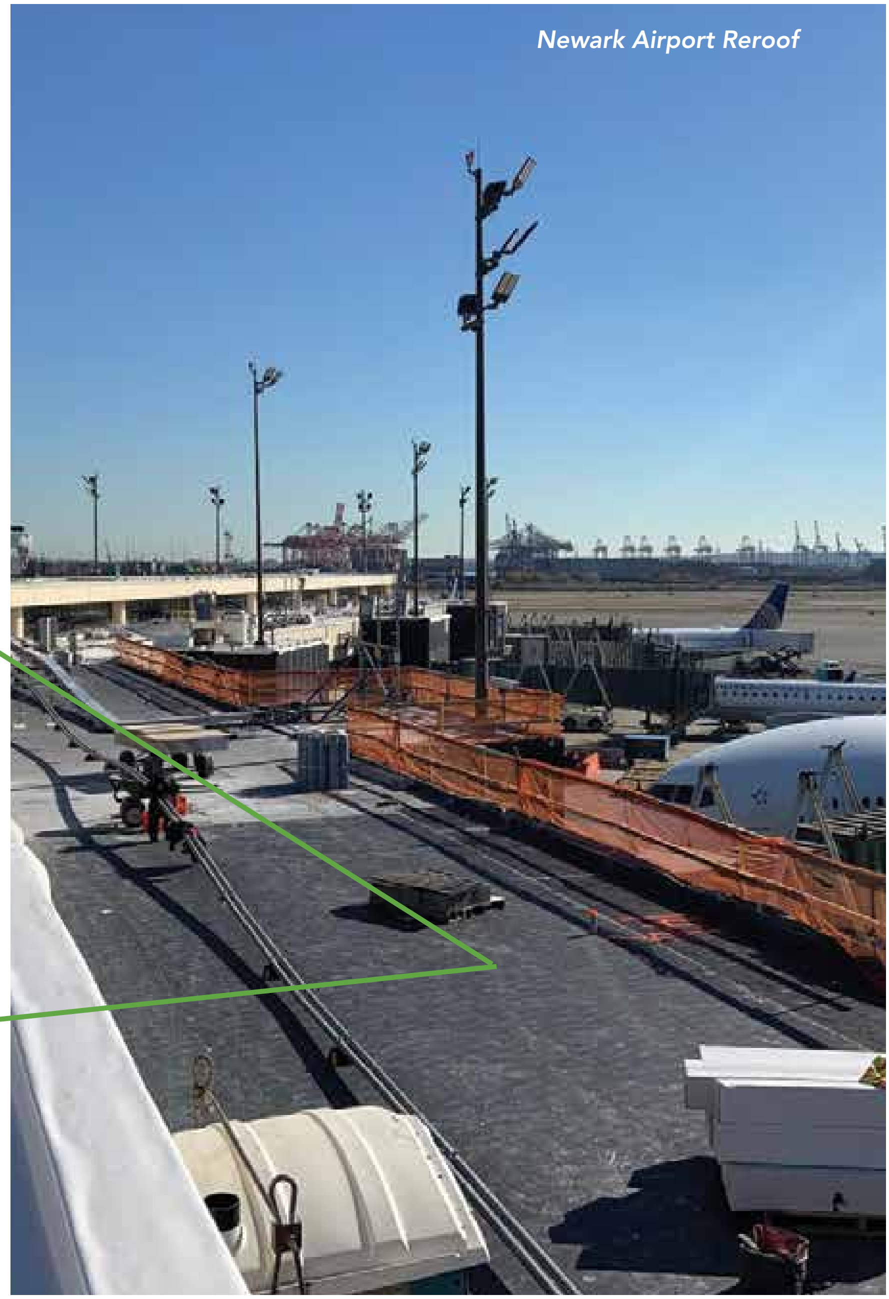

- **A** 60 mil PVC roof covering *(by others)*
- **B** Additional gypsum coverboard *(by others)*
- **C** New insulation *(by others)*
- **D** SlopeShield Plus SA breathable underlayment
- **E** Recovery board *(by others)*
- **F** Re-used existing insulation

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Sheet Roofing,[4] is 2,400 lb/ft (3,570 kg/m) or approximately 30 times greater than the withdrawal capacity of the installed curb and 12 times greater than the capacity of a curb installed in conformance with ANSI/SPRI/FM 443/ES-1. Even at half the published capacity (that is, 1,200 lb/ft [1,785 kg/m]), which would account for material imperfections and weakened sections at welded seams, the membrane would be highly unlikely to tear before the roof curb fasteners were pulled out.

Material Properties of PVC Membrane

The observed pattern of wrinkles on the PVC membrane and the evidence of the concentric direction of stress suggested that the roof system (PVC roof membrane and rigid insulation) could be experiencing stress due to material contraction. This hypothesis appears to align with the published material properties of these components and their expected response to changes in temperature.

We looked at two material properties of PVC while considering the effects of thermal contraction—the coefficient of thermal expansion and dimensional stability. The coefficient of thermal expansion does not need explanation, but it is worth remembering that this property remains constant and is "recoverable." In other words, a material will continue to expand and contract as a function of temperature and return to its previous state unless otherwise restricted. Dimensional stability can generally be described as a material's capacity to maintain its dimensions (length, width, and thickness) and shape over time with changes in variables such as temperature.

ASTM D4434 defines three types of PVC membranes: Types II, III, and IV. Of these, only Type II is reinforced to provide "dimensional stability." Type II is defined as "reinforced sheet in which fibers are incorporated into a production process . . . [that] may provide other desirable characteristics, such as dimensional stability."[4] ASTM D1204, *Standard Test Method for Linear Dimensional Changes of Nonrigid Thermoplastic Sheeting or Film at Elevated Temperature*,[5] is the relevant standard for measuring the dimensional stability of PVC.

For this test, samples of PVC membrane are heated to 176°F (80°C) for a period of six hours and allowed to cool. The change in length is measured and represents dimensional stability—the membrane's ability to maintain or keep its original shape. The maximum linear dimensional change as tested per ASTM D1204 in Type II membranes is 0.1%, compared with 0.5% in Types III and IV membranes. Despite this difference, and the expected exposure to an extreme climate, a Type III membrane was installed for this project. This test is not a perfect substitute for the conditions observed on the subject building; it involves heating the membrane first, not cooling to -40°F (-40°C). We suggest it here only as an additional consideration during the specification process. The difference between 0.1% and 0.5% may seem negligible but could have been as great as 11 in. (280 mm) over 240 ft (73 m). Again, we are not saying this occurred, only that not all PVC membranes respond equally when subjected to temperature changes and that a permanent change in dimension has an associated force that must be restrained.

Alpine, Alaska, is the closest weather station to Deadhorse. Between the substantial completion of the building in the fall of 2015 and the discovery of roof edge failures in the

Figure 9. *Top of roof curb.*

Figure 10. *Built-up roof curb.*

Figure 11. *Failed roof edge at north elevation.*

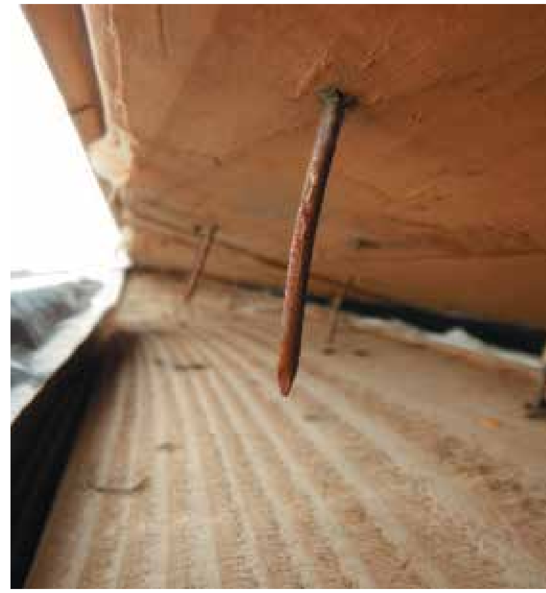

Figure 13. *Failed roof edge at south elevation.*

Figure 12. *Failed roof edge at west elevation.*

spring of 2017, Alpine registered seasonal temperature swings of over 100°F (38°C) between summer and winter, with the lowest temperature recorded being -44°F (-42°C). The average temperature in January 2016 was -4°F (-20°C), and the lowest temperature was -29°F (-34°C). The average temperature in January 2017 was -4°F, and the lowest temperature was -44°F (-42°C). The conditions for the months of December and February after were similar. We consulted with material scientists, who calculated that the combined coefficient of thermal expansion for PVC membrane adhered to EPS is approximately 4.0×10^{-5} in./in. °F (9.0×10^{-5} cm/cm ·°C), meaning the total unrestrained thermal movement of the roof assembly in this climate would be approximately 12 in. (305 mm). The installed roof assembly was fully adhered, mechanically anchored at the perimeter, and theoretically restrained against movement. But these values indicate that the roof was subjected to substantial forces of contraction in the winter.

Refer to Fig. 5 and note that the membrane at the perimeter is in "shear" with respect to the main field of the roof; also, the pattern of distress is consistent with membrane that is being "drawn" toward its center. Also note, ridges in the membrane at insulation panel joints indicate lack of adhesion, but there was also a significant amount of "extra" membrane at these joints, and it would not have been possible to install the membrane in this manner. These ridges occurred after the original installation, and they were most likely the result of contraction of combined PVC and EPS in the winter followed by expansion of the PVC membrane in warmer weather.

Material Properties of Insulation

Since both membrane and insulation displaced inward and the membrane was largely well adhered to the insulation, thermal movement in the insulation was also a significant consideration in determining whether thermal deflections could manifest in the structure. The approved project submittal stated that the rigid insulation was Type II EPS.

As with the PVC membrane, we considered both the coefficient of thermal expansion for EPS and its dimensional stability as part of our analysis. The test method for measuring dimensional stability is described in ASTM D2126, *Standard Test Method for Response of Rigid Cellular Plastics to Thermal and Humid Aging.*[6] The dimensional stability, or percent

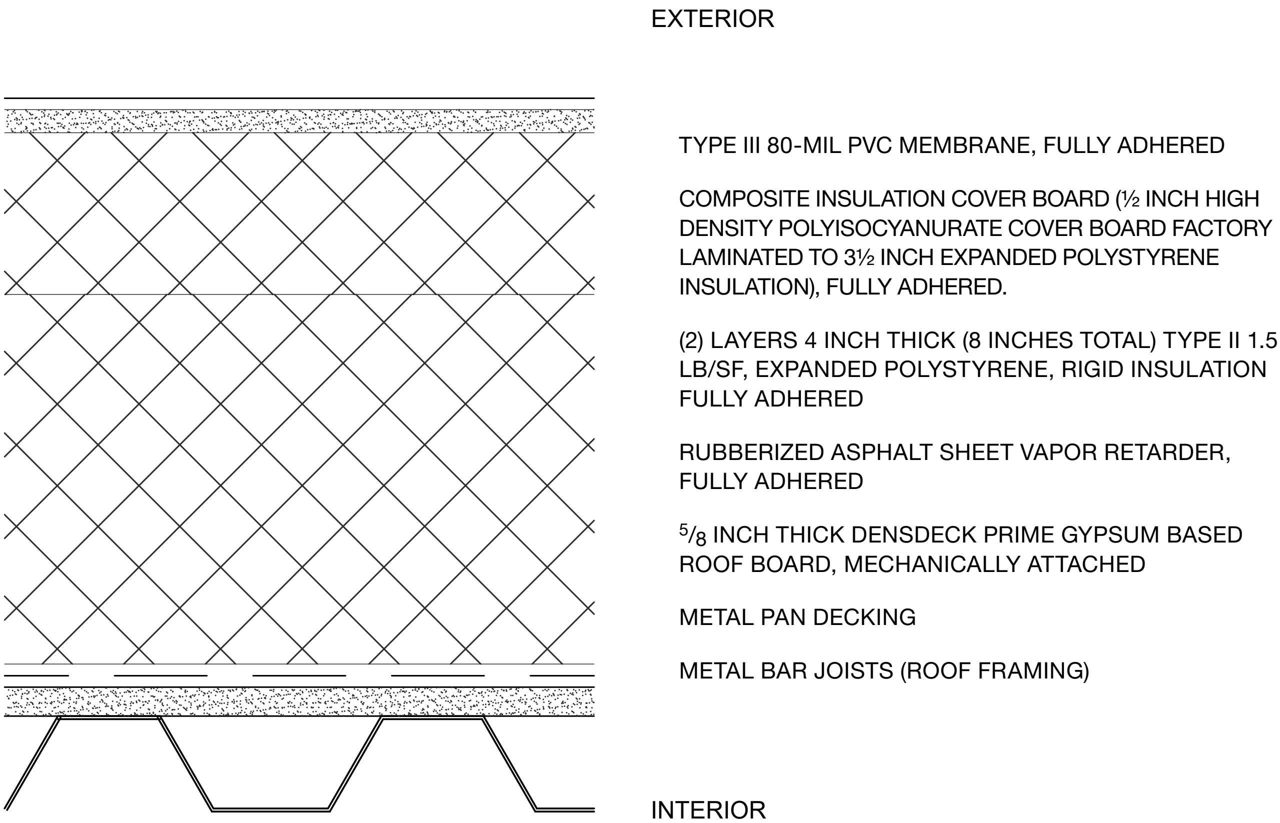

Figure 14. *Typical detail for the roof assembly.*

As with the PVC membrane, we considered both the coefficient of thermal expansion for EPS and its dimensional stability as part of our analysis.

linear change, allowed by this standard is 2%. In other words, an 8 ft (2.4 m) insulation board could permanently shrink by 1.9 in. (48.3 mm) and still be considered within tolerance. It is our understanding from studies carried out by Structural Research Inc.[2] and RDH Building Science[7] that permanent shrinkage of insulation (dimensional stability) is primarily a chemical change and a function of heating (above 176°F / 80°C), not cooling. But the amount of shrinkage allowed by this standard is large in the context of a 240 ft (73 m) building and has not been ruled out as a contributing factor. As a reminder, we observed an approximate 2 in. (50 mm) gap at each end of the roof representing a total of 4 in.

Figure 15. *An approximate 2 in. gap was observed at both openings.*

Figure 16. *Membrane under tension at fastening plate.*

Figure 17. *Downward view of rotated membrane screw tears through insulation.*

Figure 18. *Close up look at the bottom of the insulation, showing more damage on the bottom layer of insulation.*

(100 mm) of shrinkage over 240 ft (73 m), so substantially less shrinkage than is allowed by ASTM D2126.

The coefficient of thermal expansion for Type II EPS is 3.5×10^{-5} in./in. °F (6.0×10^{-5} cm/cm °C), ASTM D696,[8] and unrestrained EPS cooled from 5°F (-15°C) to -40°F (-40°C) would shrink by approximately 4.5 in. (114 mm) over the length of the roof. Likewise, a fully adhered and restrained roof assembly would need to resist the force associated with the thermal contraction of EPS.

Due to the limitations of the short arctic roofing season and logistics of getting multiple experts to this remote location, we were limited to one day of exploratory investigation and two openings. We observed an approximate 2 in. (50 mm) gap at both openings, but we suspect that this gap existed around the entire perimeter of the roof. The original contractor indicated that the insulation was installed tight to the curb, i.e., the insulation gap was not present initially and therefore developed over time, which is consistent with our field observations. Out-of-plumb membrane fasteners tore through the insulation in a manner suggesting all components were in place prior to failure, with small particles of EPS insulation balanced delicately on one side of the fastener only. This result would have been difficult to achieve during installation of a rotating screw.

Figure 16 shows the roof membrane displaced locally around the washer, indicating tension between the membrane and fastener/washer and that anchorage of the membrane at this location had failed. The screw orientation, membrane displacement, and the characteristics of torn insulation indicate that the 2 in. (50 mm) gap observed at both roof openings was not present at the time of installation and that roof assembly had in fact shrunk.

CONCLUSION

The roof assembly as designed and installed does not seem to be appropriate for the extreme climatic conditions of Alaska's North Slope Borough. Multiple winters with two to three months of average 4°F (-15°C) temperatures and periodic lows of -40°F (-40°C) caused the membrane or the insulation (or possibly both) to contract, resulting in pull-out failure of the nails connecting the built-up wood curb and water intrusion into the interior. Several steps could have been taken to mitigate the effects of thermal contraction and the associated force imparted on the roof perimeter. A layer of stone wool insulation could have been used on top to isolate the EPS from direct contact with the exterior temperatures.[7] A better effort at connecting the wood curb to the structure to at least meet the requirements of ANSI/SPRI[3] would have been appropriate. A different choice of PVC membrane, one with greater dimensional stability, while not a surefire fix, seems like inexpensive insurance in retrospect.

Roofing in arctic, and even subarctic, climates may deny designers and installers a level of forgiveness otherwise available in milder climates. Temperatures below 40°F (-40°C) induce abnormal thermal movement and associated force into materials such as PVC roofing and EPS insulation that must be accounted for.

In our research, we found that design guidelines for PVC roofing tend to focus on issues such as fastener pullout from wind uplift, and recommendations for movement joints in metal components, including edge flashings and gutters; however, we did not find widely accepted standards on how to accommodate thermal movement in extreme climates.

We recommend that additional research and material testing be conducted so that easy-to-use guidelines and industry best practices can be developed to help designers choose appropriate materials and details for extreme cold climates.

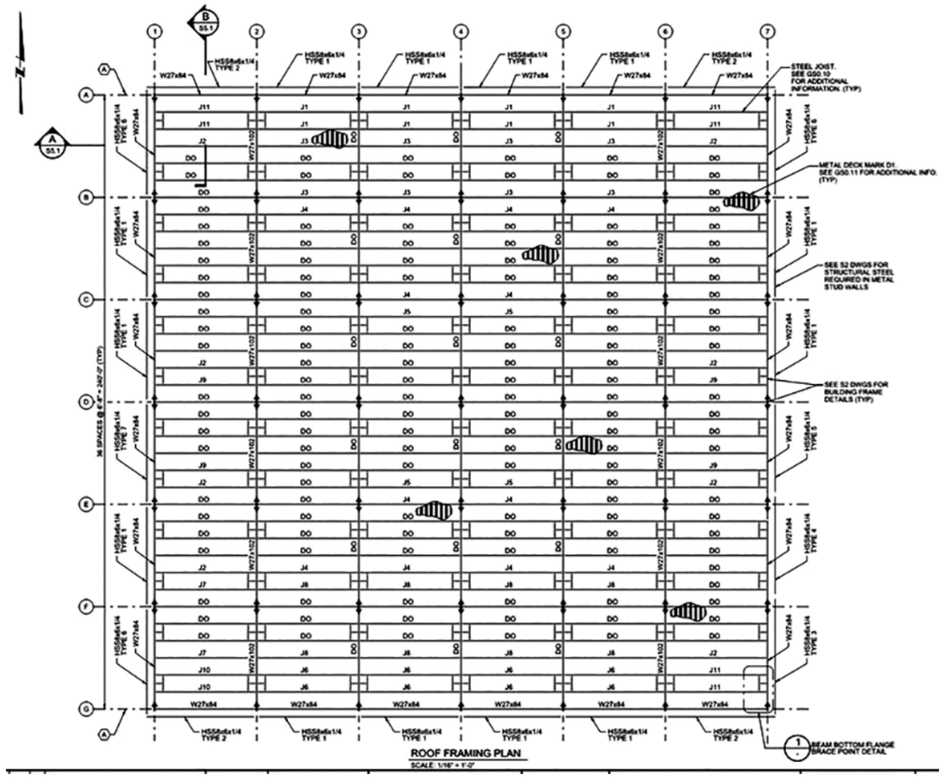

Figure 19. *Roof framing plan.*

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