

EPDM —

Solution to Airport Roof Problems

By Nick A. Lovato

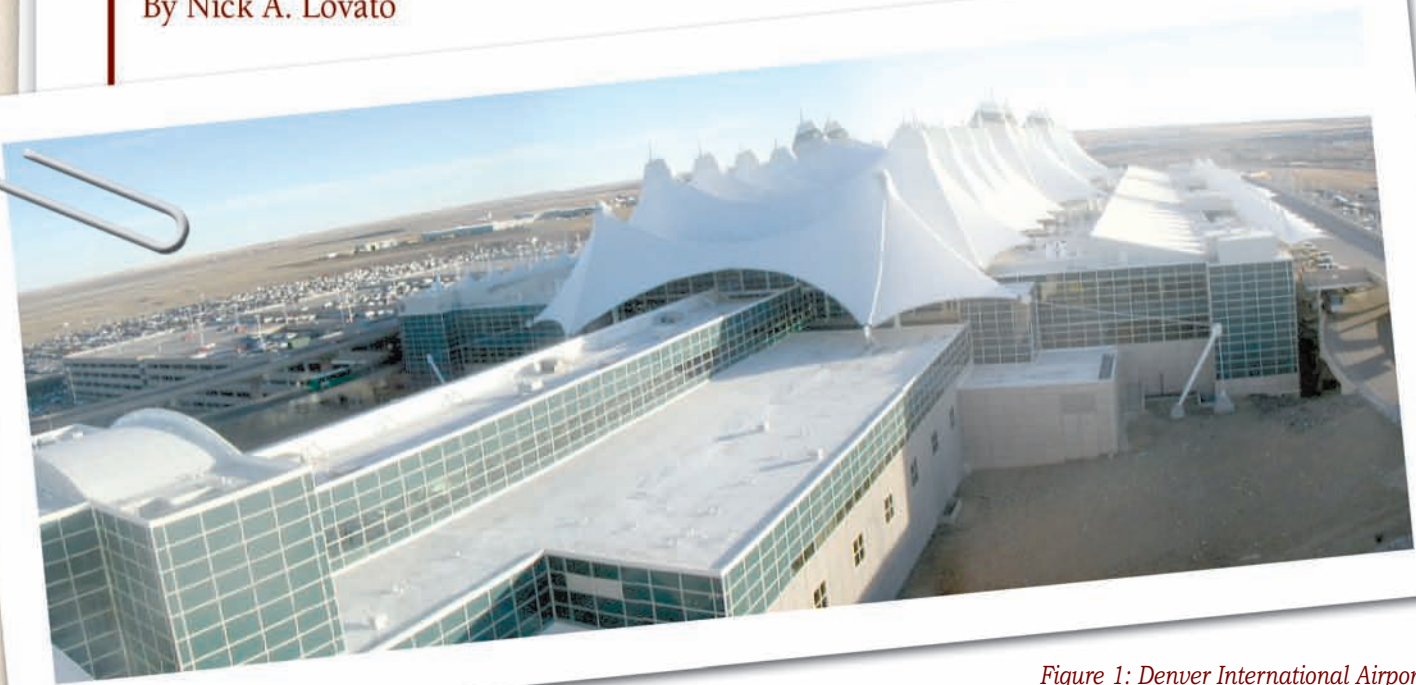


Figure 1: Denver International Airport.

ABSTRACT

As a result of a moderate hailstorm in June of 2001, the original eight-year-old reinforced PVC single-ply membrane on the flat roofs over the Jeppesen Terminal and passenger bridge at the Denver International Airport (DIA) experienced moderate to extensive hail damage. The subject roofs are adjacent to the impressive and renowned Bird Air tent roofs, which were not damaged by the hail. After careful consideration of many different roof systems, the roof membrane was replaced with a non-reinforced, fully-adhered, 90-mil ethylene propylene diene monomer (EPDM) that was painted with a white elastomeric roof coating. The evaluation, design, and construction of the new roof presented the owner, design team, and contractor with some unique challenges and experiences that are shared in this case study. The topics that will be discussed are:

1. Logistics of reroofing an aviation facility and the security challenges of post 9/11/2001,
2. Emergency measures that were taken to prevent further damage to the roof and building components prior to and during construction,
3. Results of the evaluation of the roof systems and existing conditions,

4. The selection process for the new roof membrane, recover board, and roof coating; and
5. Design parameters of the project.

For this project, the fully-adhered, 90-mil EPDM roof was determined to be the least intrusive and the best system to provide adequate resistance to hail and mechanical damage. The designers and owners expect the new EPDM roof to provide excellent service in a hail hazard zone and achieve a useful life that far exceeds the norm.

Client: City and County of Denver

Architect: DMJM H+N, Denver, CO

Roof consultant: CyberCon Engineering, Inc., Centennial, CO

Roofing contractor: Earl F. Douglass Roofing, Commerce City, CO

Product supplier, roofing membrane: Firestone Building Products Corp.

Product supplier, coverboard: Georgia Pacific

Product supplier, premanufactured coping: Peterson Aluminum

INTRODUCTION

This article will discuss the results of CyberCon's initial investigation of the roofs at the DIA, design considerations for reroofing, and some of the challenges that were encountered during the reroofing process. This paper will also discuss the characteristics, physical properties, and some of the pitfalls of the roofing products used and the rationale for selecting an elastomeric thermoset roofing membrane and dense, water resistant coverboard for reroofing. For most discerning readers, the information provided will be a quick refresher on polymer chemistry, mechanics of materials, moisture vapor transmission, thermal properties, and sound roofing practice. For the roof consultant in training, it is hoped that the information provided will inspire further study of the topics discussed.

DIA is a commercial air carrier facility 23 miles northeast of the metropolitan Denver area, on 34,000 acres of the high mountain desert prairie of Colorado. The airport has six active runways and handles approximately 104,000 enplanements each day. The terminal and concourse facilities represent a total of 5.45 million square feet with a total of 94 passenger-loading gates. The airport structures consist of a main terminal and three remote concourse buildings (A, B, and C), which are connected via an underground automated transportation system. Concourse A is connected to the North terminal via a pedestrian bridge.

An international airport presents challenges that are unique due to its 24/7 operations, ongoing public activity, security, and the sensitive nature of the airplanes. Special considerations are necessary for reroofing to address noise, odors, and risks to the operations of the facility.

Our findings and conclusions from the investigation of the original roof systems may also be of interest to the reader. The following will be discussed in more detail in the body of this article:

- Hail damage to weathered reinforcement PVC membranes.
- PVC degradation as a function of its environment and raw materials.
- Designing resistance to mechanical damage of a membrane.
- Long-term serviceability of a PVC membrane.
- Slip sheet damage below mechanically fastened single-ply membranes.
- Premature plasticizer migration.
- Heat degradation of polystyrene.

- Vapor diffusion and degradation of polyisocyanurate.
- Thermal profile of black EPDM membrane versus a high albedo coating.
- Failure of butyl-based glued seams on an elastomeric membrane.

In the final analysis, it was determined that a fully-adhered EPDM membrane, coated white, installed over a glass-faced gypsum coverboard, mechanically fastened over the existing polystyrene and polyisocyanurate rigid insulation, would be the best reroof option for the DIA. The new roof has passed severe hail and wind tests and has excellent weathering characteristics. It is anticipated that the roof coating will weather away at approximately 1 mil per year and therefore have to be reapplied in approximately 12 to 15 years. The serviceable life of the roof should extend well beyond 30 years. The life cycle cost was deemed to be comparable to other membrane systems, despite the anticipated cost of recoating the roof. The rationale for selecting an EPDM roof system will also be discussed in this article.

DEFINITIONS

Absolute Humidity – A measure of the actual amount of water vapor contained in a unit volume of air; distinct from “relative humidity,” which is the ratio of air’s absolute humidity to the air’s water vapor holding capacity.⁹

Diffusion – The process whereby water vapor or gases migrate through permeable membranes or partitions by osmosis. Gases always migrate from regions of high concentrations to regions of low concentrations until equilibrium is reached.

Elastomer – A macromolecular material that, at room temperature, returns rapidly to approximately its initial dimensions and shape after substantial deformation by a weak stress and release of the stress.⁴

Glass Transition Temperature – The temperature at which a polymer becomes brittle, and above a certain point, the polymer is deemed prone to failure.²

Plasticizer – An important component in the formulation of PVC membranes to give them flexibility to withstand elongation, strain, and thermally-induced stresses normally experienced by a roof system. Most plasticizers are esters of phthalic acid. The molecular weight and compounds vary from one manufacturer to the next. The plasticizer content in a new membrane is around



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PROBLEMS WITH THE EXISTING ROOF SYSTEMS		
SYSTEM NO.	EXISTING CONDITIONS:	OBSERVATIONS:
1. Low-slope areas of terminal, east and west of the tent roof	Deck: Structural concrete (sloped at 1/4"/ft.) Insulation: 4" of extruded polystyrene (XEPS) Slip Sheet: Manninglass felt Membrane: 60-mil reinforced mechanically-attached PVC	<ul style="list-style-type: none"> • Extensive hail damage and mechanical damage from icicles falling off of tent roof • Plasticizer loss • Damaged slip sheet • Thermal degradation of PVC • Isolated heat degradation of polystyrene • Minor corrosion of fasteners • Consolidation of insulation in high-traffic areas
2. Low-slope roofs on North Terminal and Customs areas	Deck: Structural concrete (flat) Insulation: Tapered XEPS 4.5" start, (sloped at approximately 1/4"/ft.), total maximum thickness 16" Slip Sheet: Manninglass felt Membrane: 60-mil reinforced mechanically-attached PVC	<ul style="list-style-type: none"> • Extensive hail damage • Plasticizer loss • Damaged slip sheet • Thermal degradation of PVC • Isolated heat degradation of polystyrene
3. Mechanical and elevator penthouses at terminal	Deck: Metal (sloped at 1/4"/ft.) Barrier Board: 5/8" Type X gypsum Insulation: 2 layers of XEPS, 1" and 3" for a total thickness of 4" Slip Sheet: Manninglass felt Membrane: 60-mil mechanically-attached PVC	<ul style="list-style-type: none"> • Minor hail damage • Plasticizer loss • Damaged slip sheet • Thermal degradation of PVC
4. Steep-slope areas of Terminal East and West	Deck: Structural concrete (sloped at 3"/ft.) Insulation: 2.6" polyisocyanurate Membrane: 60-mil mechanically-attached PVC	<ul style="list-style-type: none"> • Extensive hail damage • Plasticizer loss • Thermal degradation of PVC • Minor corrosion of fasteners • Minor facer delamination
5. Passenger bridge (slope 0" to 1"/ft.) and barrel roof over Customs (0" to 3"/ft.)	Deck: Metal (sloped 0" to 3"/ft.) with fireproofing on bottom side Barrier Board: 5/8" Type X gypsum Insulation: 2.6" of polyisocyanurate Slip Sheet: Manninglass Membrane: 60-mil mechanically-attached PVC	<ul style="list-style-type: none"> • Extensive hail damage • Plasticizer loss • Thermal degradation of PVC
6. Airport Operations Building (AOB) above 10th floor offices	Deck: Structural Concrete (sloped at 1/4"/ft.) Insulation: 2.6" polyisocyanurate mechanically attached Membrane: Fully-adhered .060" un-reinforced EPDM	<ul style="list-style-type: none"> • Severe buckles and deformation of polyisocyanurate • Severe facer delamination • Degradation of insulation cell structure (1/4" to 1/2" of the top layer turned brown and friable). • Extensive failure of adhesive seams • Corrosion of fasteners
7. AOB Penthouse	Deck: Metal (sloped at 1/4"/ft.) fireproofing on bottom side Insulation: 2.6" polyisocyanurate, mechanically attached Membrane: Fully-adhered .060" unreinforced EPDM	<ul style="list-style-type: none"> • Deterioration of lap sealant <i>The rigid insulation was deemed salvageable</i>
8. AOB 6th floor offices	Deck: Structural concrete (flat) Insulation: Tapered polyisocyanurate (4" start, sloped at approximately 1/4"/ft.) Membrane: Fully-adhered .060" unreinforced EPDM	<ul style="list-style-type: none"> • Buckles and deformation of polyisocyanurate • Isolated facer delamination • Degradation of insulation cell structure (1/4" to 1/2" of the top layer turned brown and friable). • Failure of adhesive seams • Minor corrosion of fasteners

Table 1: Problems with existing roof systems.

36%. A loss of 10 to 12 percent can result in premature failure of the roof system. Low molecular weight plasticizers are more volatile than those that have higher molecular weight.¹

Thermoplastic - A material that becomes plastic or viscous when heated and semi-rigid when cooled. Asphalt and PVC are classic thermoplastic materials.

BACKGROUND

Construction of DIA

The construction of the terminal and Airport Operations Building (AOB) was completed in 1991 and the passenger

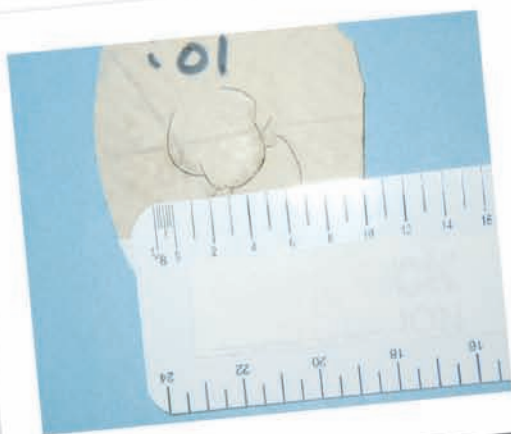


Figure 2:
Hail-damaged membrane.

bridge was completed in 1993. The roofs on the terminal, AOB, and passenger bridge were replaced in 2002. Eight different roof systems were identified. The following is a brief description of the roof system components and the type of problems noted.

DISCUSSION

Thermoplastic PVC Membranes

As early as 1999, only eight years after the original roof was installed, the PVC roofs on DIA began showing signs of degradation and premature plasticizer loss. Melting of the extruded polystyrene rigid insulation was also noted, particularly in super insulated areas with southern exposure to the sun. In June of 2001, a moderate hailstorm hit the airport, causing extensive damage to the PVC membrane on the terminal. The membrane did not shatter (unlike some of the first-generation PVC roof systems); however, concentric cracks were noted in the membrane at points of hail impacts. In most cases, the cracks ran completely through the membrane, rendering the roof system unsuitable as a waterproofing system. In some instances, the cracks emanated from the underside of the single-ply membrane, but did not manifest on the top or exposed side of the membrane.

The damage noted was more extensive on the darker discolored sheets used to construct the PVC membrane, (which apparently had different run numbers), and in areas that were exposed to more solar radiation. New cracks developed in the membrane at hail impacts that were not noticeable during the first visual inspection. The visible cracks were repaired immediately with EPDM primer and EPDM peel-and-stick flashing tape. The repairs were paint-

ed white to prevent thermal degradation of the polystyrene insulation below.

Frequent inspections were performed to identify new cracks and to effect repairs to prevent water infiltration through the existing single-ply membrane. Fortunately, the re-roof project was performed during a drought, which was recorded as the driest period in the previous 50 years.

The original roof system specified and installed on the vast majority of the buildings at DIA was an off-white, 60-mil, polyester scrim reinforced, mechanically-fastened PVC single-ply membrane, which was produced using the calendaring process. PVC is a thermoplastic material, which means that it becomes softer (or more plastic) with heat and semi rigid with cold. PVC is known for its resistance to acids, alkalis, and many other chemicals, as well as its self-extinguishing properties when subjected to fire. It is soluble in certain solvents, such as tetrahydrofuran, which is used in PVC cements.³

One of the main reasons PVC was used on the airport is that it was perceived that the membrane might be exposed to jet fuel. It was also one of the few membranes on the market that had a UL fire rating for all roof slopes encountered at the airport. The membrane, with its heat-welded and solvent seams, was also touted to be superior to other conventional roof systems, despite the lack of a long-term performance history.

Much has been learned about thermoplastic PVC single-ply membranes since they were introduced in the U.S. from Europe in the late 1970s. The non-reinforced sheet is no longer produced or marketed due to the shattering phenomenon and hail damage that occurred with the product. All of the sheet goods marketed and sold in the U.S. today (except for flashing materials) are reinforced with polyester or fiberglass mats or scrims, which

have greatly improved the dimensional stability of the original non-reinforced products. The membrane can be manufactured white or tinted in various colors with pigments, which is an advantage when solar reflectivity or an architectural statement is desired. The heat welding of the seams, using hot air welders, is also fairly consistent and reliable.

PVC copolymers in their normal state are rigid, brittle, and easily shatter under stress. Plasticizers, fillers, pigments, processing oils, biocides, and stabilizers are compounded with the PVC resins to impart the desired physical properties to the membrane. Plasticizers are used to give the sheet flexibility and suppleness over a wide range of temperatures. Stabilizer packages are introduced to provide resistance to thermal and photochemical degradation.

Plasticizers begin to migrate out of the sheet and the chemical bonds begin to change as soon as the membrane leaves the production line. This phenomenon, known as weathering, is normally a very slow and gradual process, which under favorable conditions, allows a PVC membrane to provide a useful life commensurate with other conventional roof systems. The glass transition temperature and specific gravity are increased and shrinkage of the membrane occurs as a result of thermal degradation and plasticizer loss. Exposure to heat, ultraviolet radiation, and various absorbent



Figure 3:
Patches from hail damage.

compounds will accelerate the degradation of PVC. Thermal degradation is manifested by a brown color, as the membrane goes through dehydrochlorination of the polymer.² Plasticizer loss occurs by migration, evaporation, washout, hydrolysis, and exposure to microbes.¹

Polystyrene rigid insulation (which was used extensively on the airport) has an affinity for PVC plasticizers; therefore, the two roof components must be adequately divorced for the duration of the roof's useful life. PVC membranes should also be adequately divorced from asphalt-contaminated surfaces for the same reason.

As PVC weathers, it loses some of its elasticity and flexibility. It has been demonstrated that new PVC membranes will generally produce a tensile load of 4-6 pounds per inch when subjected to a 100°F temperature drop. As the membrane weathers and becomes more brittle, the thermal load profile can increase fourfold to 20 plus pounds per inch.¹ It has been suggested that the shrinkage and thermal load profile of a PVC membrane can be affected by the manufacturing process and raw materials used in the products.² The extent of the effects from manufacturing is beyond the scope of this article.

The shattering phenomenon that occurred with the first generation PVC non-reinforced membranes can be attributed to plasticizer loss, shrinkage, lack of flexibility, and increased thermal loads during sudden drops in temperature. Hail and impact

damage to reinforced thermoplastic membranes can also be attributed to the same changes in physical properties; however, the mat or scrim prevents a weathered membrane from shattering into thousands of smaller pieces. Isolated cracks through the membrane, generally in the form of concentric circles, are usually noted after a hail event or impact, which compromises the watertight integrity of the membrane. The kinetic energy of a missile is converted to strain energy in the membrane, compressive yield stress in the substrate, disintegration of the missile, and momentum after impact.

Hailstorms are usually preceded by a sudden drop in temperature, which, as discussed above, causes the membrane to shrink, resulting in thermally induced loads in the material. At the moment of impact, the membrane begins to deform, and, as with any material "under load," develops additional tensile stresses on the underside and compressive stresses on the top side of the membrane. If the strain exceeds the elastic limit of the material at the time of impact, cracks begin to emanate from the bottom side toward the top surface. An underside view of the membrane is needed to ascertain the full extent of hail damage,

since cracks may develop but not penetrate completely through the membrane.

Impact resistance of the membrane can be improved by providing a denser substrate below the membrane, which resists deformation and elongation, thus minimizing the strain energy imparted to the membrane. Bridged or unsupported areas are still vulnerable to damage.

The long-term serviceability of a PVC roof membrane is a function of its dimensional stability and flexibility throughout the temperature range it will experience during its anticipated serviceable life. The stability of these physical properties is a function of the raw materials, manufacturing process, and environment to which the roof system is exposed.

Polystyrene Rigid Insulation

The vast majority of insulation used on the original roof at the airport was extruded polystyrene, which ranged in thickness from 4" (R-20 on structurally sloped areas) to 14" (R-20 to R-70 on the flat decks with tapered insulation). Most of the insulation board was deemed salvageable, which represented a sizeable investment by the owner, the city, and the county of Denver.



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Figure 4: Melted XEPS.

The new roof system had to be compatible with the existing polystyrene rigid insulation. A new, ballasted, single-ply membrane over a coverboard would have been an economical choice on any other project. The owner's choice to eliminate any roof system with loose rocks, which could become missiles during high winds, was respected and other reroof options were considered.

Extruded polystyrene is a plastic foam, closed-cell rigid insulation with a fluorocarbon blowing agent. The polymer that makes up the cell walls is relatively impermeable to water vapor, which renders the product useful in areas that may become exposed to moisture, (i.e., foundation walls, roofs, wall cavities, protected membrane roof assemblies, etc). It has a fairly stable aged R-value of 5.0 per inch.

Extruded polystyrene is considered a sustainable roofing product and can be salvaged for subsequent membrane replacements, under favorable conditions. The product has a published service temperature range of -100 to 165°F; therefore, it must be protected from temperatures above this range. This can be accomplished with slip sheets, coverboards, and reflective membranes or coatings. Polystyrene will disintegrate when exposed to various solvents, including membrane adhesives, cold process cements, and other petroleum-based chemicals. A limited number of adhesives are suitable for laminating polystyrene boards to one another and to other products. Solvent-free, rubberized emulsion adhesives have been developed that are compatible with polystyrene.

When the existing membrane was removed, it was noted that some of the

extruded polystyrene rigid insulation boards had melted or deformed from heat, particularly where the slip sheet was damaged or missing, and in areas next to the reflective clerestory windows (refer to *Figure 1* for view of window areas). To melt extruded polystyrene, the temperature needs to reach 165°F or greater, according to the manufacturer's published literature.

The ambient air temperature directly above the membrane was noted to be 95°F on a hot summer day. The melting indicates that the temperature between the membrane and the polystyrene

exceeded the air temperature by 60°F to 70°F, which is incongruous with static thermo profiles of building envelopes that have been presented in the past. The slip sheet protected the polystyrene somewhat, but did not prevent deformation of the insulation board. Insulation boards that were severely deformed or melted were replaced with like kind.

A single layer of 5/8" glass-faced gypsum board with a primed surface was installed over the existing polystyrene rigid insulation (secured with mechanical fasteners and Galvalume™ metal plates) to provide a dense, hail-resistant substrate for the new membrane and divorce the polystyrene from the elevated temperatures that were anticipated with the new black EPDM membrane. A couple of isolated areas, near clerestory reflective windows, experienced some heat degradation and had to be repaired (*Figure 4*).

The new black EPDM membrane was painted white to lower the surface temperature of the roof during the hot summer months, which will prevent the polystyrene from melting. During re-roofing (after the new black 90-mil EPDM membrane was installed, and prior to the application of the white elastomeric coating), and when the ambient air temperature reached

or exceeded 100°F, some severe deformation in the underlying polystyrene rigid insulation occurred in isolated areas (next to intersecting clerestory windows). The surface temperature of the black EPDM membrane was measured at 180°F at approximately 1:30 p.m. on a hot summer day. The membrane in these areas, next to the reflective windows, received much more solar radiation than other areas of the roof. As soon as the high-albedo, white roof coating was installed, the surface temperature dropped significantly to approximately 105°F, which prevented any further damage to the top layer of the polystyrene rigid insulation board.

Polyisocyanurate Rigid Insulation

Polyisocyanurate rigid insulation (PRI) with a permeable organic facer was used on some areas of the airport. When the roof was installed, hydrochlorofluorocarbons (HCFCs) were used as blowing agents for the plastic foam insulation boards. Various roof systems, using this product, were encountered:

- Mechanically-fastened reinforced PVC membrane over a single uniform layer of PRI over a structurally sloped concrete deck.
- Mechanically-fastened reinforced PVC membrane over a single uniform layer of PRI over a structurally sloped metal deck.
- Fully-adhered non-reinforced EPDM membrane over tapered PRI boards, mechanically fastened over a flat concrete deck.



Figure 5:
Damaged oxidized polyisocyanurate.

- Fully-adhered, non-reinforced EPDM membrane over a single uniform layer of PRI, mechanically fastened over a structurally-sloped concrete deck.
- Fully-adhered non-reinforced EPDM membrane over a single uniform layer of PRI, mechanically fastened over a metal deck.

On the concrete deck areas, several problems (moderate to severe) were noted that were not evident on the metal deck areas. The organic facer was deteriorated, the membrane was delaminated from the facer, the insulation board was buckled in a convex fashion, the top 1/4" layer of the board was discolored and friable, the insulation fasteners and plates were corroded, and the glued EPDM seams were delaminated (refer to Figure 5). Each one of these problems can be attributed to the effects of moisture. Residual water from the poured-in-place concrete was the probable source of the initial moisture, causing the EPDM seams to fail within a relatively short time, which precipitated the damage to the insulation board and fasteners. More water entered the roof system via open seams, which exacerbated the deleterious effects of moisture on the roofing components. There was evidence that patches and repairs were made when leaks occurred, but the residual moisture was probably not removed.

The facer is a critical and integral part of polyisocyanurate rigid insulation products. It provides dimensional stability and fire resistance to the insulation board and a means to adhere a roof membrane to an otherwise unstable and friable material. If organic facers become wet, the fibers expand, allowing the dimensionally unstable plastic foam board to expand or contract, resulting in "bowing" or "cupping" of the board. When the cellulosic facer dries, it shrinks, imparting stress on the board. If the roof system goes through enough wetting and drying cycles, the structural integrity of the facer becomes compromised and a fully-adhered membrane will eventually become disbonded.

Polyisocyanurate foam is a cellular plastic insulation that entraps a gaseous blowing agent within microscopic cells of a polymer matrix. The cells of the foam are primarily closed, and due to the low thermal conductivity of the entrapped gas, the foam is an effective insulator. The cell walls are permeable and, with time, the blowing agent(s) can escape from the cells while ambient gases such as N₂, O₂, and H₂O vapor diffuse relatively quickly through the cell walls and permeate the foam. The resulting change in the gas composition of the foam over time, and the corresponding decrease in its insulating capability, are referred to as "aging" of the foam.⁸

Studies have shown that in the presence of heat and moisture, the aging process of plastic foam insulation products is accelerated and the physical properties – thermal conductivity, compressive strength, density, coefficient of linear expansion, and vapor permeability – are affected substantially above 120°F (49°C). Under dry conditions, polyisocyanurate foam insulation is dimensionally stable (<5% change in dimension and <15% by volume) up to 220°F (104°C). At temperatures above 120°F (49°C) and a relative humidity above 90%, the

product becomes dimensionally unstable: (5 to 20% dimensional changes in each direction and 15 to 60 percent change in volume can occur).¹

Over wet substrates, weathering, moisture gain, and dimensional changes in polyisocyanurate foam insulation products tend to be more pronounced with dark roofs, due to the elevated temperatures. The designer or installer of a roof system should properly evaluate the presence of moisture. Non-destructive moisture evaluations are highly recommended for recovers where trapped moisture is probable. Cementitious decks should be checked for moisture content if a vapor retarder is not used or specified. On new construction, vapor retarders are recommended over concrete decks to prevent the residual moisture from affecting the roof system components. Studies are being done on the drying effects of loose-laid, pressure-equalized venting single-ply roof systems. The long-term viability is still being researched.¹¹

Water vapor always diffuses from regions of high absolute humidity to regions of low absolute humidity. The greater the difference in absolute humidity across a permeable structure, the faster the rate of

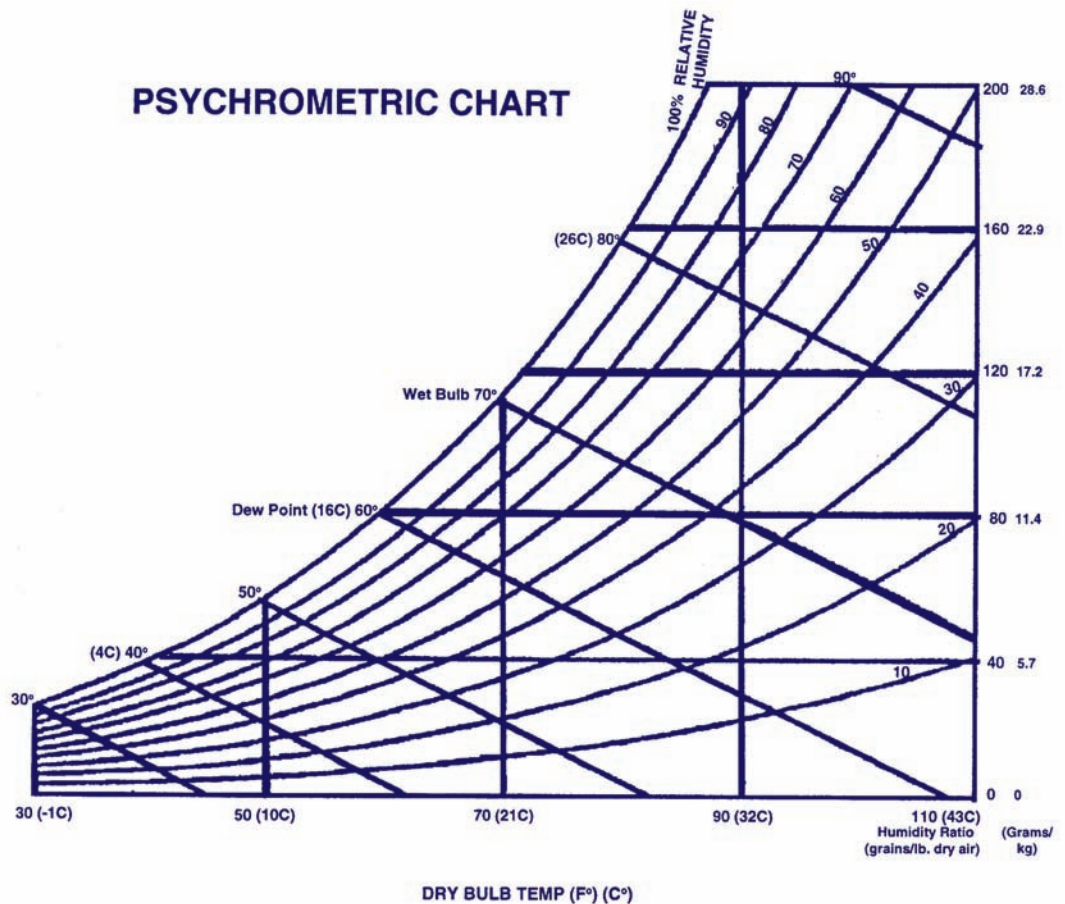


Figure 6: Psychrometric chart, courtesy of RIEL.

YEAR OF INTRO:	TECHNOLOGY IMPROVEMENTS
1985 - 1986	Butyl-based splice adhesive replaces water- and heat-sensitive Neoprene-based adhesives.
1985 - 1986	EPDM-based wall flashings replace heat- and ozone-sensitive Neoprene-based flashings.
1987 - 1988	Tape laminates replace adhesive seams at roof edges and battens.
1988 - 1989	Metal battens and screw fasteners replace treated wood nailers and nails at base tie-ins.
1991 - 1992	Reinforced perimeter fastening strips introduced as an alternative to metal battens for base tie-ins.
1992 - 1993	Seam tape with high solids primer replaces seam adhesive.

Table 2

diffusion. Thickness of a material also affects the permeability or rate of diffusion. In most building situations, warm air tends to have a higher absolute humidity than cooler air. This gives rise to the adage, "water vapor goes from hot to cold." This is not necessarily true for buildings with unusually high or low interior humidity or buildings with wet or moisture-laden components. Water vapor migration is usually not a concern until the gaseous molecules reach the dewpoint temperature and condense into liquid water.¹⁰

Foam insulation products can become wet by vapor diffusion followed by condensation. Water accumulates in the foam when vapor drive acts in concert with thermal gradients and the vapor is restricted on the cold side of the building envelope. Moisture accumulation is reversible, which means foam insulation can eventually dry out, if allowed to, by vapor diffusion.

On the airport project, evidence shows that the permeability of the EPDM membrane was not sufficient to allow adequate amounts of water vapor to escape to the atmosphere. The polyisocyanurate rigid insulation and facer at the DIA project experienced numerous cycles of wetting and drying as a result of the residual moisture trapped between the deck and black EPDM membrane. The black membrane reached temperatures of 180°F in the summer, which increased the thermal gradient, vapor pressure, and therefore, the vapor diffusion rate, thereby accelerating the degradation of the foam insulation and facer on the top side of the boards. This, however,

would not explain the brown discoloration of the top surface of the insulation board (refer to *Figure 5*), which is usually indicative of photochemical oxidation. The solvents in the bonding adhesive, in concert with moisture and heat, may have reacted with the polymer matrix of the insulation board. Further study is needed. This demonstrates the need for a vapor retarder over freshly-poured (moisture-laden) concrete decks.

Elastomeric EPDM Single-ply Membranes

EPDM is an elastomeric thermoset polymer synthesized from ethylene propylene and a small proportion of a diene monomer with rubber-like or elastic properties. The black membrane, which has carbon black as a UV inhibitor, has excellent weathering characteristics. EPDM is not resistant to petroleum oils and gasoline.³ The membrane will swell and soften when exposed to these chemicals. Other than silicone, EPDM has the best service temperature range of any elastomeric membrane on the market (-65 to 300°F). A non-reinforced membrane has a tensile strength of 1400 lbf/in² and an ultimate elongation of 300%. EPDM also performs very well under heat and exposure to ozone. EPDM membranes have a proven track record. Due to improved product technology and superior details, problems with shrinkage and failed seams have greatly diminished since the product was first introduced to the roofing market more than 25 years ago.¹²

It was decided that a black, 90-mil, non-reinforced EPDM membrane would be



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ROOF REPLACEMENT OPTIONS	PROS AND CONS
Built-up roof	Rejected because of asphalt fumes, loose rock, and potential for melting existing polystyrene.
SBS modified, hot- or cold-applied	Rejected because of asphalt or solvent fumes and potential for melting existing polystyrene.
APP modified, torch or cold-applied	Rejected because of risk of open flames and the negative effect of solvent fumes on polystyrene.
PVC	Rejected because of past experience at airport.
TPO	Rejected because of limited performance history.
EPDM ballasted	Rejected because of loose rock or pavers.
EPDM mechanically attached	Rejected because of dynamic forces on membrane and fasteners and noise from the extensive use of fasteners.
EPDM fully-adhered	Accepted because of durability, low life cycle cost, excellent resistance to wind and hail, and minimal intrusion on facility operations.

Table 3

installed over a layer of 5/8" glass-faced gypsum board, which was mechanically fastened over the existing salvaged polystyrene rigid insulation. The only drawback perceived with the EPDM roof on the airport was its black color, which gets hot during the summer months from solar radiation. The temperatures would get hot enough to cause deformation of the existing polystyrene insulation board.

White EPDM, which has a titanium dioxide UV inhibitor, was rejected because the product does not have the same weathering properties as black EPDM, which uses carbon black. It was decided to coat the roof with approximately 15 mils of a high albedo white acrylic elastomeric roof coating, after washing and priming the membrane. Prior to coating, seams of the EPDM sheets were mated with 3"-wide butyl seam tape and a high-solids, butyl-based primer. The seams were then covered with a 5"-wide, butyl-backed, self-curing EPDM flashing tape. This seaming method provided redundancy and ensured that any small pinholes – particularly at tee joints – were sealed watertight for the serviceable life of the roof membrane.

The hail and puncture resistance are excellent with EPDM when installed over a

hard board. The fully-adhered EPDM over 5/8" glass-faced gypsum board has passed the most severe hail tests and has received the highest ratings from United Laboratories (UL), the National Institute of Standards and Technology (NIST), and Factory Mutual (FM) for hail resistance. A 2" hail warranty was issued by the roofing manufacturer.

The membrane installation was rather innocuous, but some precautions were needed to avoid adhesive fumes from being drawn into the building through the fresh air intakes of the mechanical air handling system. Plywood chutes eight feet high were built around the fresh air intakes and were very effective.

High Albedo White Roof Coating

A white roof coating was specified and installed to lower the surface temperature of the roof in order to prevent the polystyrene rigid insulation from heat degradation. The coating also provides the following benefits:

- Encapsulates all seams and edges of the membrane and flashing materials, thereby providing additional redundancy in the waterproofing system.
- Protects the membrane and flash-

ings from heat and UV exposure, extending service life.

- Greatly reduces the temperature gradient of the roof, which lowers the relative humidity and vapor drive within the roof system components.
- Provides an aesthetic appearance to the roof.

It is anticipated that the coating will weather at the rate of 1 mil per year. This gradual chalking process is what keeps the roof white and highly reflective for the life of the coating. It is anticipated that the roof may need to be recoated at least once during its useful life. The cost of the coating is offset by the savings achieved from the extension of the useful life and reduced energy consumption during the summer to condition the air in the building.

The peel strength and adhesion of water-based acrylic roof coatings have improved greatly since primers or "pre-washes" were introduced. Practically all manufacturers of roof coatings and EPDM membranes offer white coating specification and warranties. The prewash was lightly sprayed on the surface of the finished EPDM roof and then rinsed off with water. After the membrane dried, the water-based coating was applied with rollers. To avoid overspray, a spray apparatus was not used.

Water-based acrylic coatings perform best on roofs with adequate slope and drainage. Ponding water will cause the coating to swell and peel away from the membrane. When exposed to standing water for prolonged periods, moisture will be absorbed into the coating, causing dimensional changes. This induces shear stress at the adhesive bond. If the water absorbed into the coating freezes, the coating will break down and eventually delaminate from the substrate.

ROOF SYSTEM SELECTION PROCESS

Owner's Concerns

As one can imagine, the facility management and engineering staff had several concerns and expectations with regard to the new roof systems. With the exception of one roof area (System No. 7), the original roofs did not perform as anticipated and had to be replaced prematurely due to hail damage and degradation of the physical properties of the polyisocyanurate rigid insulation and PVC roof membranes. The manufacturer's roof guarantee did not cover hail damage, and the manufacturer would not participate

in replacing the roof because of the change in the membrane's physical properties and likelihood of further hail damage. Because of the premature degradation of the PVC membrane, foot traffic on the roofs had to be limited to times when the outdoor ambient temperature was 40°F or above. The design team had to come up with a roof that would address the following issues:

- **Heat Aging:** The high R-values (super insulated roof at apex of tapered insulation system) and the reflective glass on the clerestory windows places the membrane in an environment with abnormally high heat and solar radiation. The new membrane must have good heat aging properties.
- **Sustainable:** The new roof system must be compatible with the existing polystyrene insulation boards. A large investment had already been made with the thermal insulation and tapered system.
- **Low Meltpoint of XEPS:** The temperature of the membrane must remain well below the melt point of the polystyrene insulation board.
- **Hail Resistance:** The new membrane must be proven to withstand hail.
- **Facility Operations:** The roof replacement process must be as non-intrusive as possible, and the finished roof must not utilize loose-laid components that could become missiles in the event of a tornado or high winds. Removing the polystyrene rigid insulation also posed a high risk for the tarmac operations, particularly on windy days.
- **Maintenance:** The roof system should be easy to repair and require little maintenance.
- **Temperature Limitations:** The adhesives and products must be workable during all four seasons of the year, due to the long duration of the project.

Options Presented to Owner

Several roof replacement options were presented to the airport staff. The pros and cons were discussed for each roof type.

PROJECT CHALLENGES

The first and foremost challenge was selecting a roof system that would be as unintrusive and risk free as possible for the facility operations and customers of the airport. The transfer of materials on and off of the roof had to be minimized and the roofing products had to be rather innocuous. By salvaging the majority of the existing insulation board, the owner enjoyed cost savings as well as reducing the risk of debris blowing onto the tarmac.

Security issues were paramount, especially after the September 11, 2001, terrorist attack on the U.S. The contractor had to provide a sufficient number of laborers who could pass the stringent screening methods imposed by the government. Even moving tools onto the jobsite was cumbersome. Personnel on the roof had to be badged and escorted by qualified persons.

Staging was limited and difficult. The airport officials required that staging plans be submitted and approved weeks in advance. Most of the material and debris handling was done at night. Underground tunnels and buildings precluded crane setups to specific areas. Special cranes with long booms were utilized to move materials on and off of the ten-story Airport Operations Building.

Debris, flammable goods, and loose materials could not be stockpiled on the roof. Products and materials that were not properly bundled together had to be removed from the jobsite at the end of each day.

Some parapet wall sections were curved. New sections of coping had to be custom fabricated and pre-finished. Each curved section had to be measured with a template and shipped to the metal supplier for fabrication. Over 100 different coping sections had to be custom made.

The roof had to be installed during dry and warm weather because of the water-based roof coating, which is subject to damage from freezing prior to curing. The established schedule was from April to Novem-

ber. Over 4,000,000 square feet of roofing had to be installed in six months.

Return air intakes were located near the roof level, which presented a potential problem with offensive solvent fumes being drawn into the air handling units and dispersing them into the occupied building. Plywood chutes were constructed around the intakes and anchored with tie-backs to resist wind pressures. This precaution was deemed effective, and no complaints were received with regard to the solvent fumes (refer to *Figure 7*).

CONCLUSIONS

Weathered reinforced PVCs are subject to hail damage. In hail zone areas, designers should consider a hard coverboard that offers more resistance to impact deformation and lowers the strain energy imparted to the membrane.

Polystyrene rigid insulation is subject to heat degradation, even when a light-colored membrane and slip sheet are provided, particularly when exposed to extraordinary solar radiation that occurs with reflective clerestory windows.



Figure 7: Return air chutes.

Fiberglass slip sheets are subject to damage on mechanically-fastened, single-ply roof systems due to fluttering of the membrane on windy days. Slip sheet displacement will result in premature plasticizer migration of PVC over polystyrene.

High thermal R-values and solar reflection from windows accelerate weathering of a PVC roof membrane, resulting in premature plasticizer loss and degradation.

Manufacturing processes, compounds, and environmental exposure can have a major affect on long-term flexibility and serviceability of PVCs.


Generally, polyisocyanurate rigid insulation products perform very well under extreme heat or temperatures often experienced in a roof assembly, even when installed below dark or black membranes which can achieve surface temperatures of 180°F. When moisture is introduced and becomes trapped in the insulation from membrane leaks, vapor diffusion, or residual water in cementitious roof decks, the weathering and degradation of polyisocyanurate rigid insulation are intensified. In such instances, the physical properties and dimensional stability of polyisocyanurate rigid insulation are eventually compromised, and the sustainability of the product is negated.

Concrete decks on new construction are apt to contain large amounts of residual moisture that can have a deleterious effect on some plastic foam insulation products, organic facers, and adhesive seams of elastomeric membranes. Designers and installers should consider vapor retarders over moisture-laden concrete decks to pre-

vent moisture migration and condensation within an insulated roof assembly.

Construction traffic can cause scarring of the roof membrane that will cause latent problems post construction.

The product quality and long-term serviceability of roof membranes differ greatly among manufacturers. In the selection process of a roof system, there is no substitute for time-proven performance.

To be successful, difficult projects require extraordinary planning, synergies from all parties, cooperation, and constant open lines of communication. 

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This article, originally entitled, "Reroof Project Case Study: Denver International Airport Terminal Flat Roofs," was presented as a part of the 19th RCI International Convention & Trade Show in April 2004 in Reno, Nevada.

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