# HAIL RESISTANCE TEST OF SPRAYED POLYURETHANE FOAM (SPF) ROOF SYSTEMS

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This report analyzes the resistance of different types of elastomeric-coated SPF roof systems to severe [Factory Mutual severe hail (FM-SH) test level] and oversized hail and identifies performance factors relative to the resistance of hail damage. It also includes the study of the impact resistance of elastomeric-coated SPF roof systems at lower temperatures. This research effort is unique in the following ways:

- It uses the process of "information theory" and "intelligent processing" to modify the FM-SH test process to improve the hail resistance test of the SPF roof systems.
- It identifies the hail resistance of SPF roof systems near freezing temperatures.
- It relates the damage of severe hail with oversized hail.
- It expands the FM-SH test to predict the damage of oversized hail.

**KEYWORDS**

Elastomeric-coated sprayed polyurethane foam, Factory Mutual severe hail (FM-SH) test, hail resistance, severe and oversized hail damages, sprayed polyurethane foam (SPF) roof systems.

## INTRODUCTION

Severe hail damage to roof systems in the midwestern United States[1] caused by hail ranging in size between a golf ball [45 mm (1¾ inches)] and a softball [102 mm (4 inches)] has raised concern about the hail resistance capability of various types of roof systems. In 1996, the areas surrounding Dallas and Big Springs, Texas, were impacted with heavy hailstorms, causing an estimated $25 million in property/roof damage. The annual estimated damage to buildings, since 1989, caused by hail throughout the United States is estimated at $1.94 billion.[2] The extensive damage to SPF roof systems caused by hailstones has caused facility owners and insurance carriers to raise the following question about SPF roof systems:

- Were SPF roof systems damaged sufficiently enough by hail to warrant the high cost of tear-off and replacement with a new roof system?
- Could the damaged SPF roof systems be economically repaired?
- Could the SPF roof system be enhanced to minimize the risk of future hail damage?
- Is the SPF roof system a viable option for a facility owner attempting to reduce the risk of future hail damage?[3]

Manufacturers, seeking to reduce risk on their SPF roof systems, approached the Performance Based Studies Research Group (PBSRG) at Arizona State University (ASU) to perform research to:

- identify the relative performance of their different SPF roof system products by applying "information theory" based on laboratory tests, by testing the existing in-field installations, and by quantifying the past performance;
- identify whether a properly installed SPF roof system is a viable option to reduce the risk of future hail damage.

## BACKGROUND

Hailstorms occur throughout the United States in varying regions and intensities. The average number of days, by region, with hailstorms across the United States is shown in Figure 1. Hailstorms are selective (hitting some areas and not others). Hailstones have a variety of conditions, including different sizes, speeds, angles, shapes, and temperatures. Hailstorm data shows that the falling of hailstones to the earth's surface, under thunderstorm conditions (refer to Figure 2), can have a cooling effect on roof systems. This cooling effect is caused by an initial downdraft of cool air preceding the hailstorm. The first hailstones, cold water on the roof surface, and accompanying winds [speeds ranging from 64 to 96 km/h (40 to 60 mph)] also lower the roof temperature. Because the physical properties of polymer products are temperature-dependent, the impact of hail on cold surfaces may increase the amount of damage to roof systems.[4,5,6]

SPF roof systems have been around since the late 1960s.

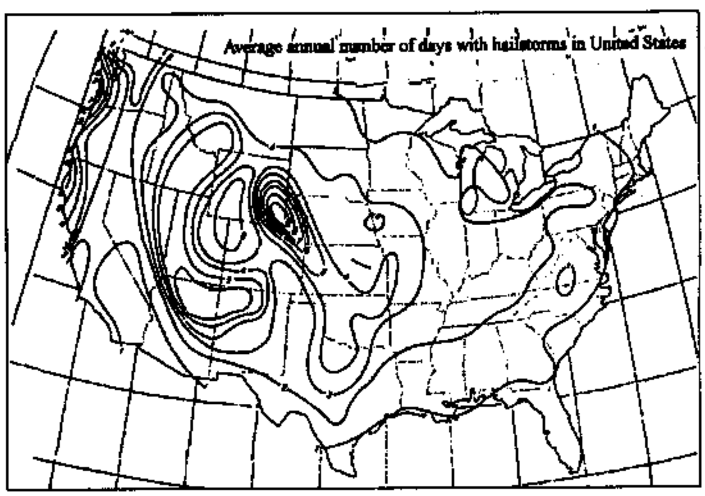


*Figure 1. Average annual number of days with hailstorms. (U.S. Weather Bureau,* Hydrometeorological Report No. 5, *extracted from Flora, Snowden D.,* Hailstorms of the United States, *1956 (1).)*

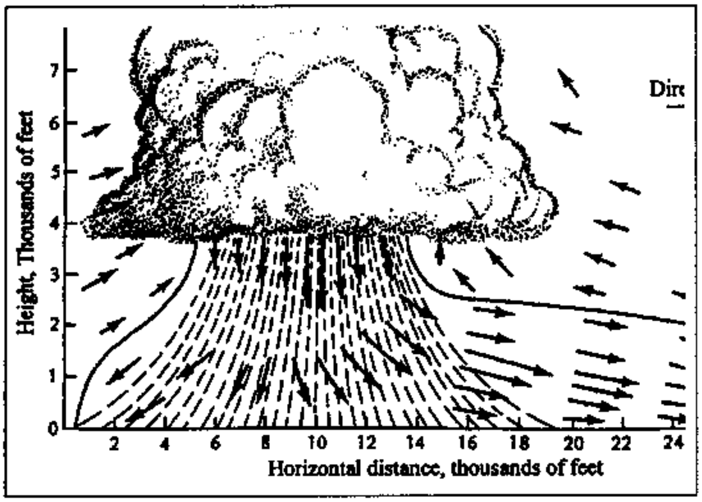


*Figure 2. Typical thunderstorm condition during hailstorms. (After H. Byers and R. Braham,* The Thunderstorm, *U.S. Government Printing Office, extracted from Donn, William L.,* Meteorology, *4th edition, 1975, (13).)*

SPF roof systems consist of a minimum of 25 mm (1 inch) of SPF and surfacing (e.g., elastomeric coating and aggregate). Performance studies at ASU on more than 1,600 roofs across the United States, which were inspected every two years during a 13-year period, identified the following:

- The SPF roof system requires more technical understanding as compared to other commercially available roof systems. Therefore, the experience and training of performing contractors are the most influential factors in installing a performing SPF roof system.
- Acrylic, polyurethane, silicone-coated, and aggregate-surfaced SPF roof systems with proven performances of 26, 18, 22, and seven years, respectively, have been installed by performing contractors in the United States.
- Different SPF systems have a variety of strengths in different areas. Acrylic coatings are water-based and are the easiest and most economical to manufacture, but they also have the greatest variance of performance of the different elastomeric-coated SPF roofs. Acrylic coatings are dominant in the southwest and western United States. Silicone coatings are the most UV-resistant, have the greatest application window and are dominant in the midwestern and eastern United States.
- The research conducted to identify the past performance of SPF roof systems has shown that performing polyurethane-coated SPF systems have the greatest resistance to traffic, hail, and other mechanical damage of all the SPF coated systems. However, the problem with polyurethane coatings is the lack of consistency of product performance. Some polyurethane coatings have showed delamination, cracking, and reversion problems, exemplifying the difference in performance among polyurethane coatings. Only one of the major four polyurethane coatings has had third-party, nonbiased, published performance information of 15 years or more from a large sample size (average 50 roofs) in multiple locations. This is not to say that the other manufacturers products have not performed. The author has been attempting to collect more performance information of polyurethane coatings for the past 10 years and has been unsuccessful in documenting the performance of other performing polyurethane systems or identifying other third-party test or research groups that have a sizable database of performing polyurethane-coated SPF roof systems.

The problem with many of the installed SPF roof systems that must perform in areas with potential hail damage include:

- Inconsistency in meeting the physical properties specified by the manufacturer.
- Elastomeric coating thickness specified in "gallons of coating per square" and/or average thicknesses[7] that are difficult to verify.
- The lack of uniformity in the designations of coating thicknesses, which makes comparisons of various samples difficult. For example, depending on which manufacturer's specification is used, a 0.76-mm (30-mil) coated acrylic sample can mean the following:
  - 76-mm (30-mil) minimum
  - 0.76-mm (30-mil) average and 0.38-mm (15-mil) minimum
  - 76-mm (30-mil) average with no minimum thickness requirement

Data collection has shown that there are also variances in installed SPF compressive strengths and densities.[8] Figure 3 shows that only seven out of 33 random in-field samples of SPF from roof installations installed by performing contractors in 1995 met the manufacturer-specified 38 to 48 kg/m$^3$ (2.5 to 3.0 pcf) density and 262,002 to 344,740 N/m$^2$ (38 to 50 psi) compressive strength requirements.[2] The fluctuation in the SPF system application lead to higher variation in SPF physical properties, which may place a higher hail-resistance requirement on the elastomeric coating system. These variations in installed SPF roof systems lead to a high level of risk and confusion toward liability of premature failure of SPF systems caused by hail damage. The lack of understanding of SPF roof systems' behavior may result in the marketing of coated SPF roof systems with no proven performance history of hail damage resistance in areas with severe hailstorms and

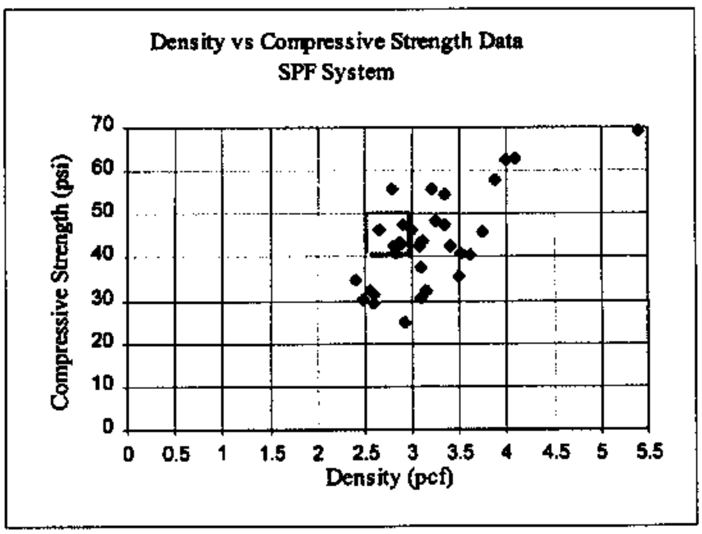


*Figure 3. Density vs. compressive strength data for HCFC in-field SPF system (uncorrected for elevation), 1995.*

the setting of standards that have no correlation to in-field installation or hail-resistance performance.

## OBJECTIVE OF HAIL STUDY RESEARCH AT PBSRG

The objective of ongoing PBSRG hail study research is to identify the level of hail resistance and damage for different SPF roof systems. The research study covers the following levels of damage:

- Factory Mutual-Severe Hail (FM-SH) #4470 Class-I test level [45-mm (1.75-inch) hailstones]
- Oversized hailstones [51-, 64-, 76-, 89-, 102-mm-(2-, 2.5-, 3-, 3.5-, 4-inch-)diameter hailstones]
- Small hailstones [3-mm- (⅛-inch-) diameter hailstones]

Objectives include the following:

- Identify the relative hail resistance of different elastomeric-coated SPF roof systems using the FM-SH test methodology.
- Identify the impact of weathering, granulation, increased coating thickness, SPF density and compressive strength, and different surface temperatures (moderate, freezing, and subfreezing) on the hail resistance of elastomeric-coated SPF roof systems.
- Correlate in-field test results of aged, coated SPF roof systems with the FM-SH test results.
- Correlate the performance of coated elastomeric SPF roof systems in hail areas with the results of the hail testing.
- Identify occurrences of oversized hailstones and record damages caused by the oversized hailstones.
- Expand the FM-SH test procedure to simulate oversized hail for laboratory testing and in-field testing.
- Correlate the damage of severe and oversized hailstones.
- Analyze the impact of small hail (smaller than FM-SH size) on silicone coating in the midwestern United States to see if granulation can improve the hail resistance.

## METHODOLOGY FOR DETERMINATION OF HAIL DAMAGE

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

- Using the FM-SH test [dropping a 359-g (0.8-pound) steel ball with a 45- mm (1.75-inch) diameter from a height of 5.4 meters (17.8 feet) on the sample to simulate the severe hail damage.
- Test three major (commercially available )coating types with varying thicknesses, SPF foam densities, weathering, and granulation.
- Test the successful systems (which passed the FM-SH test under FM test rules) in low temperature (freezing and subfreezing) conditions.
- Test 14 installed in-field roof systems in Torrington, Wyoming, and Dallas, Texas (two areas of the country with severe hail damage).
- Correlate FM-SH test results of laboratory samples with results of in-field roof tests and proven SPF roof system performance.
- Identify areas where damage to SPF roof systems caused by oversized hailstones has been observed.
- Observe hail damage to installed granulated and non-granulated silicone roof systems in Louisville, Kentucky.
- Correlate damage caused by oversized hailstones with severe hailstones. Future work includes the testing of installed in-field roof systems in Dallas and Big Springs for oversized hailstone damage and correlating the results with actual damage.

## TEST SAMPLE PREPARATION

Sample preparation for the testing included 96 panels [30.5 cm by 61 cm (1 foot by 2 feet)] of the commercially available elastomeric-coated SPF roof systems. The test samples were prepared based on manufacturer specifications. All tests were conducted under the direction of Dr. Kashiwagi at Arizona State University, and field tests were conducted by Dr. Kashiwagi in Wyoming and Texas. The majority of the test samples are being aged in Mesa, Arizona. Of the 96 samples that were made, 32 of the samples were control samples that 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 also could be duplicated by other testing groups. Coating thicknesses followed the industry standard[9] and manufacturers' recommendations:

- 20-mil system [0.25-mm (10-mil) minimum, 20-mil (0.51-mm) average]
- 30-mil system [0.38-mm (15-mil) minimum, 0.76-mm (30-mil) average]
- 45-mil system [0.51-mm (20-mil) minimum, 1.14-mm (45-mil) average]

Because of the roughness of the SPF, the above specification 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 test results do not address SPF systems in the above terms. FM test results[7] use gallons per square and/or average thicknesses (which are stated as minimum thicknesses), which are very difficult to verify; this results in the inability to compare alternative systems. For example, a FM-approved 0.76-mm (30-mil) system [0.76-mm (30-mil) minimum] may actually have more coating than a 1.14-mm (45-mil) system [0.51-mm (20-mil) minimum] in this test. All samples were prepared under the controlled conditions. The sample preparation included:

- conformance to SPI/PFCD sprayed polyurethane foam supplier accreditation program sample preparation guidelines;
- foam densities in the range of 40 to 48 kg/m$^3$ (2.5 to 3.0 pcf ), yielding an average compressive strength of 275,792 N/m$^2$ (40 psi) and 344740 N/m$^2$ (50 psi), respectively;
- cured for 30 days at 72°F (22.2°C) and relative humidity of 55 percent;
- subjected to 1,000 hours of accelerated weathering using a weatherometer (at the Naval Facilities Engineering Service Center, Port Hueneme, California) to test the impact of weathering on hail resistance.

The laboratory SPF samples were analyzed for variance (refer to Table 1). The source of the variance could be both the application of the SPF and the laboratory test procedure. The presence of knitlines in the SPF system also contributed towards the variance in SPF physical properties.

## TEST RESULTS

The FM-SH test has the following requirements:

- Ten drops shall be performed on each sample.
- The samples shall be conditioned for 24 hours at a temperature of 22°C (72°F) and relative humidity of 55 percent.
- New and weathered (1,000 hours of simulated UV rays, artificial weathering or natural weathering) samples of SPF systems shall be used.

The following results are from the FM-SH hail laboratory test conducted at ASU (refer to Table 2):

- Polyurethane-coated SPF samples had the highest resistance to the FM-SH simulated hail damage with the minimum specified system [30-mil (0.76-mm) coating and 276,000 N/m² (40 psi) compressive strength SPF].
- Acrylic coatings resisted the FM-SH test level of damage with 45-mil (1.14-mm) coating and 50 psi (344,740 N/m²) compressive strength SPF.
- Silicone-coated SPF samples failed the FM-SH test.
- Granulation had no influence on hail resistance of any of the systems tested.
- The FM-SH test of 1,000 hours of accelerated weathering using a weatherometer (at the Naval Facilities Engineering Service Center, Port Hueneme, California) had no impact on hail resistance.
- A higher SPF compressive strength increased the acrylic-coated SPF system's resistance to hail damage.
- The polyurethane-coated samples were the most robust performing samples, passing the FM-SH test level of damage in moderate, freezing, and subfreezing temperatures.

| Description | SPF Properties | |
|---|---|---|
| | 40 Kg/m³ (2.5 pcf) | 48 kg/m³ (3.0 pcf) |
| Density Lowest | 38 Kg/m³ (2.4 pcf) | kg/m³ (3.36 pcf) |
| Density Highest | 47 Kg/m³ (2.93 pcf) | kg/m³ (3.88 pcf) |
| Compressive Strength Lowest | 295000 N/m² (42.7 psi) | 380000 N/m² (55.00 psi) |
| Compressive Strength Highest | 365000 N/m² (53 psi) | 520000 N/m² (75.00 psi) |
| Density Average | 44 Kg/m³ (2.7 pcf) | kg/m³ (3.55 pcf) |
| Compressive Strength Average | 300000 Kg/m² (43 psi) | 460000 N/m² (66.62 psi) |

*Table 1: Data analysis of tested SPF samples.*

## CORRELATION OF FM-SH TEST RESULTS WITH IN-FIELD PERFORMANCE

Thirteen roofs were selected by Dr. Kashiwagi for evaluating the in-field performance of different types of SPF roof systems (refer to Table 3). The polyurethane-coated SPF has the only documented performance of hail resistance of the FM-SH test level of hail damage (Torrington, Wyoming, and Dallas and Fort Worth, Texas). All of the 13 roofs tested for hail resistance had documented damage from severe and oversized hail. The results supported the sample test results. A survey of polyurethane-coated SPF roof systems in southeast-

| S. No. | Coating | Aged | Coating Thickness | Granules | No. of Breaks in Sample (out of 10 hits) | |
|---|---|---|---|---|---|---|
| | | | mm (mils) | | 40 Kg/m³ (2.5 pcf) | 48 Kg/m³ (3.0 pcf) |
| 1 | A | Y | 0.76 (30) | Y | 10 | 7 |
| 2 | A | Y | 1.14 (45) | Y | 10 | 5 |
| 3 | A | Y | 0.76 (30) | N | 3 | 0 |
| 4 | A | Y | 1.14 (45) | N | 5 | 0 |
| 5 | S | Y | 0.51 (20) | Y | 10 | 10 |
| 6 | S | Y | 0.76 (30) | Y | 10 | 10 |
| 7 | S | Y | 0.51 (20) | N | 10 | 10 |
| 8 | S | Y | 0.76 (30) | N | 10 | 10 |
| 9 | U1 | Y | 0.76 (30) | Y | 0 | 0 |
| 10 | U1 | Y | 1.14 (45) | Y | 0 | 0 |
| 11 | U1 | Y | 0.76 (30) | N | 0 | 0 |
| 12 | U1 | Y | 1.14 (45) | N | 0 | 0 |
| 13 | U2 | Y | 0.76 (30) | Y | 0 | 0 |
| 14 | U2 | Y | 1.14 (45) | Y | 0 | 0 |
| 15 | U2 | Y | 0.76 (30) | N | 0 | 0 |
| 16 | U2 | Y | 1.14 (45) | N | 0 | 0 |
| 17 | A | N | 0.76 (30) | Y | 10 | 0 |
| 18 | A | N | 1.14 (45) | Y | 10 | 5 |
| 19 | A | N | 0.76 (30) | N | 2 | 0 |
| 20 | A | N | 1.14 (45) | N | 2 | 0 |
| 21 | S | N | 0.51 (20) | Y | 10 | 4 |
| 22 | S | N | 0.76 (30) | Y | 10 | 10 |
| 23 | S | N | 0.51 (20) | N | 10 | 7 |
| 24 | S | N | 0.76 (30) | N | 11 | 9 |
| 25 | U1 | N | 0.76 (30) | Y | 0 | 0 |
| 26 | U1 | N | 1.14 (45) | Y | 0 | 0 |
| 27 | U1 | N | 0.76 (30) | N | 0 | 0 |
| 28 | U1 | N | 1.14 (45) | N | 0 | 0 |
| 29 | U2 | N | 0.76 (30) | Y | 0 | 0 |
| 30 | U2 | N | 1.14 (45) | Y | 0 | 0 |
| 31 | U2 | N | 0.76 (30) | N | 0 | 0 |
| 32 | U2 | N | 1.14 (45) | N | 0 | 0 |

Legend:
A: Acrylic Coating
S: Silicone Coating
U1: Polyurethane I Coating
U2: Polyurethane II Coating
SIG: Significant Differential

Notes:
Aging: 1000 hours weatherometer.
Granulation: #11 granules.
Density: 2.5 and 3.0 pcf
Coating Thickness in mils

*Table 2: FM-SH hail resistance test results.*

ern Wyoming was completed, and the results are shown in Table 4.

Many of the metal mechanical penetrations on the roofs showed hail damage from severe (golf-ball-sized) hailstones, but none of the roofs exhibited any rupture from the impact of hailstones, and the damage did not lead to premature failure of the SPF system. The customer satisfaction (100 percent), percent of roofs that never leaked (94 percent), and percent of roofs that currently leak (0 percent) verify the performance of polyurethane-coated SPF roof systems in a hail area.

## PERFORMANCE OF SPF ROOF SYSTEMS AT LOWER TEMPERATURES

The FM-SH test procedure does not provide information on the behavior of SPF systems in near freezing and subfreezing conditions. Using the theory of relativity in information theory, only those SPF systems that passed the FM-SH test were further tested under the cooler temperatures[8, 11] using the following procedure:

- Wet ice was placed on the sample.
- The temperature of the coated SPF sample was checked periodically with an infrared thermometer.
- When the surface temperature became close to 0°C (32°F), the hail drop was conducted.
- The temperature was then lowered to subfreezing temperatures using dry ice. When the surface temperature dipped below freezing, the simulated hail drops were conducted. The average subfreezing temperature range was -8°C (18°F) with a minimum of -18°C (0°F).

The observations of the test results were:

- One of the polyurethane- (U2-) coated [1.14-mm (45-mil)] SPF systems [48.1 kg/m$^3$ (3.0 pcf)/344,740 N/m$^2$ (50 psi) compressive strength] performed without any ruptures/damage at freezing temperatures. It was the only system that also performed at subfreezing temperatures.
- The other polyurethane- (U1-) coated [0.76-mm (30-mil) SPF system [48.1 kg/m$^3$ (3.0 pcf)/344,740 N/m$^2$ (50 psi) compressive strength] performed well at freezing temperatures and not at subfreezing temperatures. Increasing the coating thickness from 0.76 mm (30 mils)

| S.No. | Performance Criteria | Polyurethane |
|---|---|---|
| 1.0 | Proven Service Period (Years) | 12 |
| 2.0 | Average Performance Length | 7 |
| 3.0 | Average Square Feet Installed | 13400 |
| 4.0 | Average Square Feet Of Roof Per Penetration | 954 |
| 5.0 | Percent Insulated Roofs | 100 |
| 6.0 | Percent Roofs With Slope Less Than 1/4" | 49 |
| 7.0 | Percent Of Roofs Applied On The Concrete Deck | 3 |
| 8.0 | Percent Of Roofs Applied On The Wood Deck | 66 |
| 9.0 | Percent Of Roofs Applied On The Metal Deck | 23 |
| 10.0 | Percent Retrofit Roofs | 79 |
| 11.0 | Number Of Roofs That Never Leaked | 50 |
| 12.0 | Number Of Roofs That Leaked And Were Fixed | 3 |
| 13.0 | Number Of Roofs That Still Leaked | 0 |
| 14.0 | Percent Of Roofs That Never Leaked | 94 |
| 15.0 | Percent Of Roofs That Leaked And Were Fixed | 100 |
| 16.0 | Percent Of Roofs That Still Leaked | 0 |
| 17.0 | Percent Of Roofs Not Requiring Maintenance | 63 |
| 18.0 | Percent Of Roofs With Traffic Greater Than 12 Times /Year | 4 |
| 19.0 | Percent Of Roofs With More Than 5% Ponded Water | 23 |
| 20.0 | Percent Of Roofs With Less Than 1% Deterioration | 98 |
| 21.0 | Percent Of Roofs Requiring Less Than 1 % Repair | 94 |
| 22.0 | Percent Of Satisfied Customers | 100 |

*Table 4: Performance of the SPF system in severe hail area (Ref: performance-based research of SPF systems in the USA by PBSRG (3)).*

| S. No. | Facility name and Location | Coating Type | Installed Date | Avg. Coat Thk. [mm (mils)] | Avg. SPF Density [Kg/m$^3$ (pcf)] | No. of Drops | No. of Breaks |
|---|---|---|---|---|---|---|---|
| 1 | Industrial Electronics, Fort Worth, TX | Acrylic | 1993 | 0.76 (30 mils) | 48 (3 pcf) | 5 | 5 |
| 2 | Cooksey Printing, Fort Worth, TX | Acrylic | 1993 | 1.27 (50 mils) | 48 (3 pcf) | 5 | 1 |
| 3 | HEB Admin, Hurst, TX | Silicone | 1985 | Sample NA | Sample NA | 5 | 5 |
| 4 | McDonald MS, Mesquite, TX | Silicone | 1995 | 0.76 (30 mils) | 59 (3.66 pcf) | 7 | 6 |
| 5 | Ball Park | Silicone | 1984 | 1 (40 mils) | 57 (3.54 pcf) | 3 | 3 |
| 6 | Spring Garden Gym, Bedford, TX | PM I | 1986 | 1 (40 mils) | 48 (3 pcf) | 4 | 0 |
| 7 | Porter Elementary, Mesquite, TX | UR | 1994 | 0.5 (20 mils) | 46 (2.9 pcf) | 6 | 6 |
| 8 | VICA Building, Mesquite, TX | PM II | 1994 | 1 (40 mils) | 57 (3.54 pcf) | 7 | 0 |
| 9 | HEB Bell Manor Gym, Euless, TX | PM I | 1986 | 1.27 (50 mils) | 48 (3 pcf) | 3 | 0 |
| 10 | Fresnell Technology, Fort Worth, TX | PM II | 1993 | 0.96 (38 mils) | 48 (3 pcf) | 5 | 2 |
| 11 | Torrington HS | PM I | 1982 | 0.9 (35 mils) | 56 (3.5 pcf) | 4 | 0 |
| 12 | EWC I | PM I | 1987 | 0.76 (30 mils) | 48 (3 pcf) | 4 | 0 |
| 13 | EWC II | PM II | 1990 | 0.9 (35 mils) | 60 (3.74 pcf) | 4 | 0 |

Legend:
UR: Polyurethane PMII : Polyurethane II PM I: Polyurethane I

*Table 3: Infield hail resistance test data.*

to 1.14 mm (45 mils ) did not significantly improve the hail resistance of the second polyurethane-coated SPF system under subfreezing temperature condition.

- The acrylic- [1.14-mm (45-mil)] coated SPF system [48 kg/m³ (3.0 pcf)/344,740 N/m² (50 psi) compressive strength average] SPF did not perform under freezing and subfreezing temperatures.

## BEHAVIOR OF SPF ROOF SYSTEMS AGAINST NATURAL OVERSIZED HAILSTONES

Big Springs and the 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.[10] SPF roof systems at the middle school were impacted by the hailstones. The indentations created by the hailstones were measured a year and a half after the hailstorm (the results are shown in Table 5). The polyurethane-coated system, which had an average coating thickness of 1.14 mm (45 mils), 48 kg/m³ (3.0 pcf), and 310,266 N/m² (45 psi) compressive strength average SPF, withstood up to at least 76.2-mm- (3-inch-) diameter hailstones (refer to Table 3). The correlation between density and compressive strength shows that the samples that resisted the impact of oversized hailstones met the criteria specified by the manufacturers (refer to Figure 4).

The damage of the oversized hail was compared to the damage of the severe hail.[11] The diameter of the indentation created on the polyurethane-coated SPF system by the simulated FM-SH hail resistance test ranged from 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 diameter of the indentation

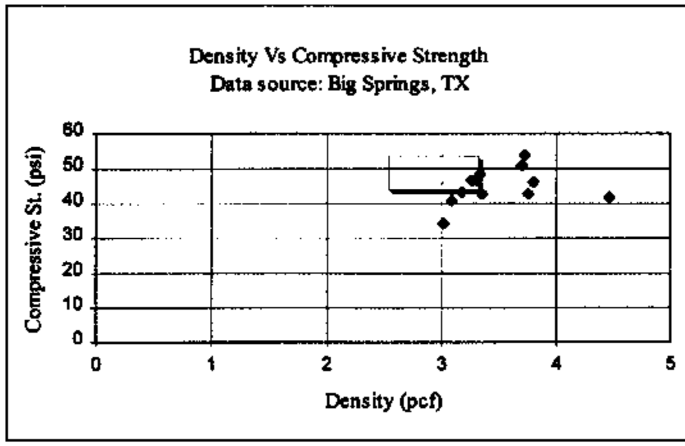


*Figure 4: Density vs. compressive strength analysis.*

created by the hailstones at Big Springs ranged between 38 mm (1.5 inches) and 76 mm (3.0 inches). The PBSRG is planning on using an expanded FM-SH test modified for oversized hailstones [51-, 64-, 76-, 89-, 102-mm- (2-, 2.5-, 3-, 3.5-, 4-inch-) diameter hailstones] to confirm the observations at Big Springs. The tests will be conducted on coated SPF samples and in-field aged SPF roof systems.

## BEHAVIOR OF SILICONE-COATED SPF ROOF SYSTEMS IN SMALL HAIL ENVIRONMENTS

Silicone-coated SPF roof systems [five to 10 years old, granulated and nongranulated, average 0.5 mm, 275790 Pa (20 mil, 40 psi) compressive strength silicone-coated SPF] were inspected for hail damage in Louisville, Kentucky, in August 1996. Not all of the total 650,321 m² (7 million square feet)

| S. No. | Type | W/NW | Density | Thk. | 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 |

Legend:
A: Acrylic Coating
S: Silicone Coating
U1: Polyurethane I Coating
U2: Polyurethane II Coating
W: Weathered

Notes:
Aging: 1000 hours Weatherometer
Density: 3.0 PCF
Coating Thickness is in mils.

*Table 5: Hail test data at freezing temperatures.*

of roofing was damaged by small-sized hail that was estimated to be no larger than the 3 mm (⅛ inch) in diameter. The damage was verified by the contractor, the facility manager, and the insurance company. The damage was very light, forcing the inspectors to look at a certain angle, based on the direction of light, to see the tears in the silicone coating. The size of the hail was confirmed by the length of the slit in the silicone coating and very slight indentations in the SPF. The inspectors inspected granulated and nongranulated areas that were side by side and observed that the granulated silicone-coated areas were not damaged. In comparison, the damage to the nongranulated areas was widespread. The granulation of silicone coatings resisted damage from the small hail. The in-field damages to silicone-coated SPF systems caused by small-sized hail [3-mm (⅛-inch) diameter or less], can be minimized by granulation. However, as discussed previously, granulation does not improve the hail-resistance properties of silicone-coated SPF system for the FM-SH- sized hailstone.

## CONCLUSIONS AND RECOMMENDATIONS

The study produced the following conclusions:

- Polyurethane-coated SPF roof systems have the highest hail resistance of elastomeric-coated SPF systems and are a performing system in areas with the FM-SH test level of damage under moderate and freezing temperature conditions.
- Acrylic-coated SPF roof systems also resist the FM-SH test level of damage with 1.14-mm (45-mil) acrylic coating and 344740 $N/m^2$ (50 psi) compressive strength SPF. The acrylic-coated SPF systems do not perform under freezing temperatures.

| Sample No. | Indentation Diameter | Indentation Depth | Indentation Diameter | Indentation Depth |
|---|---|---|---|---|
| | Inches | Inches | Millimeter | Millimeter |
| 1 | 1.5 | 0.125 | 38.1 | 3.175 |
| 2 | 2 | 0.25 | 50.8 | 6.35 |
| 3 | 2 | 0.25 | 50.8 | 6.35 |
| 4 | 2 | 0.5 | 50.8 | 12.7 |
| 5 | 2 | 0.5 | 50.8 | 12.7 |
| 6 | 2.125 | 0.5 | 53.975 | 12.7 |
| 7 | 2.125 | 0.5 | 53.975 | 12.7 |
| 8 | 2.25 | 0.5 | 57.15 | 12.7 |
| 9 | 2.25 | 0.625 | 57.15 | 15.875 |
| 10 | 2.375 | 0.625 | 60.325 | 15.875 |
| 11 | 2.5 | 0.625 | 63.5 | 15.875 |
| 12 | 2.625 | 0.625 | 66.675 | 15.875 |
| 13 | 2.75 | 0.625 | 69.85 | 15.875 |
| 14 | 2.75 | 0.75 | 69.85 | 19.05 |
| 15 | 2.75 | - | 69.85 | - |
| 16 | 2.75 | - | 69.85 | - |
| 17 | 2.75 | - | 69.85 | - |
| 18 | 3 | - | 76.2 | - |
| 19 | 3 | - | 76.2 | - |

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

- Further research can be done to identify if FM-SH test procedures should be modified to include the cooling of samples.
- The accelerated weathering requirements for the FM-SH test should be increased.
- FM-SH should clearly specify minimum, average, and maximum thicknesses of coating.
- FM test results can be confirmed by in-field tests and by the proven past performance of similar installed systems in hail areas to verify product consistency, which reduces risk and life cycle cost.
- 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.
- It is recommended that oversized hail damage history be identified and tests be conducted to identify the maximum level of performance of SPF roof system in oversized hail damage areas.

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

## REFERENCES

1. *The Torrington Telegraph* midweek edition, "Hail wreaks havoc on town; leaves multimillion dollar trail," June 27, 1984, Vol. 77-No.
2. Doug Kramer, IPI, Telephone Interview, February 04, 1997.
3. Chuck Allen, State of Wyoming, General Interview, January 1995.
4. Krause, Stephen, Professor, Department of Chemical, Bio, and Materials Engineering, fax response to PBSRG, April 3, 1996.
5. Hendrickson, Lester, Professor, Department of Chemical, Bio, and Materials Engineering, fax response to PBSRG, April 3, 1996.
6. Properties of rigid polyurethane foams, Product Information.
7. Technical report on minimum thickness requirement, fax report from Factory Mutual Research, Engineers Material Section, October 21, 1996.
8. Kashiwagi, Dean T. and Manoj K. Pandey. *Hail Resistance of SPF Roof Systems*, Performance Based Studies Research Group, Arizona State University.

9. *Polyurethane Foam Physical Sampling Methodology*, SPI-PFCD, 1989, 15-17.
10. Texas Press Service Inc. (Press Clips), "Storm Ravages Region, Softball Size Hail Injures Dozen," Damon Cline, *Odessa American*, May 11, 1996.
11. Pandey, Manoj K. *Hail Resistance of SPF Roof Systems*, thesis work for Masters of Science, Arizona State University, 1996.

## ADDITIONAL RESOURCES

Kashiwagi, Dean T. "Performance issues of sprayed polyurethane foam roof systems," *Professional Roofing*, January 1996.

Kashiwagi, Dean T., C. Halmrast, and J. Conner. *1996 Roofing Contractors/Systems Performance Information*, Performance Based Studies Research Group, Arizona State University, 1996.

Dupuis, Rene M. "SPF roof systems: Field survey and performance review, *Professional Roofing*, March 1996.

Fricklas, D. "Polyurethane foam another study," *RSI*, June 1995.

Smith, Thomas L. "Hail resistance: The need for enhanced performance," *Professional Roofing*, 1994.

Donn, William N. *Meteorology*, 1975.

Greenfeld, Sidney H. *Hail resistance of roofing products*, National Technical Information Service, National Bureau of Standards., U.S. Department of Commerce.

Snowden, Flora D. *Hailstorms of the United States*, University of Oklahoma Press: Norman, 1956.