Space PV Concentrators for Outer Planet and Near-Sun Missions, Using Ultra-Light Fresnel Lenses Made with Vanishing Tools

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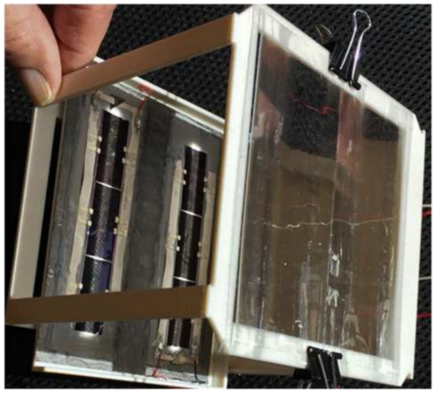
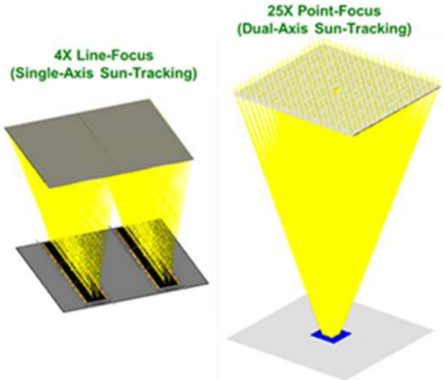
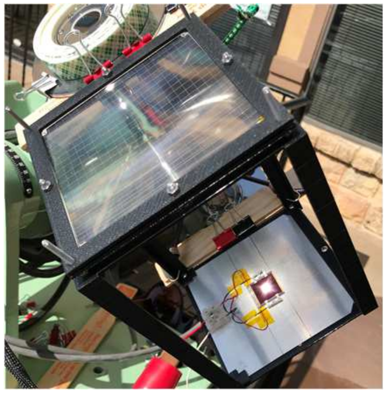
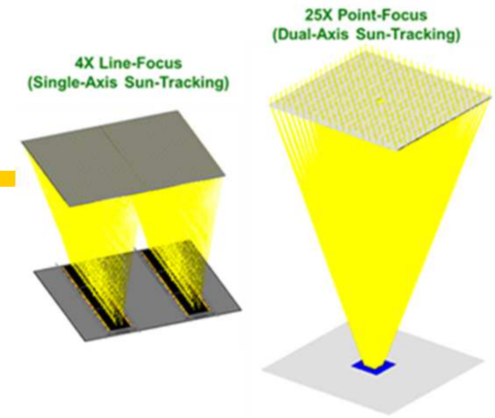




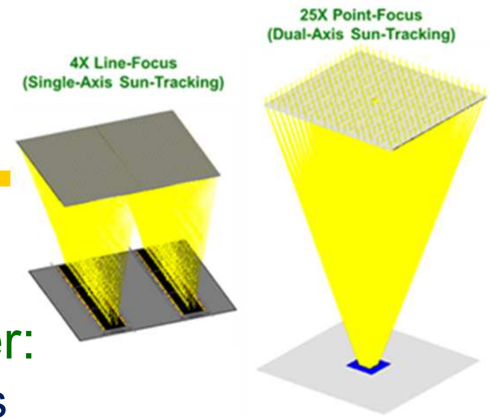


Acknowledgements



The Advances in Space Refractive Photovoltaic Concentrator Technology Discussed in this Paper Were Made Possible by NASA Contracts.

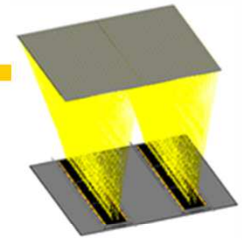
Our Latest Space Photovoltaic Concentrator Technology Uses Three Key Elements for Either One-Axis-Tracking Line-Focus or Two-Axis-Tracking Point-Focus Systems



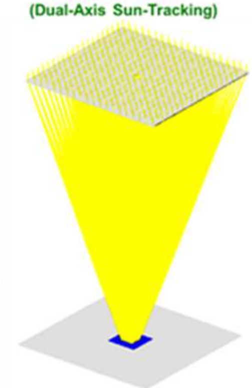
1. Ultralight, robust, color-mixing, flat Fresnel lens optical elements. The latest lenses are strengthened with either:
   - A ceria-doped glass superstrate to support the silicone prisms forming the lens, or
   - An embedded mesh in the silicone lens itself.
2. Advanced multi-junction solar cells of two types:
   - 3-junction germanium based solar cells, or
   - Inverted metamorphic multi-junction (IMM) solar cells with at least 4 junctions to enhance conversion efficiency.
3. Waste heat radiators made from graphene, a material with unprecedented in-plane thermal conductivity. The latest radiators also have new features:
   - The graphene is deposited onto the back side of a reflective aluminum foil using innovative methods, and
   - The bi-material radiator can mitigate both low-intensity, low-temperature (LILT) effects and high-intensity, high-temperature (HIHT) effects for deep space and near-sun missions, respectively.

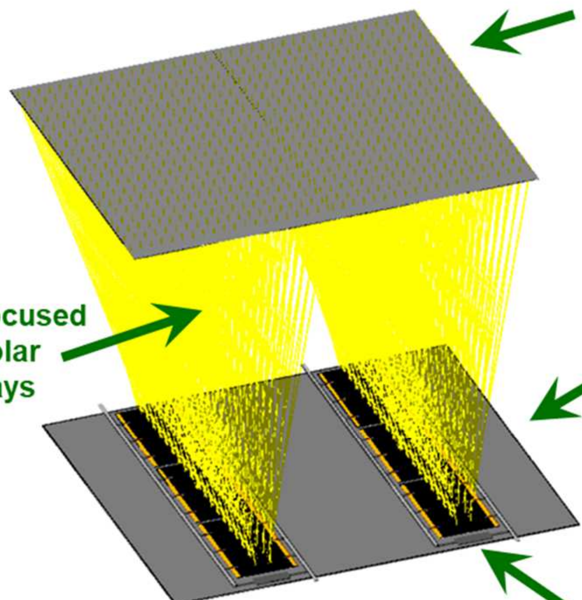
4X Line-Focus and 25X Point-Focus PV Concentrators Share Many Common Features

4X Line-Focus
(Single-Axis Sun-Tracking)



25X Point-Focus
(Dual-Axis Sun-Tracking)





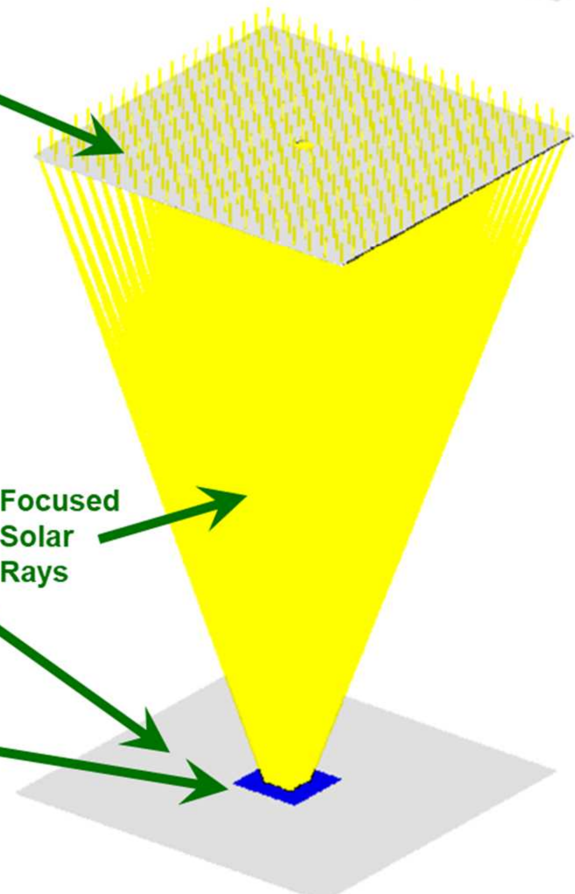
10 cm x 10 cm Flat Color-Mixing Fresnel Lens Comprising a Single Sheet of 50 μ CMG Glass (or 50 μ Silicone with Embedded Mesh) with 100 μ Tall Silicone Prisms Molded onto the Bottom Surface Forming Either 4X Line-Focus or 25X Point-Focus Lenses

Focused Solar Rays

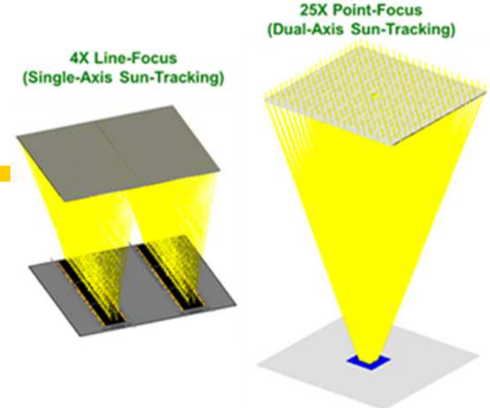
25 μ Solar-Reflective Aluminum Foil on Top of 25-40 μ Graphene Radiator for Waste Heat Dissipation with Coatings on Both Sides for Emittance Enhancement

Multi-Junction Cells with Encapsulation, Isolation, and Appropriate Front and Back Shielding for Mission Requirements

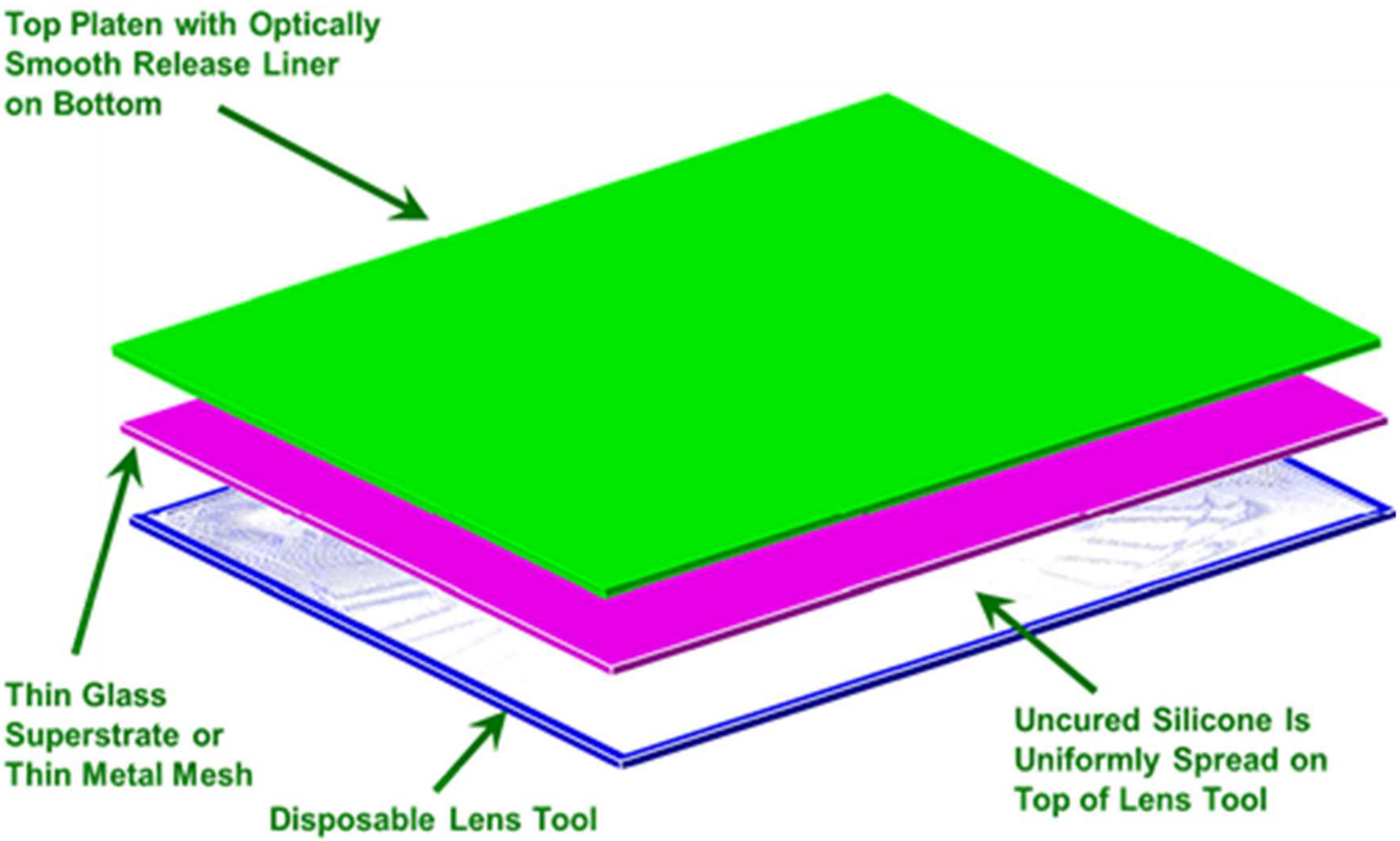
Focused Solar Rays



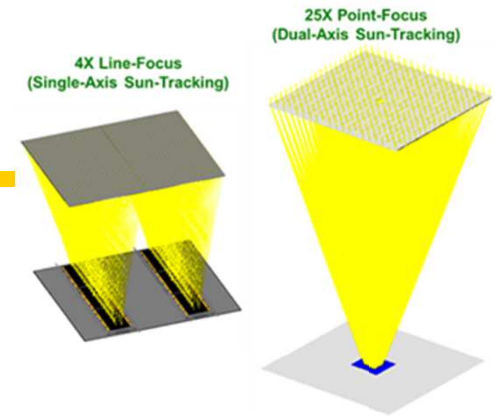
Ultra-Light Fresnel Lens Manufacturing Approach



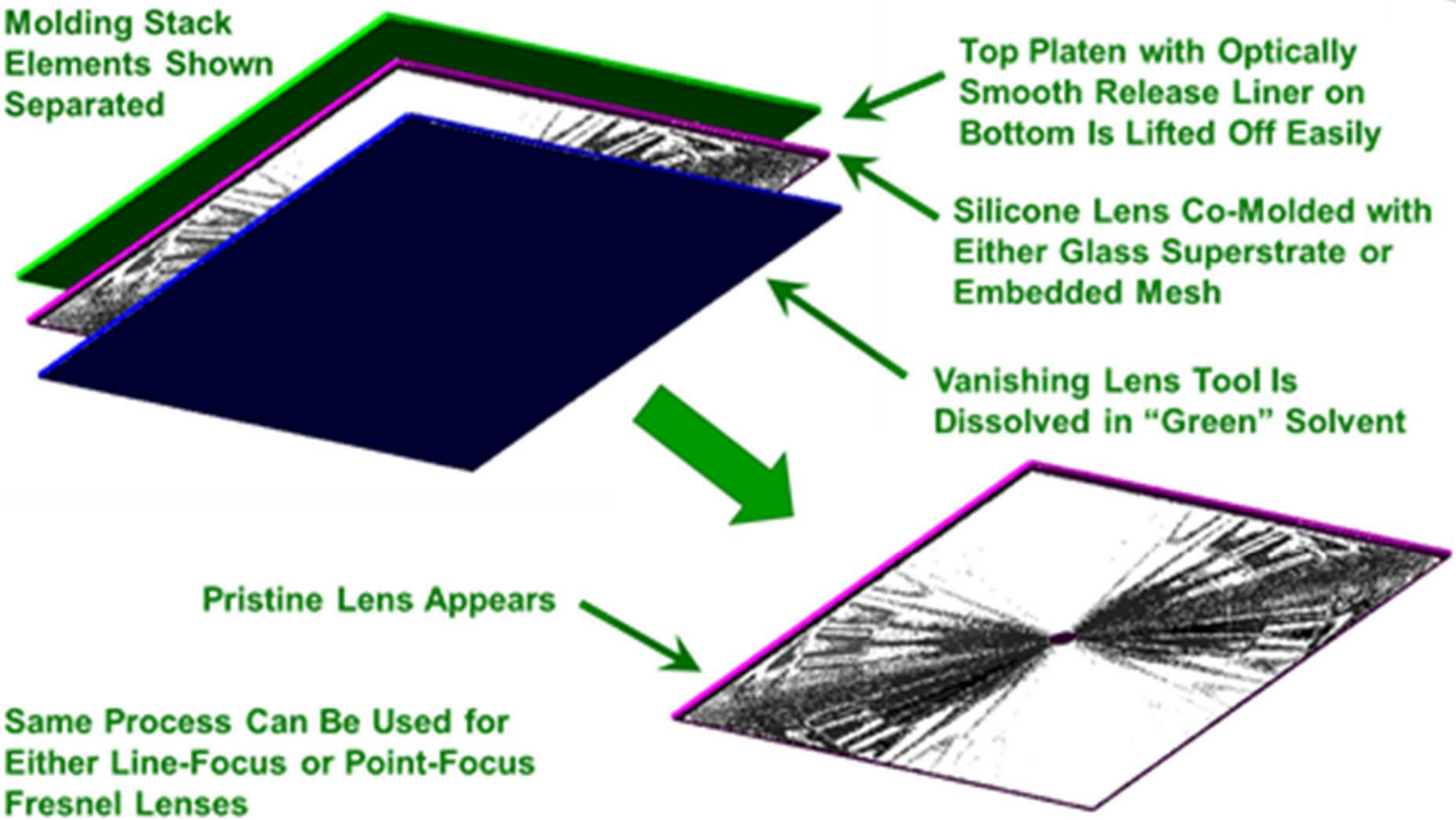
The Only Difficult Step in Making Ultra-Light Lenses in the Past Was in Removing the Disposable Lens Tool Without Damaging the Thin Glass Superstrate or Thin Metal Mesh



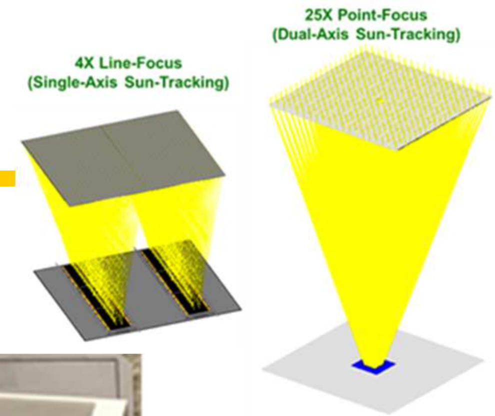
"Vanishing" Lens Molding Tool Approach



Our Latest Innovative Lens Manufacturing Approach Eliminates the Lens Molding Tool Removal Step by Dissolving the "Vanishing" Tool

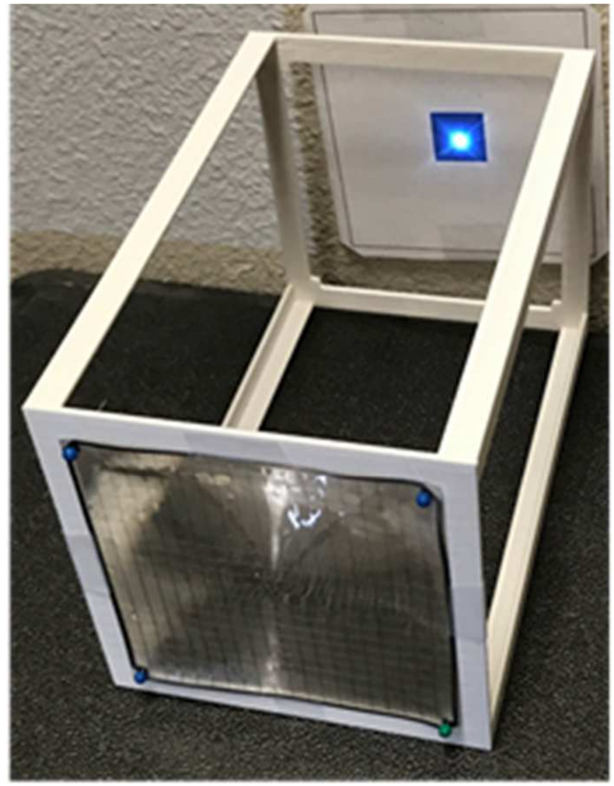


Prototype Lenses Made with "Vanishing" Lens Molding Tools, Showing the Focal Spot



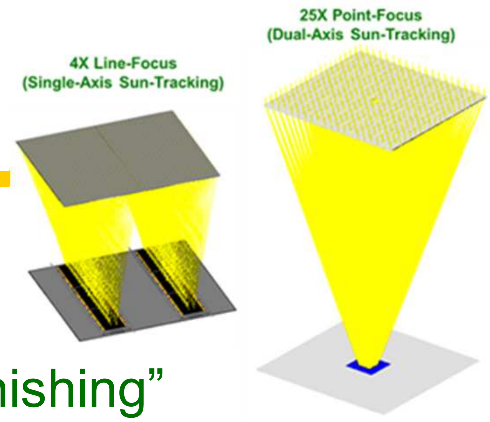
The Process Works Exceedingly Well! 100% Yield in Pilot Runs for Both Types of Lenses (Glass Superstrate and Embedded Mesh)

Lens with Thin Ceria-Doped Glass Superstrate



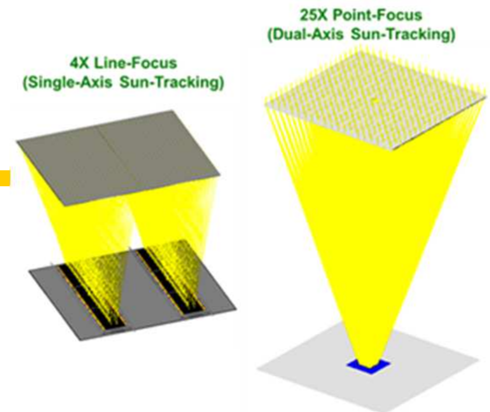
Lens with Embedded Titanium Mesh

After Evaluating Different Materials and Solvents, We Found Two Leading Contenders



- We have had success with several different pairs of "vanishing" lens molding tool materials and appropriate green solvents, including:
  - Polystyrene (PS) molding tools and limonene solvent
  - Polymethyl methacrylate (PMMA) molding tools and anisole solvent.
- Molding tools of both polymer materials were made by 10X Technology using nickel electroform replicas of the master diamond-turned tool.
- We were able to make ultra-light lenses using both pairs of polymer materials and solvents.
- The PMMA tool dissolved in anisole solvent has been selected as the better approach based on decades of success in mass production of PMMA prismatic material in roll-to-roll processes

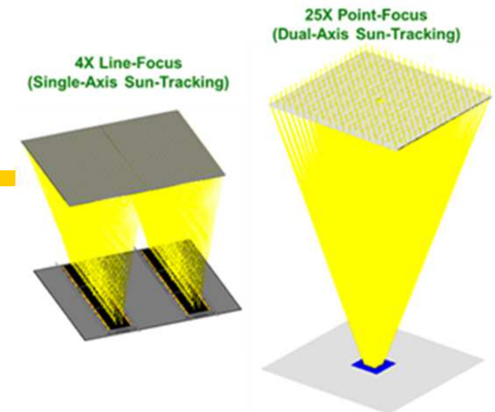
To Prove the Technical Feasibility of the New Manufacturing Process, We Replicated Existing Point-Focus Lens Tooling



Nickel Electroform Replica of Master Tool

Polymer (PMMA) Molding Tool Made from Electroform

Two Glass Superstrate Lenses in Ultrasonic Solvent Bath and One Resulting Lens

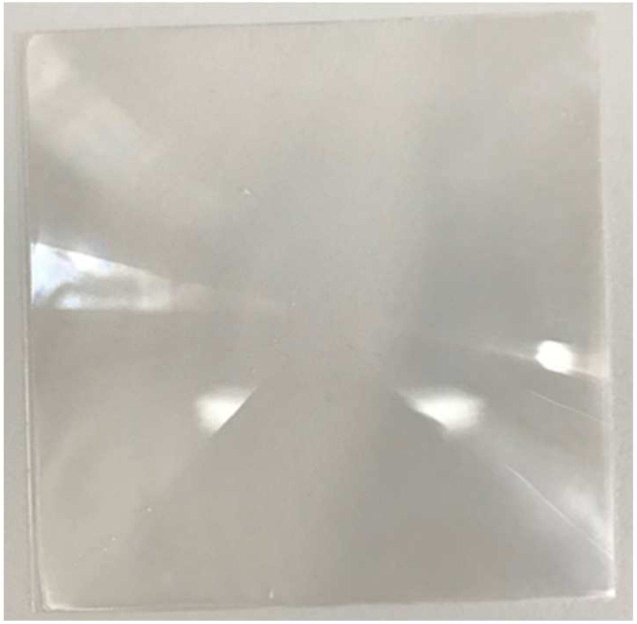


PMMA Tool Dissolving in Anisole Solvent

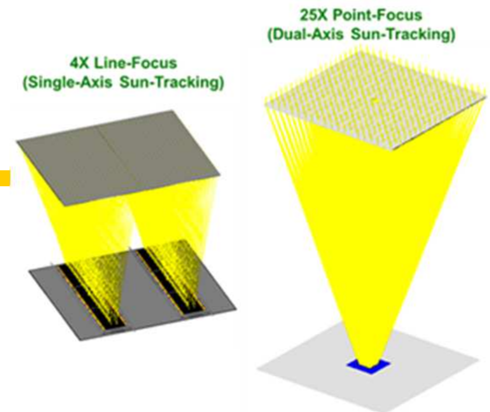
Mesh Baskets Were Used to Handle the Lenses Without Glass Breakage

The Unoptimized Process Takes Just a Few Minutes for the Lens Molding Tool to Disappear

We Did a Pilot Run to Produce a Number of Lenses with Zero Glass Breakage and 100% Yield



Two Silicone Lenses with Embedded Titanium Mesh in Ultrasonic Solvent Bath and One Resulting Lens

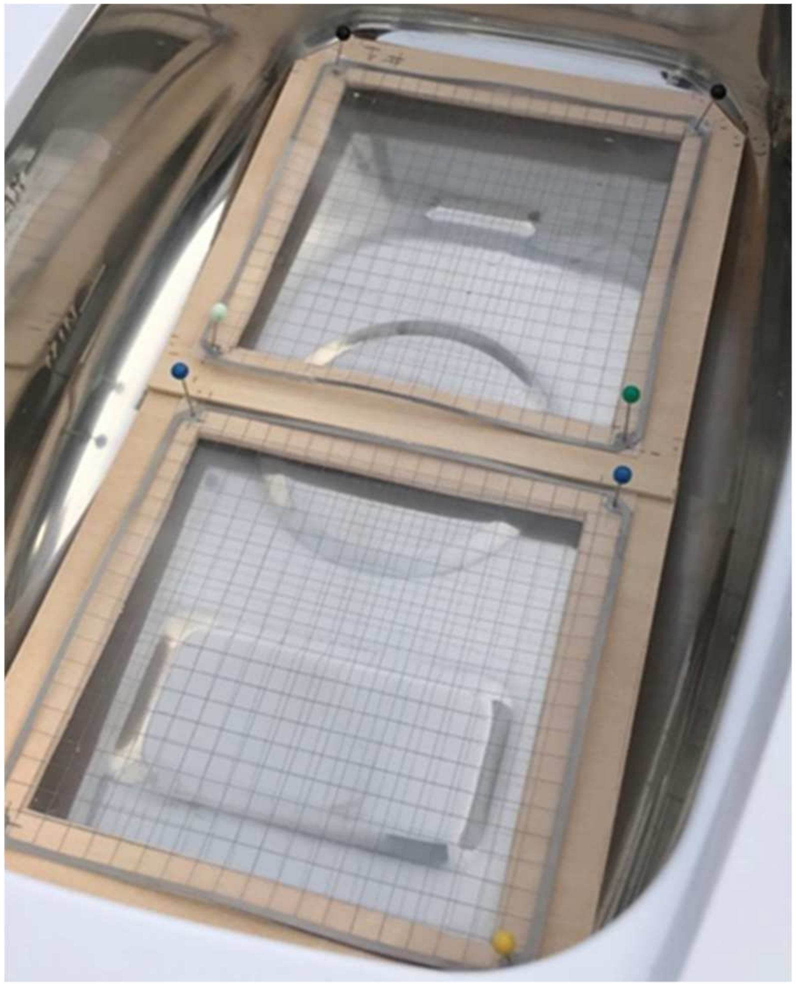


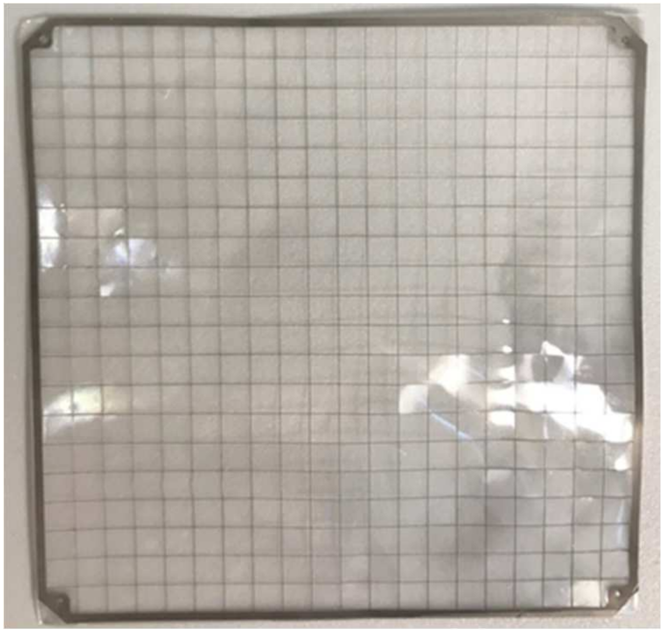
PMMA Tool Dissolving in Anisole Solvent

Pinning the Corners of the Titanium Mesh Prevents Curling During the Dissolving Process

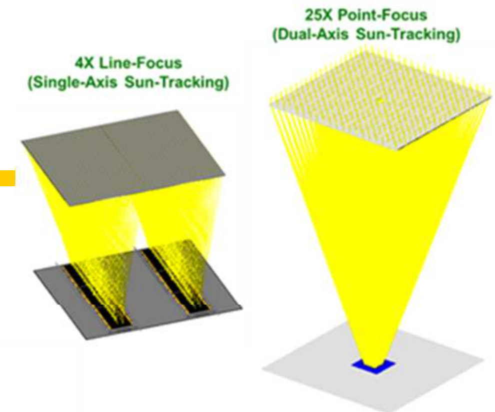
The Mesh Lenses Produced Are the Lightest Lenses We Have Ever Made:

The Average Mass of the Mesh Lenses Produced in a Pilot Run with 100% Yield Was 1.1 gram for a Lens with an Aperture Area of 10 cm x 10 cm

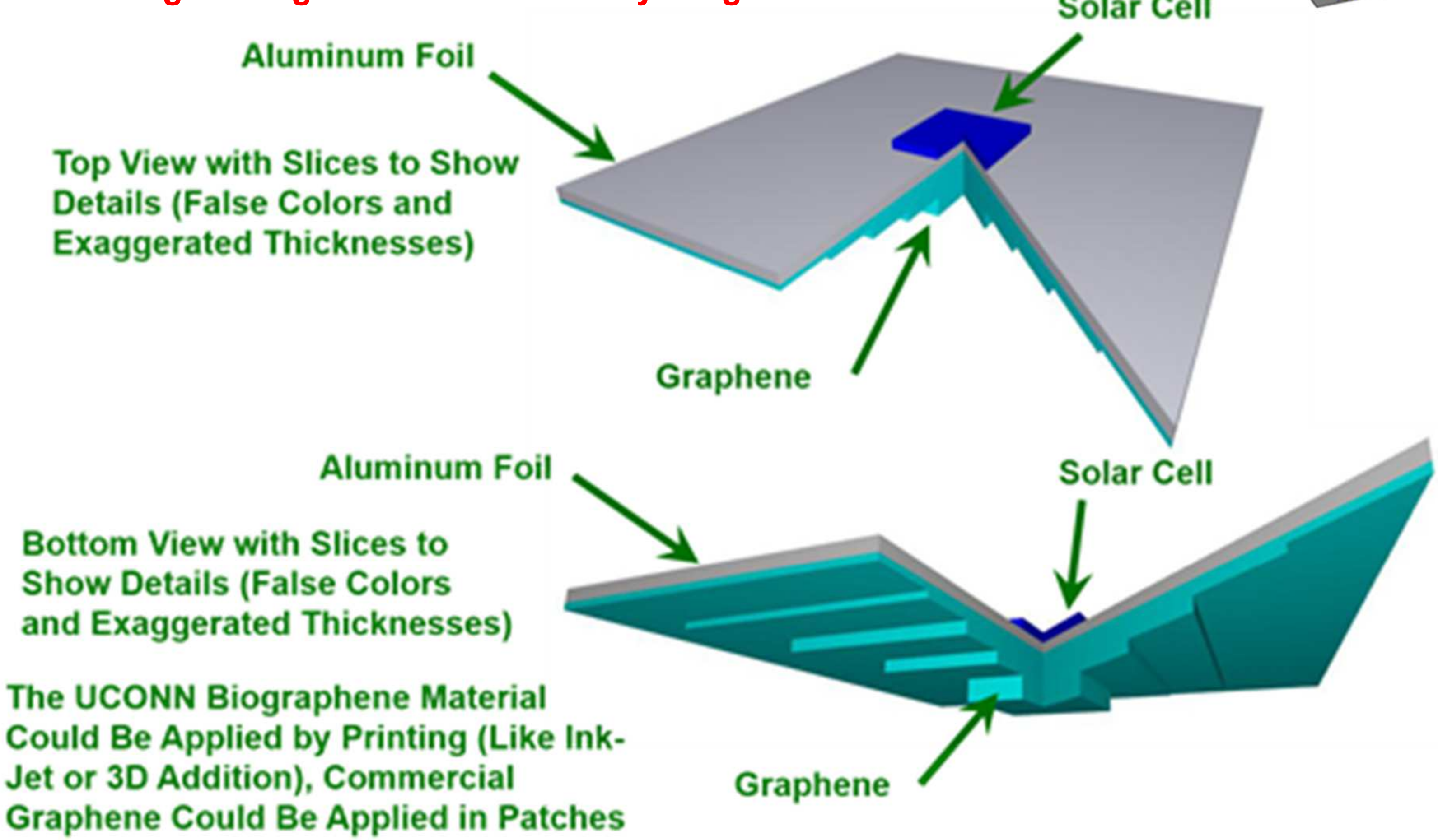




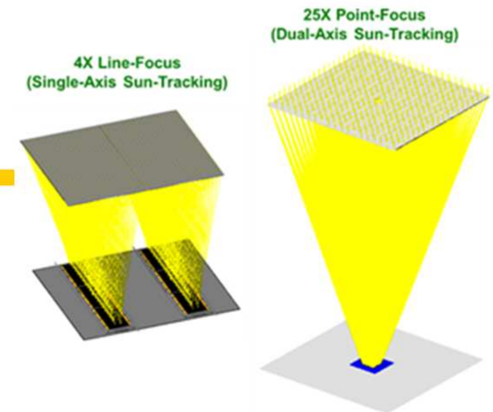
Crude Schematic of Graphene Tapering Concept

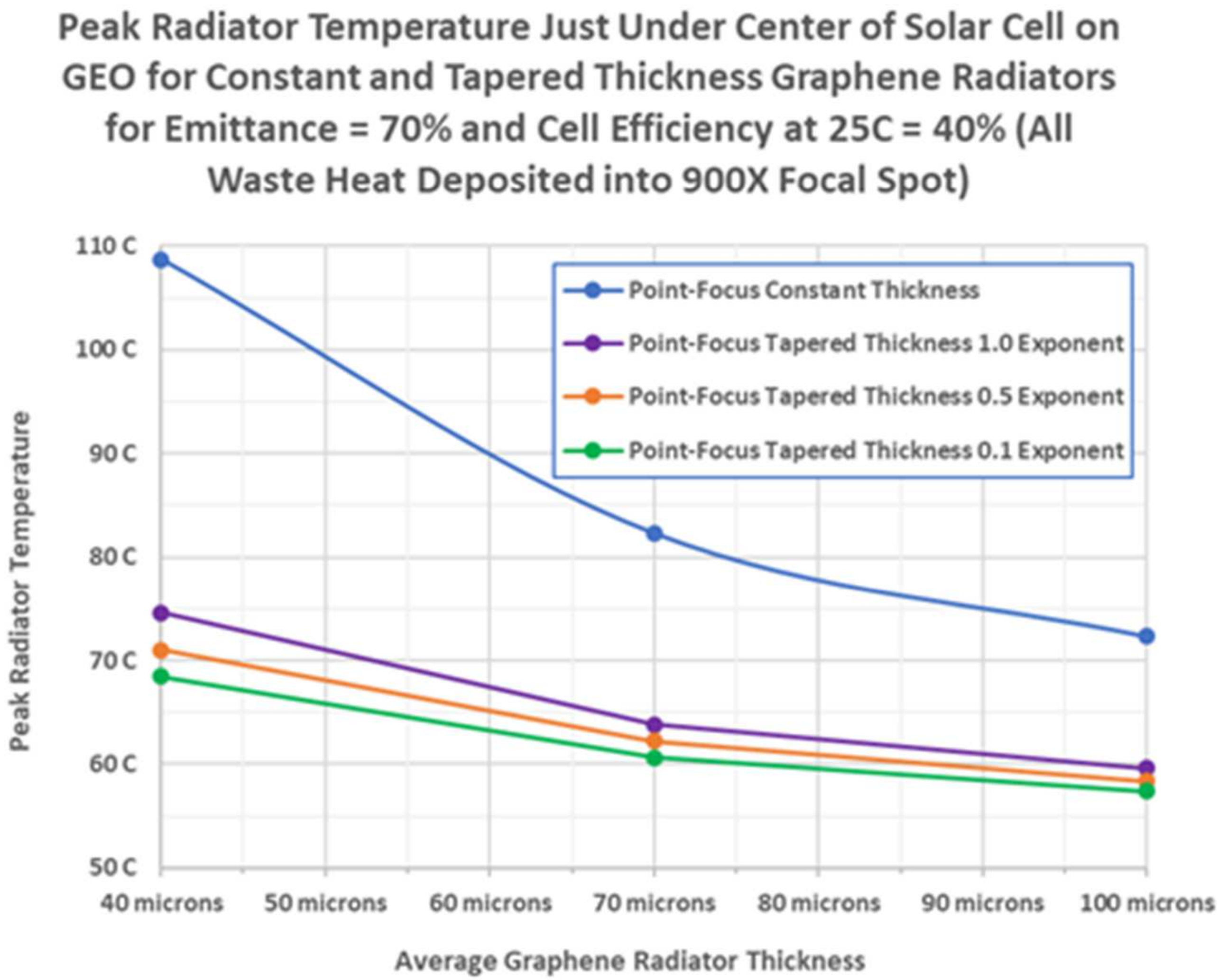


The total mass of a 10 cm x 10 cm radiator using 25 μ aluminum foil, 40 μ average thickness graphene, and a 25 μ emittance-enhancing coating on both sides is only 2.1 grams



Thermal Performance of Tapered Versus Constant Thickness Graphene Radiators on GEO

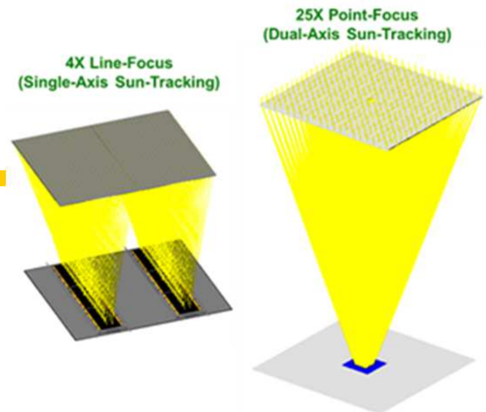




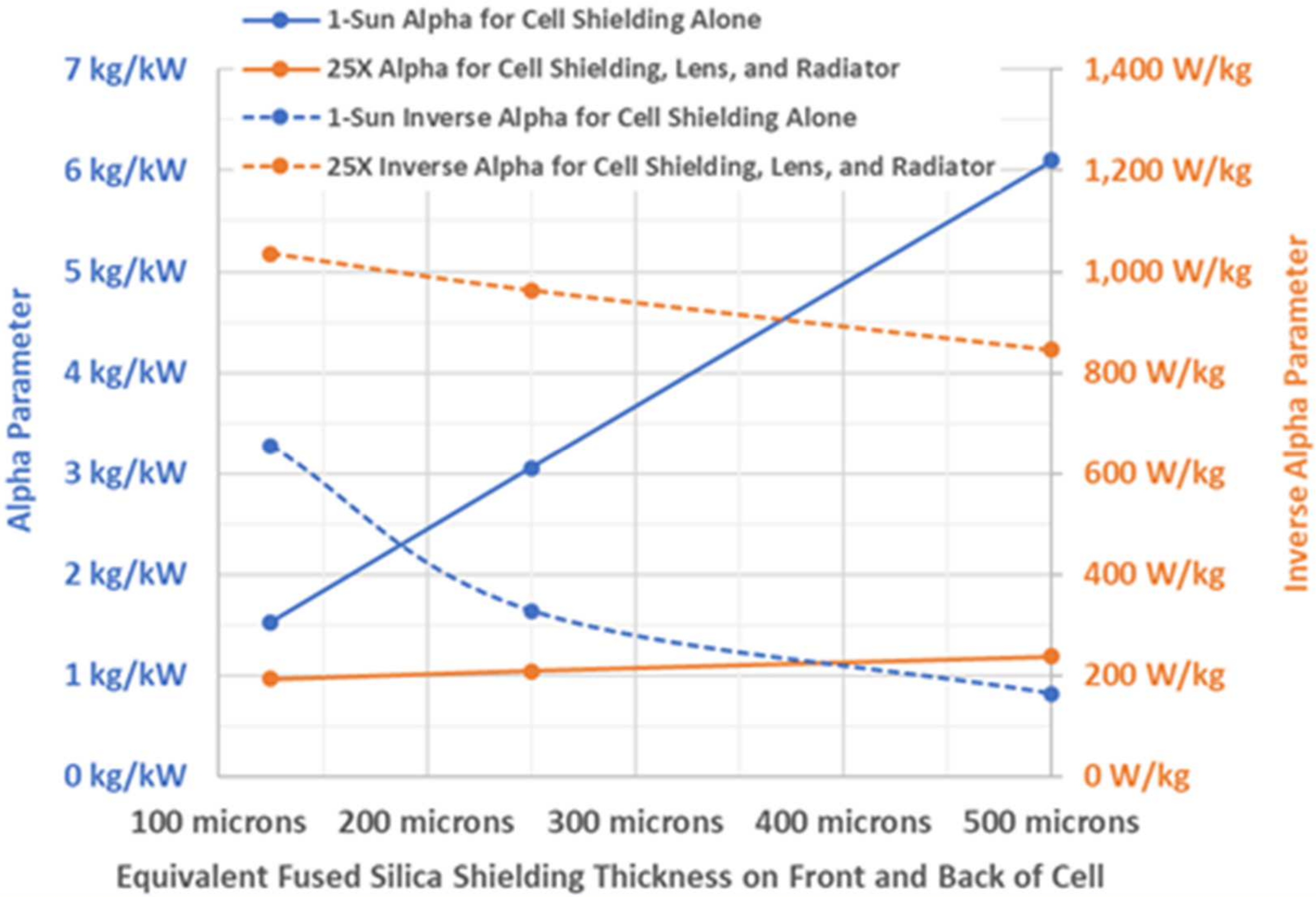
A Tapered Graphene Radiator of 40 μ Average Thickness Performs as Well as a 100 μ Constant Thickness Graphene Radiator, While Saving 60% of the Graphene Mass

The Different Exponents Apply to Differing Taper Profiles, Showing Very Little Difference

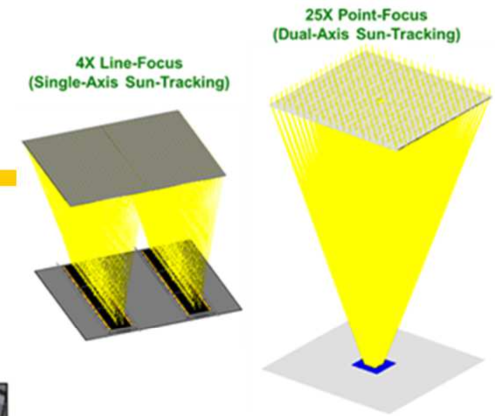
Alpha, in kg/kW, and Specific Power (Inverse Alpha) Parameters for Key Elements (Lens + Cell Package + Radiator) of 25X Concentrator vs. One-Sun Cells



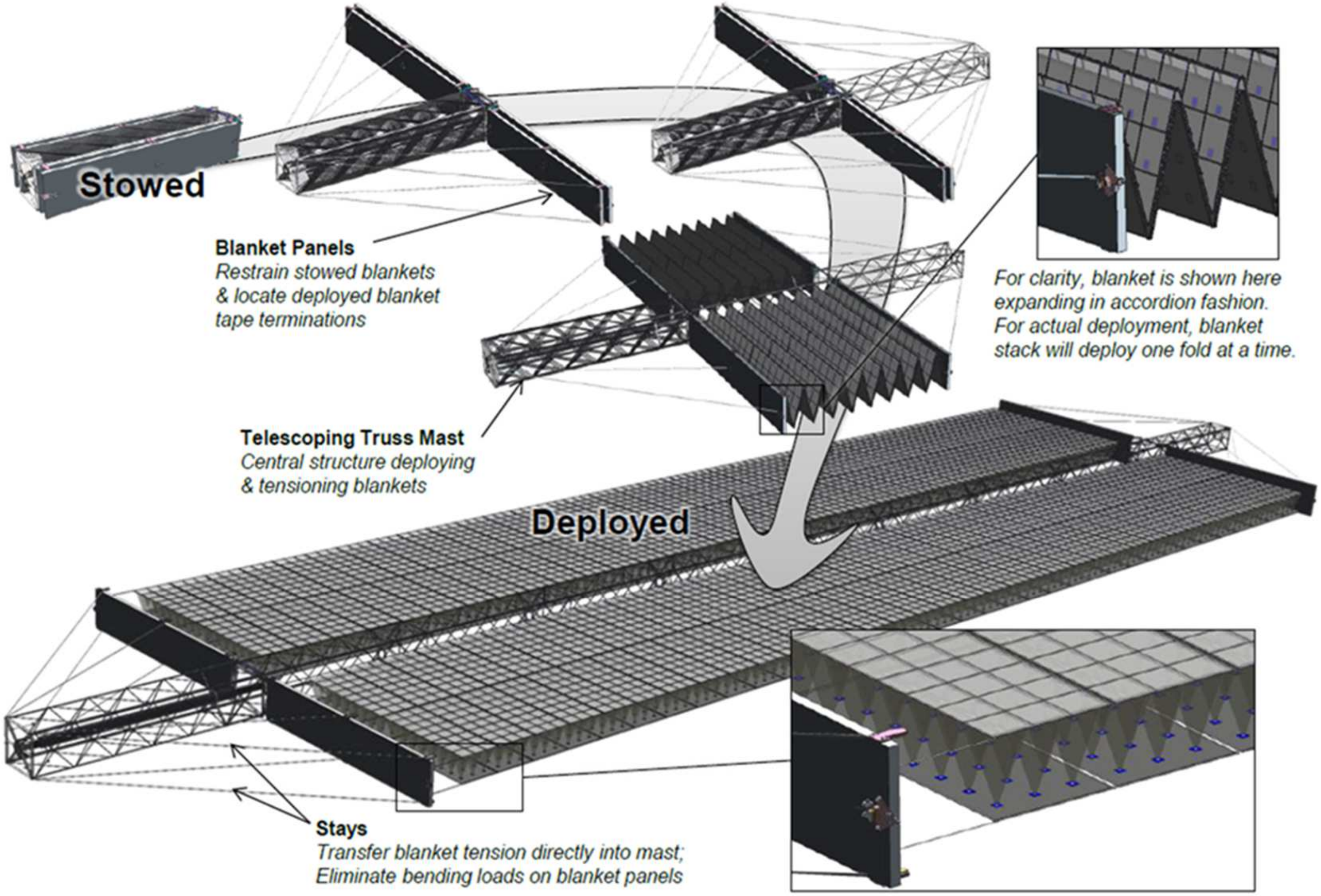
For Significant Cell Shielding (e.g., 300 microns equivalent fused silica), the 25X Concentrator Provides >3X Better Specific Power than a One-Sun Cell



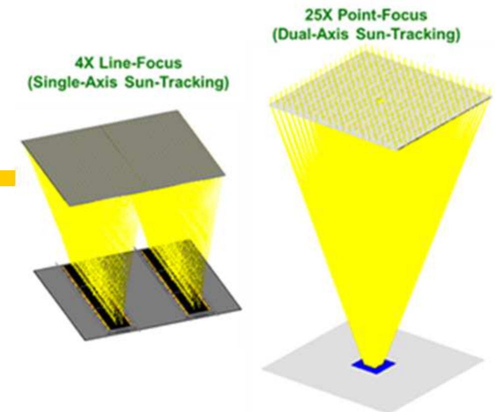
25X Point-Focus Concentrators on Compact Telescoping Array Platform for NASA's Extreme Environment Solar Power (EESP) Deep Space Missions



Source: M. McEachen et. al., "Point-Focus Concentration Compact Telescoping Array," Extreme Environments Solar Power Base Phase Final Report, Orbital ATK, Dec. 2017, NASA/CR-2017-219712.



Cost and Performance Metrics of Point-Focus Concentrators on Compact Telescoping Array



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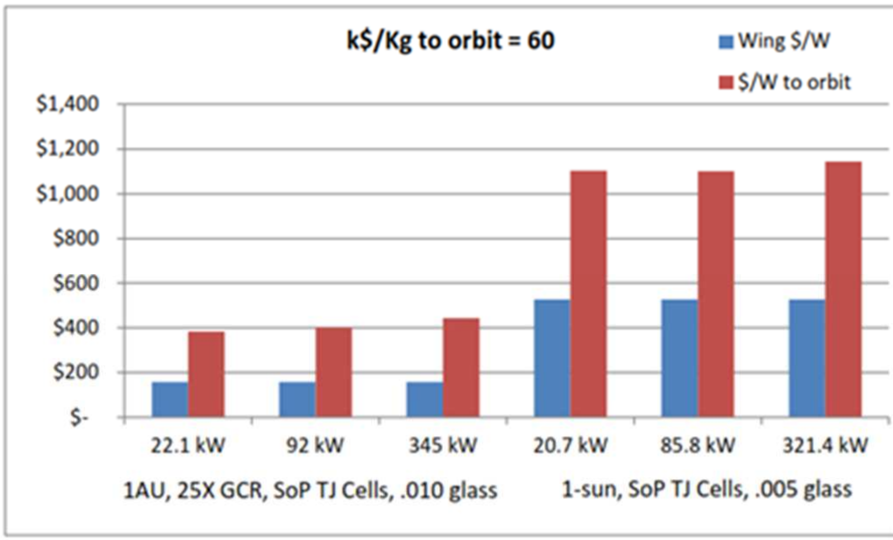
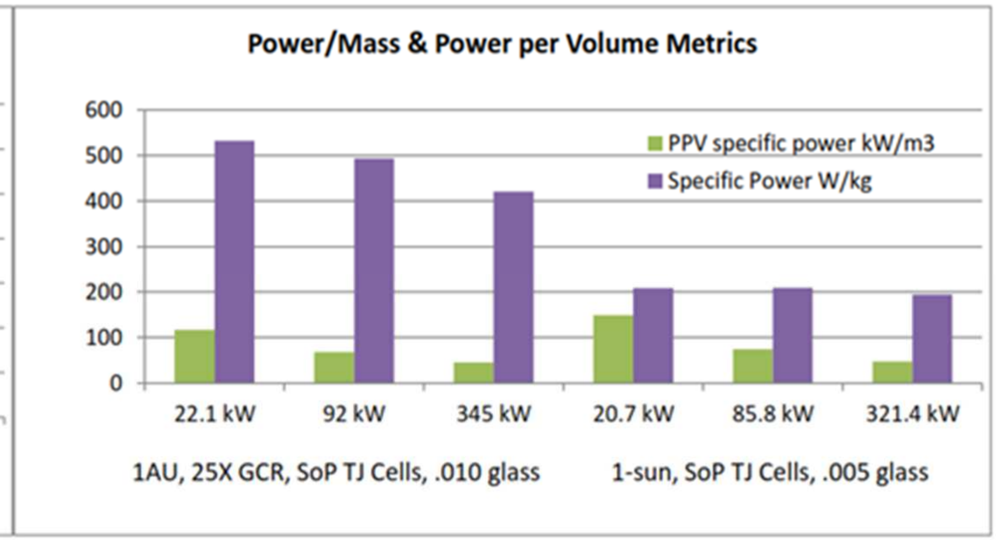
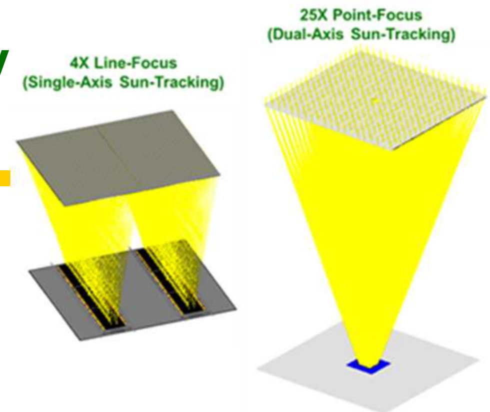


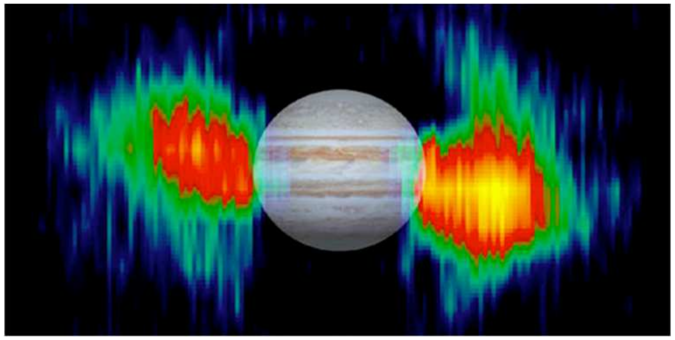


The Concentrator Saves More than 50% in Cost/Watt and Provides More than 2X Better Specific Power Even with Twice the Cell Shielding

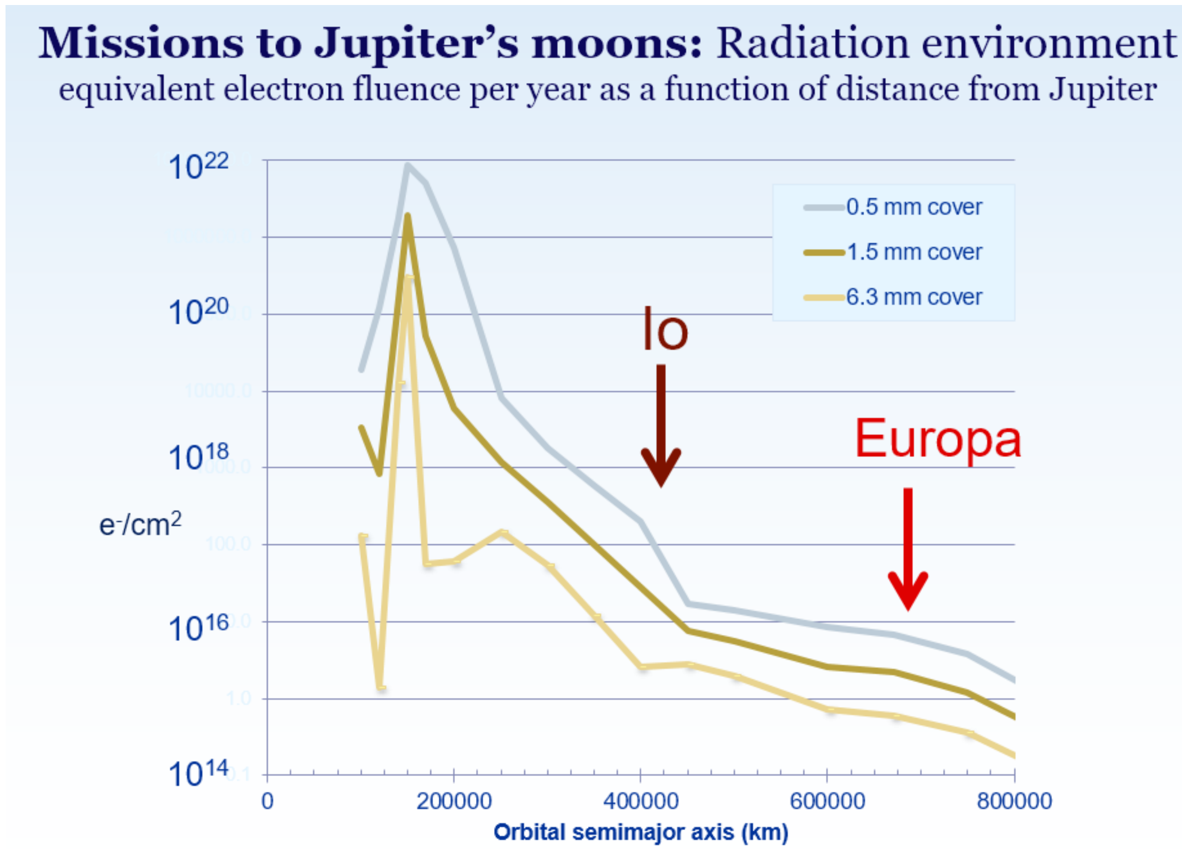
Previous NASA Studies* Have Shown the Major Benefits of PV Concentrators Over One-Sun Cells for Missions to Jupiter



Jupiter's Radiation Belts



Radiation Shielding Mass for a 25X Concentrator Cell Is 96% Less than for a One-Sun Cell

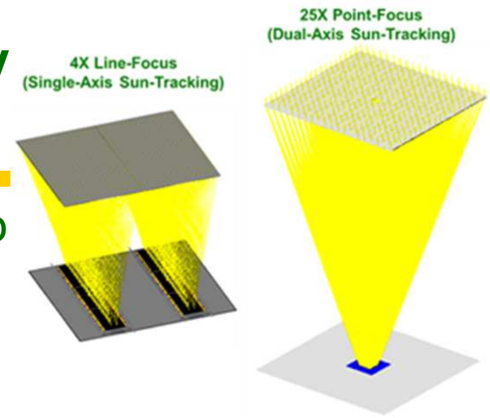


Equivalent fluence at Europa Orbit

Shielding (coverglass) thickness	Fluence (e^-/cm^2 per year)	P/P_o
0.25 mm	20.0 10^{15}	*
0.5 mm	9.0 10^{15}	0.67
1.5 mm	3.6 10^{15}	0.76
6.3 mm	1.3 10^{15}	0.84

Assumptions: 0º inclination, semimajor axis= 671100 km (Europa distance); P_{max} DENI fluence, triple-junction cell (electron/proton damage ratio=612 for P_{max}).

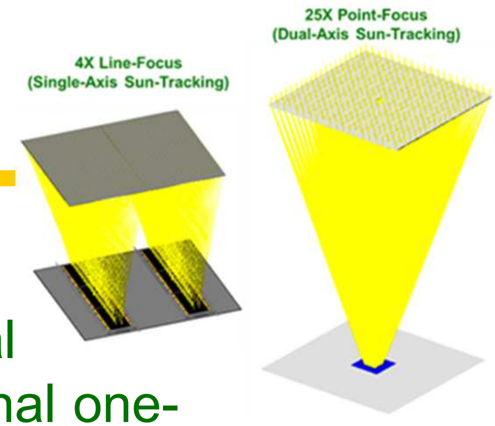
Previous NASA Studies* Have Shown the Major Benefits of PV Concentrators Over One-Sun Cells for Missions to Jupiter



- Intensity of 1 sun (AM0) on the cells requires concentration ratio 25-30
  - Easily achieved by Fresnel lens concentration systems
- One sun (AM0) intensity at the cell avoids the reduction in efficiency at low intensity and the LILT effect.
- Advanced concentrator systems reduce weight
- Concentrator systems reduce cost
  - At Jupiter intensity, array cost is 25 times higher per Watt
- Concentrator systems have improved radiation tolerance
  - Thick glass cover on the photovoltaic element, with low effect on mass
- Incorporating intensity, LILT, and radiation, NASA calculation suggests concentrator systems have ~50% higher end-of-life power for 1-year mission at Europa
  - Greater improvement for longer mission lifetime
  - Greater improvement for mission further into the radiation belts (e.g., Io)

***Geoffrey Landis and James Fincannon, “Study of Power Options for Jupiter and Outer Planet Missions,” 42nd IEEE Photovoltaic Specialists Conference, 2015, New Orleans.**
***Geoffrey Landis et al., “Photovoltaic Power for Jupiter and Beyond,” Space Photovoltaic Research & Technology 2016, Brook Park OH, Sept. 20-22, 2016.**

Conclusions



- The latest concentrator technology provides substantial benefits in both cost and mass compared to conventional one-sun arrays
- The latest lens manufacturing approach enables ultra-light lens mass production at high yield and low cost
- For single-axis sun-tracking applications such as solar electric propulsion (SEP) tugs to carry cargo from earth orbit to the lunar neighborhood, a 4X line-focus version is the best fit
- For dual-axis sun-tracking applications such as missions to the Jupiter neighborhood, a 25X point-focus version is the best fit