Hail Resistance and Performance Analysis of Elastomeric Coated SPF Roof Systems

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ABSTRACT

THE ROOFING INDUSTRY SUFFERS MILLIONS OF DOLLARS OF DAMAGE FROM "SEVERE" (GOLFBALL-sized) and "oversized" (baseball- to softball-sized) hail. Facility managers and insurance carriers with extensive damage to their roofs are concerned with the performance of sprayed-in-place elastomeric-coated (Sprayed Polyurethane Foam; hereinafter referred to as SPF) roof systems. This report analyzes the resistance level of different types of elastomeric-coated SPF roof systems from "severe" [FM-SH test level (1-3/4 inch hail diameter)] and "oversized" hail (above 1-3/4" diameter). This research effort is unique in the following ways:

1. Identifies performance factors relative to the resistance of the SPF roof systems to hail damage.
2. Identifies the performance level of different types of elastomeric coatings on a relative basis.
3. Improves the hail resistance test of the SPF roof systems by using the process of "information theory" and "intelligent processing" by modifying the FM-SH test process and expands it to predict the damage of "oversized" hail.
4. Identifies "oversized" hail resistance of the SPF roof system near freezing temperatures.
5. Uses documented performance information to confirm different hail resistance levels for FM Class I roofs.
6. Relates the damage of "severe" hail with "oversized" hail across the United States.

Introduction

SPF roof systems have been installed since the late 1960s due to their insulating qualities, lightweight nature, maintainability, and renewability (Fricklas 1995). Extensive hail damage to SPF roofing systems caused by golfball- (1-3/4" diameter) to softball-sized hail (3-1/2" diameter) has raised concerns regarding hail resistance capability and the ability to predict the performance of SPF roof systems. The potential damage to SPF roof systems has raised questions about their performance in heavy hail areas. This situation prompted the manufacturers and end-users of SPF roof systems to approach the Performance Based Studies Research Group (PBSRG) at Arizona State University (ASU) to determine the following:

1. Can a properly-installed SPF roof system be a viable option for facility owners seeking to reduce their risk against hail damage caused by "severe"-sized (1.75") hailstones?

2. Identify the impact resistance level of SPF roof systems against "oversized" hailstones (bigger than 1.75" diameter).

3. Were damaged SPF roof systems damaged sufficiently enough by hail to warrant the high cost of tearoff and replacement with a new roofing system? Can SPF roof system be economically repaired and enhanced to minimize the risk of future hail damage?

4. Is there a difference in the performance levels of different types of commercially available elastomeric-coated SPF roof systems?

5. Can occurrences of "severe" and "oversize" hailstones in the United States be documented to make the information easily accessible to designers and facility owners?

Performance Issues of Elastomeric Coated SPF Roof Systems

SPF roof systems consist of a minimum of 25 mm (1 inch) of SPF and a surfacing of elastomeric coating. SPF roof systems have been installed since the late 1960s. Dr. Kashiwagi has been collecting performance information on SPF roof systems since 1983 in all geographical areas of the U.S. Performance studies at ASU on over 1,600 roofs across the U.S. inspected every two years over 13 years, identify the following:

1. The experience of craftspeople is the most influential factor in installing a performing SPF roof system.

2. The SPF roof system requires more technical understanding as compared to other commercially available roof systems.

3. Acrylic, polyurethane, silicone-coated, and aggregate-surfaced SPF roof systems with proven performance of 26, 20, 22, and 7 years (Kashiwagi 1996) respectively, have been installed by performing contractors in the U.S. (refer to *Table 1*).

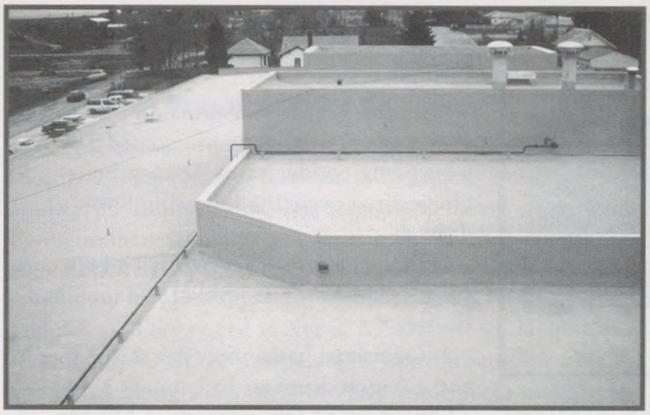

Figure 1: Typical performance-based SPF roof systems in heavy hail areas of Wyoming with 100% customer satisfaction based on 1997 Customer Evaluation Surveys conducted by PBSRG, Arizona State University.

4. Different elastomeric coating systems have different strengths. Acrylic coatings are water-based and the easiest and most economical to manufacture, but have the greatest variance of performance of the different elastomeric-coated SPF roofs. Acrylic coatings are dominant in "dry" and "moderate" temperature areas of the Southwest and Western U. S. Acrylic polymers can be easily acquired and the manufacturing of acrylic elastomeric coatings is the simplest of the coating systems. The acrylic coatings are marketed as "all the same" to uneducated facility owners.

5. Silicone coatings are the most UV resistant, have the greatest application window, and are dominant in the Midwest and Eastern U.S., due to their ease of application and long-term performance.

6. Polyurethane-coated systems are the most maintenance-free systems and the best systems to handle high traffic and impact.

7. The PBSRG has identified the lack of qualified applicators as the major problem in the SPF industry (Kashiwagi and Pandey, 1996). The lack of understanding of SPF roof systems' resistance to hail damage may result in the marketing of SPF roof systems which have no proven hail resistance.

8. The performance level of the contractor is an integral part of the performance of the SPF roof system's resistance to "severe" hail damage. Elastomeric-coated SPF systems that pass the FM-SH laboratory test may not be duplicateable in the "field" due to misapplication or a difference in the material's physical makeup and quantity.

9. There is variation in the performance of polyurethane-coated SPF roof systems. There are only two polyurethane coatings which have had consistent documented performance over the last 15 years. There have been major delamination, cracking and reversion problems with other "non-performing" polyurethane coatings.

10. The performing polyurethane coatings have had "third party," nonbiased, published performance information of 15 years or more from a large sample size (average 50 roofs) in multiple locations (refer to *Figure 1*). This is not to say that the other polyurethane coating products have not performed in isolated cases. The authors have been attempting to collect more performance information on polyurethane coatings for the past ten years and have been unsuccessful in documenting the performance of other polyurethane systems, or identifying other "third party" test or research groups that have sizable databases which could document the performance of other polyurethane-coated SPF roof systems. The two polyurethane coatings with documented performance are used in the testing against "severe" hail.

Variation in Physical Properties of the SPF Component of the Roof System

Problems with SPF roof systems which must perform in areas with potential "severe" and "oversized" hail damage include:

1. Inconsistency in meeting the physical properties specified by the manufacturer.

2. Elastomeric coating thickness specified in "gallons of coating per square" which are difficult to verify and sometimes meaningless due to the variation in coating thickness caused by the unevenness of the SPF application.

3. A more even SPF surface profile on a SPF installation requires less elastomeric coating (*Figure 2A*) to meet the min-

Performance Criteria	Performance Rating		
	Polyurethane	Acrylic	Silicone
Maximum Service Period (yrs.)	20	26	22
Average Service Period (yrs.)	7	5	7
Average Installed Area (sq. ft.)	23,079	29,403	46,652
% of Roof that Never Leaked	85	77	61
% of Roofs with Traffic Greater than 12 Times/Year	27	16	16
Satisfied Customers (%)	100	99	99

Table 1: Overall performance information of SPF roof system installed by 43 performance-based contractors (during 1996-97) based on survey rating of 50 roofs (average). Data Source: 1997 Performance Roofing Contractors/Systems Performance Information (Kashiwagi and Conner, 1997).

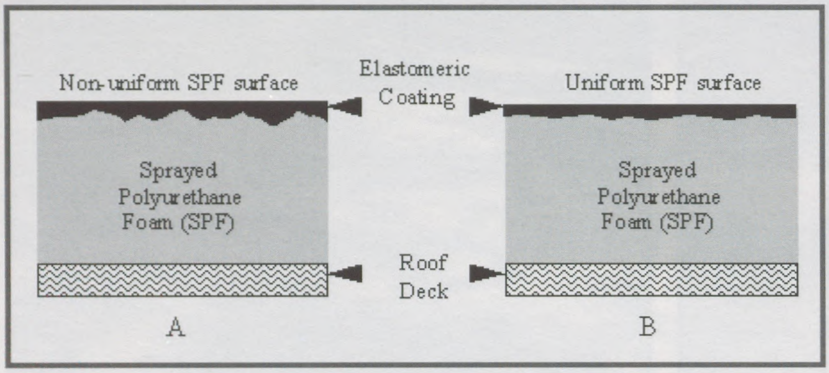

Figure 2: Sprayed Polyurethane Foam (SPF) roof system showing uniformly- and nonuniformly-applied SPF surface.

imum coating thickness requirement. Conversely, a more uneven SPF surface profile requires more coating material (*Figure 2B*) to be applied (due to high spots where the coating will gravitate to lower areas.)

4. The lack of uniformity in the designations of coating thicknesses makes comparisons of various samples difficult. For example, depending on which manufacturer's specification is used, 30 mil coated acrylic sample can mean the 30 mil minimum, 30 mil average with 15 mil minimum, or 30 mil average with no minimum thickness requirement.

Major hail resistance qualities of the elastomeric-coated SPF system are the tensile strength and elasticity of the elastomeric coating, core density, and the compressive strength of the SPF. The fluctuation in the SPF physical properties places a higher hail resistance requirement on the elastomeric coating system.

Data collection has shown that installed SPF compressive strengths and densities (Pandey, 1996) have large variations. *Figure 3* shows that only 7 out of 33 random "in-field" samples of SPF from roof installations installed by performing contractors in 1995 met the manufacturer-specified (Kashiwagi and Pandey, 1996) 2.5 - 3.0 pcf density and 38 to 50 psi compressive strength requirements.

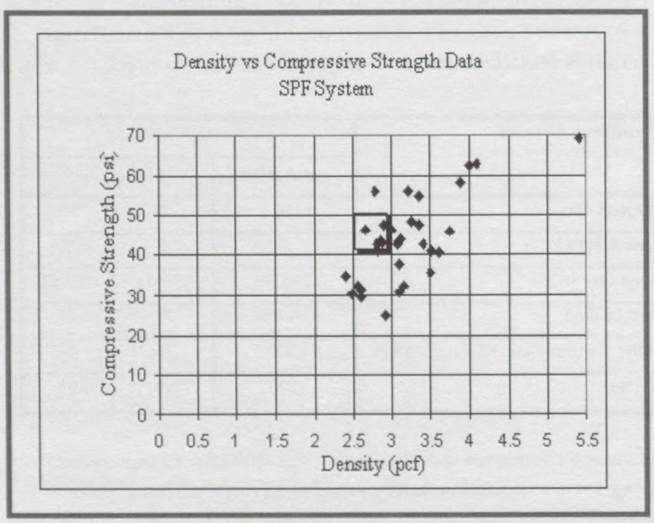

Figure 3: Density vs. compressive strength data for HCFC in-field SPF system (uncorrected for elevation), 1995.

Objective of Hail Study Research at PBSRG

The current research effort on performance issues of elastomeric-coated SPF systems being conducted at Arizona State University covers the following levels of damage:

1. Factory Mutual-Severe Hail #4470 Class-I (FM-SH) test level (1-3/4 inch hailstones).
2. Oversized hailstones (2.0, 2.5, 3.0, 3.5, and 4.0 inch diameter hailstones).

Objectives of SPF research at Arizona State University include the following:

1. Identify the relative hail resistance level of different elastomeric-coated SPF roof systems using the FM-SH Class I test.
2. Identify the impact of weathering, granulation, increased coating thickness, SPF density and compressive strength, and different surface temperatures (moderate, freezing, and sub-freezing) on hail resistance of elastomeric-coated SPF roof systems.
3. Identify the maximum hail resistance level of SPF roof systems by using the modified FM test methodology to simulate "oversized" hail resistance tests for laboratory testing and in-field testing.
4. Correlate the damages of "severe" and "oversized" tests for "laboratory" and "in-field" SPF roof systems.
5. Correlate the artificially-weathered SPF system hail test results with naturally-weathered "in-field" severe hail test results.
6. Identify occurrences of oversized hail in the U.S.
7. Identify the correlation of property damage with "severe" and "oversized" occurrences.

Methodology For Determination of Hail Impact Resistance Level

The methodology for simulating and verifying hail damage resistance of SPF systems include:

1. Using the FM-SH test (dropping 0.8 lb. steel ball of 1.75 inches diameter from a height of 17 feet, 9-1/2 inches) on the sample to simulate the "severe" (golfball-size) hail damage.
2. Test three major coating types (silicone, acrylic, and polyurethane) with varying thicknesses (commercially available), SPF foam densities, weathering and granulation.
3. Test the successful systems (which passed the FM-SH test under FM test rules) in low temperature (freezing and subfreezing) conditions.
4. Subject the FM-SH passed SPF systems to simulated "oversized" hail test for sizes 2.0, 2.5, 3.0, 3.5, 4.0 inches.
5. Record the severe and oversized hail damages on SPF roof systems in heavy hail areas.
6. Test installed "in-field" roof systems in Torrington, WY; Dallas, TX; and Big Springs, TX (areas of the country with heavy hail damage) for impact resistance against "severe" and "oversized" hail.
7. Correlate FM-SH and OSH test results of laboratory-

weathered samples with results of "in-field" roof tests, and proven SPF roof system performance.

Test Sample Preparation for Hail Test

Sample preparation for the testing included 96 panels (1.0 foot by 2.0 feet) of the commercially-available elastomeric-coated SPF roof systems. The test samples were prepared based on manufacturer's specifications. All laboratory tests were conducted at Arizona State University. Field tests were conducted in Wyoming and Texas. The majority of the test samples are being aged in Mesa, AZ. Of the 96 samples that were made, 32 of the samples were control samples which were kept for verification if the test results were not consistent. The tests were conducted so that the results could not only be verified, but duplicated by other testing groups. Coating thicknesses followed the industry standard and manufacturer's recommendations:

1. Twenty mil system (10 mil minimum, 20 mil average).
2. Thirty mil system (15 mil minimum, 30 mil average).
3. Forty-five mil system (20 mil minimum, 45 mil average).

Due to the roughness of the SPF (refer to *Figure* 2) the above "industry-specified" methodology is the only method whereby the simulated laboratory test samples can be consistently prepared and have meaningful correlation to the performance of "in-field" application.

It is important to note that FM-SH test results do not address the elastomeric coating in the above terms. FM test results use gallons per square, and/or average thicknesses (which are stated as minimum thicknesses) which are very difficult to verify and correlate to other systems. For example, a FM-SH approved 30 mil system may actually have more coating than a 45 mil system (20 mil minimum) in this test.

All samples were prepared under controlled conditions. The sample preparation included:

1. Conformance to SPI/PFCD spray polyurethane foam supplier accreditation program sample preparation guidelines.
2. Foam densities in the range of 2.5-3.0 pcf yielding an average compressive strength of 40-50 psi, respectively.
3. Cured for 30 days at 72 degrees F and relative humidity of 55%.
4. Subjected to 1000 hours accelerated weathering using a weatherometer (at Naval Facilities Engineering Service Center, Port Hueneme, CA) to test the impact of weathering on hail resistance.

FM-SH Test Methodology

The FM (Severe Hail) test has the following requirements:

1. Ten drops on each sample.
2. The samples shall be conditioned for 24 hours at a temperature of 72 degrees F and relative humidity of 55%.
3. New and weathered (1000 hours of simulated UV rays or natural weathering) samples of SPF systems.

If any of the drops results in breakage of the elastomeric coating system, the elastomeric coated SPF system does not pass the FM-SH test. The following characteristics were tested:

1. Granulation.
2. Different compressive strengths of SPF (30/45 psi).
3. Different coatings (silicone, acrylic, and two polyurethane coatings).
4. Different thicknesses of coating determined by commercially-available systems.

FM-SH Test Results

The test provided the following results (refer to *Table* 2):

1. Polyurethane-coated SPF samples had the highest resistance to the FM-SH simulated hail damage with the minimum specified system [30 mil average coating (15 mil minimum) and 40 psi compressive strength SPF].
2. Acrylic coatings resisted the FM-SH test level of damage with 45 mil coating (20 mil minimum) and 50 psi compressive strength SPF.
3. Silicone-coated SPF samples failed the FM-SH test requirements.
4. Granulation had no influence on hail resistance of any of the systems tested against FM-SH test level damage.
5. The FM-SH test of 1,000 hours of accelerated weather-

S. No.	Coating	Aged	Coating Thk. (mils)	Granules	Breaks in Sample	
					2.5 pcf	3.0 pcf
1	A	Y	30	Y	10	7
2	A	Y	45	Y	10	5
3	A	Y	30	N	3	0
4	A	Y	45	N	5	0
5	S	Y	20	Y	10	10
6	S	Y	30	Y	10	10
7	S	Y	20	N	10	10
8	S	Y	30	N	10	10
9	U1	Y	30	Y	0	0
10	U1	Y	45	Y	0	0
11	U1	Y	30	N	0	0
12	U1	Y	45	N	0	0
13	U2	Y	30	Y	0	0
14	U2	Y	45	Y	0	0
15	U2	Y	30	N	0	0
16	U2	Y	45	N	0	0
17	A	N	30	Y	10	0
18	A	N	45	Y	10	5
19	A	N	30	N	2	0
20	A	N	45	N	2	0
21	S	N	20	Y	10	4
22	S	N	30	Y	10	10
23	S	N	20	N	10	7
24	S	N	30	N	11	9
25	U1	N	30	Y	0	0
26	U1	N	45	Y	0	0
27	U1	N	30	N	0	0
28	U1	N	45	N	0	0
29	U2	N	30	Y	0	0
30	U2	N	45	Y	0	0
31	U2	N	30	N	0	0
32	U2	N	45	N	0	0

Table 2: FM-SH hail resistance test results. Legend/Notes: A: Acrylic, S: Silicone, U1: Polyurethane I, U2: Polyurethane. Aging: 1000 hours weatherometer. Granulation: #11 granules.

S. No.	Facility	Coating Type	Install Date	Thickness Avg. (mils)	SPF Density Avg. (pcf)	No. of Drops	No. of Breaks
1	Industrial Electronics, Fort Worth, TX	Acrylic	1993	30	3	5	5
2	Cooksey Printing, Fort Worth, TX	Acrylic	1993	50	3	5	1
3	HEB Admin, Hurst, TX	Silicone	1985	Sample NA	Sample NA	5	5
4	McDonald MS, Mesquite, TX	Silicone	1995	30	3.66	7	6
5	Ball Park	Silicone	1984	40	3.54	3	3
6	Spring Garden Gym, Bedford, TX	PM I	1986	40	3	4	0
7	Porter Elementary, Mesquite, TX	UR	1994	20	2.87	6	6
8	VICA Building, Mesquite, TX	PM II	1994	40	3.54	7	0
9	HEB Bell Manor Gym, Euless, TX	PM I	1986	50	3	3	0
10	Fresnell Technology, Fort Worth, TX	PM II	1993	38	3	5	2
11	Torrington HS	PM I	1982	35	3.51	4	0
12	EWC I	PM I	1987	30	2.98	4	0
13	EWC II	PM II	1990	35	3.74	4	0

Table 3: In-field hail resistance test data. Legend/ Notes: UR: Polyurethane; PMII: Polyurethane II; PM I: Polyurethane I.

ing using a weatherometer (at the Naval Facilities Engineering Service Center, Port Hueneme, CA) had no impact on hail resistance. Because there was no differentiation of results, the 1000 hours of UV exposure is insufficient to give any information.

6. Higher SPF compressive strength increased the acrylic coated SPF system's resistance to hail damage.

7. Presence of knitlines increases the variance in the physical property of SPF. Variance in SPF properties can be minimized by reducing the number of knitlines.

Correlation of FM-SH Test Results with "In-Field" Performance

Thirteen roofs were selected for evaluating the in-field performance of different types of elastomeric-coated SPF roof systems (refer to *Table 3*). All the thirteen roofs tested for hail resistance had documented damage of "severe" and "oversized" hail damage. The results supported the sample test results. The results of the performance of polyurethane-coated SPF roof systems in both the "in-field" and laboratory tests are also verified by the performance of the "in-field" polyurethane SPF roof system in southeastern Wyoming (refer to *Table 4*.)

Many of the metal mechanical penetrations on the roofs showed hail damage from "severe" hailstones (golfball-sized hail), but none of the roofs exhibited ruptures from the impact of hailstones. The customer satisfaction (100%), percent of roofs that never leaked (94%), and percent of roofs that currently leak (0%) verify the performance of polyurethane-coated SPF roof systems in this heavy hail area.

Performance of SPF Roof Systems at Lower Temperatures

Hailstorms are associated with a variety of conditions (Gokhale 1975, Snowden 1956), including different hailstone sizes, speeds, angles, shapes, density, and surface temperatures. Hailstorm research data show that the falling of hailstones to the earth's surface under thunderstorm conditions is accompanied by downdrafts of cool air. The initial downdraft of cool air (Donn 1975), the first wave of smaller hailstones, cold water on the surface, and accompanying winds (speeds ranging from 40 - 60 mph) have a cooling effect (heat transfer) which lowers the roof temperature. Since the physical properties of polymer products are temperature-dependent, the impact of hail on cold surfaces increases the amount of damage to roofing systems.

The FM-SH test procedure does not provide information on the behavior of an SPF system at near freezing conditions that is characteristic of building surfaces in hailstorms. Using Information Measurement Theory (IMT), only those SPF systems which passed the FM-SH test were further tested under the cooler temperatures. The temperature was allowed to fluctuate near 32 degrees F to give general information on behavior of the SPF test samples under freezing /sub-freezing temperature conditions. The following procedure was used:

1. Wet ice was placed on the sample.
2. The temperature of the coated SPF sample was checked

S. No.	Performance Criteria	PU	S. No.	Performance Criteria	PU
1	Proven Service Period (Years)	12	12	Number Of Roofs That Leaked And Were Fixed	3
2	Average Performance Length	7	13	Number Of Roofs That Still Leaked	0
3	Average Square Feet Installed	13400	14	Percent Of Roofs That Never Leaked	94
4	Average Square Feet Of Roof Per Penetration	954	15	Percent Of Roofs That Leaked & Were Fixed	100
5	Percent Insulated Roofs	100	16	Percent Of Roofs That Still Leaked	0
6	Percent Roofs With Slope Less Than 1/4"	49	17	Percent Of Roofs Not Requiring Maintenance	63
7	Percent Of Roofs Applied On The Concrete Deck	3	18	Percent Of Roofs W/ Traffic Greater Than 12 Times /Yr.	4
8	Percent Of Roofs Applied On The Wood Deck	66	19	Percent Of Roofs With More Than 5% Ponded Water	23
9	Percent Of Roofs Applied On The Metal Deck	23	20	Percent Of Roofs With Less Than 1% Deterioration	98
10	Percent Retrofit Roofs	79	21	Percent Of Roofs Requiring Less Than 1% Repair	94
11	Number Of Roofs That Never Leaked	50	22	Percent Of Satisfied Customers	100

Table 4: Performance rating of polyurethane-coated SPF system in heavy hail area.

S. No.	Type	W/NW	Density pcf	Thk. mils	Cooling Medium	Breaks (deg. F)		Total Drops	No. of Breaks
						Yes	No		
1	U1	W	3	30	N. Ice	-	32,36,37,31,40,26, 34,42, 52, 47,30,24	12	0
2	U1	W	3	30	Dry Ice	10,10,15	-	3	3
3	U2	W	3	30	N. Ice	35,38	33,38,38	5	2
4	U2	W	3	30	Dry Ice	19,10,5,15	37,26,20	7	4
5	U2	W	3	45	N. Ice	-	37,37,37,41,42,41	6	0
6	U2	W	3	45	Dry Ice	-	11,17,26,9,10,9,11,28,36, 22,2,10,22, 22,23, 0,8	17	0
7	U1	W	3	45	N. Ice	-	42,42,43,45,45	5	0
8	U1	W	3	45	Dry Ice	8,13,16,14,22,5, 0,14	8,57,3,28,14,34, 34,10,24, 28,19	19	8
9	A	W	3	45	N. Ice	41	39,43,43,44, 45,46,44	8	1
10	A	W	3	45	Dry Ice	23,24,28,21,42, 18,13,30,14,23	-	10	10

Table 5: FM-SH hail test data under freezing temperatures. Legend/ Notes: A: Acrylic; U1: Polyurethane 1; U2: Polyurethane II; W: 1000 hours weatherometer.

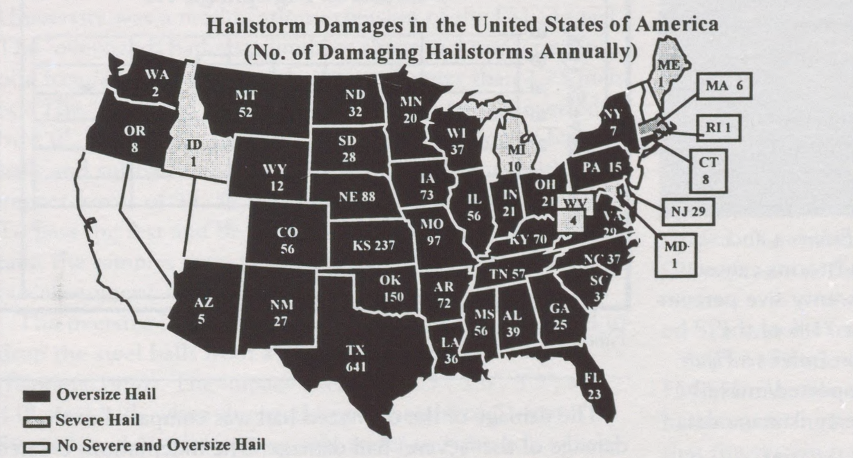

Figure 4: Hail map showing the number of damaging hailstorms in the United States annually.

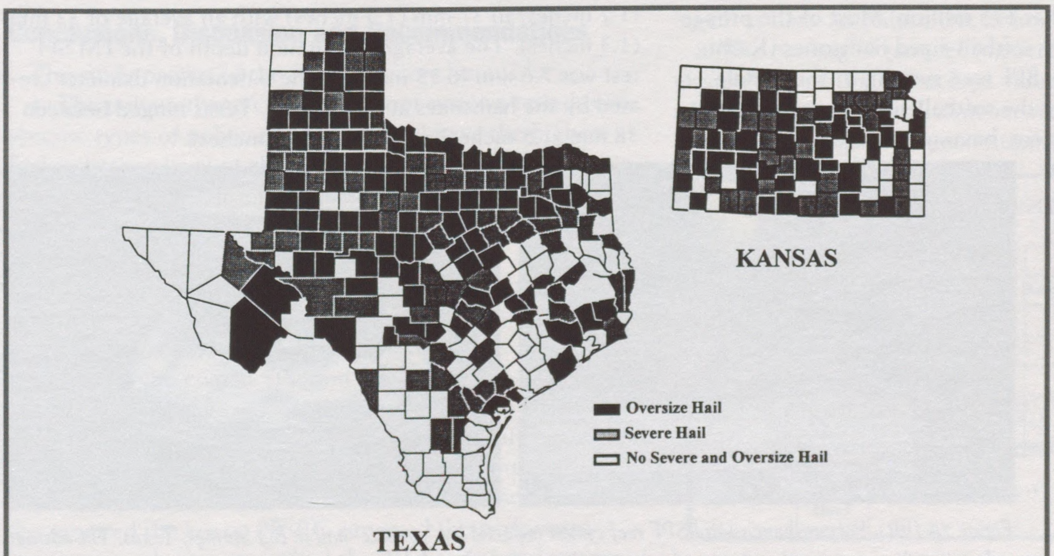

Figure 5: Texas and Kansas rank top among all the U.S. states impacted by oversized and severe hailstorms.

periodically with an infrared thermometer.

3. When the test sample surface temperature was measured close to 32 degrees Fahrenheit, the hail drop was conducted.

4. The temperature was then lowered to subfreezing temperatures using dry ice. When the surface temperature reached below the freezing temperature, the simulated hail drops were conducted. The average subfreezing temperature range was 18 deg. F with a minimum of 0 deg. F.

The observations of the test results were (refer to *Table 5*):

1. One of the polyurethane (U2) coated 45 mils SPF system 3.0 pcf/50 psi compressive strength performed without any ruptures/damage at freezing temperatures. It was the only system that also performed at subfreezing temperatures.

2. The other polyurethane- (U1) coated 30 mils SPF system 3.0 pcf/ 50 psi compressive strength performed well at freezing temperatures and not at subfreezing temperatures. Increasing the coating thickness from 30 mils to 45 mils did not significantly improve the hail resistance of the second polyurethane-coated SPF system under subfreezing temperature conditions.

3. The acrylic 45 mil coated SPF system 3.0 pcf/50 psi compressive strength average SPF did not perform under freezing and subfreezing temperatures.

Oversized Hailstorms in the U.S.

Most U.S. states experience "severe" and "oversized" hailstorms (Storm Data 1994-95). The data analysis of National Weather Service documentation shows that almost every

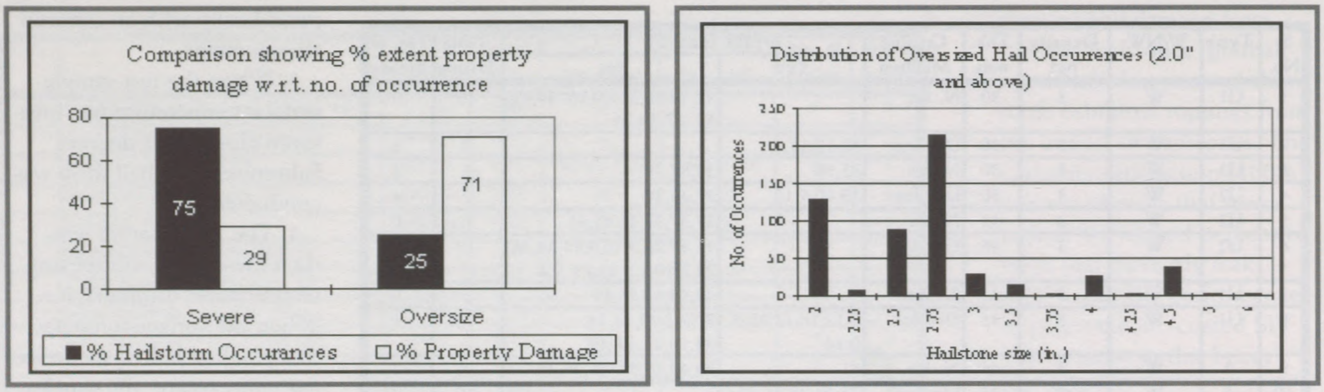

Figure 6A and 6B: Comparison showing the extent of property damage vs. the number of occurrences and the distribution of occurrences of oversize hail in the United States (1994-95 data).

state experiences hailstorms. The largest recorded hailstone fell in Coffeyville, Kansas on September 3, 1970 with hailstone measuring more than 7.0 inches in diameter and weighing 1.7 pounds which would have generated an impact force of 578 lbf (41 times the impact force of a severe size [1.75 inches] hailstone).

In the U.S., the areas exposed to the highest average number of hail days are the Midwest and Southwest (Kashiwagi and Pandey 1996). Studies of 1994-95 hailstorm data show that hailstorms are most frequent in Texas, followed by Kansas and Oklahoma (refer to *Figures 4* and *5*).

The 1994-95 "severe" and "oversized" hailstorms caused property damage totaling $427 million. Twenty-five percent of the "oversized" hailstorms accounted for 71% of the property damage, estimated at $303 million (refer to *Figure 6*). This estimate does not include the unreported/unavailable severe and oversized hailstorms property damage data.

Performance of SPF Roof System Against Natural Oversized Hailstones

Big Springs, Texas and its surrounding area experienced heavy hailstorms on May 10, 1996. The damage to property and crops was estimated at $25 million. Most of the property damage was caused by softball-sized hailstones (Kashiwagi and Pandey, 1998). SPF roof systems at the middle school were impacted by the softball-sized hailstones. The polyurethane-coated system, having an average coating thickness of 45 mils, 3.0 pcf, and 45 psi compressive strength average SPF, withstood up to at least 3-inch diameter hailstones. The correlation between density and compressive strength shows that the samples which resisted the impact of oversized hailstorm met the criteria specified by the manufacturers (refer to *Figure 8*).

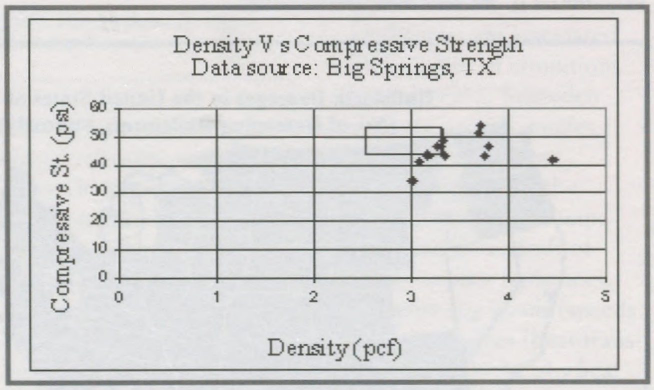

Figure 8: Density vs. compressive strength analysis.

The damage of the oversized hail was compared to the damage of the "severe" hail damage. The indentations created by the hailstones were measured a year and a half after the hailstorm (results shown in *Table 6*). The indentation diameter created on the polyurethane-coated SPF system by the simulated FM SH hail resistance test has the range of 31 mm (1.2 inches) to 37 mm (1.5 inches) with an average of 33 mm (1.3 inches). The average indentation depth of the FM SH test was 7.6 mm (0.25 inches). The indentation diameter created by the hailstones at Big Springs, Texas ranged between 38 mm (1.5 inches) and 76 mm (3.0 inches).

Figure 7A (left): Polyurethane-coated SPF roof system impacted by "oversize" hail in Big Springs, Texas. The average indentation diameter was almost 2.7 inches (210% bigger than the indentation created by FM-SH golfball-size (1.3 inches) hail impact). Figure 7B: HVAC unit showing the indentations created by "oversized" hail in Big Springs, Texas (May, 1996).

S. No.	Indentation Dia. (in.)	Indentation Depth (in.)	S. No.	Indentation Dia. (in.)	Indentation Depth (in.)
1	1.5	0.125	11	2.5	0.625
2	2	0.25	12	2.625	0.625
3	2	0.25	13	2.75	0.625
4	2	0.5	14	2.75	0.75
5	2	0.5	15	2.75	-
6	2.125	0.5	16	2.75	-
7	2.125	0.5	17	2.75	-
8	2.25	0.5	18	3	-
9	2.25	0.625	19	3	-
10	2.375	0.625			

Table 6: Indentations created by the oversized hailstones at Big Springs, Texas.

Oversized Hail Test Methodology

"Oversized" hail testing (Pandey 1996) conducted by the Performance Based Studies Research Group at Arizona State University was a modification/extension of the FM-SH test. The "oversized" hail test simulates the actual impact energy of a free-falling "oversized" hailstone (bigger than 1.75 inches). The "oversized" hail test simulates the impact exerted by 2.0", 2.5", 2.75", 3.1", and 3.4" (representation of baseball- and softball-sized hailstones) size hailstones with impact forces of 22, 52, 89, 140, and 204 lbf respectively. To pass the test and be classified as "oversized" hail resistant, the samples must not exhibit breakage in the continuous elastomeric coating.

The oversize hail resistance test employs a tripod stand to drop the steel balls from a maximum height of 21 feet (Pandey, 1996). The impact energy of 2.5", 3.0", 3.5", and 4.0" steel balls when dropped from a height of 21 feet is 52, 89, 140, and 204 lbf respectively (refer to *Figure 10*), which is representative of OSH2.5, OSH2.75, OSH3.1 and OSH3.4 level of "oversized" hail damage respectively. This experimental arrangement can be applied for both laboratory and in-field oversized hail tests.

Conclusions, Discussion and Recommendations

The study produced the following conclusions:

1. The polyurethane-coated SPF roof systems tested (two specific types of polyurethane coatings) have the highest hail resistance level of all elastomeric-coated SPF systems tested and are a performing system in areas with FM-SH test level of damage in both moderate and freezing temperature conditions.

2. The polyurethane coatings (two specific types) minimize the risk of hail damage and are an alternative solution to the modified and built-up roof systems.

3. The acrylic-coated SPF roof systems also resist FM-SH test levels of damage with 45 mil acrylic coating and 50 psi compressive strength SPF. The acrylic-coated SPF systems tested did not perform under freezing temperatures.

4. Very few acrylic-coated SPF roof systems are applied at the required thickness. PBSRG surveyed the performing contractors who have supplied the database of performing SPF roof systems, and only one contractor has acrylic-coated SPF systems installed at the required thickness.

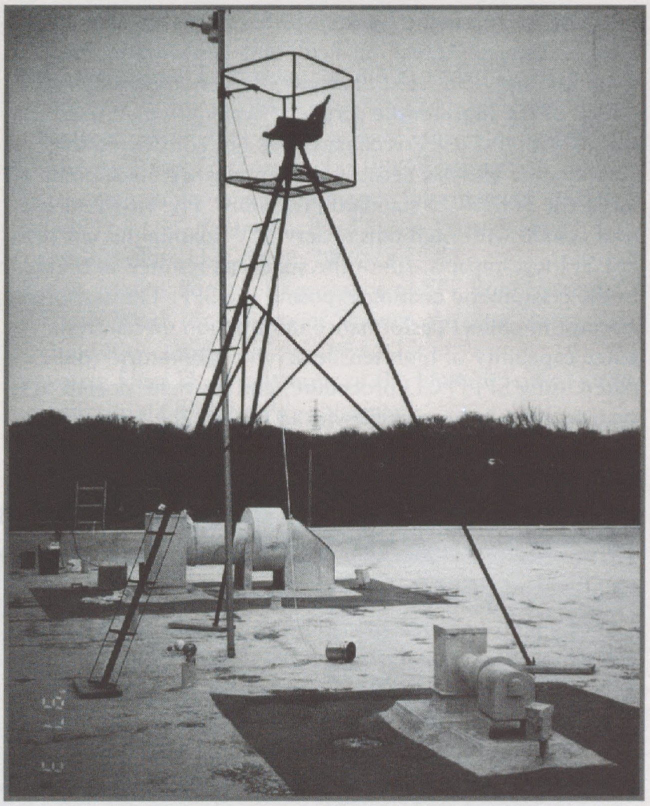

Figure 9: Oversized hail equipment being tested on polyurethane-coated SPF roof system in Dallas, Texas.

5. The silicone-coated SPF system tested did not pass the FM-SH test. Silicone systems should not be used in "severe" hail areas without risk of damage. FM-SH test ratings show that the system tested passed the FM-SH test requirements. This was not substantiated by the multiple tests conducted.

6. The 1000 hours of weathering does not have an influence on the hail resistance test.

7. FM-SH tests should be confirmed by "in-field" tests on "aged" systems to reduce risk of non-performance.

8. The cooling of samples impacts the hail resistance of elastomeric coatings. Based on videotaping of a hailstorm and information on hailstorm activity, the cooling of samples represents hailstorm conditions.

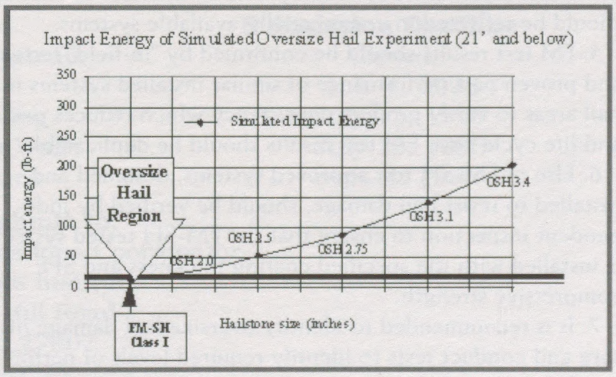

Figure 10: Comparison of impact energy of oversize hail vs. FM-severe hail.

9. The polyurethane coatings tested passed the FM-SH level of damage. Actual, "in-field" data show that polyurethane coatings can resist damage of larger-size hailstones.

One of the high tensile acrylic V systems which resisted the FM-SH test level of damage was not considered for comparative analysis because the samples were not prepared using the SPI-PFCD standard procedure. The two-year-old roof coated with high tensile acrylic V coating did not resist FM-SH test impacts. All of the six drops resulted in breaks in the elastomeric coating exposing the SPF. The authors' attempt to collect performance information on hail resistance capability of high tensile acrylic "laboratory" (prepared using SPI/PFCD procedure) and "in-field" coated SPF systems has not been successful so far. For the system to be categorized as performing, both the "laboratory" and "in-field" samples have to pass the FM-SH requirements and the installed in-field SPF system should have a documented performance record.

Analysis of PBSRG Results Vs. FMRC Results

1997 Factory Mutual Research Corporation (FMRC) product Approval Guide manual shows that silicone (30 mils minimum), acrylic (36 mils minimum), and the polyurethane (37 mils) pass the 1.75-inch hailstone impact test. This gives the impression that the silicone is the most hail-resistant and the polyurethane is the worst. This is exactly opposite of the PBSRG test results and the in-field test results based on the following observations:

1. Test results using the FMRC minimum thicknesses have not been reproducible by the PBSRG.
2. The material quantities are inconsistent.
3. As stated in the FMRC manual, the "three systems listed" are not commercially available.

The following recommendations are made by the authors:

1. Use coating systems (manufacturer-specific) that have proven documentation against hail damage. Do not depend on "industry" recommendations.
2. FM-SH test procedures should be modified to include "cooling" of samples.
3. Increase accelerated weathering requirements for the FM-SH test to show differentiation of resistance to hail damage.
4. FM-SH should clearly specify minimum, average, and maximum thicknesses of coating. The thicknesses of coating should be reflected in commercially-available systems.
5. FM test results should be confirmed by "in-field" tests, and proven past performance of similar installed systems in hail areas to verify product consistency which reduces risk and life cycle cost. FM test results should be duplicatable.
6. Use of FM-SH test approved systems, designed and installed to resist hail damage, should be verified by independent inspection to ensure that the FM-SH tested system is installed with the specified coating thickness and SPF compressive strength.
7. It is recommended to identify oversize hail damage history and conduct tests to identify required levels of performance of SPF roof system in oversize hail damage areas.

PBSRG-Arizona State University Future SPF Research Efforts

The PBSRG is continually testing the Performance Based Procurement System to identify and procure performing construction and facility systems. The following requirements were generated from the results of this study for elastomeric-coated SPF roof systems to minimize the risk of premature failure during the service period of the roofing system:

1. A sample of the elastomeric-coated SPF system shall be submitted with the bid. The sample will be tested with the FM-SH test. Samples shall be tested without the final layer of granules. If the sample passes, the minimum thickness of the coating thickness is used as the requirement.
2. The installed system (without granules) is tested using the FM-SH test. The thickness of the coating is also verified to meet the requirement set forth by the sample. The installed system shall meet both the FM-SH test requirement and the thickness requirement.
3. The installed system shall be tested with the FM-SH test at the five-year service period. If the system does not pass the test, the manufacturer will at his own cost (labor and materials), recoat the coated SPF roof system to pass the FM-SH test requirement. This is repeated for the length of the warranty.

This process will do the following:

1. Ensure that the elastomeric-coated SPF system has sufficient coating thickness to perform against "severe" hail impact.
2. Encourage the manufacturers/contractors to document performance information over time and ensure that hail resistance is not diminished over time. The manufacturers will be encouraged to test their "aged" systems and to not "market" unproven systems.

The PBSRG's report on "oversized" hail resistance capability of SPF roof system is being compiled for review and publication. This report focuses on:

1. Maximum hail resistance capability of different SPF roof systems.
2. High risk "oversized" hailstorm areas in the United States.

Acknowledgments and Further Information

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For further information, or a copy of the research report, contact the PBSRG at PH (602) 965-4273 or FAX (602) 965-4371.

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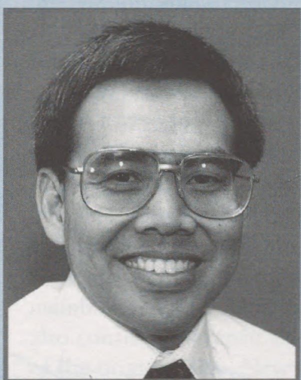

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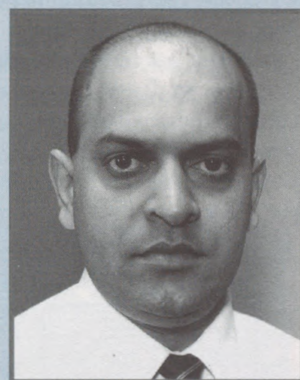

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