Prototype Development of Self-Cleaning CSP Collectors

Boston University

Award # DE-EE0005794

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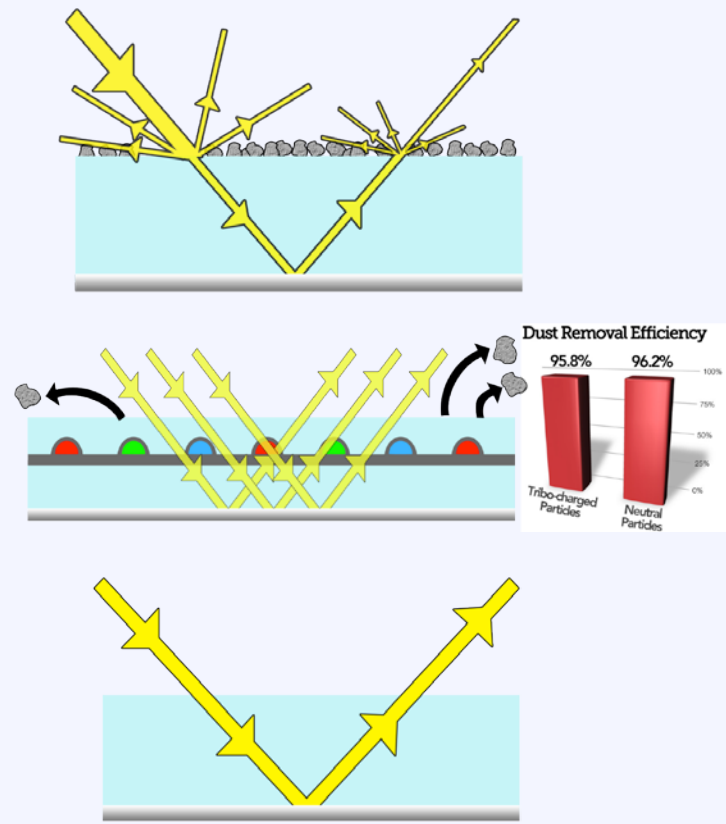

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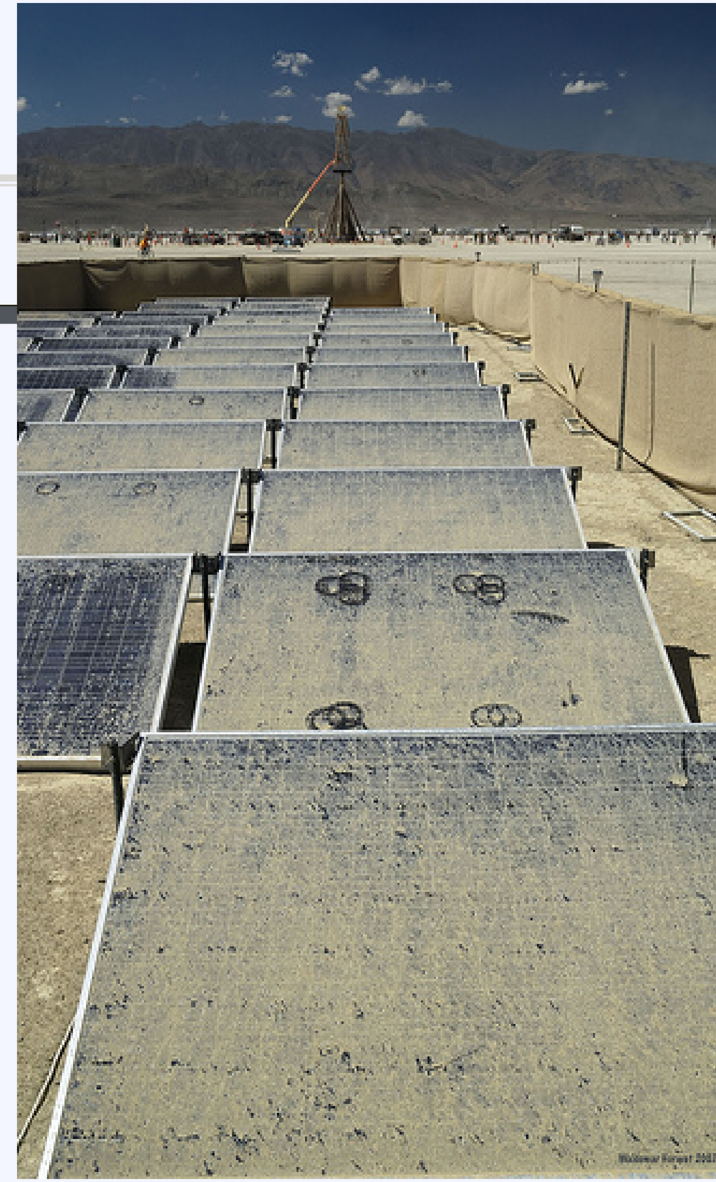
Project Objectives

- Maintain high optical efficiency of CSP systems by keeping solar collectors dust free
- Proof-of-concept of Electrodynamic Screens (EDS) for self-cleaning solar concentrators
- Prototype EDS-based self-cleaning solar collectors
  - Dust removal efficiency > 90%
  - Cleaning time period < 2 minutes
  - Energy consumption < 0.1% of solar collector production
  - Without requiring any water or manual labor
- Complete lab and field evaluations of prototype EDS integrated mirrors in collaboration with Sandia National Lab and Abengoa Solar Inc.

Examples of Dust Deposition

Dust storms severely decrease power output



- Nellis Air Force Base Solar Plant (Nevada)
- Currently, panels must be cleaned frequently with water.

Reflectance (CSP) and Transmission (CPV) Losses Reported from Different Plants

Location (latitude)	Specimen Type	Exposure period	Affected parameter	Maximum recorded loss
Albuquerque, NM (35.11N)	Silvered glass mirror	5 weeks	Reflectance	25%
China Lake, CA (35N)	Heliostat mirror	7 months	Reflectance	25%
Albuquerque, NM (35.11N)	Silvered glass heliostat	200 days	Reflectance	24.5%
Albuquerque, NM (35.11N)	Mirror samples	8 weeks	Reflectance	14%
Albuquerque, NM (35.11N)	Silvered glass mirror	60 days	Reflectance	12.6%
Henderson, NV (36N)	Glass mirror	1 month	Reflectance	52%
	Aluminized acrylic mirror	2 months	Reflectance	73%
San Antonio, TX (29N)	Glass mirror	2 months	Reflectance	20%
Dalton, GA (34N)	Mirror	1 month	Reflectance	3%
	Aluminized acrylic mirror	1 month	Reflectance	8%
Riyadh, Saudi Arabia (24N)	CPV	12 day	Output power	30.6%
Madrid, Spain (40N)	CPV	5 months	Short-circuit current	6.5%

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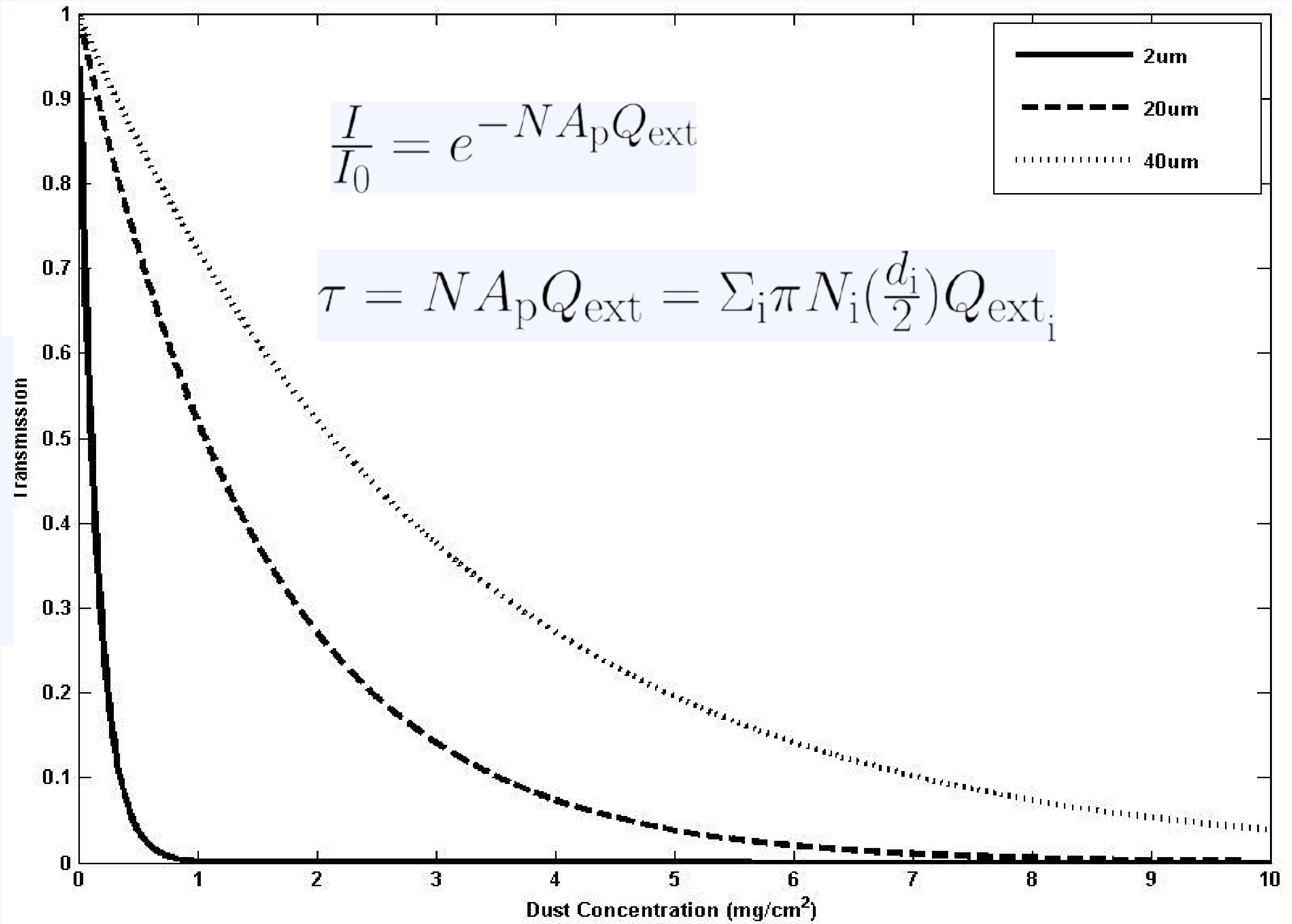
Silvered Glass Mirror (5 weeks) : 25%

Heliostat Mirror (7 Months): 25%

CPV (12 Days) : 30.6%

Transmission Loss Due to Dust Deposition



Transmission

Dust Concentration

Fundamental Studies on Transparent Electrodynamic Screens (EDS)

- Dust charging mechanisms on the EDS surface
- Effects of size, shape, & chemical composition of dust particles, dielectric film on EDS surface, and pulsed voltage applied to electrodes
- Simulation of particle trajectories on EDS
- Theoretical analysis
- Experimental investigation

Fundamental Studies of EDS Operation

Particle adhesion and removal forces

- Forces of particle adhesion: $F_{adh} = F_{vdw} + F_{im} + F_{AB} + F_{CB} + F_g$
- Gravitational force: $F_g = m_d\, g$,
- Van der Waals force, $F_{vdw} = Ad/(12\, z^2)$,
- Capillary force of attraction due to surface tension:

  $F_s = 2\pi d\gamma \cos\theta + 2\pi d\gamma_{sl}$,
- Image force of adhesion: $F_{im} = q^2/(16\, \pi\, \varepsilon_o \varepsilon_d\, t^2)$

Repulsive forces for dust removal during EDS operation:

- Coulomb Repulsive Force: $F_c = q_d E$
- Dielectrophoretic (DEP) Force $F_d = (P\nabla)E$
- The ratio of maximum repulsion force to the maximum force of attraction: $E(z)_{max} \cdot q_{max}, / F_{adh}\,(max) = E(z)_{max} \cdot q_{max} \;/\; q_{max}{}^2/(16\, \pi\, \varepsilon_o \varepsilon_d\, t^2)]$

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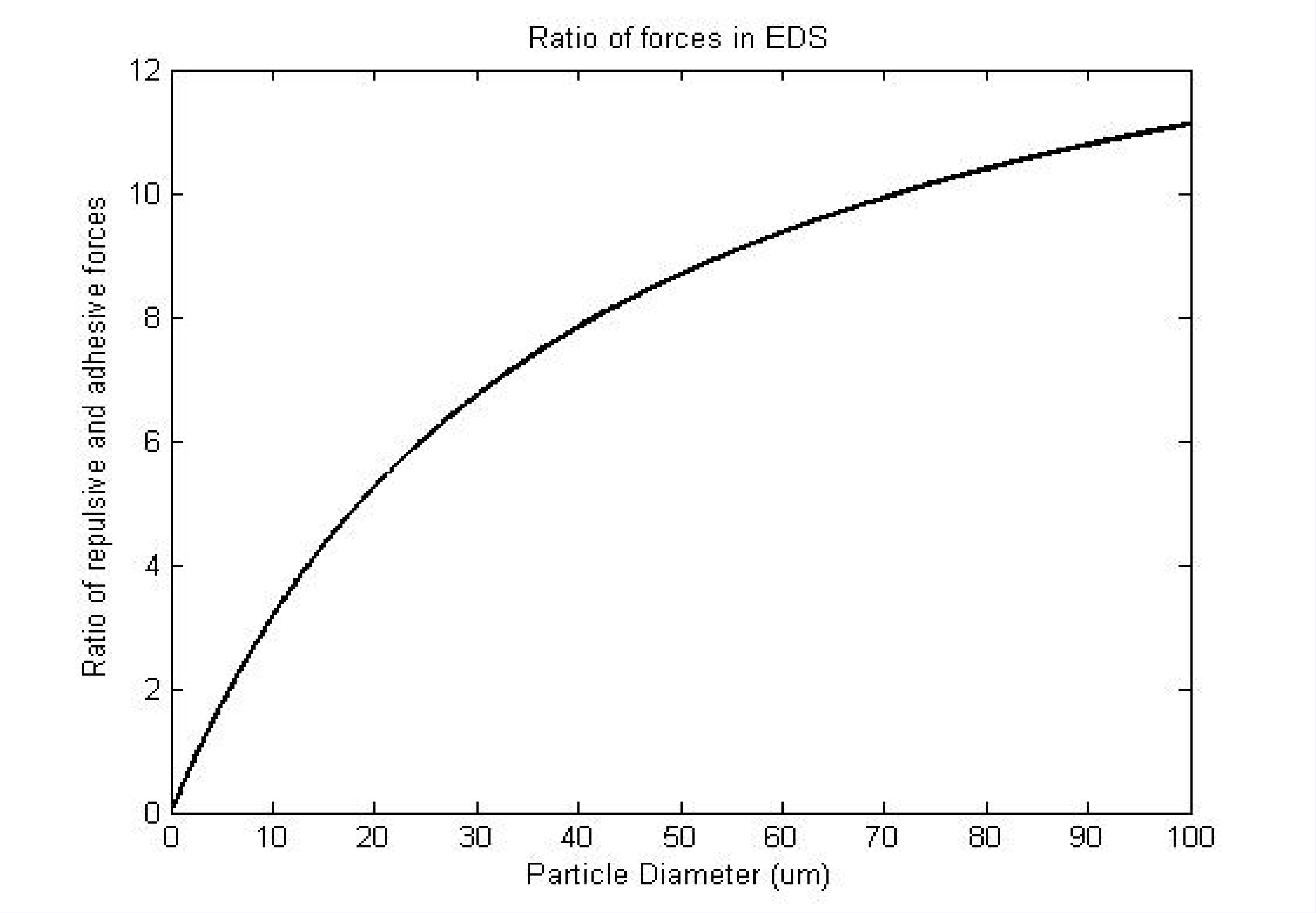
Ratio of repulsion to adhesion forces



(RH <50%)

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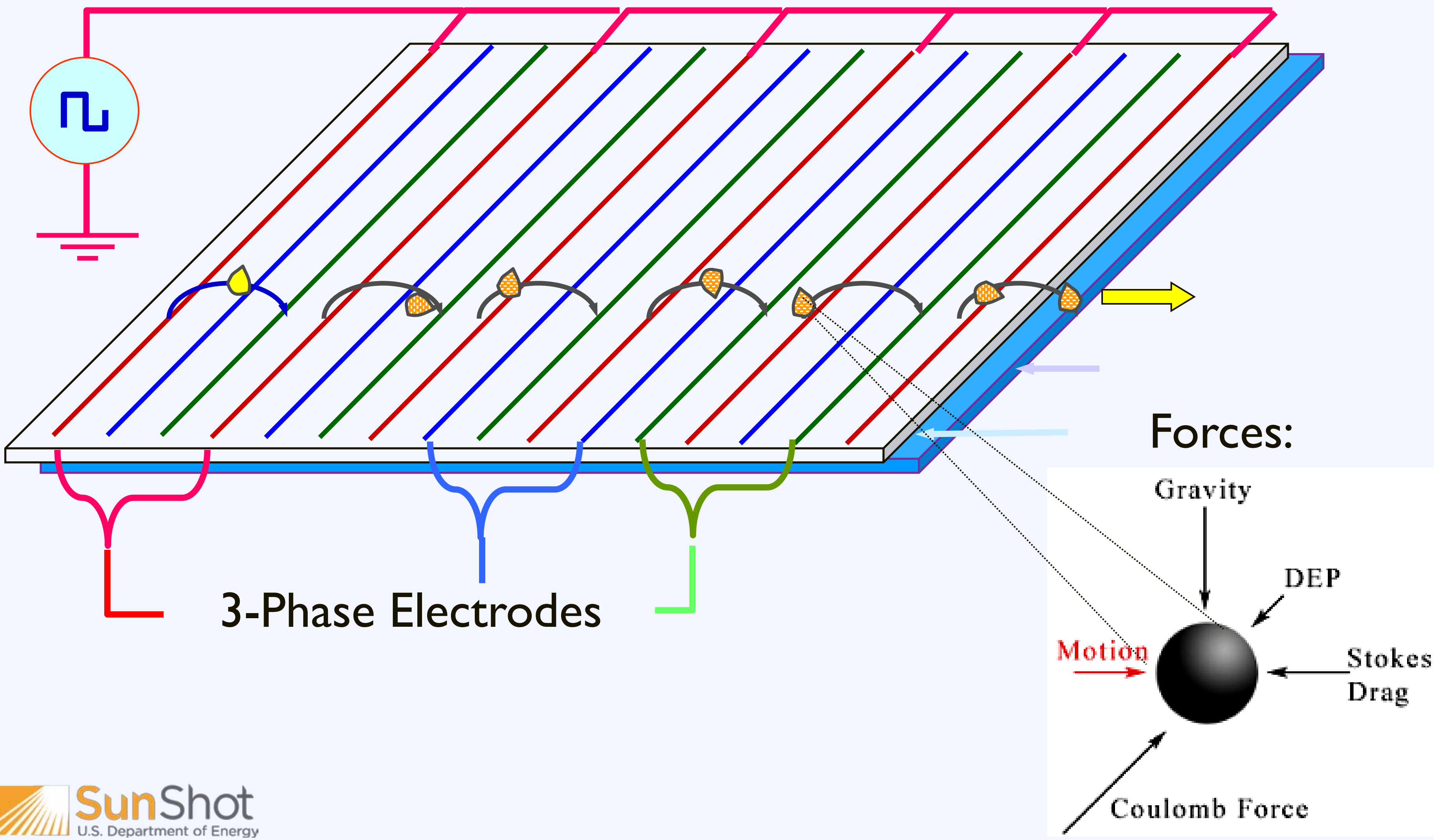
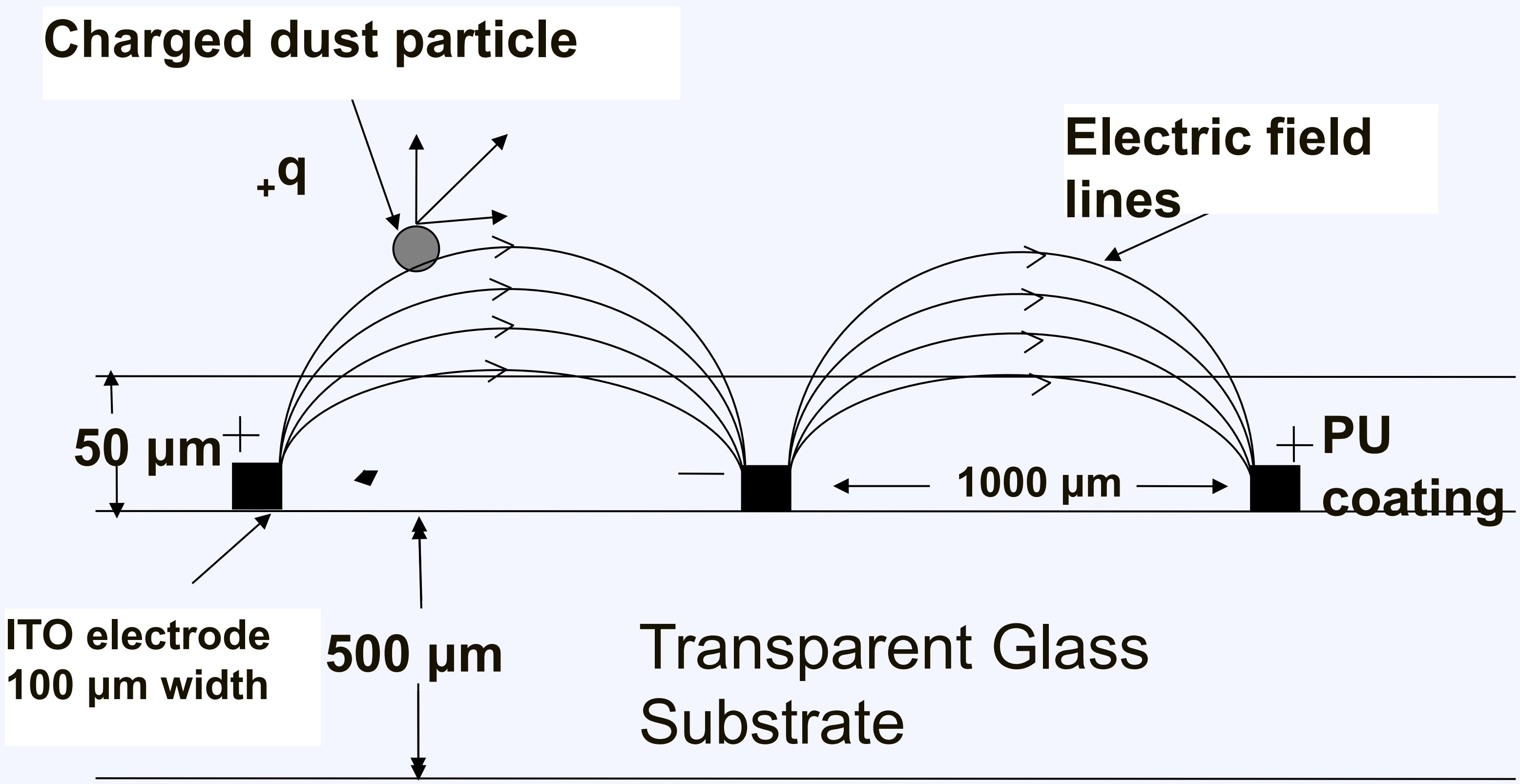
Methodology and Approach for EDS Use

Account for all forces on a single particle and compute its trajectory



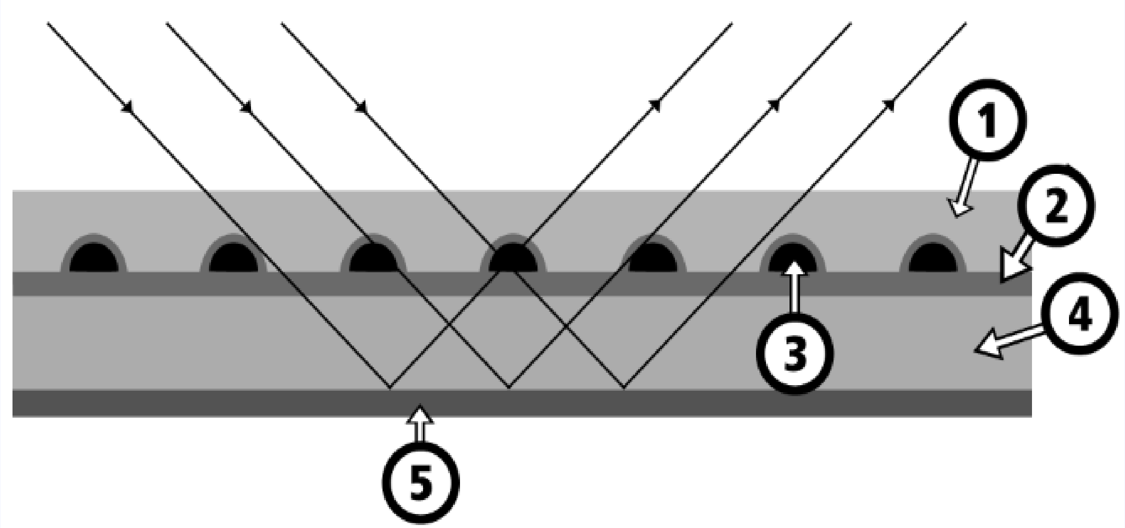
Dust Removal Mechanism



$$m_{\mathrm{p}} \frac{\mathrm{d}V_p}{\mathrm{d}t} + 6\pi\eta r V_p(\bar{r}, t) = qE_0(\bar{r}) \cos \omega t + F_{\mathrm{ext}}$$

Alternating coulomb force pushes dust particles upwards and laterally. Traveling wave causes deposited dust to slide off of the screen.

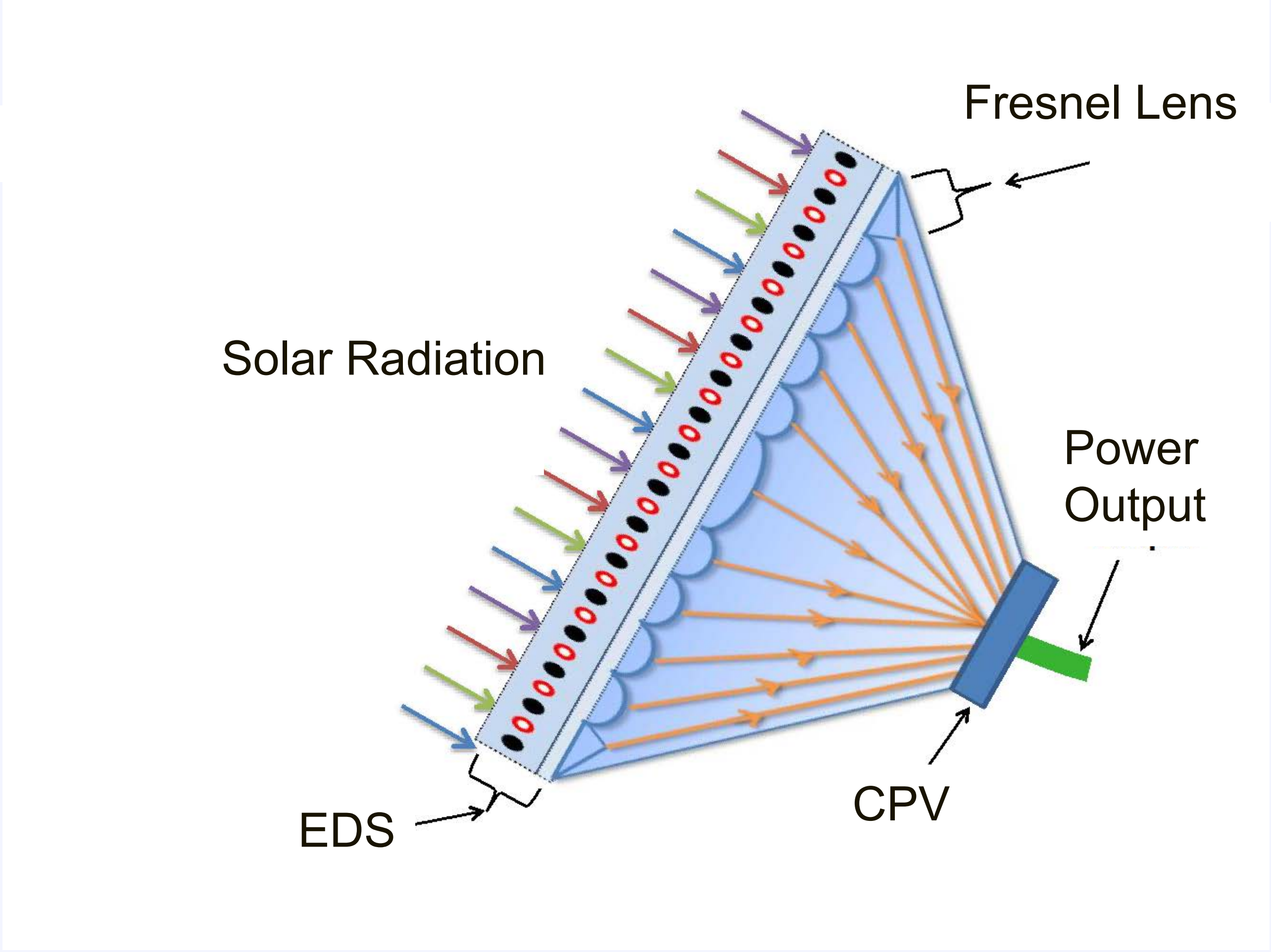
Optical Modeling Analysis
(Collaboration with Sandia National Labs)



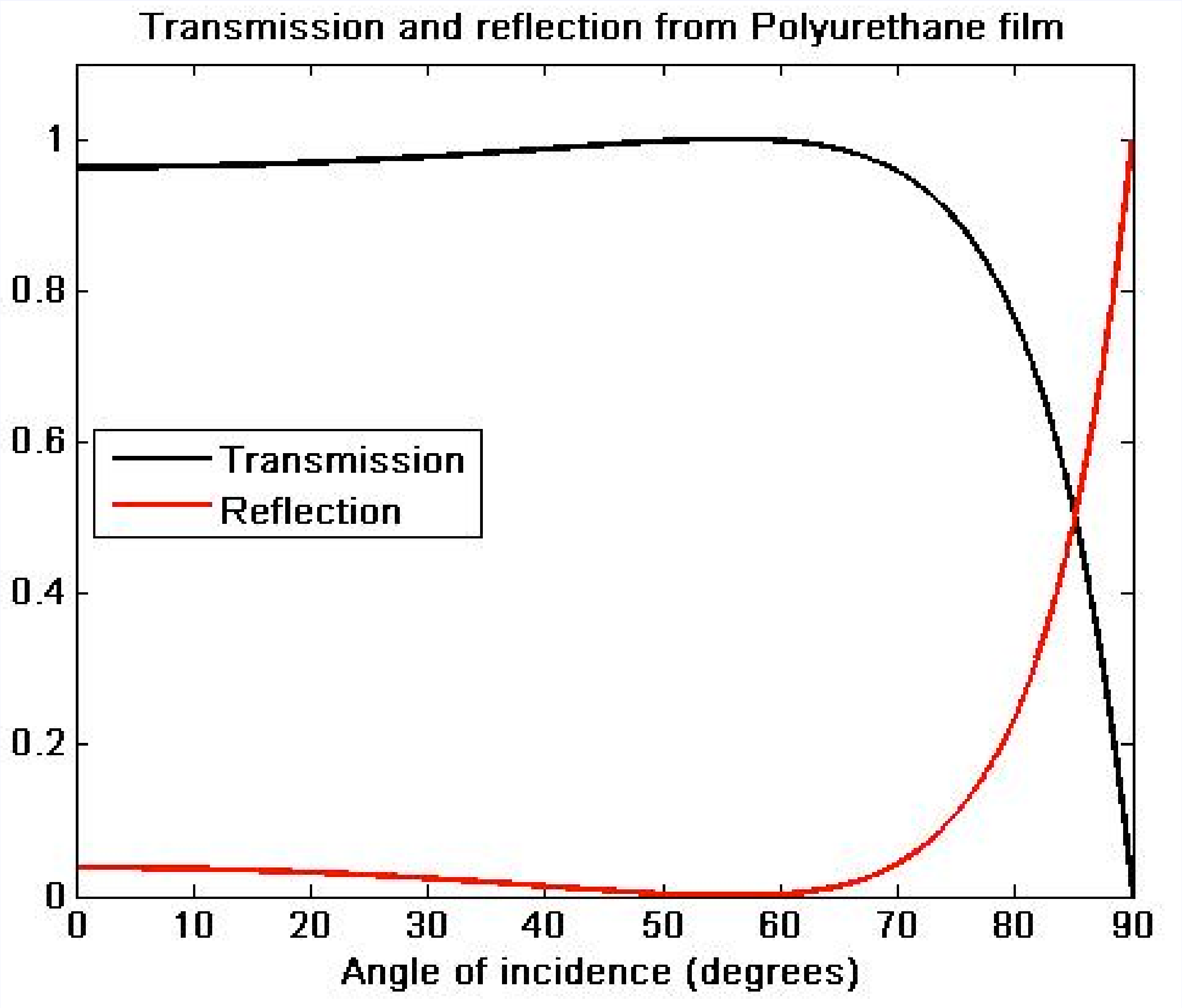
Electrodynamic screen integrated with solar-concentrator mirror

(1) Fluoropolymer film
(2) Thin layer of SiO_2
(3) Parallel transparent electrodes
(4) Borosilicate glass plate
(5) Silver coating of back-surface reflectors

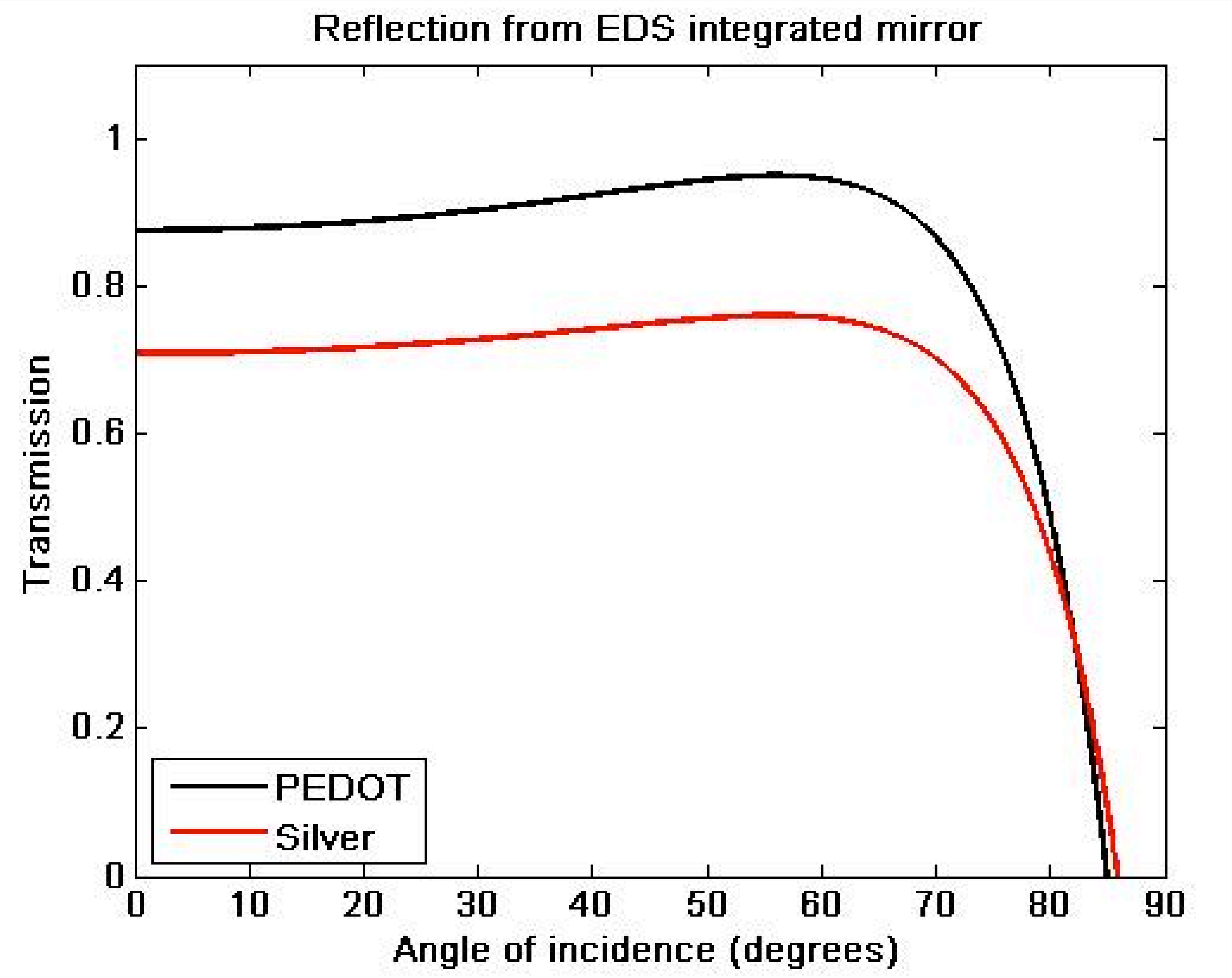
CPV Optics with EDS



Reflection efficiency by PU film (50 µm)



Reflection loss vs. transparency of electrodes



Materials being studied

- **Substrates:** Borosilicate glass, Heliostat mirrors, Polymer films
- **Electrodes:** Silver ink, PDOT:PSS, Silver nanowires, AZO
- **Dielectric Film:** Polyurethane, Urethane, ETFE, Tefzel
- **Dust Samples:** Sample dust from different deserts: Mojave Desert, Negev Desert, Gobi Desert, dust samples from Abu Dhabi, Saudi Arabia

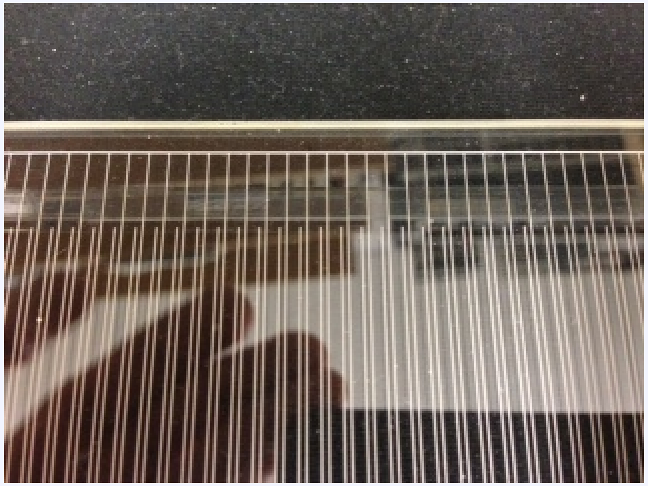
Prototype EDS Development

- Surface treatment of substrates (Borosilicate glass or Second surface mirrors)
- Deposition of electrodes
  - Screen-printing
  - Ink-jet printing
  - Photolithography
- Application of transparent dielectric film to embed electrodes
- Production of power supplies, interconnection to EDS
- EDS testing for dust removal

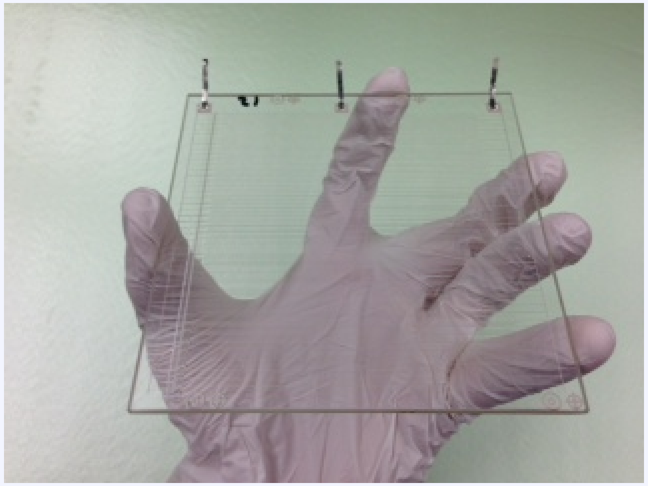
Images of Screen-Printed EDS

First screen printing: two electrode phases

Third phase printed on the dielectric stop-gap

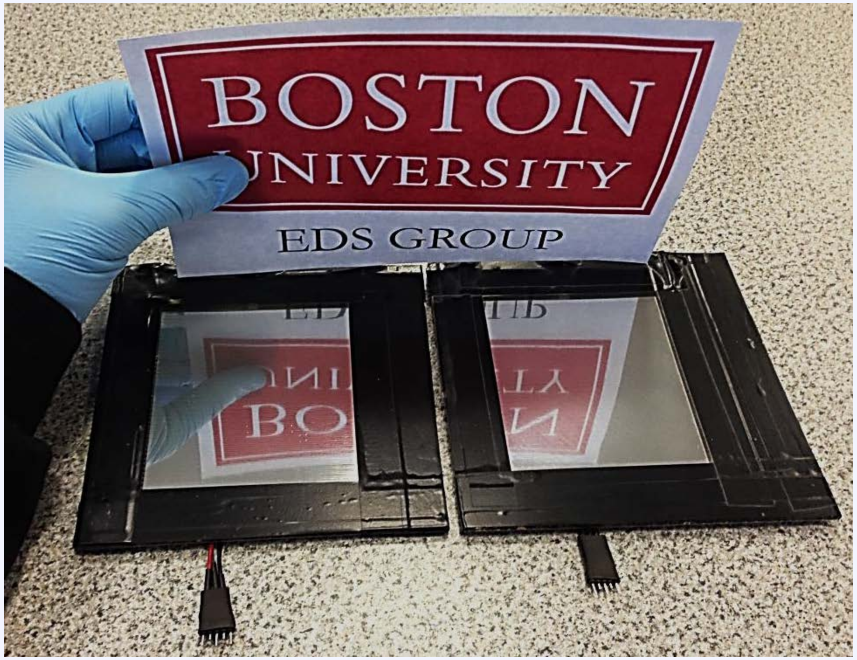


Dielectric stop-gap printed over one phase



Finished EDS fabricated with screenprinting

EDS on Rio-Glass Mirror

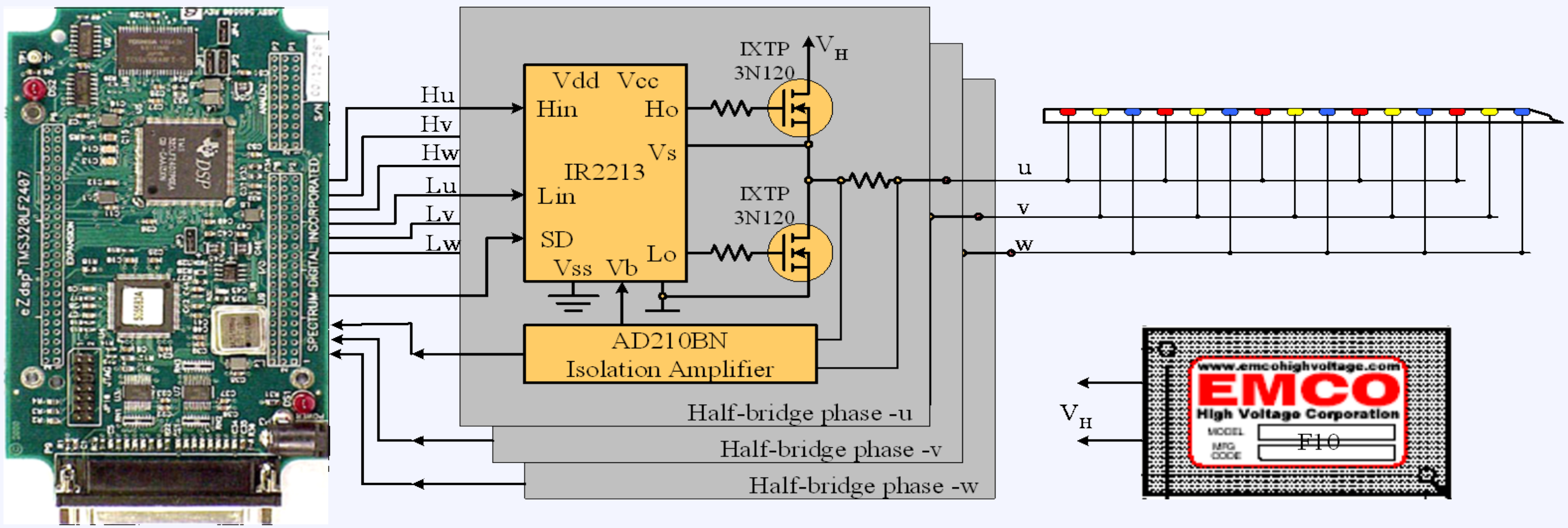


Left: Two fully functional EDS showing reflectivity of the mirror beneath the shield
Right: Close-up of mirror image from the EDS-mirror system

EDS with transparent conducting ink

Low Frequency Low-Power Pulsed HV Supply

Power management



- CSP self-powers its own EDS
- Cleaning is automatically triggered by dust sensor on panel
- Operation for short periods only (not continuous)

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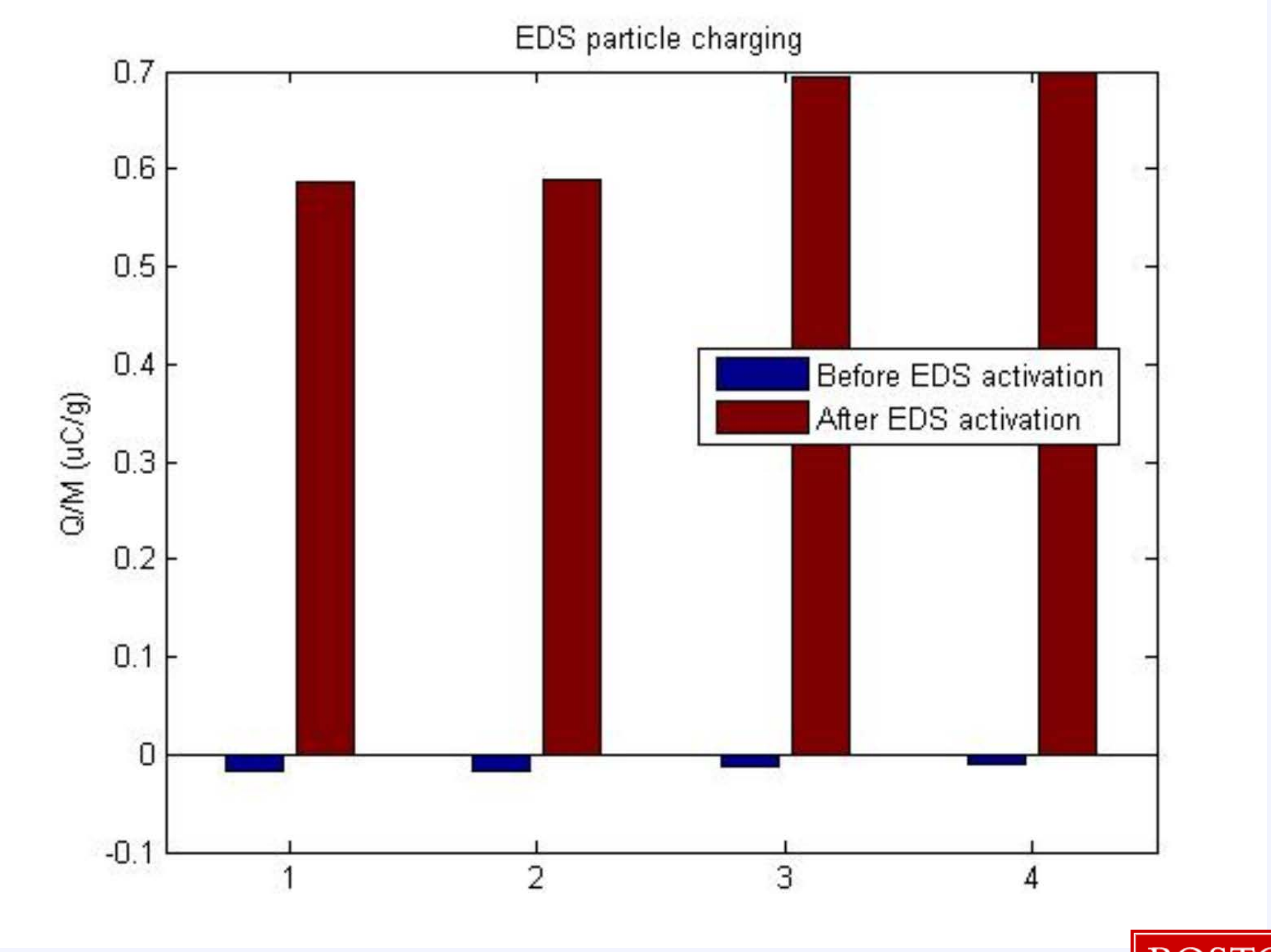
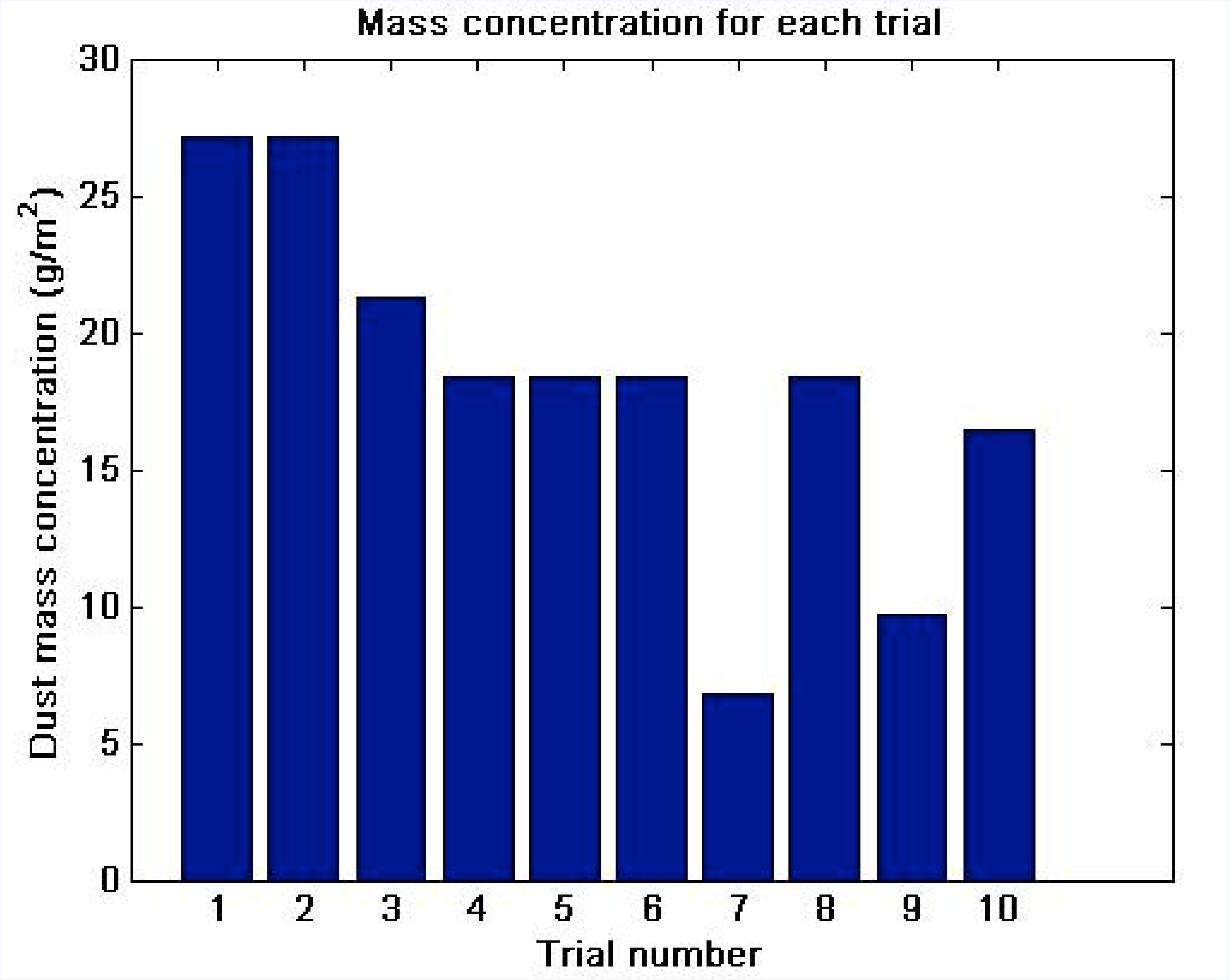
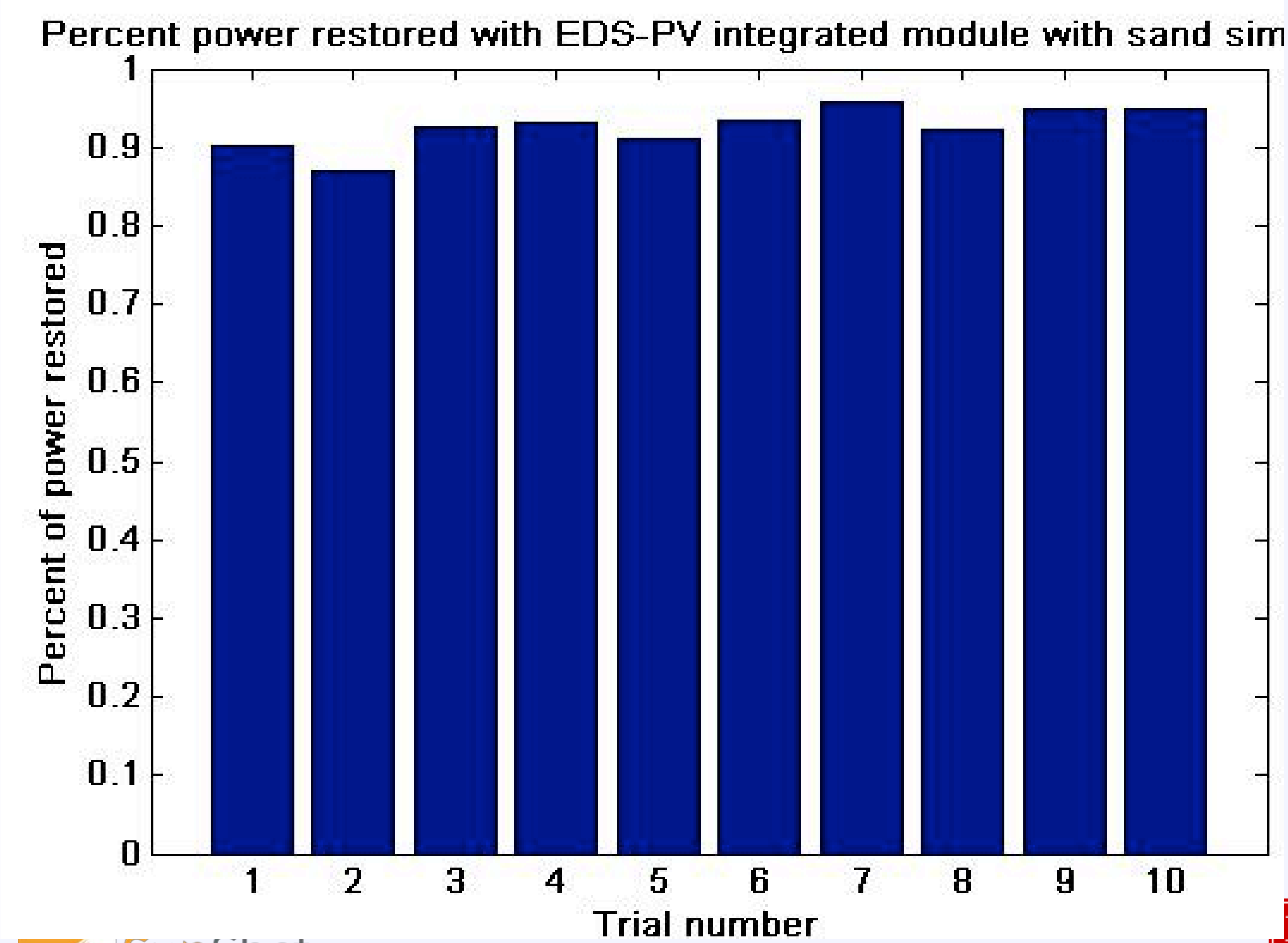
Electrostatic Charging of Particles by EDS



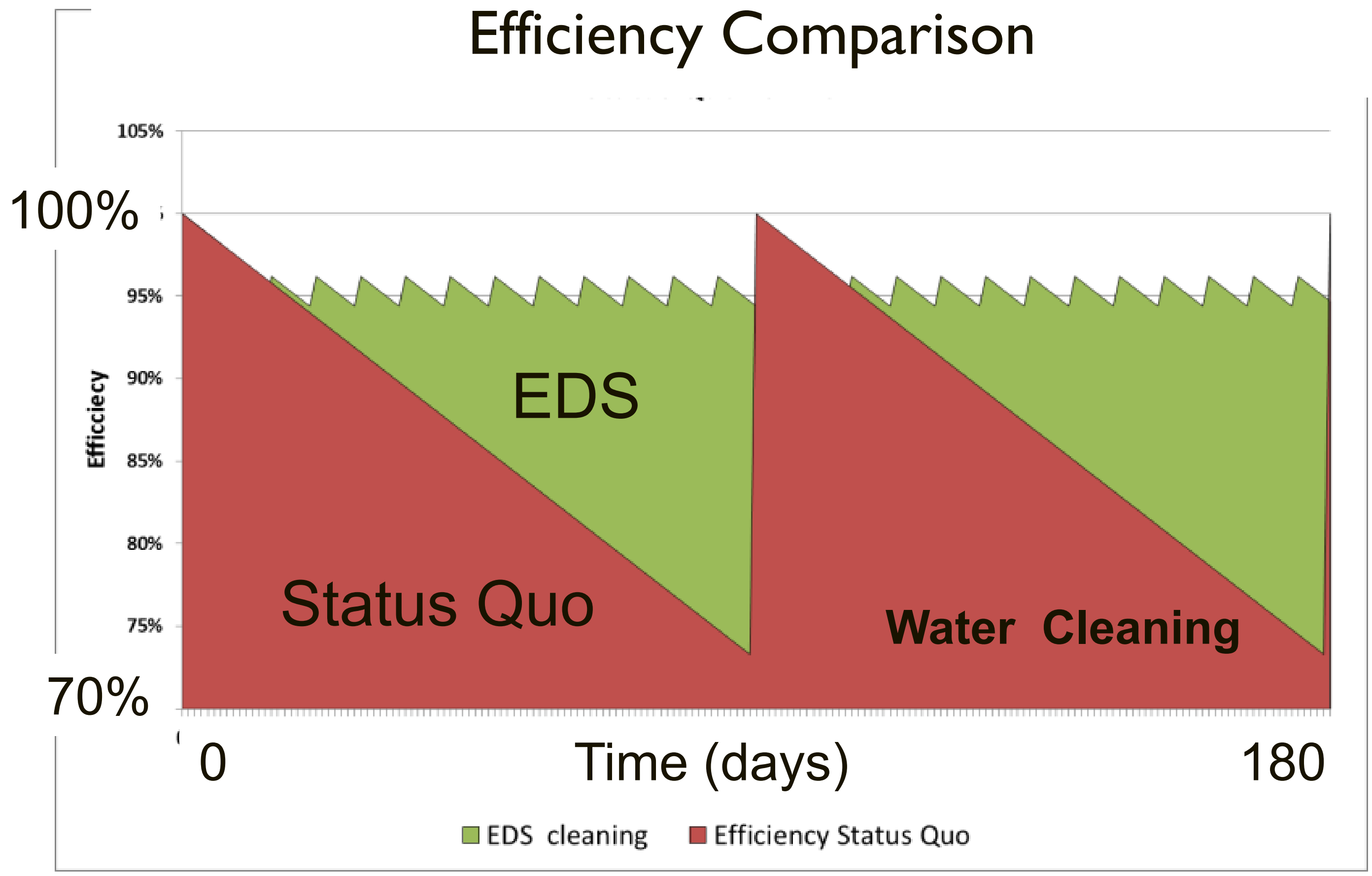
Surface mass concentration of desert dust on EDS surface



EDS Dust Removal Efficiency



Water Cleaning vs. EDS Cleaning



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EDS Cost Analysis
(Collaboration With Abengoa Solar Inc.)

Accomplishments

- Development of manufacturing cost module
  - Collaboration with Abengoa Solar regarding input parameters
  - Addition of power supply to cost module
  - Module analysis to isolate cost drivers
    - Cost driver variation analysis
- Operational cost module progress
  - Gathered data for general EDS operational expression

*EDS prototype module pertains to 15cm square borosilicate substrate

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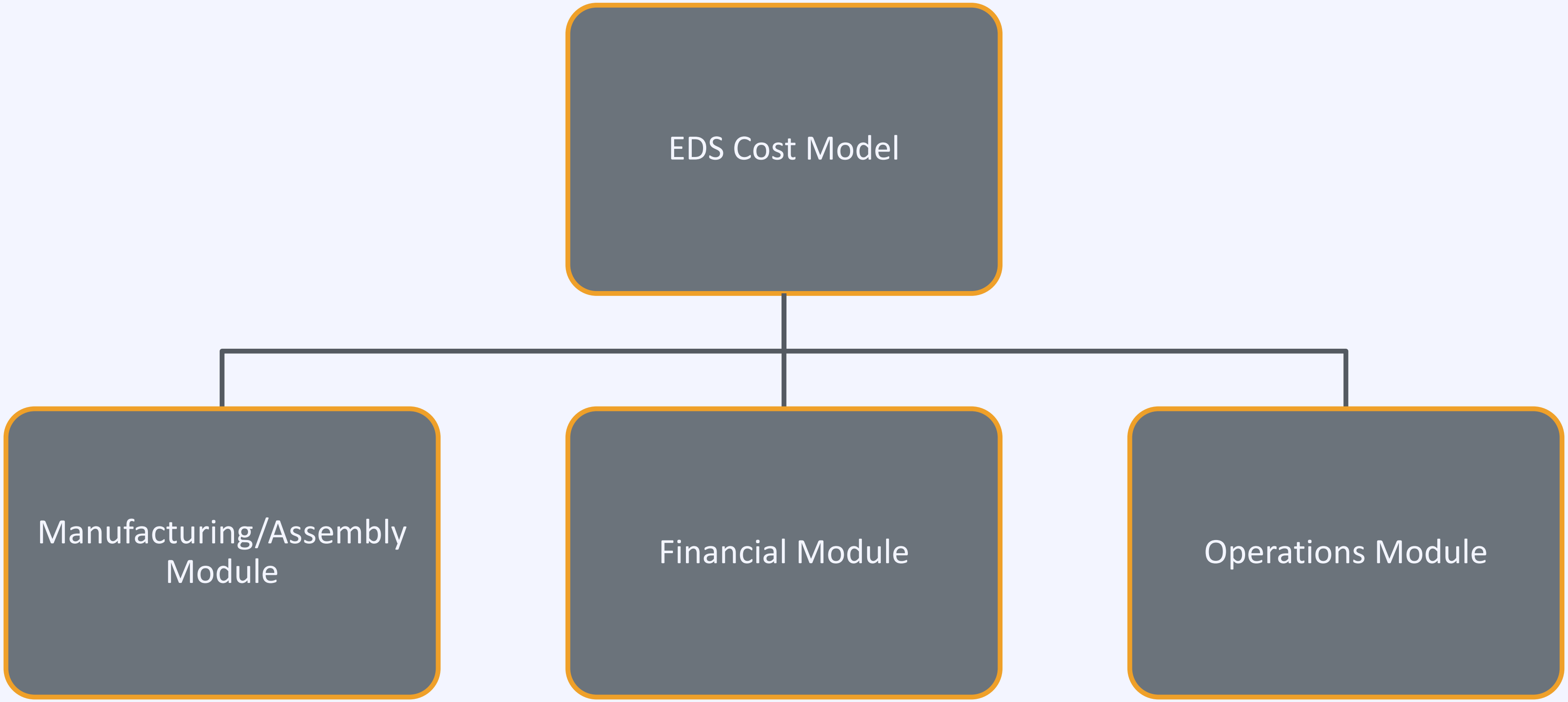
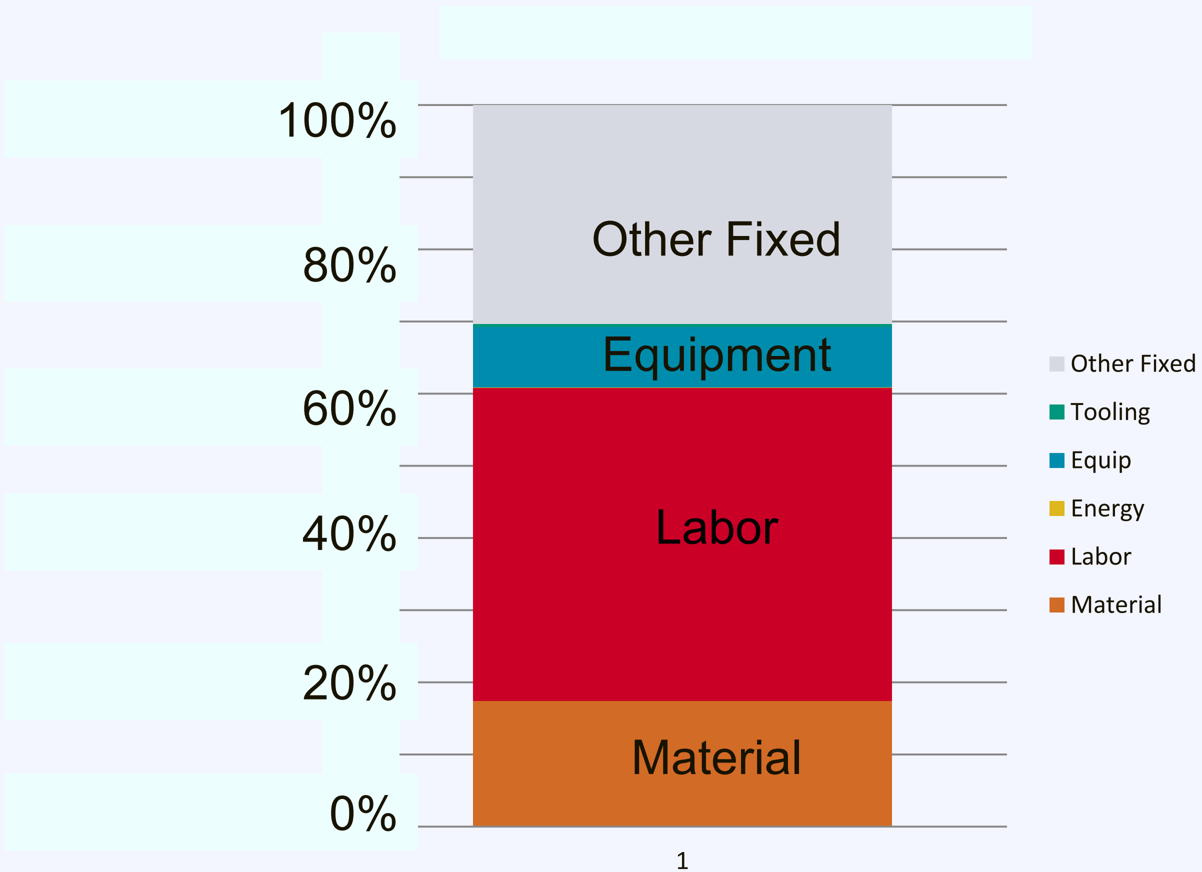
Modeling Overview



Purpose: To qualify major cost elements, and provide economic insights on tradeoffs associated with design and operational decisions

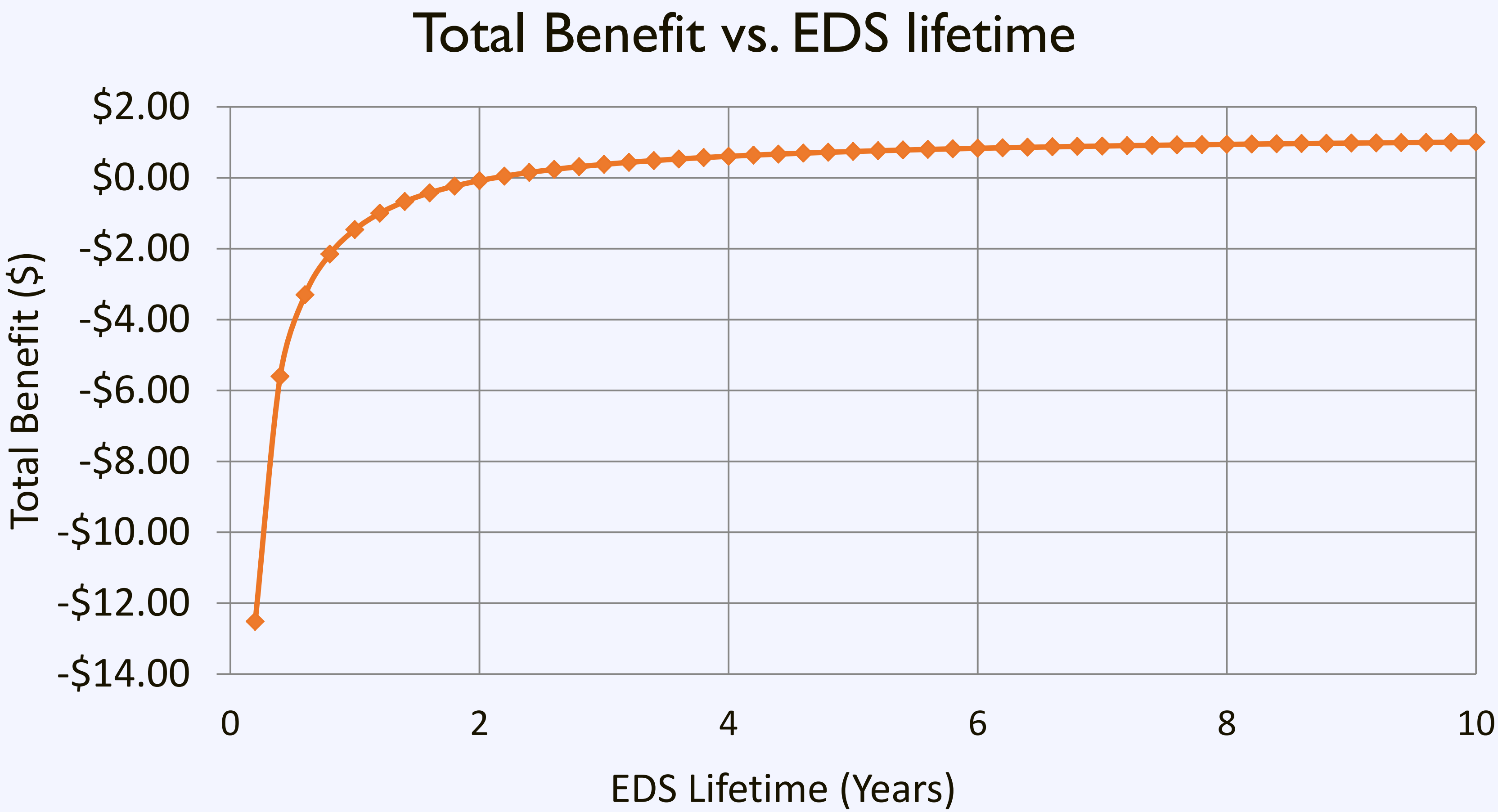
Cost Analysis for Prototype Production

- Cost Breakdown



Sample output of fixed and variable cost breakdown for the manufacturing-cost model

EDS Payback Time Period Analysis
Based on estimated EDS cost* per m^2



Data taken from manufacturing cost module estimates

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Conclusions

Our Studies Show Feasibility of:

- Production and Evaluation of Self-cleaning CSP Optics
- Demonstration of Low-cost Self-cleaning Technology to Industry Partners, Investors (Abengoa Solar Inc.)
- Modeling and Field Testing at Sandia National Labs
- Partnership with Manufacturing Companies
- Cost-analysis of prototype production and scale-up
- Cost-effective application of EDS in CSP, CPV, and PV Optics

Video Demonstration

Acknowledgement

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Abengoa Solar

Sandia National Laboratories