Systems Approach to High Performance CIGS Material Set Including Flex Ultra-Moisture Barrier and Hi-Temp MLI Substrate

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The miracles of science™

Flexible CIGS modules can accelerate advancement to grid parity

Copper Indium Gallium Diselenide (CIGS) has the highest efficiency of all thin-film PV technologies

- 19.9% cell in the lab (NREL)
- 13% in a module

Flexible modules can drive lower system cost

- Lower manufacturing cost
  - Potential for high productivity with roll-to-roll processing
- Lower installation cost
  - Lighter modules, no frames

However, moisture accelerates CIGS cell degradation

A flexible, transparent ultra barrier is needed

DuPont's Growing Portfolio of Solutions for the PV Industry

A Frontsheet Materials
Lighter and less fragile than glass, durable DuPont frontsheet materials deliver high performance to help increase power output and offer more design options for BIPV applications.

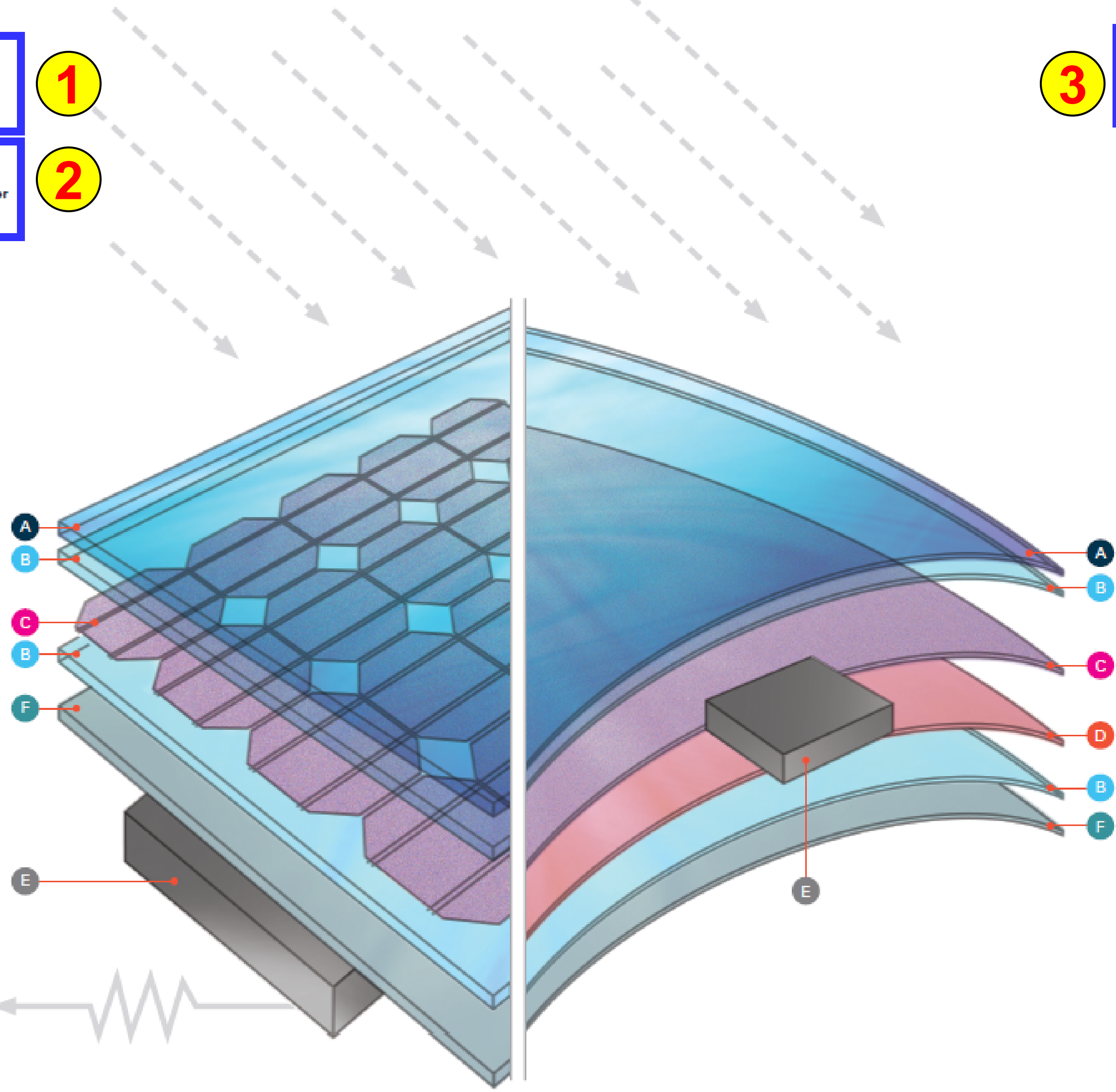
1

B Photovoltaic Encapsulants
With a broad portfolio of innovative solutions, DuPont encapsulation materials deliver long-term protection for the most sensitive portions of photovoltaic modules.

2

C Photovoltaic Metallizations
DuPont is raising the bar for PV cell metallizations. With a broad range of characteristics, these high performance metallization compositions help lower the overall cost per installed watt.

THE DUPONT PORTFOLIO
OF INNOVATIVE MATERIALS
FOR CRYSTALLINE SILICON
PHOTOVOLTAIC MODULES



3

D Thin Film Substrates
DuPont substrate materials deliver robust processing for both CIGS and a-Si modules with high temperature tolerances and low CTE capacity to minimize stress and increase productivity.

E Junction Box and Structural Component Materials
With a broad range of UL-recognized solutions, DuPont materials can help increase safety, eliminate corrosion and provide long-lasting performance for junction boxes and structural components in harsh environments.

F Backsheet Materials
For superior, long-lasting backsheet protection against the elements, choose the products industry leaders trust.

THE DUPONT PORTFOLIO
OF INNOVATIVE MATERIALS
FOR PHOTOVOLTAIC
THIN FILM MODULES

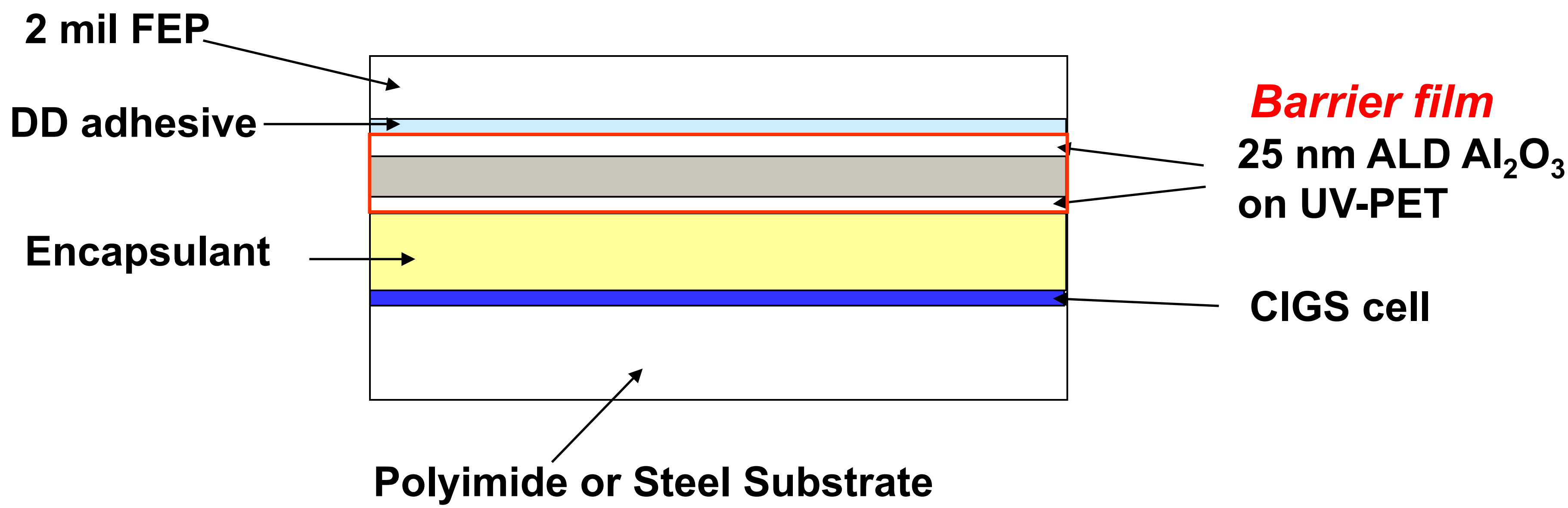
Sodium Metal for Poly-silicon Manufacturing
DuPont sodium metal enables alternative low cost manufacturing processes for poly-silicon.

Wet-Etch Additives for PV Manufacturing
DuPont fluorosurfactants provide unrivaled wetting aids in semiconductor texturing, offering etch control, reduced waste and improved cell efficiencies.

High Performance Parts
For improved solar cell manufacturing productivity, choose DuPont high performance parts that help increase throughput and equipment uptime.

energy for a thriving world™

Frontsheet barrier/encapsulation of PV cell with Ultrabarrier:

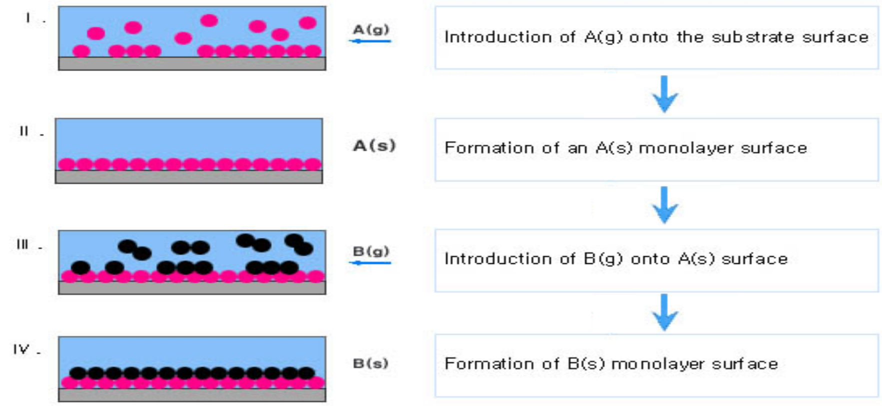


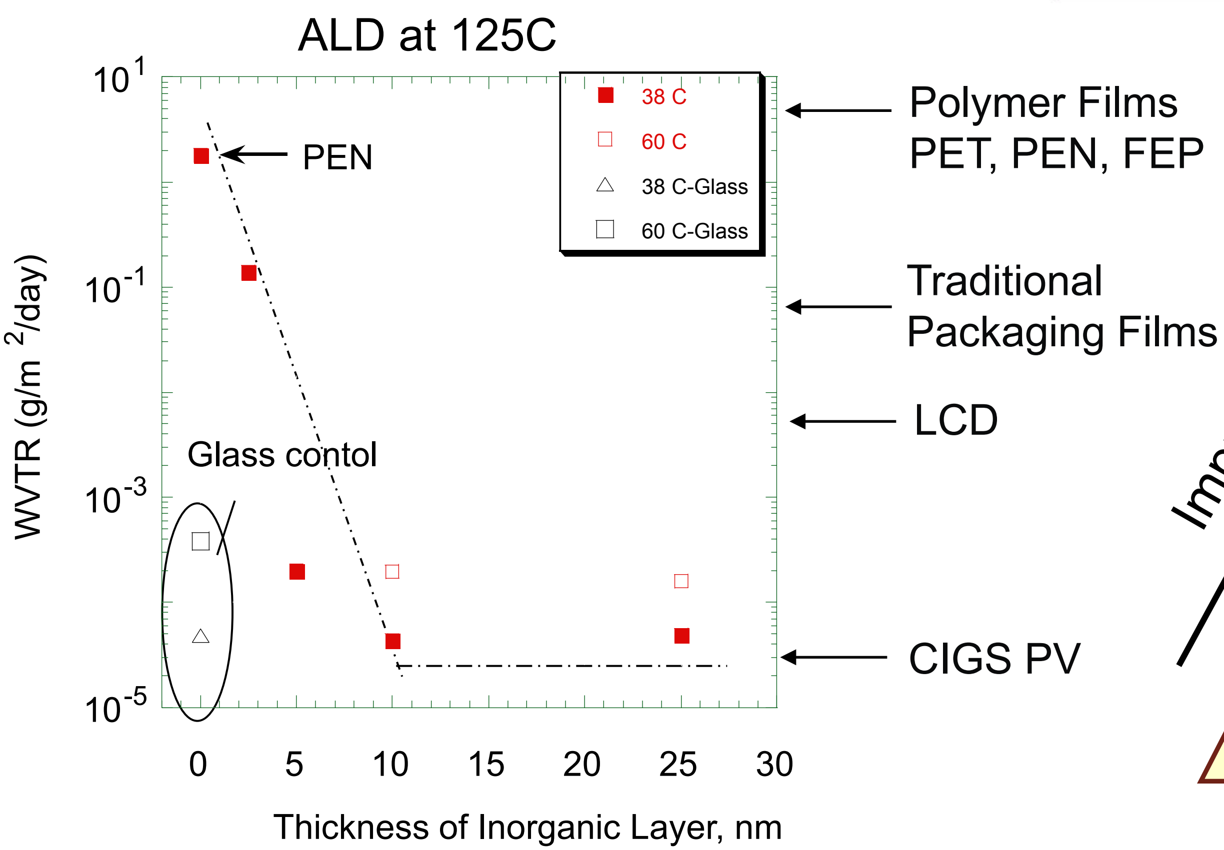
Performance Targets

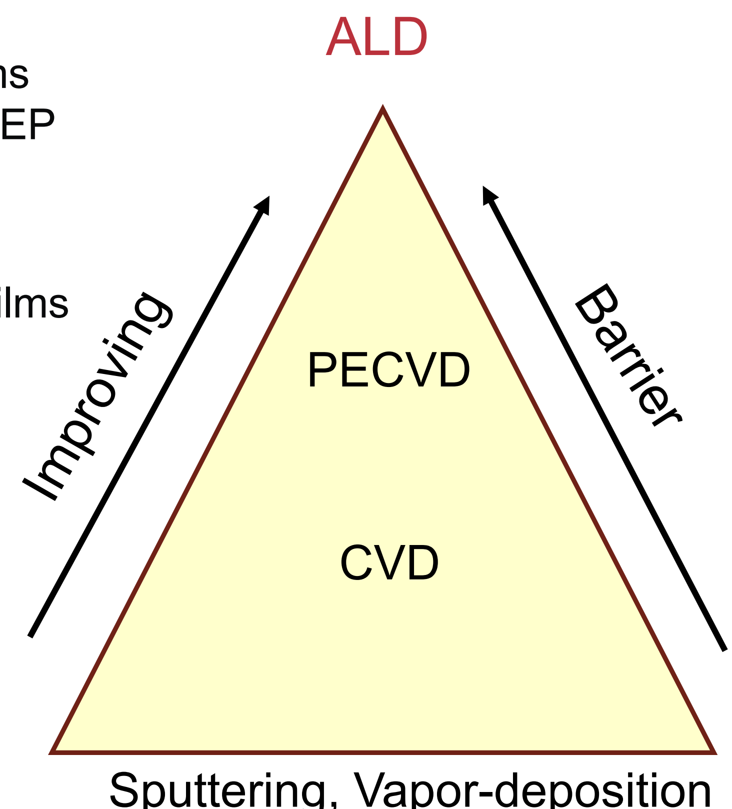
- Simple manufacturing process
- Compatible with plastics
- Barrier film that is transparent and flexible
- Water Vapor Transmission Rate (WVTR) < 10^{-4} $gH_2O/m^2/day$

Approach - Atomic Layer Deposition (ALD) on plastic

- Simple process
- Compatible with plastics
- Final film product is transparent and flexible
- WVTR < 10^{-4} $gH_2O/m^2/day$



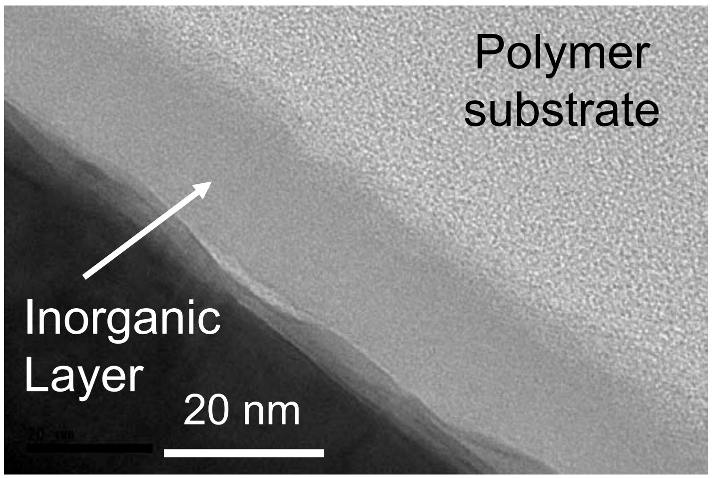




ALD Can Provide a Uniform, Pinhole-free, Flexible Barrier Layer

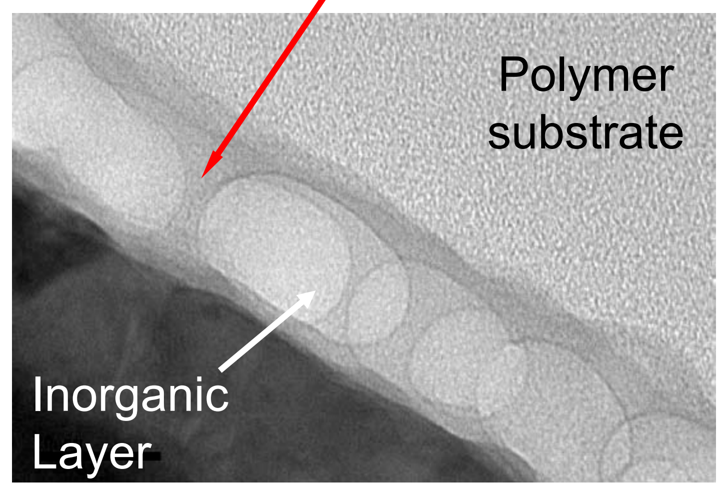
Transmission Electron Microscopy (TEM) images

ALD inorganic layer on polymer



Grain boundaries which can lead to water transmission

Vapor deposited inorganic layer on polymer



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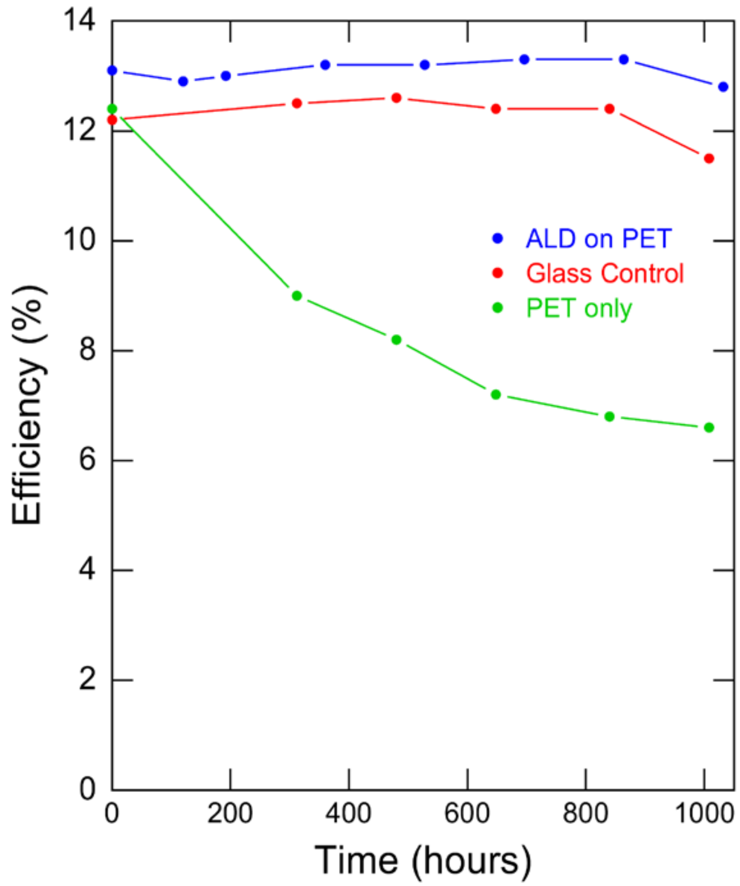
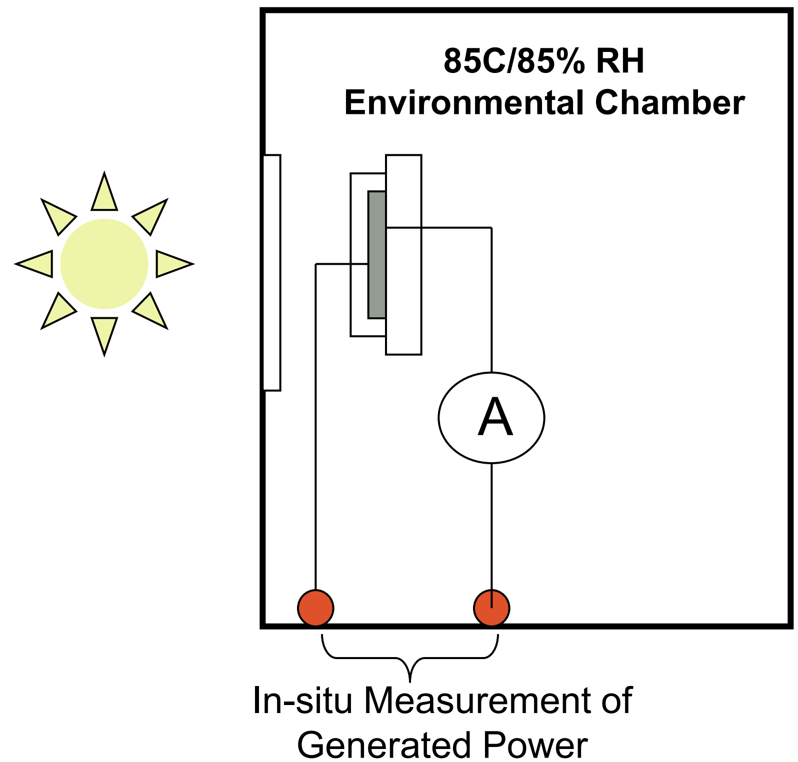
A Flexible UltraBarrier Layer Can Enable CIGS on Flex

- Our initial lab results indicated that ALD-on-plastic could effectively protect CIGS cell with accelerated aging performance comparable to glass
- Program objective now is to demonstrate manufacturing feasibility of ALD-on-plastic with water vapor transmission rate below 10^{-4} g/m^2/day at “low” cost

85C/85 % RH with illumination for 1032 hr



Measured at partner institute



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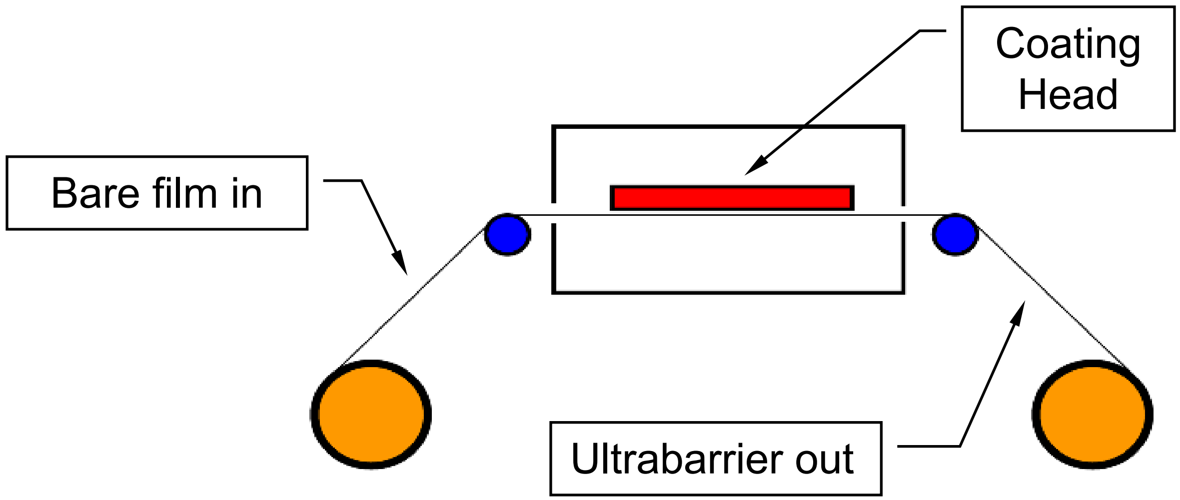
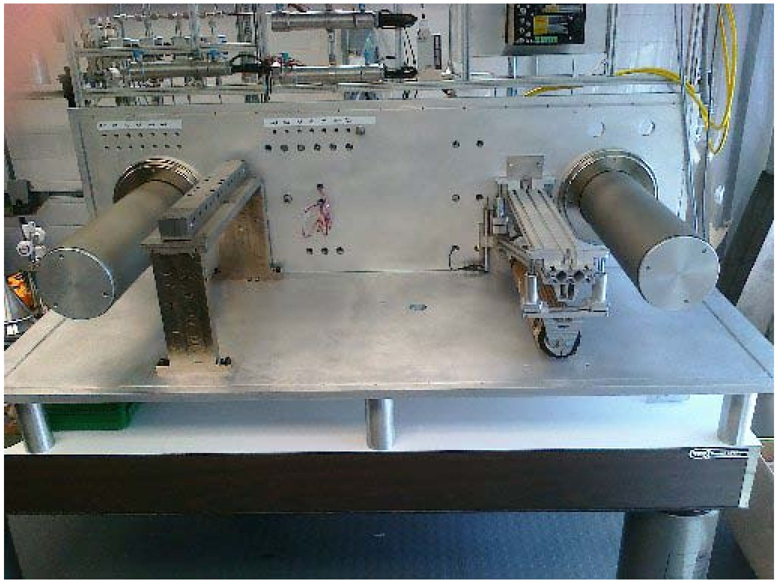
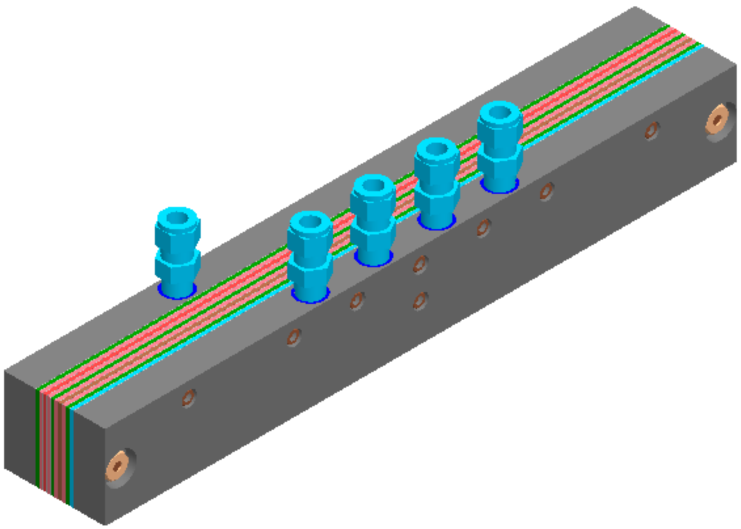
Building prototype roll-to-roll equipment for ALD



- Prototype will demonstrate high throughput and low cost feasibility
- Funded in part by DOE





Results – Modeling & Design

Proprietary coating head enables roll to roll manufacturing

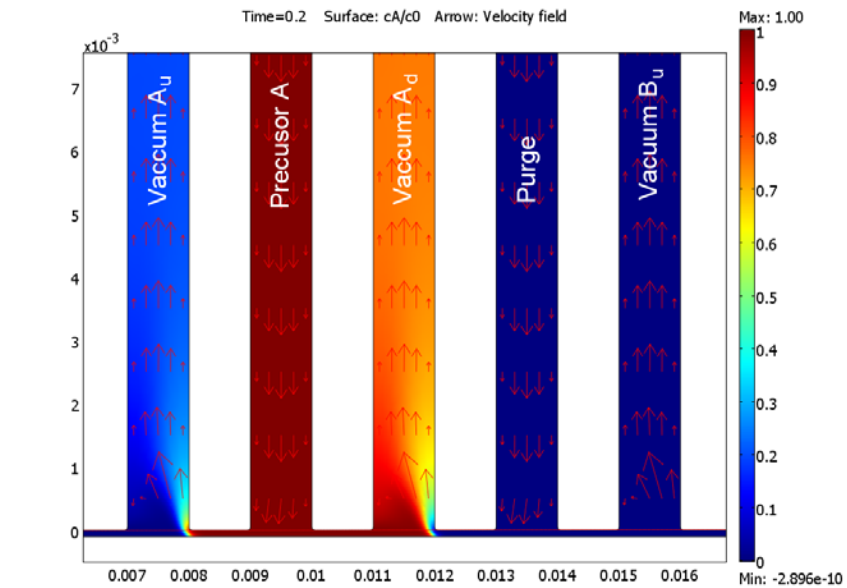
- Design confirmed by computational fluid dynamics & numerical modeling

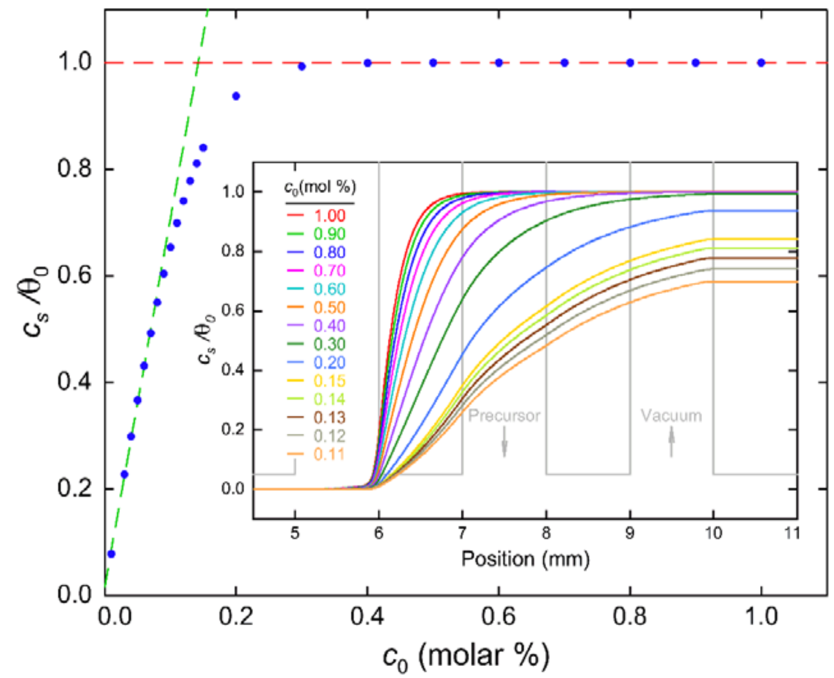
Model indicates feasibility of 1 m/sec web speed

- Initial target is 0.1 m/sec
- Process self-stabilizes in ~0.1 sec
- Negligible cross-talk between precursors

Optimization from model

- Shown process stable against expected variations in head to web gap
- Explored materials efficiency: precursor concentration can be reduced to 0.4%



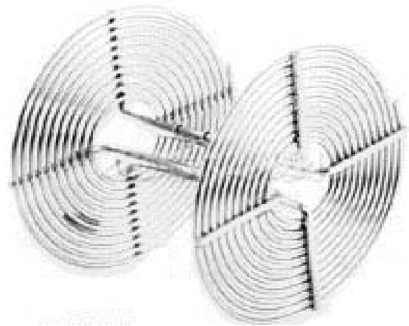


Take-home message: Modeling predicts feasibility

Batch ALD Coating Process

Cassette in batch chamber approach

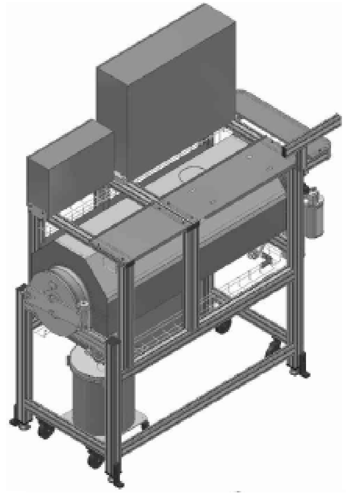
- Technical challenges:
  - Cassette fabrication
  - Film loading/unloading
  - Process control
  - Scale-up plan
  - Batch ALD process modeling



Empty Cassette

Cassette with UB Film Loaded

VIEWS OF THE TOOL FRAME



A number of cassettes (polycarbonate and aluminum metal) were fabricated and used in about 500 ALD batch depositions resulting in films with WVTR consistently below $5x10^{-4}$ (detection limit)

Detailed economic modeling concludes that R2R likely will still be the preferred commercial process

Batch process has been key to product validation and market development while continuous process is developed

Cassette inside ALD Batch Chamber

Remaining Technical Hurdles for Ultrabarrier Frontsheet Development

- Optimization of frontsheet lamination process that fully retains the barrier performance of the barrier film
- WVTR measurement capability that will allow for accelerated process development and resolution in targeted product performance range ($<10^{-6}$ g/m^2/day)
- On-line measurement capability to predict WVTR and/or product-by-process control strategy to ensure performance of film over large area
- Confirmation of model that relates frontsheet WVTR to CIGS module lifetime
- Demonstration of continuous ALD process prototype to generate basic data for pilot and/or commercial-scale

Summary and Next Steps for Ultrabarrier Frontsheet

- Transparent, flexible ALD-coated polymer protects CIGS cells against moisture and degradation
- Batch ALD process operated at scale that supports market and product development consistently generates film with WVTR < $5*10^{-4}$ $g/m^2/day$
- Modeling predicts that ALD-on-plastic can be produced at high throughput
- Prototype roll-to-roll equipment fabrication complete and ALD coating trials underway
- Partnering with academic, industrial, market and government partners
- Making progress against plan for further scale-up

  (pilot plant/commercial)

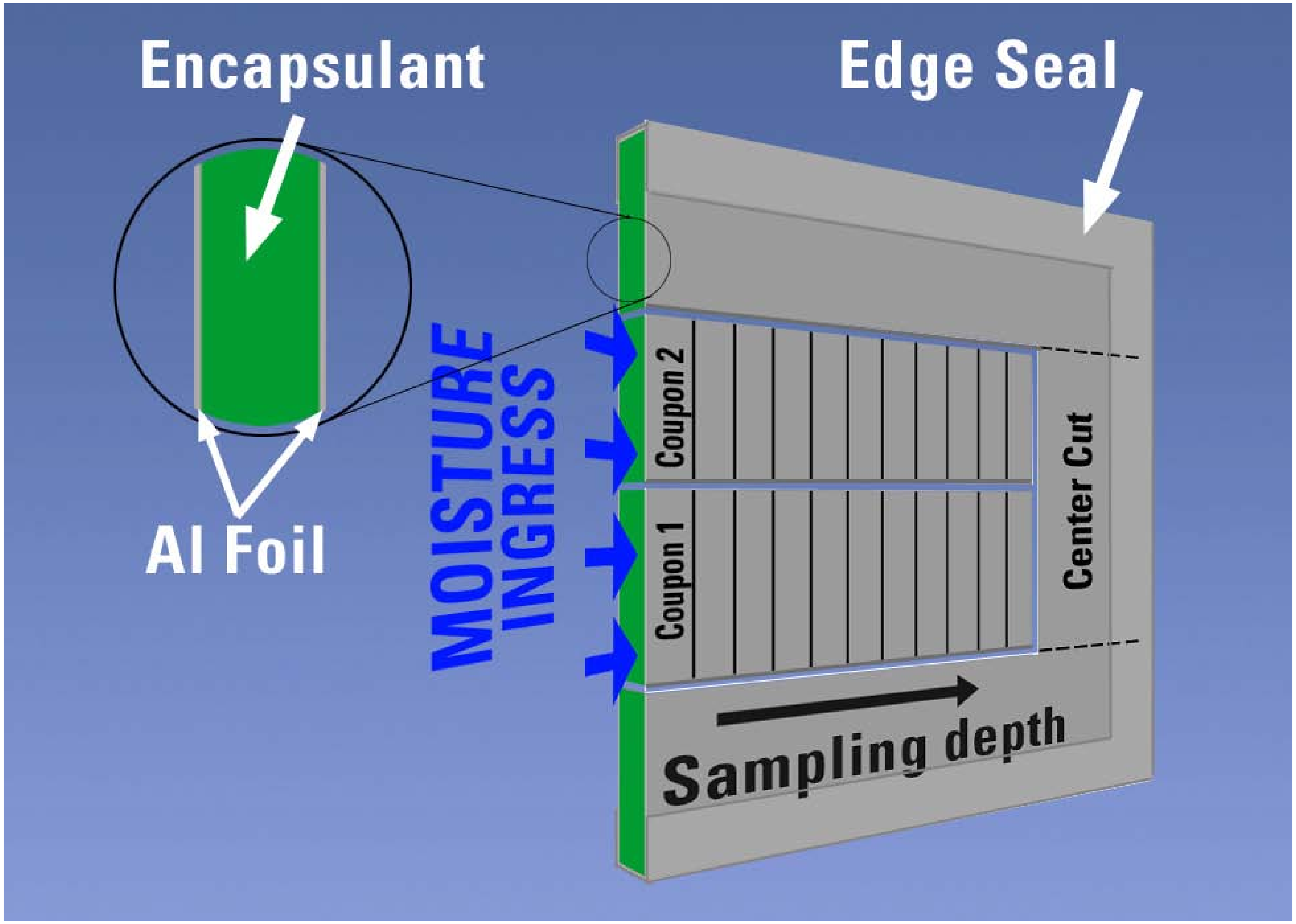
Moisture ingress can affect module lifetime

- Water permeability and equilibrium moisture content in the encapsulant may degrade module performance by metal corrosion or other adverse interactions, e.g. TCO degradation.

- Various other defects, such as delamination, bubble formation and edge cloud, are also known to be influenced by the presence of moisture.

- Using accepted methods to measure moisture ingress, we have quantified performance of commercial encapsulants and are developing new ones for moisture-sensitive technologies.

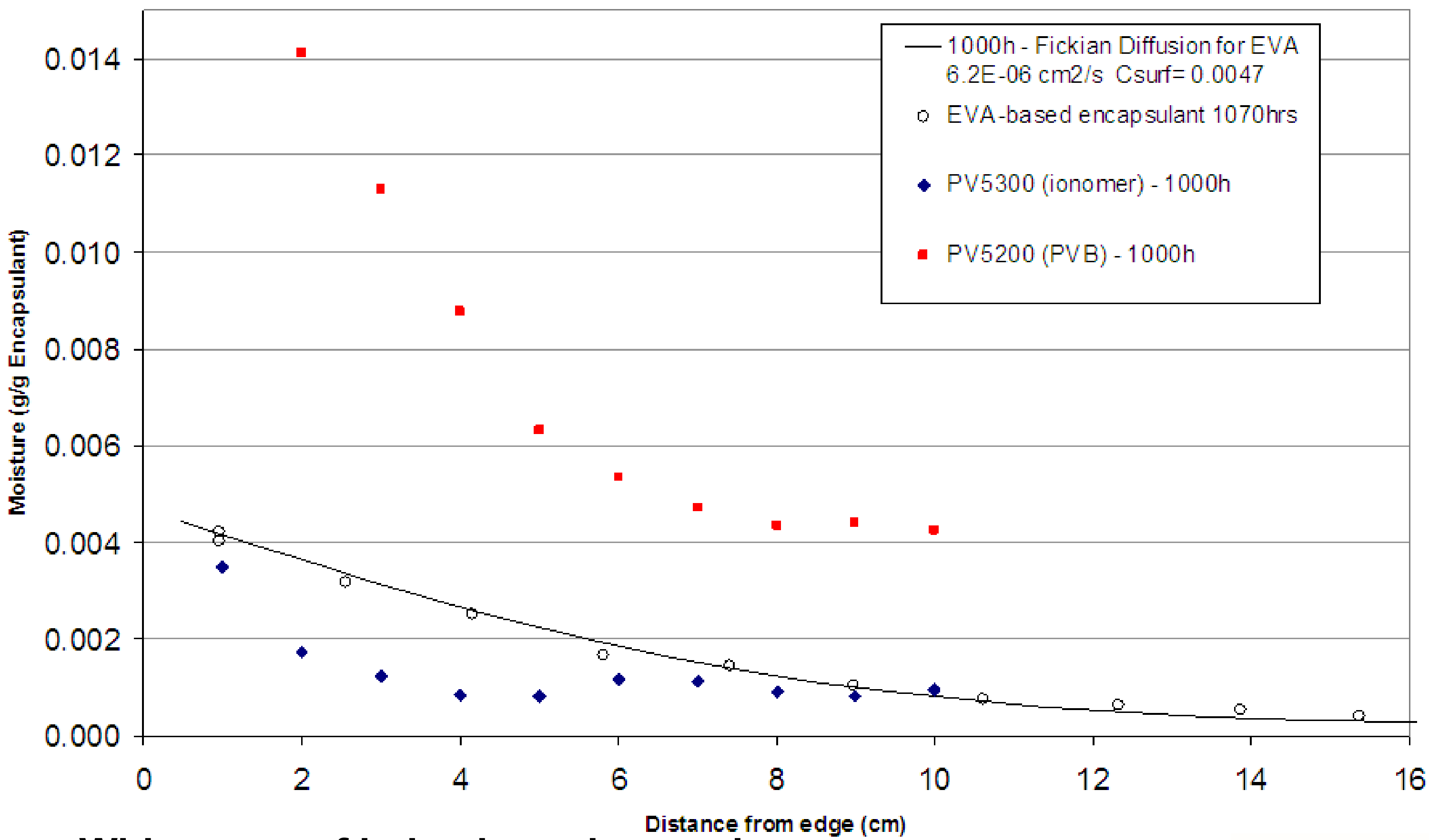
Measuring moisture ingress via RH sensor method ASTM D7191



"One dimensional" foil-clad moisture intrusion specimens are laminated as shown.

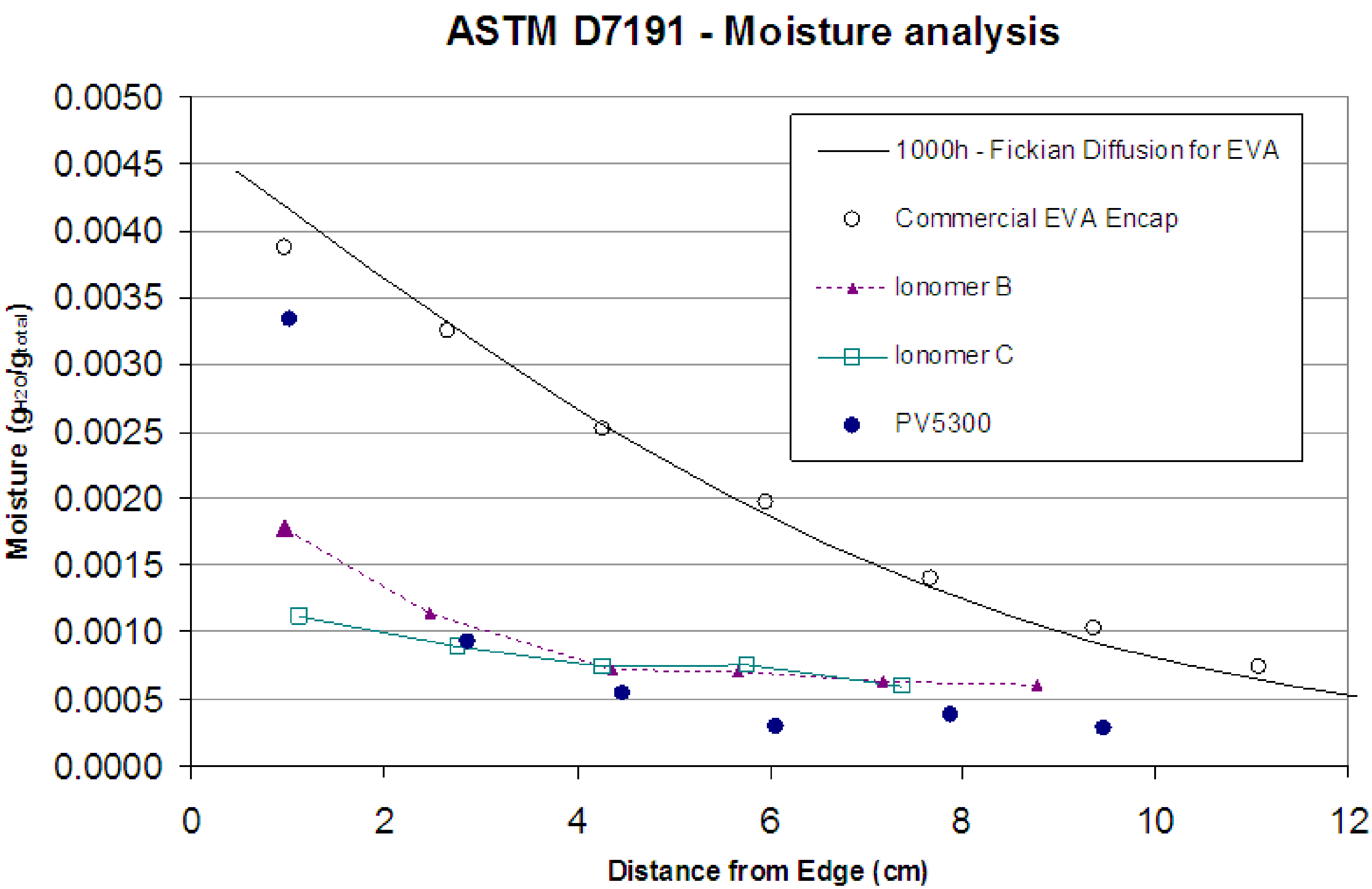
After DH exposure, coupons are die cut for each measurement. Coupons are cut into thin strips & placed in vial for moisture analysis.

Moisture Ingress to Commercial Encapsulants after 1000hr DH exposure



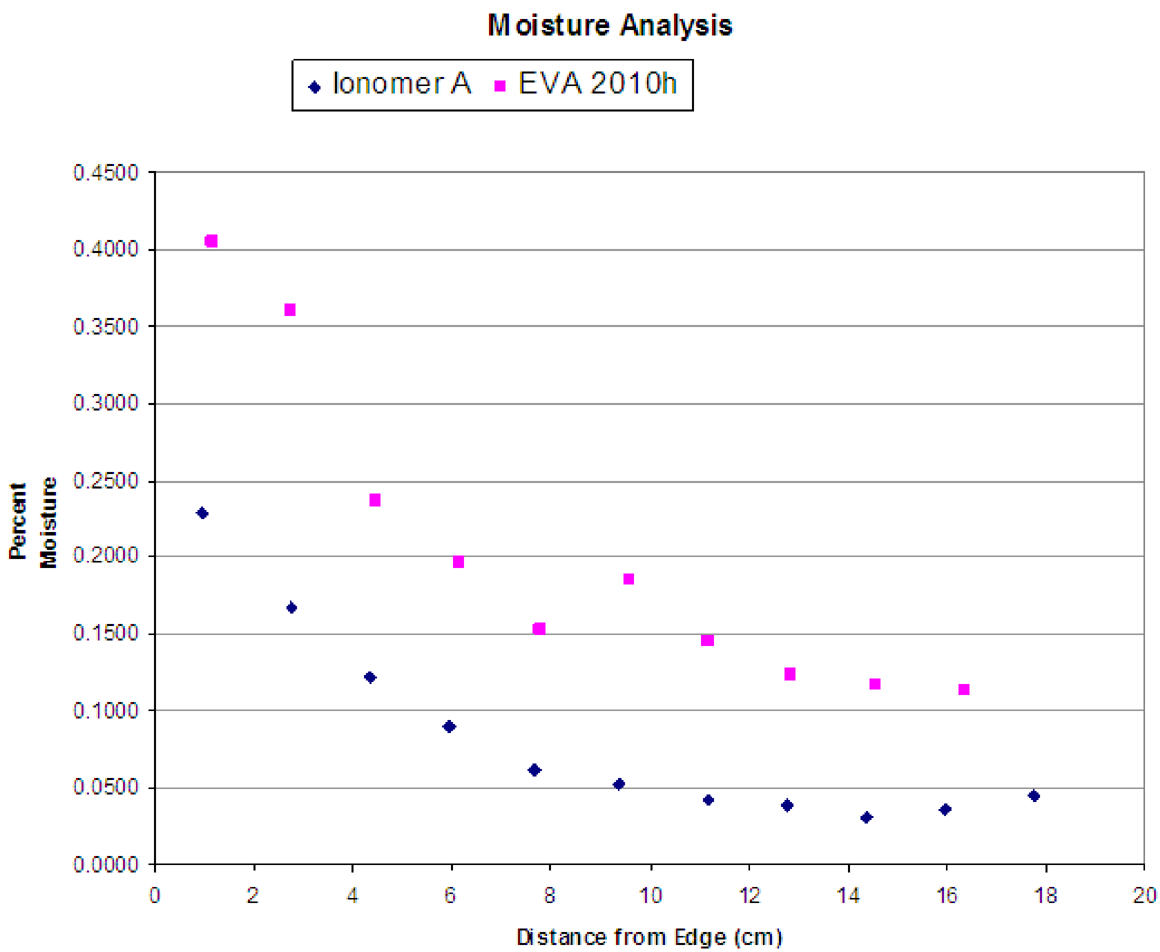
- **Wide range of behaviors observed**
- **Equilibrium moisture content (at the exposed edge) and moisture transport rate through PVB is much greater than EVA**
- **Ionomer has lower rate of moisture transport rate than EVA**

Moisture Ingress of EVA and Developmental Ionomer Encapsulants after 1000 hr DH



• **Encapsulants with even lower equilibrium moisture content (exposed edge) are being developed for moisture sensitive PV technologies**

Moisture Ingress of EVA and Developmental Ionomer Encapsulants after 2000 hr DH



- **Even after 2000 hr DH exposure, developmental encapsulants retain desireably low moisture ingress characteristics.**

Summary and Next Steps for CIGS encapsulant

• A methodology for evaluating moisture transport through encapsulants has been developed.

• Encapsulants with reduced equilibrium moisture content and moisture transport rates have been developed.

• A new ionomer encapsulant with reduced moisture sensitivity and transport has been scaled up and is being evaluated in thin film applications.

• Continue to develop and introduce encapsulants with enhanced properties needed for future generation PV module designs, e.g.

- Transmission
- Environmental stability (UV, temperature, moisture)
- Adhesion
- Moisture Transport
- Other interactions with module components

Glass Coated Stainless Steel Characteristics

Thermal Stability

Monolithic Integration

Higher Efficiency

Surface Smoothness

Ion barrier

Enable CIGS growth

Flexibility

Dimensional Stability

Adding Functionality to Stainless steel

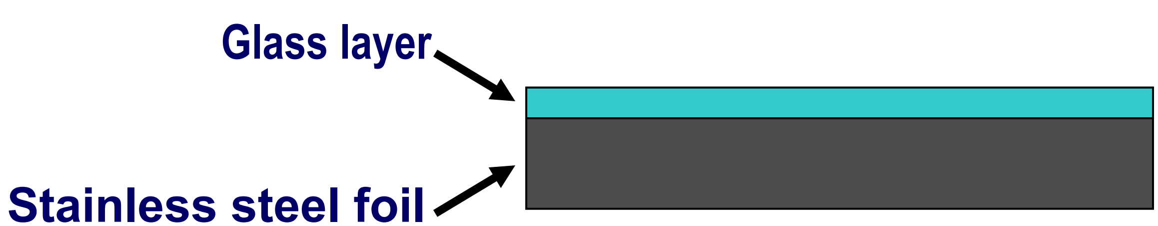
Stainless Steel

- Roll to roll processing
- High tensile strength
- High tear strength
- High temperature capability
- Currently used in manufacturing
- Electrically conducting

+

Glass

- Solution deposition
- Film thickness from up to 5μm
- Dielectric strength
- Ion barrier
- Enable sodium doping
- Smooth surface



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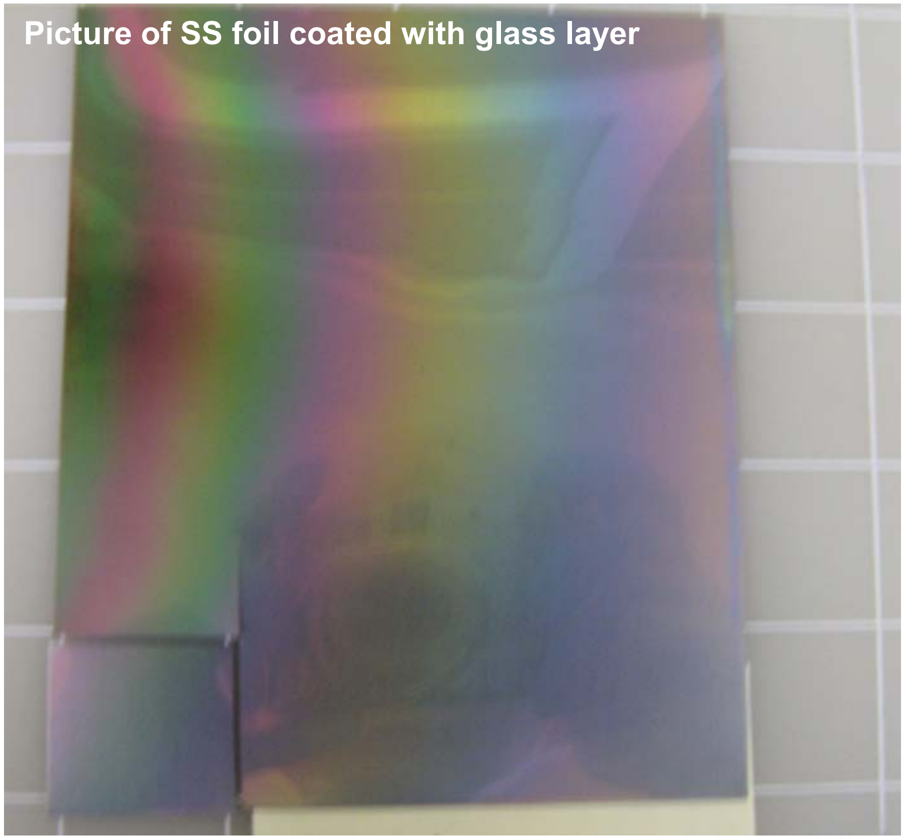
Coating Stainless Steel foil with Thin Glass Layer

Substrate:
2mil SS430

Solution:
Tunable composition in aliphatic alcohol

Film:
Drying

Firing

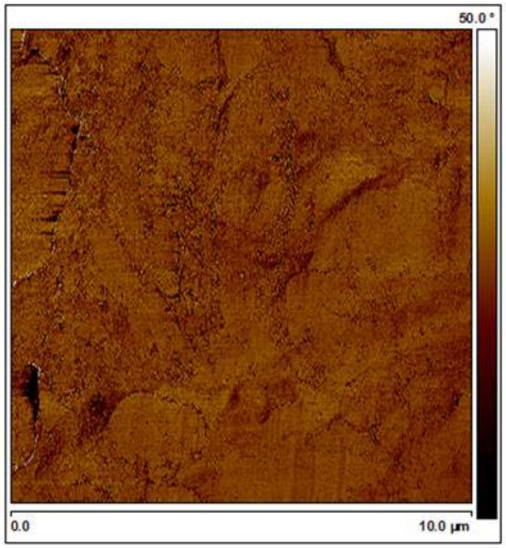


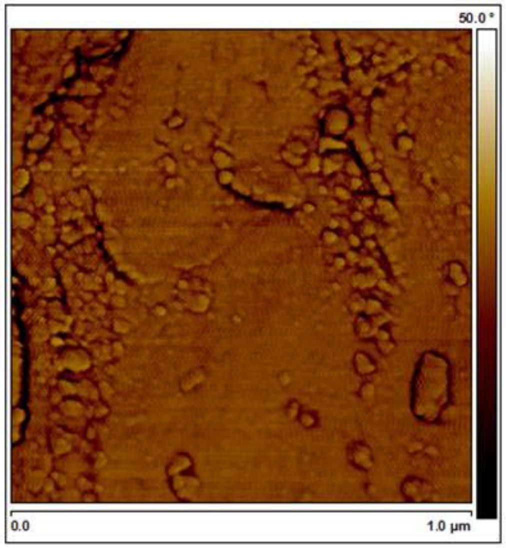
Stainless steel foil coated with 0.5μm glass layer

Impact of glass coating on roughness of stainless steel

AFM – Surface topology

Stainless Steel

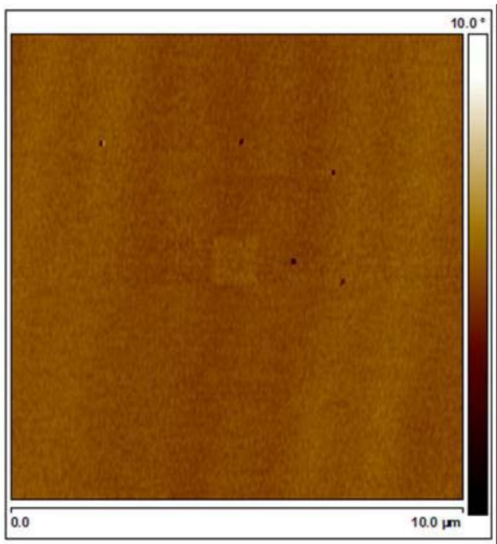


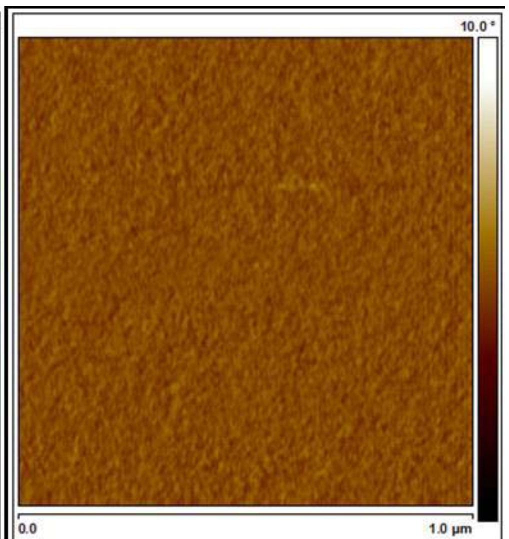


SS 2 mil	10 x10 (um²)	1 x 1 (um²)
Location 1 (nm)	81.0	6.6
Location 2 (nm)	87.0	8.0
Location 3 (nm)	91.8	5.6
Average (nm)	86.4	6.7

Avg. Ra =86.4nm

Glass coated stainless steel





Coated SS	10 x10 (um²)	1 x 1 (um²)
Location 1 (nm)	6.9	0.19
Location 2 (nm)	6.3	0.13
Location 3 (nm)	6.6	0.16
Average (nm)	6.6	0.16

Avg. Ra =6.6nm

Glass layer reduced surface roughness of stainless steel

TEM cross-section by FIB: Gen#3 vs. Soda lime glass

ITO ~170 nm
CdS ~100 nm
CIGS ~2 μm
Mo ~550 nm
SLG substrate

CIGS ~1.7 μm
Mo ~700 nm
Glass ~ 1.3 μm
SS Substrate

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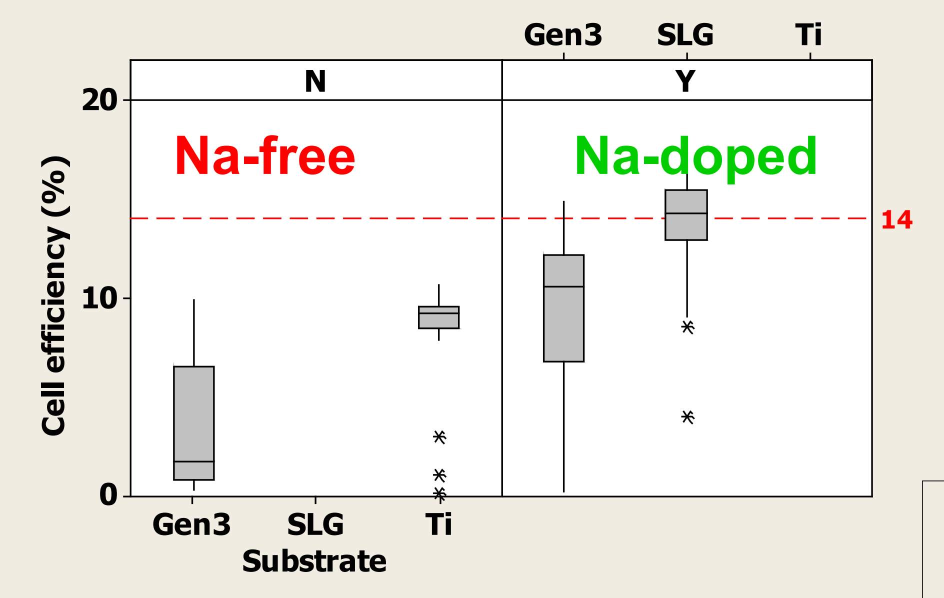
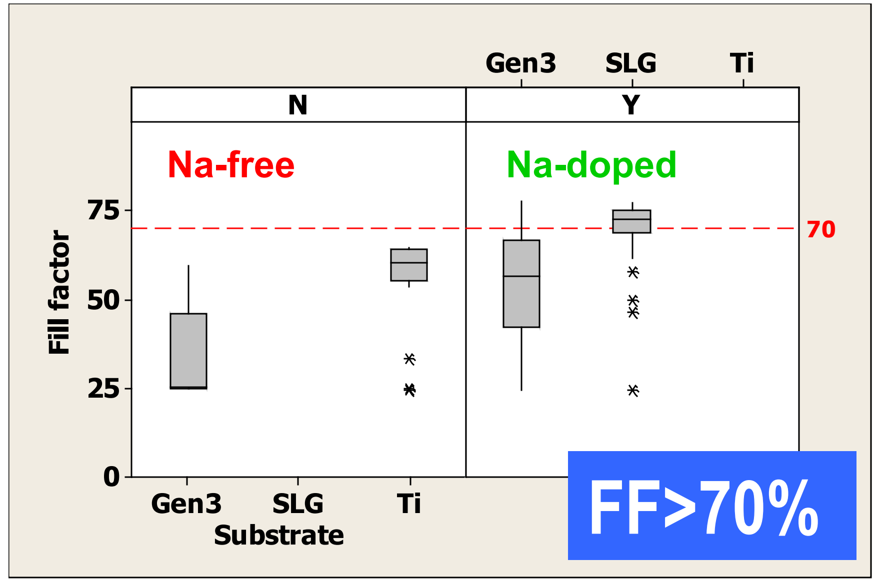
TEM: Transmission Electron Microscopy, FIB: Focused Ion Beam

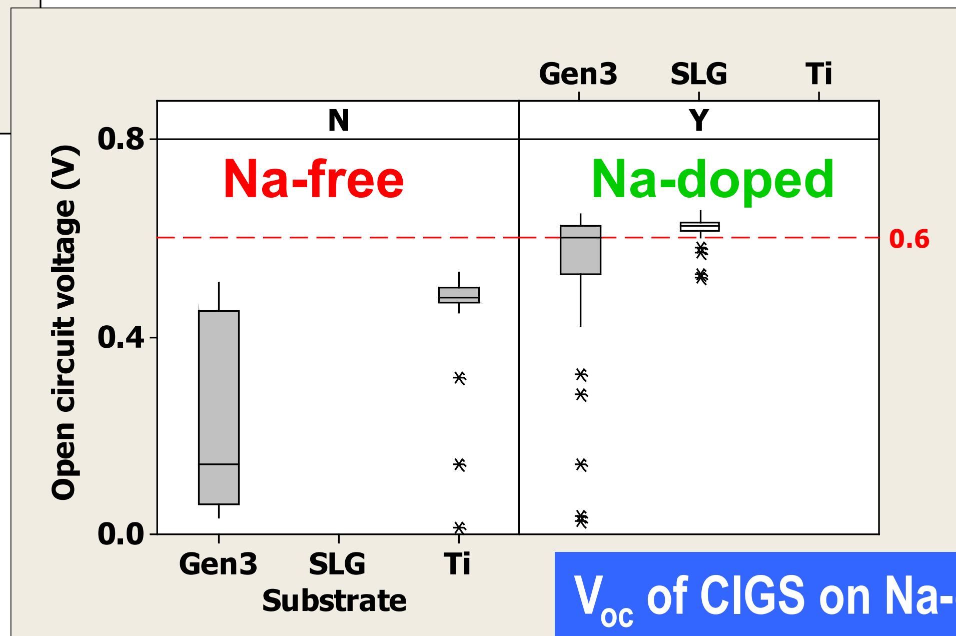
Performance of CIGS Solar Cells on Gen#3

SLG is the Na-doped reference and Ti foil is the Na-free reference to Gen3





FF>70%



V_{oc} of CIGS on Na-doped glass/SS ≥ 0.6V

Best device efficiency on Gen#3 is ~14.9% (without AR coating)

Best device efficiency on SLG is ~15% (without AR coating)

Summary for Glass Coated Stainless Steel Substrate

Developed a glass coating as integrated solution with key features:

1- Barrier to ion migration

2- Na delivery to enable CIGS doping

3- Smooth surface

4- Match SLG cell efficiency

Summary

DuPont's strategy in support of the CIGS thin film, flexible PV industry:

- Build on our existing portfolio of product materials for PV
- Utilize our core competencies in material science and engineering, polymer films, fluoropolymers, process development and advanced process control to generate new products including:
  - Flexible, robust frontsheets that provide ultrabarrier to water vapor transport
  - Encapsulents with property sets that are optimized for CIGS modules
  - Flexible substrate systems that provide key features of importance to CIGS