“Examination of a Size-Change Test for Photovoltaic Encapsulation Materials”

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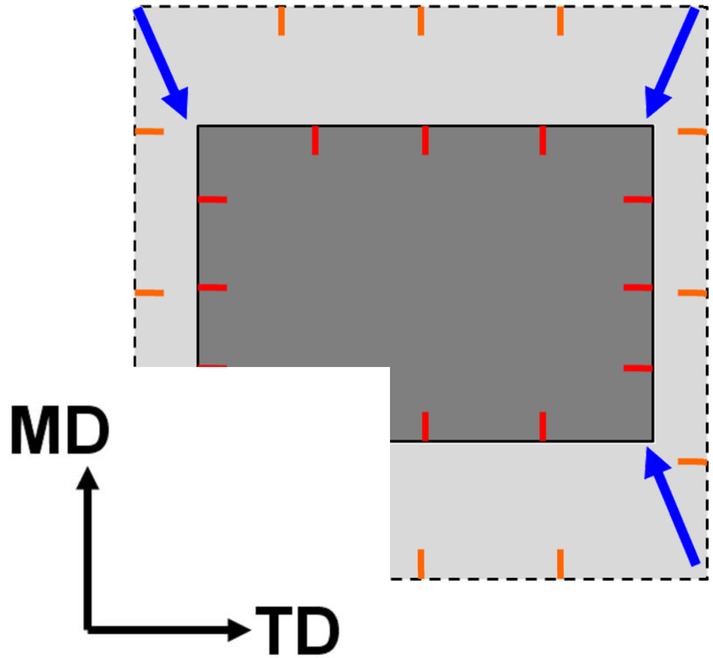
Motivation

- Encapsulation will change size (*e.g.*, shrink) during module processing (lamination)

- Possible consequences for mechanically displaced cells/interconnects/bus-bars: broken solder joints (opens), electrical contact (shunts… cell to cell, ground fault…), cracked cells, delamination, voids in encapsulation
- The long term effects in a field deployed module are unknown



Example demonstrating a size change of –45% and –20% in the machine extrusion (MD) and transverse (TD) directions

- The encapsulation work-group within IEC TC82 WG2 has proposed a test standard that may be used to assess size change for encapsulation sheet
- Test aids material and module manufacturers in performing material acceptance, process development, design analysis, or failure analysis

Scope and Timeline of the Project

- Measure the maximum representative change in linear dimensions of encapsulation sheet material, resulting from processing during the fabrication of photovoltaic (PV) modules
- A "frictionless" test (between the material and substrate, rendering the maximum size change) is easiest to standardize and interpret
- No existing standard. ISO 11501, ASTM D1204, ASTM D2732 considered

Basis for the test: BP Solar internal test procedure

Task-group formed: Autumn 2010

Discovery experiments and method draft: Spring & summer 2011

Interlaboratory study: Summer and autumn 2011

Method submitted to IEC: Autumn 2011

Revision of draft (from interlaboratory study & IEC vote): 2012

Revised method submitted to IEC: Autumn 2012 or spring 2013

Details of the Proposed Test Method

- 100 mm x 100 mm specimens: (≥ 6), cut from ≥ 2 rolls,
  MD and TD marked, not preconditioned (test promptly)

Test Procedure:

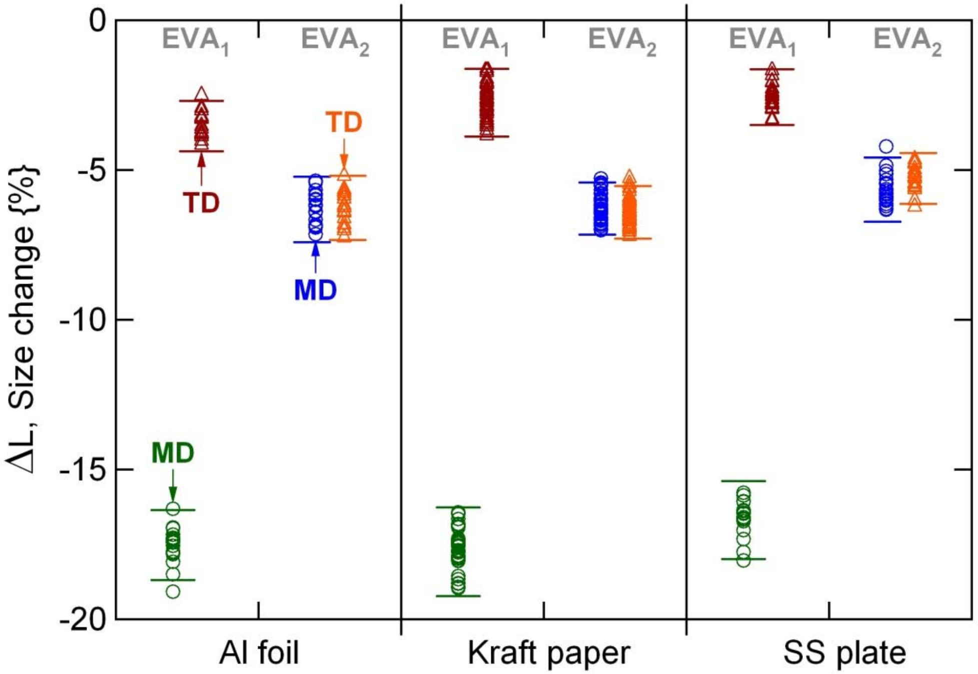
1. Place Al foil (heat spreader) on hot plate (now a circulating oven)
2. Add 2-4 mm thick layer of sand on Al foil
   weight of sand improves thermal contact of foil
   low friction to standardize the measurement & its interpretation
3. Equilibrate to the maximum processing temperature
4. Measure & record specimen initial dimensions (5 each for MD, TD)
5. Place specimen on sand for 5 minutes
6. Remove, cool then measure specimen final dimensions

7. Calculate size change: $\Delta L = 100 \cdot \frac{L_f - L_i}{L_i}$

(maximum and difference; average and standard deviation)

Different "Substrates" Yielded Comparable Shrinkage

- Early work explored talc powder on a glass carrier
- Curvature of glass ⇒ localized thermal contact ⇒ temperature heterogeneity
- Talc is not heavy. Kaolin used in ISO 11501



- Discovery experiment explored sand/carrier combinations for 2 EVA's

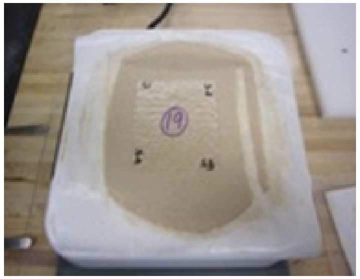
Comparison (data and images) of carrier/sand for 2 EVA's (unbalanced and balanced).

"Kraft paper "= release liner paper

- No significant (2σ) difference observed. Al chosen.

Aluminum Foil

Kraft Paper

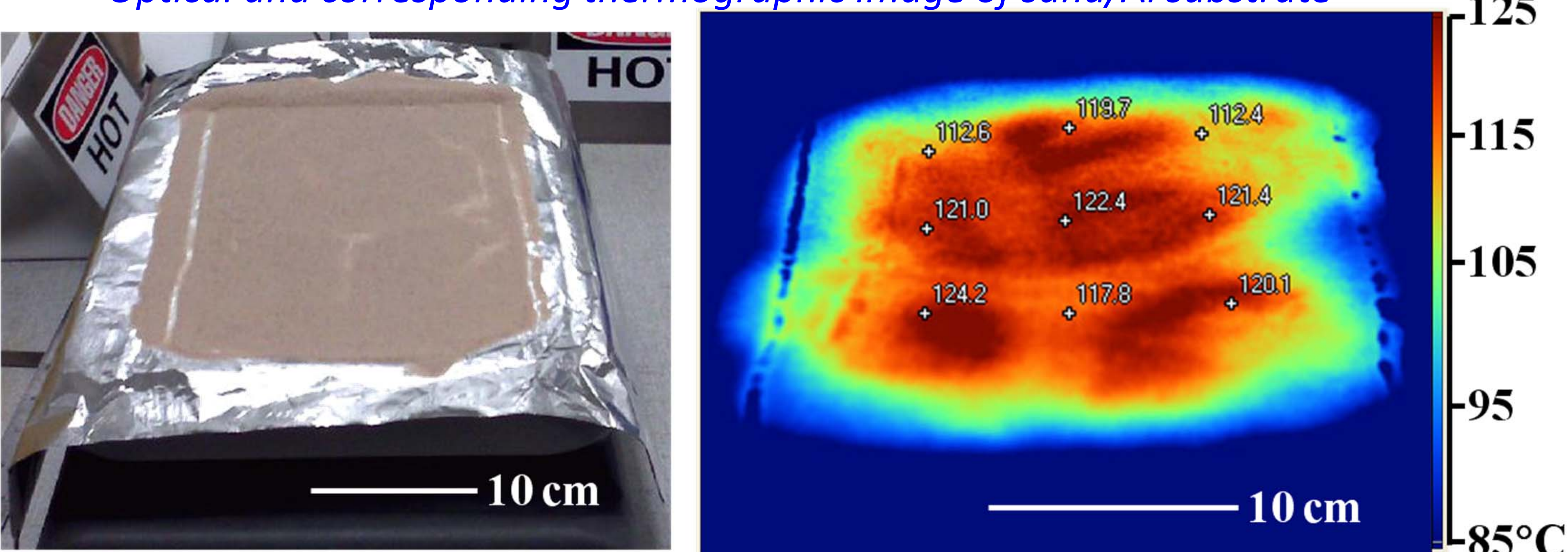


Stainless Steel Plate

Quantifying the Temperature Uniformity of Sand

- Sand (unlike Al) is a high ε material, readily enabling thermography
- A 4-8°C (2σ) T range was observed for well manicured sand
- Most heterogeneous at thin regions or for partially raked sand
- Circulating oven can improve temperature stability and uniformity: no temperature gradient through the sand, no radiative heat transfer, greater thermal capacitance, better recovery time, safety

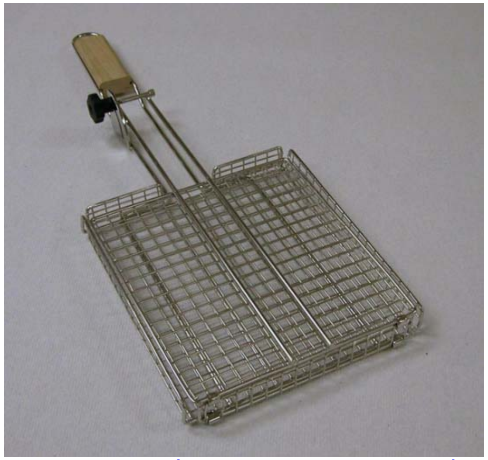
Optical and corresponding thermographic image of sand/Al substrate



The Possibility of a Liquid "Substrate" Seems Unlikely

Scenario:

- A liquid-based test was identified (as in ASTM D2732) from the IEC vote
- Some voters advocated the use of water (@ 80°C) to evaluate EVA



wire tray (www.eysters.com)

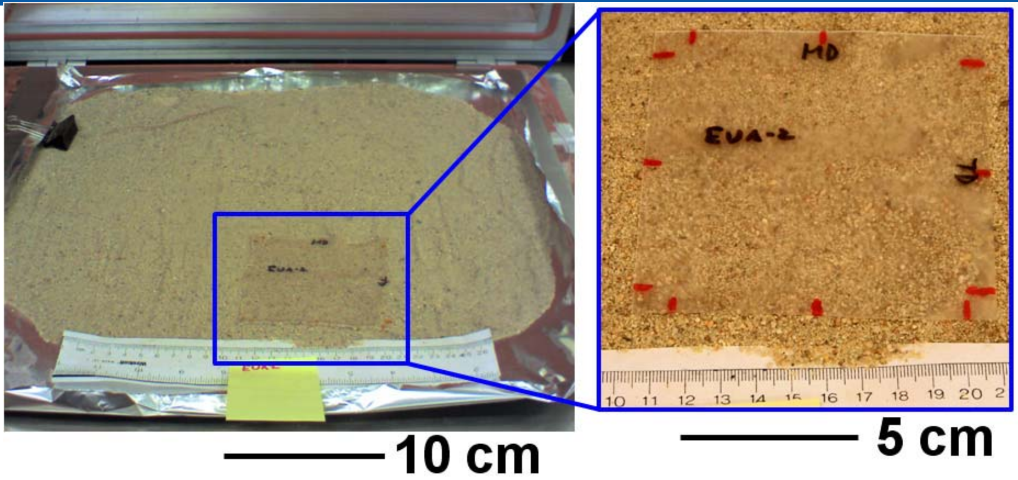
wire basket (www.sockmete.info)

Difficulties:

- 80°C not expected to cure EVA. ΔL from melt transition only.
- The standard is intended to rapidly test all encapsulation materials (including those that are processed at >100 °C)
- Many new encapsulation materials do not cross-link and are processed near/above their melting temperatures
- How to handle molten materials without introducing shape change?

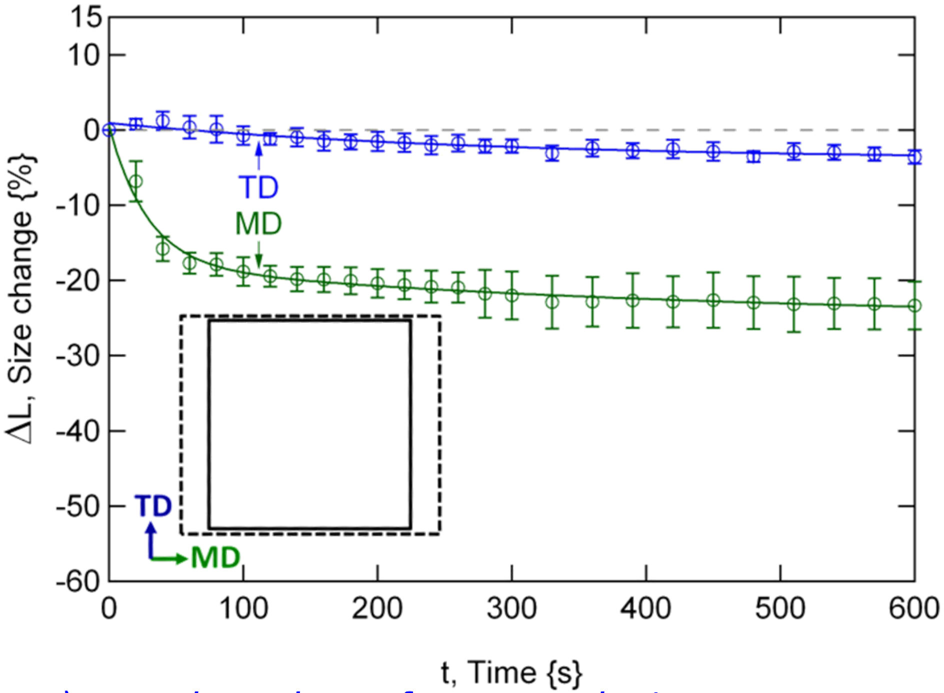
Experiments Confirm the Test Duration for EVA

- Photographs taken every 20s for specimens marked at middle and near the corners
- Size change can be determined optically (~±1%) using the scale in the image



"Hot plate" (vacuum laminator) and specimen setup for the time characterization

- Experiment temperature = 132°C
- Negative ΔL = shrinking
- The initial (dashed) and final (solid) profiles are shown (scaled) in the figure inset
- EVA: most activity within 1st two minutes (EVA cross-links)



Results for "EVA$_1$" (unbalanced), before and after (inset). Error bars shown for max and min measurements.

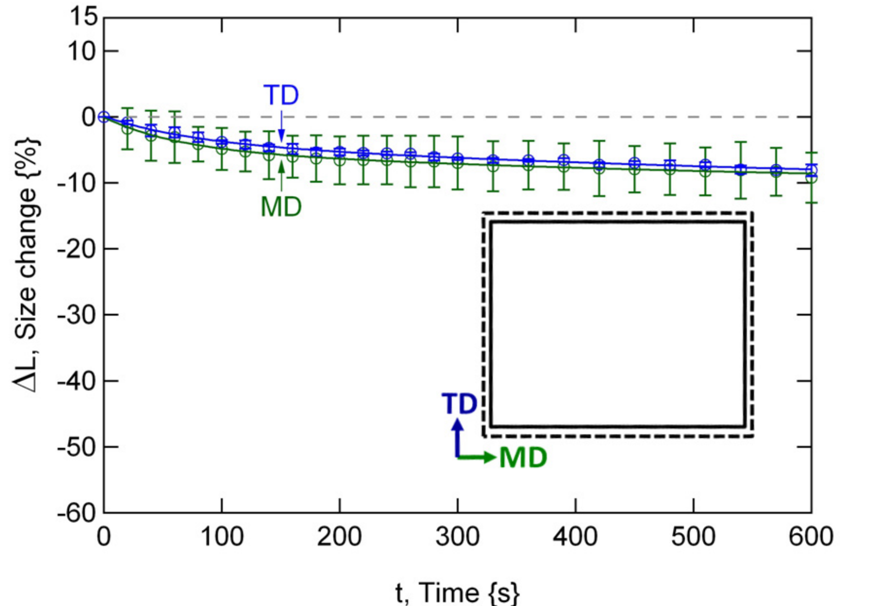
Experiments Confirm the Test Duration for Other Encapsulation

- The thermoplastics do not cure, but demonstrate most size change within 5 minutes
- Some materials tested at 165°C

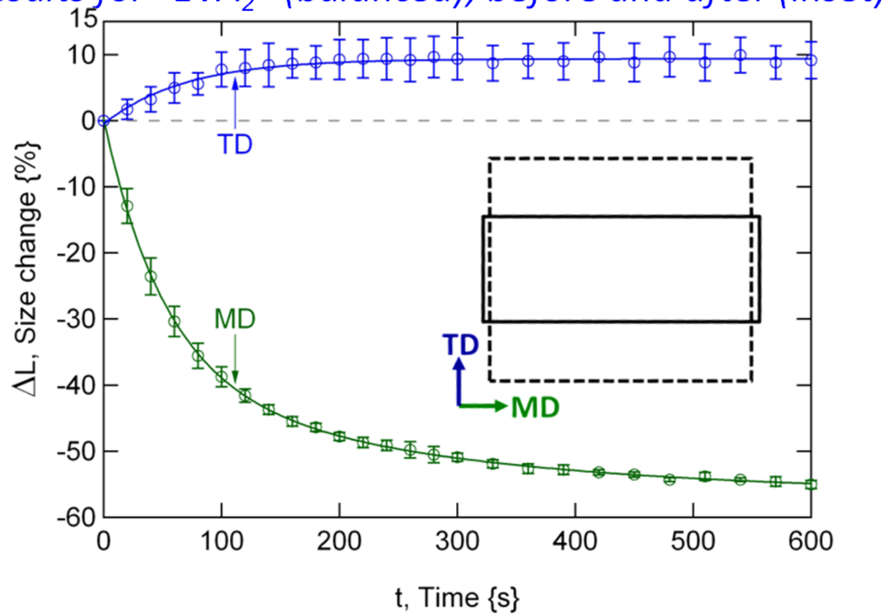
- Examples:

balanced EVA (10%→minimal size change)
TPO (55%→substantial size change)

- Some materials (*e.g.*, TPO, PVB, and ionomer thermoplastics) shrink in one direction and expand in the other!
- Some materials not optimized to reduce size change, as vendors are likely unaware of the issue
- The implications for the stress in a module are unclear (try FEA) but may become more significant with time



Results for "EVA_2" (balanced), before and after (inset)



Results for TPO, before and after (inset)

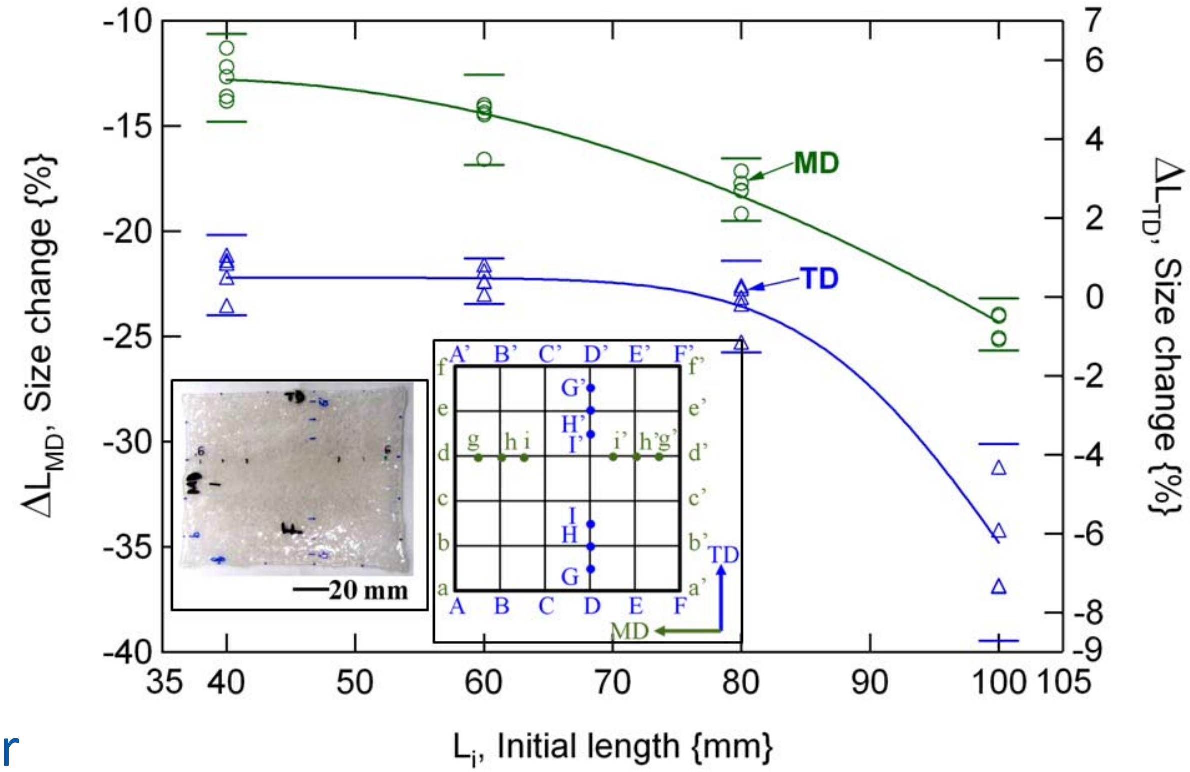
A Minor Specimen Size-Effect is Evident

Experiment:

- Is there a size-effect?
- Obtain measurements from within and up to the specimen edges
- L_i = 40, 60, 80, 100 mm

Results:

- ΔL at edge for EVA's (as in *TD* for EVA_1)
- Monotonic trend for "isotropic" PVB, TPO, ionomer (like *MD* for EVA_1)



Size-specific results for "EVA_1" (unbalanced).

(a) Final photograph of one of the specimens.

(b) Sign convention and coordinate system used.

Implications:

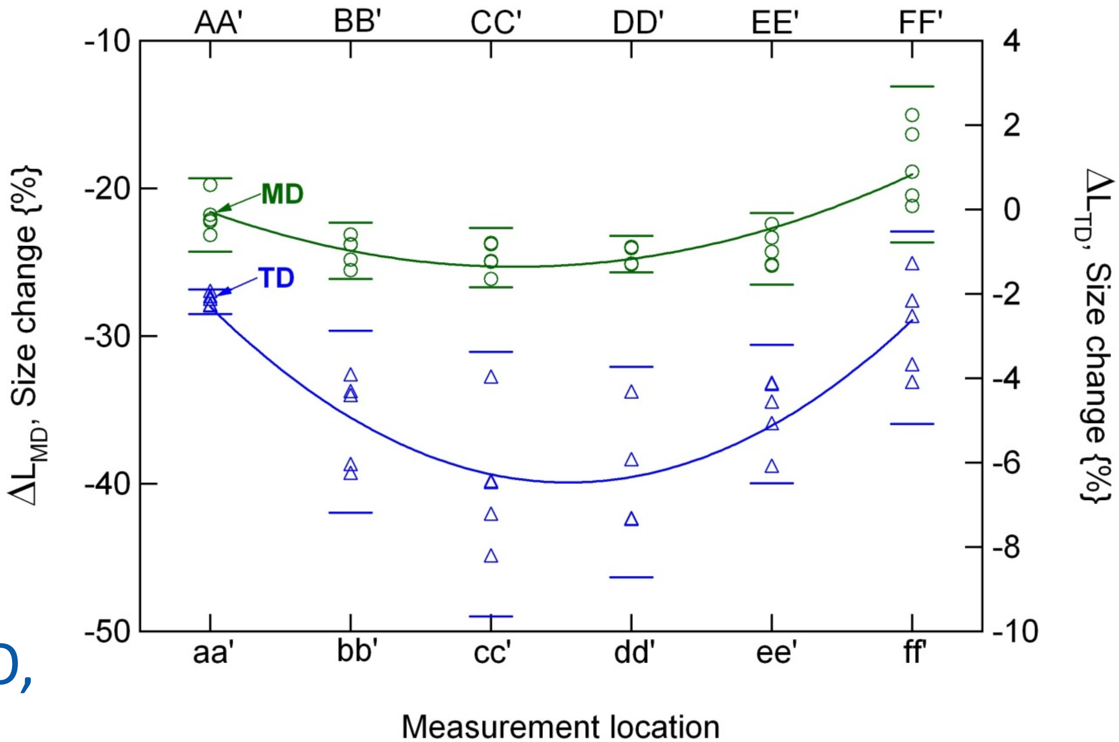
- Possible causes: friction (from sand), stretching during cutting, uneven & rapid cooling, heterogeneous stress

A Minor Edge-Effect is Evident

Experiment:

•Intentionally measure at locations along specimen edges, including the corners

•A minor effect (few %ΔL) is evident in all specimens



Location-specific results (100 mm gage length) for "EVA$_1$" (unbalanced)

Results:

•Similar behavior for EVA, TPO, ionomer: $\Delta L_{DD'} > \Delta L_{AA'}$

•Opposite trend for PVB: $\Delta L_{AA'} > \Delta L_{DD'}$

Implications:

•Specify the # and location of measurement sites

•Measure middle and ≥ 1cm from the corners, using an odd # sites)

•Sample ≥ 200mm (location) from the edge of a roll

How to Treat Out of Plane Curvature?

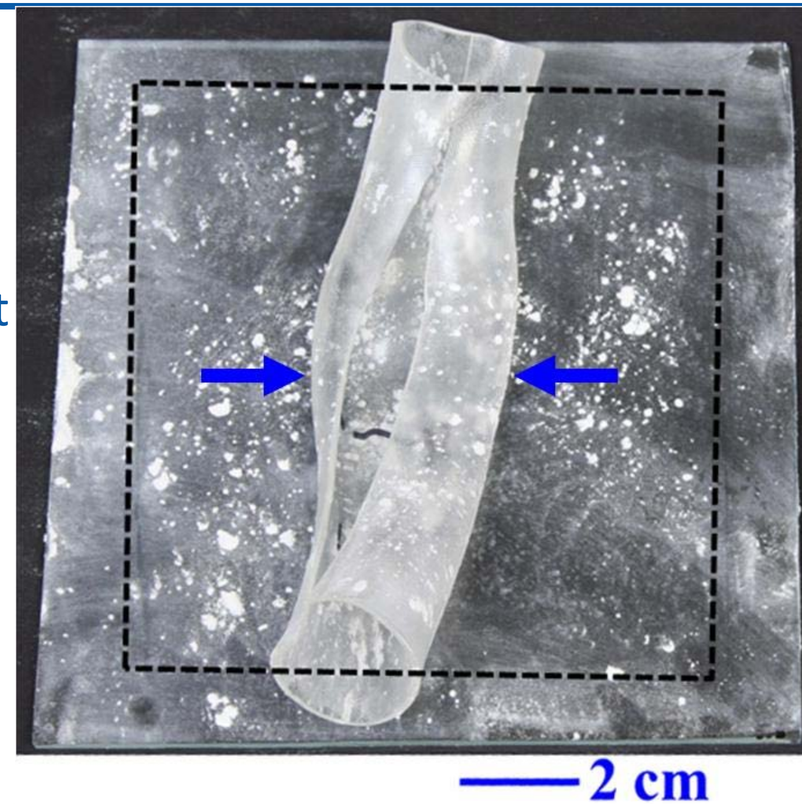


Image of final shape of ionomer (arrows at edges), with outline (dashes) of original shape

- Early generation ionomer product:

$\Delta L_{MD} \leq$-50%, $\Delta L_{TD} \geq$15%, significant curvature

- ΔL could probably be significantly improved
- Not practical to uncurl and measure @ end of test

- For in-plane result, one could cover with Teflon FEP sheet /weight (*e.g.*, glass)

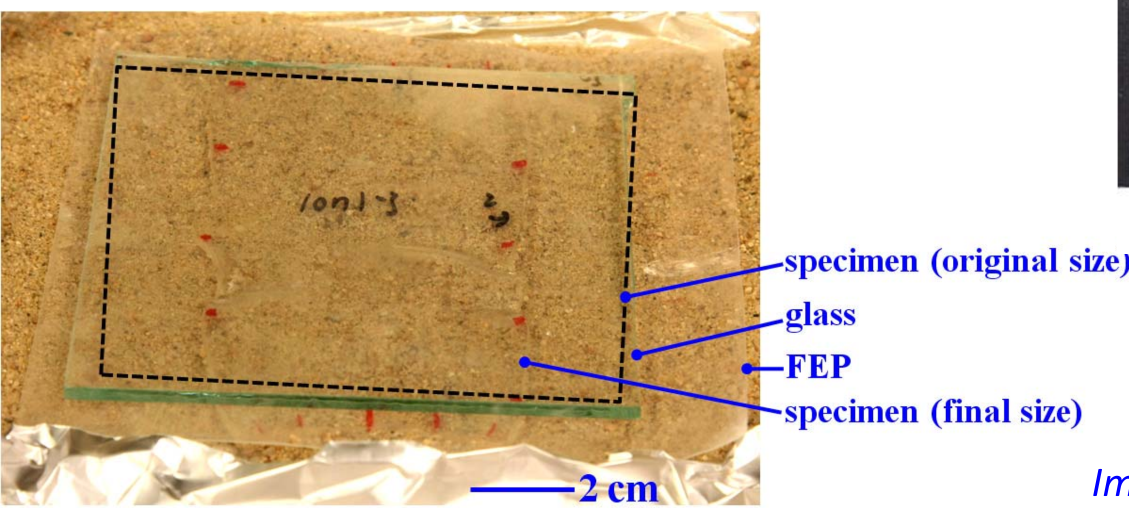


Image of final shape of ionomer/FEP/glass

- This solution does, however, affect the result (magnitude and material profile)
- Are there better practices? Note: glass weight often not “required”

Details of the Interlaboratory Study

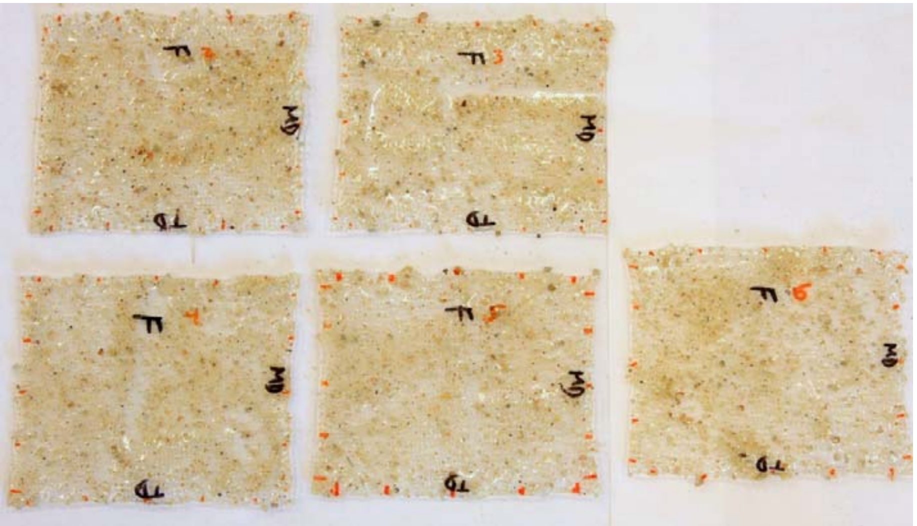
- Five materials were circulated:

EVA$_1$ (unbalanced; T_{set}=132°C; T_m=55°C), EVA$_2$ (balanced),

←thermosets; thermoplastics→ TPO (T_{set}=140°C; T_m=60°C),

PVB (T_{set}=160°C; T_g=15°C), ionomer (T_{set}=165°C; T_g=86°C)

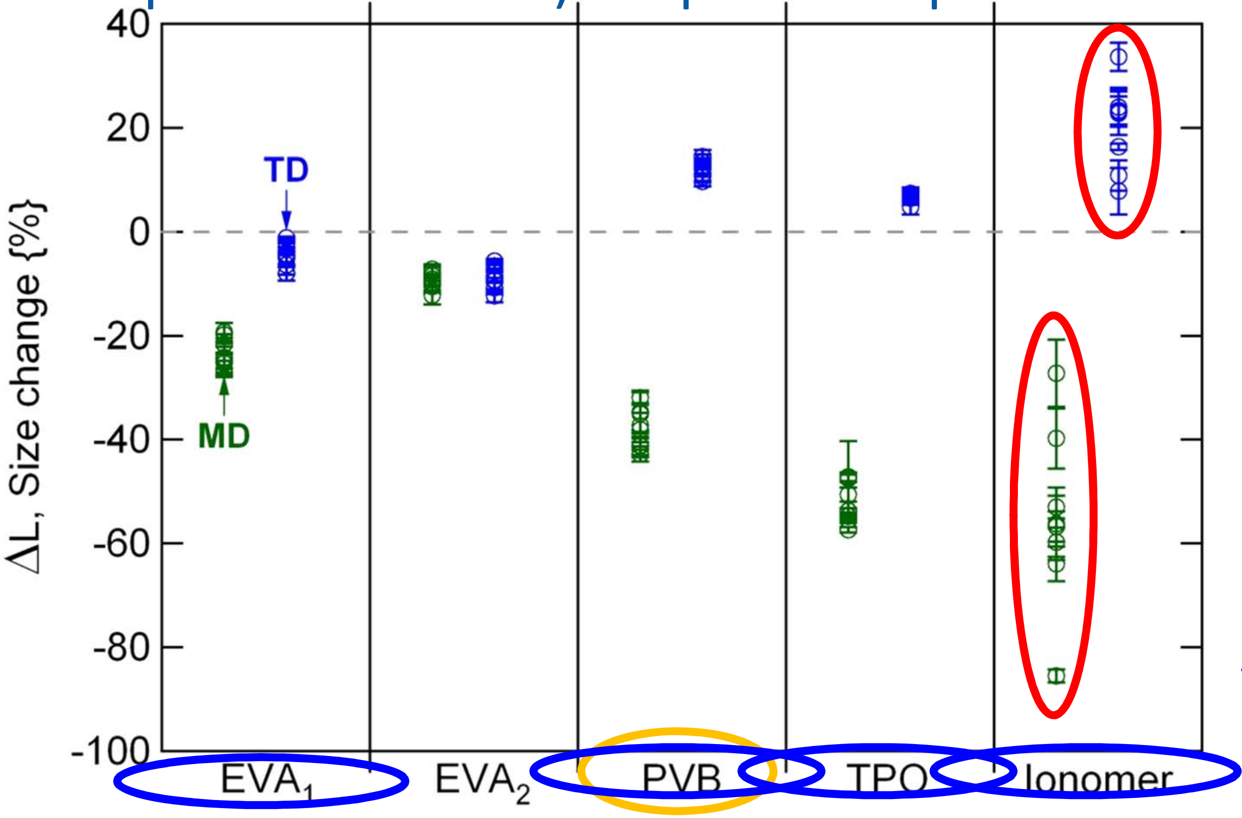
- ΔL measurements for MD, TD according to the draft procedure
- Tests were performed using a hot-plate or oven with Al foil
- Unspecified sand substrate (now ASTM C778)



EVA$_1$ (unbalanced) specimens after the test

Results of the Interlaboratory Study

- Most materials (except PVB) were examined in the melt state
- $\Delta L_{MD} > \Delta L_{TD}$ for EVA_1, PVB, TPO, ionomer
- Results are reproducible between participating laboratories (within ±5% absolute [from L_i], up to 40% relative [from ΔL])
- The ionomer was not very repeatable between labs (out of plane curvature) … open to improved method for this issue!



Box plot of average and st dev of size-change from the interlaboratory study

Summary

•Proposed test standard to evaluate the maximum change in linear dimensions of sheet encapsulation products resulting from their thermal processing. Discovery and interlaboratory studies performed.

Sand substrate, aluminum carrier:

- Reduce friction (maximum size change) standardizing the test
- Sand can be used at a wide range of test temperatures
- Specify to use circulating oven
- We anticipate a 5°C (2σ) range within the oven

Related details:

- Verified 5 minute duration for the test
- Minor size-, edge-effects ⇒ specify size, measurement locations
- Difficult to reduce effects of out-of-plane curvature

Interlaboratory study:

- Substantial size change (>10%) observed for several materials
- Often observed shrinking in MD, expansion in TD
- Results reproducible within ±5% absolute size-change

Acknowledgments

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See also the manuscript: “Examination of a Size-Change Test for Photovoltaic Encapsulation Materials”, Proc. SPIE 2012, 8472-29.