Analysis of Hot Spots in Crystalline Silicon Modules and their Impact on Roof Structures

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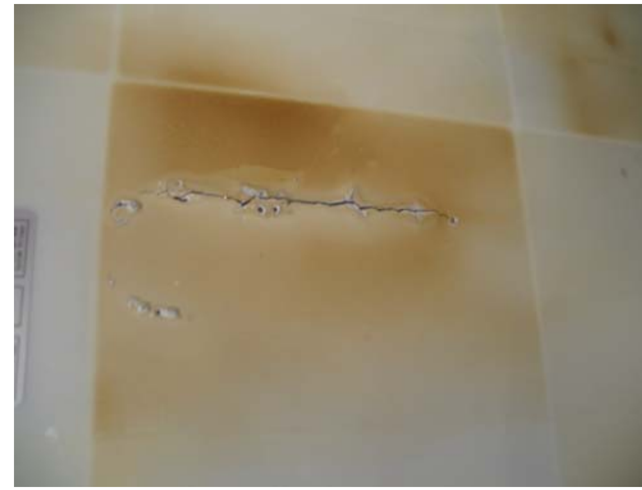
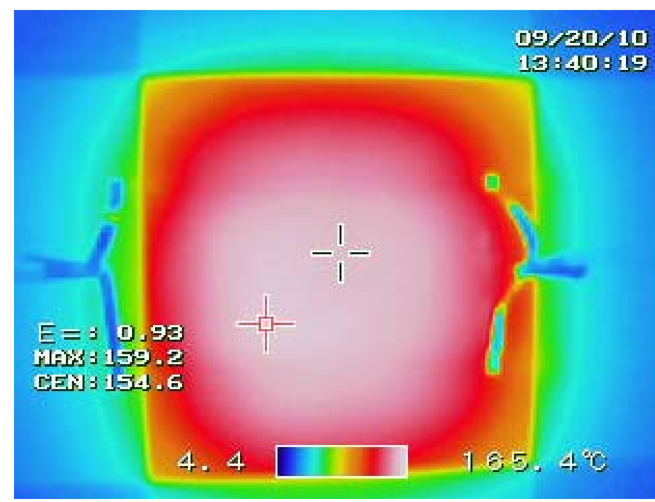
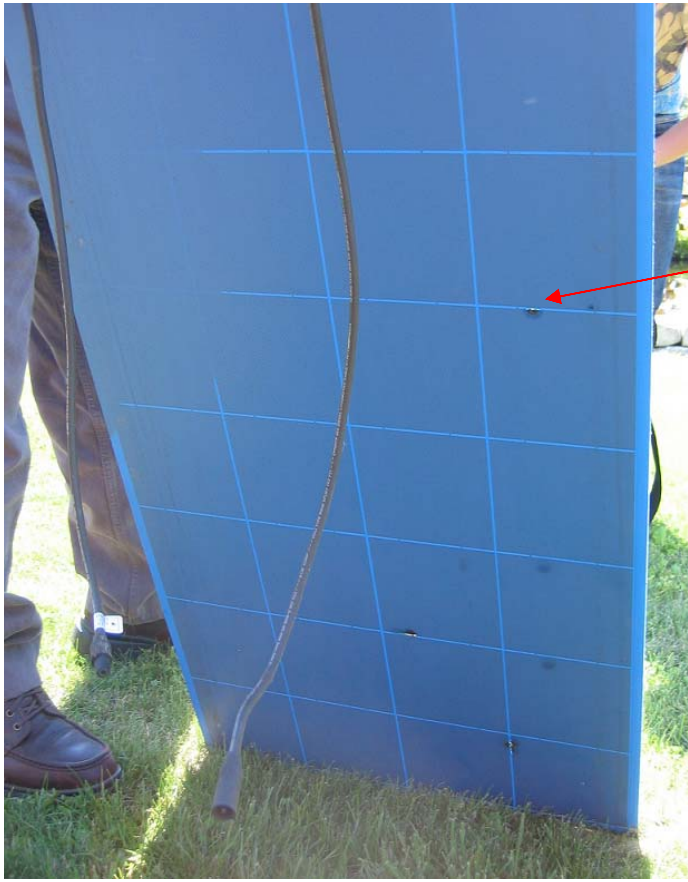
Introduction

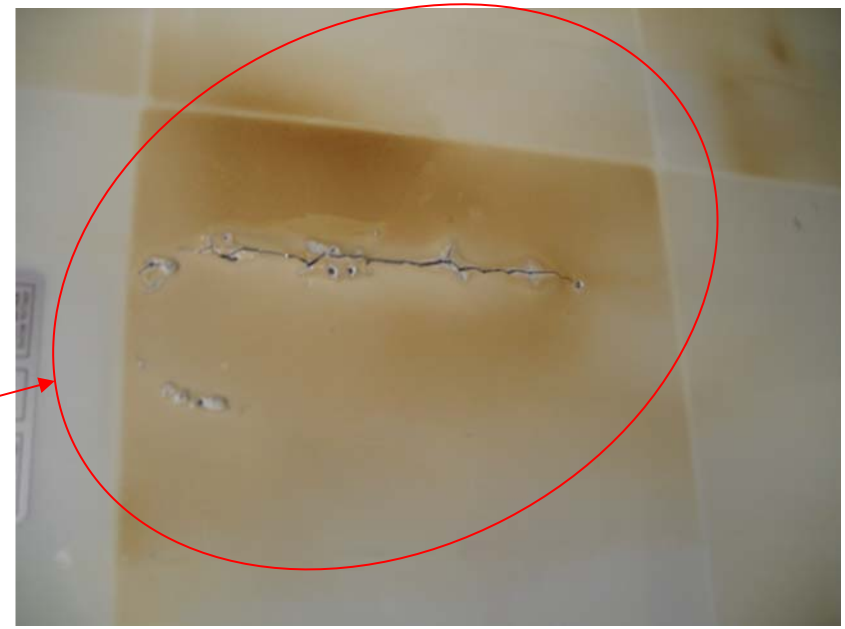
- **What are hot spots?** What the standards say:
- **IEC definition:** “Hot-spot heating occurs in a module when its operating current exceeds the reduced short-circuit current of a shadowed cell or group of cells within it”
- **UL definition:** “This reduced short-circuit current capability can be the result of a variety of causes including:
  - non-uniform illumination of the module (local shadowing)
  - individual cell degradation due to cracking
  - ..or loss of a portion of a series-parallel circuit due to individual interconnect open circuits.”
- These hot spot mechanisms are the result of reverse biasing of cells which can lead to localized p-n junction breakdown
- **Not all hot spots are the results of the p-n junction effect**





Example: By pass diode failure





Localised hot spot

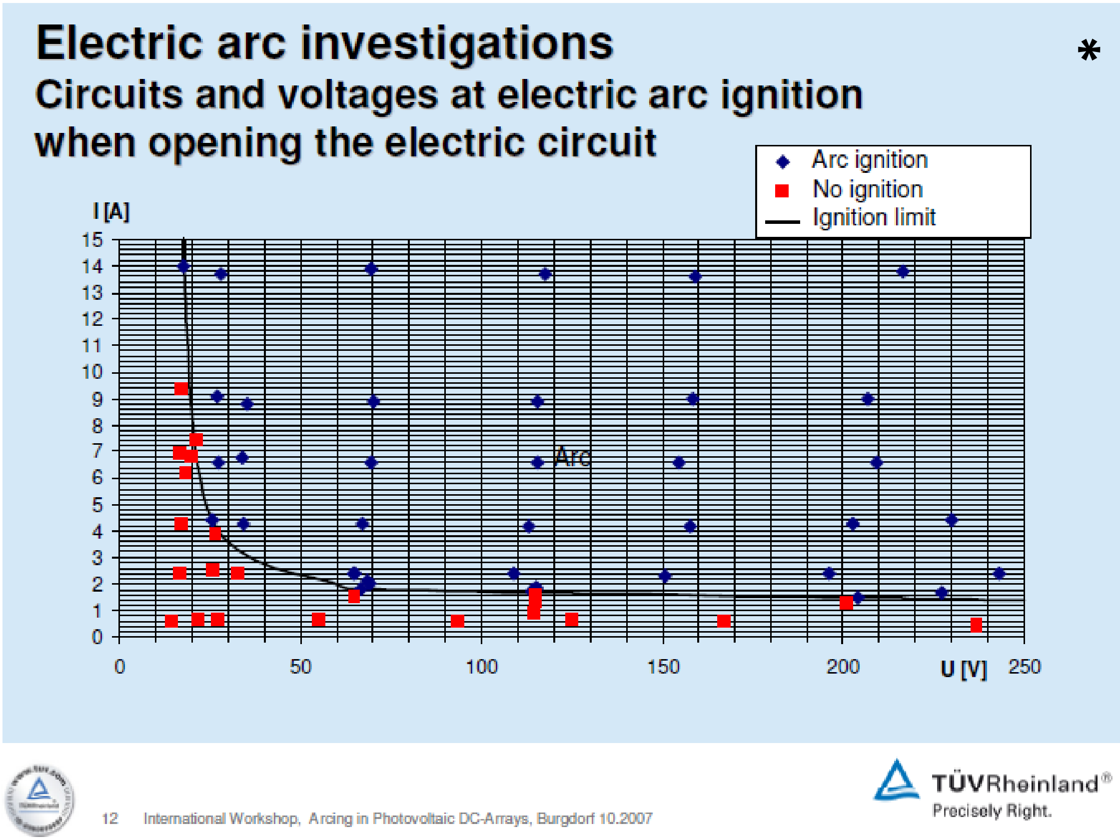
More uniform hot spot

- Loss of protection from a faulty by pass diode during periods of shading can lead to hot spots
- The highest temperature occurs where current density is highest. This can produce non uniform heating
- Cell shunt resistance influences hot spot formation on shading. Shunt limits have increased as a result

Example: Non cell hot spots

- Resistive heating is not associated with reverse bias conditions
- The heating is localized at the defect and can discolor the encapsulant and back sheet
- Poor workmanship can lead to soldering defects. These are not seen at the solar simulator
- The hot spot can be stable, does not increase in temperature
- In some cases, the contact will open

Arc effects



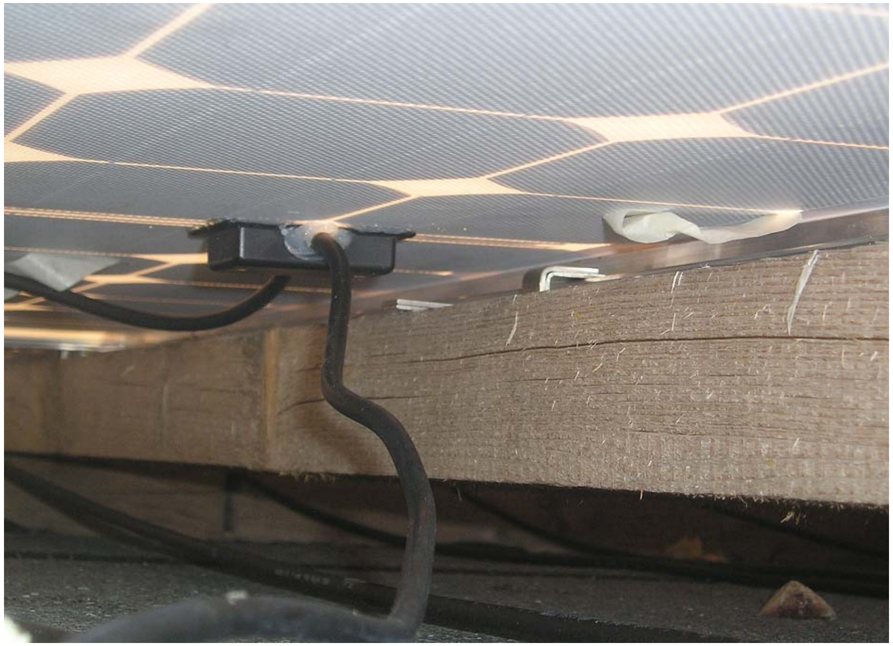
- DC arcs are another non reverse bias hot spot phenomenon
- Initiated under specific voltage/current conditions with a gap between conductors
- Current / Voltage ignition limits are well known
- The impact from this type of hot spot can be severe

* **Author acknowledges W Vassen of TUV Rhineland for permission to use the above chart**

Example: Structural interference

- Root cause is DC arc generation due to back sheet damage
- US systems: Negative ground needs single short
- EU systems: Typically need 2 shorts due to double isolation approach

Impact of roof structure proximity



- BIPV designs often require close proximity of the module to the roof structure
- The study performed between BP Solar and the Fraunhofer Institute was initiated to better understand and quantify the risks and behavior

2010 F-ISE/BP Solar hot spot study

- **Scope of the study:**
  - Perform a statistical evaluation on a sample of modules exhibiting hot spots.
  - Quantify the occurrence and temperature range/severity of hot spots
- **Characterization included**
  - Categorise the hot spots into specific root cause; cell contact, cell mis-match, cracked cell, etc
  - Determine highest temperature for hot spots
  - Perform electroluminescence and infra-red thermography
  - Effect of thermal cycling & mechanical load on hot spots
  - Heating influence on adjacent/close proximity structures with limited ventilation
  - Evaluate effect of rear side module damage at high voltages

Module samples used in study

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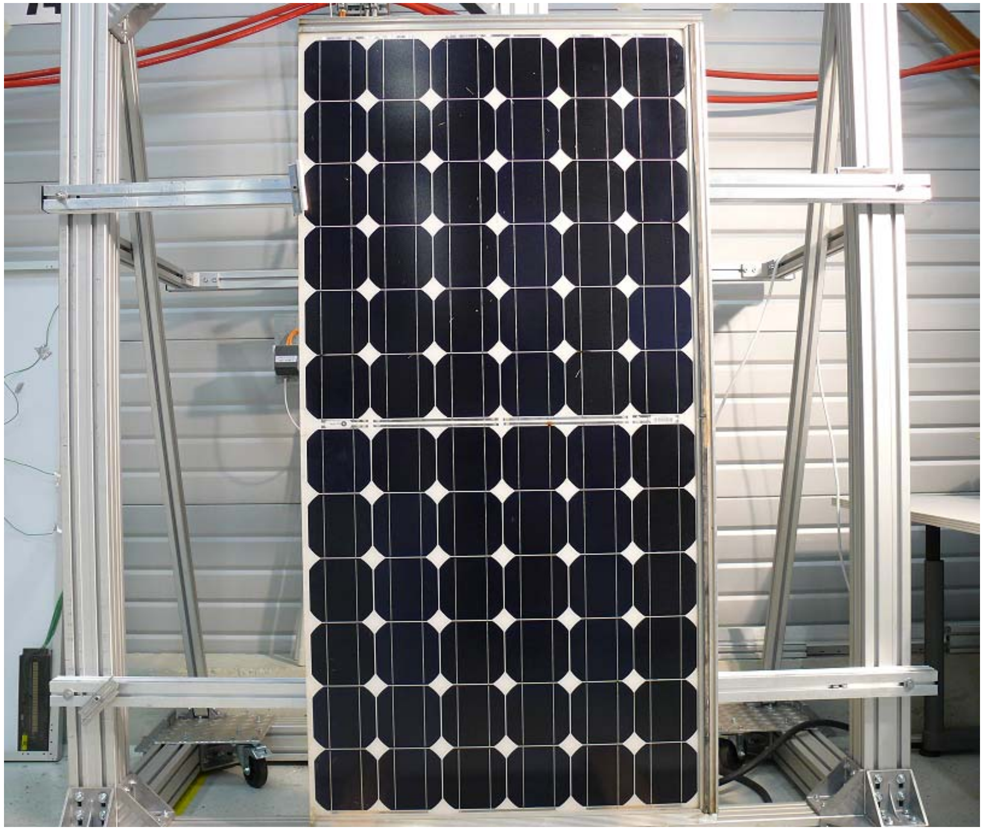

- BP Solar supplied 28 modules with varying degrees of hot spots
- Tests were performed at F-ISE, Freiburg
- Structures were custom built to replicate real field conditions
- Test protocols were followed according to IEC61215 & UL1703

Hot spot characterization

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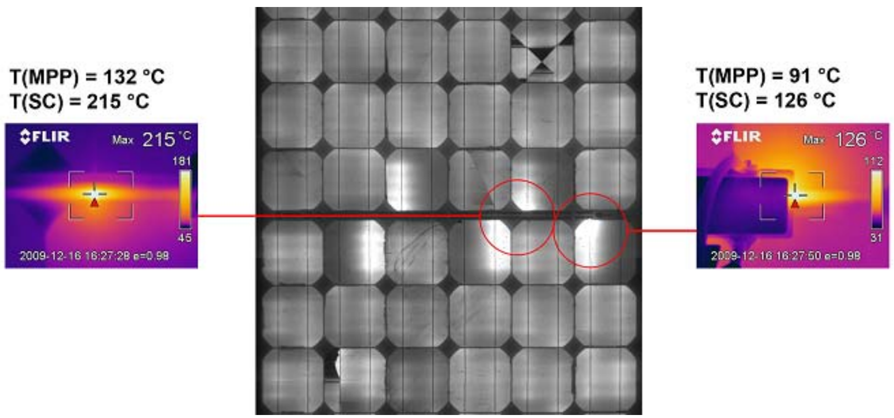
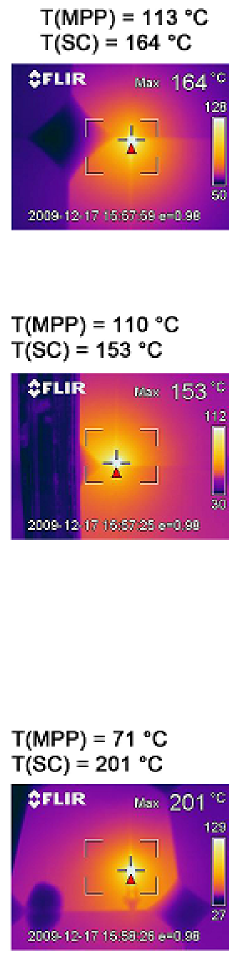
- Full visual inspection, EL, & IR images was made on all modules
- Hot spot temperatures were measured under illumination (Class B-B-A solar simulator at 1000W/m^2).
- Both Isc and Imp current condition were investigated
- Initial condition: Ambient temperature was 20^{o}C and ventilation was not limited
- Table below shows the 5 highest hot spot temperatures found in the study

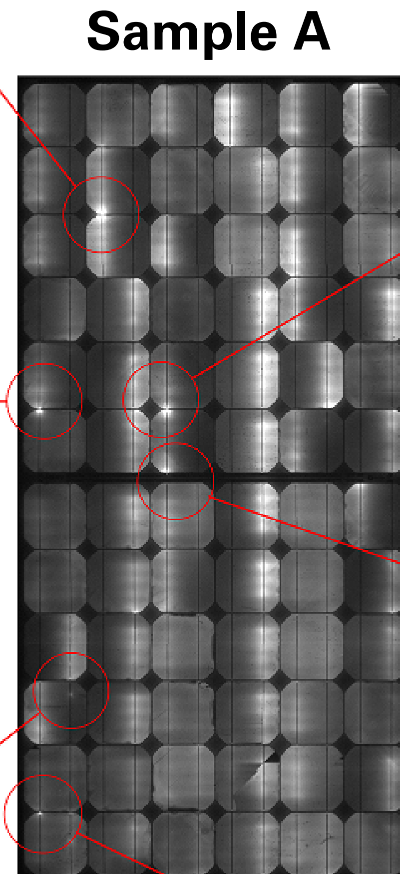
		Maximum hot spot temperature measured	
Sample	Isc (A)	T(C) @ Isc	T(C) @ Imp
A	4.9	301	144
B	5.1	312	267
C	5.0	272	147
D	4.9	296	210
E	4.6	287	172

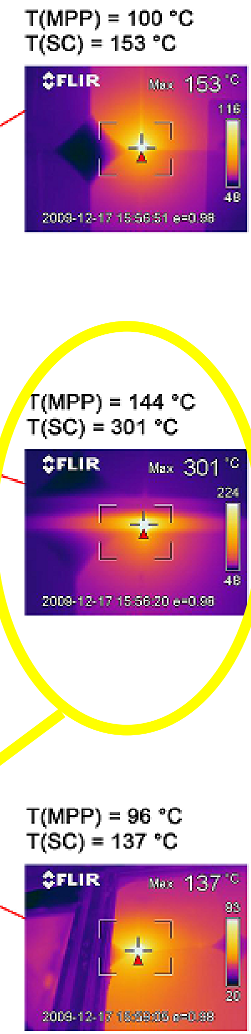
EL and IR images



- Some broken cells were observed in module



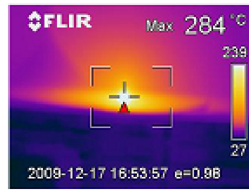




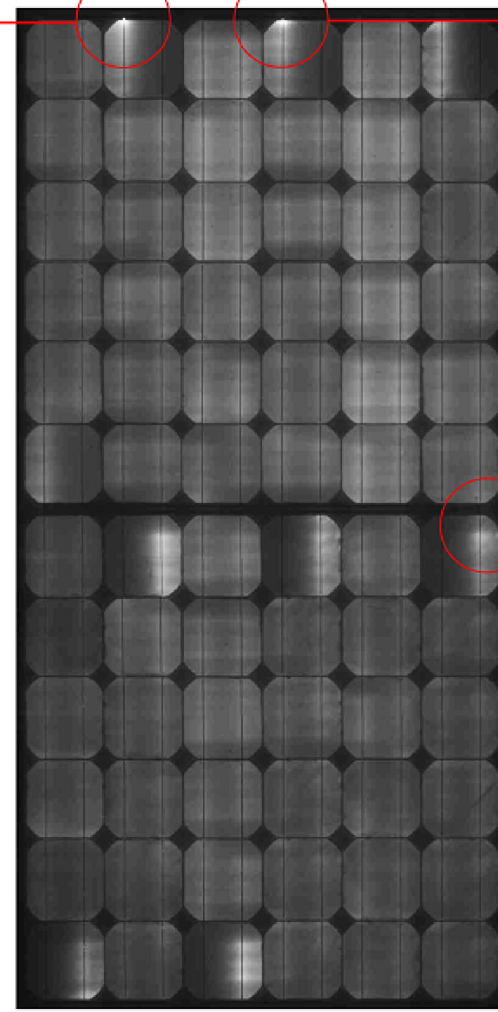
- The most serve hot spots observed in the group were from high resistance solder joints

EL and IR images continued

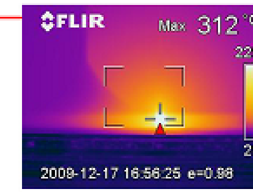
T(MPP) = 190 °C
T(SC) = 285 °C



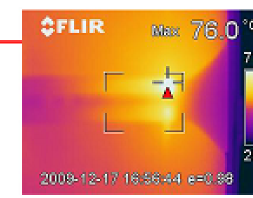
Sample B



T(MPP) = 267 °C
T(SC) = 312 °C



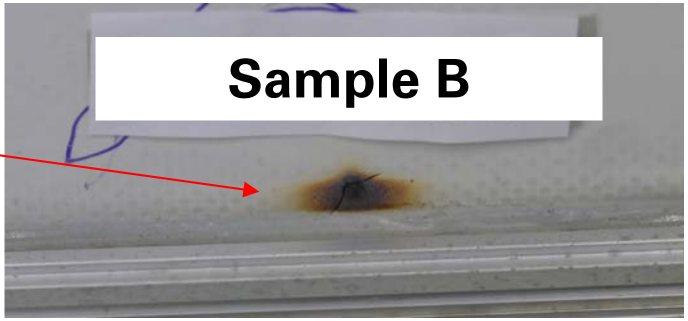
T(MPP) = 69 °C
T(SC) = 76 °C



Hot spot with restricted ventilation

- Rear side of the module (samples A thru E) was closed off using a wooden panel
- Air gap: 38mm
- Ambient raised to 40^{o}C with modules held at Isc
- Top 5 highest hot spot temperatures are shown below
- Temp trend was not consistent; 3 increased in temperature, 1 decreased, 1 unchanged
- Suggests that the hot spot source and properties can vary
- The module with the highest temperature hot spot was chosen for a “worse case” test
- This worse case test was designed to measure temperature rise in very proximity

Maximum hot spot temperature measured		
Sample	Isc (A)	T(C) @ Isc
A	5.2	300
B	5.2	343
C	5.2	283
D	5.0	251
E	4.7	332



Worse case experiment
Hot spot behavior in 10mm enclosure

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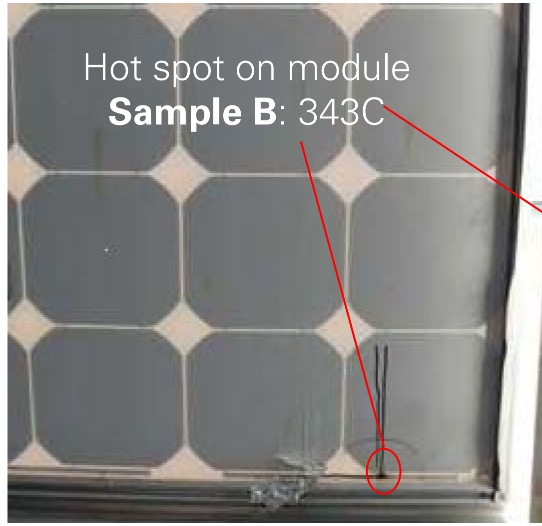
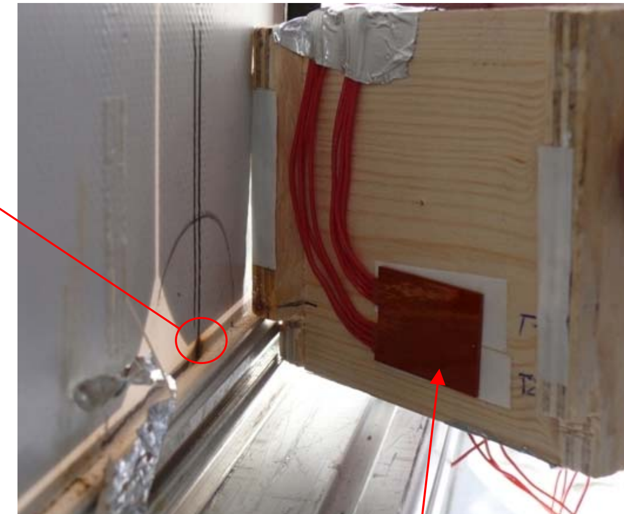
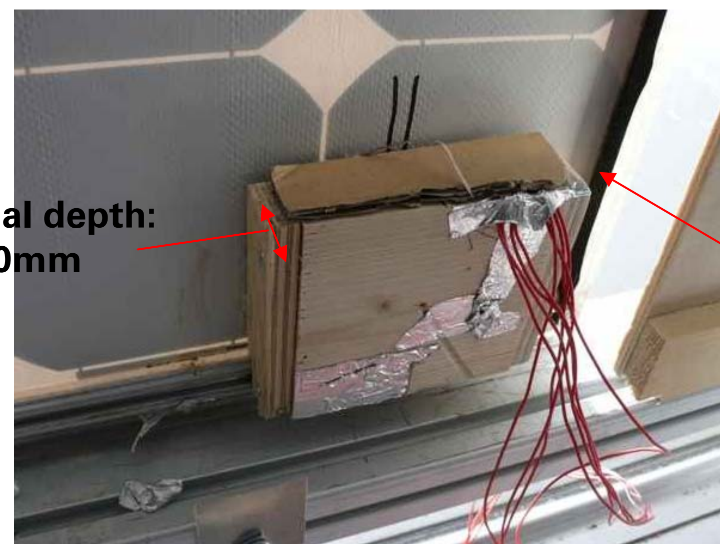
Back of module (**Sample B**) **completely enclosed** before start of test





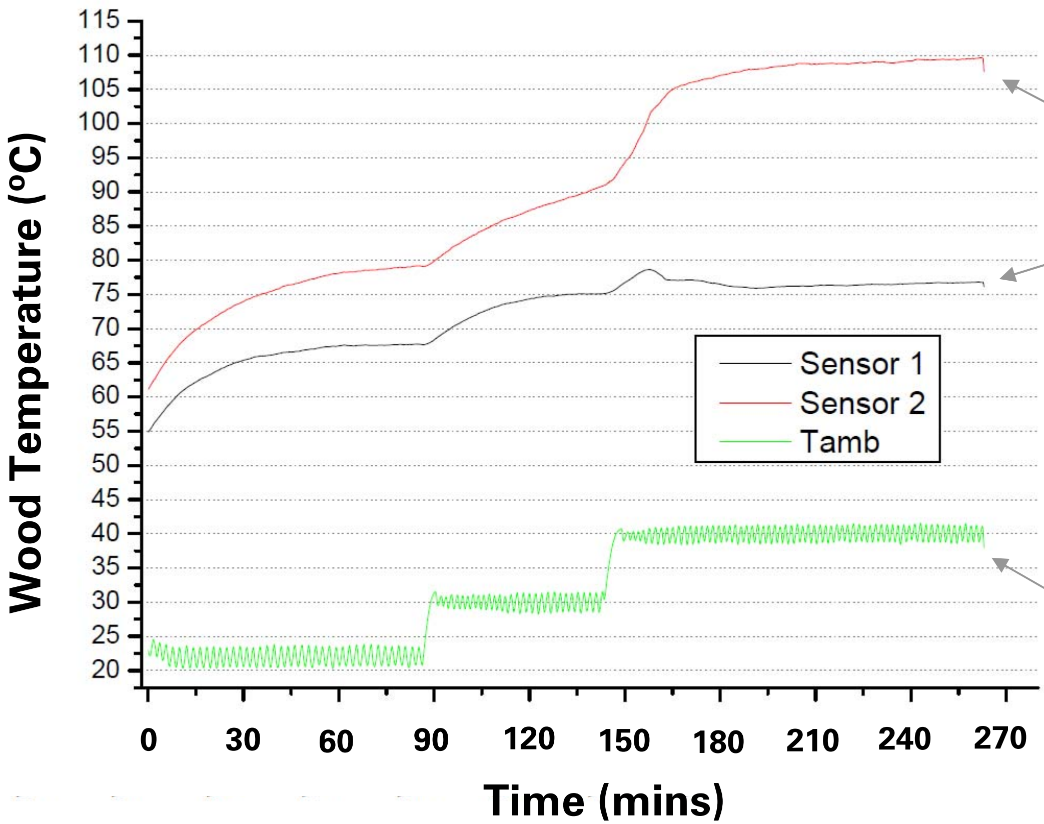
PT100 sensors

Internal depth: 10mm



Enclosure to restrict air flow

Max temp at 10mm from structure



Auto ignition temperature of wood: 300°C

Sensor 2: max 109°C

Sensor 1: max 76°C

Secondary heating from hot spot low for such an extreme condition!

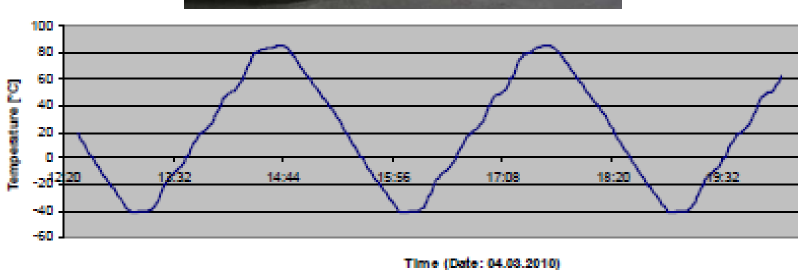
~120 mins soak time at 40°C ambient

- Ambient temp stepped from 25°C to 40C° while module illuminated to produce Isc current
- Maximum temperature range at wood surface by end of test: 76°C to 109°C
- **While absolute temperature of hot spot is high, the dissipated energy from it is very small**
- This accounts for the relatively low temperatures of adjacent surfaces

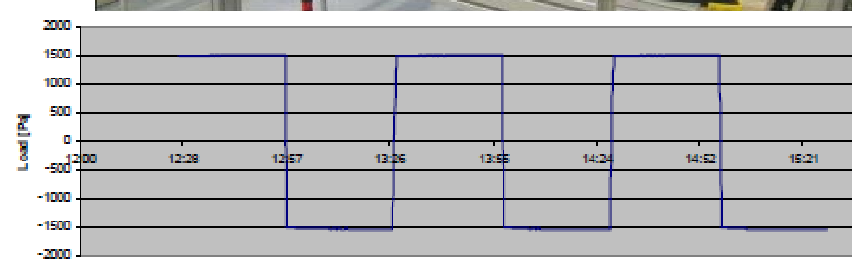
Thermal & mechanical loading

- As part of the study, the effect of thermal and mechanical cycling of hot spot propagation was investigated
- IEC 61215ed2, 10.11 and 10.6 (thermal & mechanical cycling respectively) procedures were followed
- Thermal cycling: -40°C to +85°C, 200 cycles
- Mechanical cycling: 2400Pa and 1500Pa, cycling front & rear, 1 hour period

1) Thermal cycling



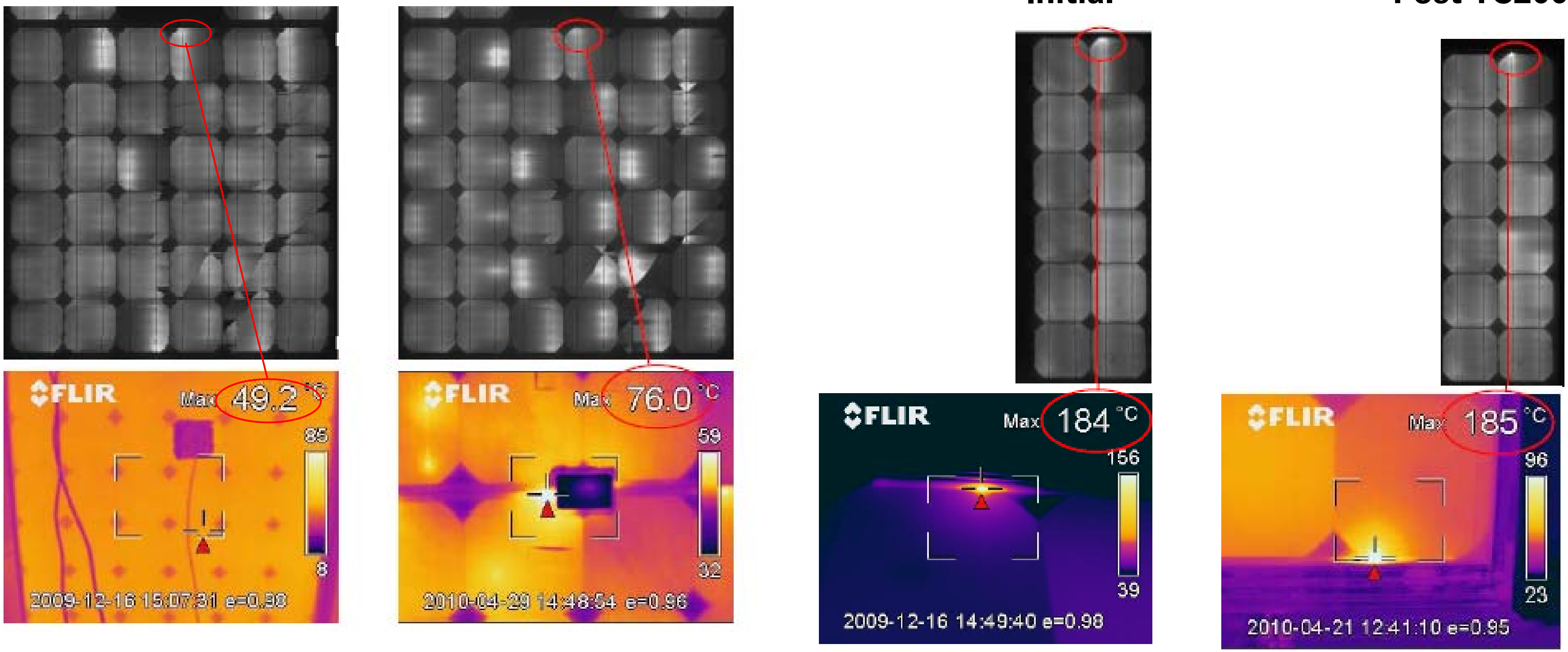
2) Mechanical cycling



Thermal cycling effect

Sample 1: Thermal cycling | **Sample 2: Thermal cycling**

Initial | **Post TC200** | **Initial** | **Post TC200**



- For the examples used in the study, there was not a strong influence of thermal cycling on the propagation hot spots
- In the case above, the hot spots were located at interconnect to bus bar interface

Mechanical cycling effect: Results

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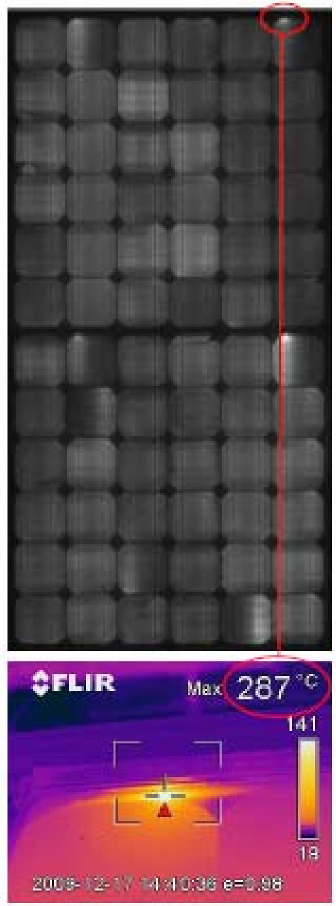
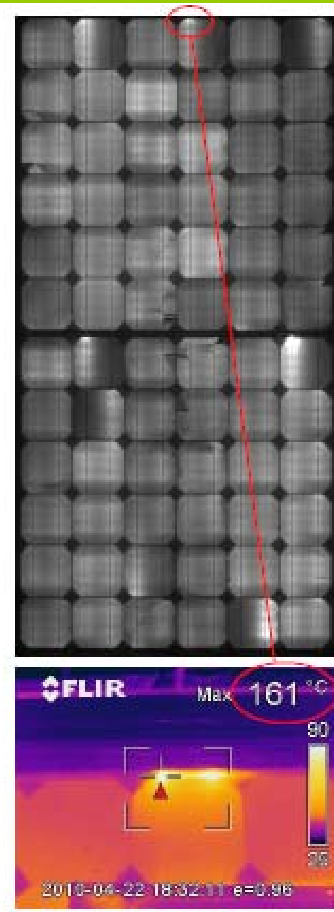
Sample 3

Mechanical cycling

3 front/rear cycles to 1,500Pa

Initial EL & IR images





Final EL & IR images

- Nature and severity of hot spot in this sample changed after repetitive load cycling
- Suggests that this type of stress could be a factor in perturbing the extent of hot spots
- Dependant on weather conditions including local wind and snow conditions
- This could take many years in the field

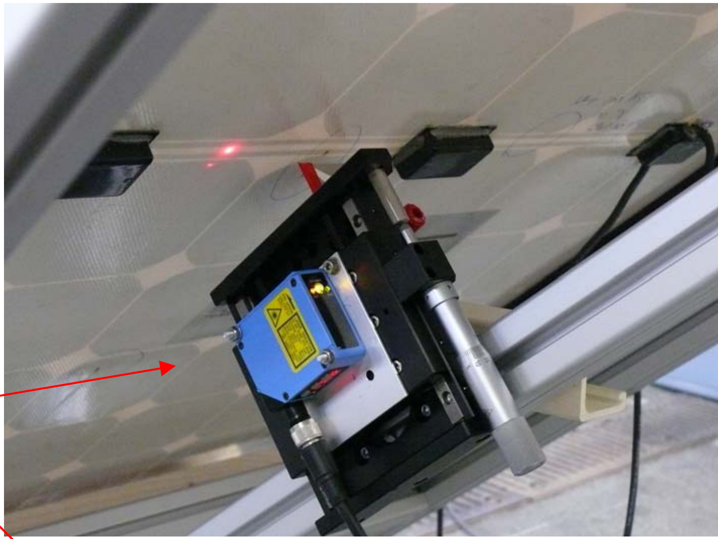
Simulated rear side damage at high voltages

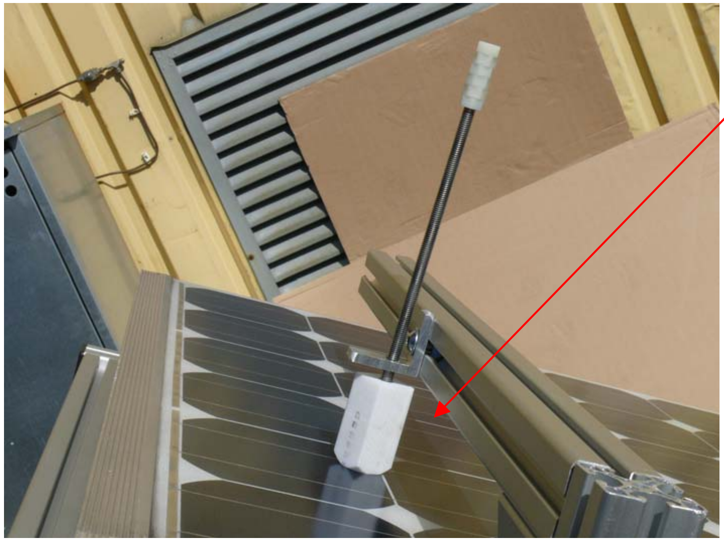
Isolated structure with metal probe at -1000V

+ve to output cables

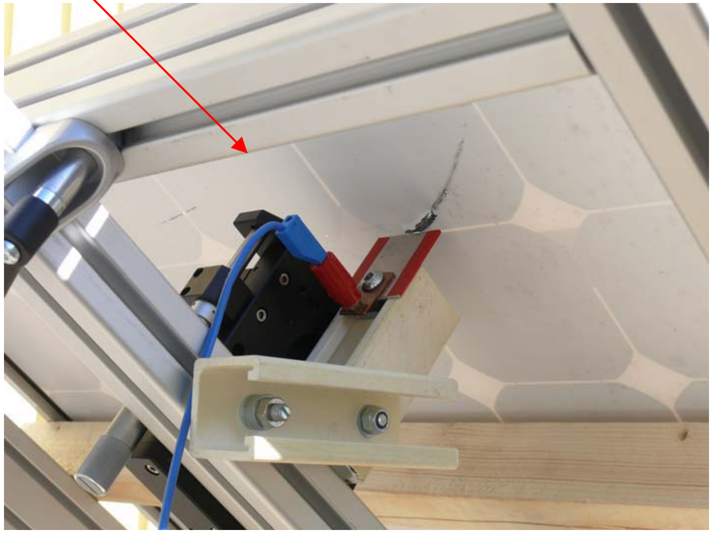
Current limit: 1A

Sensor measures the distance to the back sheet: 0 to 20mm

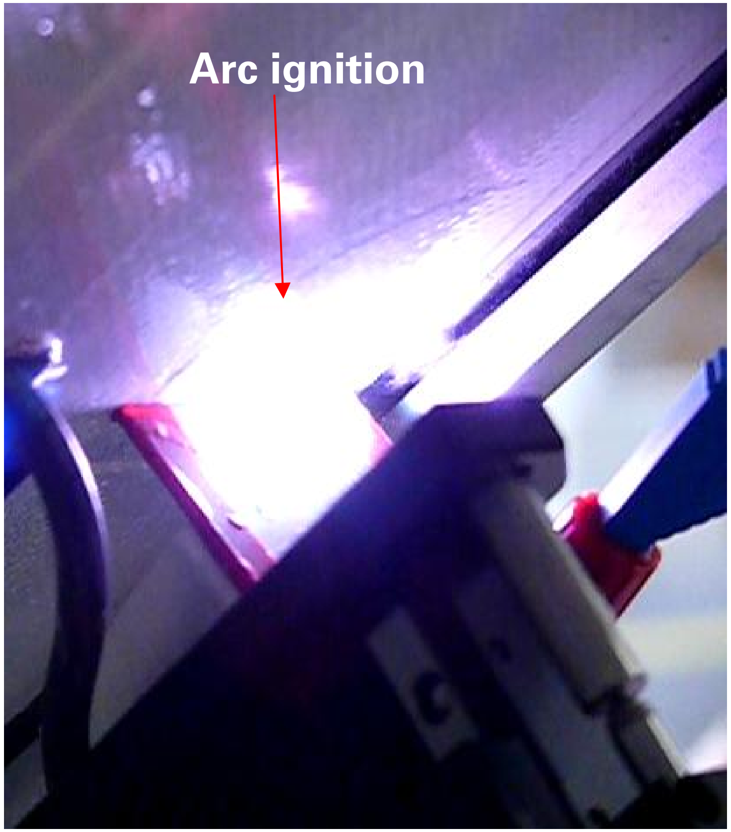




Pressure applied to front of glass to generate deflection



Simulated back sheet damage
Arc initiation



- **Flash over occurred when the probe was in close proximity (<2mm) or direct contact**
- **Flash over occurred in dry environments but the presence of water greatly increased the chance for occurrence**
- **For these conditions, flash over was detected at voltages of 300V or higher**
- **<u>Undamaged back sheets</u> did not lead to leakage current or arc initiation**

Summary

- Many different failure modes can create a hot spots not just p-n junction effects from shading
- A study between BP Solar, Fraunhofer Institute, and VDE examined 28 modules with examples of hot spots
- Broken cells were present but the most common root cause was resistive heating due to defective solder joints
- Maximum temperature measured was 343^{o}C, however the heating effect on the adjacent wooden structure was low
- This is due to the small physical size of the hot spot and low energy dissipation
- Stress testing showed a greater effect from mechanical cycling compared to thermal cycling
- However, this did not significantly increase the hot spot temperature
- By far the biggest risk for secondary damage from hot spots is if their source is a DC arc
- This was demonstrated by simulated back sheet damage at high voltage