# Module Encapsulation Materials, Processing and Testing

**John Pern, Ph.D.**
**National Center for Photovoltaics (NCPV)**
**National Renewable Energy Laboratory (NREL)**
Golden, Colorado, USA

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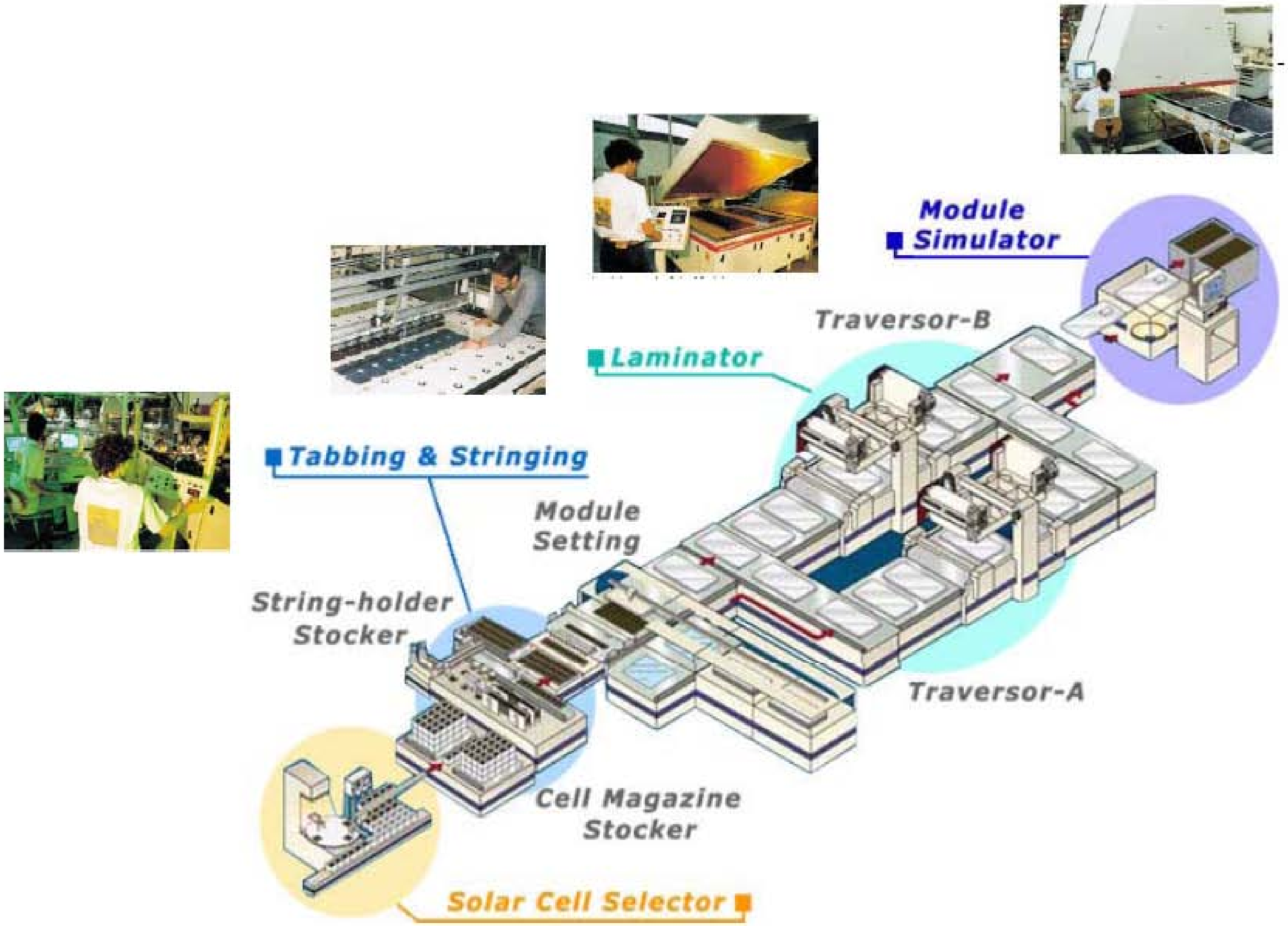
# Outline

- **Encapsulation Components (Commercial Products)**
  - Superstrates: Glass or Tefzel/Tedlar
  - Encapsulants (EVA and Non-EVA - TPU, PVB, … etc.)
  - Substrates: Back Foils (or Backsheets) or Glass
  - Edge Seals
  - Materials Properties
- **Processing**
  - Typical module constructions
  - Module Lamination – Curing Process
- **Materials-Level Testing**
  - Optical, Electrical, Mechanical
  - Photothermal and damp heat tests
- **Field-Degraded Modules (Photos)**
  - Effects of materials and encapsulation quality
- **Conclusions**

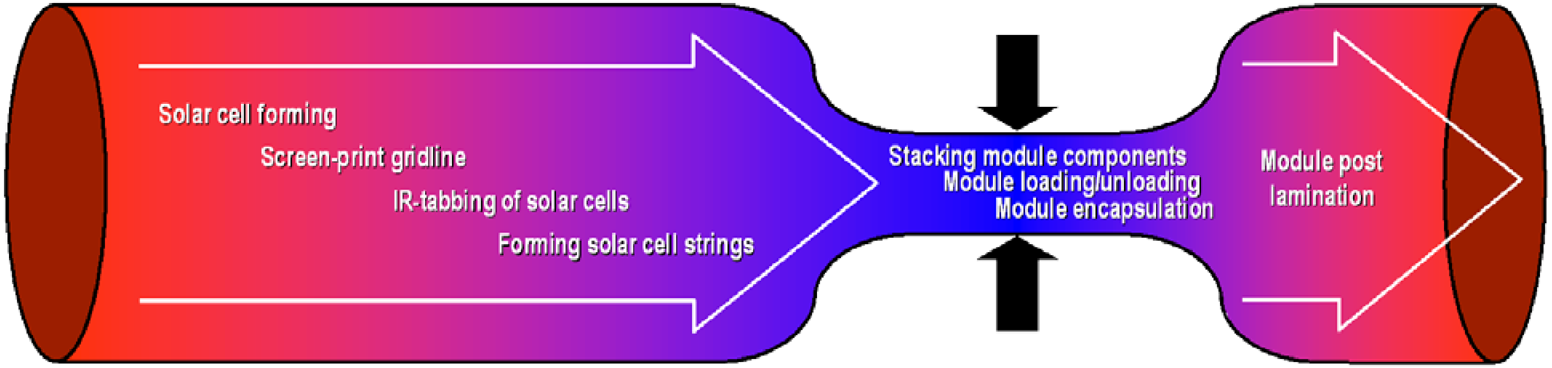
# PV Module Production Line




cell-interconnection
↓
inspection
↓
module lay-up
↓
lamination
↓
inspection
↓
Frame and junction box
↓
Final quality check

Viewgraph showing the module production schematically

# Encapsulation:
## Manufacturing Bottleneck in (c-Si) PV Module Fabrication Process

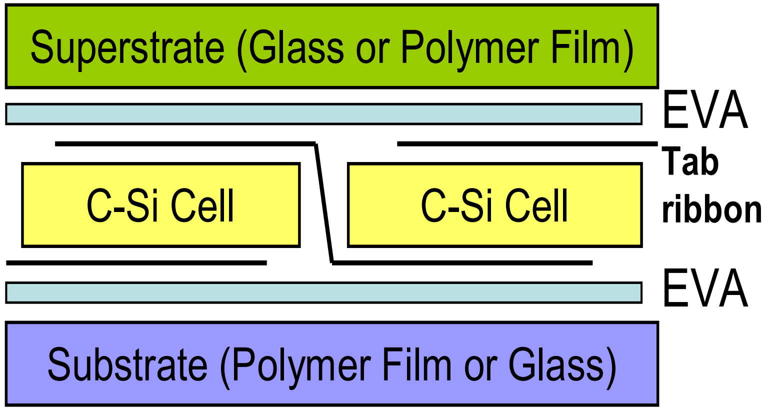



**Importance of PV Module Packaging --**

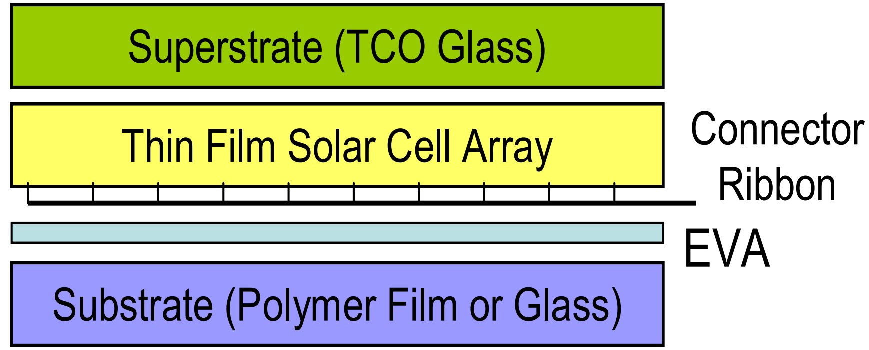
- High module reliability for 20-30 year service life
- "Packaging is the predominant cause of failure in modules" – remark of a DOE SETP PV Program reviewer, 2006

# Typical PV Module Encapsulation Configurations

## I. Crystalline Si-based Module




## II. Superstrate-Deposited Thin Film Module



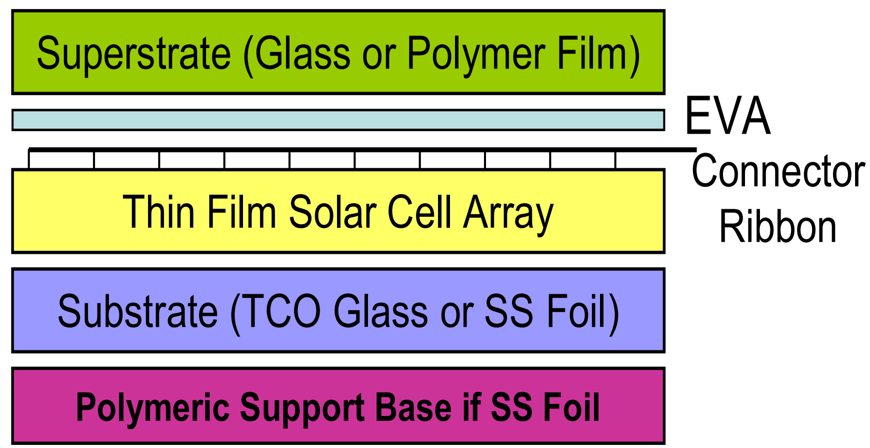

**Common feature:**

Glass/EVA/c-Si Cells/EVA/backfoil

**Backfoil selection:**

TPT: Tedlar/PET/Tedlar
TPE: Tedlar/PET/EVA
PET: Polyester

## III. Substrate-Deposited Thin Film Module



# Elements for Making Good Encapsulation of (c-Si) PV Modules

- Good (right) glass super-/substrate
- High-performance encapsulant
- Good (right) backfoil or substrate
- Good (correct) lamination process with proper handling of stack and temperature-pressure-time (T-P-t) profile
- Good edge seal if the design needs

# Module Encapsulation Materials - 1

- **Polymeric Encapsulants (Pottants):**

  **Most critical element in module encapsulation and reliability**

  – EVA (most commonly used and cheapest; the only field-proven over 20 years)

  – Non-EVA
    - TPU
    - PVB
    - Silicones
    - Silicone/PU hybrid
    - Ionomer
    - Other new polymers

  – UV-Curable Resin

- **Edge Sealants** (for Al-framed c-Si or thin-film modules)
  – Polybutyl
  – Silicones
  – Desiccant-type
  – PIB-type

# Module Encapsulation Materials - 2

**Superstrate:**

- Glass
  - Low-Iron
  - Tempered
  - Plain or Textured
  - UV filtering (Ce-glass)
  - $SiO_2$ AR Coatings
- Fluoropolymer
  - Tefzel
  - Tedlar
  - THV220
    (to replace EVA/Tefzel)

**Substrate:**

- Polymer Multi-laminates
  (Backsheet; Backfoil)
  - Tedlar-based:
    - **TPT**: **T**edlar/**P**ET/**T**edlar
    - **TPE**: Tedlar/PET/**E**VA
    - **TAT**: Tedlar/**Al** foil/EVA
    - **TPAT**: Tedlar/PET/**Al** foil/Tedlar
    - **TPOT**: Tedlar/PET/**O**xide/Tedlar
    - **PAP**: PEN/Al foil/PET
  - PET or PEN-based (to replace expensive Tedlar)
    - Protekt
    - Teijin Teonex
    - $BaSO_4$-filled PET
- Glass

# Primary Functions and Requirements of Encapsulant

**Functions:**

- **Optical coupling** – refractive index (n) matching
- **Electrical Insulation** – dielectric strength and volume resistivity
- **Mechanical support** – fixation of cells and adhesion strength
- **Physical insulation** – separate cells & cell strings
- **Physical protection** – from weathering-induced and environmental damages
- **Thermal conduction**

**Requirements:**

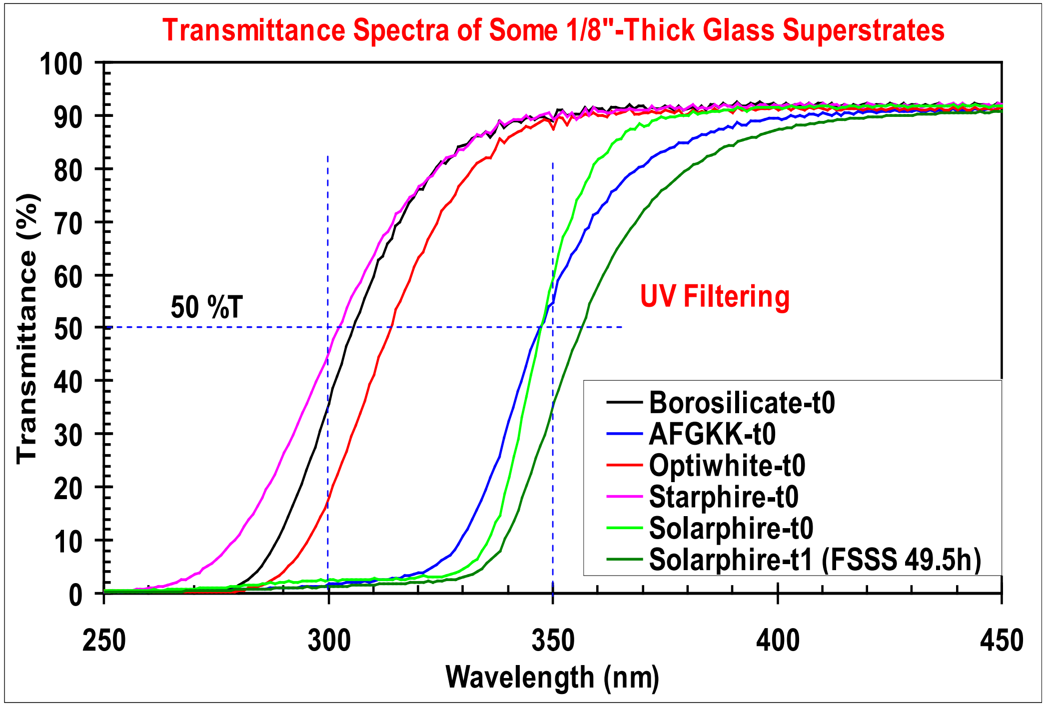
- High T%
- Matching R.I. (n)
- High dielectric breakdown
- High volume resistivity
- High adhesion strength
- Mechanically strong, resistant to break or tear
- Low moisture absorption
- High resistance to UV-induced yellow-browning
- High resistance to UV and moisture-induced delamination

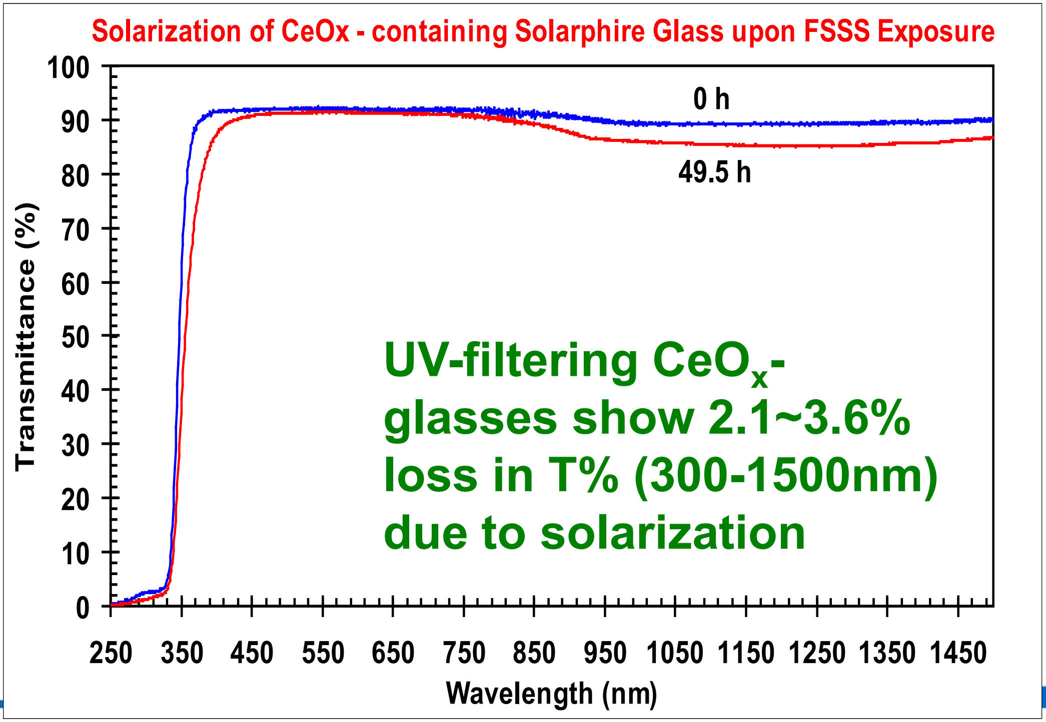
# Select Encapsulant

- **Based on Module Design and Construction**
- **Cost Consideration**
- **Processing Equipment, Method, Conditions**
- **Materials:** EVA, PVB, TPU, Silicone, Ionomer, UV-curable resin,..
- **Tests:**
  - **Film transmission before and after processing or testing**
    - UV & Heat - induced yellowing (photothermal stability)
    - damp heat and thermal cycle – induced yellowing
  - **Proper processing conditions (T-P-t profile) with your laminator**
    - Curing degree & gel% (EVA)
  - **Adhesion strength** (e.g., 90$^o$ or 180$^o$ peel, or lap-shear test)
    - Initial (e.g., EVA to glass, Tedlar, or PET)
    - thermal cycle
    - humidity freeze
    - damp heat
  - **Electrical insulation** (e.g., volume resistivity, breakdown V)
  - **Mechanical strength** (tensile)

# Select Glass Superstrate

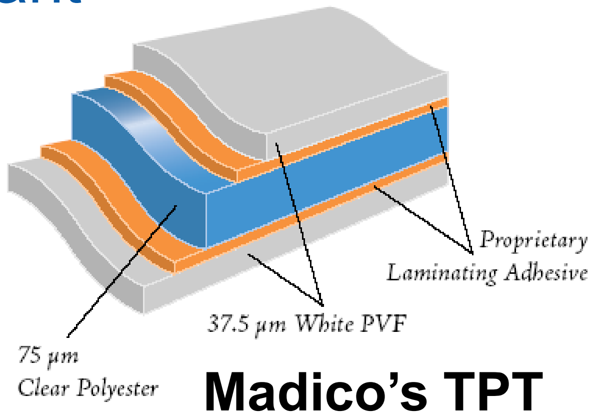
- Low-Iron
- Tempered (c-Si PV)
- Type:
  - Plain or Textured
  - UV-transmitting
  - $CeO_x$ UV-Filtering
  - $SiO_2$ AR Coating
- Test T% and degree of solarization
- Affect photo-(UV) stability of encapsulant
- Correctly use the non-float (non-tinned) side
- Cleaning - affects adhesion (delamination)



# Select Backfoil (Backsheet)

- **Type (more commonly used) –**
  - **TPT-primed:** Tedlar/PET/Tedlar
  - TPE: Tedlar/PET/EVA (low VA%)
  - PET-based (polyester, primed or corona-treated)
  - PEN-based
- **Cost consideration**
- **Tests –**
  - adhesion strength with encapsulant
  - electrical insulation
  - mechanical strength
  - moisture-blocking (WVTR)
  - weathering durability




**Madico's TPT**

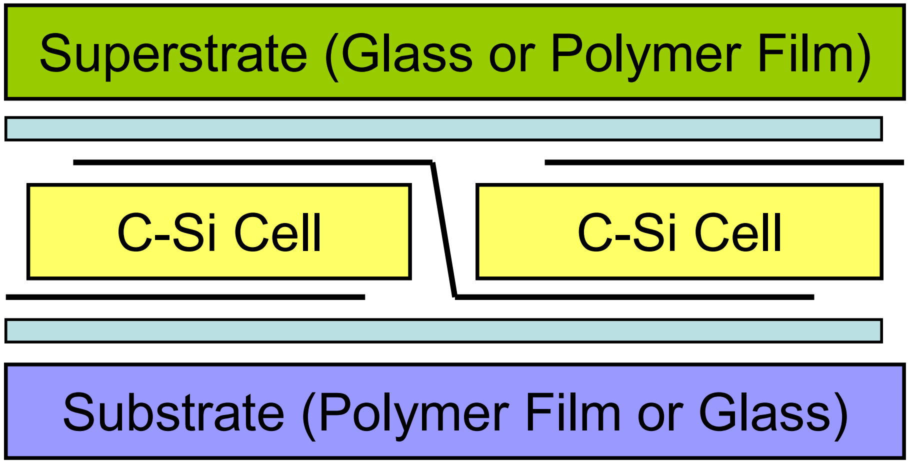
# Select Edge Sealant

- Primary function: to block moisture/water ingress
- Use depends on module design/construction
- Al-framed c-Si modules:
  - Polybutyl (“hot butyl”)
  - Silicones (needs to know moisture-blocking property)
  - PIB-type (maybe the best)
  - Others (“U”-shaped rubber tapes)
- Thin-Film CdTe and CIGS (glass/glass):
  - Desiccant-type tapes (mechanical and adhesion strength may be weak)
- Conduct immersion/hot-pot leaking tests

# An Example showing Various Tests Conducted to Determine Materials Properties and Processing

| Material | T% (400-1000 nm) | Gel (%) | Volume Resistivity (ohm-cm) | | Adhesion Strength (N/mm) (90° Peel) | Water Vapor Transmission Rate T (°C) | RH (%) | ($g/m^2$-day) |
|---|---|---|---|---|---|---|---|---|
| Tefzel (1.5 mil) | ~94 | | | | | 20 | 85 | 1.80 |
| Tefzel(1.5 mil)/EVA cured | | | | | | 38 | 82 | 6.55 |
| Tefzel (5 mil) | 87-92 | | 7.60E+16 | | | | | |
| | Cured Film | Fast-Cured | Uncured | Cured | To Plain KK glass | | | |
| China EVA-1 | 91 ± 1 | 95 | (deep texture) | 2.3~5.8E+14 | | | | |
| China EVA-2 | 91 ± 1 | 84 | 2.2E+14 | 1.1E+14 | | | | |
| China EVA-3 | 91 ± 1 | >90 | 8.8E+13 | | | | | |
| Europe EVA | 91 ± 1 | 86 | | | | | | |
| Japan EVA-1 | 91 ± 1 | 94 | 1.1E+14 | 1.2E+14 | 9~12 | | | |
| Japan EVA-2 | 91 ± 1 | 86 | (deep texture) | 3.4E+14 | 10~14 | | | |
| NREL EVAs | 91 ± 1 | 88 | 0.6~5.5E+14 | 0.2~1.4E+16 | 9~12 | | | |
| US EVA-1 | 91 ± 1 | 88 | 0.8~1.1E+14 | 0.7~7.0E+14 | 9~10.5 | 20 | 88 | 7.02 |
| | | | | | | 38 | 82 | 28.45 |
| US PVB | 91 ± 1 | 0 | 4.4E+12 | | Glass/Glass only | 39 | 100 | 33.36 |
| Japan PVB | 91 ± 1 | 0 | 1.7E+12 | | Glass/Glass only | 39 | 100 | 40.05 |
| Europe PVB | 91 ± 1 | 0 | 8.4E+12 | | Glass/Glass only | | | |
| US TPU | 90 ± 2 | 0 | 6.4E+13 | | | | | |
| US TPU | 90 ± 2 | 0 | 7.3E+14 | | | | | |
| Europe TPU | 90 ± 2 | 0 | 1.1E+12 | | | | | |
| TAT (Tedlar/Al/Tedlar) | | | 4.31E+14 | | | 20 | 87 | 0.10 |
| | | | | | | 85 | 100 | 0.83 |
| TPT-primed | | | 2.7~3.5E+15 | | ~ 4 - 9 (to EVA) | 20 | 84 | 0.89 |
| | | | | | (EVA formulation dependent) | 83 | 100 | 142.77 |
| TPE Type | | | 1.1~3.3E+16 | | > 12 (break up) | 20 | 83 | 0.63 |
| | | | | | | 85 | 100 | 94.39 |
| Teonex Q65F (PEN) | | | 5.5E+16 | | | 28 | 100 | 1.04 |
| | | | | | | 85 | 100 | 35.24 |
| Protekt HD | | | 1.0E+17 | | | 40 | 100 | 3.20 |
| | | | | | | 85 | 100 | 60.02 |

# Encapsulation Process --
# Double-Bag Vacuum Lamination (+ Oven)




**High-performance vacuum laminator**

- Use high-speed pump-down to ensure good vacuum before EVA is melted
- Ensure proper pressing of the module stack
- **Optimize temperature-pressure-time (T-P-t) profile that is materials, formulation, and system-dependent**

## Process with EVA:

**One-Step, One (Two)-Temp:** Lamination and Curing in the laminator (**Fast-cure** EVA)

**Two-Step, One (Two)-Temp**: Lamination in laminator, Cure in Oven (**Slow-cure** EVA)

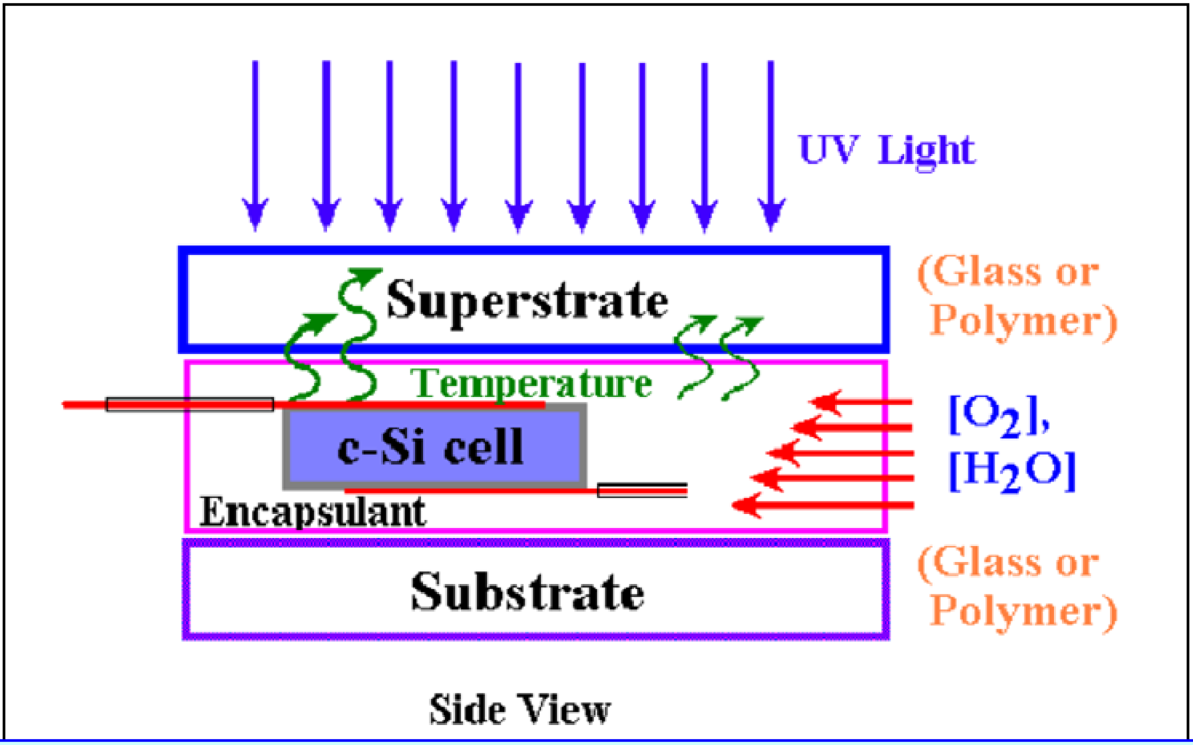
**=> No Industry-wide Standard!**

## Typical Conditions for EVA:

- Lamination:110° – 120°C for 4~10 min
- Curing at 140° – 150°C for ~6 to 30 min (depending on EVA formulation and process)
- **Gel ≥ 80%**

**PVB and TPU: Roll-press possible and reworkable**

# Testing vs. Performance Reliability




**Diurnal and Seasonal Temperature Variation; Rain/Snow/Hail; Air pollutants**

**Potential Degradation: Optical, Electrical, and/or Mechanical (+ Delamination)**

**EVA Degradation:** (Photo-discoloration vs. Photo-bleaching: $O_2$ diffusion limited; acetic acid generation);
**Moisture Ingress:** Delamination, corrosion, current leakage, T% loss

# Equipment for Accelerated Exposure Tests:

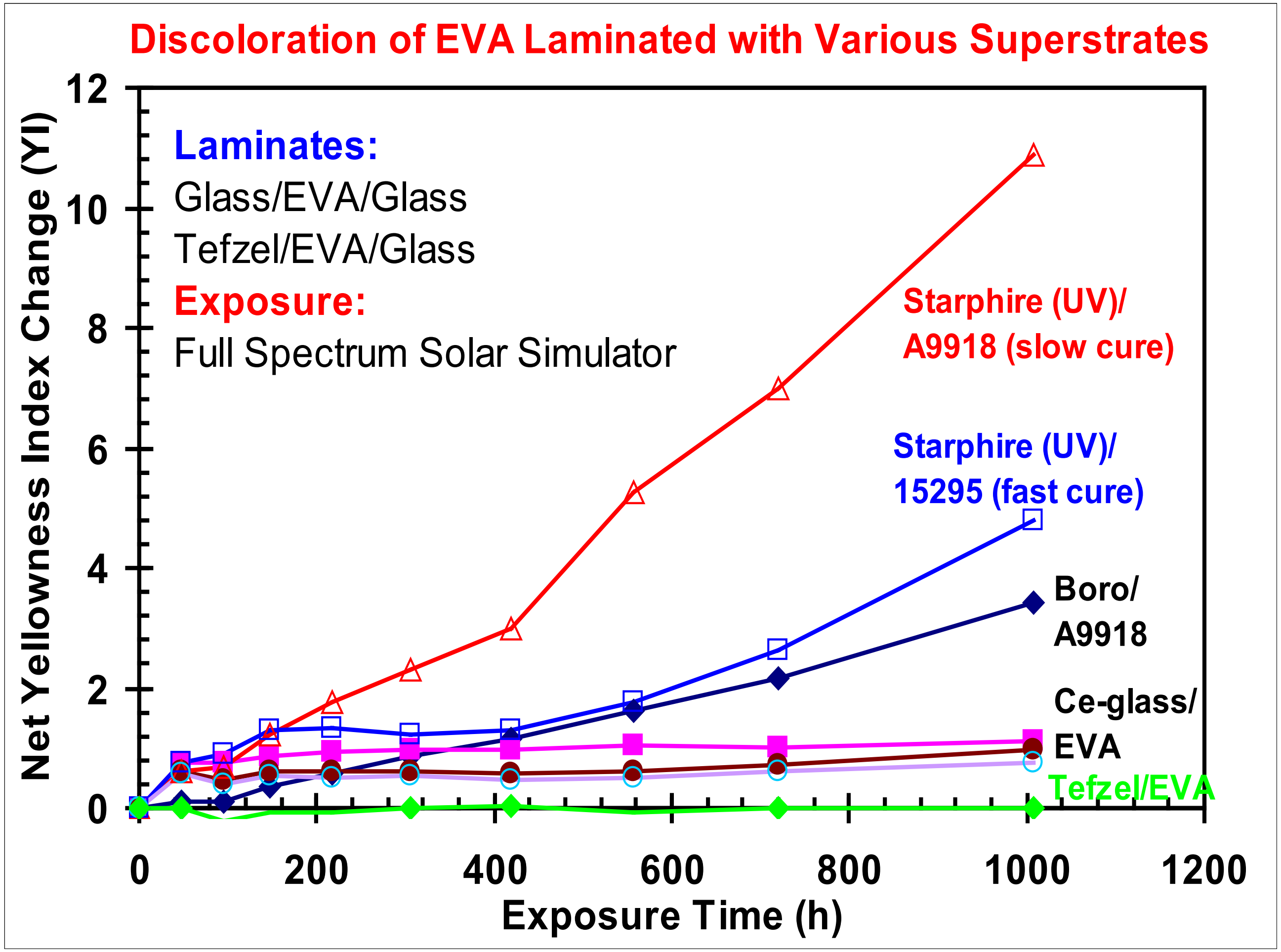
## Solar simulators, Weatherometers, Damp Heat Chamber

**Xe arc lamps for better simulation of solar spectrum**

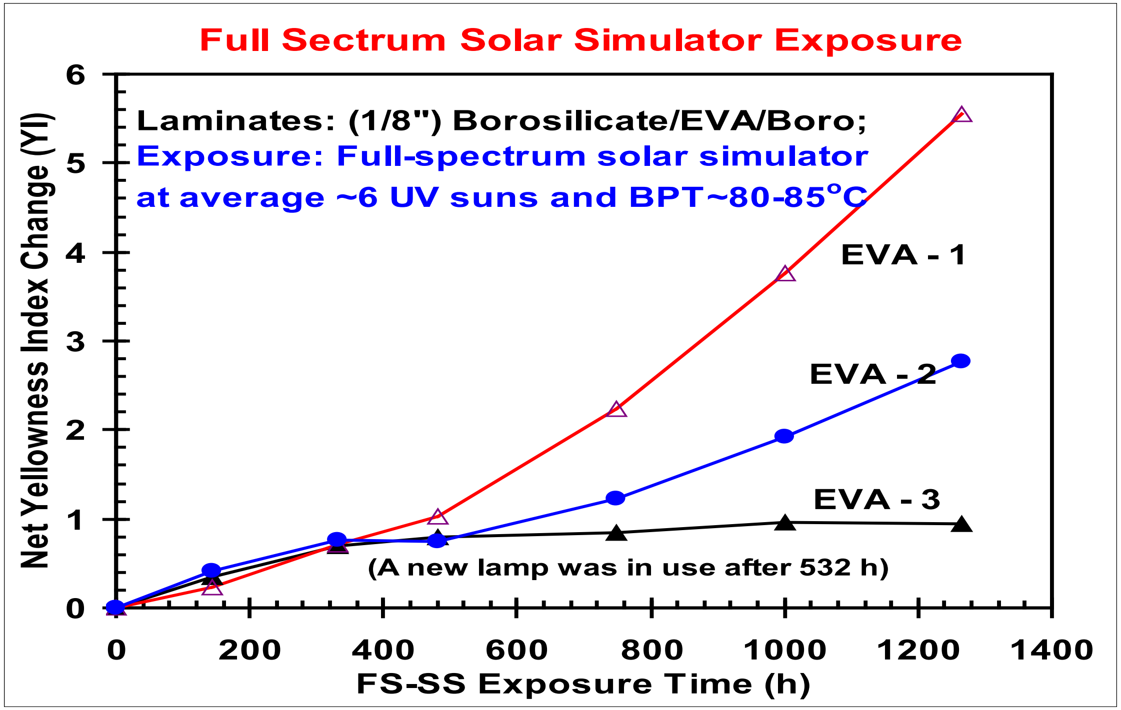


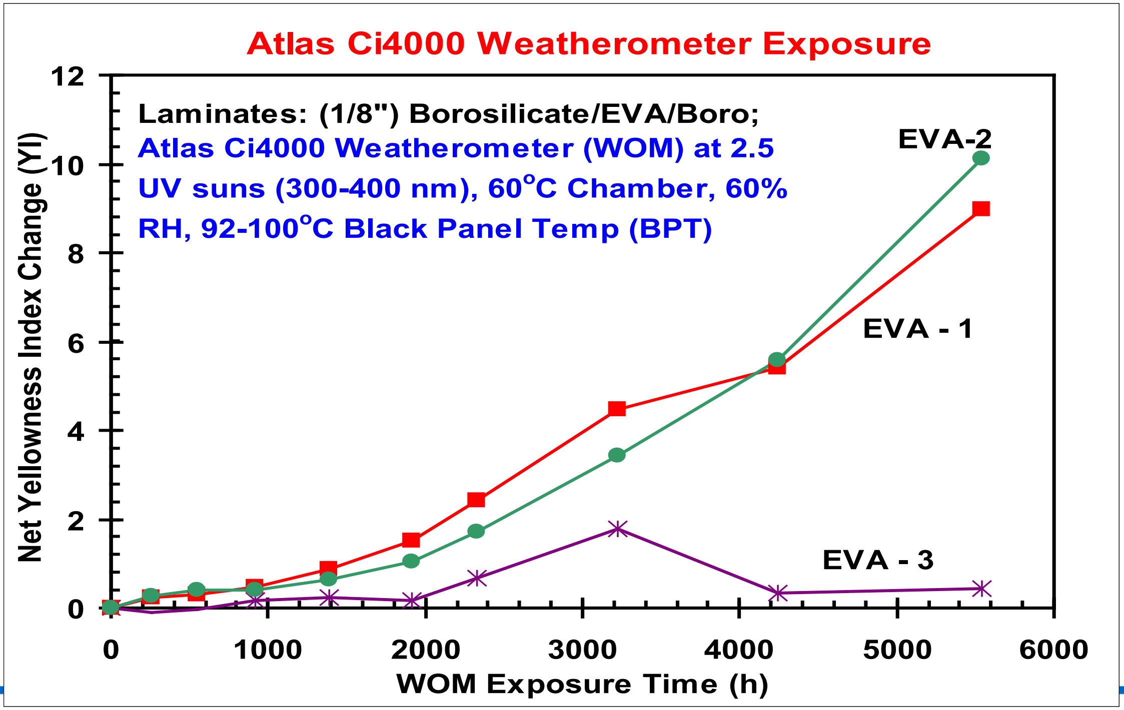



# EVA Yellowing Rate is affected by Formulation, Processing, UV Filtering, and Air Permeability of Superstrate




1. Slow-Cure > Fast Cure
2. UV-transmitting glass >> UV-filtering (Ce glass)
3. No yellowing with air-permeable Tefzel (photobleaching)
4. Competition between photo-discoloration (yellowing) and Photo-bleaching



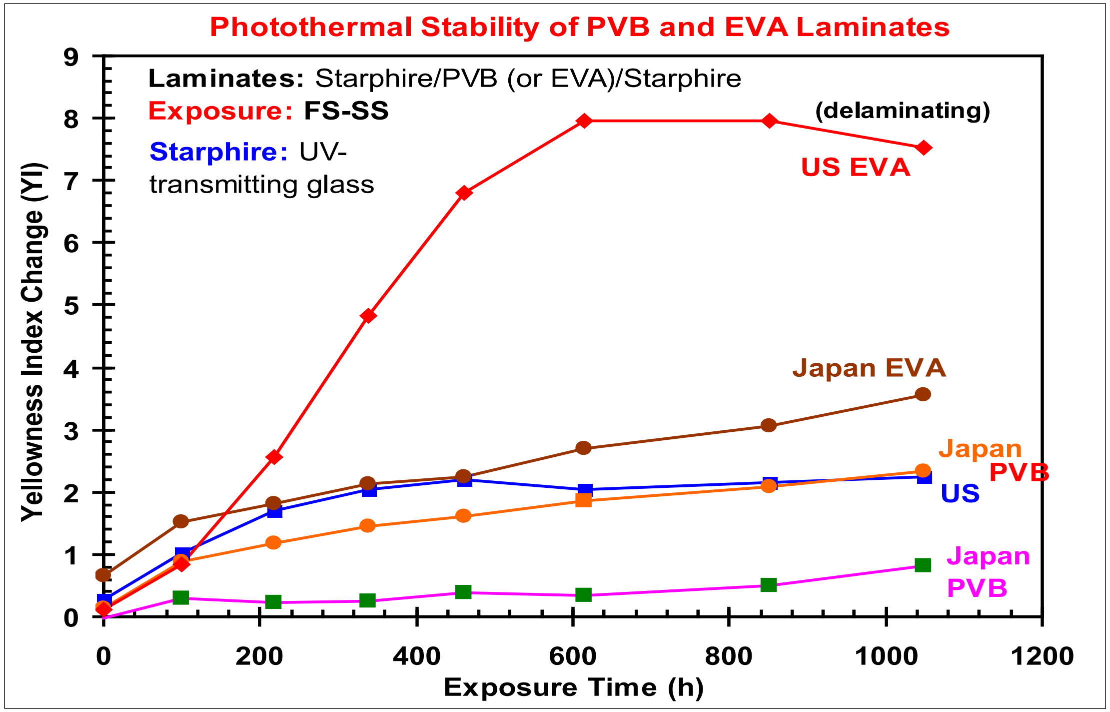

# Accelerated Life Test (ALT) for Photothermal Stability of EVA

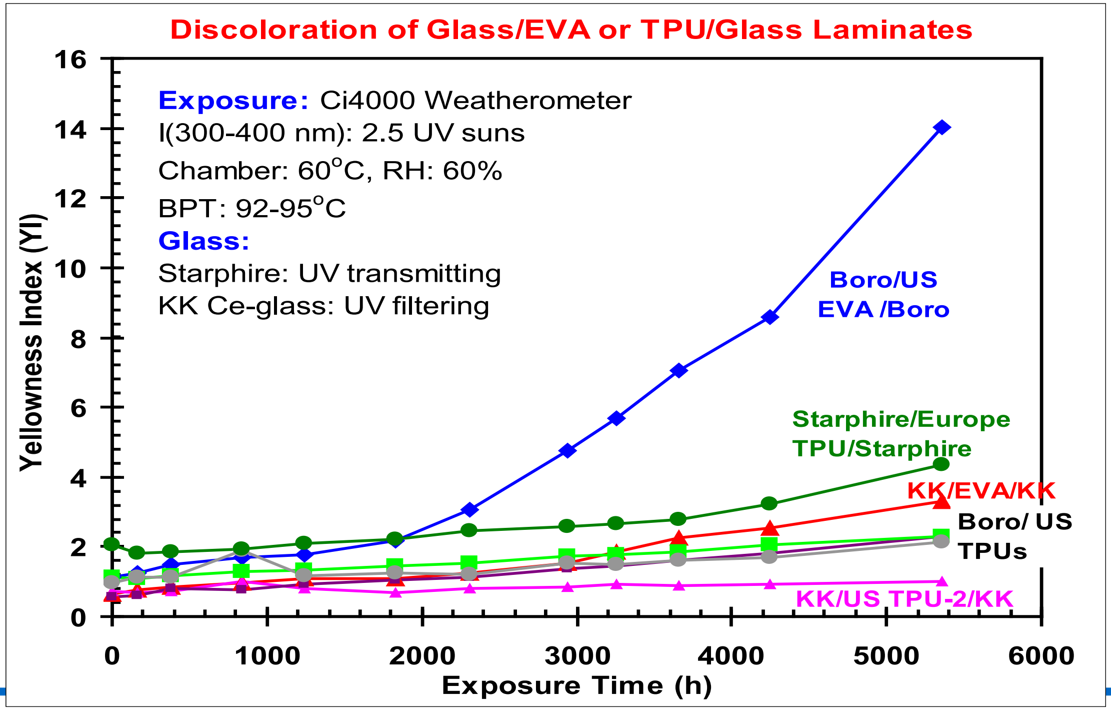
**EVA Yellowing Rate is:**

1. dependant on product formulation
2. higher under solar simulator (~7 UV suns) than in weatherometer (2.5 UV suns)
3. different in two test methods, but the trend remains unchanged

=> Shorter test time with greater light intensity

# Photothermal Stability ALT of PVB and TPU



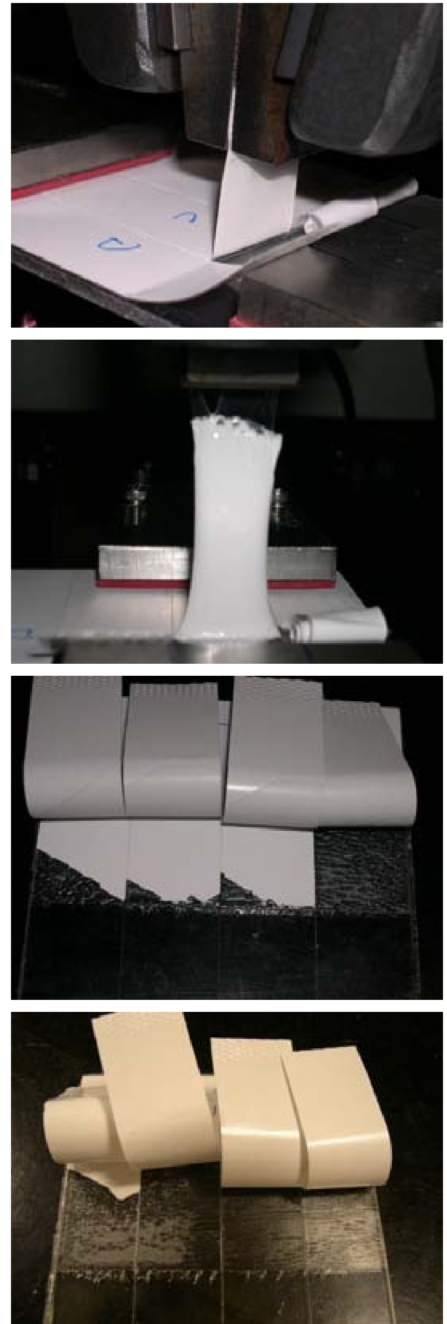




1. Both PVB and TPU showed much less UV-induced yellowing than EVA
2. PVB can be used only on glass/glass laminates
3. Delamination of TPU from UV-transmitter glass can be serious depending on product quality
4. Adhesion of TPU to glass can be largely degraded by damp heat exposure

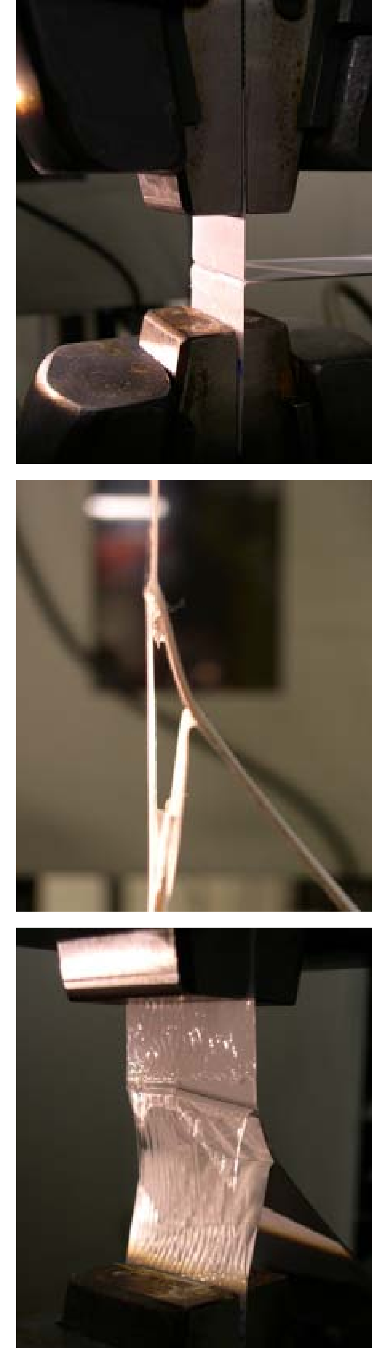
# Mechanical Tests

**PC-controlled Instron Mechanical Tester**

**Tensile Test**

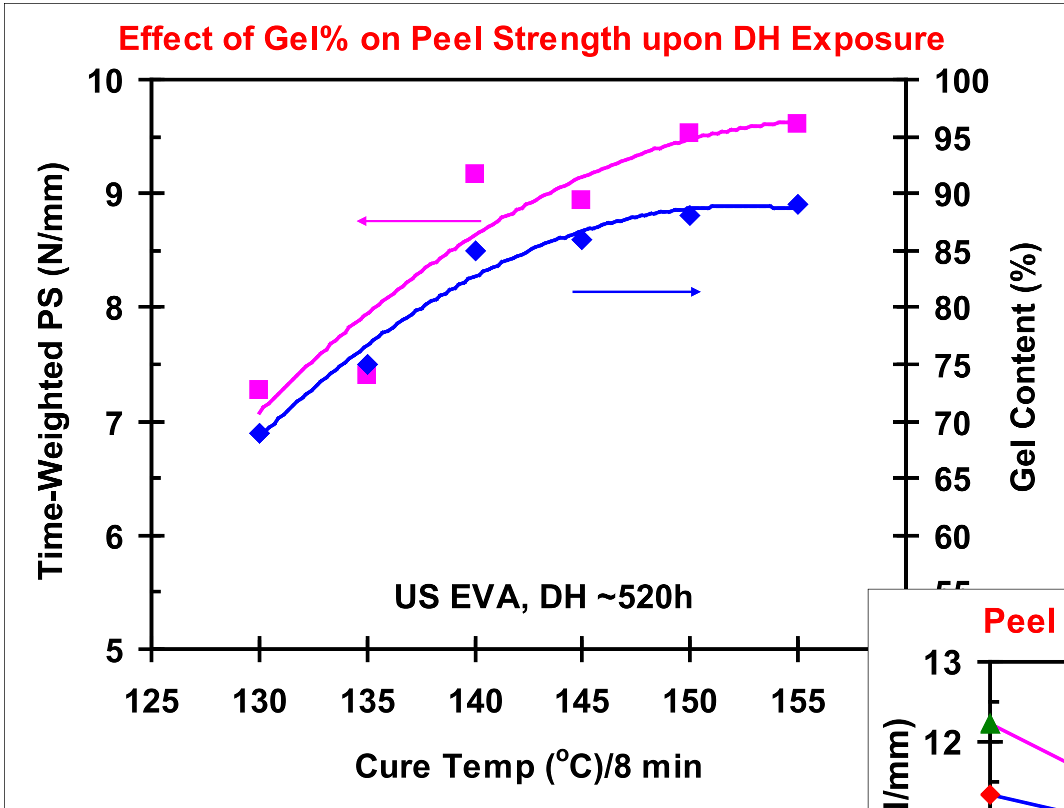


**90º Peel Test**

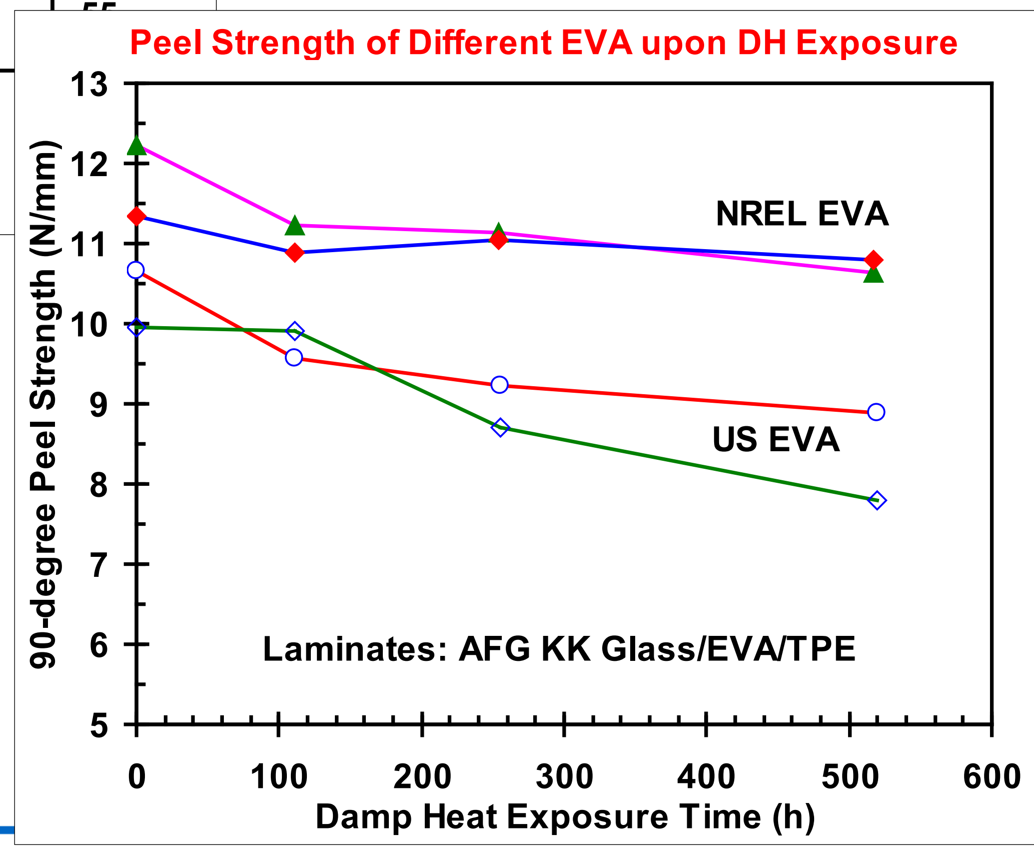


**T-Peel Test**

# EVA Adhesion Strength affected by Processing Condition




## and by Damp Heat Exposure Time



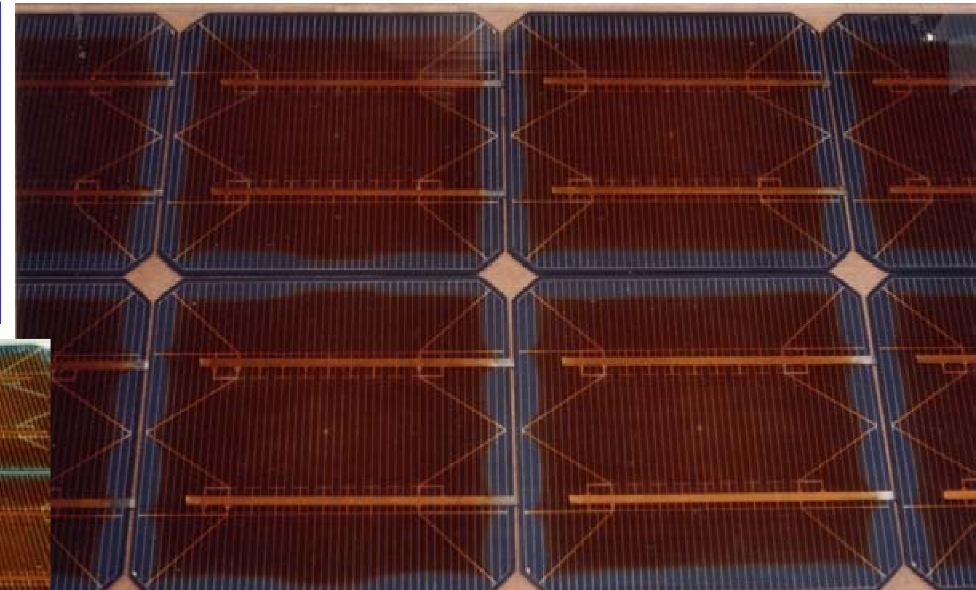
# Some Photos of Field Modules

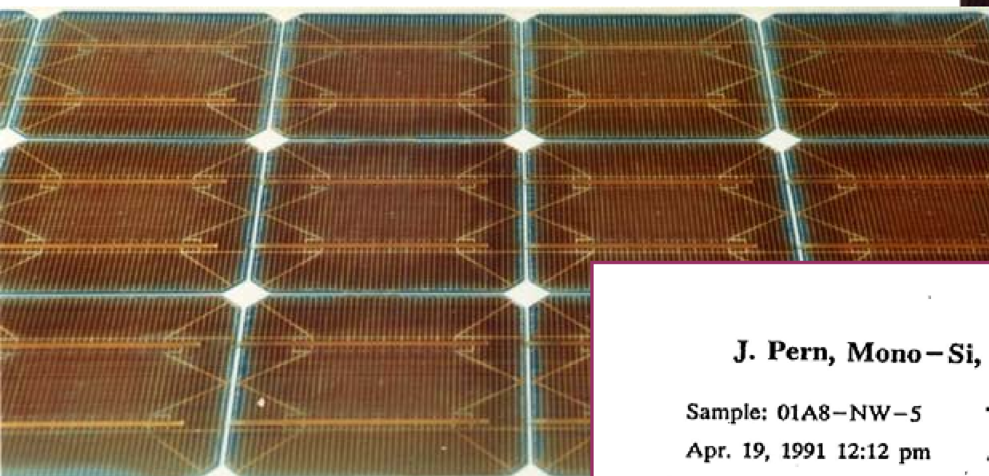
- Degraded by
  - Yellow-browning
  - Backsheet blistering & delamination
  - Corrosion by moisture ingress
  - Glass cracking by stress (glass/glass)
  - Other factors

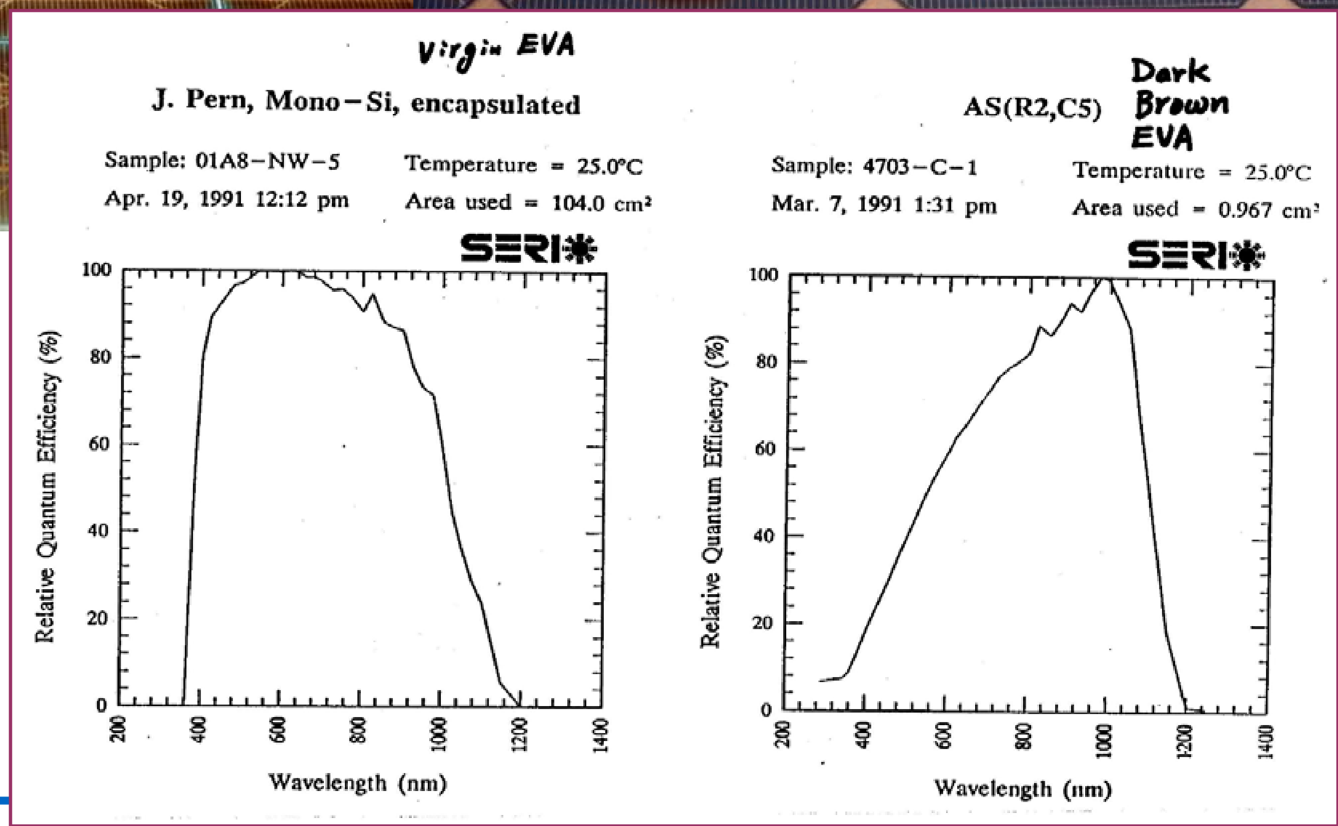
# EVA Browning in Field PV Modules

**<u>1990 EVA Browning Crisis:</u>** Severe EVA browning on mirror-enhanced PV arrays at Carrisa PV Power Plant, CA. Annual Power Output degraded by >45% from 1986-1990 (original: ~6 MW)

# Large T% Loss and so Power Loss due to EVA Browning





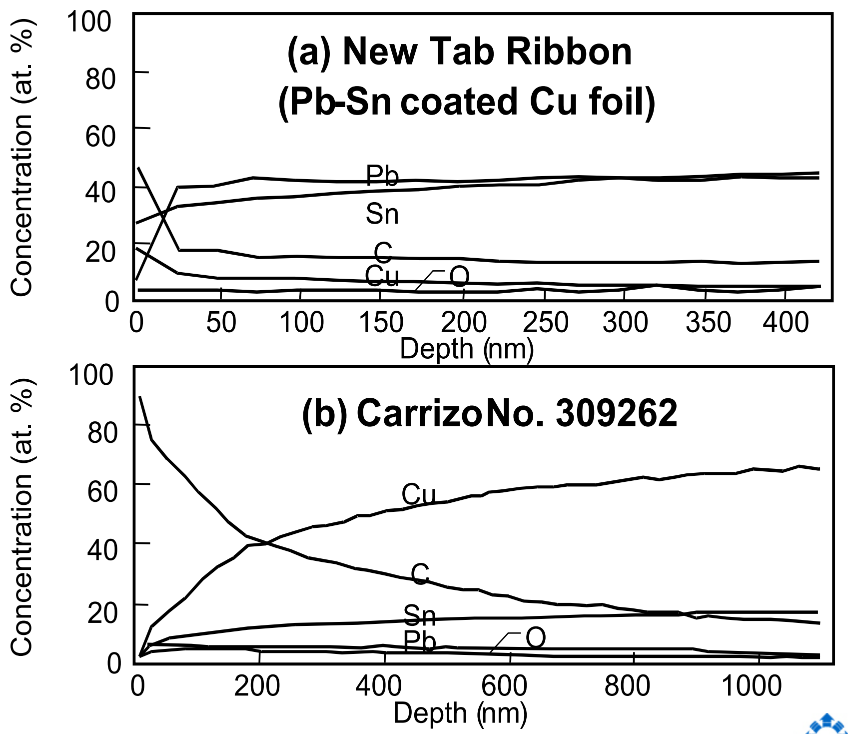


# Corroded Pb-Sn Alloyed Cu Tab Ribbons by Acetic Acid from Browned EVA

## EPMA Composition Analysis for the New and Exposed Tab Ribbons

| Sample Source PV Module No. | Solar Cell Location | Side of Tab Ribbon | EVA Color | Sn-L | Pb-M | Cu-L | O-K |
|---|---|---|---|---|---|---|---|
| New Tab | | | | 60.48 | 39.52 | | |
| Carrizo 1B | L9, R2 | EVA | Light yellow | 68.57 | 10.96 | 5.35 | 15.12 |
| Carrizo 309259 | L9, R2 | EVA | Brown | 5.80 | 41.13 | 13.27 | 39.80 |
| Carrizo 309262 | L9, R2 | EVA | Dark brown | 30.60 | 15.91 | 20.41 | 33.08 |
| Carrizo 309262 | L7, R3 | EVA | Dark brown | 4.62 | 46.56 | 8.08 | 40.74 |

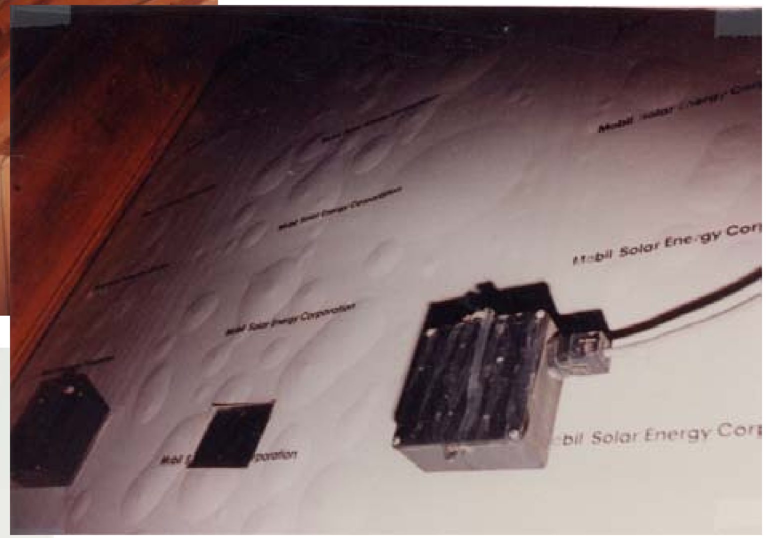
## Auger Depth Profile Analysis



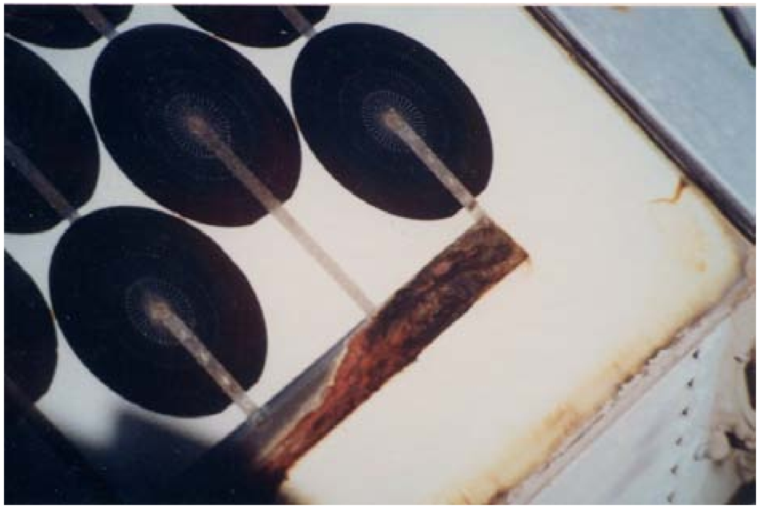

P110-A048804

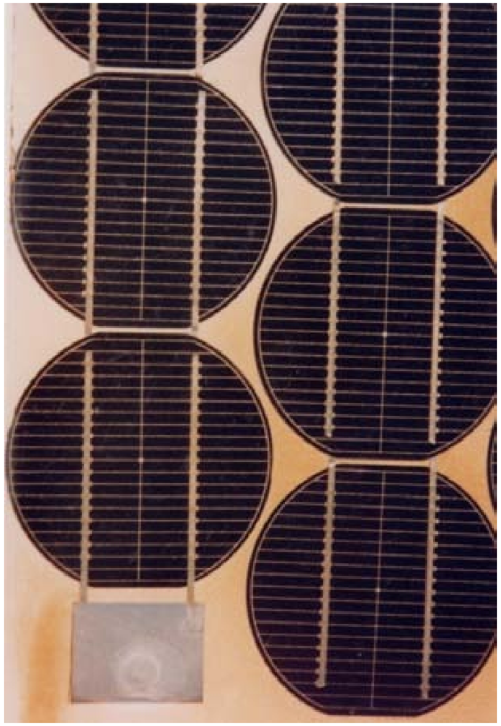
# Irregular PVB Browning at ASU

# Blistering & Delamination of Backfoils

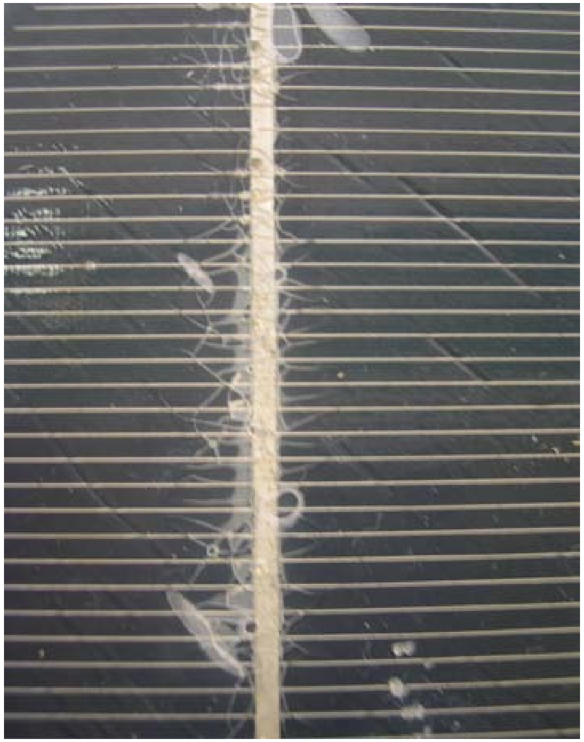


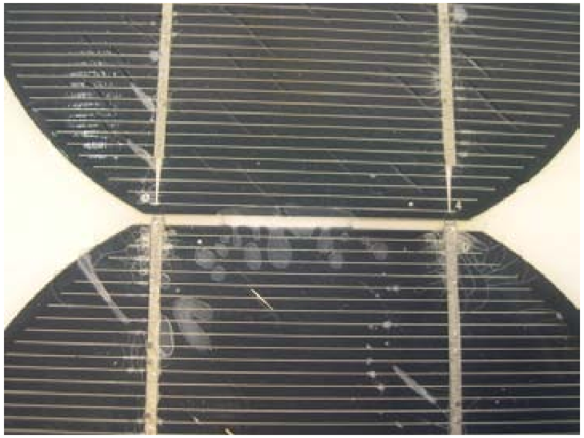
# Water Ingress and Corrosion

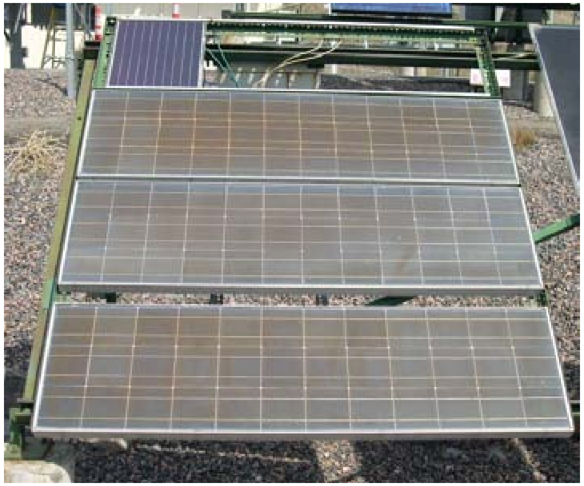


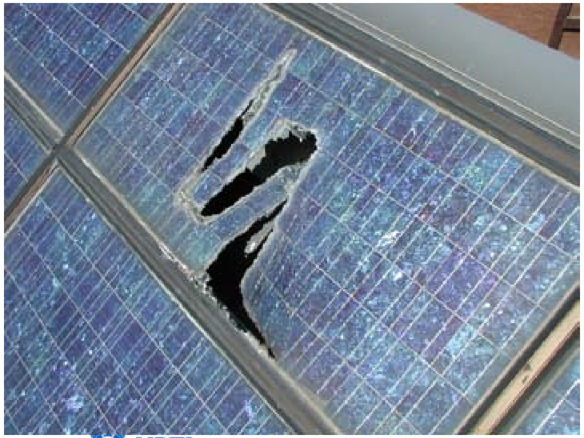


# More Degraded Modules

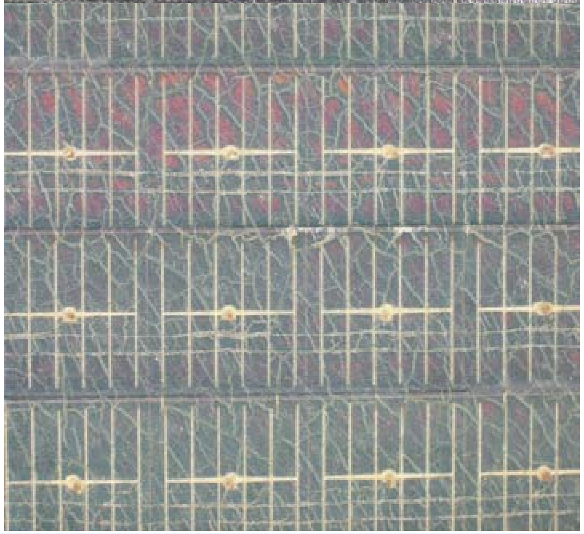




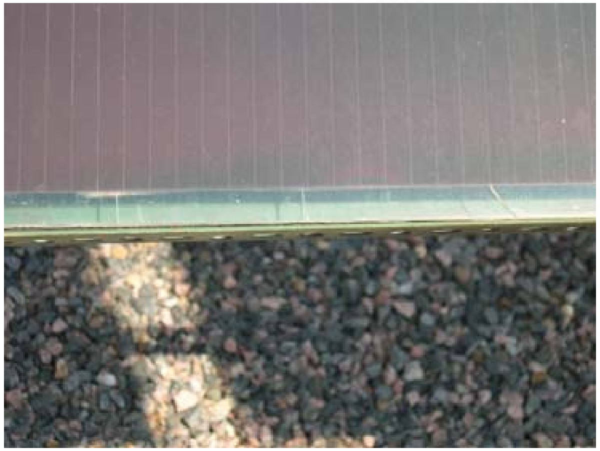


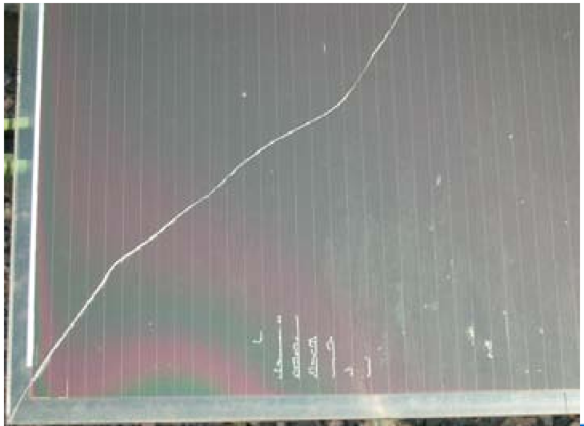






# Thin Film Modules at NREL OTF

# Field-Degraded Thin Film Modules

(photos: PowerLight)

# Conclusions

- Proper selection and initial tests of encapsulation materials are important.
- Different encapsulant formulations (e.g., EVA) give different quality and performance.
- Encapsulation method and processing conditions can affect the laminate quality and reliability of PV modules.
- Adequate accelerated exposure tests can be useful to assess the performance expectation of materials and quality of processed components.
- Overall module reliability is determined by all component materials and processing factors.