NATIONAL RENEWABLE ENERGY LABORATORY

Innovation for Our Energy Future

"Examination of a Junction-Box Adhesion Test for Use in Photovoltaic Module Qualification"

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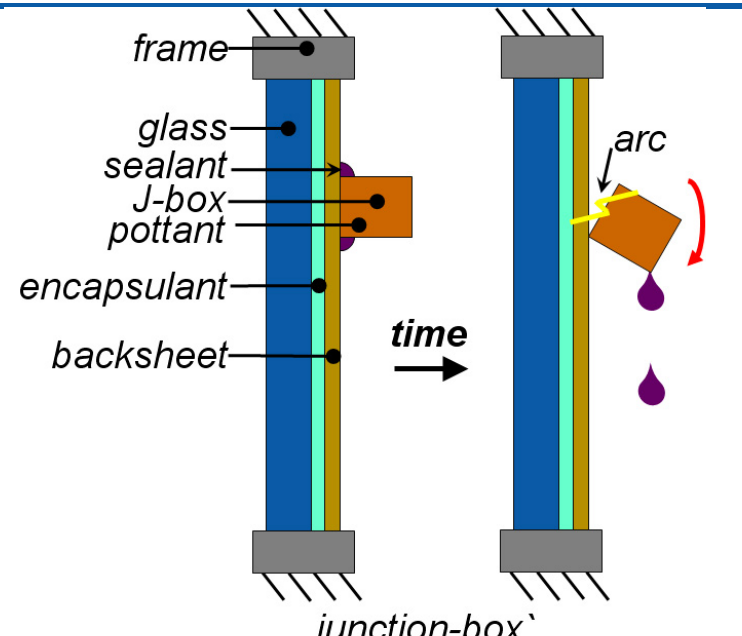
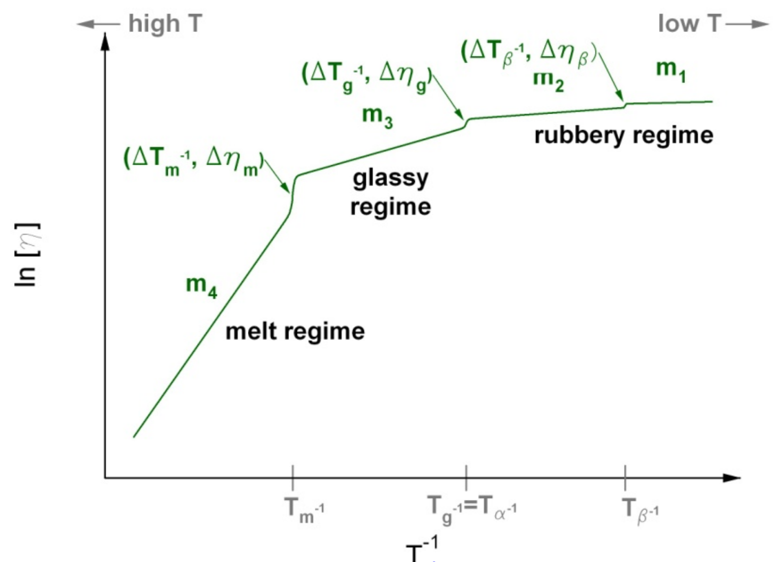
Motivation for the Project

- 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 the damp heat and creep tests



possible field failure mode(s) at the junction-box

D.C. Miller et. al., Proc. IEEE PVSC, 2010, 262-268.



viscosity (flow rate) vs. 1/T for thermoplastic polymer

Field-Installation Can Facilitate J-box Dettachment (Motivation)

Ideally:

•Cable routing trays and cable ties limit the load exerted on j-box

•Subject to intermittent wind, snow, external (*e.g.*, animal) loads

Example:

Cable management is not present (load relief then occurs at the j-box)

•In examples (photos) j-box supports the pigtails + ILF + joint+ harness.

•The typical weight of these components (combined) is ~0.2 kg (0.4 lbs).

•Most j-box systems are not designed to carry notable weight

Field installation with poor (no) cable management

Detail of the cable routing. Photos courtesy of industrial partner.

(Temperature) Conditions Present in the Field

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

  D.L. King et. al., SAND2004-3535 2004; 1-43.
  D. Faiman D, Prog. Photovolt: Res. Appl. 2008; 16: 307–315.

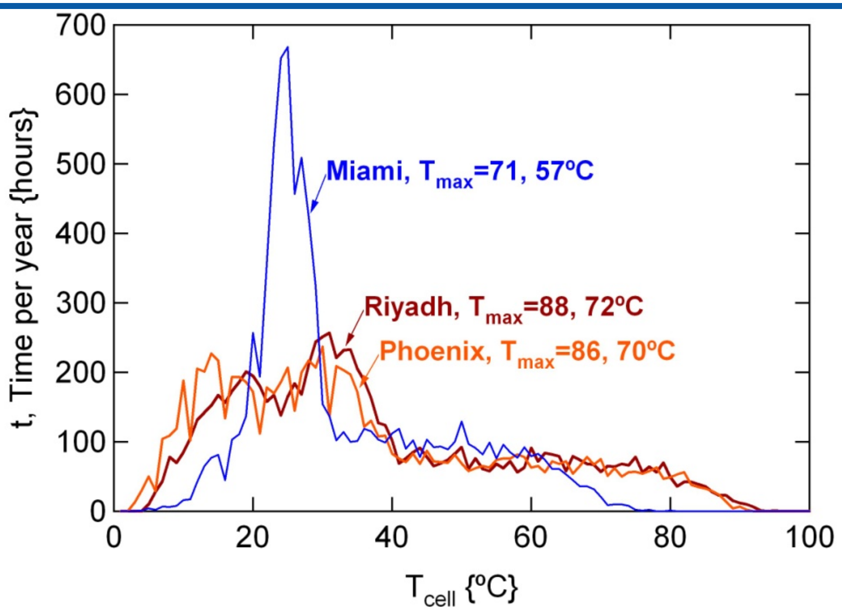
- T_{max} of 105°C achievable for open circuited, roof-mounted modules in desert location

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

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

  E. Molenbroek et. al., Proc. IEEE PVSC 1991; 547-552.
  Oh and TamizhMani, Proc. IEEE PVSC, 2010; 984 – 988.

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



Time-temperature histories for the cell in roof-mounted modules for a typical year. T_{max} given for roof and rack-mounted modules.

LOCATION	T_{max}, ROOF {°C}	T_{max}, RACK {°C}	$T_{max, record}$, AMBIENT {°C}
Death Valley, CA	108	90	57
Riyadh	103	84	48
Phoenix, AZ	103	85	50
Yuma, AZ	100	83	51
New Delhi	97	79	45
Seville	97	79	45
Kuwait City	99	83	51
Daytona, FL	90	73	39
Denver, CO	89	72	40
Miami, FL	86	70	37
Bangkok	85	69	38
New York, NY	89	73	41
Munich	79	64	36
Fairbanks, AK	70	59	36

*T_{max} predicted from 30 year **record** temperature data*
D.C. Miller et. al., Proc. IEEE PVSC, 2010, 262-268.

Summary of Experiments

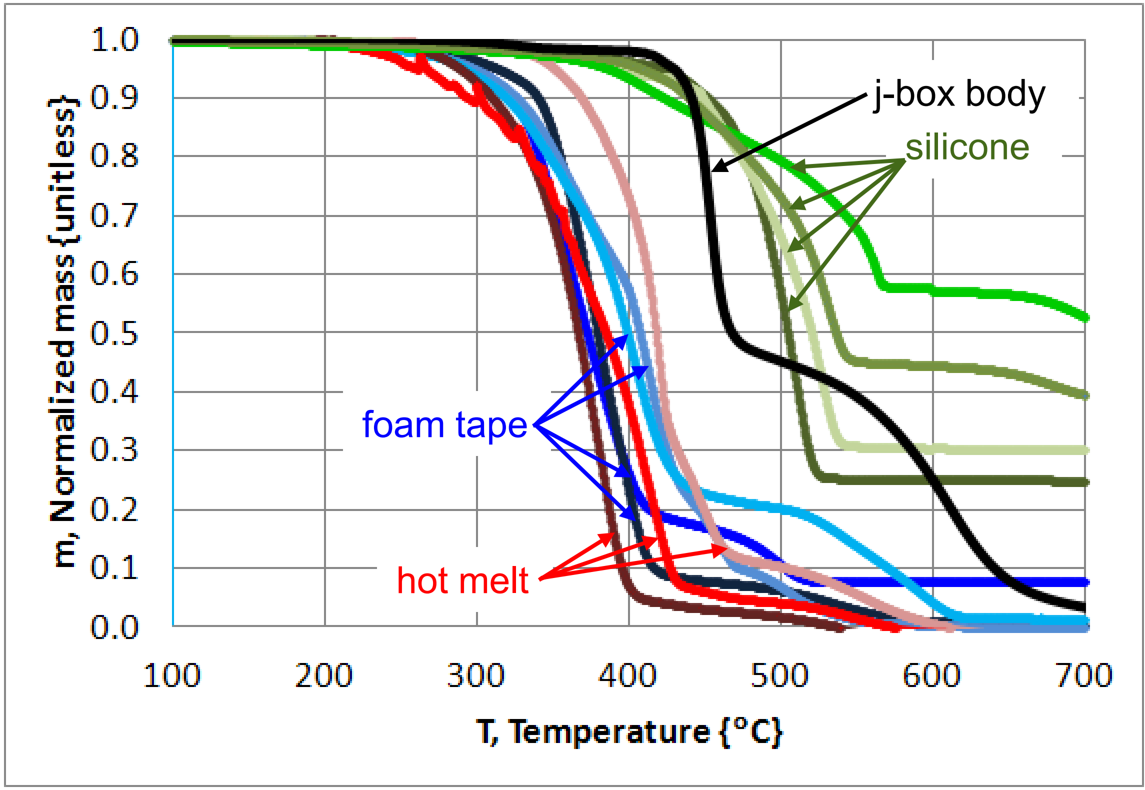
- Specimens:
  - foam tapes (closed cell: acrylic, polyurethane, polyethylene)
  - silicones (condensation cure: acetoxy, oxime, alkoxy cure)
  - hot melt (thermoplastics: EVA, polyolefin, polyamide)

- 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:
  - $T_{5\%} > 200°C$ (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 (Ti), and EVA hot melt approach this criteria: evaluate at slower test rate to verify



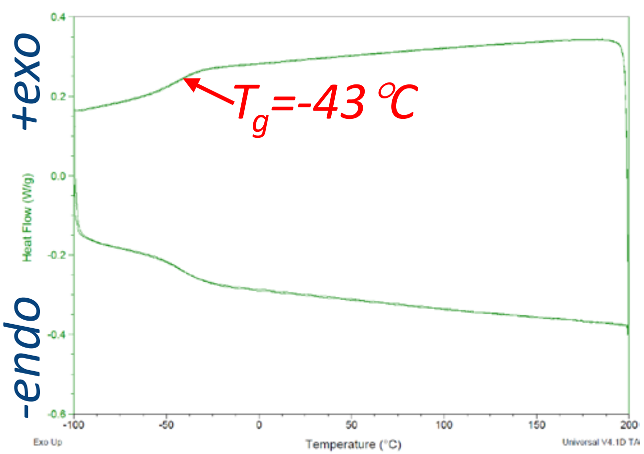
TGA characterization of silicones, foam tapes, and hot melts

DSC Identifies the Likelihood of Creep

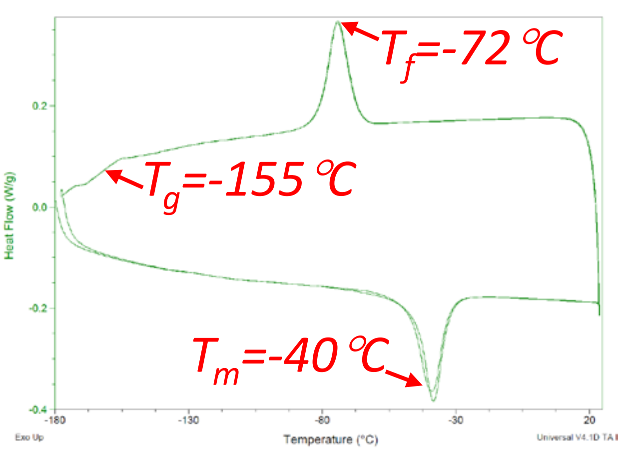
- Glass transitions (T_g aka T_α) may signify likelihood for creep
- The T_g's here are well below the typical operating temperature within fielded modules

- 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)

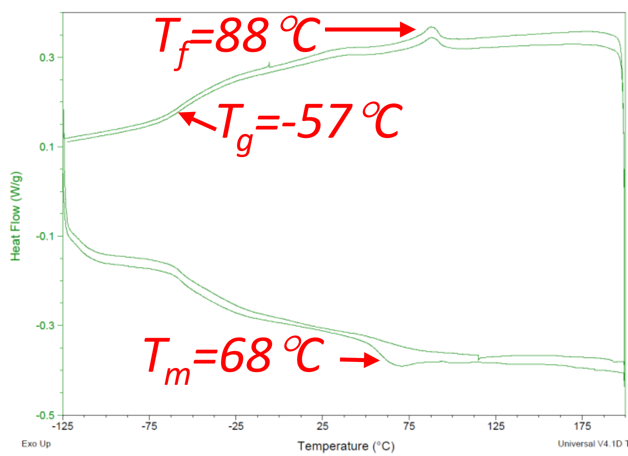
How will the hot melts fare in component tests?



DSC for 1st acrylic foam tape

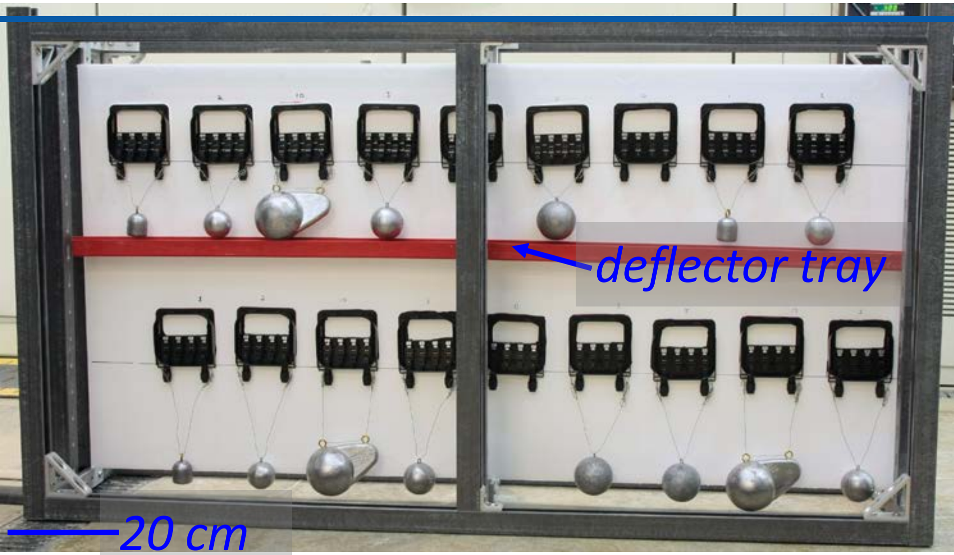


DSC for condensation silicones



DSC for PA hot melt

Two Sets of Discovery Experiments Examine the Adhesives



TF j-box (2 rail) on glass:

- Pb Weights: 0, 0.5, 0.9, 1.4, 2.3, 4.5 kg
- Adhesives:

acrylic tape 2, PU tape, acetoxy silicone, alkoxy silicone, oxime silicone, PO melt, PA melt

- Attached to Sn side of (cleaned) glass
- Primer applied when recommended

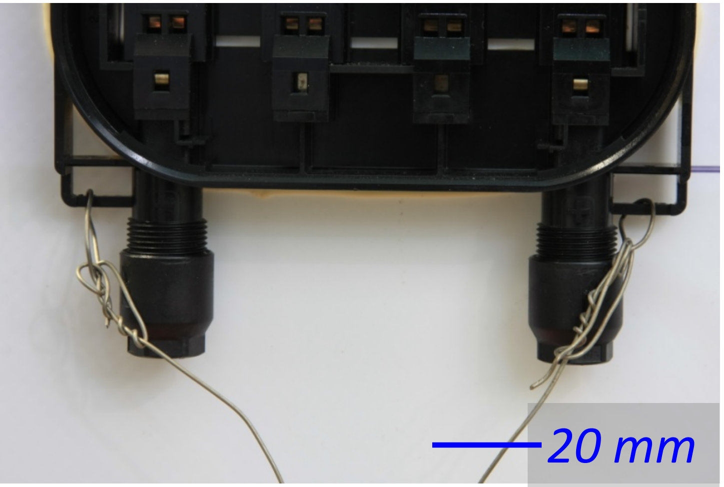
c-Si j-box (4 rail) on PET:

- Pb Weights: 0, 0.5, 0.9, 1.4, 2.3, 4.5 kg
- Adhesives:
  - acrylic tape 1
  - acrylic tape 2
  - PE tape
  - acetoxy silicone (Sn)
  - alkoxy silicone (Ti)
  - oxime silicone (Sn)
- Primer applied when recommended

*Deflector tray does not support weights

The Details of the Weight Attachment

- All weights were attached using 0.81mm ∅ 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:

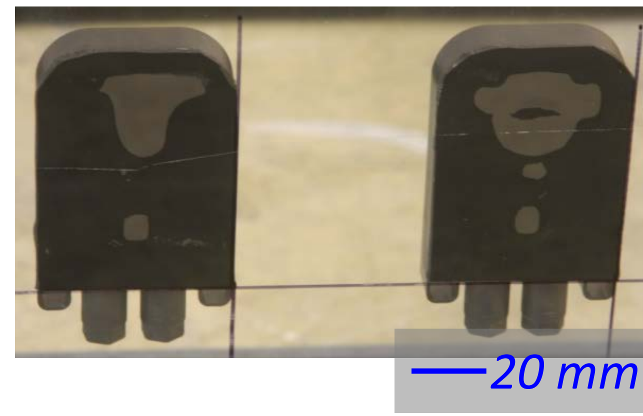
- Wire attached thru vias (cable & glands removed)

All:

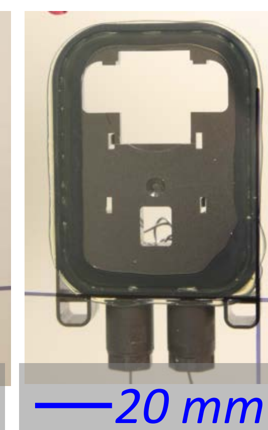
- Predominant shear loading mode
- Boxes left uncovered through the test

Details of the Specimen Attachment

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

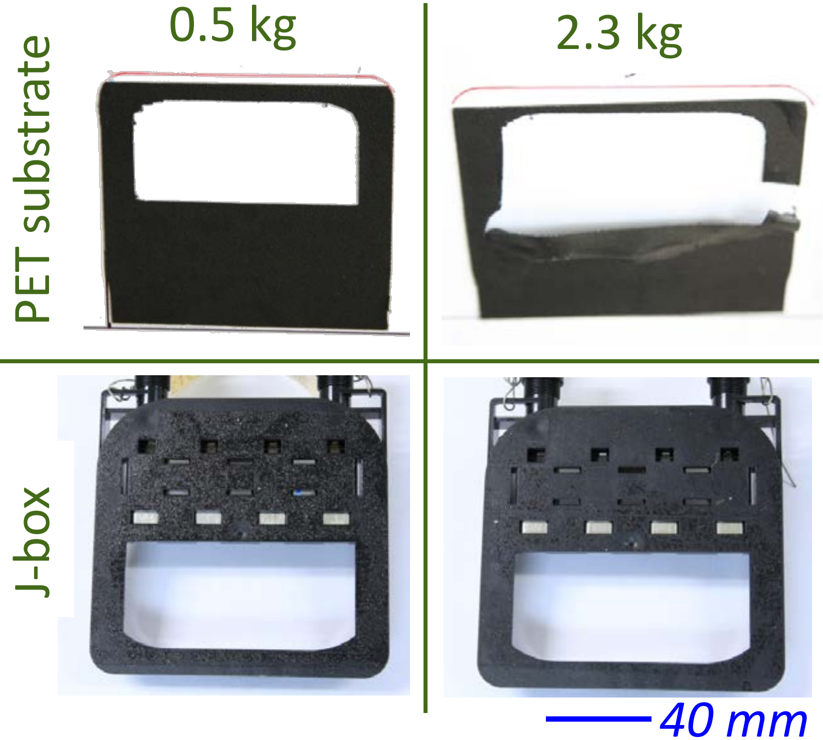


- Tapes: good wet-out, except @cut-out regions (TF)
- No tape used at cut-outs in c-Si specimens

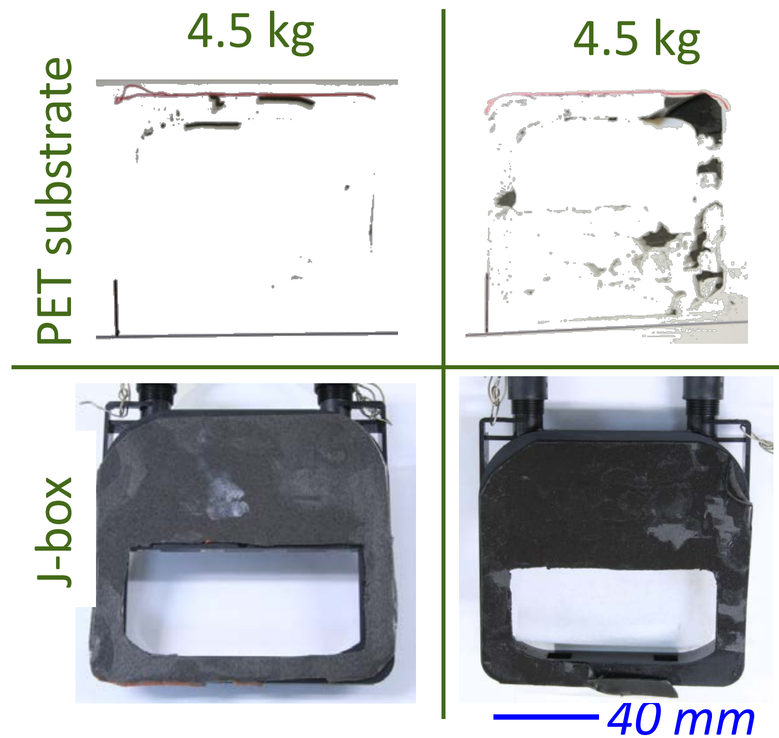


- Melts: adhered by (flatten) bead placed around periphery using heated "gun"
- Original bead for melts smaller than that for silicones

Loss of Adhesion for Tape During the c-Si Test



- all weighted PE tape lost adhesion ≤ 24 hrs
- decohesion @ top adhesive surface layer (tape core remains on the backsheet)
- 2.3, 4.5 kg weights: torn tape (mixed mode failure)
- use system of compatible materials (j-box, adhesive, and substrate)



- acrylic tape (1 & 2) lost adhesion 6-7, 7-14 days (4.5 kg weight only)
- delamination @ tape/substrate interface (tape remains on j-box)
- load exceeded the manufacturer's design guideline

Deformation of Tape During the c-Si Test

- Elongation of acrylic tape 2 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) ⇒ asymmetric j-box geometry?
- Careful not to stretch tape during application
- Polymer adhesives: H_2O may plasticize in 85/85

Summary of the c-Si Results

- Included for reference.
- 7 out of 36 c-Si specimens detached in damp-heat

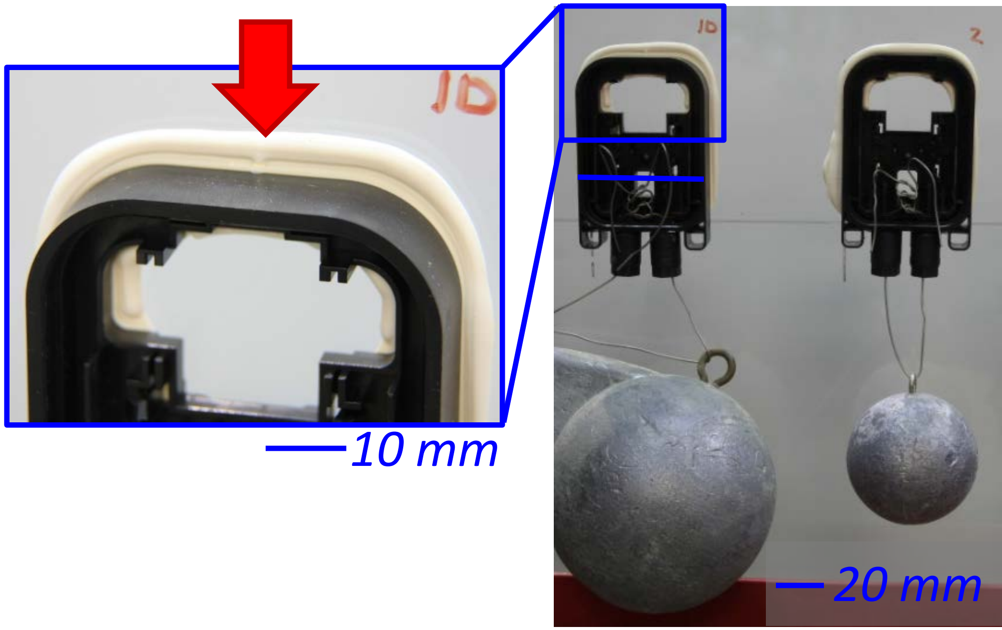
MATERIAL	DESCRIPTION or CURING SCHEME	observation/time/comment APPLIED WEIGHT {kg}					
		0	0.5	0.9	1.4	2.3	4.5
acrylic 1	foam tape	none	none	none	none	none	delamination 0<*t*<7d at tape surface/PET
acrylic 2	foam tape	none	none	none	elongation 7d<*t*<14d	elongation 14d<*t*<21d	delamination 7d<*t*<14d at tape surface/PET, mm
PE	foam tape	none	decohesion 0<*t*<24h of tape surface layer	decohesion 0<*t*<24h of tape surface layer	decohesion 0<*t*<24h of tape surface layer	decohesion 0<*t*<24h with mixed mode	decohesion 0<*t*<24h with mixed mode
PU	foam tape	N/A	N/A	N/A	N/A	N/A	N/A
PA	thermoplastic hot-melt	N/A	N/A	N/A	N/A	N/A	N/A
PO	thermoplastic hot-melt	N/A	N/A	N/A	N/A	N/A	N/A
EVA	thermoplastic hot-melt	N/A	N/A	N/A	N/A	N/A	N/A
silicone	acetoxy (Sn catalyst)	none	none	none	none	none	none
silicone	oxime (Sn)	none	none	none	none	none	none
silicone	alkoxy (Ti)	none	none	none	none	none	none

Summary of the results for c-Si, with an observation, time specification, and comment for failed specimens.

none – material examined, no notable behavior observed
N/A – not applicable (material not examined)
mm - mixed-mode failure observed

Perceived Deformation of Silicone During the TF Test

•4.5 kg weighted alkoxy (Ti) silicone appeared displaced @ 5-7 days



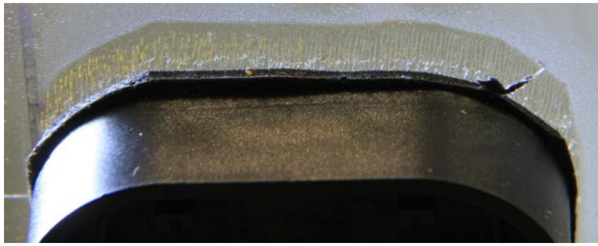
•Actually displaced (bumped) during specimen preparation and unchanged through the test

•Condensation silicones require H_2O to cure (CO is dry)

•21 day cure recommended prior to material tests in dry climates

(safe to assemble and use in modules more rapdily)

Loss of Adhesion for Tape During the TF Test



20 mm

creep of 0.5 kg weighted PU tape at 14 days

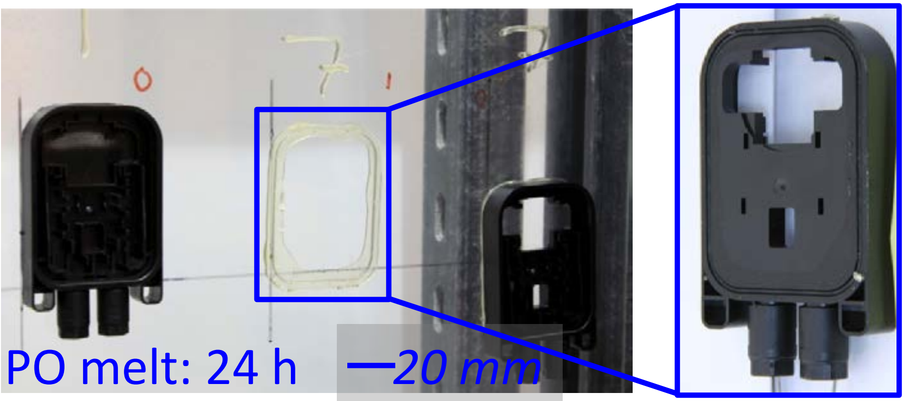
PU tape:

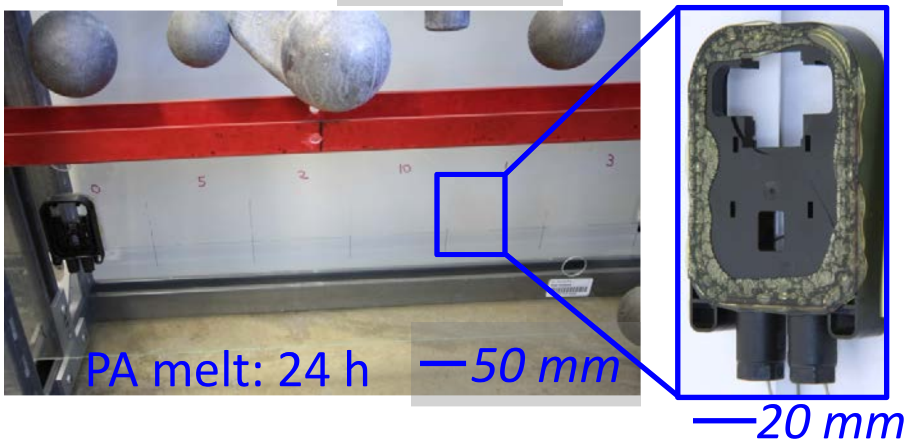
- Weights > 0.5 kg lost adhesion within 24 hours
- Decohesion @ top adhesive surface layer (tape core remains on j-box)
- 0, 0.5 kg weighted specimen remained attached through test
- *0.5 kg weighted specimen displaced (adhesive/glass) during the test*

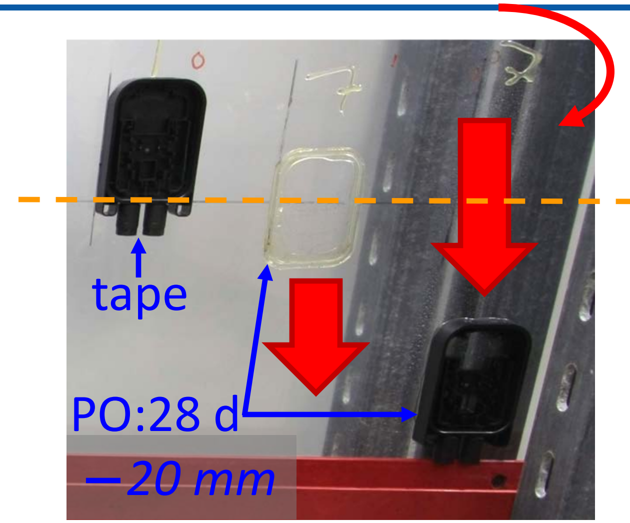
acrylic tape 2:

- 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

Summary of the TF Results

- Included for reference
- 17 out of 42 TF specimens detached or creeped in damp-heat

MATERIAL	DESCRIPTION or CURING SCHEME	observation/time/comment					
		APPLIED WEIGHT {kg}					
		0	0.5	0.9	1.4	2.3	4.5
acrylic 1	foam tape	N/A	N/A	N/A	N/A	N/A	N/A
acrylic 2	foam tape	none	none	none	none	delamination 0<*t*<24h at tape surface/j-box	delamination 0<*t*<24h with mixed mode
PE	foam tape	N/A	N/A	N/A	N/A	N/A	N/A
PU	foam tape	N/A	creep 0<*t* at tape surface/glass	decohesion 0<*t*<24h of tape surface layer	decohesion 0<*t*<24h of tape surface layer	decohesion 0<*t*<24h of tape surface layer	decohesion 0<*t*<24h with mixed mode
PA	thermoplastic hot-melt	creep 0<*t*	delamination 0<*t*<24h at melt/glass	delamination 0<*t*<24h at melt/glass	delamination 0<*t*<24h at melt/glass	delamination 0<*t*<24h at melt/glass	delamination 0<*t*<24h at melt/glass
PO	thermoplastic hot-melt	creep 0<*t*	delamination 0<*t*<24h at melt/j-box	delamination 0<*t*<24h at melt/j-box	delamination 0<*t*<24h at melt/j-box	delamination 0<*t*<24h at melt/j-box	delamination 0<*t*<24h at melt/j-box
EVA	thermoplastic hot-melt	N/A	N/A	N/A	N/A	N/A	N/A
silicone	acetoxy (Sn catalyst)	none	none	none	none	none	none
silicone	oxime (Sn)	none	none	none	none	none	none
silicone	alkoxy (Ti)	none	none	none	none	none	elongation *t*<0

Summary of the results for c-Si, with an observation, time specification, and comment for failed specimens.

none – material examined, no notable behavior observed
N/A – not applicable (material not examined)
mm - mixed-mode failure observed

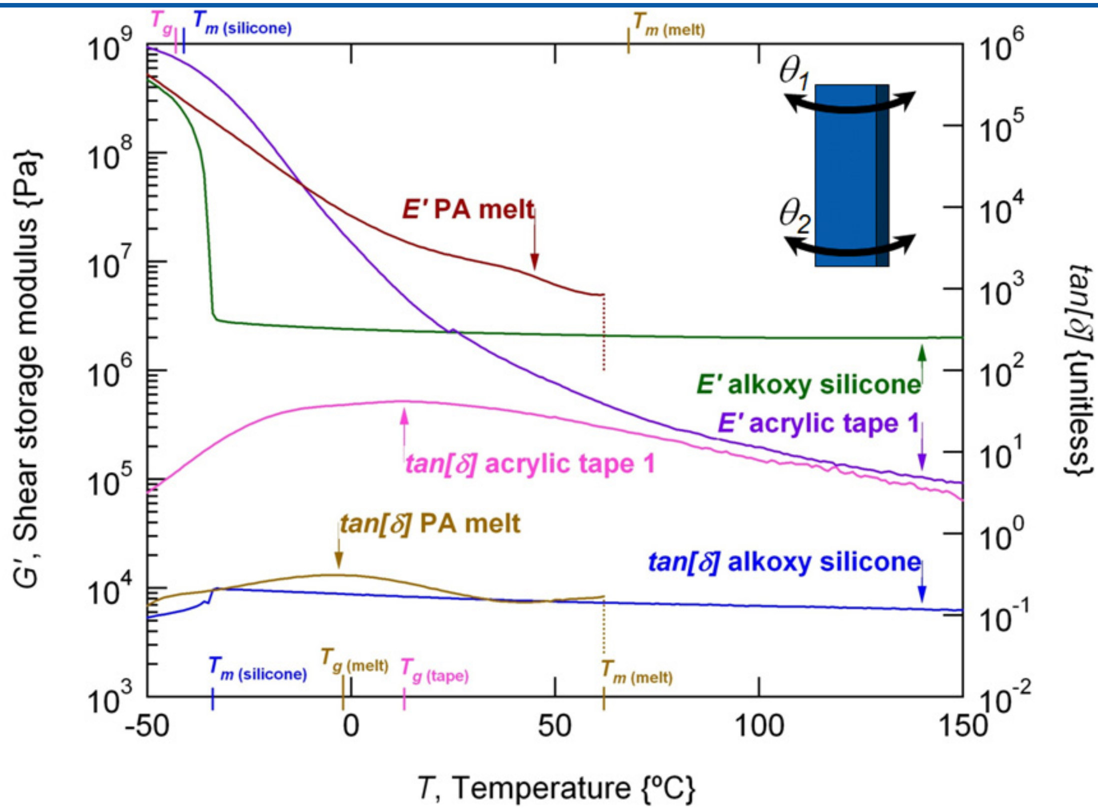
DMA Confirms the Behaviors Observed in the Component-Level Tests

silicones:

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

tapes:

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



10's of Hz: order of magnitude for mechanical resonance
K.-A. Weiss et. al., Proc. SPIE, 7412, 2009, 741203.

melts:

- Softening of modulus with glass transition
- More significant softening of modulus (terminates test) with melt transition
- Phase transition confirmed in DSC, and manifest 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 9 (some likely failures, many expected successes)

[acrylic tape (1 & 2), PE tape, PU tape, acetoxy silicone (Sn), oxime silicone (Sn) , alkoxy silicone (Ti), alkoxy silicone (Ti, high green strength) , PO hot melt]

J-boxes

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

Substrates

- TPE, THV, KPK, glass

Test sites

- Miami (FL), Phoenix (AZ), Golden (CO – field), indoor test chamber

Test orientation

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

Test duration

- 1 year (field) or 1000 + 200 hours (indoors)

Summary

- Proposed change to qual. test: add weight to j-box during DH and creep
- 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 between indoor and field results
  - compare more adhesive/substrate systems

Acknowledgments

- NREL: Dr. Peter Hacke, Dr. Michael Kempe, Dr. Heidi Pilath, Thomas Bethel, Ed Gelak, Greg Perrin, Kent Terwilliger, David Trudell

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See also the manuscript: “Examination of a Junction-Box Adhesion Test for Use in Photovoltaic Module Qualification”, Proc. SPIE 2012, 8472-22.

A Comparison of the DMA Results at Different Test Rates

- 10's of Hz: mechanical resonance vs.

  1's of mHz: thermal time constant

  K.-A. Weiss et. al., Proc. SPIE, 7412, 2009, 741203.
  D.C. Miller et. al., Proc. IEEE PVSC, 2010, 262-268.

- T_m for PA is more obvious from the *tan[δ]*
- The melt temperatures are not strongly strain rate dependent
- T_g reduced with strain rate for PA melt, more so for 1st acrylic tape
- The tape is less dissipative at low strain rates (reduced T_g, reduced area of *tan[δ]* envelope)