PV Module Arc Fault Modeling and Analysis

Presented to the NREL PV Module Reliability Workshop

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Microsystems & Engineering Sciences Applications (MESA)

Sandia National Laboratories

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Module Failure Analysis

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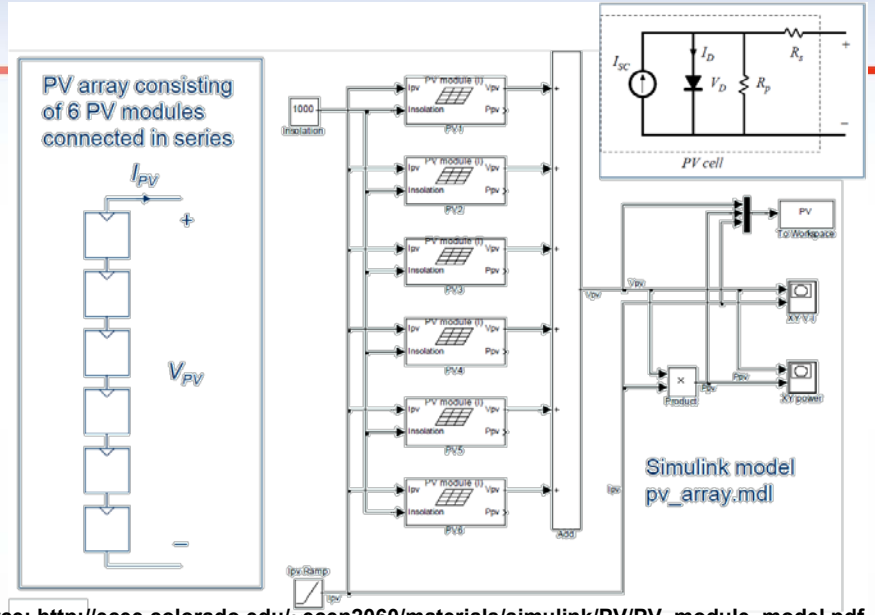
This presentation will help to answer the question of the potential for electrical arcing in the ubiquitous module busbar solder joint failures, as well as provide insights into the time domain of these failures and material effects.

Topics:

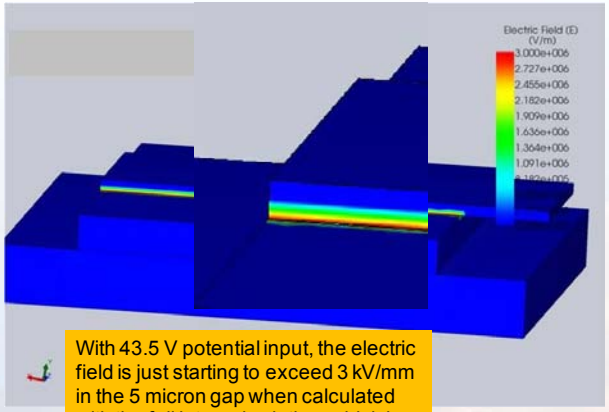
- Background and testing
- Description of observed failures
- Description of model and assumptions
- Model of electrical conditions to cause arc
- Analysis of glass breakage conditions
- Analysis of busbar connector ribbon deformation
- Conclusions

Arc Fault Modeling

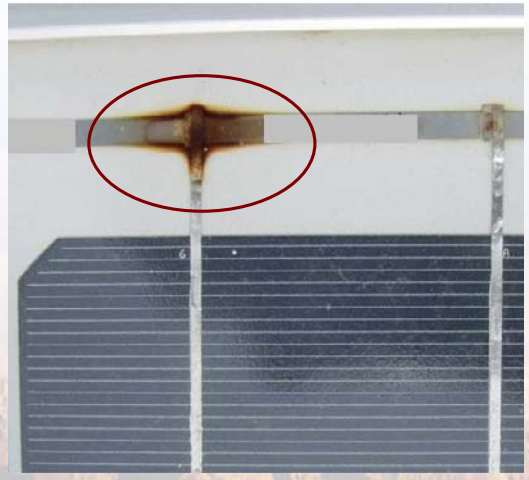
- **Frequency modeling**
  - Development of cell, module, and array models for AC studies
  - Studies investigate attenuation effects of PV components
- **Electrical modeling**
  - Simulation of current, voltage, and resistance changes preceding and for the duration of the arcing event

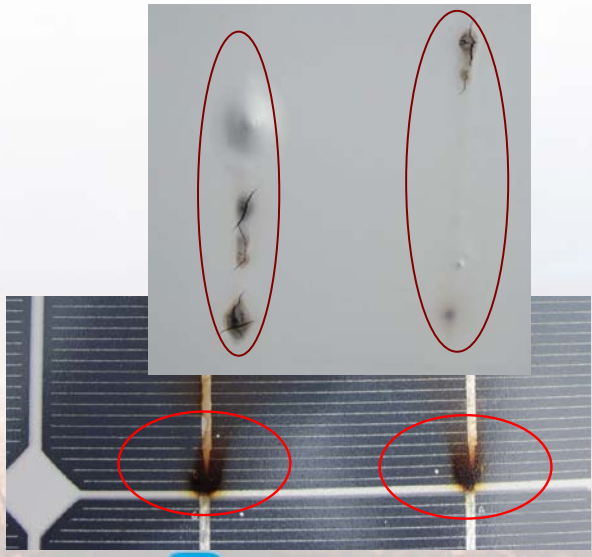


Source: http://ecee.colorado.edu/~ecen2060/materials/simulink/PV/PV_module_model.pdf



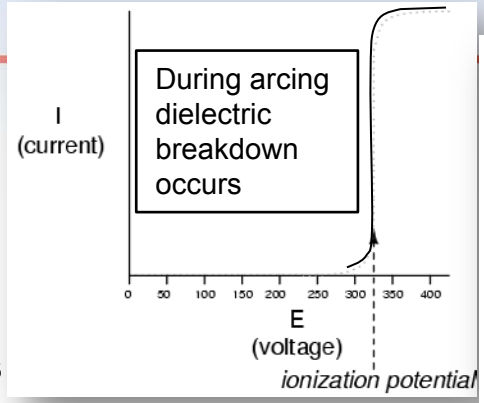
With 43.5 V potential input, the electric field is just starting to exceed 3 kV/mm in the 5 micron gap when calculated with the full integral solution, which is lower than the linear $\frac{43.5\text{V}}{5\text{micron}} = 8.7\frac{\text{kV}}{\text{mm}}$

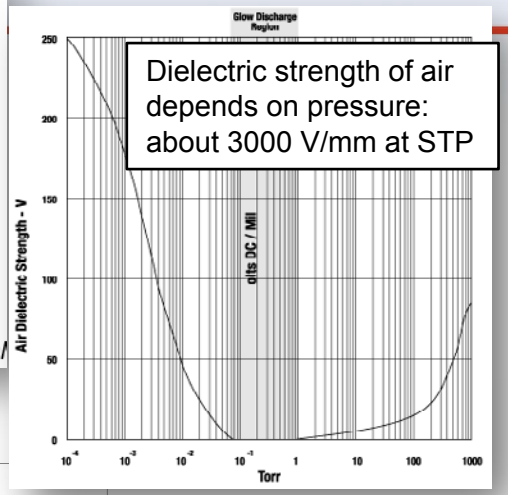


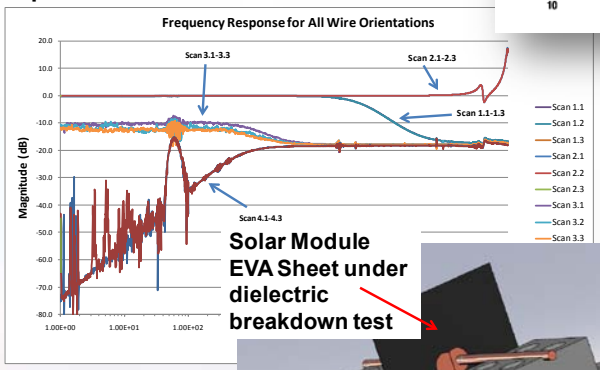


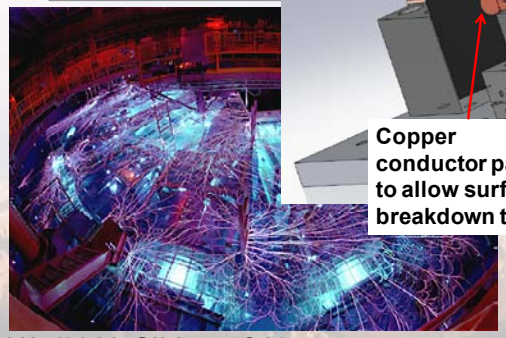
Arc Fault Testing

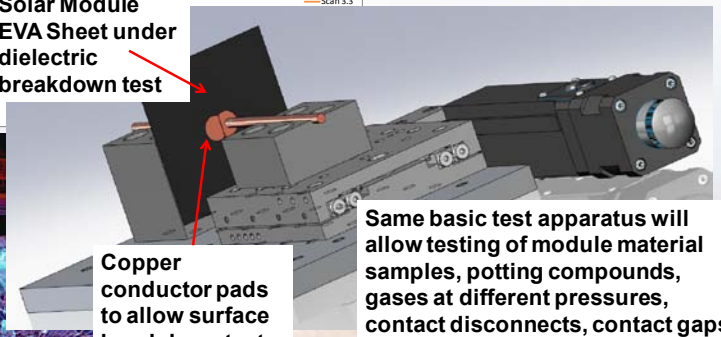
- **Testing includes**
  - Conditions that allow arcing
    - Materials for dielectric strength
    - Geometry
    - Voltages/potentials, boundary conditions
  - Introduction of simulated arcs into PV systems
    - Measure electrical frequencies present during arcing events
  - Filtering created by PV modules and other components
- **Testing facilities**
  - Manufacturers' laboratories
  - Standard developers' labs
  - National labs
- **Sandia National Laboratories facilities:**
  - PSEL: Photovoltaic Systems Evaluation Lab
    - Tests for module and cell manufacturers
  - Pulsed Power, Z machine
    - The big 'daddy' of man made arc generators
    - Understanding of the physics of arcs
  - DETL: Distributed Energy Testing Lab











Solar Module EVA Sheet under dielectric breakdown test

Copper conductor pads to allow surface breakdown test

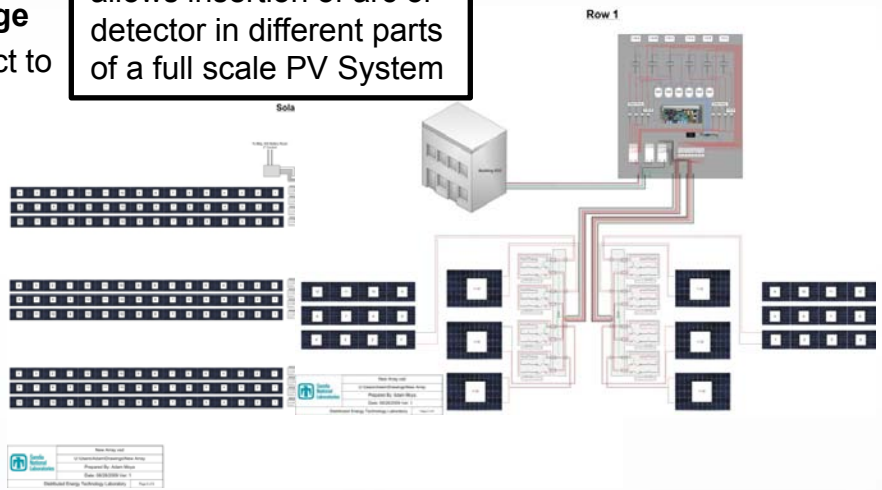
Same basic test apparatus will allow testing of module material samples, potting compounds, gases at different pressures, contact disconnects, contact gaps, parallel path arcs and be used with the solar simulator and in the field hooked up to various locations.

Arc Fault Testing, Sandia DETL Facility

Distributed Energy Testing Lab, DETL:

- **Many combinations of grid tied generation, loads and storage**
  - Inverter, AFCI and component manufacturers able to connect to PV arrays at any number of insertion points
- **Advanced R&D**
  - System level performance and reliability testing
  - Component interoperability testing
- **Advanced Power Electronics Components and Systems**
  - Solar Energy Grid Integration Systems (SEGIS)
  - Controllers for distributed grid equipment based on new and existing standards
  - Advances in inverter design, integration and manufacturing through partnerships with Industry
  - Long-term inverter performance characterizations
- **Technology Solutions for Communications and Security**
  - Secure Supervisory Control and Data Acquisition (SCADA) applications
  - Technology development and applications capable of supporting multiple communications protocols
- **Solar Standards and Codes**
  - Development of new procedures for performance and reliability testing
  - Assuring accountability, applicability and metrics of new standards development

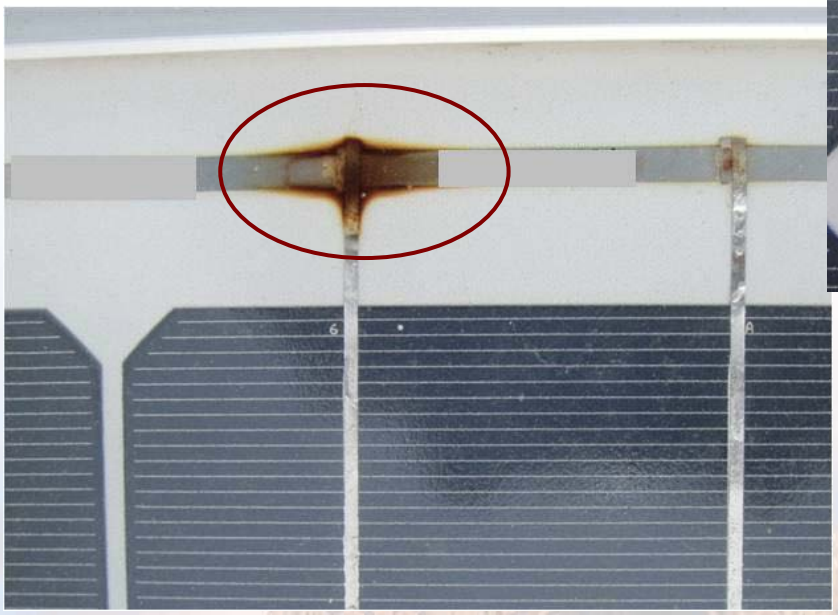
Sandia DETL Facility allows insertion of arc or detector in different parts of a full scale PV System

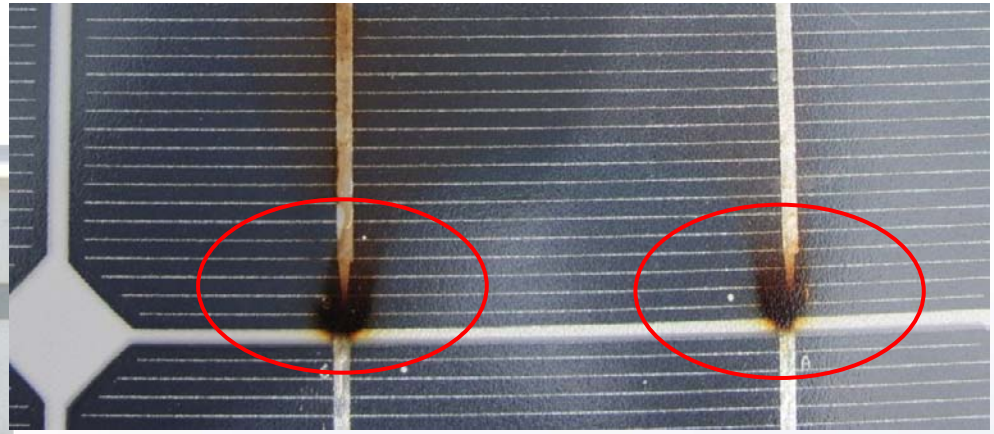


Module Failures and Discussion

- **Three primary failures can be seen:**
  1. Busbar discoloration, most common, seen in multiple locations and modules. Also busbar shifting and bending.
  2. Collector ribbon discoloration at location ribbon goes from cell back contact to front grid, also common
  3. Discoloration in the middle of the topside grid collector ribbon
- **All 3 of these failure modes have charring, burning and backsheet bubbling on the backside of the modules.**
- **The busbar discoloration appears to be linked to the front side glass fracture in one case**

Busbar discoloration shown below. Collector ribbons appear to be shifted to the right and the solder joint between the ribbons and busbar appears to be broken.





Discolored collector ribbon as they pass from the top of the PV cells to the backside contact.

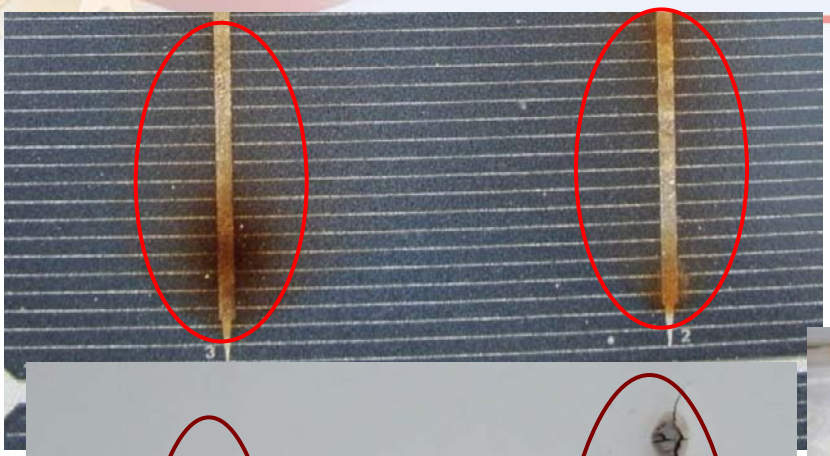
Some of the melting, boiling and maximum use temperatures of module materials are shown below.

$Tmelt_{Si} := 1687K$ $Tboil_{Si} := 3538K$ $Tmax_{Tedlar} := 200\,°C$

$Tmelt_{Cu} := 1358K$ $Tboil_{Cu} := 2835K$

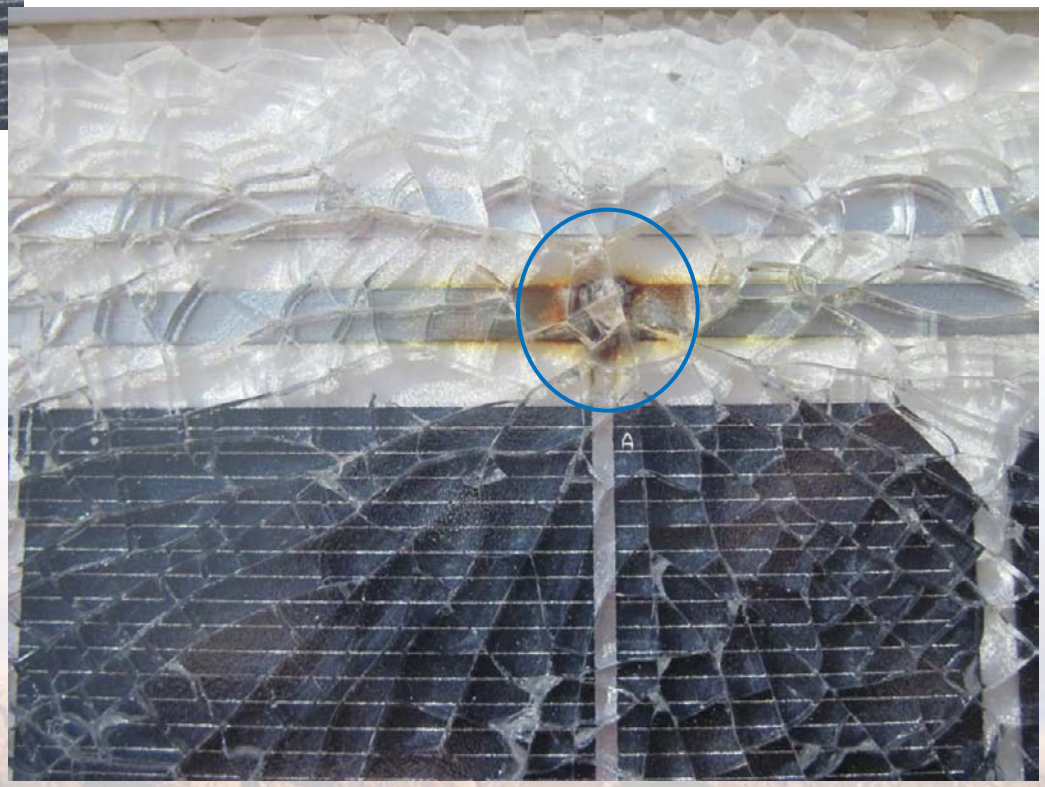
$Tmelt_{Sn} := 505K$ $Tboil_{Sn} := 2875K$

Module Failure Types and Discussion



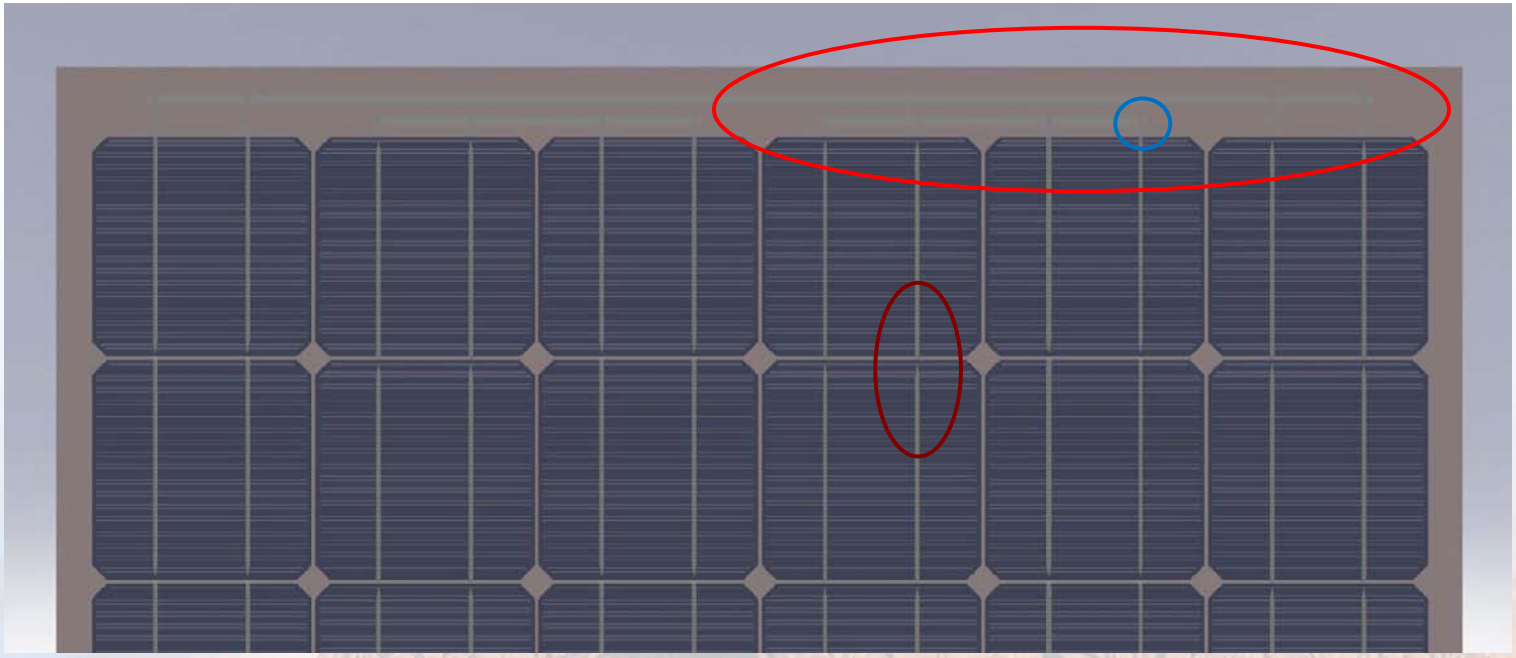
3. Discoloration in the middle of the topside grid collector ribbon

- **All 3 of these failure modes have charring, burning and backsheet bubbling on the backside of the modules.**
- **The busbar discoloration appears to be linked to the front side glass fracture in one case**
  - Note radial fracture pattern in glass, centered at busbar color



Description of model and assumptions

- **Complete module model developed:**
  - Full size with accurate geometry and materials, *except* tin plating on busbars and connector ribbons and backside contact aluminum, both of which are single micron thickness range
- **Small sections of the module model analyzed for arc generated thermal and thermo-mechanical effects**
- **Small sections of the module are analyzed for other effects.**
- **Due to the high temperature of an arc, published at minimum levels around 6000C, other heat transfer mechanisms are all neglected.**
- **Arc area of just 0.38 mm^2 at 6000K is modeled to determine if it could have resulted in glass breakage due to thermal expansion stress.**



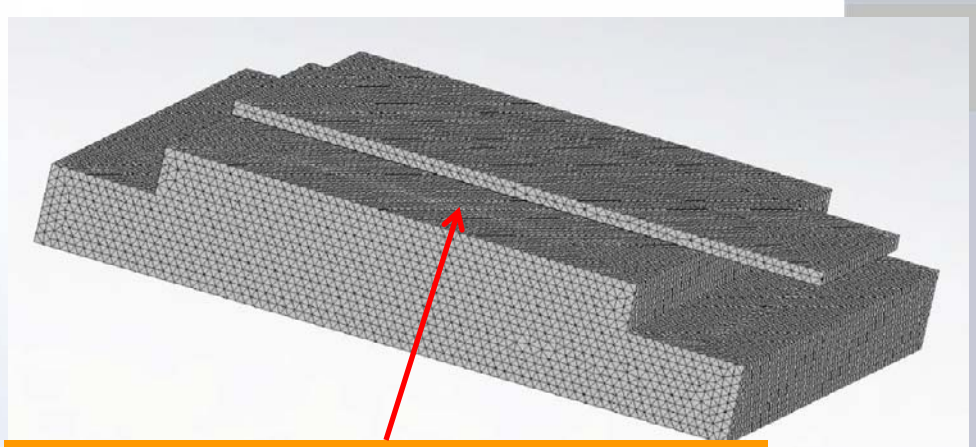
Module

- **72 125 mm cells**
- **160 W, 4.9 A Isc, 43.5 Voc**
- **54 50 x 250 micron grid lines per cell**
- **Two 2.54 mm x 150 micron collector grids per cell**
- **Large end busbars are 5.08 mm x 200 micron**
- **Areas analyzed**

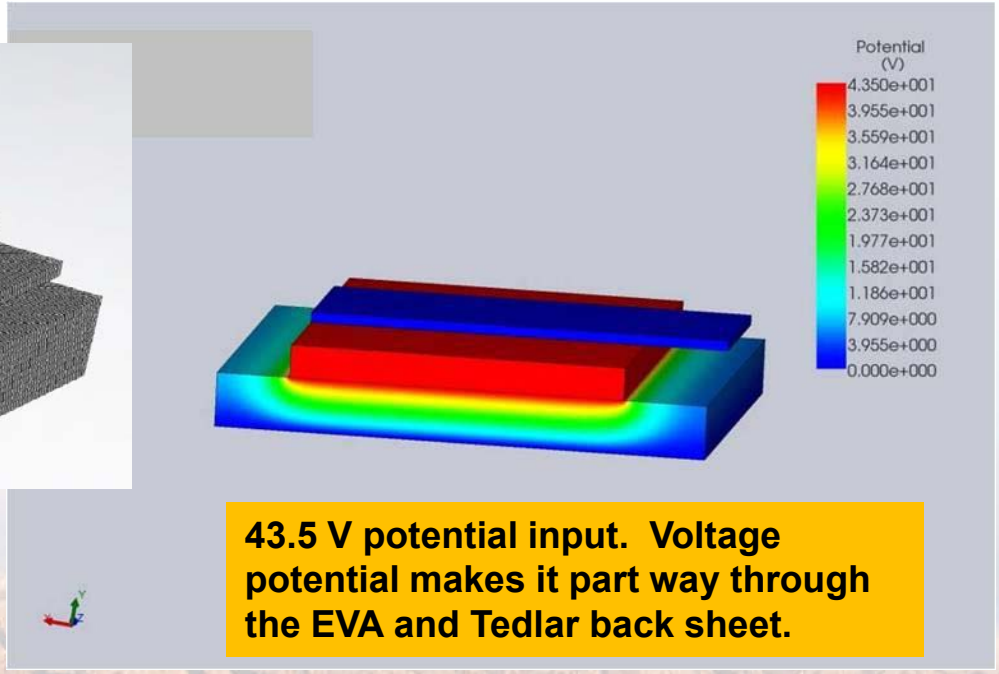
1. **Glass Break above Busbar**
2. **Busbar shifting**
3. **Ribbon between bottom and top of cells**

Electrical conditions to cause arc in busbar failures

- **To investigate the likelihood of an arc occurring at the junction between the collector bus and busbar, an electrical dielectric breakdown and discharge study was performed.**
  - Domain was reduced to 6.5 mm wide by 7.5 mm tall, and the non-electrical components, such as the top glass were removed. Air assumed to be in electrode gap.
  - A 5 micron gap was introduced between the two electrical contacts, which have an area of 2.54 mm x 5.08 mm = 12.9 mm^2 , and the potential of all the cells in the string, 43.5 V, was used to see if breakdown would occur.

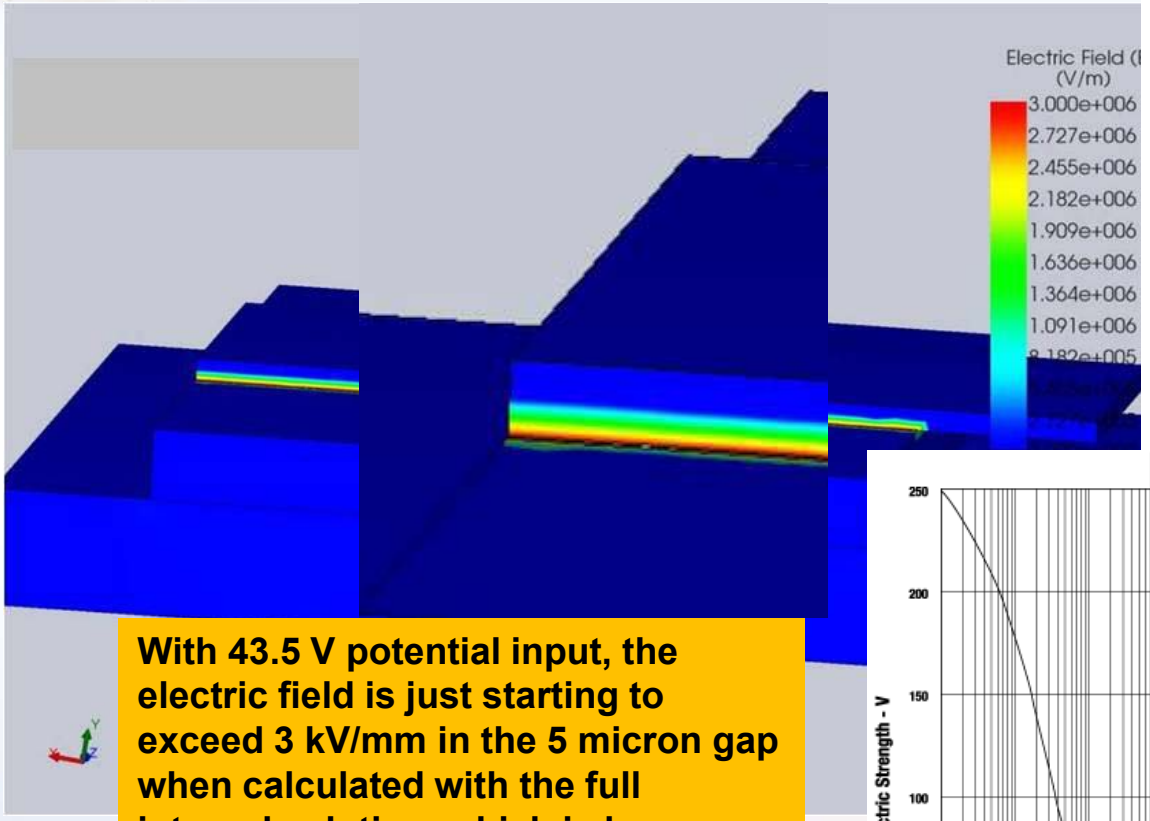


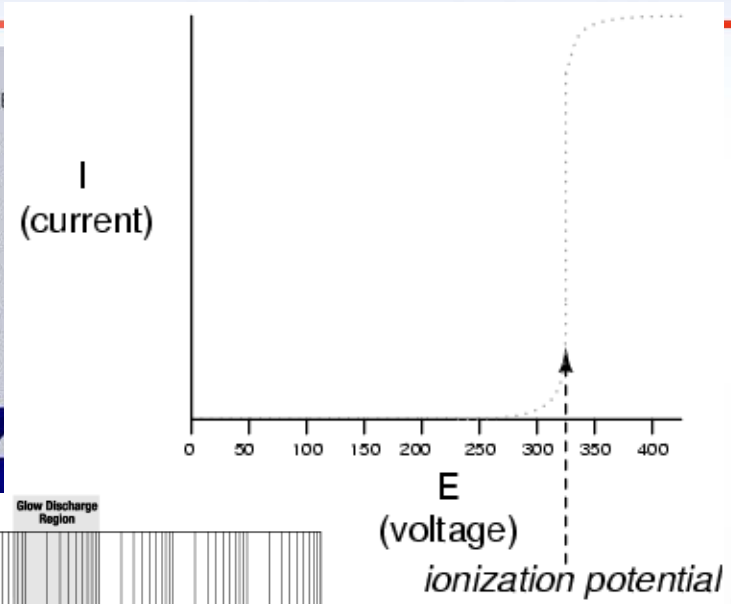
Greatly reduced domain for electrical discharge study. Mesh accounts for 5 micron air gap between parts.

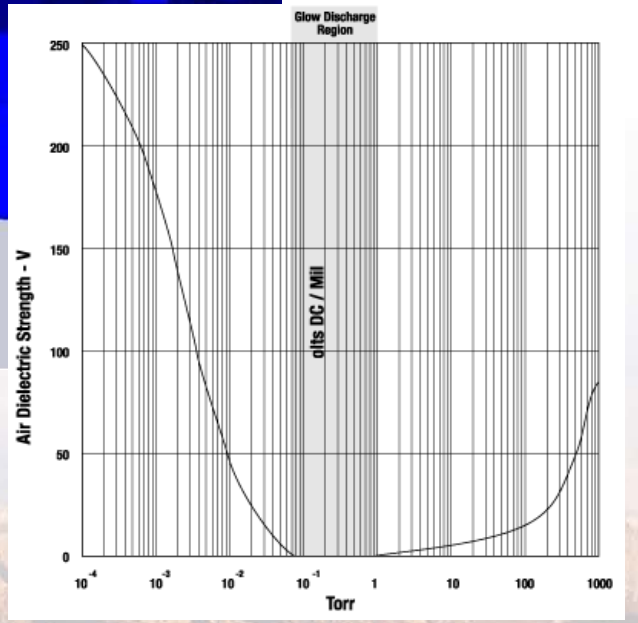


43.5 V potential input. Voltage potential makes it part way through the EVA and Tedlar back sheet.

Electrical conditions to cause arc in busbar failures, results







With 43.5 V potential input, the electric field is just starting to exceed 3 kV/mm in the 5 micron gap when calculated with the full integral solution, which is lower than the linear

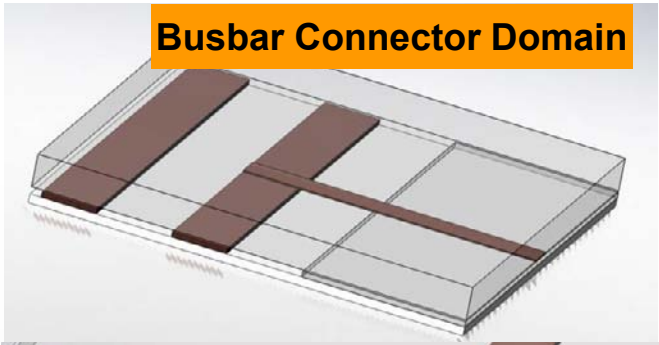
$$\frac{43.5\text{V}}{5\text{micron}} = 8.7\frac{\text{kV}}{\text{mm}}$$

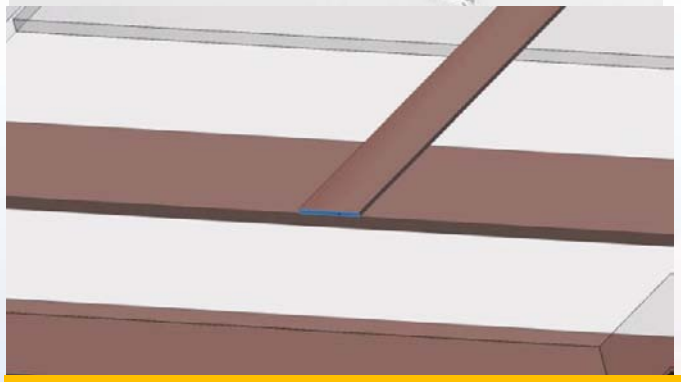
At 1 atm pressure, air dielectric strength is about 3 kV/mm, or 75 V/mil. Above this electrical potential, the air stops acting like a perfect insulator, and conducts very well.

Temperature and Time to Fracture Front Glass

- To investigate the glass fracture, a small 40 mm by 40 mm domain, including the module stack and collector grid to busbar interface was analyzed, as shown in the graphic: 6000K applied along end of grid.

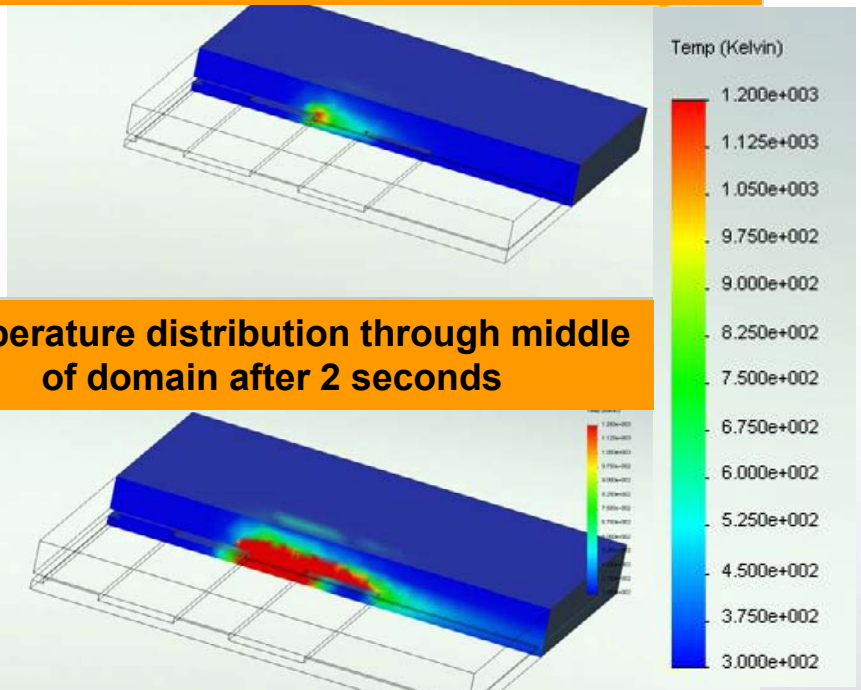
Busbar Connector Domain





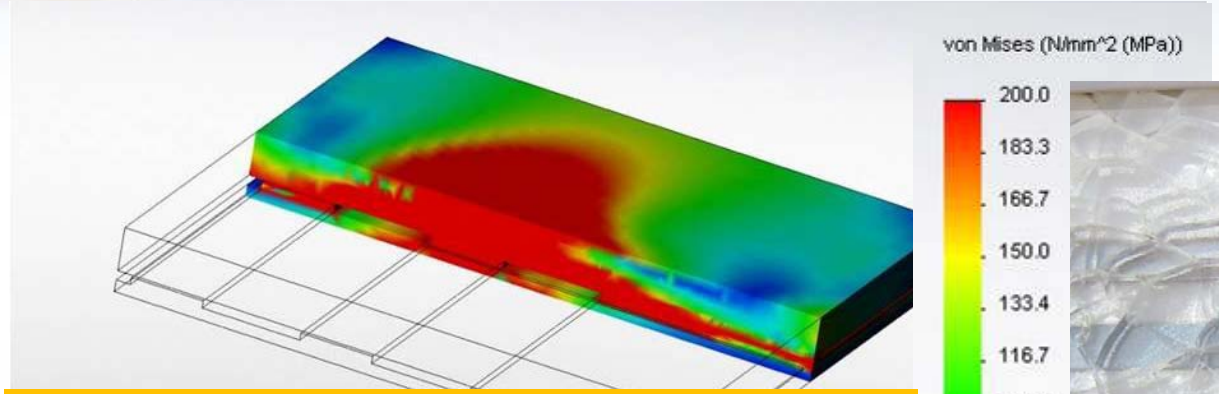
Busbar Connector Detail showing 0.381 mm^2 Arc Fault Initiation Area in blue

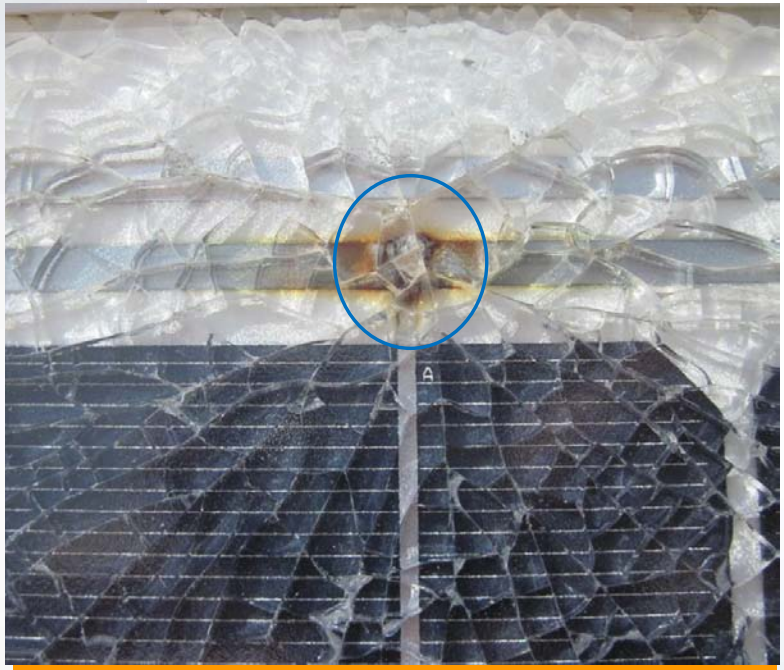
Temperature distribution through middle of domain after just 0.2 seconds



Temperature distribution through middle of domain after 2 seconds

Temperature and Time to Fracture Front Glass, cont.





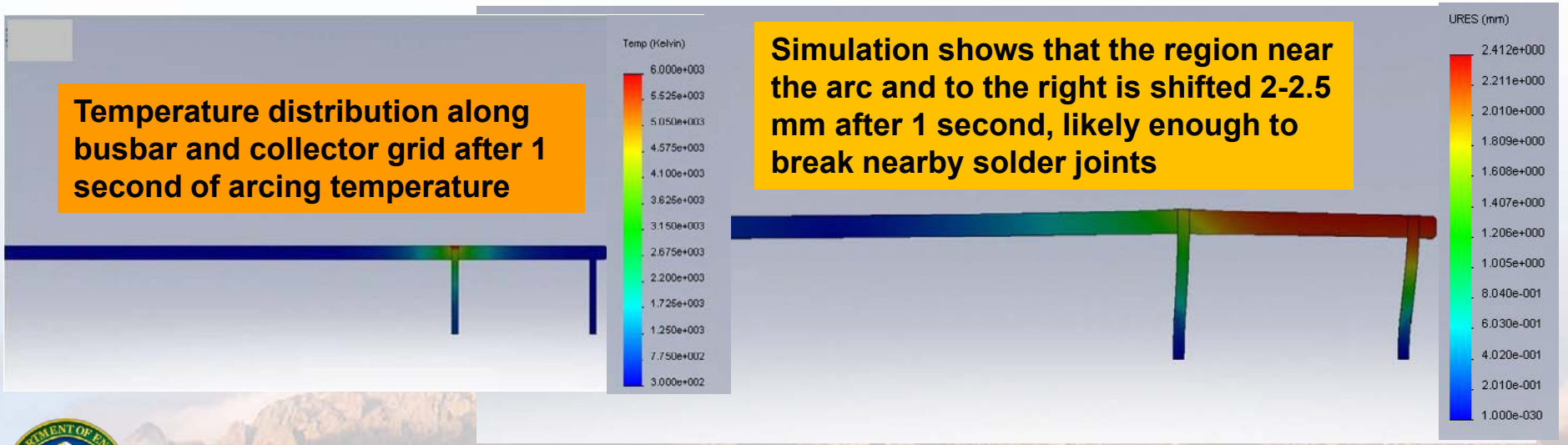
State of thermal expansion stress after 2 seconds of arcing on the ~0.4 mm^2 area. Heat tempered glass has a modulus of rupture of *at most* 160 Mpa, and near 100 Mpa is more likely for glass that has a texture or pattern, as the module does. Conclusion: Glass fractured into small pieces from this temperature.

Glass Modulus of Rupture Properties:
Float 27-62 MPa
Tempered Float 160 MPa
Also from Flabeg Solar Glass
Specifications:
Fully Tempered: 120 MPa, 90 MPa with pattern and
Heat Strengthened: 70 MPa and 55 MPa patterned.
Also annealed at 6000 psi = 41 MPa
and tempered at 24,000 psi=165 MPa

The thermal expansion of the area above the arc puts the surrounding areas into tension, which is the weaker direction for glass and ceramics, resulting in fracture centered at the heat source, with the small size pieces being typical for tempered glass.

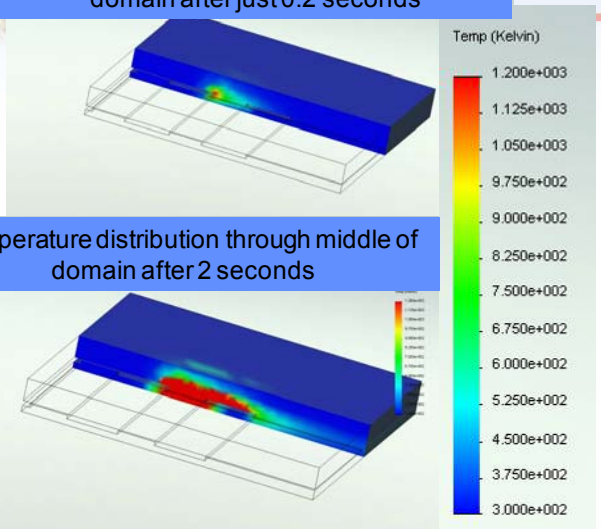
Busbar shifting and connection damage

- **To investigate if arc temperatures could have caused the busbar shifting and broken collector to busbar connection, the thermal study of applying 6000K to just 0.38 mm^2 at the end of the connector was performed.**
  - Assumed busbar was restrained in the x direction at the module center, and restrained in the z direction by the module lamination.



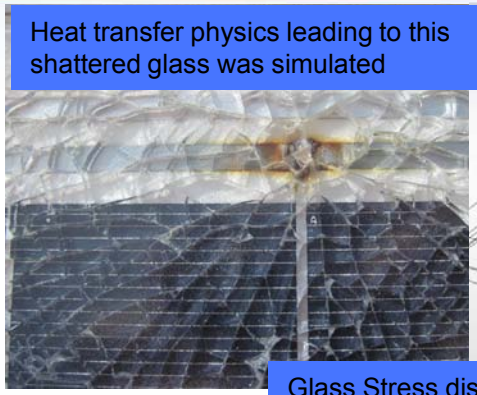
Arc Fault Modeling Summary

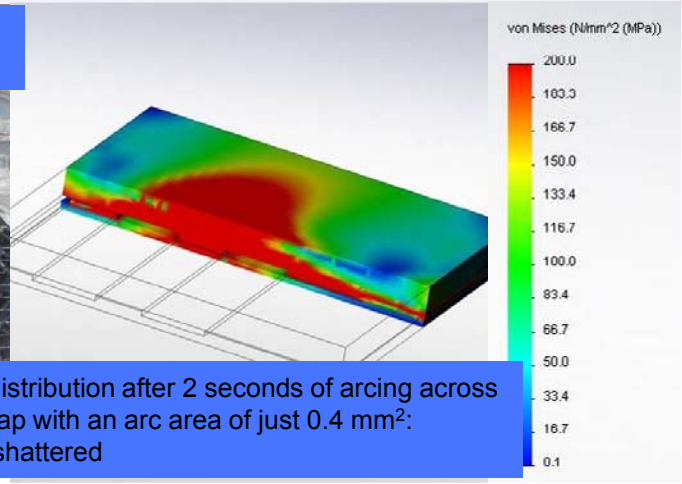
Temperature distribution through middle of domain after just 0.2 seconds



Temperature distribution through middle of domain after 2 seconds

Heat transfer physics leading to this shattered glass was simulated



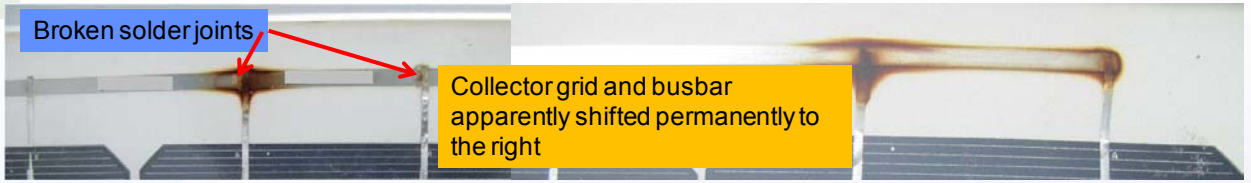


Glass Stress distribution after 2 seconds of arcing across the 5 micron gap with an arc area of just 0.4 mm^2: the glass has shattered

- **Thermo-mechanical modeling**
  - Simulation and prediction of temperature and mechanical stress effects of arcing given boundary conditions, material properties and geometry
  - Simulations provide insights into time scales for arc detection and material selection

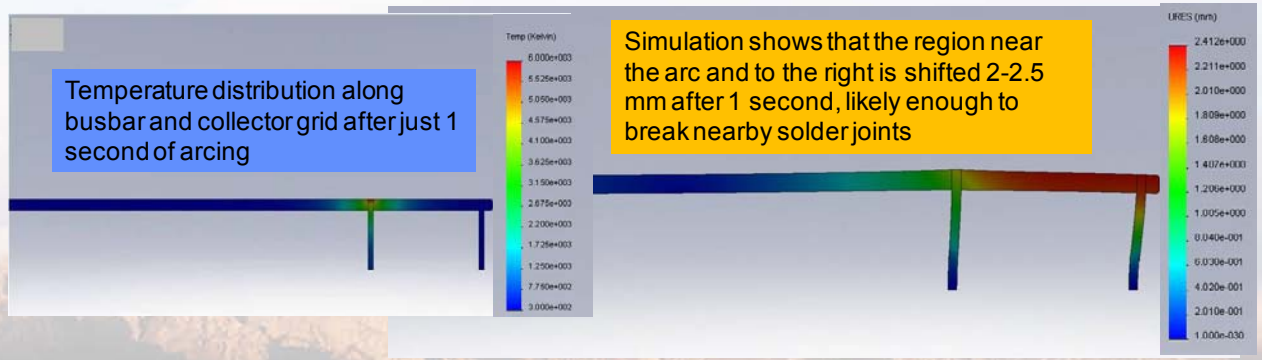
Broken solder joints

Collector grid and busbar apparently shifted permanently to the right



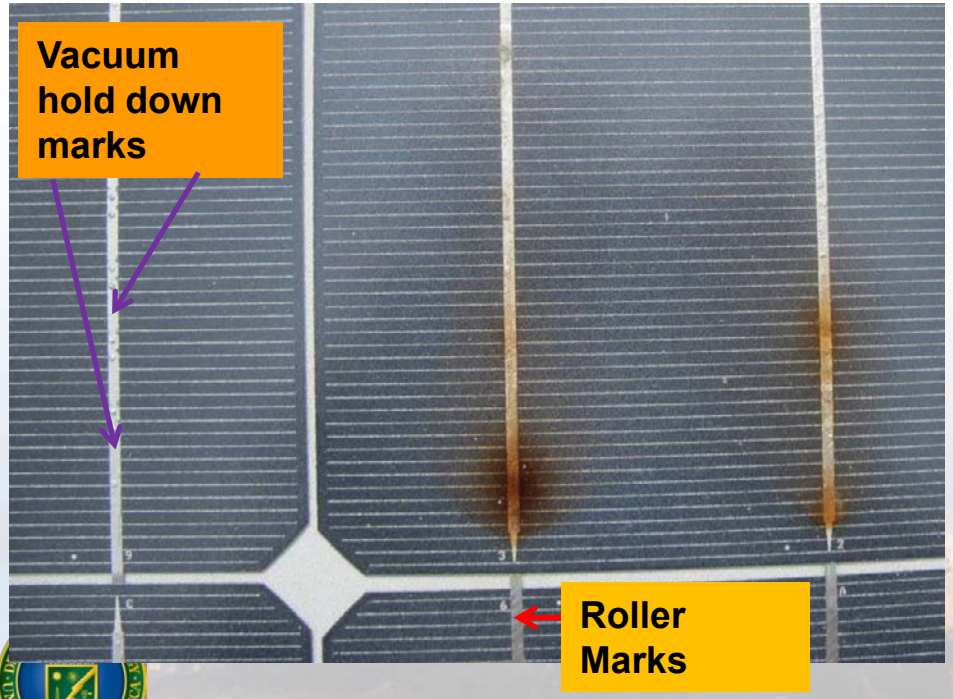
Temperature distribution along busbar and collector grid after just 1 second of arcing

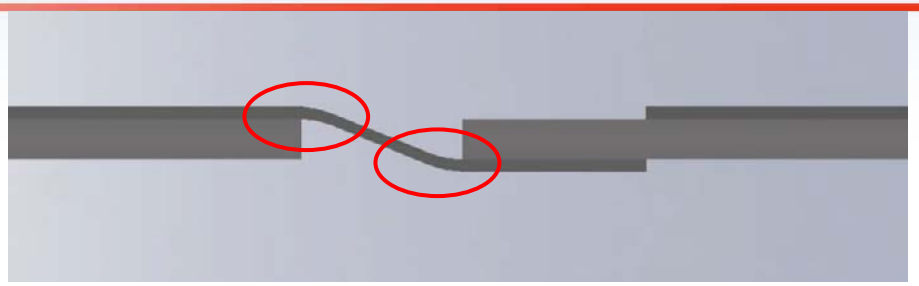
Simulation shows that the region near the arc and to the right is shifted 2-2.5 mm after 1 second, likely enough to break nearby solder joints



Conclusions

- It appears likely that some or most of the failures observed in the modules are due to high temperatures at (relatively) short durations, such as would be seen in an arcing event.
- It also appears that areas of the module that were under vacuum hold down were less susceptible to failure than those areas that were rolled, as shown below.





- Side view of ribbon from back contact to top of cells.
- Diurnal temperature shifts could have strained and broken the ribbon at either bend, leaving a tiny gap that could have arced any day the module is in the sun afterwards, leading to a common failure observed: burned collector ribbon between cells.
- Studies of Joule heating in oxidized backsheet to ribbon connections show insufficient temperatures to cause all observed effects.
- Future studies on thermal strain due to diurnal temperature fluctuations on the failed ribbons will be performed.
- Future study on limits of the current generation of Tyco Junction Boxes as well as effects of new connector materials to be performed as well.

THANK YOU!

From the Sandia PV ARC Fault Team

Questions?

Sandia National Laboratories