“A Proposed Junction-Box Stress Test (Using an Added Weight) for Use During the Module Qualification”

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(Denver West Marriot, Golden, CO)
2012/2/29,  8:20 – 8:40 am (Wednesday)
Golden Ballroom

-this presentation contains no proprietary information-

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Motivation for the Project

- J-box attachment often proves a milestone to module manufactures ... possible consequences of field failure.
- Possible failure mechanisms: phase transformation, creep, *cohesive failure*, *delamination* of the -adhesive system-
- Present qual. test: “robustness of termination” (pull ⊥ against j-box 40 N load) after [UV preconditioning, thermal cycling, humidity-freeze], and at room temperature.
- Discovery experiments suggest that problematic systems can be more readily identified with applied weight during damp heat.

Possible field failure mode(s) at the junction-box
(Temperature) Conditions Present in the Field

- The cell (module) temperature can be predicted from popular models (King, Faiman, etc.)
  

- $T_{\text{max}}$ of 105°C achievable for open circuited, roof-mounted modules in desert location

- A greater $T_{\text{max}}$ may be realized during the reverse bias condition induced by partial shading, current mismatch, cell or interconnect failure

- Localized $T_{\text{max}} \geq 150$°C achievable during the “hot-spot” condition
  

- Other factors (e.g., moisture) are also present in the field

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>$T_{\text{max, ROOF}}$</th>
<th>$T_{\text{max, RACK}}$</th>
<th>$T_{\text{max, record, AMBIENT}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Death Valley, CA</td>
<td>108</td>
<td>90</td>
<td>57</td>
</tr>
<tr>
<td>Riyadh</td>
<td>103</td>
<td>84</td>
<td>48</td>
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<td>Phoenix, AZ</td>
<td>103</td>
<td>85</td>
<td>50</td>
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<td>Yuma, AZ</td>
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<td>97</td>
<td>79</td>
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<td>Seville</td>
<td>97</td>
<td>79</td>
<td>45</td>
</tr>
<tr>
<td>Kuwait City</td>
<td>99</td>
<td>83</td>
<td>51</td>
</tr>
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<td>Daytona, FL</td>
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<td>Miami, FL</td>
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<tr>
<td>Bangkok</td>
<td>85</td>
<td>69</td>
<td>38</td>
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<td>New York, NY</td>
<td>89</td>
<td>73</td>
<td>41</td>
</tr>
<tr>
<td>Munich</td>
<td>79</td>
<td>64</td>
<td>36</td>
</tr>
<tr>
<td>Fairbanks, AK</td>
<td>70</td>
<td>59</td>
<td>36</td>
</tr>
</tbody>
</table>

Summary of Experiments

• Specimens:
  foam tapes (closed cell: acrylic, polyurethane, polyethylene)
  silicones (condensation cure: acetoxy, oxime, alkoxy cure)
  hot melt (thermoplastics: EVA, polyolefin, polyamide)

• Material-level tests:
  thermogravimetric analysis (TGA)
  differential scanning calorimetry (DSC)
  dynamic mechanical analysis (DMA)

• Component-level tests:
  indoor chamber: 1000 hours @ 85°C, 85% RH
  polyester (PET) “substrate”
  glass “substrate”
The Decomposition Temperature: Measured vs. Required

- To ensure long term durability in the event of a prolonged hot spot condition:
  \[ T_{5\%} > 200^\circ C \] (approximation for test @ 20°C⋅min\(^{-1}\))
  - Examining the event of prolonged hot-spot condition ~ 150°C
  - \( T_{5\%} \) could occur on the order of 50°C lower at slower test rate

- No overt failures relative to this criteria

- Only PU tape, alkoxy silicone, and EVA hot melt approach this criteria: evaluate at slower test rate to verify

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TGA characterization of silicones, foam tapes, and hot melts
DSC Identifies the Likelihood of Creep

- Glass transitions ($T_g$ aka $T_\alpha$) may signify likelihood for creep
- The $T_g$'s here are well below the typical operating temperature within fielded modules

- Melt & freeze transitions ($T_m$ & $T_f$) more commonly correlate to creep in thermoplastics
- The silicones are cross-linked during cure, preventing creep
- $T_m$ hot melts: 75°C (EVA), 81°C (PO), 68°C (PA)

How will the hot melts fare in component tests?

- $T_g$ for acrylic foam tape: -43°C
- $T_g$ for condensation silicones: -155°C
- $T_g$ for PA hot melt: -57°C
- $T_f$ for acrylic foam tape: -72°C
- $T_f$ for condensation silicones: -40°C
- $T_f$ for PA hot melt: 88°C

DSC for acrylic foam tape  DSC for condensation silicones  DSC for PA hot melt
Two Sets of Discovery Experiments Examine the Adhesives

**c-Si j-box (4 rail) on PET:**
- Pb Weights: 0, 0.5, 0.9, 1.4, 2.3, 4.5 kg
- Adhesives:
  - acrylic tape
  - acrylic tape
  - PE tape
  - acetoxy silicone
  - alkoxy silicone (Ti)
  - oxime silicone
- Primer applied when recommended

**TF j-box (2 rail) on glass:**
- Pb Weights: 0, 0.5, 0.9, 1.4, 2.3, 4.5 kg
- Adhesives:
  - acrylic tape, PU tape, acetoxy silicone, alkoxy silicone (Ti), oxime silicone, PO melt, PA melt
- Attached to Sn side of (cleaned) glass
- Primer applied when recommended
The Details of the Weight Attachment

- All weights were attached using 0.81mm Ø stainless steel wire
- Wire ends secured with knots

**c-Si j-box (4 rail) on PET:**
- Wire attached to tab features
- Slight torque possible

**TF j-box (2 rail) on glass:**
- Wire attached thru vias (cable & glands removed)

**All:**
- Predominant shear loading mode
- Boxes left uncovered through the test
Details of the Specimen Attachment

- Easily visualized through substrate for TF specimens
- Silicones adhered by (flatten) bead placed around periphery using “gun”

- Tapes: good wet-out, except @ cut-out regions (TF)
- No tape used at cut-outs in c-Si specimens

- Melts: adhered by (flatten) bead placed around periphery using heated “gun”
- Original bead for melts smaller than that for silicones
### Loss of Adhesion for Tape During the c-Si Test

<table>
<thead>
<tr>
<th>PET Substrate</th>
<th>0.5 kg</th>
<th>2.3 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>J-box</td>
<td><img src="image1.png" alt="Image 1" /></td>
<td><img src="image2.png" alt="Image 2" /></td>
</tr>
</tbody>
</table>

- all PE tape lost adhesion within 24 hrs
- delamination @ tape/j-box interface
- 2.3, 4.5 kg weights: torn tape (mixed mode failure)
- use system of compatible materials (j-box, adhesive, and substrate)

<table>
<thead>
<tr>
<th>PET Substrate</th>
<th>4.5 kg</th>
<th>4.5 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>J-box</td>
<td><img src="image3.png" alt="Image 3" /></td>
<td><img src="image4.png" alt="Image 4" /></td>
</tr>
</tbody>
</table>

- acrylic tape lost adhesion 6-7, 7-14 days (4.5 kg weights only)
- delamination @ tape/substrate interface
- loaded exceeding the manufacturer’s design guideline
Elongation of acrylic tape observed for 1.4, 2.3 kg weights @ 7-14, 14-21 days.

Remained attached through test (41 days).

Consistent with intended dissipative behavior: adjustment facilitating mechanical support.

Not observed during TF test for same material (similar load).

Careful not to stretch tape during application.

Polymeric adhesives: H₂O may plasticize.
Perceived Deformation of Silicone During the TF Test

- 4.5 kg weighted alkoxy (Ti) silicone appeared displaced @ 5-7 days
- Actually displaced (bumped) during specimen preparation and unchanged through the test
- Condensation silicones require H_2O to cure (CO is dry)
- 21 day cure recommended prior to material tests in dry climates
Loss of Adhesion for Tape During the TF Test

PU tape:
- Weights > 0.5 kg lost adhesion within 24 hours
- Delamination at tape/glass interface (tape remains on j-box)
- 0, 0.5 kg weighted specimen remained attached through test
- 0.5 kg weighted specimen displaced (adhesive/glass) during the test

creep of 0.5 kg weighted PU tape at 14 days

acrylic tape:
- Only 2.3, 4.5 kg weighted specimens lost adhesion within 24 hours
- Delamination at tape/j-box interface (tape remains on glass)
- Results as expected from manufacturer’s design guideline
Delamination & Creep in Hot Melts During the TF Test

• Delamination of weighted PO & PA melts within 24 hrs
  • PO adhered to glass; PA to j-box

• Unweighted PO & PA melts displaced over days, even without the j-box!
• Melt composed lettering rotated through test

• Result consistent with DSC characterization
• Melts identified by material vendor:
  understanding product (field) requirements can be critical! 85°C<105°C
DMA Confirms the Behaviors Observed in the Component-Level Tests

- **silicones:**
  - Stable modulus after melt transition @ low temperature
  - Would likely creep, if not cross-linked (cured)

- **tapes:**
  - Significant ($10^4$x) softening of modulus with temperature
  - Significant mechanical dissipation ($\tan[\delta]$) at all $T$ (advantageous in vibration or impact-prone environment)
  - Some tapes melt @ $T>100^\circ$C

- **melts:**
  - Softening of modulus with glass transition
  - More significant softening of modulus (terminates test) with melt transition
  - Phase transition confirmed in component-level (TF) test

The Formal Experiment (Future)

Goal: Test the proposed test (indoor vs. field) using a representative set of known good, known incompatible, and intermediate systems

Weights
- 0, 0.5, 1 kg (0, 1, 2 lbs). Consider 4x weight of (2) 1.5m connector cables = 0.7 kg

Adhesives
- 13 examined in the discovery experiments
- Down-selected to 7 (some likely failures, many expected successes)
  [acrylic tape, PE tape, PO hot melt, acetoxy cure silicone, oxime cure silicone, alkoxy cure silicone (Ti), alkoxy cure silicone (Ti, high green strength)]

J-boxes
- A c-Si and thin film version have been selected

Substrates
- TPE, PET, THV, glass

Test sites
- Miami (FL), Phoenix (AZ), Golden (CO – outdoors), indoor test chamber

Test orientation
- 45° (shear & tensile) or 0° (vertical: shear only, indoors)

Test duration
- 1 year (outdoors) or 1000 hours (indoors)
Summary

• Proposed modification to qual. test: add weight to j-box during DH

• Discovery experiments to select weights & adhesive systems

• Silicones: allow adequate curing prior to handling
cross-linking limits deformation above $T_m$

• Foam tapes: some incompatible material systems, e.g., PE/j-box
  adhesion within manufacturer’s design guidelines, e.g., acrylic
  possible feature: significant mechanical dissipation (all)

• Hot melts: delamination & creep observed
  $T_m$ too low for materials examined (not cross-linked)
  know the product (field) requirements

• The formal experiment (intended to validate the test) will:
distinguish between proposed weights (0.5 or 1 kg)
compare indoor and outdoor environments
compare adhesive/substrate systems
Acknowledgments

• NREL: Dr. Peter Hacke, Dr. Michael Kempe, Dr. Heidi Pilath, Ed Gelak, Kent Terwilliger, David Trudell

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Pending manuscript: “Initial Examination of a Junction-Box Adhesion Test for Use in Module Qualification”, Proc. SPIE 2012.
A Comparison of the DMA Results at Different Test Rates

- 10’s of Hz: mechanical resonance vs. 1’s of mHz: thermal time constant
- $T_m$ for PA is more obvious from the $\tan[\delta]$
- The melt temperatures are not strongly strain rate dependent
- $T_g$ reduced with strain rate for PA melt, more so for acrylic tape
- The tape is less dissipative at low strain rates (reduced $T_g$, reduced area of $\tan[\delta]$ envelope)