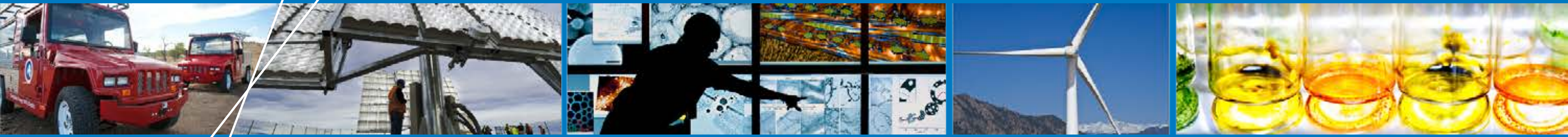
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

"Trial-Run of a Junction-Box Attachment Test for Use in Photovoltaic Module Qualification"



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IEEE PVSC Conference (June 8-13,2014, Denver, CO)

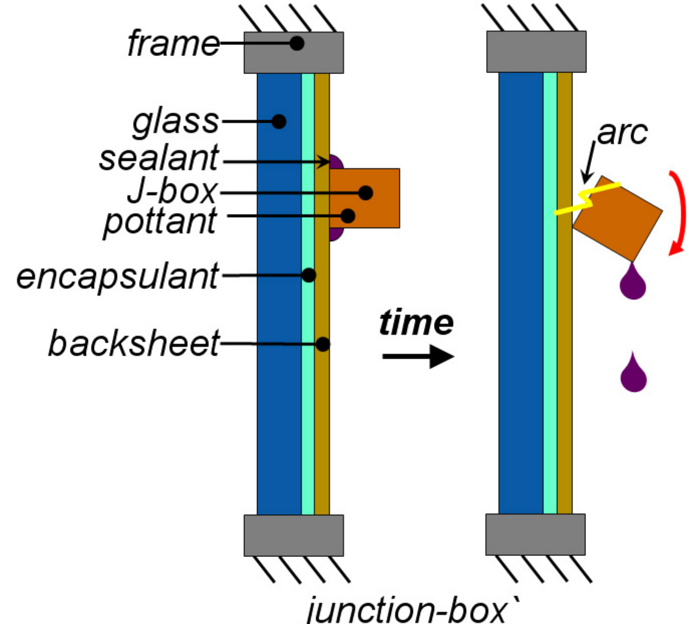
Colorado Convention Center , #617 in Session "Area 12", Mile High Ballroom 2B

2014/06/11 (Weds) 11:15 – 11:30 am

NREL/PR-5200-62111

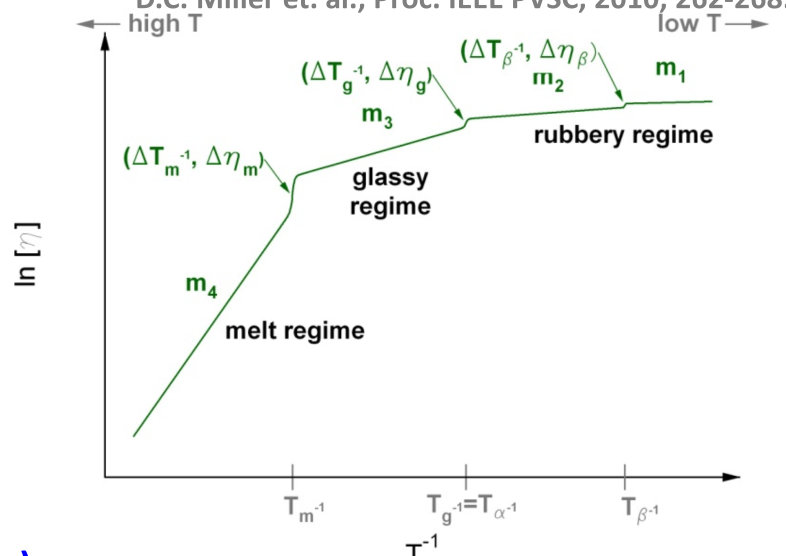
Motivation for the Project

- J-box attachment often proves a milestone to module manufacturers … possible consequences of field failure
- Possible failure mechanisms: phase transformation, creep, *cohesive failure*, **delamination** of -attachment system-
- Present qualification test: “robustness of termination” [Pull ⊥ against j-box 40 N load]. Perform at room temperature, after: [UV preconditioning, thermal-cycle, humidity-freeze]
- Discovery experiments suggest that problematic systems can be readily identified with an applied weight during the safety & qualification protocols.



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

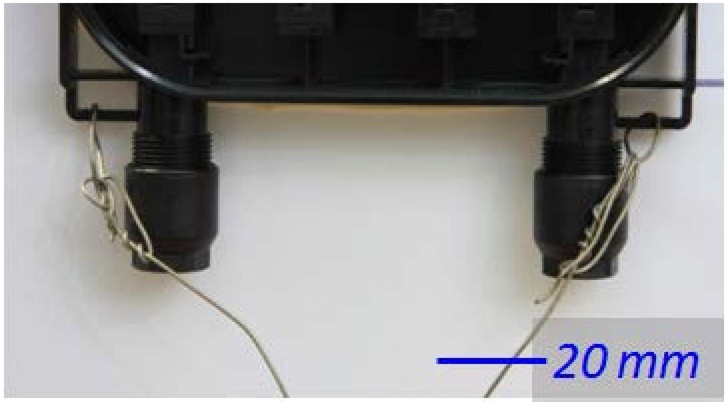
***Miller et. al., Proc. SPIE, 2012, 8472-22*. (*paper* and *presentation*)**

Proposed Use of the Weighted Junction-Box Test

- Apply in:
  "damp-heat" (85°C, 85% RH for 1000 hours), and
  "thermal-cycle" (-40°C↔85°C for 200 cycles), protocols as in IEC 61215;
  "creep" (105°C, nominally dry for 200 hours) as in IEC 61730-2.
- Attach weight (*e.g.*, 1 kg) to the junction box.
  J-box is in condition (sealed) as in use.
  Use wires, clips, *etc*. for attachment.

Details of the attachment (using steel wire) for the weights in a 4-rail specimen.

***Miller et. al., Proc. SPIE, 2012, 8472-22*. (*paper* and *presentation*)**



- Modules oriented upright (maximum packing density in chamber).
  Typically renders applied shear load, with possible out of plane strain.
- Emulate intermittent wind, snow, external (*e.g.*, animal) loads in installations with limited cable management
  (routing trays and cable ties).

Details of (Recent) Discovery Test for the (Present) Trial-Run

Scope

- (10) adhesives examined: acrylic, polyethylene, polyurethane foam tapes; acetoxy, oxime, alkoxy cured silicones; ethylene-co-vinyl acetate, polyethylene/polyoctene, polyamide hot melts.
- (2) substrates examined: PET backsheet or glass, with corresponding 4- or 2-rail j-boxes.
- (6) "weights" examined in damp-heat: 0, 0.5, 0.9, 1.4, 2.3, 4.5 kg.
- Materials characterizations: TGA (T_d), DSC (T_g, T_m, & T_f), DMA (G' & tan [δ]).

Outcomes

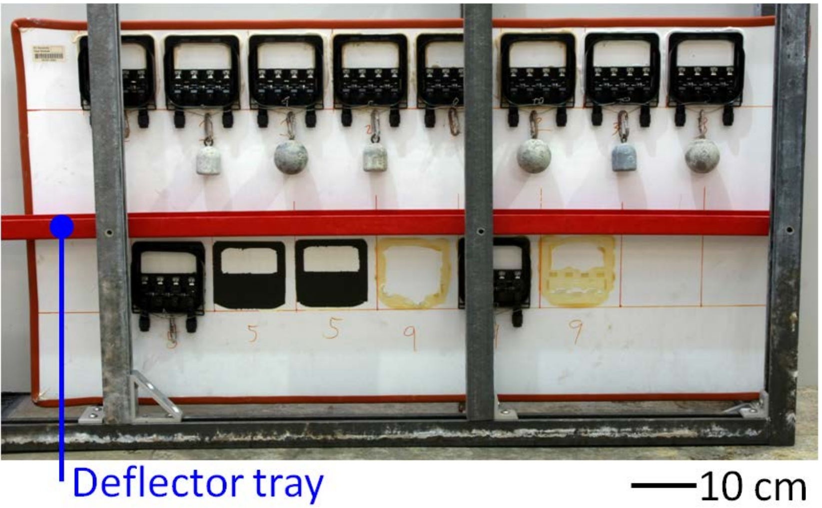
- Durable and incompatible foam tape, silicone, and hot melt enabled attachment systems were identified.
- Merits of each adhesive type identified from chamber & material tests.
- Failure modes of delamination, creep, and low green strength were observed.
- Down-selected to the proposed weights: 0.5 or 1 kg.

Discovery experiments, see:
Miller et. al., Proc. SPIE, 2012, 8472-22.

All module-level experiments were previously performed in damp-heat.

Goals and Considerations for the Present Trail Run Experiment

- Examine a representative set of known good, known incompatible, and intermediate attachment systems.
- Validate the test protocol by comparing indoor- and field-aging ("climate") conditions.
- Compare indoor- and field-configurations (0° vs. 45°, respectively).
- Examine a variety of outdoor environments, 1 year in: hot-dry (Phoenix), hot-humid (Miami), steppe climate (Golden).
- Examine a wider variety of attachment systems (substrate/adhesive/j-box).



Representative specimen, constructed for the trial-run, photographed after completing the "damp-heat" indoor aging. The deflector tray used to protect the second (lower) row of specimens is labeled.

Photo of specimens fielded in Phoenix after 1 week.

The Specimens Used in the Present Trail Run Experiment

Adhesives:

- acrylic, PE, PU foam tapes
- PO hot-melt
- acetoxy, alkoxy, alkoxy, oxmine silicones

Substrates:

- Kynar/PET/EVA
- Tedlar/PET/EVA
- THV/PET/EVA
- low-iron, soda-lime glass (untempered)

Weights: 0, 0.5, or 0.9 kg.

J-boxes: 4- and 2-rail, as in *Miller et. al., Proc. SPIE, 2012, 8472-22*.

(a) 1 m (b) 1 m

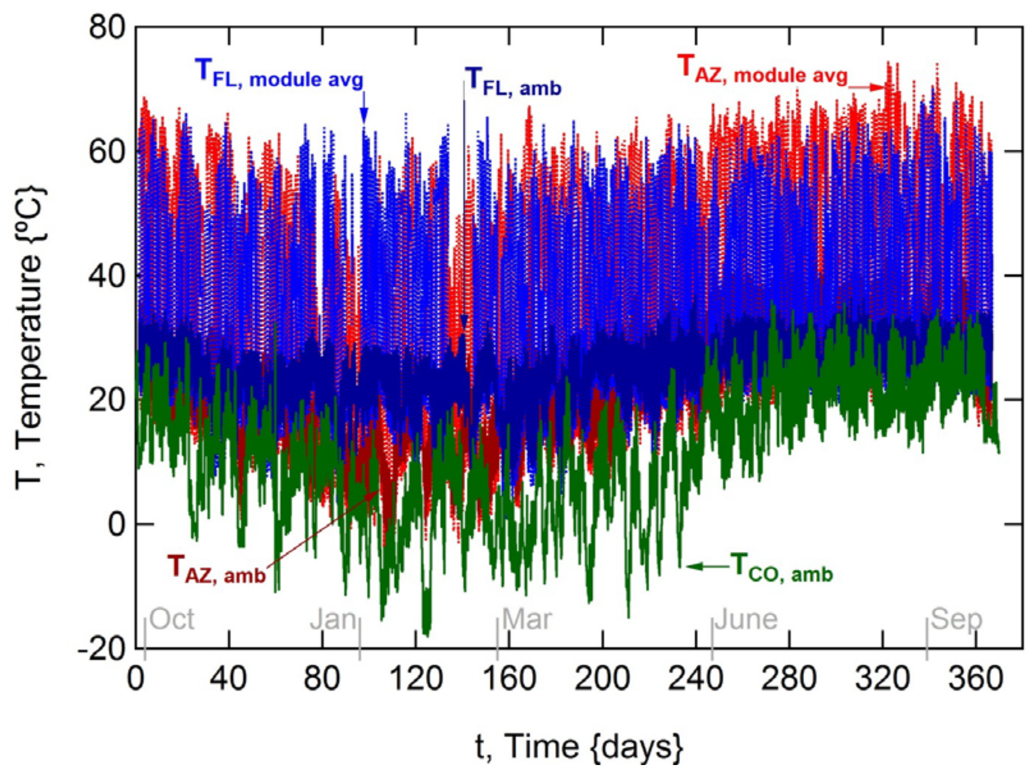
Photos of the (a) front and (b) back of the specimens fielded in Golden after 25 days.

Comparison of Ambient Conditions at the Field Sites

- Temperature (ambient and module back), relative humidity, and wind speed were recorded at the field sites.
- Phoenix had the greatest T_{max} and w_{avg}.
- Miami had the greatest RH_{avg}. (it was <85%).
- Golden had the lowest T_{min}. (greatest T range).
- Golden had the greatest w_{max}. (foothills location).

LOCATION	MEASURAND	T_{avg} {°C}	T_{max} {°C}	T_{min} {°C}	RH_{avg} {%}	w_{avg} {m·s^{-1}}	w_{max} {m·s^{-1}}
Golden	ambient	12.9	36.4	-18.1	42.0	2.0	17.2
Miami	ambient	23.8	36.8	4.2	74.8	2.4	15.0
Phoenix	ambient	22.7	45.8	-3.4	32.2	3.0	13.7
Miami	module	28.5	74.0	0.0	N/A	N/A	N/A
Phoenix	module	28.4	78.3	-6.5	N/A	N/A	N/A

Summary of the ambient and module temperature conditions. The average, maximum, and minimum temperatures; average relative humidity; and average and maximum wind speed are provided for the 1-year deployment period (conditions including both day and night).



Summary of the measured ambient and module average temperature conditions. The ambient (dark red) and module (red) values are given for Phoenix; the ambient (dark blue) and module (blue) values are given for Miami. The ambient (dark green) values are given for Golden.

Summary of the Results of the Trial-Run

- 108 specimens per location
- 432 total specimens
- 66 failures

- Observed failure modes: delamination or creep.

LOCATION: INDOOR, DAMP HEAT & CREEP

MATERIAL	DESCRIPTION or CURING SCHEME	SUBSTRATE: Kynar/PET/EVA, APPLIED WEIGHT (kg): 0	0.5	0.9	Tedlar/PET/EVA, APPLIED WEIGHT (kg): 0	0.5	0.9	THV/PET/EVA, APPLIED WEIGHT (kg): 0	0.5	0.9	untempered glass, APPLIED WEIGHT (kg): 0	0.5	0.9
		observation/time/interface											
acrylic 1	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
acrylic 2	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
PE	foam tape	delaminated t<1d at tape surface layer	delaminated t<1d at tape surface layer	delaminated t<1d at tape surface layer	N.F.	delaminated t<1d at tape surface layer	delaminated t<1d at tape surface layer	creep (rotation) t~20d	delaminated t<1d at tape surface layer	delaminated t<1d at tape surface layer	N.F.	delaminated t<1d at tape surface layer	delaminated t<1d at tape surface layer
PU	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	creep t~14d	N.F.	N.F.	N.F.	N.F.
PO	thermoplastic hot-melt	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t<6d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	creep t<1d	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box
silicone	acetoxy (Sn)	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
silicone	alkoxy (Ti)	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
silicone	alkoxy (Ti) GS	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
silicone	oxime (Sn)	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.

LOCATION: Miami, FL

MATERIAL	DESCRIPTION or CURING SCHEME	SUBSTRATE: Kynar/PET/EVA, APPLIED WEIGHT (kg): 0	0.5	0.9	Tedlar/PET/EVA, APPLIED WEIGHT (kg): 0	0.5	0.9	THV/PET/EVA, APPLIED WEIGHT (kg): 0	0.5	0.9	untempered glass, APPLIED WEIGHT (kg): 0	0.5	0.9
		observation/time/interface											
acrylic 1	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
acrylic 2	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
PE	foam tape	N.F.	delaminated t~268d at tape surface layer	delaminated t~25d at tape surface layer	N.F.	N.F.	N.F.	N.F.	N.F.	delaminated t~186d at tape surface layer	N.F.	delaminated t~21d at tape surface layer	delaminated t<4d at tape surface layer
PU	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
PO	thermoplastic hot-melt	delaminated t~0d at melt/j-box	delaminated t~0d at melt/j-box	delaminated t~0d at melt/j-box	delaminated t~12d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t~0d at melt/j-box	delaminated t~333d at glass/melt	delaminated t<4d at melt/j-box	delaminated t~0d at glass/melt
silicone	acetoxy (Sn)	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
silicone	alkoxy (Ti)	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
silicone	alkoxy (Ti) GS	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
silicone	oxime (Sn)	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.

LOCATION: Phoenix, AZ

MATERIAL	DESCRIPTION or CURING SCHEME	SUBSTRATE: Kynar/PET/EVA, APPLIED WEIGHT (kg): 0	0.5	0.9	Tedlar/PET/EVA, APPLIED WEIGHT (kg): 0	0.5	0.9	THV/PET/EVA, APPLIED WEIGHT (kg): 0	0.5	0.9	untempered glass, APPLIED WEIGHT (kg): 0	0.5	0.9
		observation/time/interface											
acrylic 1	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
acrylic 2	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
PE	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	delaminated t<6d at tape surface layer
PU	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
PO	thermoplastic hot-melt	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t~157d at TPE/melt	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t~0d at melt/j-box	delaminated t~0d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t~60d at glass/melt	delaminated t<1d at glass/melt	delaminated t<1d at glass/melt
silicone	acetoxy (Sn)	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
silicone	alkoxy (Ti)	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
silicone	alkoxy (Ti) GS	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
silicone	oxime (Sn)	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.

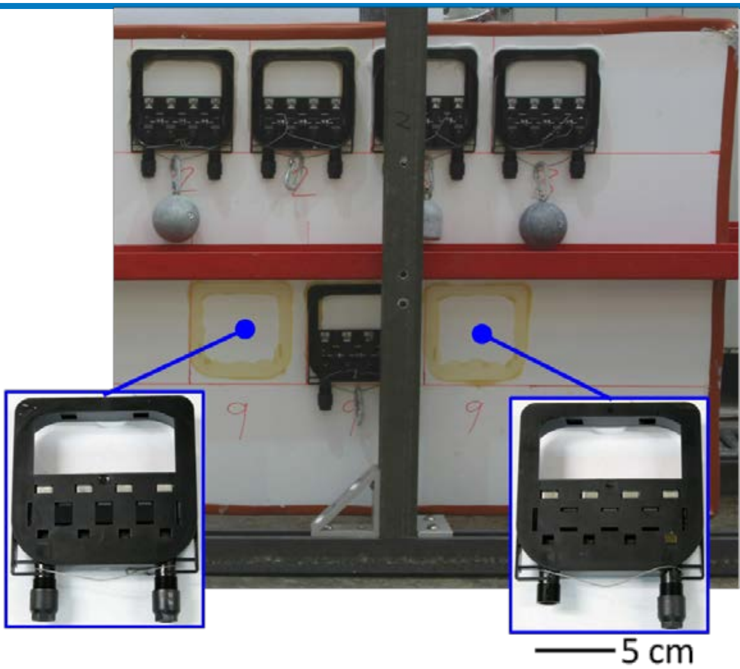
LOCATION: Golden, CO

MATERIAL	DESCRIPTION or CURING SCHEME	SUBSTRATE: Kynar/PET/EVA, APPLIED WEIGHT (kg): 0	0.5	0.9	Tedlar/PET/EVA, APPLIED WEIGHT (kg): 0	0.5	0.9	THV/PET/EVA, APPLIED WEIGHT (kg): 0	0.5	0.9	untempered glass, APPLIED WEIGHT (kg): 0	0.5	0.9
		observation/time/interface											
acrylic 1	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
acrylic 2	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
PE	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	delaminated t~54d at tape surface layer	delaminated t<4d at tape surface layer
PU	foam tape	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
PO	thermoplastic hot-melt	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t~339d at TPE/melt	delaminated t<4d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t<1d at /melt/	delaminated t<1d at melt/j-box	delaminated t<1d at melt/j-box	delaminated t~285d at glass/melt	delaminated t<1d at glass/melt	delaminated t<1d at glass/melt
silicone	acetoxy (Sn)	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
silicone	alkoxy (Ti)	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
silicone	alkoxy (Ti) GS	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.
silicone	oxime (Sn)	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.

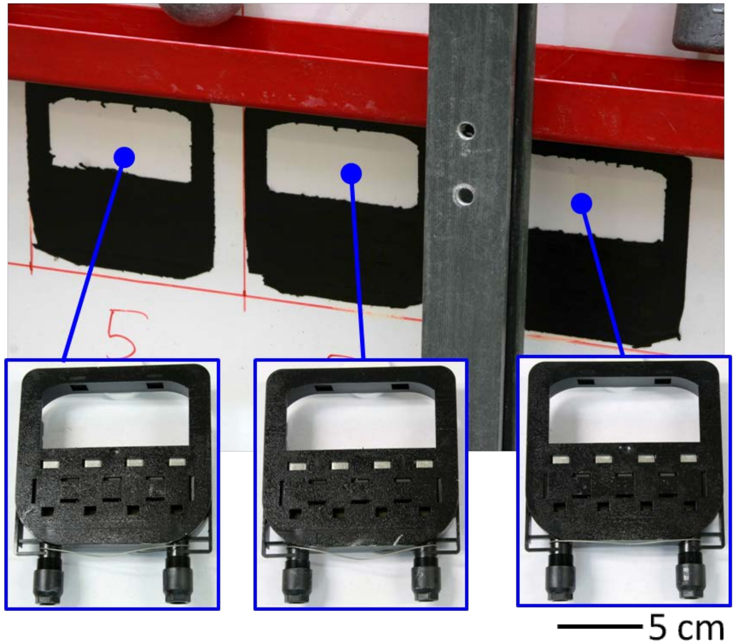
Results for the aged mock module specimens. The results for the damp-heat test are indicated in green font (failures are shaded yellow, with indications including: failure mode; time to failure, in days; and the failure interface). The results for the subsequent creep test are similarly indicated in red font. The results for the field-aged specimens are not distinguished by color. "N.F." indicates that no failure occurred during the trial-run experiment. "GS" indicates the high green-strength alkoxy silicone.

Characteristics of Failure By Delamination

- 46 failures at melt/j-box interface for PO melt.
- 10 failures at substrate/melt interface, specifically on glass or TPE substrates.
- Melt/j-box failure observed indoors; glass/melt common outdoors.
- Latent delamination of TPE/melt only in Phoenix & Golden.
- All PO results likely affected by T_m = 81°C.



- 17 for failures for PE foam tape.
- All failures at surface/core interface.
- Likely affected by T_m = 51°C.



Examples of delamination: (above) loss of adhesion between the j-box surface and PO melt; (below) loss of adhesion between the PE foam tape surface- and core-layers.

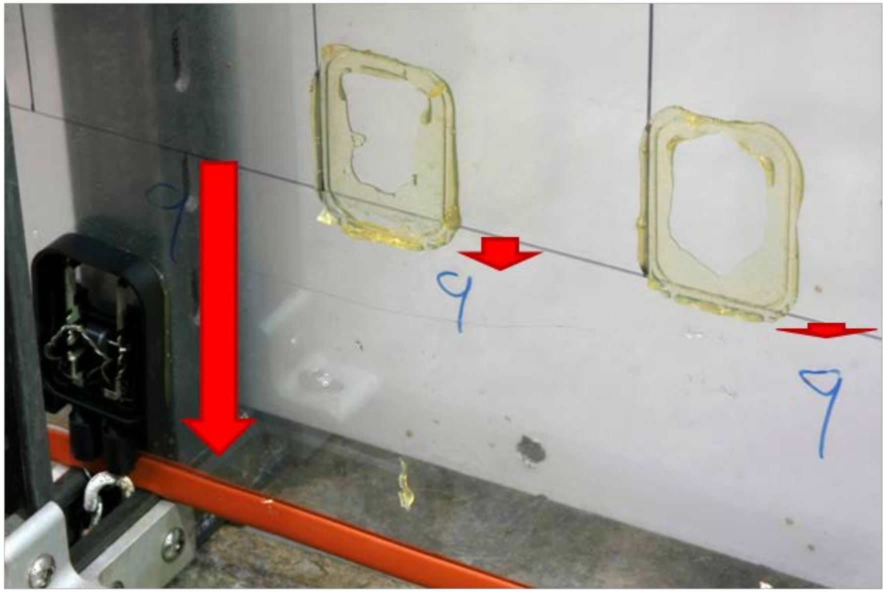
***Miller et. al., Proc. SPIE, 2012, 8472-22*. (*paper* and *presentation*)**

Characteristics of Creep Failure

- Creep for (1) PE and (1) PU foam tape specimen.
- T_m = 51°C; T_g = -26°C, respectively.
- Rotation, observed for indoor damp heat test only.

5 cm

- Creep for (1) PO melt specimen.
- T_m = 81°C.
- Translation for indoor DH test only. Same samples instead delaminated outdoors.



5 cm

Examples of creep failure: (above) rotation of the PU foam tape on KPE substrate; (below) displacement of PO melt or detachment at the PO melt/j-box surface with subsequent displacement of the PO melt.

Observations and Implications of the Test Results

Indoor results:

- Most failures in damp heat occurred quickly, *i.e.*, <1 day.

⇒Sustained high humidity contributes to failure.

- Additional failures, comparable with field results, observed for creep test.

⇒Suggests creep test is required in addition to DH and/or TC.

Field results:

- Most failures occurred at Miami.
- Miami showed the most delamination failures.
- DH results exceeded Miami field results.

- Failures observed quickest for PO melt in Phoenix.
- 1 additional delamination observed, PE tape in Golden.
- Creep test better correlated to Phoenix field results.

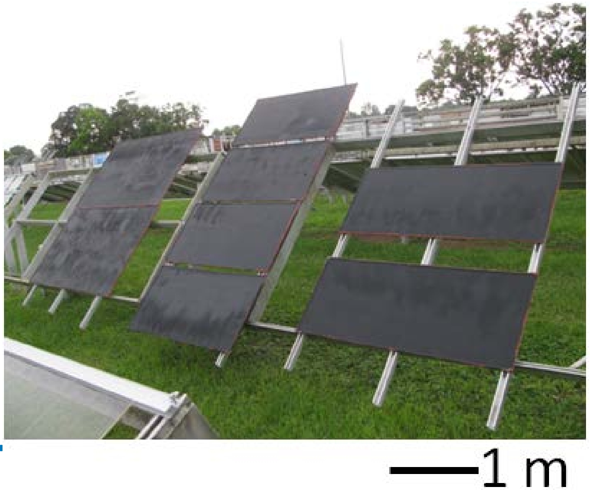


Photo of specimens fielded in Miami.

Comparison of indoor- and field-results:

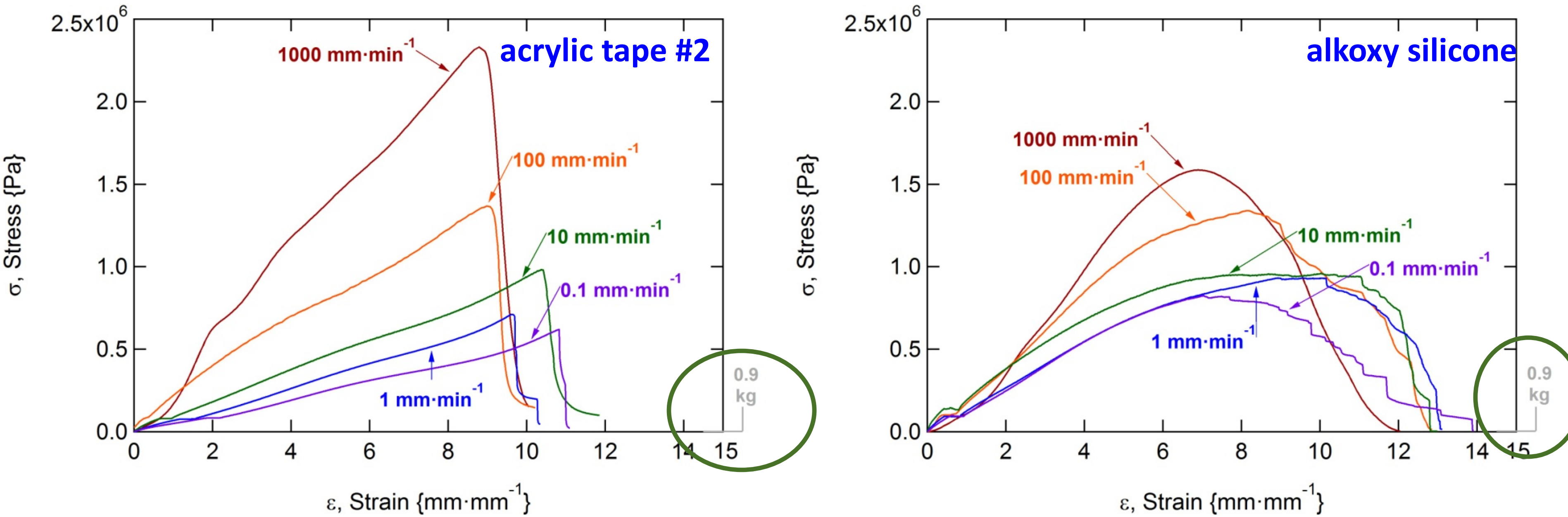
- Good correlation: PO melt & PE tape consistently identified as weakest systems.
- Instances of different duration of longevitiy, and modes (interfaces) of failure: PE tape failed with weights; but not always without weights.

  ⇒Suggests weight is required to adequately assess the system during the test.

Perspective From Attachment Strength Tests

- Overlap-shear (ISO 4587) and butt joint (ISO 6922) tests applied to acrylic tape and alkoxy silicone adhesives. Al/adhesive/glass coupons.
- Both types of material demonstrated substantial elongation at failure.
- Acrylic tape demonstrated an overt rate dependence for attachment strength.
- Greatest σ and corresponding ε for: the tape in shear or silicone in tension.

- Attachment strength greatly exceeds corresponding stress for j-box weights. $\Rightarrow \sigma/\varepsilon$ results akin to “robustness of termination” test, not a sustained load.



Results of the adhesion strength characterization (overlap-shear test) for: foam tape (left, acrylic #2) and silicone (alkoxy cure with Ti catalyst, right). A representative (median) data profile is provided for each of the test rates used.

Summary

- In trial-run, good correspondence between indoor- and field-results, *i.e.*, between mode types & specific material systems affected.
- A weight is required to adequately assess the j-box attachment system.
- 1 kg weight is recommended to more rigorously examine the attachment system.
- Multiple indoor test conditions (DH & creep) correlated best to the outdoor field results.
- The sustained load condition (far below the maximum attachment strength) emulated in the weighted j-box test is very different from the existing "robustness of termination" test.

Acknowledgements

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

NREL STM campus, Dennis Schroeder

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory.

See also the manuscript: “Examination of a Junction-Box Adhesion Test for Use in Photovoltaic Module Qualification”, Proc. IEEE PVSC Conf. 2014.

Additional Slides Follow for Reference…

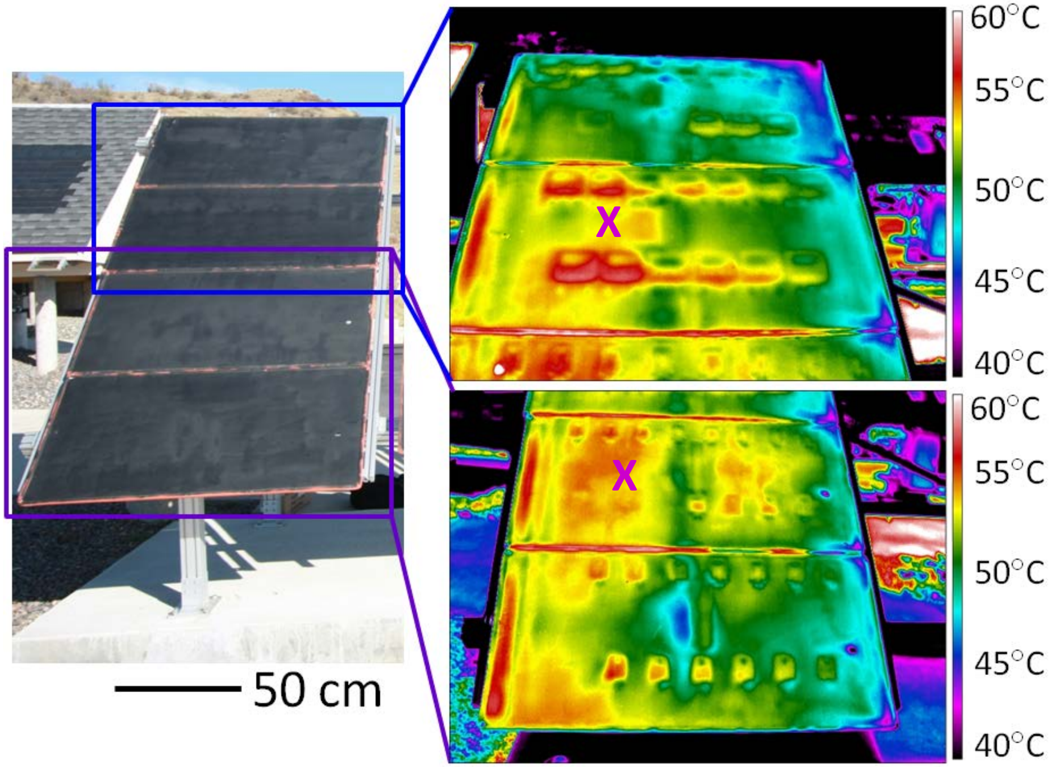
The J-Box Temperature Can Vary From the "Module" Temperature

Recent *T* data for a thin-film T-type TC taped to the back of PV modules:

- A ~15°C range may exist across a module (center to frame).
- T_{max} of 105°C for roof-mounted modules in Phoenix.
- Roof-mounted ~15°C warmer than rack-mounted modules.

This study:

- Measurement site: module center, between j-boxes.
- In the field, j-box is typically hotter than the module interior (cell temperature).
- Thermography identified j-box as ~5°C hotter than module interior.

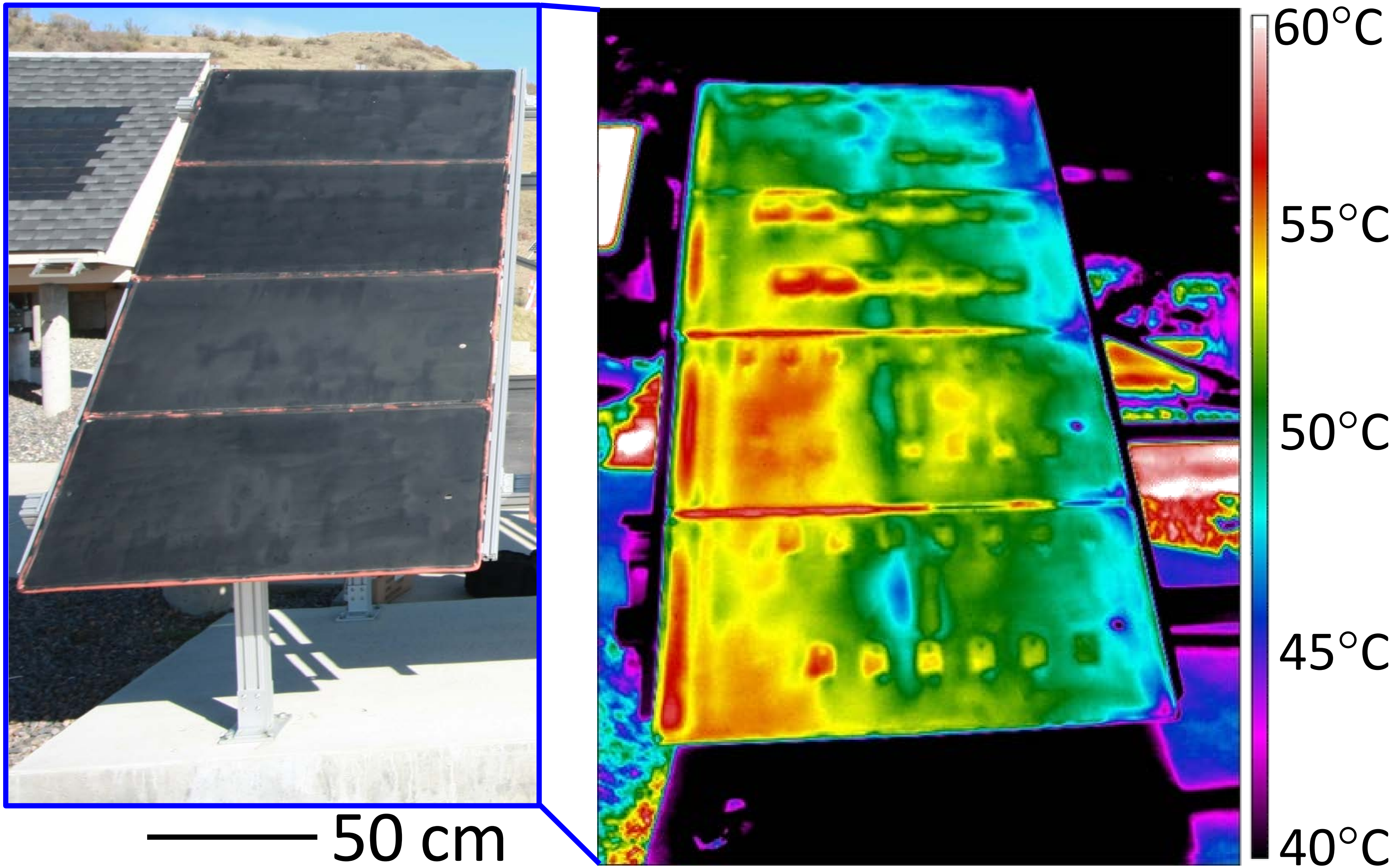


Optical and infrared images of modules in Golden on a hot summer day (July 2013). Typical TC site marked with an 'X'.

Kempe et. al., Field Testing of Thermoplastic Encapsulants in High Temperature Installations, *submitted*.

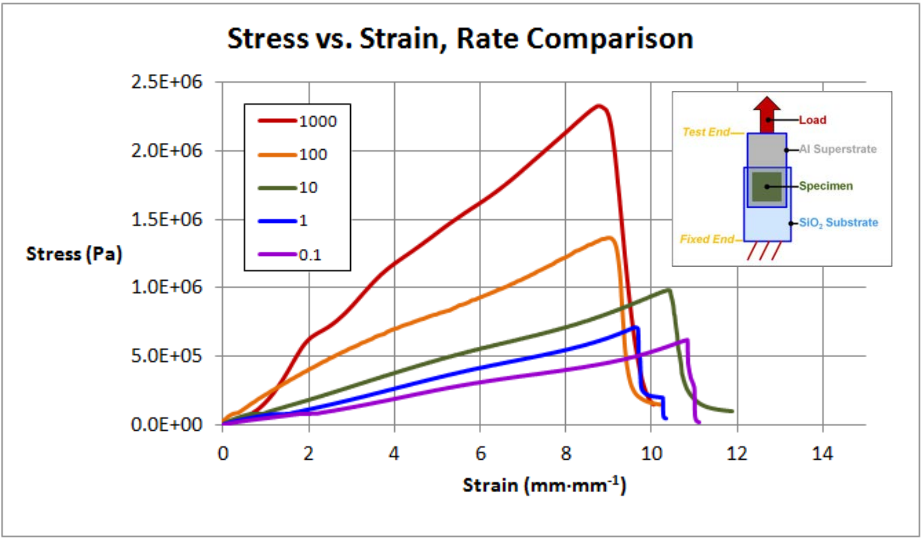
King et. al. SAND2004-3535 2004; 1-43.
Miller et. al., Proc. IEEE PVSC, 2010, 262-268.

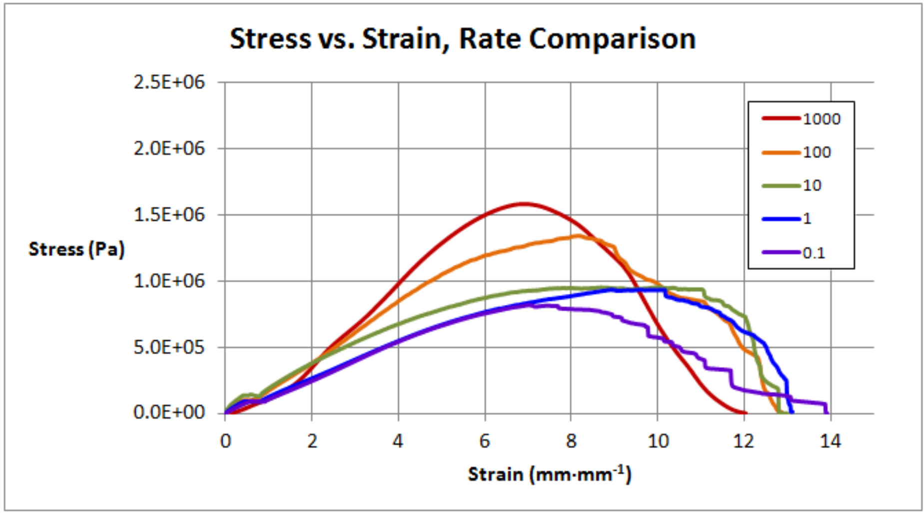
The J-Box Temperature in the Field Tests

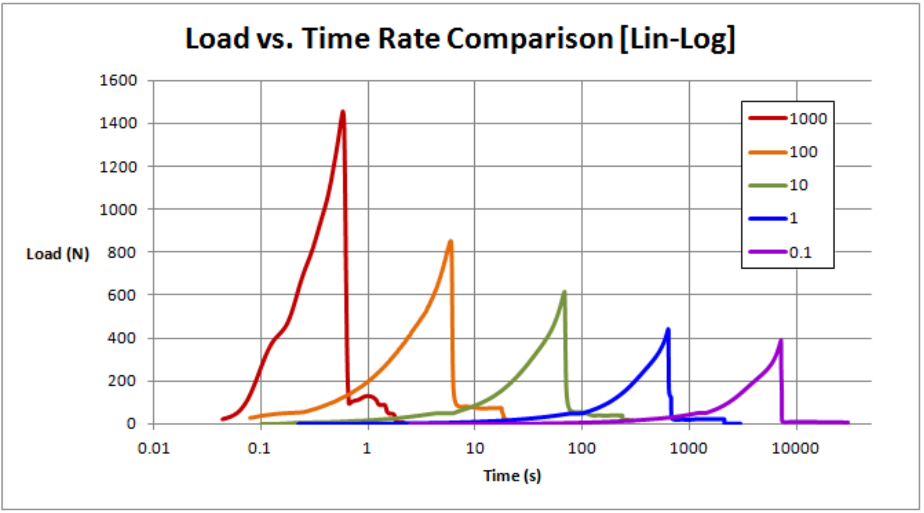


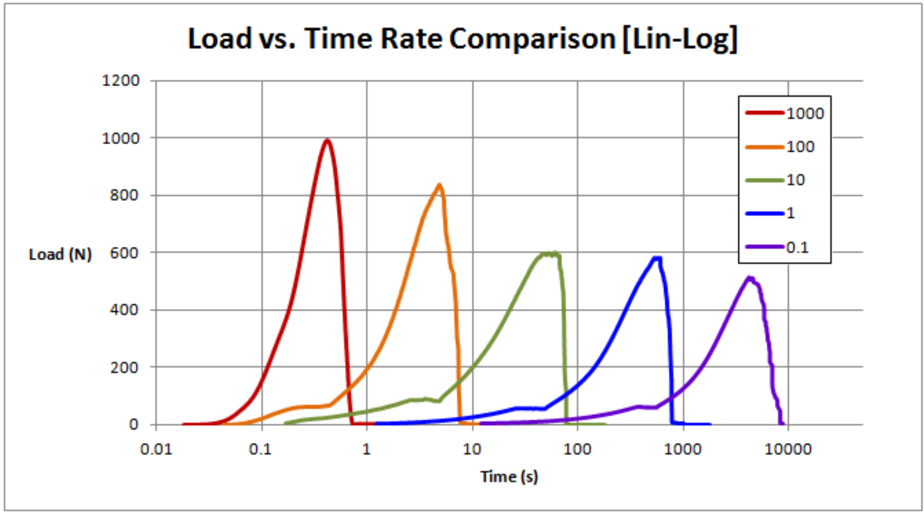
Optical and infrared images of modules in Golden on a hot summer day (July 2014).

Overlap-Shear Test Results





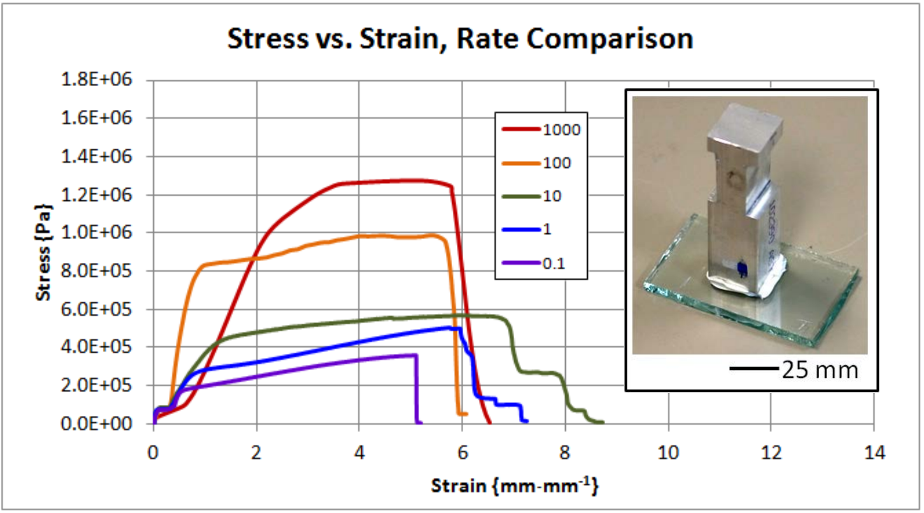


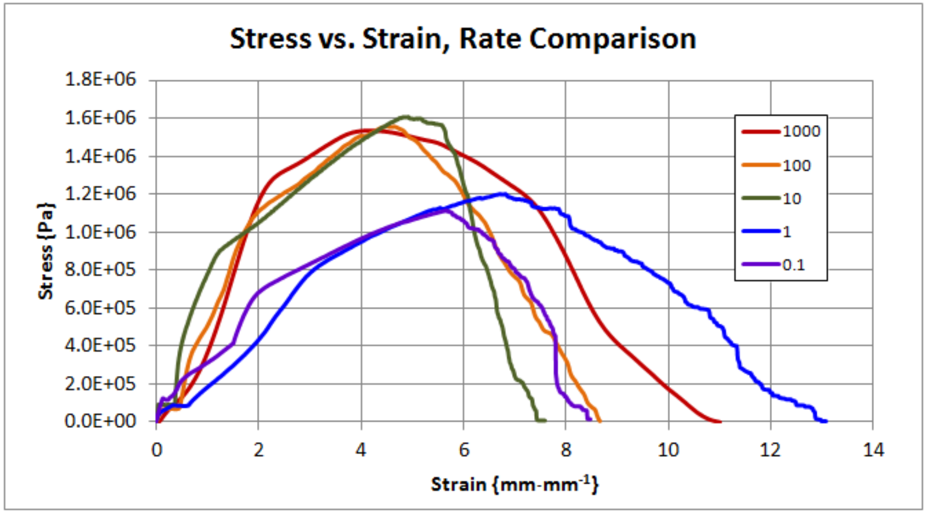


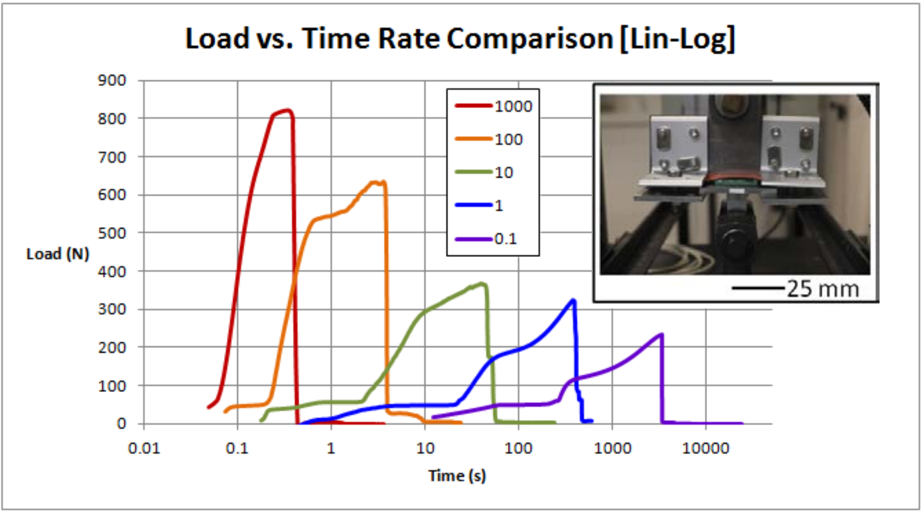
- The tape and silicone would both typically elongate in shear before delamination.

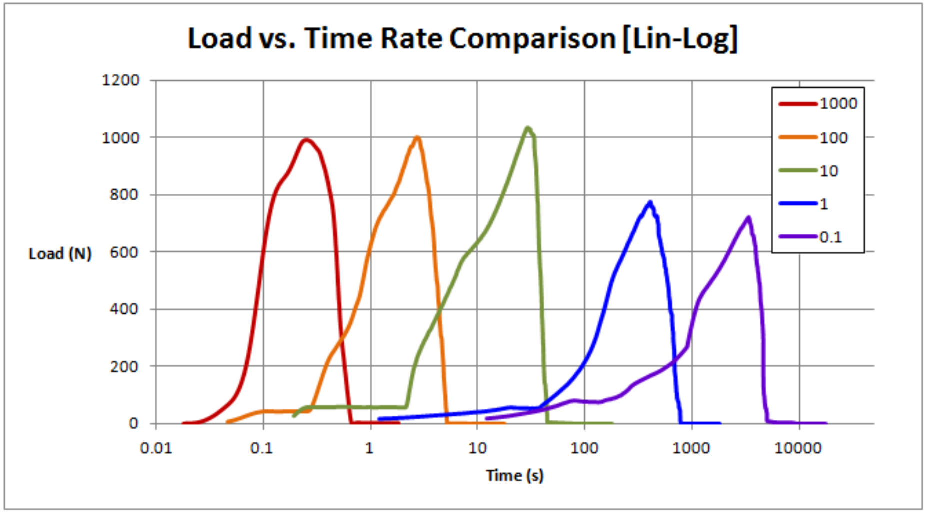
Overlap-shear test results for: foam tape (left, acrylic #2) and silicone (alkoxy cure with Ti catalyst, right).
A representative (median) data profile is provided for each of the test rates used.

“Pluck” (Butt Joint) Test Results









- Tape & silicone sudden failures in pluck

Butt joint test results for: foam tape (left, acrylic #2) and silicone (alkoxy cure with Ti catalyst, right). A representative (median) data profile is provided for each of the test rates used.