11.1 An Overview of the IBHS Hail Research Program

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1. INTRODUCTION

Building components, particularly roofing systems (Marshall et al. 2002), are frequently damaged in hailstorms, leading to large insured losses. Annual insured losses attributed to hail are now approaching the $10 billion mark (Gunturi and Tippett 2017), which represents a sharp increase compared to the $850 million estimated in 2009 (Changnon et al.). Unfortunately, hail is a natural hazard that we currently do not account for very well in our building practices.

The Insurance Institute for Business & Home Safety hail research program, launched in 2010 (Brown et al. 2012; Brown et al. 2014; Giammanco et al. 2014), has focused on understanding the damaging potential of hail on building systems, and specifically roofs. The program has combined laboratory experimental testing and field research to develop a new way to test the hail impact resistance of roof products, specifically asphalt shingles. The program has also delved into radar detection of hail, storm-scale environmental conditions that yield different hail material properties, and spatial coverage of hail swaths.

This paper describes the challenges with existing impact test methods for roofing products, the datasets necessary to create a new test method, and provides an overview of the new method.

2. EXISTING IMPACT TEST METHODS

Roofing products have varying resistances to hail, based on the material properties and the hailstone characteristics. There are impact resistant roofing products available to consumers in the marketplace, which are marketed to perform better in hailstorms. These products are rated according to standard test methods, most notably UL 2218 (2012) or FM 4473 (2005) for steep-slope roof products.

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These test standards assume that damage states will scale perfectly with impact kinetic energy. The test methods match the theoretical impact kinetic energy of projectiles to that which similarly-sized hailstones would have when falling at theoretical terminal velocities (assuming a spherical hailstone), and hailstone density equal to that of pure ice at 0.9 g cm^{-3}. All of which were based on the work of Laurie (1960). The UL 2218 test method utilizes steel balls of given mass and diameter dropped from specific heights to achieve the theoretical kinetic energy. The FM 4473 method utilizes pure water ice spheres propelled at velocities above the theoretical speeds given by Laurie (1960) as a factor of safety.

However, post-event assessments and closed claims studies have shown discrepancies between building product performance and laboratory test ratings. This may be due in part to the focus only on theoretical kinetic energy, and not the material properties of the projectiles, which subsequently influences the response of the hailstone and the material that it hits.

The UL 2218 method concentrates the damage area since the steel ball itself is too hard to respond and crushes the granules on the shingle surface (Figure 1), whereas natural hailstones are not hard enough to do that. The FM 4473 method creates more representative damage modes, but the severity is often too high (too damaging) for the representative hail size due to the higher mass and velocity assumptions that are too high.

Figure 1: The steel ball utilized in UL 2218 tests crushes granules on shingles.

Recent studies have highlighted challenges with the assumptions made in these methods, namely with density (mass), and shape and its effect on aerodynamic drag. An inaccurate assessment of drag will produce poor estimates of terminal velocity and the resulting impact energy (Heymsfield and Wright 2014; Heymsfield et al. 2014; Heymsfield et al. 2018). Additional knowledge gaps also existed regarding the material properties of natural hail (Kim and Kedward 2000; Schulson and Duval 2009; Swift 2013). Historical studies often qualitatively describe hailstones as: “hard”, “soft” or “slushy” with no quantitative means to describe them (Bilhelm and Relf, 1937; Carte 1966; Knight and Knight 1973). Knight *et al.* (2008) speculated that little property damage was likely associated with an observed hail event which produced “soft” hailstones of sizes larger than 4 cm, which is much larger than the 2.54 cm (1 inch) severe hail criteria. The hypothesis that the material properties affected impact mechanics and the resulting damage in real hail events lead to the development of the IBHS hail field research program.

Additionally, the existing test methods rely on human subjective judgement to determine whether the tested product meets a specific pass/fail criterion. Products that show evidence of a crack or tear fail the test, but human visual interpretation can be variable among investigators, and even for individual impacts for a single investigator. An objective-based method for determining product performance is sorely needed.

3. IBHS FIELD RESEARCH ON HAILSTONE CHARACTERISTICS

In 2012, the Insurance Institute for Business & Home Safety (IBHS) launched a comprehensive field research program to measure hailstone material properties. Data have primarily been collected for Great Plains supercell thunderstorms. The initial years of the program (2012-2016) focused on producing a large database of physical measurements (mass, dimensions, compressive strength) of hail at the ground (Giammanco et al. 2015). The latter years of the program (2015-2018) have turned towards in situ measurements to examine storm-scale variability (i.e. swaths, size distributions) and collecting 3D laser scans of hailstones to produce digital models for various analyses (Giammanco et al. 2017).

The database of hailstone physical measurements includes more than 3800 hailstones from over 60 parent thunderstorms with

- diameter measured by calipers for two or three dimensions
- mass measured by a scale
- compressive strength measured by the IBHS field measurement device (Giammanco et al. 2015)
- photographs of each hailstone

These data have been directly used in recent studies to provide updated and improved understanding of hail kinetic energy (Heymsfield and Wright 2014; Heymsfield et al. 2014). The data provided in Figure 2 have been directly used in the new IBHS hail impact test method. The data show the impact kinetic energy in the historical studies and existing test methods are too high, which provides some explanation as to why the damages imparted by the FM 4473 test method were too severe.

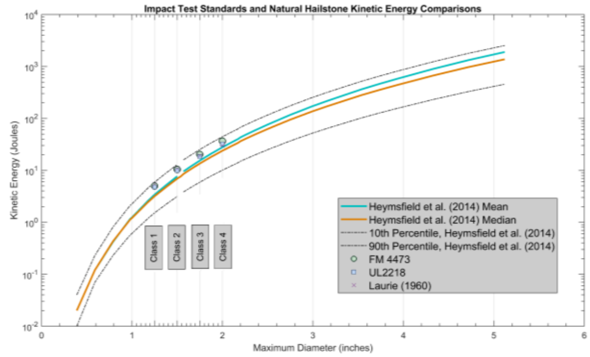

Figure 2: Updated impact kinetic energy data from Heymsfield et al. (2014), compared to the values used in existing impact test methods (FM 4473 and UL 2218) and in Laurie (1960).

The hailstone mass (Figure 3) and compressive strength (Figure 4) data have been used to provide a basis for laboratory production of ice spheres in the IBHS hail impact test method, to better mimic hailstone material properties. While IBHS has collected 3D scans and produced digital hail models to determine specific hailstone shapes (Giammanco et al. 2017), at this time the IBHS hail impact test method focuses on the propulsion of spheres. It may be possible to investigate the effects of different hailstones shapes in the future.

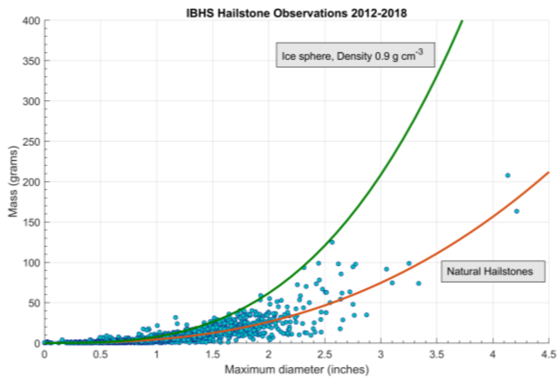

Figure 3: Distribution of the relationship between natural hailstone diameter and mass compared to a curve fit based on the density of pure ice.

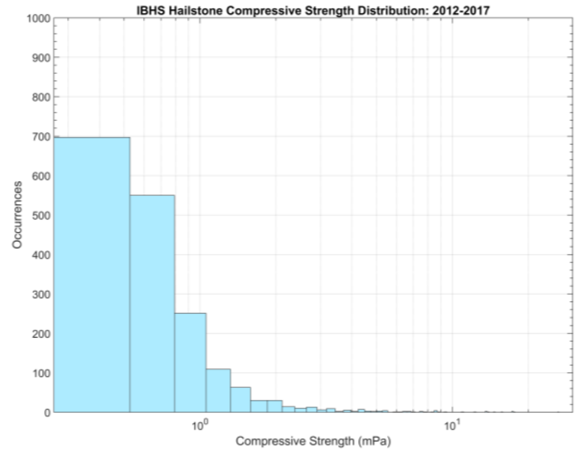

Figure 4: Distribution of compressive strength measurements of natural hailstones.

Data from the IBHS field research program are also being leveraged to understand performance of radar detection algorithms (Sorber et al. 2018; Giammanco et al. 2018; Jiang et al. 2018), and storm-scale environments which affect the hailstone material properties (Sirico et al. 2018).

4. IBHS IMPACT TEST METHOD

The IBHS impact test method is comprised of three main pieces, outlined in Figure 5. The hail characteristics based on IBHS field research provide the basis for laboratory production of ice spheres used for impact testing to drive the "impact mode". The impact configuration describes the construction and storage of test panels and provides requirements for impact locations on the test panels. The damage and functionality assessment provide a method for determining a performance "score" based on objective, quantitatively-assessed damage of several "damage modes" using image processing techniques.

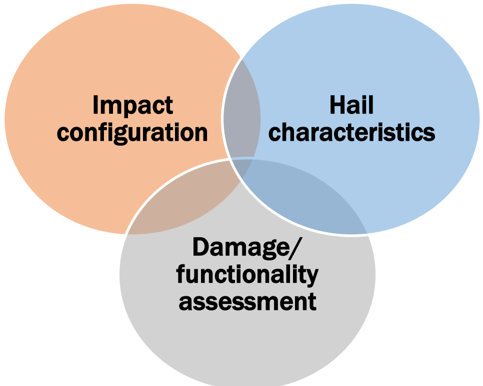

Figure 5: The primary components of the IBHS impact test method.

To systematically replicate the hailstone characteristics of mass, diameter, and strength, IBHS contracted Accudyne Systems to design and develop a custom machine to manufacture laboratory ice sphere for use in impact testing of building materials (U.S. Patent No. 20170122636). The machine can diffuse gas (typically CO_2) into water to adjust the density, and correspondingly, the mass of the ice produced. The ratio of gas to water, diffusion pressure, as well as the diffusion length, freeze/thaw times, and storage conditions allow for control of ice sphere strength. Several “recipes” or combinations of machine settings have been developed to replicate specific hailstone characteristics, which drives more accurate “impact mode” and “damage mode”

The IBHS operational test method, tests performance against laboratory hailstone spheres of 1.5 in. (2.54 cm) and 2.0 in. (5.08 cm) diameters, propelled at the appropriate speed to achieve the impact kinetic energy in Heymsfield et al. (2014). The impacts are conducted such that the ice sphere strikes the test panel at a perpendicular angle, which maximizes the momentum transfer between the two materials (ice and asphalt shingles).

There are three specific “impact modes” that were identified. Each correspond to specific behaviors of the ice spheres when they react with the shingle surface being tested. The material properties of the ice drive them, specifically the peak compressive force before the hailstone fractures and the uniaxial compressive stress (used by Giammanco et al. 2015 as a proxy for hardness). Ice spheres with a higher compressive stress (> 1.5 mPa) produce impact modes described as “hard bounce” or “hard shatter” (Figures 6 and 7) and are generally more likely to cause deformations in the shingle surface. Ice spheres with a relatively lower strength (< 0.8 mPa) produce impact modes described as “soft” (Figure 8) and are generally more likely to cause loss of the granule surface of the shingle. The impact modes are visually assessed by the test operator, where the “soft” mode leaves a slushy residue on the surface of the shingle after impact, whereas the “hard” modes do not (Figures 6-8).

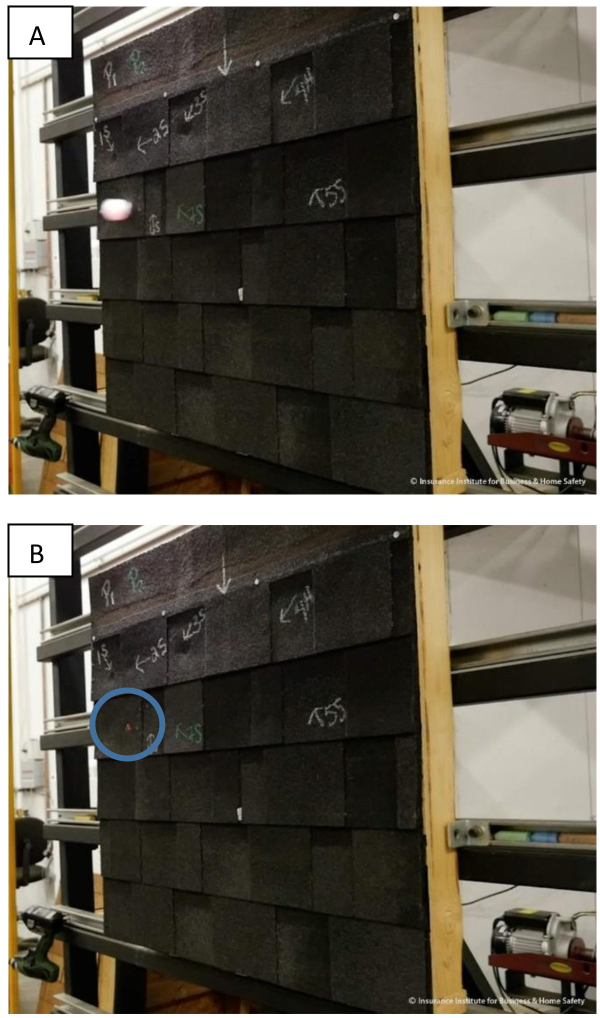

Figure 6: Hard bounce impact mode ice spheres will not break upon impact with the test sample, will bounce back as a single piece, and will not leave a slushy residue on the test panel.

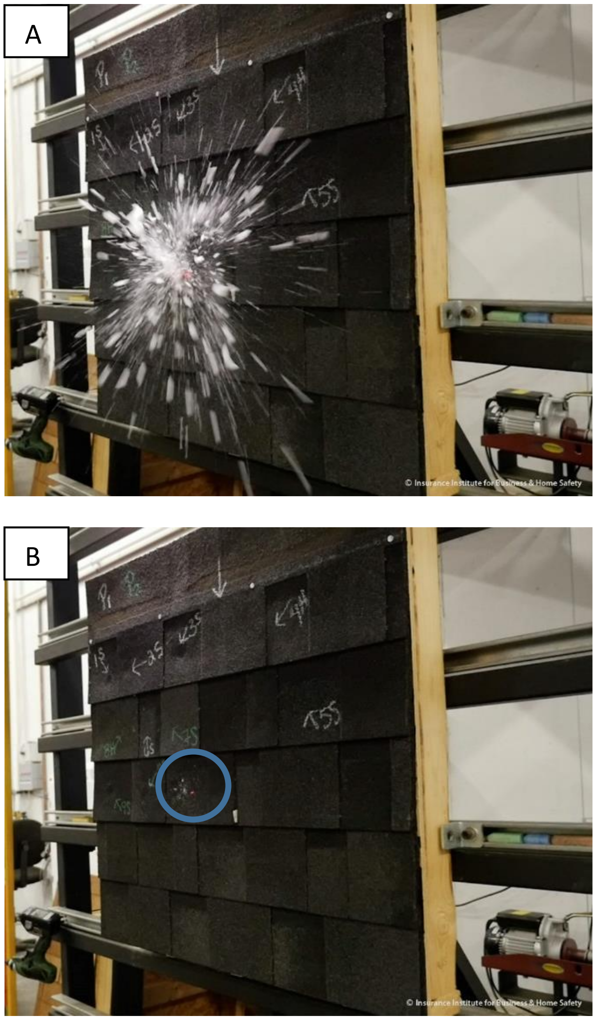

Figure 7: Hard shatter impact mode ice spheres will break into many fragments upon impact with the test sample and will not leave a slushy residue on the test panel.

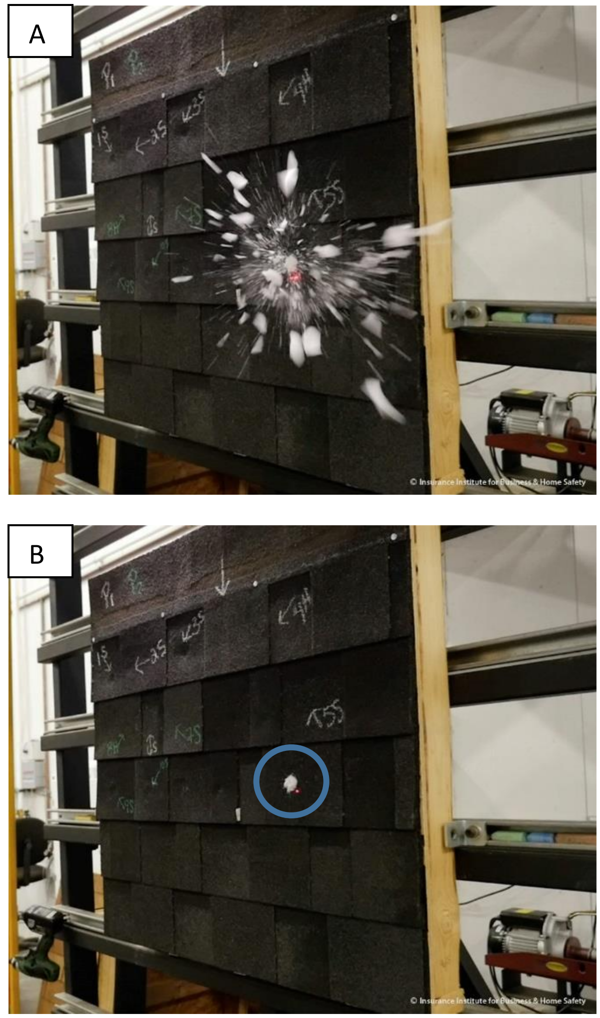

Figure 8: Soft impact mode ice spheres will break into many fragments upon impact with the test sample and will leave a slushy residue on the test panel.

The five damage modes assessed in the IBHS impact test method are illustrated in Figures 9-12. These represent the damages commonly seen in the field in real-world hail events. They are commonly thought to affect the functionality of the shingle, as well as its ability to withstand exposure to weather and climate factors for its full expected service life. A damage assessment tool using image processing algorithms to build a 3D digital model of the impact and quantify each of the five damage modes is currently being developed. The data outputs for each damage mode will be systematically combined to determine an overall performance score that allows for comparison of performance between products.

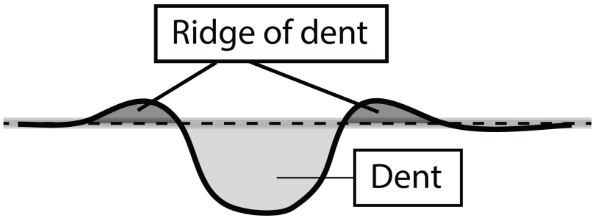

Figure 9: The negative local deformation caused by a "dent" and the positive local deformation caused along the "ridge of the dent". These 3D measurements are expressed as a volume.

Figure 10: Clusters of granules missing that result in exposed asphalt and/or fibers are known as "patch granule loss". These 2D measurements are expressed as an area.

Figure 11: Single or many granules missing that are not clustered and give a pitted appearance to the shingle surface are known as "individual granule loss". These 2D measurements are expressed as an area.

Figure 12: A tear, crack, or rupture is a 1D measurement expressed as a length.

5. SUMMARY

The hailstone characteristics data collected by IBHS during its annual field research program have been leveraged for numerous purposes, including the development of an improved laboratory test method for evaluating the hail resistance of asphalt shingle roof materials presented here. The field data have driven the ice sphere characteristics produced in the lab. The new test method better recreates the correct damage modes and severities compared to existing test methods, and utilizes an objective, quantitative-based approach to categorize damage, rather than a binary subjective based approach.

This methodology should ultimately result in improved differentiation in performance between shingle products and a better prediction of real-world performance. The results of an initial performance study will be publicly released in early 2019 to allow consumers and contractors transparency into resilient product choices, which should drive manufacturer improvements to provide better performing products.

6. FUTURE WORK

IBHS will continue its field research effort to increase data sample size of hailstone characteristics, particularly to gain more understanding into the influence of environmental characteristics that control hailstone mass/density and strength, as the laboratory testing has shown that these characteristics affect the damage mode and severity. Field research will also continue to provide more data to support research aimed at understanding and improving the performance of radar detection of hail.

In the laboratory, the newly-developed impact test method is focused on new asphalt shingles. In the future, naturally aged shingles will be tested, as well as other new roofing materials, such as metal, membranes or emerging technology materials. Additionally, the test method could be adapted to address non-roofing products such as siding, windows, and metal trim. The effects of different angles of impact and different hailstone shapes may also be investigated in the future.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Bilham, E. G., and E. F. Relf, 1937: The dynamics of large hailstones. *Quart. J. Roy. Meteor. Soc.*, **88**, 117-135.

Brown, T.M., I.M. Giammanco,and D.S. Robinett, 2012: Observations of hailstone characteristics utilizing a new instrumentation platform. *26th Conference on Severe Local Storms,* Nashville, TN.

Brown, T.M., I.M. Giammanco, M.R. Kumjian, 2014: IBHS Hail field research program: 2012-2014, *27th AMS Conference on Severe Local Storms*, Madison, WI.

Carte, A.E., and R.E. Kidder, 1966: Transvaal hailstones. *Quart. J. Roy. Meteor. Soc*., **92**, 382-391.

Changnon, S.A., D. Changnon, and S.D. Hilberg, 2009: Hailstorms across the nation: An atlas about hail and its damages. Illinois State Water Survey Contract Report 2009-12, 78 pp.

FM Approvals, 2005: Specification test standard for impact resistance testing of rigid roofing materials by impacting with freezer ice balls (FM 4473), West Glocester, RI, FM Approvals, 8 pp.

Giammanco, I.M., T.M. Brown, M.R. Kumjian, A.J. Heymsfield, 2014: Observations of Hailstone Sizes and Shapes from the IBHS Hail Measurement Program. *27th Conference on Severe Local Storms,* Madison, WI.

Giammanco, I.M., T.M. Brown, R.G. Grant, D.L. Dewey, J.D. Hodel, R.A. Stumpf, 2015: Evaluating the hardness characteristics of hail through compressive strength measurements. *J. Atmos. Tech.,* **32**, 2100-2113.

Gunturi, P. and M.K. Tippett, 2017: Managing severe thunderstorm risk: Impact of ENSO on US tornado and hail frequencies, *Tech Rep*., WillisRe, Minneapolis, Minnesota.

Heymsfield, A. J., and R. Wright, 2014: Graupel and hail terminal velocities: Does a "Supercritical" Reynolds Number apply?, *J. Atmos. Sci.*, **71**, 3392–3403.

Heymsfield, A. J., I. M. Giammanco, and R. Wright, 2014: Terminal velocities and kinetic energies of natural hailstones. *Geophysical Research Letters*, **41**, 8666-8672.

Heymsfield, A.J., M. Szakall, A. Jost, I.M. Giammanco, R. Wright, 2018: A comprehensive observational study of graupel hail terminal velocity, mass flux, and kinetic energy. *J. Atmos. Sci.,* **75,** 3861-3885**.**

Jiang, Z., M.R. Kumjian, R.S. Schrom, I.M. Giammanco, H.E. Estes, R. Maiden, A.J. Heymsfield, 2018: Hailstone S-band radar signatures and comparisons to spheroids, *29th AMS Conference on Severe Local Storms,* Stowe, VT.

Kim, H., and K.T. Kedward, 2000: Modeling hail ice impacts and predicting impact damage initiation in composite structures. *AIAA Journal,* **38**, 1278-1288.

Knight, C.A., and N.C. Knight, 1973: Quenched, spongy hail. *J. Atmos. Sci.,* **30**, 1665-1671.

Knight, C.A., P.T. Schlatter, and T.W. Schlatter, 2008: An unusual hailstorm on 24 June 2006 in Boulder, Colorado. Part II: Low-density growth of hail. *Mon. Wea. Rev.,* **136**, 2833-2848.

Laurie, J. A. P., 1960: Hail and its effects on buildings. Council for Scientific and Industrial Research, Report No. 176, Pretoria, South Africa, 12 pp.

Marshall, T.P., R.F. Herzog, S.J. Morrison, and S.R. Smith, 2002: Hail damage threshold sizes for common roofing materials. *21st AMS Conference on Severe Local Storms,* San Antonio, TX.

Schulson, E.M., and P. Duval, 2009: *Creep and Fracture of Ice.* Cambridge University Press. 416 pp.

Swift, J.M., 2013: Simulated hail ice mechanical properties and failure mechanisms at quasi-static strain rates. M.S. thesis, Department of Aeronautics and Astronautics, University of Washington, 71 pp.

Sirico, R., I.M. Giammanco, M.R. Kumjian, T.M. Brown-Giammanco, 2018: The influence of environmental variables on hailstone material properties, *29th AMS Conference on Severe Local Storms,* Stowe, VT.

Sorber, J., M.R. Kumjian, I.M. Giammanco, T.M. Brown-Giammanco, 2018: Comparison of impact disdrometer and surface hailstone measurements with dual-polarization Doppler radar-based hail swaths from the 29 May 2018 Erick, Oklahoma hailstorm, *29th AMS Conference on Severe Local Storms,* Stowe, VT.

Underwriters Laboratory, 2012: UL 2218: Standard for Impact Resistance of Prepared Roof Covering Materials, Northbrook, IL, Underwriters Laboratory, 17 pp.