DuraMAT
Durable Module Materials Consortium

# Hail impact damage on PV modules

Presented by:
**James Hartley, Sandia National Laboratories**
Team:
Jennifer Braid **(SNL)**; Colin Sillerud **(CFV Labs)**

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**SAND2023-14616O**

Energy Materials Network
U.S. Department of Energy

NREL

Sandia National Laboratories

BERKELEY LAB

CFV Labs

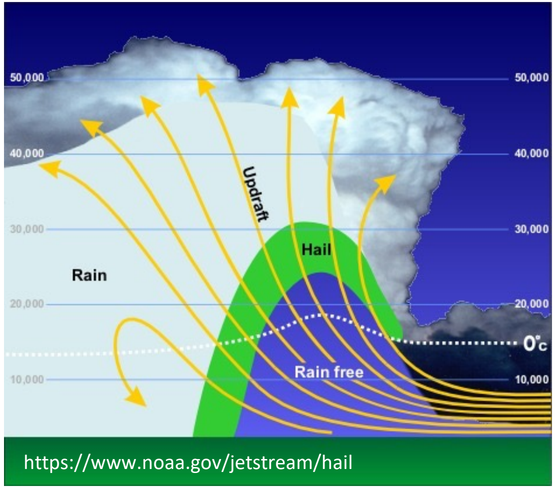
# Contents

- Introduction to the problem
- Current practices for testing modules vs. hail
  - Development and remaining limitations
- DuraMAT research: Simulating hail vs. PV module impacts
  - Ice ball and PV module models
  - Experimental validation efforts
- Various insights on hail vs. PV modules
  - Combined experimental and simulated analyses

# Introduction to the problem

- In general terms: Hail is solid precipitation which forms due to updrafts within clouds
  - Growth continues while updraft is able to sustain the mass
  - Begins to fall when mass becomes excessive or conditions shift
- May take on a wide array of shapes and sizes

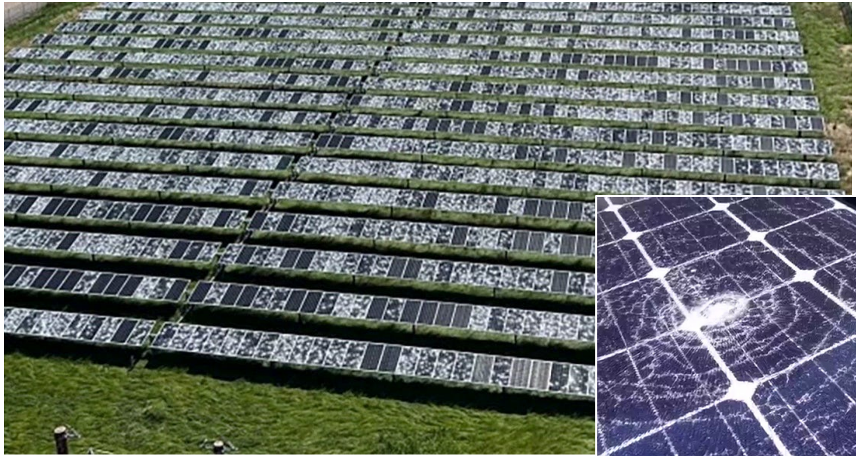
**Examples of natural hailstones**




**Weather conditions favoring hail formation**

# Introduction to the problem

- Hard ice balls + glass PV modules = bad (expensive) outcomes
  - Subcritical damage is also bad for long term performance



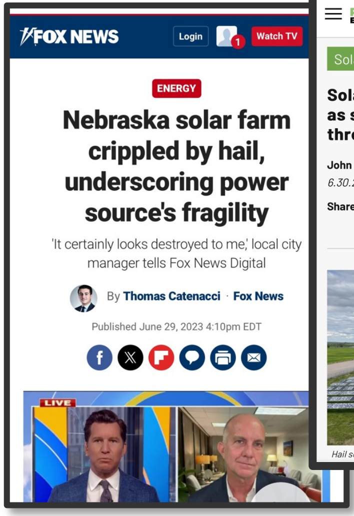
Renewable energy world

KVUE Texas

**Hail damage affects both residential and commercial deployments.**
**Apparently undamaged modules may degrade at higher rates**

# Introduction to the problem

- Nowhere is 100% safe, especially with increasing module life expectancies
- Even when hail does not happen: Insurance costs and reputation risk are damaging to PV adoption


FOX NEWS

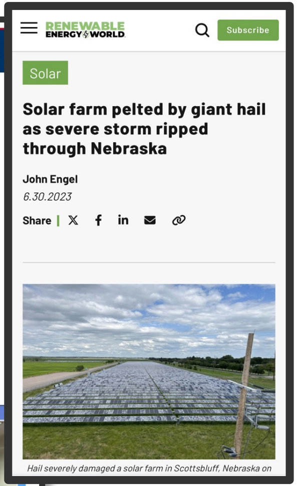
ENERGY

Nebraska solar farm crippled by hail, underscoring power source's fragility

'It certainly looks destroyed to me,' local city manager tells Fox News Digital

By Thomas Catenacci · Fox News

Published June 29, 2023 4:10pm EDT


RENEWABLE ENERGY WORLD

Solar

Solar farm pelted by giant hail as severe storm ripped through Nebraska

John Engel

6.30.2023

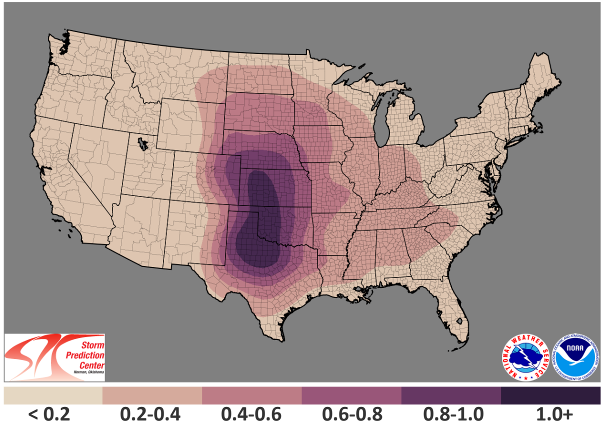
*Hail severely damaged a solar farm in Scottsbluff, Nebraska on*


KVUE

WEATHER

Hail damage causing headaches for solar customers, businesses

Hail the size of golf balls – and even baseballs, in some cases – rained down on solar panels on Sunday, leaving them cracked and shattered in multiple spots.




Mean days per year with a hail size greater than 2” (1986-2015)

**Understanding hail damage potential is crucial for informed decision making**

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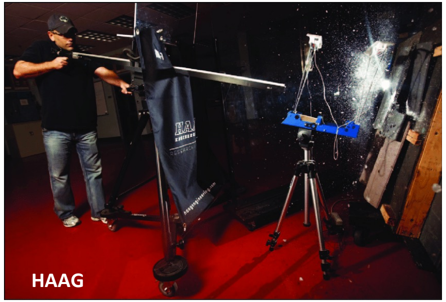
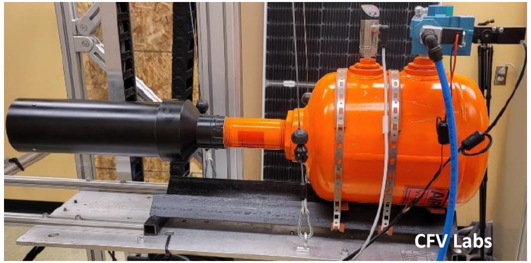
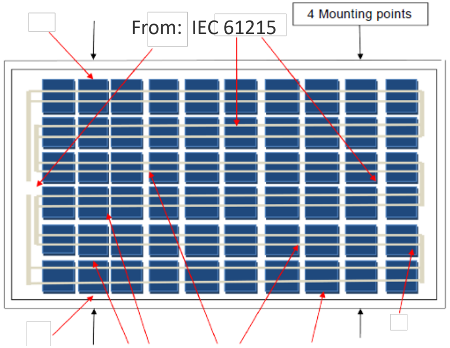
# Current practices for testing PV modules vs. hail

- Qualification tests attempt to replicate the impact event with ball drops (since deprecated) or projected ice balls (current practice)
  - Most prevalent is IEC 61215 (with various historical equivalents from ASTM, NIST, UL..)
- Tests specify a sequence of impacts at certain locations on the module, at increasing ice ball sizes until failure
- “Pass” certification is given at the largest size where the module survived the full sequence






**Various styles of ice ball launchers**

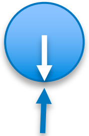



**Standard impact locations for testing**

# Current practices for testing PV modules vs. hail

- Tests are based on replicating the **kinetic energy** of falling hail at **terminal velocity**
  - At **terminal velocity**: Gravitational force matches aerodynamic drag force
  - **Kinetic energy**: Amount of energy associated with a moving mass and velocity

Gravitational force



$$F_g = mg$$

Drag force

$$F_D = \frac{1}{2}\rho U^2 C_D A$$

Kinetic Energy

$$E = \frac{1}{2}mU^2$$

| Variable | Definition | Value |
|---|---|---|
| $\rho$ | Density of air | 1.18 kg/m³, typical |
| $U$ | Velocity in air | 20-50 m/s |
| $C_D$ | Drag coefficient | ~0.5 for a sphere, typical |
| $A$ | Frontal area | $\pi r^2$, r is radius of ice ball |
| $g$ | Gravity constant | 9.81 m/s², for Earth |
| $m$ | Mass of ice ball | Ice volume times ice density |

| Diameter mm | Mass g | Test velocity m/s | Kinetic energy J |
|---|---|---|---|
| **25** | **7,53** | **23,0** | 2,0 |
| 30 | 14,0 | 25,1 | 4,1 |
| **35** | **20,7** | **27,2** | 7,7 |
| 40 | 32,3 | 29,0 | 12,9 |

**Most modules qualified here**

**Hail diameter and velocity parameters from IEC Module Qualification Test #17, Hail Test**

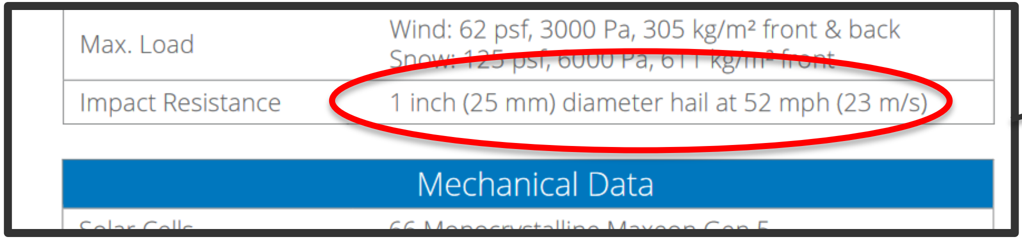
# Limitations of current test practices

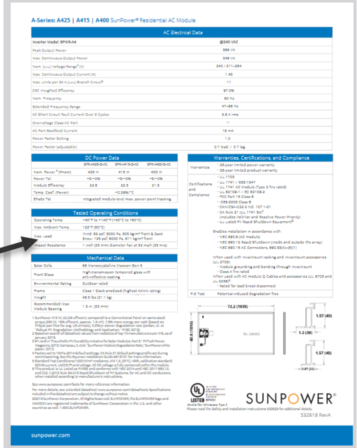
- Test ice balls are carefully controlled but are not real hail
  - As specified: Optically clear, free from cracks, spherical, prescribed velocity
  - Real hail: Extremely variable on density, drag coefficient (hence velocity)
  - Large emphasis on kinetic energy alone
    - Impact mechanics are a function of materials too


**A standard ice ball used for testing vs. natural hailstone examples**

# Limitations of current test practices

- Qualification tests produces very little differentiation between modules
  - Pass criteria based on major defects and safety only
    - No effective measure of margins
    - Some independent test labs have developed sequential sequences for impact + aging
      - PVEL: Hail Stress Sequence (HSS)
      - RETC: Hail Durability Test (HDT)
- Expensive and time consuming to perform tests




**A typical 25 mm hail certification as appearing on a module datasheet**

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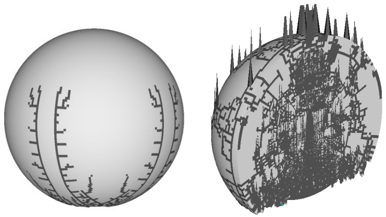
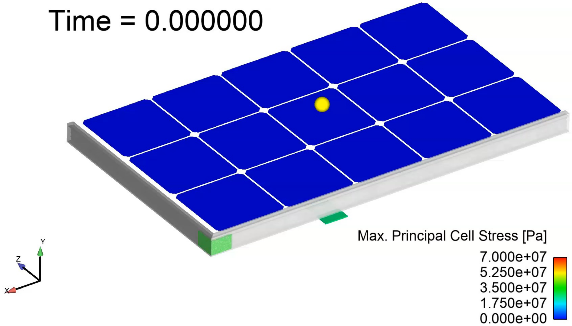
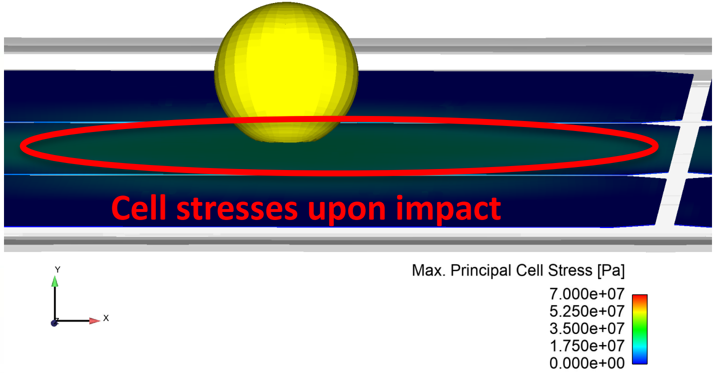
# Current research within DuraMAT: Analyzing Hail Impacts using Computational Simulation

- Simulating the hail impact event using finite element analysis methods allows it to be analyzed in full detail: glass or cell stresses as a function of module design, impact parameters, etc.
  - **Hail (ice) material model:** Exists in literature and previously implemented at Sandia
  - **Module model:** Previously developed under DuraMAT 1 projects





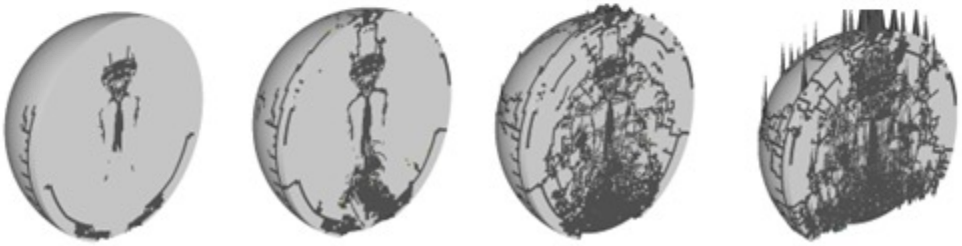




**Hail vs. PV module simulations allow the full impact sequence to be analyzed in detail**

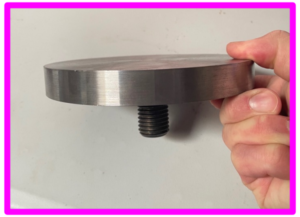

C.I. Hammetter, R.L. Jones, H.L. Stauffacher, T.F. Schoenherr, "Measurement and modeling of supersonic hailstone impacts", International Journal of Impact Engineering, Volume 99, 2017, Pages 48-57, ISSN 0734-743X, https://doi.org/10.1016/j.ijimpeng.2016.09.001

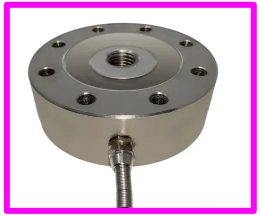
# Validating the hail ice material model

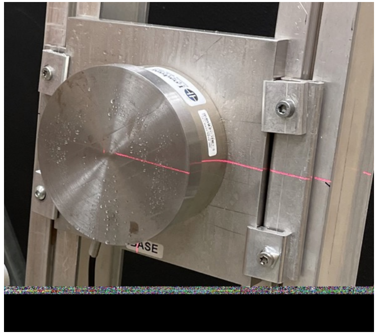
- Simulated ice ball must deliver the correct force vs. time profile to the module
- To validate: measure an impact and compare to simulated expectation
  - High frequency (50 kHz) load cell for direct measurement of impact forces vs. time



**Simulated ice material failure progression during an impact**



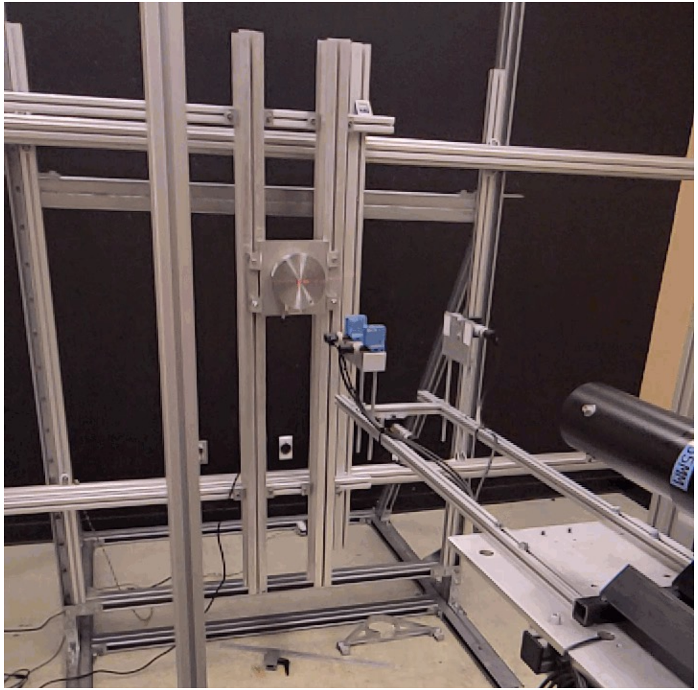




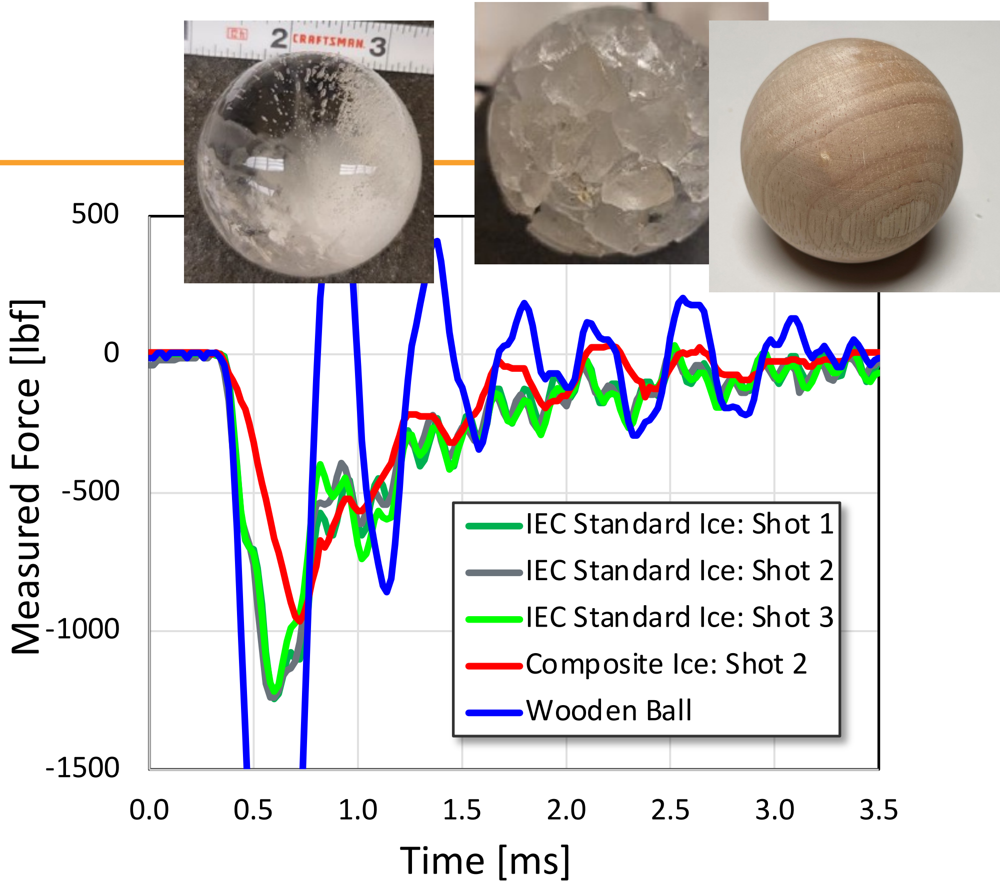

Hammetter CI, et al. (2016) Measurement and modeling of supersonic hailstone impacts, Int J of Impact Eng 99:48-57

Tippmann JD, Kim H, Rhymer JD (2013) Experimentally validated strain rate dependent material model for spherical ice impact simulation. Int J Impact Eng 57:43–54

# Example force vs. time profile



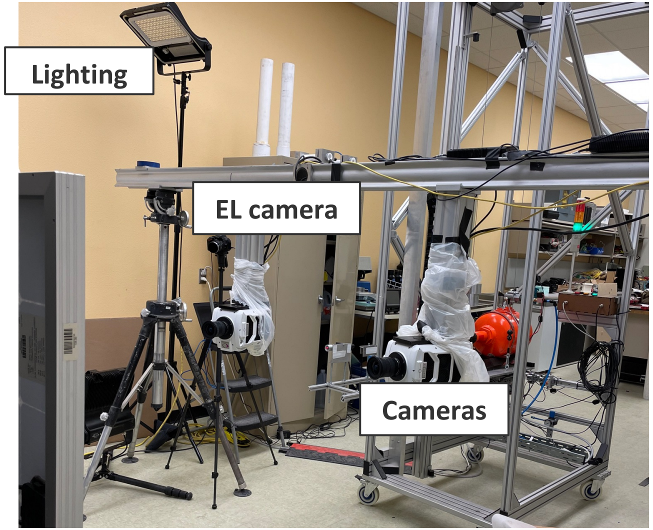
A 65 mm IEC standard ice ball



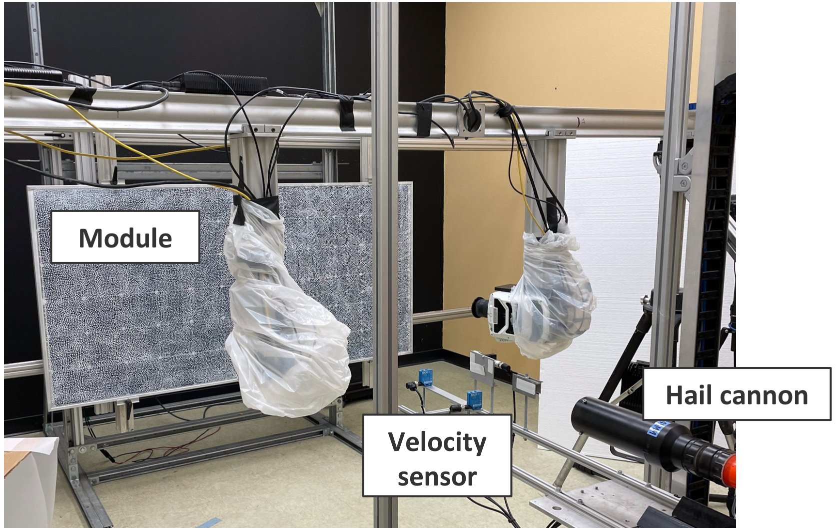

Measured force vs. time profile

# Validating the simulation: Module dynamic response

- Stereo high speed video of a hail impact was recorded for analysis with digital image correlation (DIC) to process module deflections vs. time
- Matching dynamic response to simulations provides confidence in model applicability



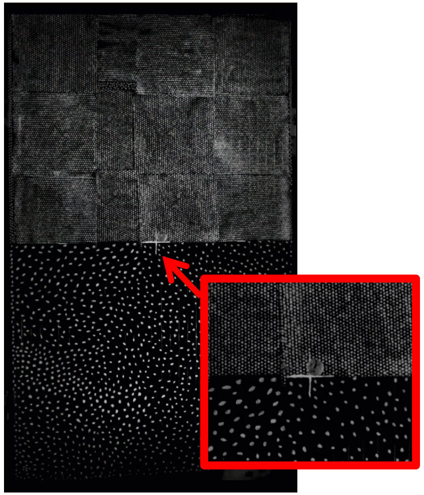

Test setup: Module view



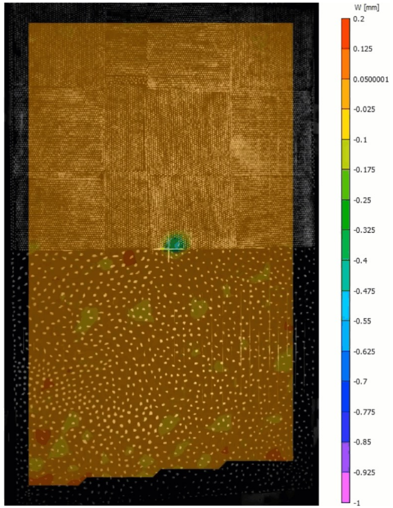

Test setup: Cannon view

# Module dynamic response comparisons

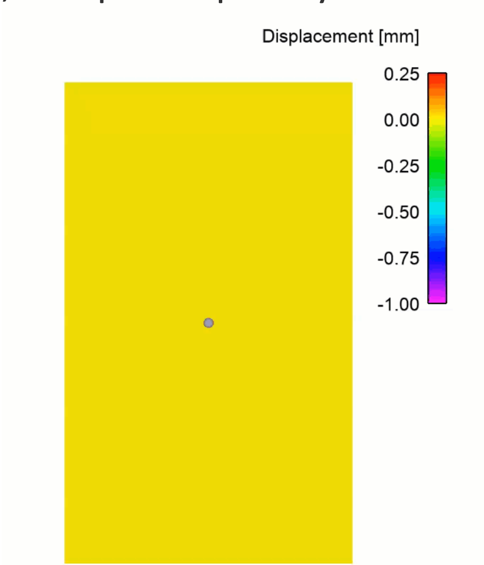
- Experimental technique has been verified to be applicable to most modules
- Measurement resolution of <0.1 mm spatially, 100 µs temporally



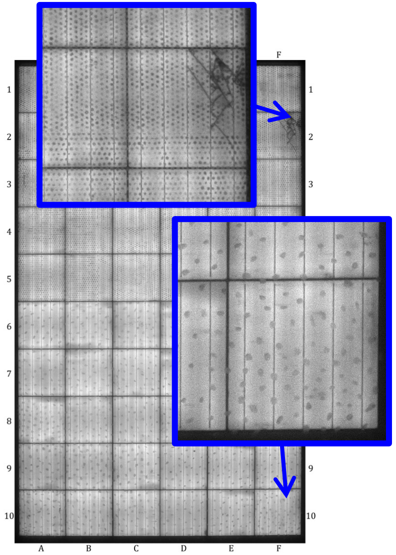
**Visual video of hail impact**




**Video processed for displacements**




**Simulated impact event showing displacements**

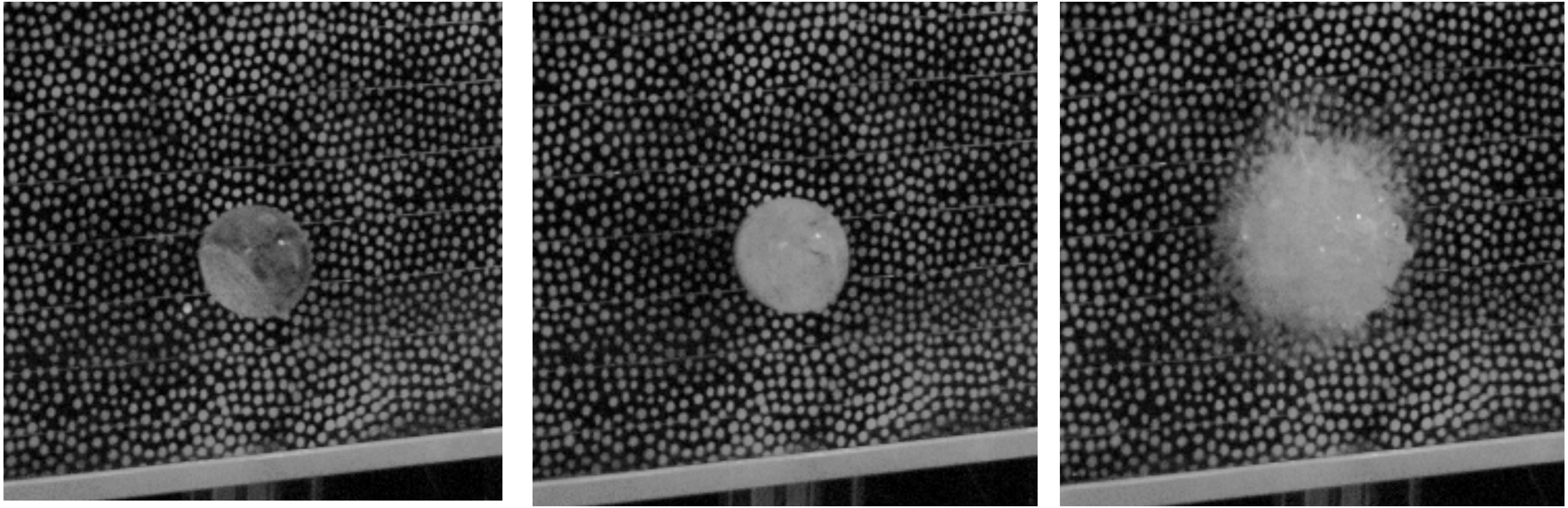


**EL images able to show cracks under DIC patterning**

# Contents

# Mechanics of an ice ball vs. PV module impact

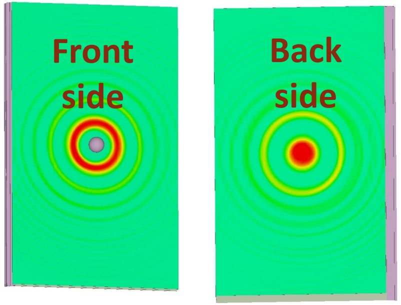
- Initial contact ($t = 0$) to 100 μs: Ice ball shatters



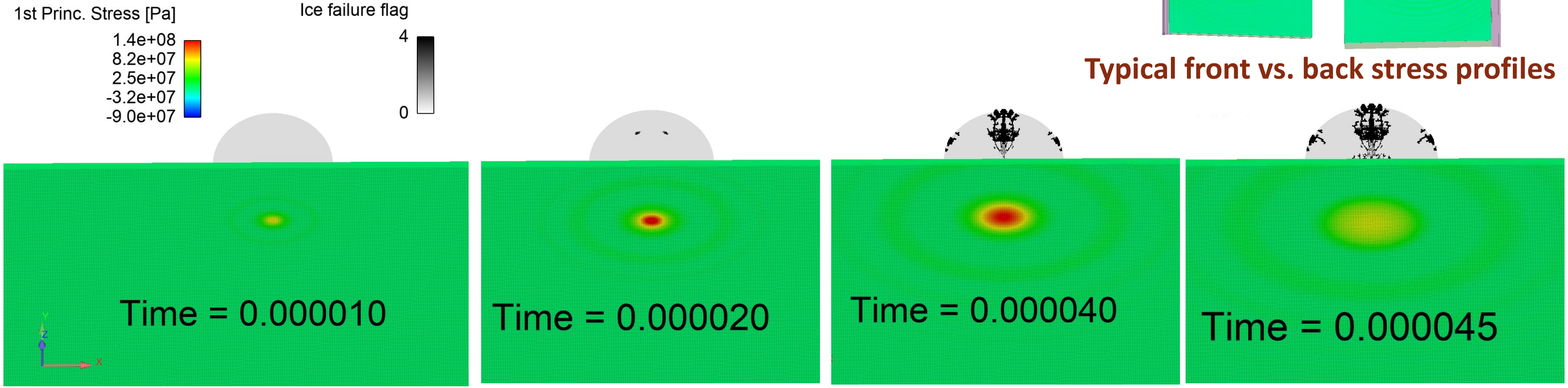
**Video frames showing ice ball initial contact and shattering. Frame rate: 11,000 Hz**

# Mechanics of an ice ball vs. PV module impact

- ~40 to ~300 μs: Stress in backside of glass reaches maximum
  - Timing and magnitude are sensitive to modeled ice behavior
  - Dissipation is extremely rapid once maximum is reached
  - Local spot of tensile stress on glass backside, ring on front side



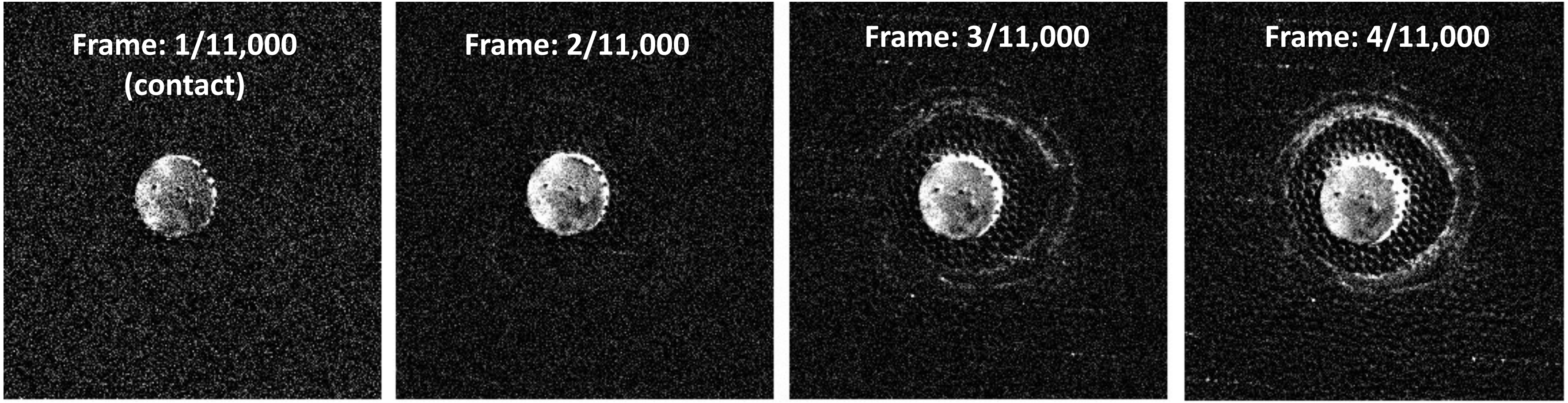

**Typical front vs. back stress profiles**




**Simulations of glass backside stress immediately after ice ball contact**

# Mechanics of an ice ball vs. PV module impact

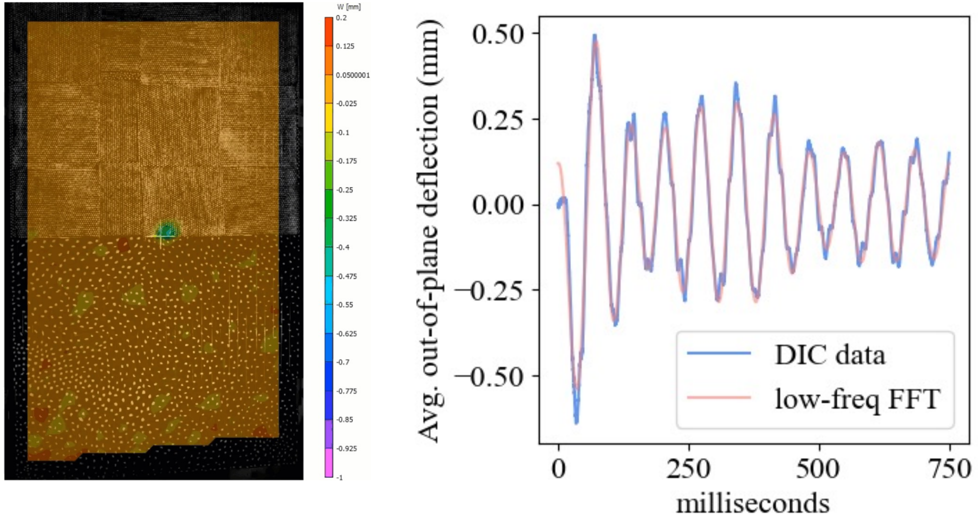
- ~100-300 µs: Glass failure initiates (when present)
  - Of interest for further study- current frame rate and visibility near ball are less definitive




**Sequential video frame image differences showing appearance of glass fracture by +300 µs**

# Mechanics of an ice ball vs. PV module impact

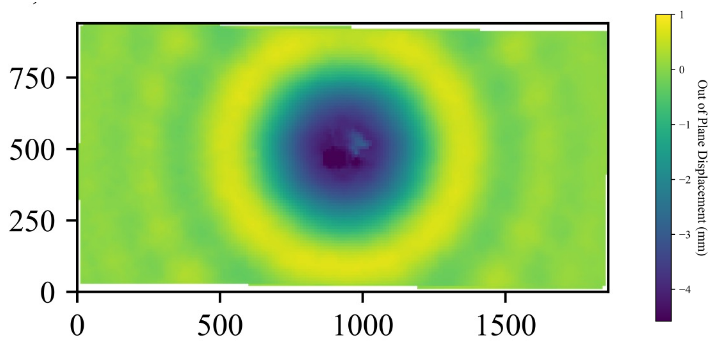
- 300 μs to 2 seconds: Module oscillates and returns to resting state
  - Key frequencies are identifiable, ~11.5 Hz and 14.4 Hz for a 60-cell module



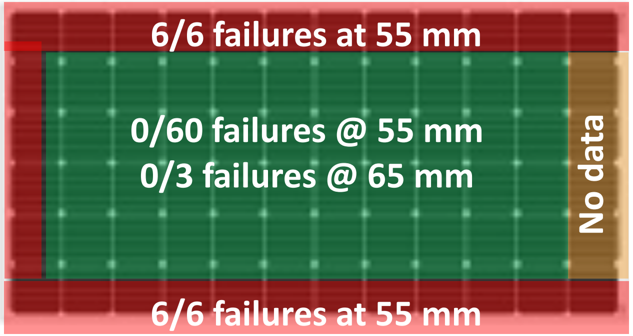

**Deformations vs. time on a 60 cell module, visualized and processed by average out of plane movement**

# Modules are much tougher than their qualification level implies (for isolated impacts)

- Most modules will survive 55 mm standardized ice impacts at normal incidence over homogeneous glass area
- Lower qualification levels of ~35 mm are due to failures from specific locations
  - Junction boxes and edges are special vulnerabilities



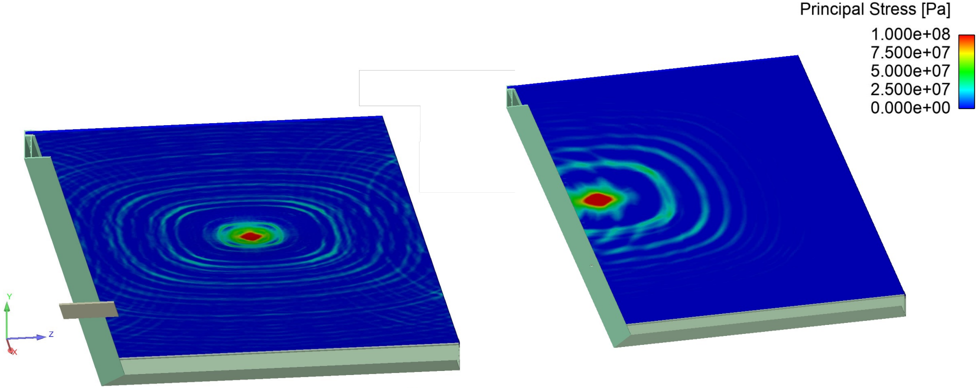

**Deformation profile for a 55 mm ice impact after 3 ms**



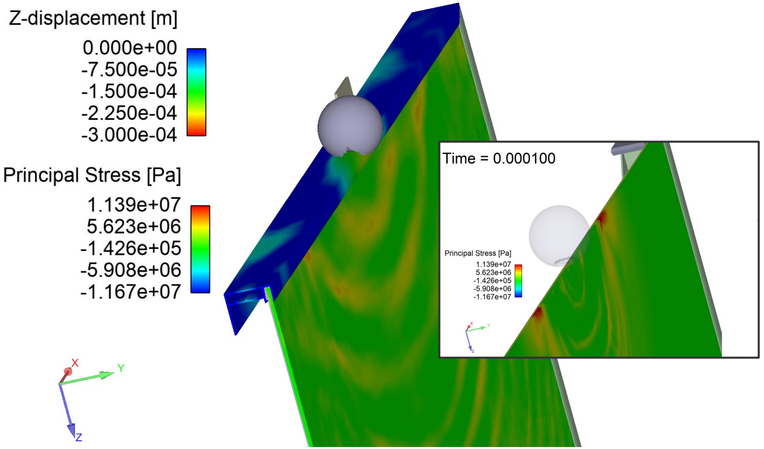

**Test results on module face from ice ball testing (glass-backsheet shown)**

# Why do frame-adjacent impacts carry a higher failure probability?

- Stresses within the glass are similar for frame adjacent vs. center area impacts
  - Mechanism appears to be crack initiation from the weaker glass edge, not necessarily an increase in stress due to the applied constraint



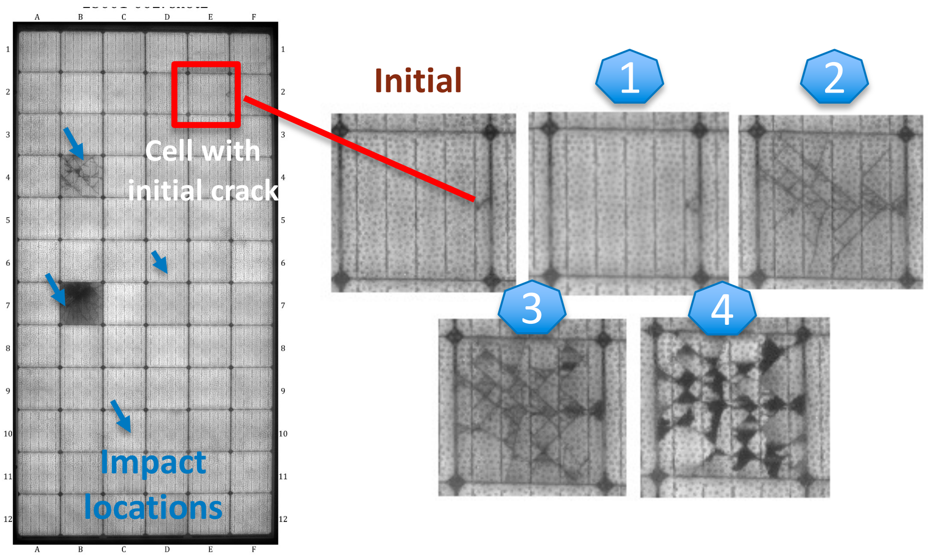

**Frame adjacent vs. center impacts show similar apparent stress**




**Direct frame hits (e.g. during high angle hail stow) don't appear especially concerning**

# Cell cracks are VERY readily propagated by impacts…

- If an initial cell crack was present at all in the module, propagation occurred with EVERY subsequent impact




**Sequential crack propagation at a cell away from actual impacts**

# Cell cracks are VERY readily propagated by impacts…

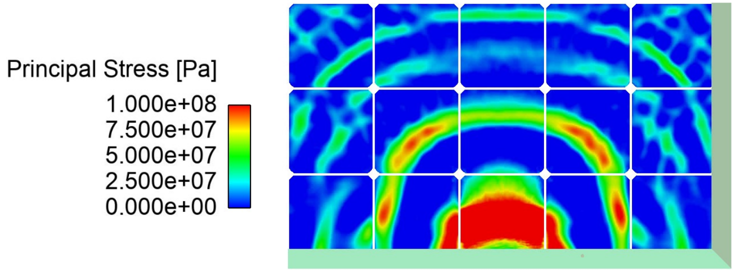

**Post-impact stress profiles places sufficient stress on remote cells to open cracks**

# … but cell cracks are not particularly easy to initiate with impact

- For **both** glass-glass and glass-backsheet packaging: Cell cracks were seldom achievable without also breaking the glass
  - Glass and cell failure thresholds overlap
  - Initial cell and lamination quality appears to be more influential than packaging type
  - Modeled cell stresses are not obviously over established crack criteria

| BOM | Modules | Total Shots | [New] Cell crack observations | Glass failure observations |
|---|---|---|---|---|
| Glass-Glass | 8 | 72 | 8 | 8 |
| Glass-Backsheet | 8 | 97 | 6 | 7 |

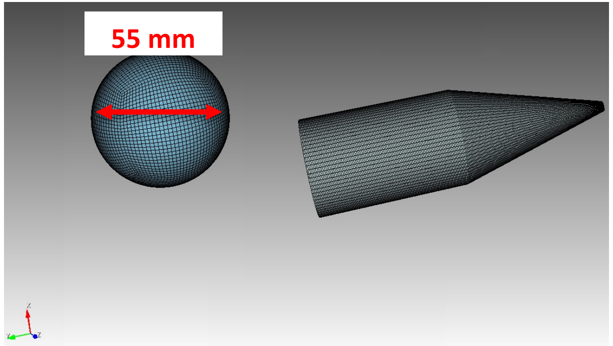
**Results of a hail test suite of 150+ impacts**



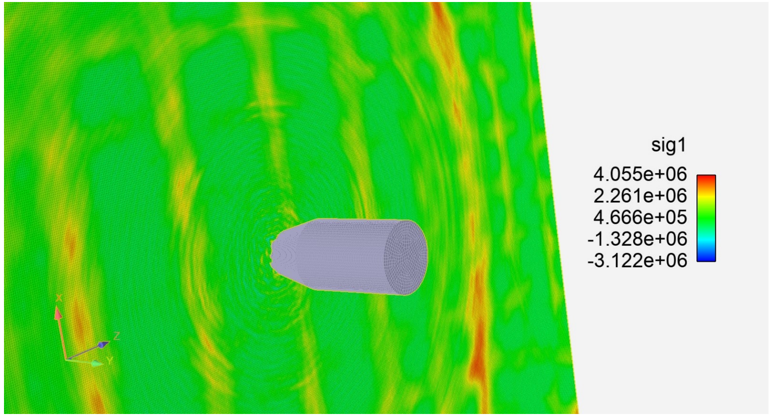

**Simulated cell stresses during a probable glass failure are near cracking threshold**

# Ice shape has a secondary effect on damage potential

- Hail ice often assumes unusual shapes including sharp points
- Is a point-first impact significantly more damaging?
  - Ice material strength appears insufficient to create major stress concentrations




**Approximating a worst-case ice shape. Energy parameters are 55 mm spherical equivalent**




**Stress profile induced by a worst-case pointed ice ball is not significantly worse than a spherical case**

# Summary

- Hail vs. PV modules is an active area of research- much is known but much more to understand
- Computational simulations can add data to augment field observations and explain phenomena
  - Many additional cases may be simulated, to best understand trends and mechanisms
- **By fully understanding the problem, optimal decisions can be made around module deployment, design, and insurance**

# Questions or comments?

**James Y. Hartley**
Sandia National Laboratories
jkyuan@sandia.gov

**Jen Braid**
Sandia National Laboratories
jlbraid@sandia.gov

**Colin Sillerud**
CFV Labs
colin.sillerud@cfvlabs.com

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