Thermal Modeling of PV Modules Using Computational Simulation

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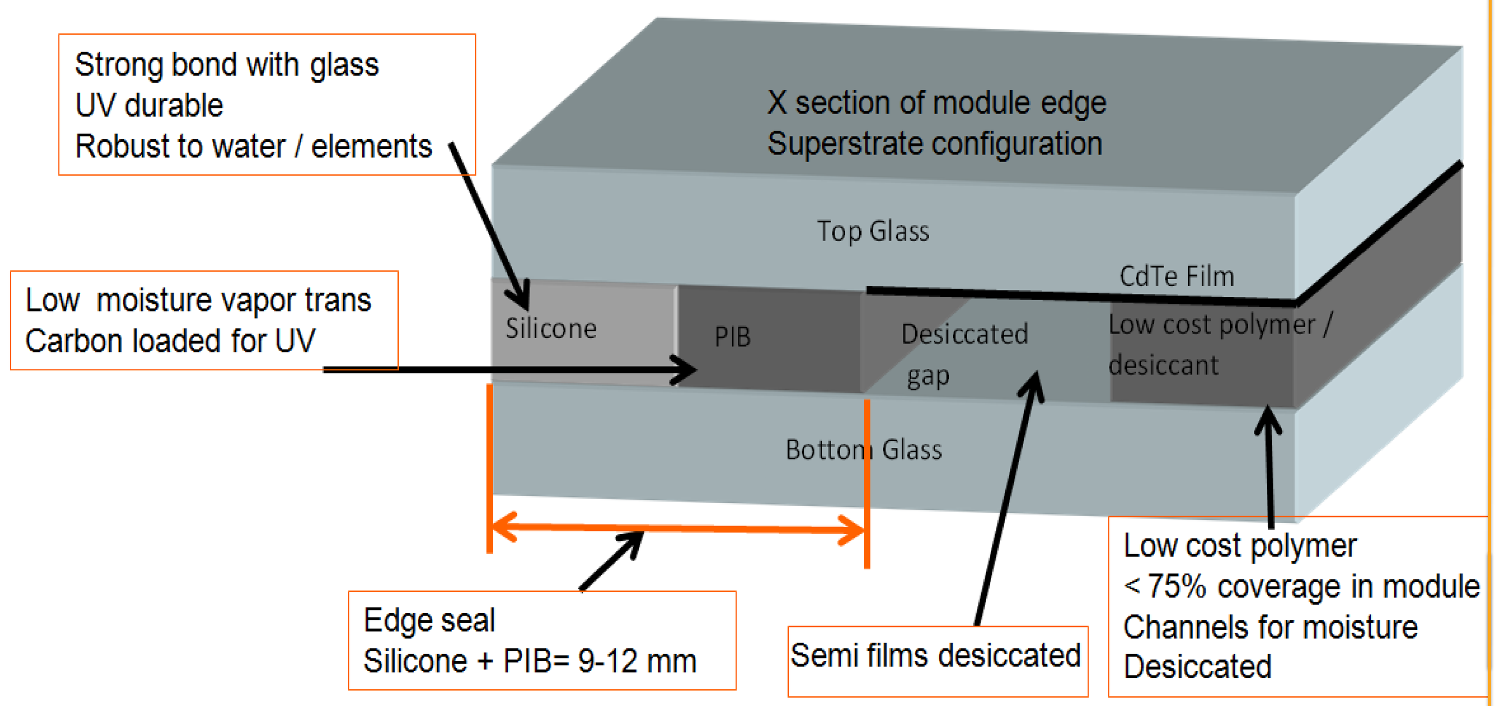
Introduction:
A novel module architecture has been created for thin film PV modules that greatly increases reliability, while minimizing process time, process equipment footprints, capital expenditure costs, and material costs. Prototype modules have already passed IEC and UL damp-heat tests without showing any degradation. This architecture has been optimized for mass-produced CdTe applications, but can be tailored to many PV technologies



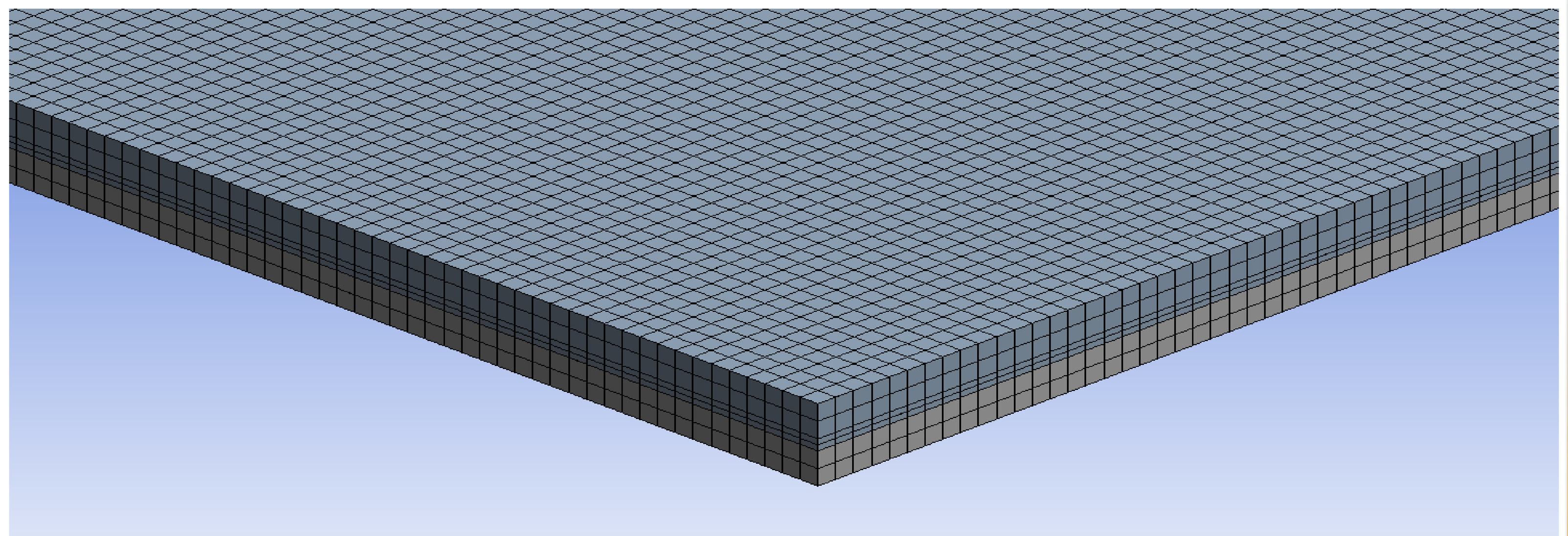
The developed edge-sealed module delivers:

- Extreme robustness to moisture
- Excellent adhesion under prolonged UV exposure
- Process cycle times under one minute
  - Similar to other processing steps
- Small manufacturing tool footprint
- Reduced materials costs
- Reduced capital costs

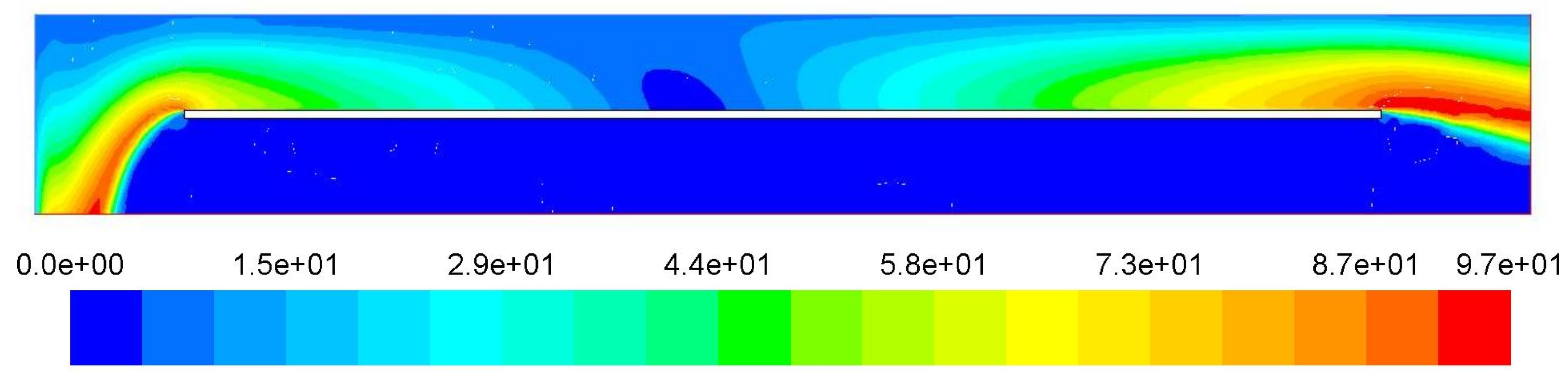
Item	Prototype module	Design A (low case)	Design B (mid case)	Laminate (Dupont) w/ edge seal
Encapsulation cost	$3.87	$1.71	$2.08	$3.84
Savings from laminate	-$0.03	$2.13	$1.76	$0
Cost **SAVINGS** for 85 watt 120x60 cm module ($/Wp)	~0	$0.025	$0.021	--

NOT INCLUDED in cost:
- Capital equipment costs
- Improved manufacturing efficiencies
- Reduced plant footprint
- Increased reliability

Thermal Performance Modeling Parameters:
- Geometry modeled within 0.1mm
- Real material properties included:
  - Thermal, Optical, and Electrical
- NREL AM1.5 spectra used for solar input
- Convection simulated using a 2D model
  - Wind speed varied from 5 → 10 → 20mph
  - Wind direction varied from 0-90° normal to the module edge at 15° intervals

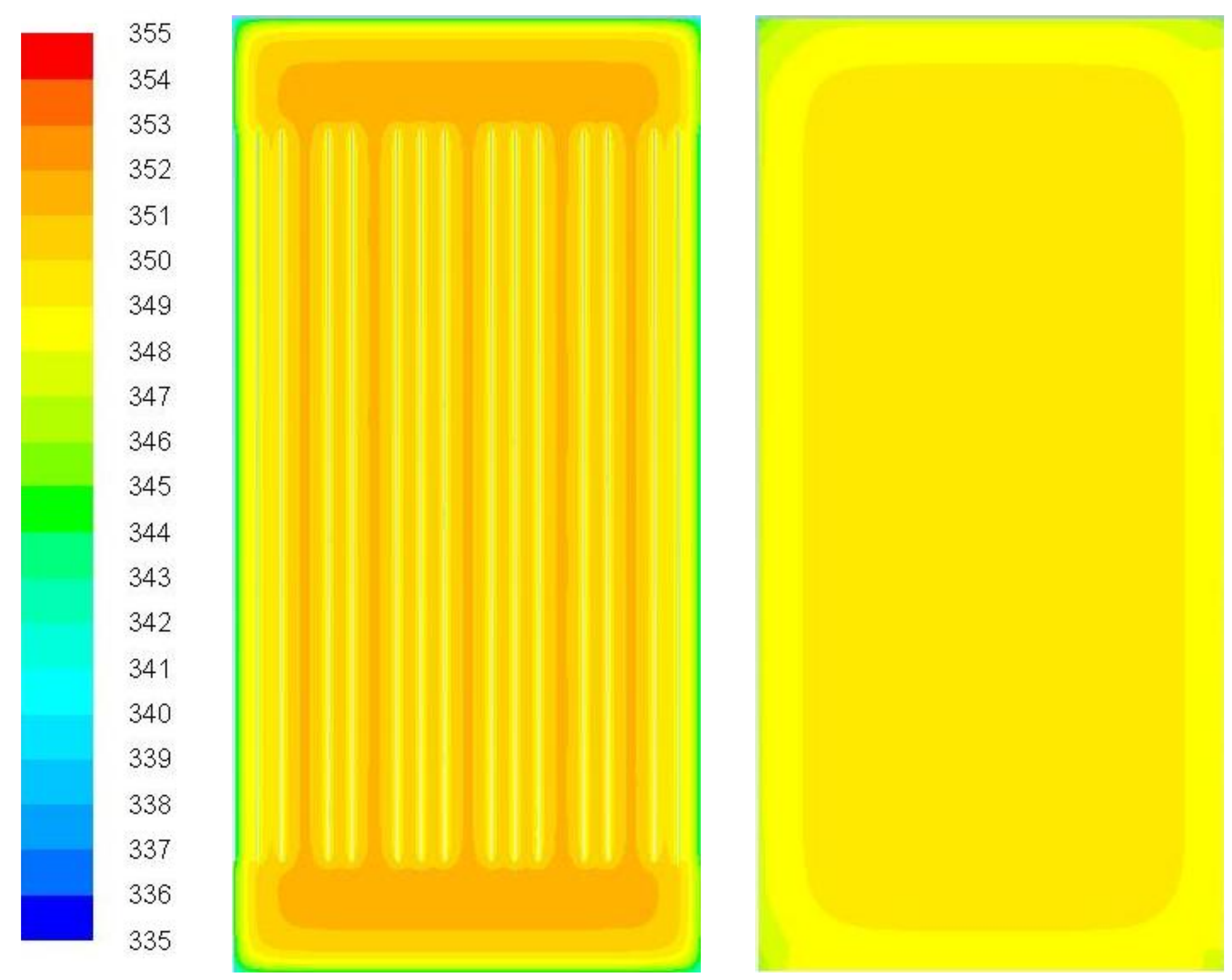


Two Dimensional Wind Model:
- Steady state wind conditions simulated
- Heat transfer coefficients obtained for each face



Two dimensional wind speed profile of a panel with forced convection at 20mph 60° normal to the module edge (in m/s)

Three Dimensional Thermal Models:
- Only panel included in domain (no outside air)
  - Conv. coef. and solar spectra boundary conditions



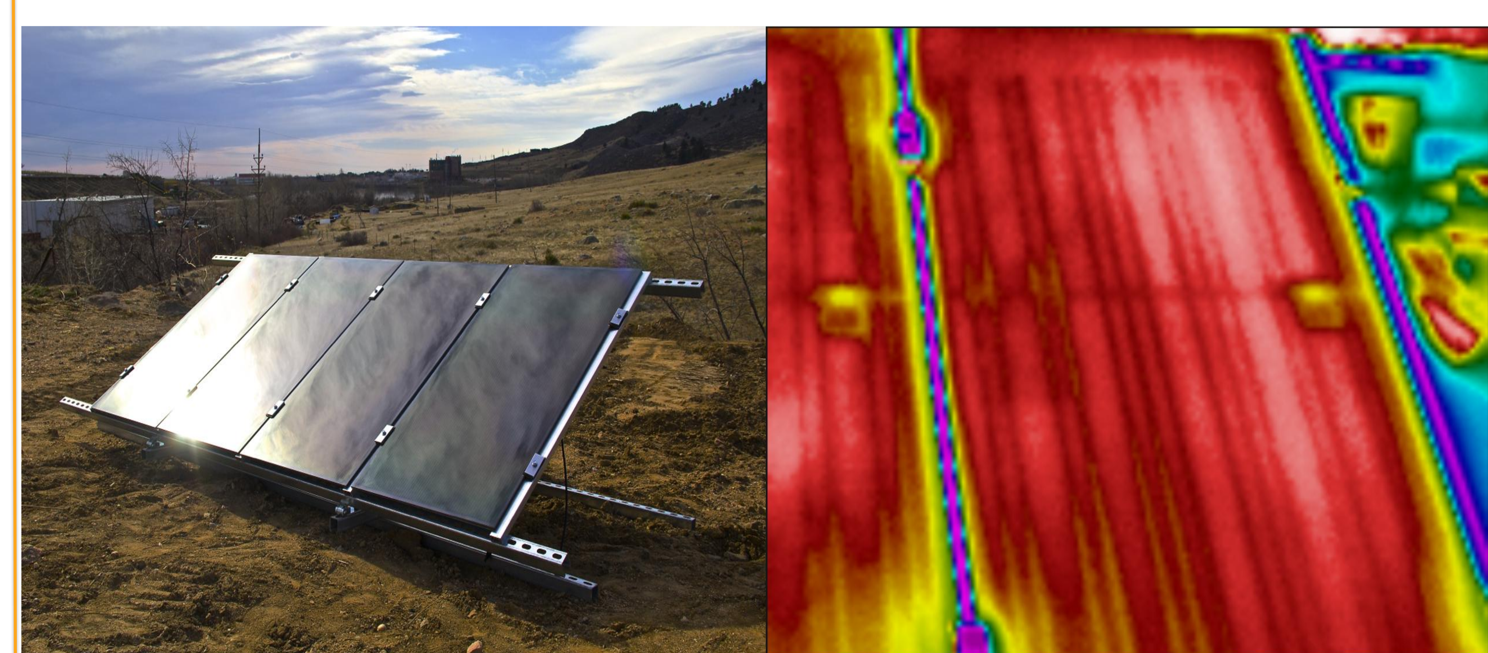
(Left) Edge-sealed and (Right) laminate modules under natural convection and full solar loading. This is the theoretical worst-case operating temperatures of both modules. (Temperature in Kelvin)

Modeling Results:

Wind Speed (mph)	Wind Direction (deg)	Edge-Sealed Module (K)	Laminate Module (K)	Difference (K)
5	0	330.28	327.70	**2.58**
	45	317.38	317.62	**0.24**
	90	313.85	313.85	**0.00**
10	0	320.08	317.28	**2.80**
	45	310.22	310.52	**0.30**
	90	308.20	308.33	**0.13**
20	0	313.21	310.67	**2.54**
	45	306.56	306.62	**0.06**
	90	305.52	305.55	**0.03**

The modeling results show little difference between the temperature of edge-sealed and laminated modules in varying wind conditions. The direction of the wind also was shown to play a large role in determining the operating temperature of the module.

Experimental Validation:
- Edge-sealed and laminated module array created
- IR camera used to monitor temperatures
- Solar / wind data obtained from nearby array
  - Environmental conditions reinserted as boundary conditions in model for validation



(Left) Test array (Right) Thermal image of array from IR camera

Conclusions:
- Wind velocity and direction affect operating temp
- Computational analysis is an effective method for predicting the thermal performance of CdTe modules in real-world conditions
  - Highly sophisticated simulation technique reduces the number of modeling assumptions
  - New module designs can now be evaluated before manufacturing
- Architecture and analysis method can be used across many PV technologies

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