Aging and Hail Research of PVC Membranes

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Key Words: Membrane, roof, plasticizer, hail, PVC.

Abstract: Viable roofing systems provide long-term waterproofing. Reinforced and non-reinforced PVC roof systems presence in the American low-slope roofing market spans the better part of three decades. This roof membrane brings particular unique features to owners of flat roofs -- significant energy savings from reflective membranes, solid performance in ponded conditions, inherent flame resistance, integral seam fusion, and ease of inspection, leak detection, and repair. However, in the American market of the mid-980s, a rash of catastrophic membrane shattering to aged, non-reinforced, monomeric-plasticized PVC roofs occurred. The reputation of PVC roof systems suffered. In response, non-reinforced roof system manufacturers discontinued these specifications and products in favor of today's standard, thicker, fabric-reinforced PVC roof systems. Currently, the Single Ply Roofing Institute (SPRI) organization reveals PVC thermoplastic roofing is once again in a growth mode in the United States low-slope roofing market.

However, the primary shattering characteristic, plasticizer migration, despite design improvements, remains a failure mode requiring definition and management. Hail, especially large hail creates catastrophic events, which, instantaneously (for instance the shatterings of the mid-80s) and completely undermines the positive aspects of this membrane system. To make matters worse, U.S. manufacturers expressly exclude hail events from their obligations to waterproofing performance, thus building owners shoulder the risk against this damage. Little direction if offered on aging and the need to monitor and replace aging, embrittled membranes. To draw a parallel: why provide attachment specifications if warranties exclude damage from all wind events when both wind <u>and hail</u> are naturally occurring events in the central heartland of the United States. Owners in these states need hail specifications and guidelines for timely replacements.

This research focuses on the relative aging and hail vulnerability of reinforced PVC membranes marketed in the 1990s by four prominent PVC manufacturers. The study centers on the sampling and testing of 87 membranes of various ages for plasticizer migration and hail simulation testing. The results indicate a dramatic range in test results between the best and worst of the four manufacturers. This paper targets roof owners, offering observations addressing membrane aging, monitoring and management.

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1.0 INTRODUCTION

Six distinct categories of membrane systems dominate the current United States low-slope roofing market: built-up asphalt; built-up coal-tar pitch; thermoset rubber (EPDM); SBS-modified bitumen; APP-modified bitumen; and thermoplastics (PVC, PVC alloys, and TPO). Selection of the optimum roofing solution for a given project is dependent upon a number of building owner's criteria (*Table 1*). Although some owners focus on only a few criteria, others may have multiple reasons for selecting a particular membrane system. All of these categories of roof systems demonstrate benefits to owners. No single classification of roof system satisfies all criteria because each brings distinct features to a vast spectrum of owner and building needs.

Initial installed cost	Speed of installation	Warranty and perceived health of supplier
Weight	Ease of leak detection	UV and ozone resistance
Impact upon energy	Ponding resistance	Ease of application
Fire rating	Aesthetic appearance	Life cycle cost
Wind rating	Chemical resistance	Impact and abuse resistance
Environmental impact (degradation/disposal)	Tolerates movement (thermal and structural)	Performance in extended extreme temperatures
Ease and integrity of repair	Ease of accurate inspection	Timeline length -- signal of degradation to replacement
Roof profile -- density of penetrations, accessibility	Compatibility with system components and deck type	Use and climate of building

Table 1: Criteria in membrane system selection

However, when selecting any roofing system, specifiers and owners must consider the potential causes of failure of their selected roofing system. Hail events in particular can undermine a careful membrane selection because of a sudden and complete loss of waterproofing, resulting in damage to equipment, product, interior finishes, business enterprise, and building structure. The authors have observed hail damage to all exposed roof systems - from thin, non-reinforced, elastomeric skins to thick, reinforced, multi-layer composites. “Exposed” here is defined as any roof system not covered with stone.

In a catastrophic hail event, building owners in the United States most often have no warranty protection. U.S. warranties for all classes of roof systems consistently contain a standard legal clause listing hail among "natural disasters," thereby eliminating any obligation of the membrane manufacturer in leak repairs. The standard listing of disasters usually includes hail in conjunction with tornadoes, winds at gale force or greater, hurricanes, fires, and earthquakes. Yet small hail is so frequent in some U.S. locations of the United States that small hail is a predictable, naturally occurring event. S.A. Changnon maps out locations in 12 states where there is a 50 percent chance that hail, 1-inch (25 mm) or larger, will fall at any given point, at least once in five years.[1] A building owner in the county of Scotts Bluff, Nebraska knows from experience that small hail is as common as the arrival of July thunderstorms. In that county, more than 70 reported hail events occurred in the past 10 years. On 19 days in that time span, hail measured 1.5-inches (38 mm) and on five of those days, the hail exceeded 2.0-inches (50 mm) in diameter.[2] Although manufacturers routinely provide roof designs for local wind conditions across the United States, specification guidelines addressing hail damage of any size are largely ignored.

Photo 1 presents two samples of impact fracture on PVC roof membranes, both from hail. One is small hail damage taken from a roof in Conroe, Texas where the membrane was 18 months old. The other sample is of large hail damage taken from a roof in Fort Worth, Texas where the roof membrane had 42 months in exposure. The characteristic fracturing of the small hail sample in the photo is a series of concentric rings of fracture. This fracturing will also occur when a large and heavy object such as a large screwdriver is dropped onto an embrittled, membrane surface.

Photo 1: Small and large hail damage to two distinct PVC roof membranes

A complete absence of answers to questions from many membrane suppliers prompted this study in the spring of 2000. Manufacturers were asked to supply empirical data available regarding the aging of roof membrane products and the product's hail vulnerability. In other words, should an owner in a hail-prone location plan for a roof replacement at a certain age, or at a certain measure of membrane degradation, even though the roof system it is still performing?

This research focuses on the hail performance of only one of these classes of roofing systems -- reinforced, monomeric-plasticized, PVC membranes. In the mid to late 1980s, the reputation and use of PVC roof systems were negatively impacted by frequent reports of membranes shattering across the United States. Those shatterings were caused by the impact of cold weather contraction on aged and embrittled PVC membranes. The membranes of those reports were non-reinforced and often thin membranes. Design improvements have been made to PVC membranes such as the routine use of fabric reinforcements and increased thicknesses. These design improvements largely restored the reputation and acceptance of conventional PVC membranes. However, the agent of destruction in those shatters remains intact - membrane embrittlement caused by plasticizer migration as a result of weathering. Hailstone impact causes most catastrophic damage to embrittled, current design PVC membranes. Owners and specifiers of PVC membranes, appreciating the benefits of this class of roofs, need to manage against this event.

Features of PVC Roofing Membranes

PVC (polyvinyl chloride) is a ubiquitous polymer. Web sites of plastic trade institutes indicate that annual North American demand for PVC resin is 14 billion pounds (three billion kilograms). A large percentage of this polymer is used in the construction industry as rigid piping, cable sheathing, cabinetry, wall covering, flooring and to a small extent, flat roofing. PVC roof membranes were introduced from Europe to the North American low-slope roofing market in the 1970s. There are many successful PVC roofing applications in service today that are older than 15 years, a common single ply warranty period in the U.S. market.

Building owners and specifiers of exposed PVC roof systems often focus on the following distinct benefits of PVC roof installations:

- competitive installation cost
- verification of details and workmanship ease
- installation may occur during very cold and/or damp conditions that would impair or prevent installations of other roof systems
- provision of inherent flame-resistant chemistry of the base polymer to the roof of commercial buildings
- across the entire roof, if properly installed is a consistent, predictable fusion of membrane panels into a single, flexible waterproofing skin
- ease of leak detection, ease of repair and long-term integrity of “the patch”

Furthermore, a recent U.S. government study consequently indicates that southern U.S. owners of large, commercial, low-slope roof systems who select white, reflective roof surfaces will fund their roofing investment by means of offsetting reductions in annual energy expenses.[3]

Mode of PVC Membrane Failure

PVC membranes provide important benefits to owners and specifiers. However, the characteristic aging of PVC membrane is noteworthy. The collective observations of the authors collaborate that long-term failure modes with conventional PVC roof membranes are largely about gradual membrane embrittlement due to exposure to the elements - heat and ultraviolet light. Although crystallization of the base resin contributes to embrittlement, it has always been observed and measured that when a conventional PVC membrane feels brittle, the plasticizer is departing from the membrane.

PVC roof membranes are comprised of fabric reinforcement and film blends both above and beneath the reinforcement. The film blends are formulations of following three main groupings:

PVC resin - 50 to 60% of the formula (by weight)
Plasticizers - 25 to 35%
“All other components” - generally 10 to 15% of the formula

The category “all other components” covers an array of ingredients added to formulations imparting specific properties to the membrane skin - UV resistance, coloration, heat and compound stabilizers, process enhancers, antifungal agents, and fillers. Fillers defined here are low-cost solids that increase the mass of a product without compromising its performance.

Each manufacturer has proprietary formulations for its PVC roof membranes. These formulations reflect a delicate balance between the limitations of process equipment, marketing and profit goals, and design objectives of products. PVC formulations are sophisticated chemistry with many choices among the three principle groupings - resin, plasticizer, and “other” ingredients. Change one component and there is an impact on the production process, membrane cost and roof performance.

Plasticizing agents are key features of PVC membrane. They impart flexibility to a solid PVC resin. They provide the ability to fuse seams and cold temperature performance. Plasticizers are also at the heart of a PVC membrane failure. Jim Koontz notes the relationship between loss of plasticizer and the resulting changes in physical properties, increase in durometer hardness, increase in specific gravity, loss of elongation and increase in tensile strength.[4]

The authors have collectively and consistently observed that PVC membranes gradually age and become brittle through exposure. Therefore, logic follows, as a result of this aging process an association between hail vulnerability and embrittlement exists. Hailstones smaller than 1-inch (25 mm) in diameter have fractured “stiff” membranes from one supplier's product as new as 3 years. However, another manufacturer's membrane, 8 years old and still supple, performed through a hailstorm where the stones were 2-inches (50 mm) in diameter. These observations indicate distinct differences in plasticizer stability between PVC manufacturers. This study attempts to isolate the products of four major PVC membrane suppliers to discover plasticizer content and the rates of plasticizer migration. Furthermore, this study provides indication of hail performance for the membranes of these four suppliers. To accomplish this discovery, a large number of PVC membranes were sampled, plasticizer analysis performed and subjected to hail simulation testing.

2.0 SAMPLE POPULATION

During September 2000, 87 conventional PVC membrane samples from the four distinct manufacturing groups were gathered from the centers of 87 low-sloped roofs scattered primarily through the central, hail-prone section of the United States (*Table 2*). The term, “manufacturing groups,” is used because over a period of years, a single manufacturer may have more than one manufacturing site. Where there was a reported change in manufacturing site and/or process, that manufacturer represented consistency in formulations and no change in performance characteristics. The manufacturing groups issued 15 year warranties for the roof systems at these locations. These warranties provided an expectation of 15 years of waterproofing performance.

Arizona	5
Colorado	12
Iowa	7
Idaho	1
Illinois	5
Kansas	6
Louisiana	2
Minnesota	6
Nebraska	2
Oklahoma	4
So. Carolina	1
Texas	35
Utah	1
Total	87

Table 2: Locations of sampling by state

With the exception of insulation board thickness, the specifications from the sampled roofs were identical.

Common to all the sampled roofing systems were the following:

- The membranes represented manufacturers producing membranes in the U.S. market for more than 15 years, each with a production capacity of at least 25 million square feet (2.3 million m^2) per year.
- Each membrane was a “conventional” monomeric-plasticized PVC.
- The membrane systems incorporated polyester fabric reinforcements.
- Roof systems were “exposed”, mechanically fastened, with rigid polyisocyanurate insulation board.
- The roof membranes were reported to comply with ASTM D 4434.
- Nominal thickness measured 45 to 50 mils (1.1 to 1.2 mm). The installed roof systems design slope measured 1.04% (1/8 in 12).

Age of Samples

The samples varied in age of exposure from the newest at 1 year and 2 months exposed in the state of Utah, to the oldest at 10 years and 3 months exposed in Oklahoma. The sample age begins as one month after the ship date of material to the construction site, allowing for installation time.

Factoring for UV Aging

The geographic location of a roof has significant impact on aging. For example, a roof in Minnesota does not receive the same heat and sun exposure as a roof in Arizona. To account for this significant climatic variation, the membrane age of each sample was factored (increased or decreased) for UV index depending upon the American state from which the sample was taken.

The National Oceanic and Atmospheric Administration’s (NOAA's) Website provides mean UV index by month and by state for the year 1997.[5] A UV index is assigned by that agency, ranging from 1 to 10. As reference points, Minnesota in January 1997 had the lowest assigned relative UV index of 1.0 and Arizona in July 1997 had the highest assigned UV index of 10.0.

Of the 13 states from which the samples were taken, the mean annual UV index was 4.71. Table 3 illustrates the methodology behind factoring for 2 of the 13 states.

1997 NOAA Mean UV Index	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Tot	(a) Mean	**(a-b/b)** Mean UV Factor
AZ	3	4	6	7	9	10	$\boxed{10}$	9	7	5	3	2	75	6.25	132.70%
MN	$\boxed{1}$	1	2	4	5	7	6	5	4	2	1	1	39	3.25	69.10%
													All States: (b)=	4.71	

Table 3: Method of UV “factoring” using two states as an example

For 1997 (the only year posted on the web site), the mean monthly UV index for Arizona calculates to 6.25 while the mean index for Minnesota is 3.25. Within the total average of all 13 states in this study (Item b in *Table 3*) roofs in Arizona were aged an additional 32.7%, while roofs in Minnesota were made 30.9% younger.

Arizona Weighting	Minnesota Weighting
(6.25 – 4.71) / 4.71 = **+** 32.7%	(3.25 – 4.71) / 4.71 = **-** 30.9 %

Thus, the age of all roof samples taken from Arizona increased by 32.7%, and the age of Minnesota samples were reduced by 30.9%. Going forward, test results that reference “UV age” or “UV factored age” are a result of this method of factoring.

This crude method of UV factoring makes the assumption that a month's aging process for a July Arizona roof is 10 times faster than a January Minnesota roof. No empirical support for this consideration exists. Consistent observations of sun and heat exposure are the two primary weathering agents of PVC roof aging. Southern U.S. PVC roofs age more rapidly than northern roofs. Regardless, as depicted in the next table, this “factoring” bias among the samples is fairly uniform in impact. Understandably the roof samples among the four manufacturing groups were evenly dispersed, both in age and geography.

Aging by Manufacturing Groups

Table 4 reports four distinct manufacturing groups (group identification here is A, B, C, & D) were sampled with mean age and mean UV-factored age.

Group ID	No. of Samples	Mean Age of Samples (Years)	Factored UV Age (Years)	DIFF	%
A	20	5.79	6.08	0.29	5.01%
B	21	4.30	4.74	0.44	10.23%
C	25	4.95	5.42	0.47	9.49%
D	21	5.83	6.05	0.22	3.77%
	87				

Table 4: Four manufacturing groups, mean and UV factored age

Notably, the newest of the four manufacturing groups was Group B with an average age of 4.3 years. This group had the greatest amount of UV factoring - an additional .44 years (about 5 months). If a false-positive bias in aging exists due to the factoring method (if a July Arizona roof does not age faster), then Group B will receive the greatest percentage of false bias. In contrast, the oldest of the four groups (group D mean exposure of 5.83 years) received the least amount of factoring - an additional .22 years (about 2-1/2months).

Sampling Method

Within a 30-day period, the 87 membrane samples were gathered from the center of each roof. Identification markings were made on both the main panel and on the "tail" of each panel so that collected data could be correlated between panel and "tail." The cross-seam "tail" samples were cut off and express-mailed to an independent chemical testing agent for plasticizer analysis. The larger membrane panels were stacked and stored in a laboratory environment at the site of the hail simulation testing. The following is a sketch of the sample taken from each roof (*Illustration 1).*

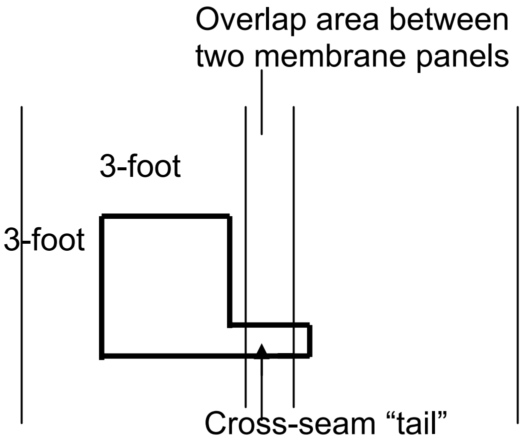


Illustration #1: Plan view of sampling, 9.0-sf (.83 m^2) membrane sample with "tail"

The tail portion of the sample provides a hidden flap underneath the seam weld of unexposed membrane. *Illustration* #2 below sketches the unexposed hidden flap and the exposed portion of a membrane sample cut out as the cross-seam "tail."

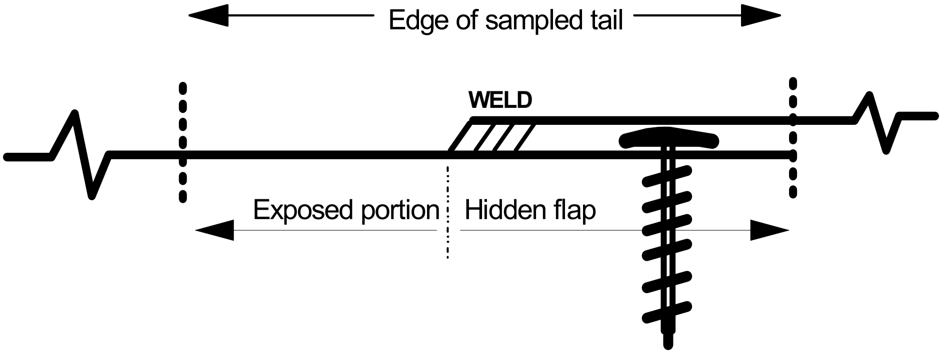


Illustration #2: Cross-seam "tail"

From the 87 membrane samples, three analyses were made:

1. Solvent extraction of plasticizer content - hidden flap and exposed portion of the same membrane.

2. Micrometer measurement of membrane thickness - hidden flap and exposed portion of the same membrane.

3. Hail simulation testing of membrane panels.

3.0 TEST PROCEDURES

Solvent Extraction of Plasticizer Content

To explore the relative rates of plasticizer loss among these four major manufacturers, plasticizer was solvent-extracted from both the hidden flap and from the exposed portion of the membrane. Solvent extraction follows ASTM D 3421 protocol. The underlying concept of solvent extraction is that a bath of aggressive solvent easily separates the liquid plasticizer from the polymer resin. The ASTM protocol defines that the average extraction is plus or minus 3.3% of a complete extraction of liquid plasticizer from the PVC membrane.

Prior to extraction, the sample is weighed and then placed into a bath of solvent for a defined period of time where the plasticizer is drawn out of the sample. The bathed sample is allowed to air dry and is weighed a second time. At this point, the plasticizer itself is captured as a dilution into the liquid solvent. The reduction in weight of the post-bath sample represents the amount of removed liquid plasticizer. *(For additional chemical analysis of the type of plasticizer, the solvent may be evaporated, leaving the plasticizer as a residue).*

By extracting plasticizer from both the hidden flap and the exposed portion of the same membrane panel, measurements of plasticizer content in both the exposed and hidden portions of the membrane can be made. The differences between these two contents reflect the amount of plasticizer that migrated from the membrane as a result of exposed weathering. Two qualifications in this analysis are highlighted:

1. Solvent extraction is only made from the top layer of the membrane.

   PVC roofing membranes are usually a composite of films above and below the fabric reinforcement. Mechanical separation was made of the film above the reinforcement and only the top film were analyzed for solvent extraction. Since the top film withstands direct sunlight and weathering, analysis only of the top film dramatically reveals the weathering effect of exposure.

Underlying logic would support that the content and quality of plasticizer below the reinforcement serves as a reservoir of replacement for plasticizer, which degrades and departs the membrane from the top surface (a sort of "balanced equilibrium"). Within this logic, however, the weave structure of the fabric reinforcement and the presence of a coating around the reinforcement potentially promote or limit the amount of migration from bottom film to top film. Regardless of logic, if the layer above the fabric surfacing loses significant plasticizer, then the top surface becomes embrittled and loses impact resistance.

2. The hidden flap undergoes some small degree of aging.

   Unlike the weathered portion of a cross-seam sample, the portion of membrane hidden under the flap looks new and feels supple. However, because the hidden flap is exposed to ambient temperature and humidity, the content of the plasticizer measured in the hidden flap is not exactly the same content of plasticizer existing in the membrane when the product was first shipped. This analysis does not incorporate an estimate of this small rate of hidden flap aging.

Micrometer Measurement of Membrane Thickness

As conventional PVC membranes are exposed and aged, a change in thickness occurs. As an additional analysis, micrometer measurements of the cross-seam samples were made for both the hidden flap and the exposed portion. Measurements were made in five locations on each side (hidden and exposed) of each cross-seam sample and the average of the five measurements are reported. Metric data is offered simply as a conversion.

Hail Simulation Testing of Membrane Panels

Jim D. Koontz & Associates, Inc. used the larger 3-foot by 3-foot (.9 m by .9 m) section of each exposed membrane for hail simulation testing. The following conditions were defined for this simulated hail testing.

Simulation of Hailstone Projectile

Spheres of frozen water were used as projectiles for impact testing against the large membrane samples. The ice sphere test method was selected since laboratory cast ice spheres closely correlate with hail. Prior studies have shown that approximately 75-percent of large-sized hail is spherical or nearly spherical in shape.[6] Hail density ranges have been reported between 0.02 lb/inch^3 and 0.03 lb/inch^3 (0.7 and 0.91 gm/cm^3) the latter value being the density of pure ice. The ice spheres used in this research were cast pure ice (*Photo 2*).

Photo 2: Sphere of frozen ice for impact testing

Vickie Crenshaw and Jim Koontz defined this test protocol of constructing ice spheres in earlier simulated hail research of various roof coverings.**[7]** Constructing the simulated hailstones in silicon molds in two stages permitted the expansion of ice without cracking. Weighing the mass of water into each mold provided consistency of sphere masses and diameters. Ice spheres were formed at 10^0 F (-12.2^0 C).

Size and Speed of Ice Spheres

The diameters of ice spheres tested were 1-inch, 1-1/2-inches, 2-inches, 2-1/2-inches, and 3-inches (25 mm, 38 mm, 50 mm, 63 mm, and 76 mm). The ice spheres were propelled from a hail gun at velocities listed by NBS Series No. 23 and impacted selected targets. A gauge measured the pressure of the compressed air from the hail gun regulated to preset values. An electronic quick-release valve opens releasing compressed air and propels the frozen spheres. A three-screen ballistics timer measured the sphere velocity. The known mass and velocity of the sphere allowed for an accurate determination of the kinetic “impact” energy.

A.P. Laurie, an early hail researcher, derived hail sizes and correlating kinetic (impact) energies in the 1960s.**[8]** Laurie developed this information from data collected by E.G. Bilham and E.F. Relf.**[9]** Laurie graphed the correlation between terminal velocity, hail diameter, and approximate kinetic (impact) energy. The values are repeated in *Table 5* for the stone diameters of this test.

Stone Diameter		Terminal Velocities		Impact Energy	
inches	mm	ft/sec	m/sec	ft/lbs	joules
1.0	25	73	22.3	<1	<1.3
1.5	38	90	27.4	8	10.85
2.0	50	105	32.0	22	29.8
2.5	63	117	35.7	53	71.9
3.0	76	130	39.6	120	162.7

Table 5: Terminal velocities and energies of hailstones

With the majority of test speeds falling within the middle range, actual speeds recorded during the test are recorded in *Table 6*.

Stone Diameter		Terminal Velocities	
inches	mm	ft/sec	m/sec
1.0	25	70-76	21.3-23.2
1.5	38	87-94	26.5-28.6
2.0	50	102-107	31.0-32.6
2.5	63	116-121	35.4-36.9
3.0	76	127-133	38.7-40.5

Table 6: Range of test measurements of terminal velocities

Test Substrate and Membrane Conditioning

Membrane panels were constructed as individual, identical target assemblies of 3-foot-square (.83 m^2) membrane samples over insulation and steel decking. All target assemblies used the same manufacture and lot number of insulation -- 2 inches (50 mm) of rigid polyisocyanurate insulation board, 2 PCF (155 mg/cm^3) density and the same 22-gauge (.75 mm) steel decking. Four coated deck screws and stainless steel washers mounted into the four corners of the assemblies comprise the stabilizing attachment. The corner fastenings were positioned outside of the impact zone.

A curtain of re-circulating, chilled water was allowed to vertically fall down the exterior, weathered face of the membrane panel until a thermocouple mounted behind the membrane indicated the panel achieved a temperature of 40^0 F (4.5^0 C). The selection of this temperature was arbitrary and without precedent. However, logically speaking, the presence of standing spheres of ice and accompanying rainwater would dramatically lower a roof's surface temperature.

Tension Not Defined and/or Introduced in This Test

Subsequently, this hail simulation test took into consideration that any hail testing should include a measurable and repeatable level of membrane tension. In North American roofing practices, thermoplastic membranes are routinely “kicked tight” prior to welding. Observations conclude that a membrane wrinkle potentially created at the time of roof application disappears with exposure. The loss of plasticizer results in a contraction of the roof membrane. Once the membrane contraction occurs, the roof membrane will be under constant tension. Additionally, tension will vary according to changes in roof surface temperature. Therefore, whether initially placed in tension or whether tension develops as a result of aging, future hail testing of membranes should incorporate a level of membrane tension meaningful to the class of roof system being tested, within a defined temperature range.

Failure Definition and Graduated Impact Testing

For this test, failure from impact testing was defined as any visible evidence of membrane fracture, either on the top surface or the underside surface. In practical terms, a large hole in the membrane surface will require immediate repair. On the other hand, a slight fracture of only the top surface of a membrane may not be a threat to waterproofing for a number of weeks or even months. Yet the definition of failure considers both of these conditions as a failure. Furthermore, microscopic examination of an impact site often reveals damage to fabric reinforcement or film delamination. However, this definition of failure for this test reduces subjective judgment to unassisted visual observation of fracture.

Beginning with the test's smallest sphere of ice, 1 inch (25 mm), successive firings were made at the target assembly in 1/2-inch increments through 3-inches (12 mm increments through 76 mm). Each successive firing was aimed higher in the target zone. After each firing, laboratory technicians used a waterproof crayon to outline the size of the ice ball at the point of impact. Also after each firing, the top surface of the membrane was examined for visible fracture. If no fracture was visible, the next larger size of ice ball was fired at the assembly at its test-design speed.

When visible fracture in the impact zone of the weathered face of a membrane panel appeared, the test ended, the panel was removed and the backside inspected. If visible evidence of a fracture on the backside of the panel was confirmed but from a smaller size of ice ball, the failure mode is defined to the smaller ice sphere size.

If the membrane sample received no visible fracture through all five firings, the panel was removed from the assembly and the backside of the membrane was reviewed for fracture. If there was no visible fracture on either side, the test result was recorded as "no failure".

4.0 TEST RESULTS

Plasticizer Loss and Thickness Change

Table 7 reports an arithmetic means for the four manufacturing groups in exposed age and UV-factored age, plasticizer contents (as a percent of weight), and thickness gauge in mils (thousands of an inch).

Sample Data by Group			(A)	(B)	(B/A)	(C)		(D)	(D/C)	(E)		(F)	(F/E)
Group ID	**No. of Samples**	**Mean Exposed Age**	**Mean Factored UV Age**	**DIFF**	**%**	**Mean % Flap Plasticizer Content**	**Mean % Exposed Plasticizer Content**	**DIFF**	**%**	**Mean Gauge Flap**	**Thickness Gauge Exposed**	**DIFF**	**%**
A	20	5.79	6.08	0.29	5.01	32.5	28.9	3.6	11.05	39.5	37.4	2.1	5.32
B	21	4.3	4.74	0.44	10.23	27.3	23.5	3.8	13.92	45.2	39.9	5.3	11.73
C	25	4.95	5.42	0.47	9.49	30.9	28.9	2.0	6.47	47.5	45.3	2.2	4.63
D	21	5.83	6.05	0.22	3.77	34.9	33.4	1.5	4.30	48.6	44.8	3.8	7.82
	87												

Table 7: Group summaries – mean data: plasticizer and thickness changes

Distinguishable in this table, manufacturing group D began with the highest average level of plasticizer content - 34.9%. After six years (on average) of UV aging, the mean exposed content of plasticizer for group D at 33.4% was still higher than the hidden flap content of the other three groups.

Manufacturing group B, with the “newest” membrane at 4.74 years, had the least amount of plasticizer in the hidden flap (27.3%), and the greatest amount of plasticizer loss, from 27.3% to 23.5%. This loss represents a 13.92% decrease in plasticizer content by weight. In addition, group B also had the largest decrease in thickness - 5.3 mils or an 11.73% reduction in thickness. In just over four years, almost 12% of thickness is gone. In this case, if more than 10% of the membrane is lost in four years, how much membrane would remain to withstand the elements at 12 years? Would there be sufficient thickness and physical properties remaining for performance?

A further analysis of the data questions how much plasticizer is lost per UV-factored year (*Table 8*).

		(A)			(B)	(B/A)	
Group ID	**No. of Samples**	**Factored UV Age**	**% Flap Plasticizer Content**	**% Exposed Plasticizer Content**	**DIFF**	**Plasticizer % Loss by UV Year**	**Pearson Correlation Plasticizer Loss by UV Age**
A	20	6.08	32.5	28.9	3.6	0.590	0.808
B	21	4.74	27.3	23.5	3.8	0.802	0.561
C	25	5.42	30.9	28.9	2.0	0.369	0.674
D	21	6.05	34.9	33.4	1.5	0.248	0.760

Table 8: Summary of means, plasticizer loss by UV aged year, four manufacturing groups

Again, group D data indicates the least percentage loss of plasticizer by year (.248%), whereas group B data indicates the greatest percentage loss of plasticizer (0.802%).

Pearson Correlation Analysis provides a statistical measurement of the dispersion of data points between two variables. For this analysis, the variables of time of exposure and the loss of plasticizer by year were taken into consideration. If all the data points were clustered perfectly in a tight linear relationship (all of the data points are located on the regression line) the value would be 1.000, or a “perfect” correlation. Conversely, a value of 0.000 signifies no relationship between the variables. Group B has the lowest value (0.561) in Pearson Correlation *(Table 7).*

4.0 HAIL SIMULATION RESULTS

Results by Group

The 87 membrane samples tested in hail simulation according to *Table 9* offers each manufacturing group two views of the data: (1) UV-factored aging in years, and (2) exposed plasticizer content % by weight. Within each set of data by manufacturing group, the results are broken down into two groupings. “Any failure” and “small sphere failure” are summarized. The category small sphere isolates the combination of failures at 1 and 1-1/2 inch sizes (25 mm and 38 mm). A small sphere fracture in the test is reported in the “any failure” and in the “small sphere failure” categories.

A review of the NOAA Website of hail events by county provides evidence that small hail commonly occurs in many areas of the central United States. The analysis focused on small hail performance.

UV Factored Aging	Group A, 20 Samples		Group B, 21 Samples		Group C, 25 Samples		Group D, 21 Samples	
	Any Failure	Small Sphere Failure	Any Failure	Small Sphere Failure	Any Failure	Small Sphere Failure	Any Failure	Small Sphere Failure
To 3.5 years	0	0	8	2	0	0	0	0
3.51 - 7.00	3	1	10	10	5	0	3	0
7.01 - older	6	5	3	3	6	3	5	0
% By Weight Exposed Plasticizer Content								
24% and less	2	2	13	12	1	0	NA	NA
24.1 - 28%	4	2	7	2	5	3	1	0
28.1 - 32%	2	1	1	1	5	0	5	0
Over 32.1%	1	1	NA	NA	0	0	2	0

Table 9: Simulated hail results, by group, by size category, according to age and plasticizer content

Group D contained no samples where the exposed plasticizer content measured 24% or less. In relation, group B had no samples where the plasticizer content was greater than 32.1%. Thus, “NA” was used within these two group summaries.

Table 10 presents a view of the total grouping of all tested conventional plasticizer samples. The summarization offers a benchmark between the two categories of age and plasticizer content -- the isolation of group B and D results. The summary results of all 87 tested membranes are skewed by the results of these two groups, group D as the most resistant to failure, group B as the least and the results of groups A and C lying between B and D.

	(A)	(B)	(B/A)	(C)	(C/A)
Net Plasticizer Content, % Weight	**No. of Samples**	**Any Failure**	**% to Total**	**Small Sphere Failure**	**% to Total**
<24%	16	16	100%	14	87.50%
24.1 to 28%	20	17	85%	7	35%
28.1 to 32%	30	13	43.33%	2	6.67%
>32%	21	3	14.29%	1	4.76%
Totals	**87**	**49**		**24**	
Group D Alone	21	8	38.10%	0	0%
Group B Alone	21	21	100%	15	71.43%
UV Aging (Years)	**No. of Samples**	**Any Failure**	**% to Total**	**Small Sphere Failure**	**% to Total**
To 3.5	22	8	36.36%	2	9.09%
3.51 to 7.0	44	21	47.73%	11	25.00%
7.01 and older	21	20	95.24%	11	52.38%
Totals	**87**	**49**		**24**	

Table 10: Impact testing, all samples, by UV aging and by net plasticizer content

Notably, group D had no samples of small sphere failure, whereas in contrast, 71% of group B samples had a small sphere failure.

The data analysis of the samples for the four groups of manufacturers provides insight into long-term impact performance. Because of the inherent technology of conventional flexible PVC membranes, plasticizer loss is an inevitable event. In other words, the membranes in each of the four groups display some degree of plasticizer loss over time with group A and group C results positioned between the relative stability of group D and the least stable group B.

Consider the following scenario: a building owner in the central U.S. is making a selection for a roof system and he decides upon a conventional PVC roof system. Four new, white, flexible membranes are offered as options, each made by a different supplier. All four membranes carry the same warranty and sales literature for each claim to provide the same features. The price difference between the four is, on a scale of the total roofing cost (membrane, insulation, fastenings, and labor), about 2-percent. If the criteria of selection is price, what price difference would be appropriate to offset the difference in impact performance between the four membranes?

To enhance the dramatic difference in performance, compare the individual sample data for group B *(Table 11)* and group D *(Table 12)* along with the hail simulation results. Impact testing is the seminal event uncovering the physical deterioration of an embrittled membrane and placing an owner at significant risk.

		(A)	(B)	(C)	(D)	(D/B)	(D/A)	
Sample No.	**State**	**UV-Factored Age of Roof**	**Hidden Flap Plasticizer Content, %**	**Exposed Membrane Content, %**	**% Lost**	**% Change**	**Plasticizer Loss by UV Year**	**Failure Point, Size in Inches**
1	TX	6.21	26.8	20.6	6.2	23.13	0.998	1.00
2	AZ	8.84	29.1	26.1	3.0	10.31	0.339	1.00
3	TX	7.91	28.8	21.8	7.0	24.31	0.885	1.00
4	TX	7.21	27.2	22.9	4.3	15.81	0.596	1.00
5	TX	6.81	29.1	25.3	3.8	13.06	0.558	1.00
6	SC	6.58	29.2	23.7	5.5	18.84	0.836	1.00
7	LA	5.91	28.2	21.8	6.4	22.70	1.083	1.00
8	TX	5.91	27.7	22.6	5.1	18.41	0.863	1.50
9	KS	5.82	31.4	29.5	1.9	6.05	0.326	1.00
10	TX	5.61	28.6	22.4	6.2	21.68	1.105	1.00
11	LA	4.81	27.9	22.0	5.9	21.15	1.227	1.00
12	TX	4.51	26.2	23.2	3.0	11.45	0.665	1.00
13	TX	4.01	24.1	20.0	4.1	17.01	1.022	1.00
14	ID	3.39	26.5	25.6	0.9	3.40	0.265	2.50
15	MN	2.70	27.0	26.3	0.7	2.59	0.259	2.50
16	IA	2.51	26.1	22.5	3.6	13.79	1.434	1.00
17	MN	2.36	25.9	24.0	1.9	7.34	0.805	3.00
18	TX	2.30	25.2	19.6	5.6	22.22	2.435	1.00
19	CO	2.30	26.2	25.1	1.1	4.20	0.478	2.50
20	MN	2.19	26.5	24.4	2.1	7.92	0.959	2.50
21	IL	1.69	25.8	24.9	0.9	3.49	0.533	2.50
Mean Summaries:		4.74	27.3	23.5	3.8	13.81%	0.802	

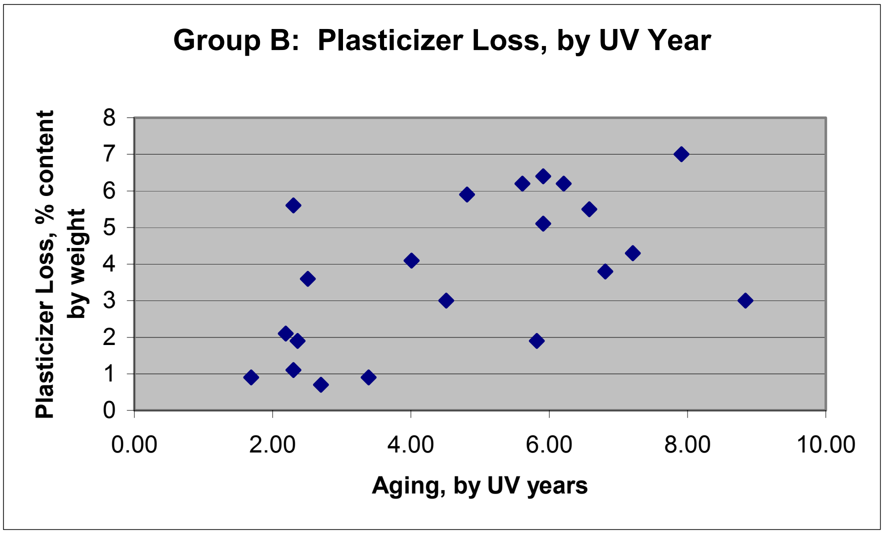
Table 11: Group B test results-- plasticizer loss and impact simulation (all samples)

		(A)	(B)	(C)	(D)	(D/B)	(D/A)	
Sample No.	**State**	**UV-Factored Age of Roof**	**Hidden Flap Plasticizer Content, %**	**Exposed Membrane Content, %**	**% Lost**	**% Changed**	**Plasticizer Loss by UV Year**	**Failure Point, Size in Inches**
1	OK	11.14	34.3	27.7	6.6	19.24	0.592	2.5
2	TX	9.92	33.6	30.8	2.8	8.33	0.282	no failure
3	TX	9.32	33.0	30.1	2.9	8.79	0.311	3.0
4	CO	7.84	33.1	33.1	0.0	0.00	0.000	3.0
5	TX	7.31	34.5	31.7	2.8	8.12	0.383	3.0
6	KS	7.13	33.0	31.2	1.8	5.45	0.252	2.5
7	KS	6.95	33.0	31.4	1.6	4.85	0.230	2.5
8	TX	6.51	36.0	33.7	2.3	6.39	0.353	3.0
9	OK	6.47	35.1	32.4	2.7	7.69	0.417	no failure
10	TX	6.01	36.4	34.6	1.8	4.95	0.300	no failure
11	NE	5.80	34.3	32.6	1.7	4.96	0.293	no failure
12	IA	5.76	34.6	31.4	3.2	9.25	0.556	3.0
13	CO	5.75	36.4	36.2	0.2	0.55	0.035	no failure
14	TX	5.71	35.7	35.7	0.0	0.00	0.000	no failure
15	TX	5.51	35.6	35.0	0.6	1.69	0.109	no failure
16	IA	5.28	33.3	33.2	0.1	0.30	0.019	no failure
17	TX	4.27	36.0	35.4	0.6	1.67	0.141	no failure
18	IL	3.66	36.2	36.2	0.0	0.00	0.000	no failure
19	TX	2.50	36.5	36.5	0.0	0.00	0.000	no failure
20	MN	2.24	36.2	36.1	0.1	0.28	0.045	no failure
21	IA	2.03	36.1	36.1	0.0	0.00	0.000	no failure
Mean Summaries:		6.05	34.90	33.39	1.51	4.34%	0.248	

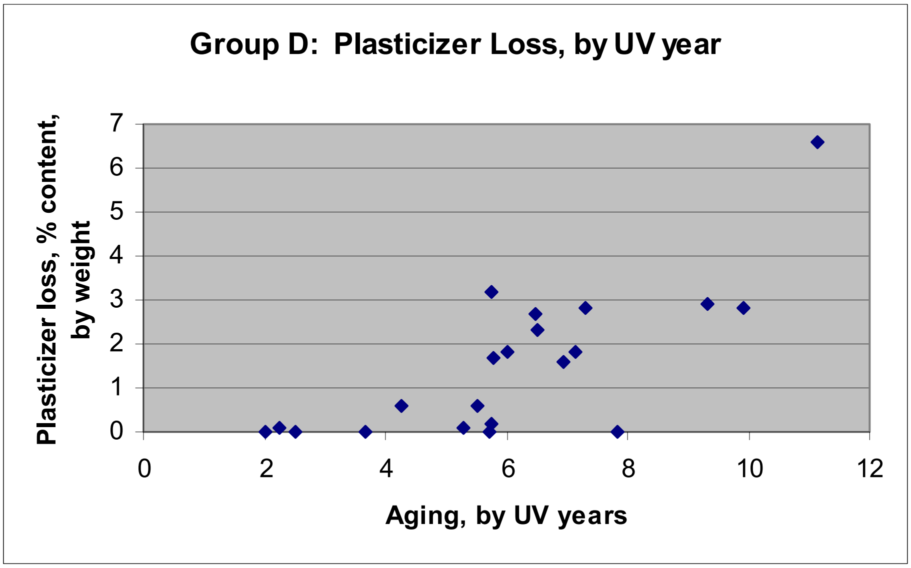
Table 12: Group D test results-- plasticizer loss and hail simulation (all samples)

The data comparison of samples from group B and group D reveal dramatic performance differences in the hail simulation testing. All of group B membranes failed. Group B membrane samples 16 and 18 were newer than three years old but fractured with ice spheres as small as 1-inch (25 mm). In consideration, no testing was made with spheres less than 1-inch (25 mm) in diameter. Therefore, understandably the 1/4 inch (12 mm) ice (or large sleet) might have damaged the membrane. On the other hand, the hail simulation testing for group D indicates a vast difference in impact performance.

The relationship between aging and plasticizer loss by UV year for both groups B and D is provided in *Graphs 1 and 2*.



Graph 1: Group B plasticizer loss by UV year



Graph 2: Group D plasticizer loss by UV year

A glance of the graphs provides two quick observations. The cluster of data for group D is much tighter than group B. This visual observation is consistent with Pearson Correlation Analysis in *Table 8*. Furthermore, plasticizer loss in the samples in group D does not actually begin until the sixth year. At least at the outset, group D plasticizer ingredients appear to be vastly more stable in the membrane to those in group B. The visual comparison of the scatter patterns of the two graphs also reveal that group D produces a far more predictable product, year-after-year, than group B. This difference might be attributable to plasticizer selection and/or manufacturing quality control.

5.0 DISCUSSIONS

Regarding the Test Procedures

Alternatives to Plasticizer Analysis

Plasticizer extraction with a solvent mixture proves a reliable test for liquid monomeric plasticizers. However, the solvents used are environmentally aggressive. Jim Koontz suggests in earlier research that changes in specific gravity might potentially be a simple alternative method for determining changes in plasticizer content as a result of exposure. [4] However, this suggested alternative has not been defined into an accepted standard.

Membrane Thickness

As mentioned previously, …..changes in membrane thickness -- measuring the hidden flap against exposed roll -- provide an indication of plasticizer loss. In *Table 7*, the mean measure of reduction in thickness was greatest for group B; this group also had the greatest loss of plasticizer. Owners may be better served laying membrane samples on the roof (*Photograph 3*) and making periodic measurements of thickness compared to original membrane samples that should be filed with the contract documents. Although there is no empirical data to support that loose flaps of membrane age at the same rate as an installed, sealed membrane, common sense suggests this opinion.

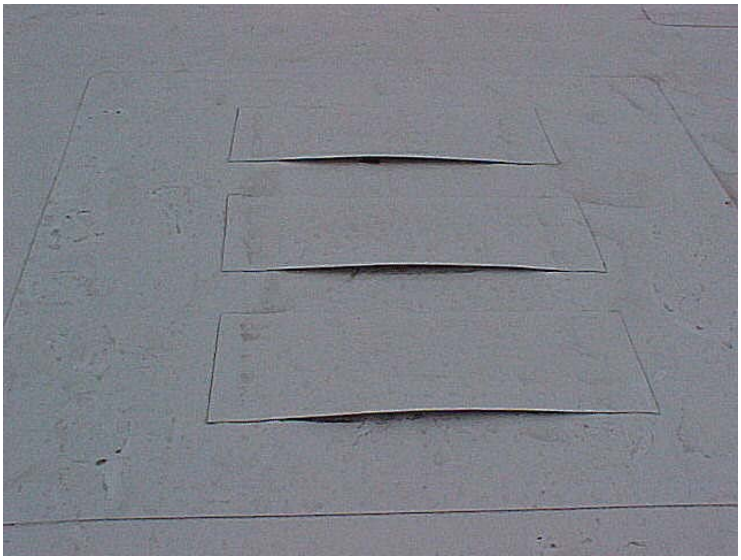


Photo 3: Membrane test strips mounted at roof center

Testing Simulation

In some cases laboratory procedures may be conservative in comparison to actual hail events. The angle of impact, the cooled surfaces, and the density of ice spheres all subject the target assemblies to severe conditions. The hail simulation procedure discussed here is an invitation to standardized future test activities. Vickie Crenshaw and Jim Koontz report various code agencies and insurance groups do not agree about test procedures. [7] However, in relation to this hail simulation, the results obtained provide meaningful comparison of performance of four manufacturing groups in the same test procedure.

Regarding the Test Results

The Role of Reinforcement: Little has been mentioned about the role of the reinforcement scrim in preventing impact fracture. The study focused on plasticizer loss and its correlation with fracture with only casual mention of polymer crystallization or fabric reinforcements. Mechanical separation of the top layer of film revealed the reinforcements among the four manufacturing groups are not identical. Two of the four reinforcements had identical, tight weave and warp, one had a smaller count of threads in its square grid, and the fourth has a distinct pattern where the weave and warp were not square to each other. These differences in fabric characteristics add another important variable to membrane impact performance.

But what is the action of impact fracture? Impact fractures from hailstones are usually concentric arches of fractures (*Photo 1).* It is proposed that the failure mode at impact is about membrane distortion as opposed to an instantaneous surface shatter. A close-up view and slow-motion impact would reveal fractures not in a single moment of contact but rather in a timed sequence of elongation and subsequent fractures. As the projectile drives deeper additional distortion would create additional, outer rings of fractures. In this view, what role would reinforcement play in the prevention of fracture failure? It is conjectured that the reinforcement would provide a limit to distortion. The stronger and tighter the fabric weave, the more limited the distortion.

However, if the film blend has lost flexibility, it is suggested that the fractures will appear (in the slow-motion view) at the moment when the elongation properties of the fabric exceed the elongation capabilities of the film. This consideration will come into play later in this study when there is a discussion about what an owner can do to mitigate damage from hail.

Test Result Anomalies

Throughout the analysis of results there were odd, inexplicable data points. As an example, Sample 9 on *Table 11*, the amount of plasticizer loss for a near 6 year old roof membrane was a mere 1.9 %, yet there was fracture with 1-inch sphere. Against the aging data points around that sample, a greater degree of plasticizer loss would have been expected. Then again, Sample 18 of group B shows dramatic loss for a relatively new sample. Another example is found in Sample 1 on *Table 12*. The significant level of plasticizer loss for this sample (19.24 %) was not characteristic for this group. This data point is also the lone, high data point on *Graph 2*.

For these reasons, the authors consider hail simulation result to be indicative rather than definitive of a relationship between plasticizer loss and impact damage. These anomalies may be the result of excess "play" in one or more variables such as tension or formula dispersion.

6.0 CONCLUSIONS

1. The older a PVC membrane, the more vulnerable the membrane to impact damage. While this is true of all roof membranes eroding or becoming more rigid, with exposed PVC membranes, this vulnerability is a particular concern.

2. Not all PVC membranes are of the same quality. The data on plasticizer loss and impact resistance demonstrates one of the four manufacturers provides a superior product to the U.S. low-slope roofing market.

3. The data suggests an initial higher content of plasticizer provides a better starting point than a lower level. What content of monomeric plasticizer is appropriate for a PVC membrane to be sold in hail states? The data suggests less than 32% would be reason for concern depending upon the quality, type, and stability of the plasticizing agent(s). More significantly, the data suggests beginning a service life below 32% plasticizer content with instable plasticizers invites impact vulnerability. The data also suggests that plasticizer levels below 28% in nominal 50 mil (1.2 mm) membrane would be a concern in hail-prone locations of the central United States.

7.0 RECOMMENDATIONS

1. On behalf of building owners in the central United States, the roofing industry needs focused research into hail protection of all classes of roofing systems achieving the level of expertise and consensus now taken for granted for wind engineering.

2. Building owners in hail-prone states should demand suppliers, regardless of class of roof system, provide warranty coverage against small hail, 1-1/2-inch (38 mm) or less. Conventional PVC roofs in hail-prone locations must be monitored for degradation. This monitoring should be a timely measurement of reduced thickness, increased durometer hardness, rising specific gravity and/or plasticizer extraction analysis. Samples and lot numbers of new membranes should be filed in contract documents, providing a "benchmark" for degradation measurement.

3. PVC membrane manufacturers have a market opportunity in defining specifications and warranties reflecting hail engineering. Thicker membranes, 60 mils (1.5 mm) and greater, <u>may provide</u> increased impact resistance. It stands to

reason that if plasticizer migrates from the top surface at a fixed rate, the supply of additional thickness would provide a deeper reservoir of plasticizer, reducing the <u>percentage</u> of plasticizer lost over a fixed period of time. Comparatively, the use of harder substrates in the roof specification may reduce the extent of hail damage and allow insulation salvage. In this scenario, limited membrane distortion by a hard substrate also limits the extent of fractures. Careful investigation proves a 4 year old PVC roof with a hard substrate survived a 3-1/2-inch (88 mm) hailstorm in the spring of 2002. No funding or effort was made in repair of the roof system. Beliefs hold that the hard substrate was critical to this positive result.

4. For hail-prone sections of the central U.S., monitoring of monomeric-plasticized PVC roof systems should begin between 2 and 8 years, depending upon the quality of the supplied membrane.

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