Innovative High-Performance Deposition Technology for Low-Cost Manufacturing of OLED Lighting
Progress Review

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OLEDWorks Introduction

- We are the only US manufacturer of OLED lighting panels.
- Founded in Rochester NY in 2010
- 22 full-time OLED experts
  - Over 200 years of combined OLED experience
  - Experience across all areas of OLED technology
- Built a state of the art OLED R&D lab
- Designed and started-up a novel, flexible, scalable OLED production facility.
- We have commercialized our first product.
- We work with many partners:
  - Suppliers to the OLED lighting industry
  - Downstream luminaire partners.

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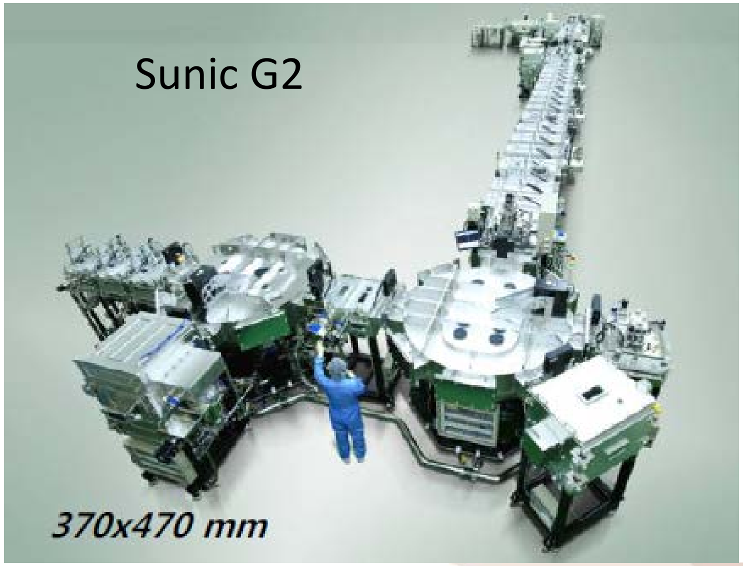
Innovative High-Performance Deposition Technology for Low-Cost Manufacturing of OLED Lighting

- For our novel approach to vaporization, control, and distribution of organic vapor, the project encompasses:
  - Design of the production-scale equipment of the deposition equipment,
  - Testing, analysis, and improvement of the equipment,
  - Implementation into production with demonstration
- The goals of this deposition system are:
  1. Improve material usage efficiency
  2. Improve deposition rate – higher throughput
  3. Lead to lower capital cost OLED deposition machines
  4. Enable use of thermally sensitive materials

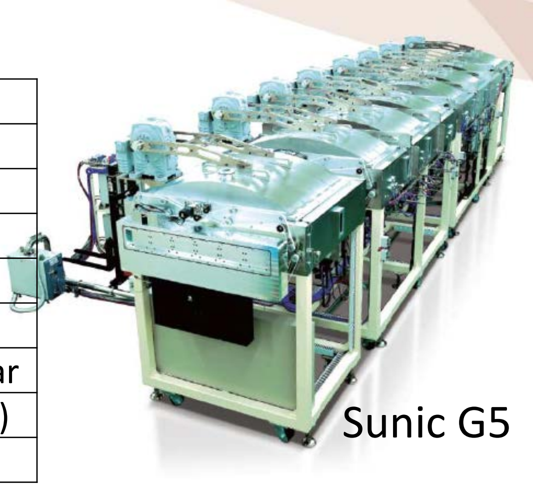
Reference Machines

- The most common OLED lighting system in production/pilot today is Sunic G2 – 370x470mm
  - E.g. LG Chem, First O-Lite, COMMED
  - This is the largest publicly disclosed production machine in use today (370x470mm)
- Future system – G5 - 1100x1300mm



Approximate Parameters

	Gen 2 Baseline	Gen 5 Future
Glass Size	370x470 mm	1100x1300 mm
Material usage	15-25%	60%
TAC time	2-6 min	1-2 min
Substrate Velocity	1.3-4 mm/sec	9-18 mm/sec
Operating Time between loading	6 days	6 days
Area of Good product	8,000-12,000 m2/year	190,000-380,000 m2/year
Estimated Capital Cost of Whole line	$50-100M (use $75M)	$150-300M (use $200M)
Depreciation per unit of production	$600-1900/m2	$100-200/m2



Standard Assumptions:

80% uptime, 80% yield, 80% glass usage efficiency

5 year straight line depreciation

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Project Targets in Terms of Reference Machines

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- The rough goals of the project are to design and build vapor generation and deposition sources to enable:
  - Capital like G2 - $50-100M
  - Material usage like G5 - ~60%
  - Substrate speed like G5 – 9-18 mm/sec
  - Depreciation like G5 - $100-200/m2
  - Easy on heat sensitive materials
- Unfortunately we cannot show the design of our production machine or the design of the new vapor generation and depositions sources.
- However, we will describe the approach, considerations, and progress.

Motivation – Why this project is important

Year	Milestones
FY10	Panel: >60 lm/W
FY12	Laboratory Panel: 200 lm/panel; >70 lm/W; >10,000 hours
FY15	Commercial Panel: <$200/klm (price); >80 lm/W; 25,000 hours; CRI>90
FY17	Commercial Panel: $100/klm Luminaire: 100 lm/W; CRI >90
FY20	High-Performance Panel: 160 lm/W Luminaire: price <$80/klm; 100 lm/W, 40,000 hours

Note: Panel size >50 cm^2; CCT < 2580-3710K

DOE SSL MYPP
April 2014
TABLE 4.5 OLED PANEL AND LUMINAIRE MILESTONES

"Meeting the panel price goal of $200/klm by 2015, or soon thereafter, seems necessary in order to create a large enough demand to justify further investments in R&D and manufacturing capability. The luminaire price goal of $80/klm is appropriate for 2020 if OLEDs are to gain sufficient market penetration to contribute significantly to global energy savings."

Motivation – Why this project is important

Table 1-6 OLED Panel Cost Estimated Progress ($/m2) from Sept '13 DOE SSL Mfg Roadmap

	2012	2013	2016	2020	2025
Integrated Substrate	500	250	150	40	20
Organic Deposition	1,400	600	250	70	30
Assembly and Test	600	350	200	50	20
Overhead (incl labor)	500	300	100	20	10
Total (unyielded)	3,000	1,500	700	180	80
Yield of Good Product (%)	15%	25%	70%	75%	80%
Total Cost	20,000	6,000	1,000	240	100
Deposition Machine Size	G2	G2	G2	G5	G5
TAC Time (min)	6	6	2	2	1
Depreciation (at capacity, after yield)	10,257	6,154	733	222	104
Total Cost with Depreciation	30,257	12,154	1,733	462	204
Fraction of Total Cost due to Dep.	34%	51%	42%	48%	51%
Gross Margins	50%	50%	50%	50%	50%
Sales Price of Panels	60,514	24,308	3,465	923	408
Price of light ($/klm at 10klm/m2)	6,051	2,431	347	92	41
DOE Milestones (2014 DOE MYPP)			200 in FY15		
Cost of Luminaire & Channel Costs	4x	4x	4x	4x	4x
Sales Price of Luminaire	242,055	97,233	13,861	3,694	1,632
Price of light ($/klm at 10klm/m2)	24,206	9,723	1,386	369	163
DOE Milestones (2014 DOE MYPP)				80	

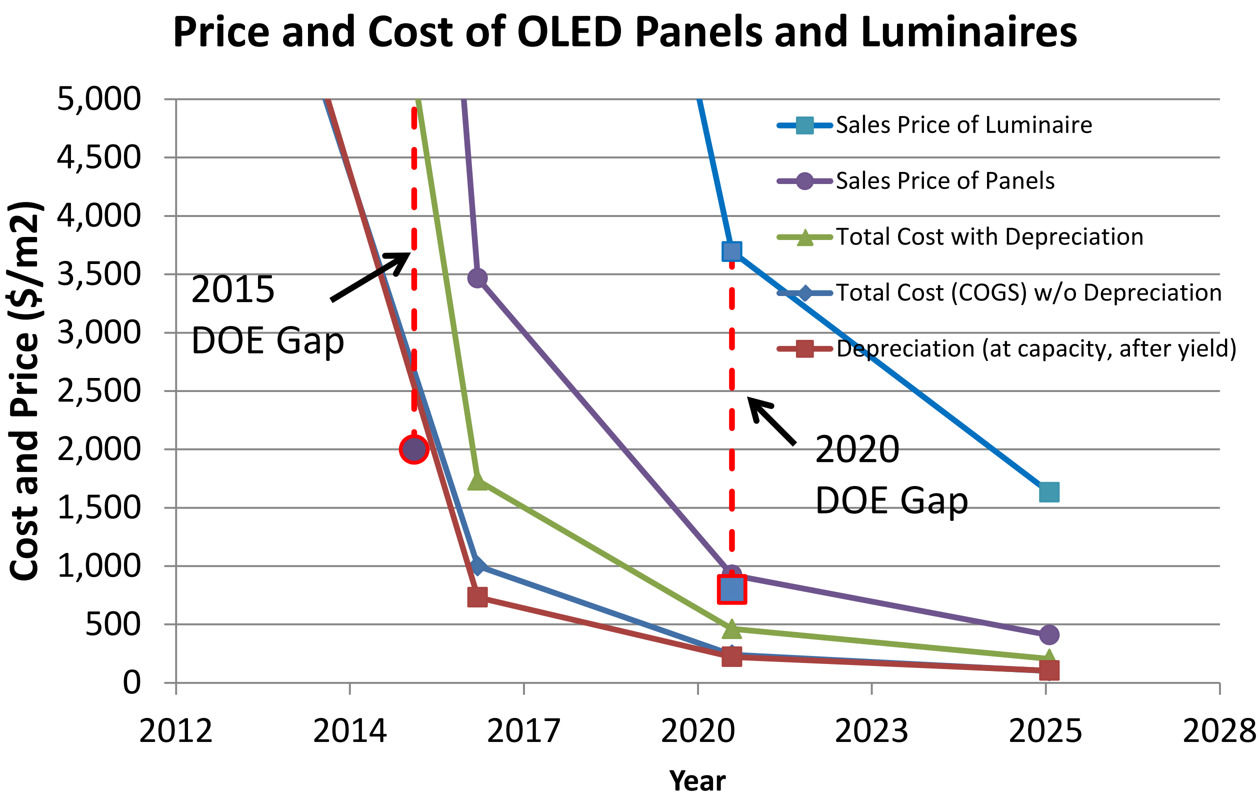
With the current equipment, we do not hit the DOE milestones for industry success.

Cost and Prices Relative to DOE Targets

Gaps between target price and predicted prices:

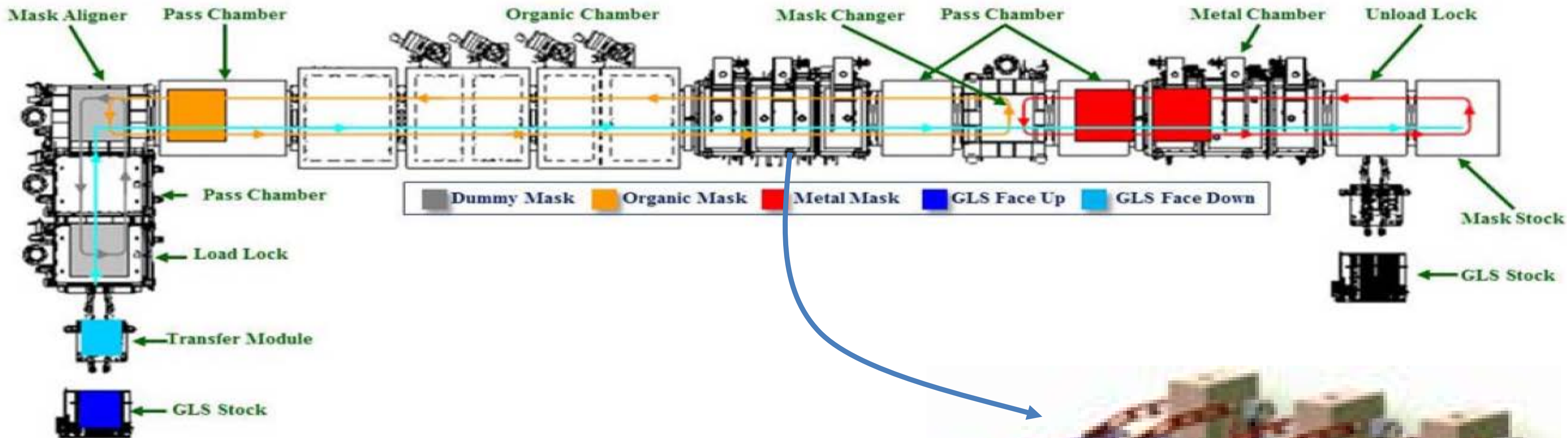
- 2015 - ~3-5x
- 2020 - ~4-5x

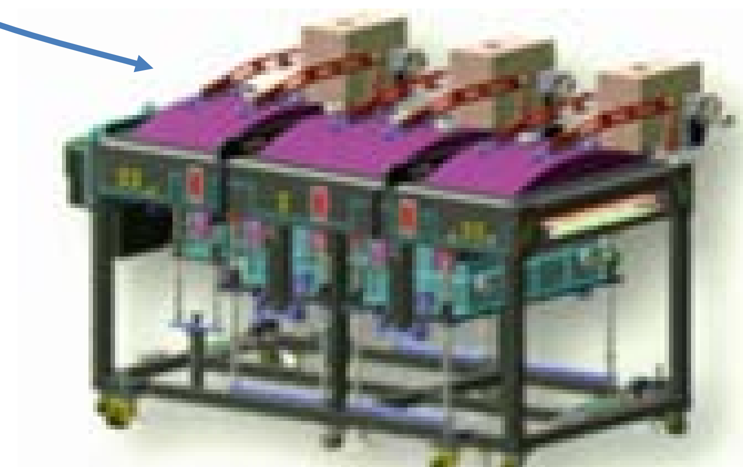
We need innovation in equipment performance (cost, throughput, flexibility) to help reach the targets



Cost data is from DOE SSL Mfg Roadmap Sept 2013
Price target data is from DOE SSL MYPP April 2014

Large-Scale Production OLED Deposition Equipment
Vacuum Thermal Evaporation of Organics





- Organic Vapor Generation and deposition sections

Reference Example – Sunic[1] G5 (1100x1300mm)

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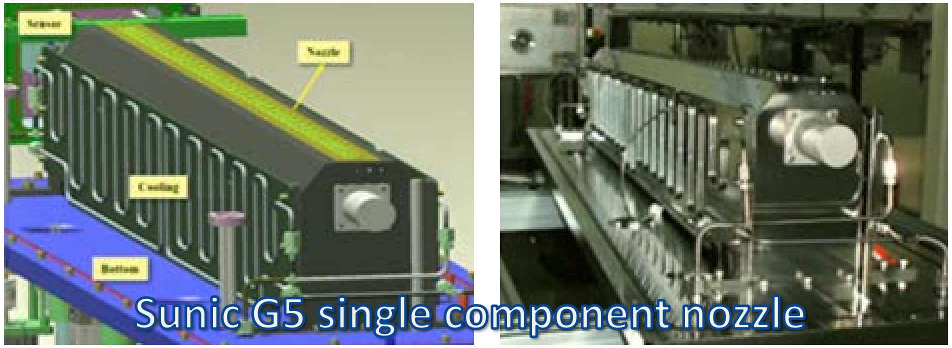
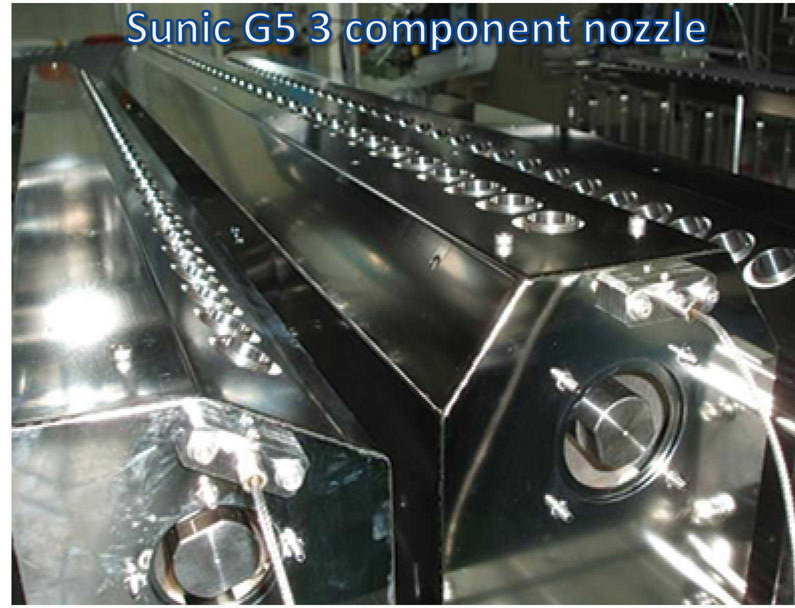
[1] SID 2013, Paper 55.4 Development of Highly Productive In-line Vacuum Evaporation System for OLED Lighting, J.M. Lim et al

Nozzle Design



Sunic G5 single component nozzle


Sunic G5 3 component nozzle

- G5 nozzles at 250mm distance achieve 60% material usage efficiency.
- We need to go closer than this to achieve same usage efficiency in less than 1450mm length (Sunic G5 length).
  - The higher the material usage efficiency, the faster the substrate can travel (for a given vapor generation rate)
- To deposit at even higher transport speeds without elevating the evaporation temperature – the nozzle must be design to operate at low pressure.
- We must integrate all of functions into a smaller package
  - Co-deposition of hosts and dopants
  - Widthwise uniformity
  - Thermal management – substrate must stay cool

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Deposition of Thermally Sensitive Materials

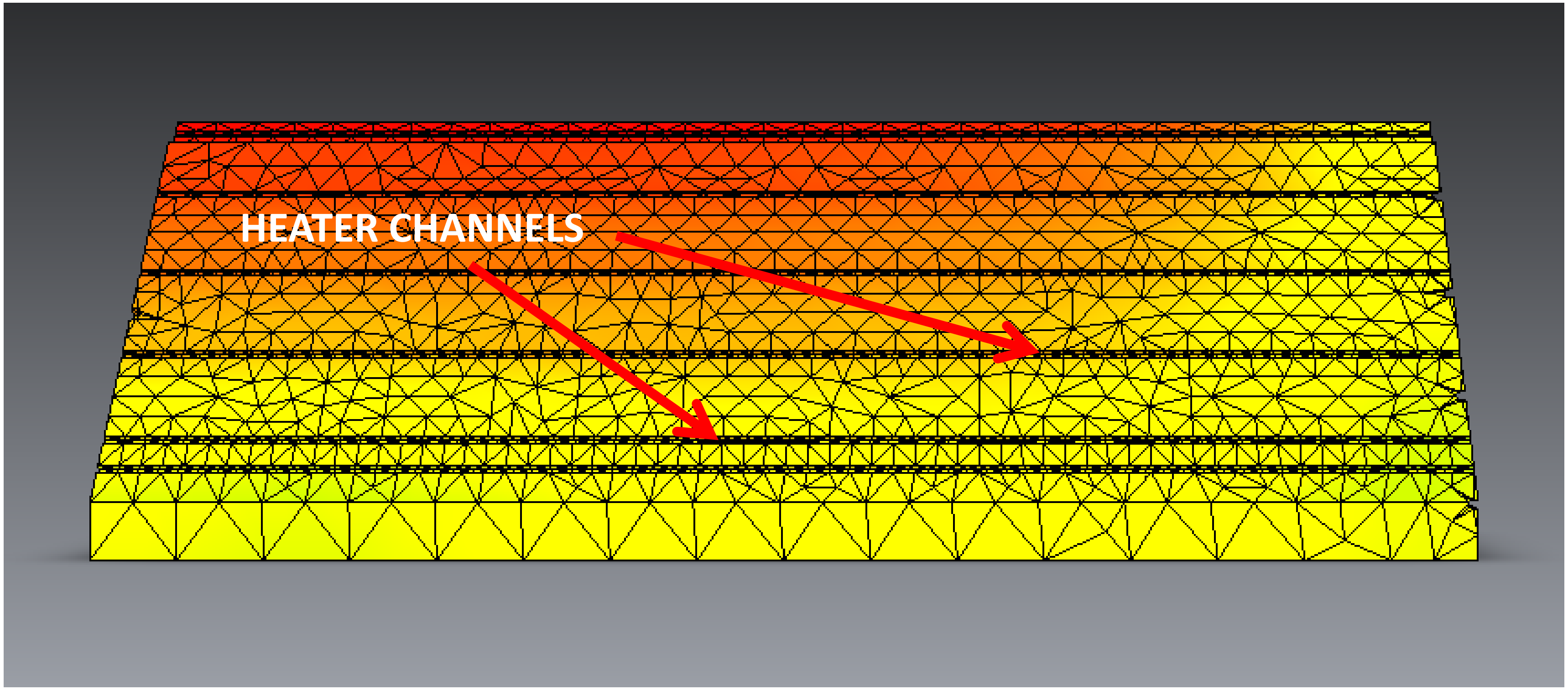
- Organic materials decompose when held at elevated temperatures for extended times
- To evaporate at high rates,
  - Use large areas for evaporation
    - Careful design of evaporator section to allow higher rates at lower temperatures.
  - Maintain low pressure
    - Careful design of nozzles
    - Careful design of conductances in system
- To extend the lifetime, heat only part of the material at a time.
  - Sunic G5 evaporators can hold up to 2kg of material to permit extended operating time.

Material	Test Duration (d)	T_{evap}	+25 K	+ 50 K	+75 K	+ 100 K
NET-164	10	227°C	252°C	277°C	302°C	327°C
SoA ETL	10	293°C	318°C	343°C (no data)	368°C	393°C

Ref "Applying OLEDs in a Manufacturing Process" Information Display, Jan 2014, K. Gilge et al.

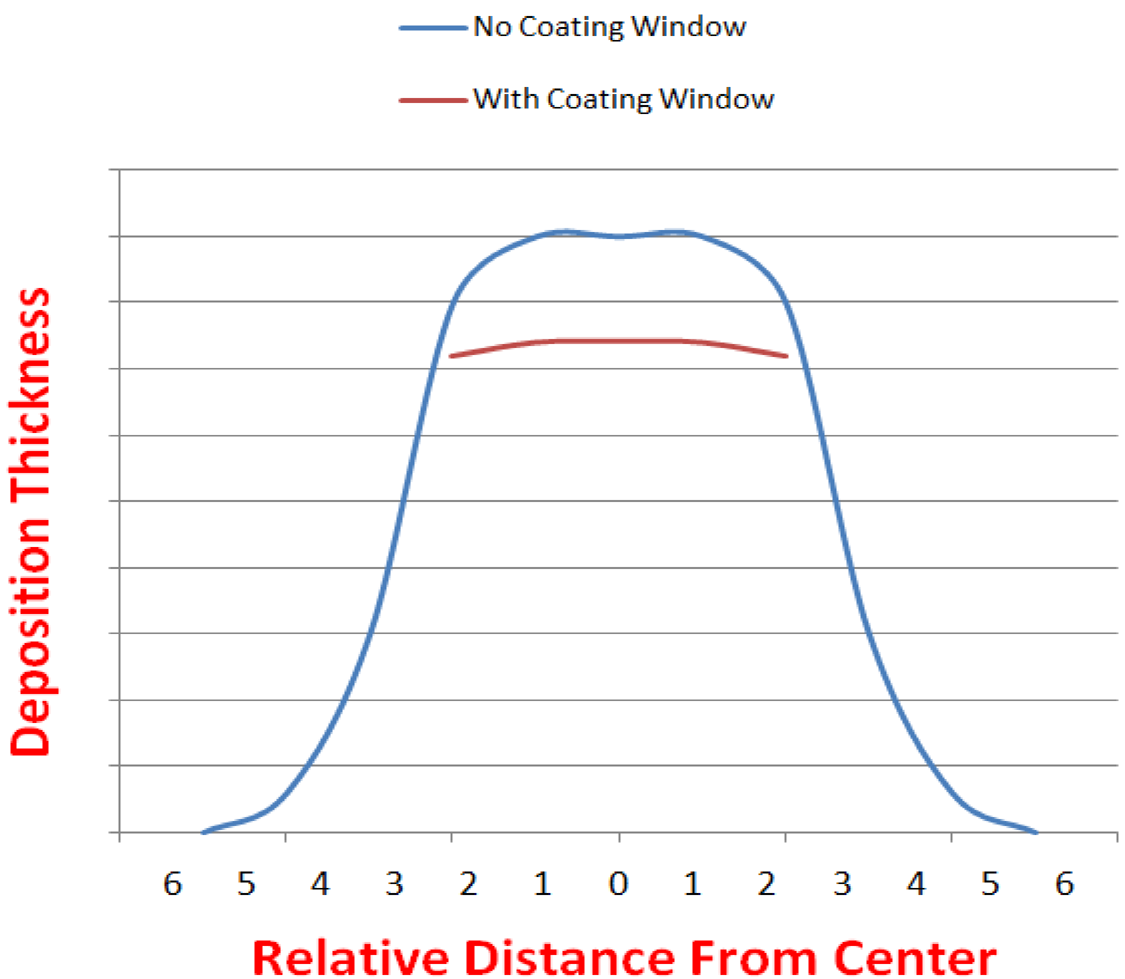
Design Methods Used for New Deposition Source - 1

Thermal Simulation to Verify of Thermal Uniformity Across a Nozzle Body



Design Methods Used for New Deposition Source - 2

Plume Modeling to Check Coating Cross Track Uniformity vs Position – Simulation of Nozzle Array



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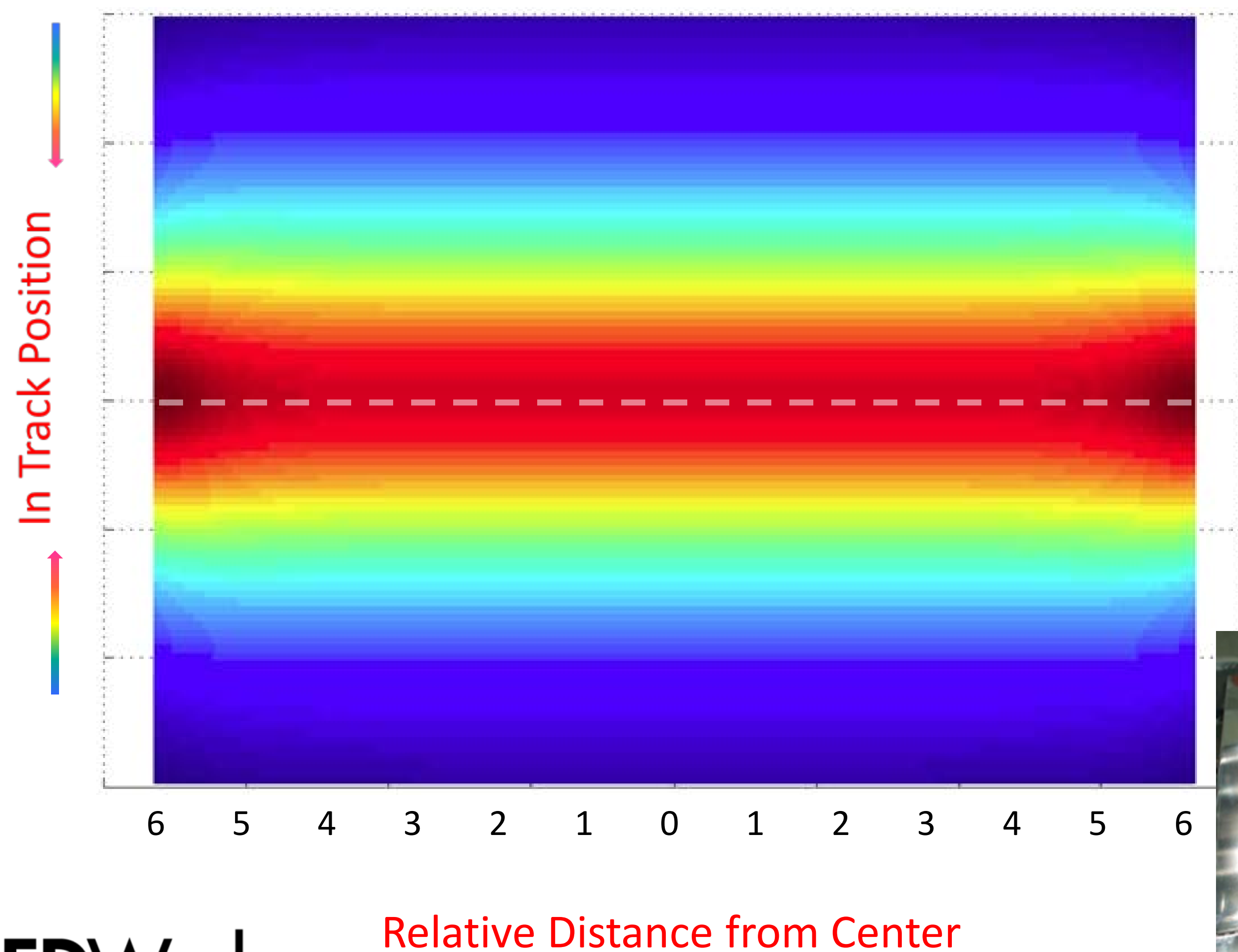
Design Methods Used for New Deposition Source - 3

Deposition Rate vs. Position – necessary for predicting composition uniformity throughout the layers on a moving substrate



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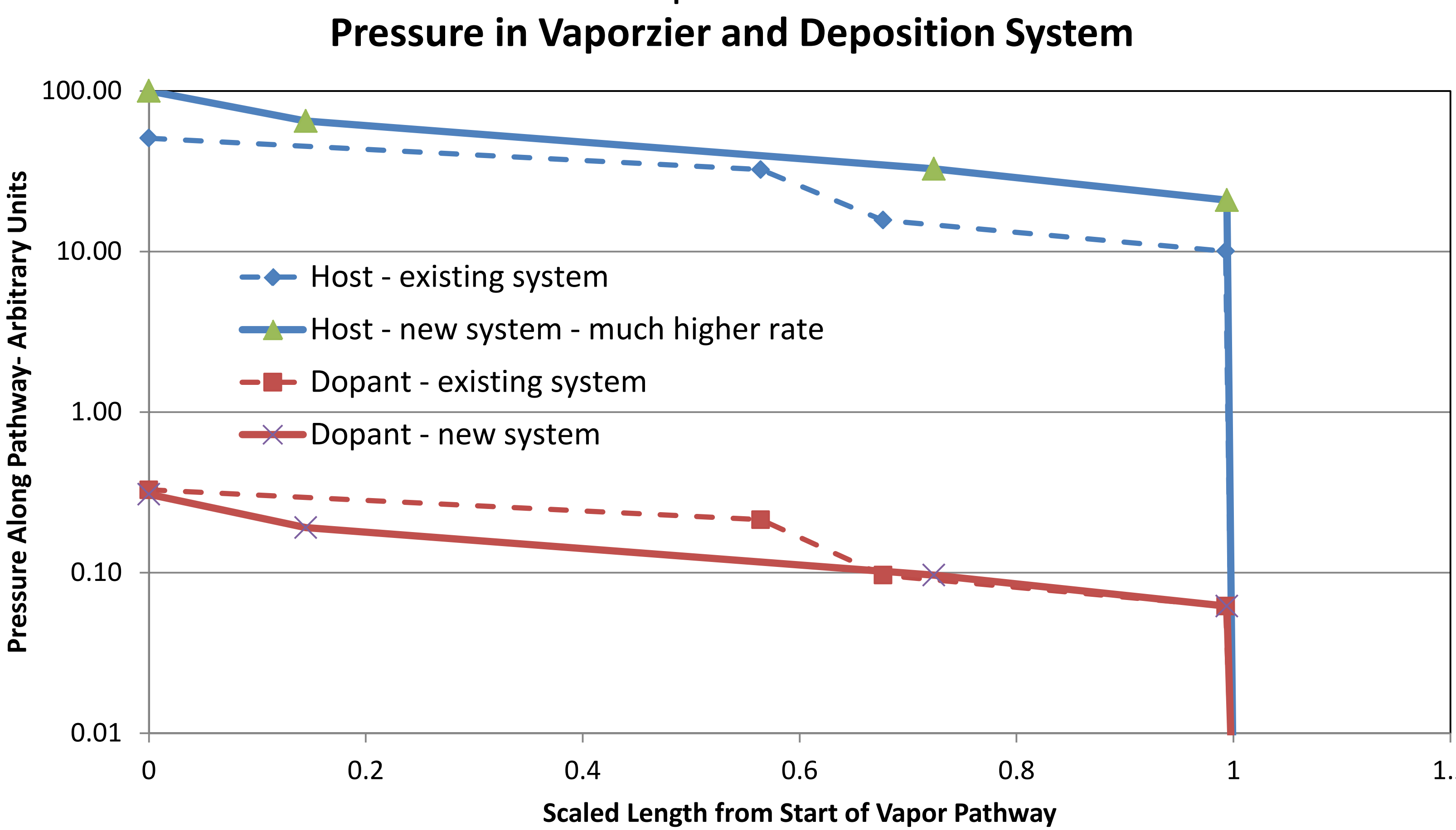
Design Methods Used for New Deposition Source - 4

Vacuum engineering to design a system to achieve the desired temperatures and pressures



Integrated Design of Evaporation and Deposition

- The goal is a synergistic design
  - Smaller system
    - Lower capital cost of evaporator and total machine
    - Closer to substrate
      - Higher material usage efficiency
        - » Faster substrate speed
  - Manage pressure and temperature
    - Less stress on materials
      - Higher evaporation rates
        - » Faster substrate speeds
    - Less degradation of materials
      - Less downtime for frequent re-loading
        - » Higher annual throughput
- All parts work together to achieve remarkable results.

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Project Overview

- Phase 1 - First year
  A. Design, build, and test the full scale vaporizer components
  B. Refine design
  C. Design, build, and test single component deposition system in production equipment with vaporizer.
- Phase 2 – Second year
  A. Design, build, and test multi-component evaporation deposition system
  B. Demonstrate performance in production equipment.

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Where are we in the project – 7 months

Project Plan

- Phase 1 - First year
  A. Design, build, and test the full scale vaporizer components.

Where are we after 7 months into the project:

- We have completed all design work including
  - Vacuum engineering
  - Thermal modeling
  - Plume shape modeling
- All major components have been fabricated or are being fabricated.
- Assembly will begin later this month.
- We are on schedule and on budget.

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