For over 40 years, our material innovations have led the photovoltaics industry forward, and helped our clients transform the power of the Sun into power for us all. Today we offer a portfolio of solutions that deliver proven power and lasting value over the long term. Whatever your material needs, you can count on quality DuPont Photovoltaic Solutions to deliver the performance, efficiency and value you require, day after day after day…
Acknowledgements

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Outline

I. Introduction to Backsheet Constructions

II. Performance and Durability
   a. Inner Layer
   b. Core Layer
   c. Outer Layer

III. Conclusions
### Backsheet Structure

PV backsheets are typically three-layer structures with the following functions:

<table>
<thead>
<tr>
<th>Layer</th>
<th>Functions</th>
<th>New Design and Material Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Layer</td>
<td>adhesion to encapsulant</td>
<td>new material compositions</td>
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<tr>
<td></td>
<td>UV protection core from &quot;filtered&quot; direct UV</td>
<td>thinner layer (&lt;2 um)</td>
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<tr>
<td></td>
<td>resistant to penetration during lamination</td>
<td>coated layers</td>
</tr>
<tr>
<td>core layer</td>
<td>primary mechanical properties</td>
<td>new materials</td>
</tr>
<tr>
<td></td>
<td>primary electrical insulation properties</td>
<td>thinner layers (~250 um to 75 um)</td>
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<tr>
<td></td>
<td>water and acetic acid barrier properties</td>
<td></td>
</tr>
<tr>
<td>outer layer</td>
<td>weatherability</td>
<td>new materials</td>
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<tr>
<td></td>
<td>UV protection of the core from indirect UV</td>
<td>thinner layer (&lt;2 um)</td>
</tr>
<tr>
<td></td>
<td>resistant to mechanical damage (handling, sand)</td>
<td>coated layers</td>
</tr>
</tbody>
</table>
DuPont™ Tedlar® PVF is Specified by Scientific Experts

NASA Jet Propulsion Laboratory Flat-Plate Solar Array Project

Most extensive study ever undertaken to improve PV module’s efficiency, lifetime, reliability and quality

- Eleven years of designs & testing from 1975-1986
- Over $700 million spent (in 2013 dollars)
- Over 400 module designs tested
- More than 22,000 modules purchased & fielded
- Five rounds of design upgrades

“Module lifetimes increased from 1 or 2 years … to lifetimes of 20 to 30 years at the end of the project.”

“The success of this approach is demonstrated by the fact that most design details of the Block V modules (final design) have been adopted internationally.”

Resulted in TPT backsheet design

Source:
Backsheet Durability Issues of Inner Layer

Yellowing
• Front-side yellowing observed in the field for PVDF and PET backsheets
• Brittleness of yellowed inner layer measured by nano-indentation

Inner Layer Cracking
• Observed in module weathering

UV transmission of Thin Inner Layers
• Impact on mechanical properties and yellowing

Thermal Stability of Inner Layers
• Observed in the field and impact on lamination
Inner Layer Backsheet Yellowing

PVDF-based backsheet
- Years in service: < 5 years
- Location: 5 countries (Belgium, Spain, USA, Israel, Germany)
- Five different manufacturers

PET-based backsheet
- Years in service: < 4 years
- Location: AZ
- 100% field affected
- Rooftop and ground mount
Embrittlement measured in yellowed inner layer

Embrittlement measured in yellowed inner layer

Stika et al., IEEE PVSC 2014

Nano-Indentation of Inner Layer of Backsheet

Gambogi et al., EUPVSEC 2013, Paris
Backsheet Yellowing in Weathering Tests

Inner layer yellowing observed in the field for single-sided PVDF and PET-based backsheets.

Front side yellowing of 1sPVDF backsheets (left, <5y in multiple locations) and PET backsheet (right, 4y in AZ).

Yellowing in single-cell modules with weathering exposure (90C BPT) and front side UV exposure of ~4 years equivalent exposure in Arizona.
Thin Inner Backsheet Layer

Thin (<2um) coated layer used in a commercial 1sPVDF backsheet on the inner layer of the backsheet

Thin (<2um) coated layer is insufficient to protect the core layer of the backsheet from long term UV exposure
Yellowing and Elongation Retention in Thin Coated Layers

Yellowing vs inner layer thickness for two different compositions

Elongation Retained vs. inner layer thickness for two different compositions

Thin (<2um) coated inner layers result in yellowing and loss of mechanical properties
Higher BPT (90C) and full structures mini-modules to assess local mechanical stresses and materials interactions

Weathering of single-cell mini-modules (above) showing cracking of the inner layer of the backsheets for **two commercial PET-based backsheets**. Backsheet exposures using glass/EVA filter show similar cracking.
Low softening and melting temperatures can lead to backsheets melting or cracking in the field due to partial shading and hot spots.

JIS K7196 Heat Deformation Test- weighted stylus impinges on sample being heated, thermal transitions noted.
Susceptibility of Inner Layer to Wire Penetration Depth

Penetration of tabbing ribbon into the inner layer of commercial backsheets under standard EVA lamination conditions

TPT: Tedlar® PVF/PET/Tedlar® PVF

Penetration of tabbing wires evaluated by optical micrograph of a cross-sectioned backsheet with a soft inner layer

UVPET/HPET/EVA
Backsheet Durability Issues of Outer Layer

**Yellowing**
- Observed in Fielded Modules with PET and FEVE Backsheets
- Mechanical Properties Related to Yellowing

**Cracking**
- Observed in Fielded Modules with PET and PVDF Backsheets
- Observed in Sequential Durability Testing
- Associated with Poor Mechanical Properties

**Delamination**
- Observed in Fielded Modules
- May Be Associated with Thermal Stability at Higher Temperatures
Outer Layer Backsheet Yellowing on Rooftop System

Yellowing of PET-based backsheet on rooftop modules after 15 years in Japan.

Yellowness measurements (b*) taken on 12 of 14 modules in the array

Overall yellowing of backsheets due to UV or combination of stresses (thermal, UV, etc.)
- High level of yellowing even on the interior of array (b* of 13-20)
- Highest yellowing is along edges with highest UV exposure (b* up to 27)

Yellowness (b*) measurements of 12 modules

<table>
<thead>
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<th>A-Up6</th>
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<table>
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<tr>
<td>13.1</td>
<td>24.2</td>
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</table>

High yellowing of PET-based backsheet in near roof mounting

Source: Modules provided by AIST; DuPont analysis

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Outer Layer Backsheet Cracking and Yellowing

Polyester-based backsheet
- Years in service: 4 years
- Location: Spain
- 5,000 modules affected

Crack in polyester-based backsheet

Exposes tabbing ribbon and potential electrical leakage path
Loss of mechanical properties correlates with yellowness for field and accelerated testing. Significant loss of elongation with yellowness $b^* > 4$. 

UVA, 65W/sqm, 70°C BPT, 3000 hours = 195kWhr/sqm, 18 year desert equivalent
Field exposures ranged from 4 to 14 years

Proposed CN backsheet standard
Maximum Elongation Loss = 40%
Mechanism of PET Degradation by Photo-Oxidation

The absorption of radiation (photolysis) leads to scission reactions centered around the ester linkage by the Norrish primary processes:

UV degradation mechanisms of PET are well understood: polymer chain breakage and formation of yellow fragments after photolysis.

Polymer chain breakage and yellow fragment formation results in increased yellowness and loss of mechanical properties.

Photo-oxidation of PET increases hydroxyl and carbonyl functional group absorption.

PET needs a durable cover layer to protect it from UV degradation.

Source: Handbook of Material Weathering
Outer Layer Backsheet Cracking

Polyester-based backsheet
• Years in service: 4 years
• Location: Spain
• 5,000 modules affected

PVDF-based backsheet
• Years in service: 4 years
• Location: North America
• 57% of modules affected
PVDF-Based Backsheet Degradation Sequence

- Initial crack formation followed by tear propagation and subsequent delamination
- Occurs consistently in the vertical direction – machine direction of backsheet
Sequential Stress Testing of Modules

DH1000/UVA1000/TC200

Damp Heat  UVA  Thermal Cycling

2x(DH1000/TC200)

Damp Heat  Thermal Cycling  Damp Heat  Thermal Cycling

Fine cracking of PVDF layer in PVDF/PET/FEVE backsheets

Large cracks in PVDF/PET/FEVE backsheets

Cracks of PVDF film found along ribbon wire in full-sized module

Sequential stress testing reproduces cracks observed in the field
Loss of Mechanical Properties of PVDF Explains Susceptibility to Cracking

Lower elongation in the TD direction makes PVDF film more vulnerable to cracking and may be responsible for cracking in sequential testing and in the field.

Test Conditions: DH (85°C, 85%RH)
Mechanical Properties at Low Temperatures

PVF retains mechanical properties
PVDF losses mechanical properties at lower temperatures
Other Outer Layer Issues Observed in the Field

PVDF-based backsheet
• Years in service: 5 years
• Location: Spain

PVDF-based backsheet
• Years in service: 7 years
• Location: Israel

Hot Spot Cracking, Yellowing, Delamination and Softening of the Outer Layer
Other Outer Layer Issues Observed in the Field

Large Amount of Delamination

Bubbling and Yellowing

FEVE-based backsheet
- Years in service: 5 years
- Location: Shanghai, Rooftop
- 30% of array affected

Adhesion Loss and Delamination of the Outer Layer
Conclusions

• Changes to backsheet materials and construction can have an impact on module durability in the field

• Degradation mechanisms of inner and outer layers of the backsheet are understood by using accelerated test methods and materials analysis and characterization

• Evaluating modules in the field is an effective approach to better understand degradation mechanisms and to validate new test methods.