Cryogenic Selective Surfaces

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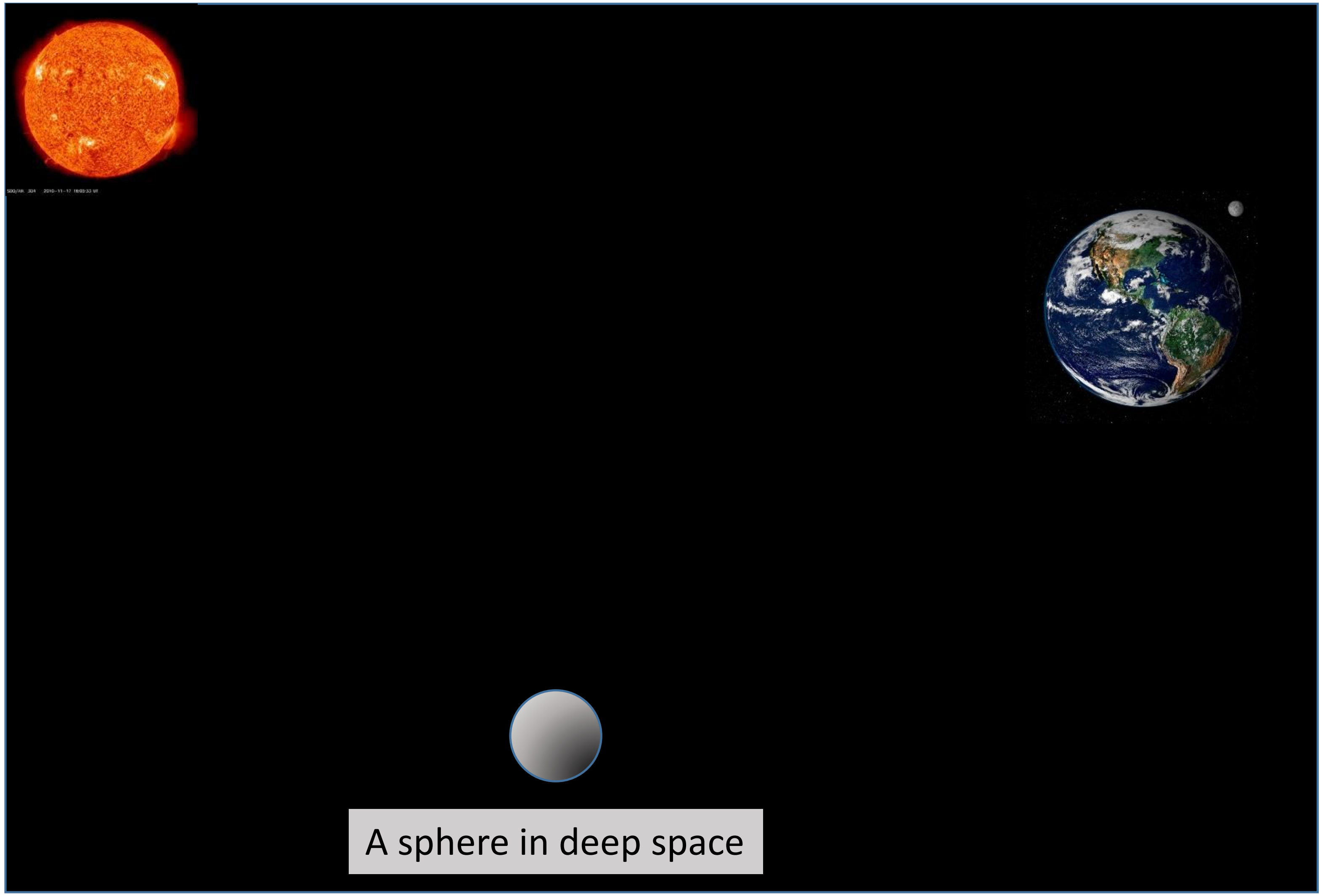

If we place a sphere in deep space at 1 AU from the sun, what will it's temperature be, assuming it absorbs radiation from the sun and emits infrared radiation in all directions?

Our goal is to find a way to make this sphere as cold as possible.

Hopefully, we can get cold enough to store liquid oxygen or operate superconductors.

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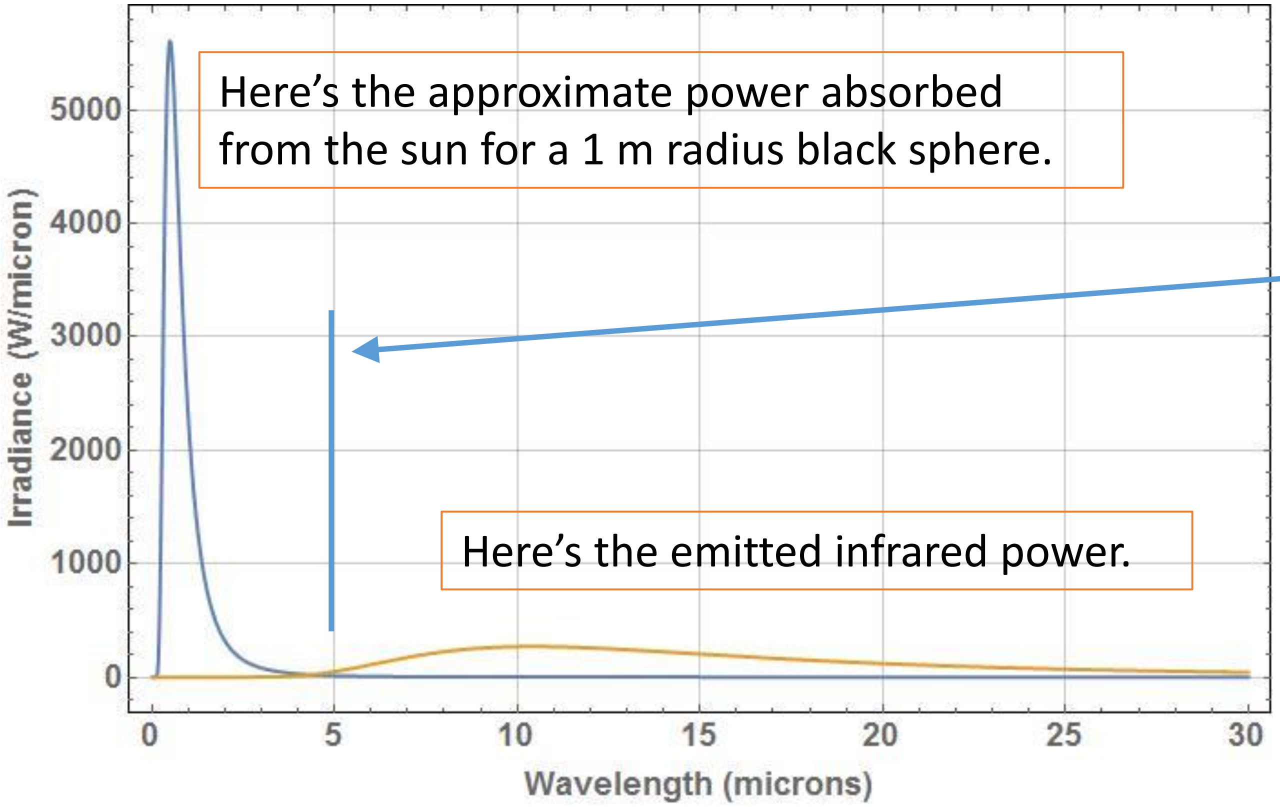
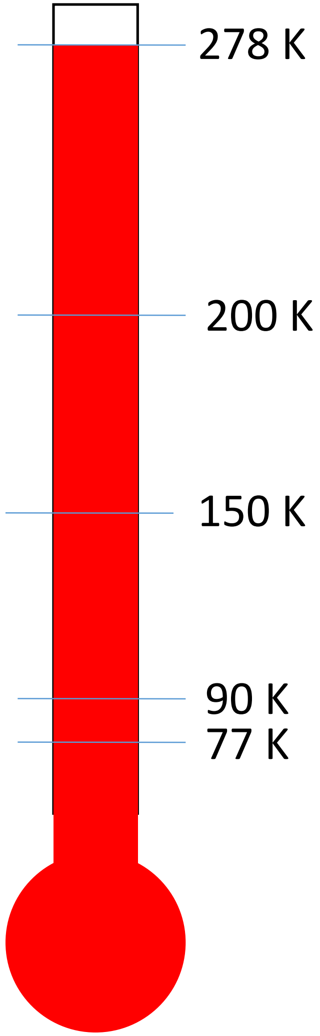
If the sphere is black, or grey, it will reach a temperature of about 278 K, 41 °F, where the solar power absorbed equals the infrared power emitted.



Here's the approximate power absorbed from the sun for a 1 m radius black sphere.

Here's the emitted infrared power.

Hibbard pointed out in 1961 that if a coating could be created that reflected all of the sun's energy below some critical wavelength, but allowed infrared emission above that wavelength that cryogenic temperatures could be reached. (5 microns corresponds to about 77 K).



A selective surface has a wavelength dependent emissivity. A Hibbard selective surface is an idealized case where the emissivity takes on only the values 0 and 1.

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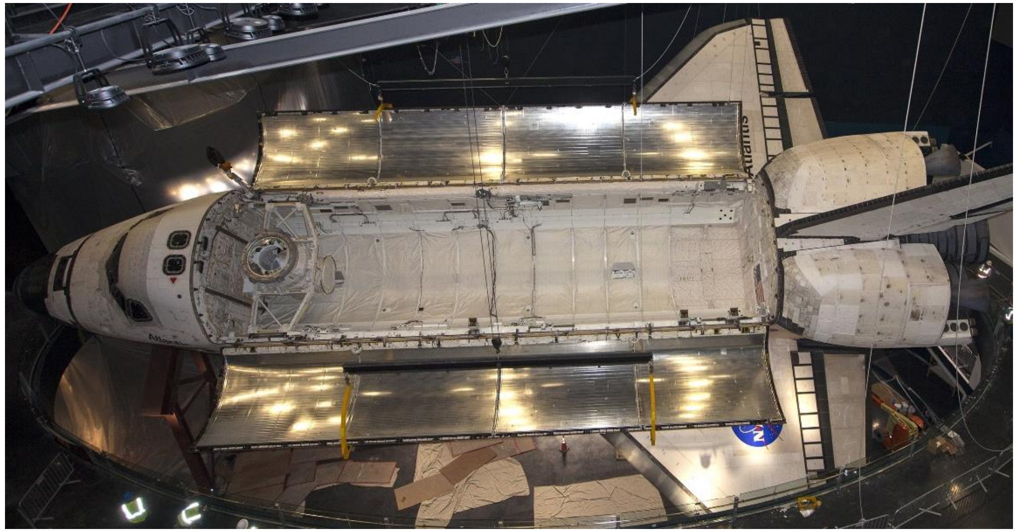
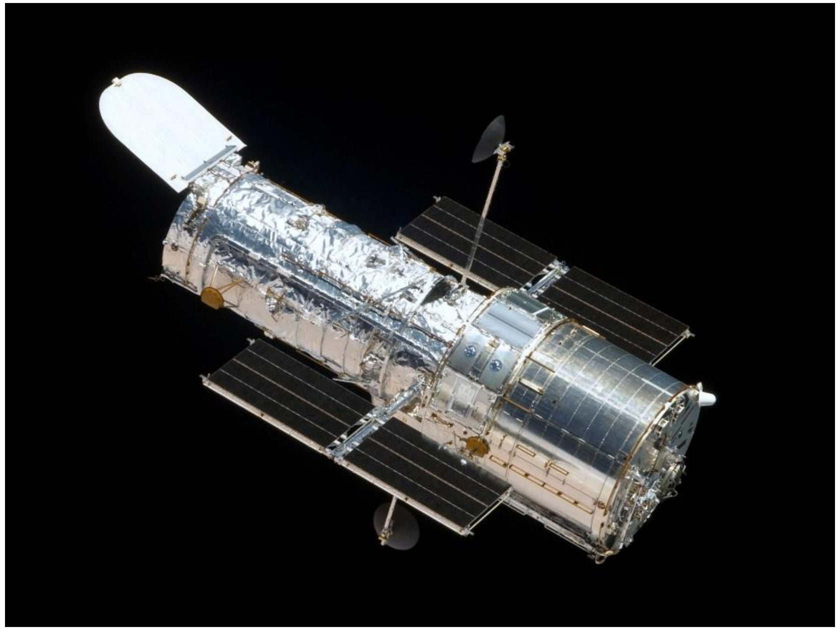
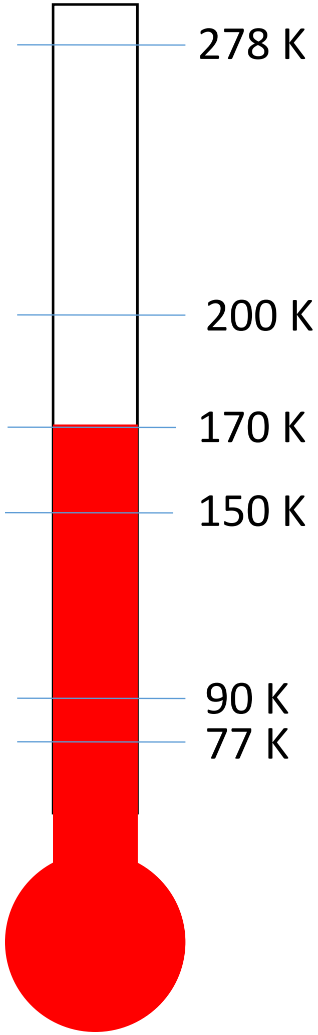
Two existing approximations to Hibbard’s ideal material are second surface mirrors and white paint. The Orbiter and the Hubble Telescope use second surface mirrors to reject waste heat.







These second surface mirrors are not ideal and absorb about 10% of the sun’s energy. If we place them on our sphere its temperature will drop to about 170 K. Cold, but not cold enough.

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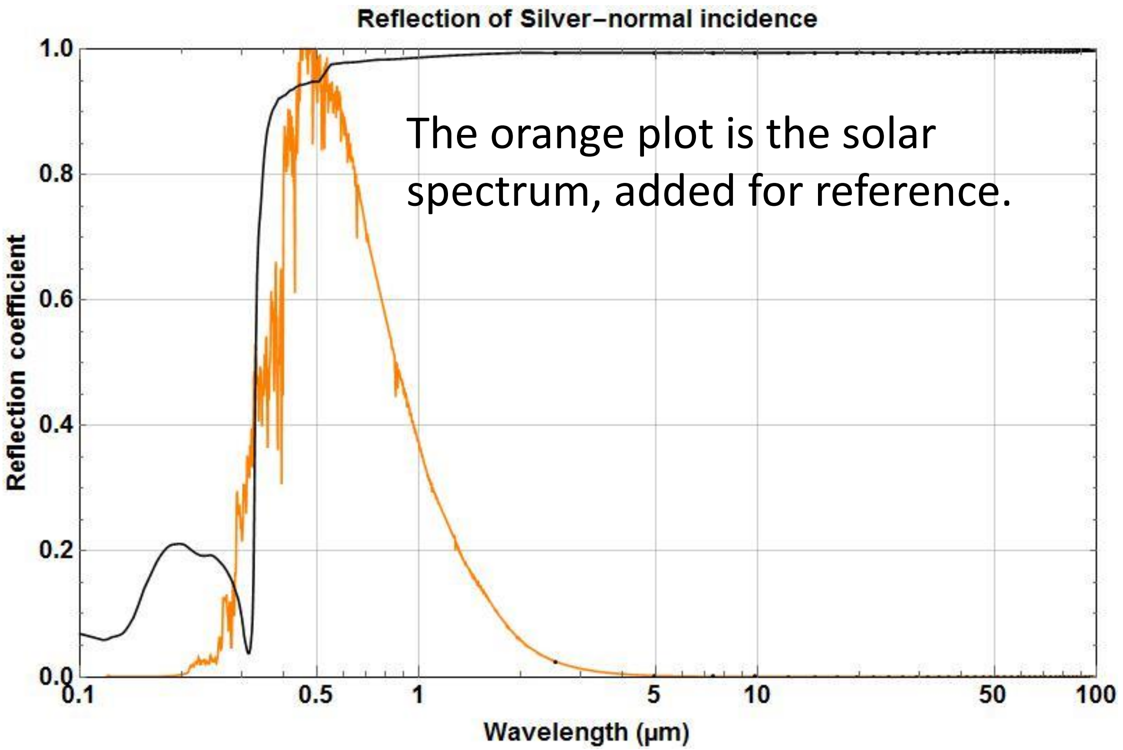
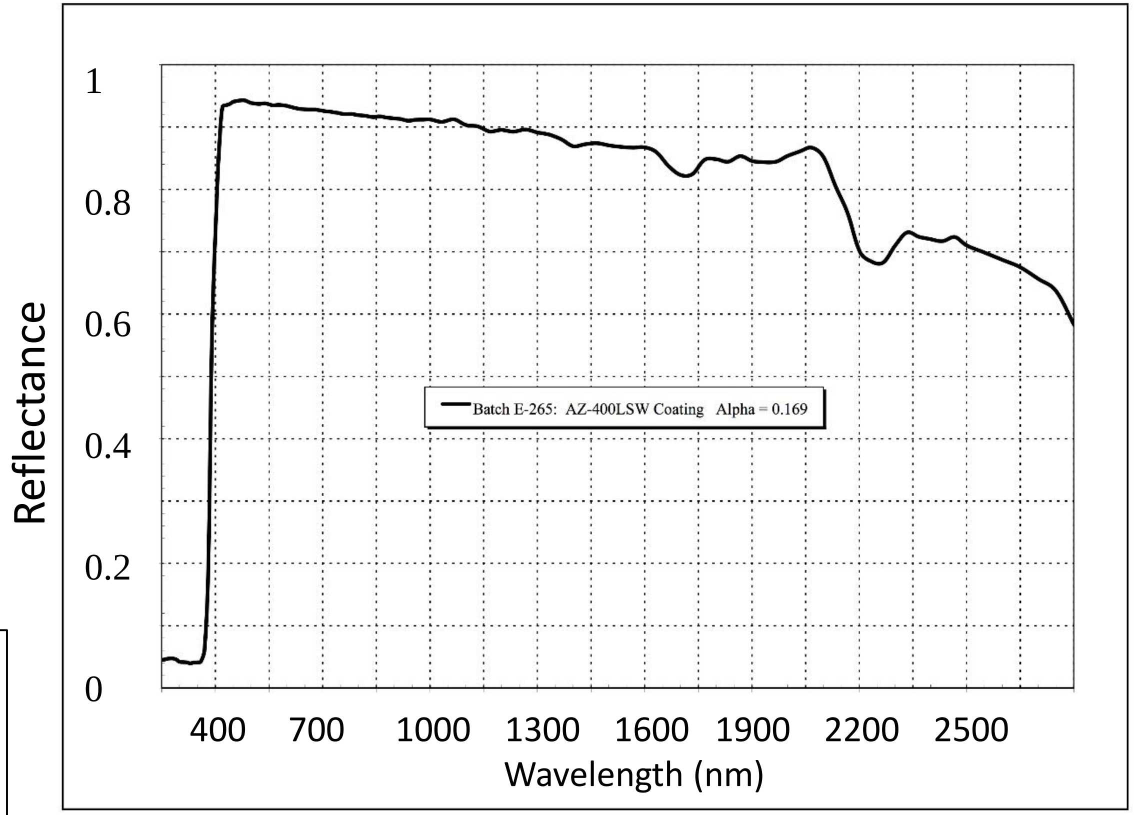


The orange plot is the solar spectrum, added for reference.

Total Hemispherical Spectral Reflectance for AZ-400-LSW White Silicone Semi-flat Marker Coating



Both second surface mirrors and white paint absorb substantial ultraviolet radiation as well as mid-IR radiation. We cannot get cold with either of these.
We need a new idea.

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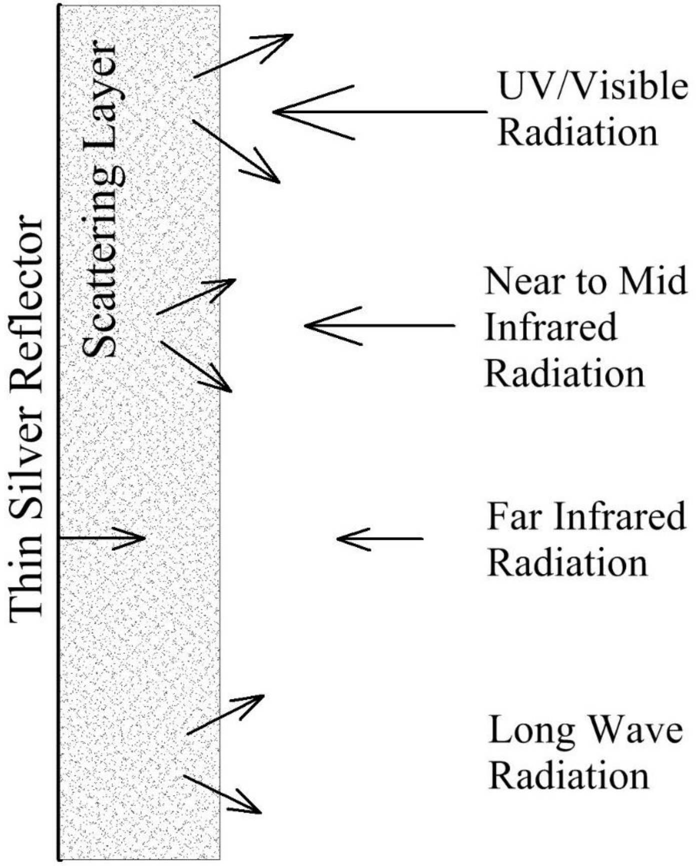
Consider the following “best of all approaches” design.



First, chose a material that absorbs essentially no radiation from 0.2 microns to the mid or far infrared range, e.g. MgF2, CaF2, BaF2, KBr, NaCl, etc.

Second, grind this material into 200-300 nm diameter particles and make a 3-10 mm layer of this powder. This layer will scatter UV, visible, and near infrared light effectively, but not longer wave radiation.

Third, place this layer on a metallic reflector (e.g. silver) to reflect the longer wave radiation that gets through the particle layer.

The coating will emit long wave radiation beyond its transparency cut-off.

We call this new coating, “Solar White”, because it is white to most of the solar spectrum.

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Titanium Dioxide Powder-0.25 micron transparent particles used to make things white, including paint, cottage cheese, skim milk, toothpaste, some cheeses and ice creams, etc. .

Before continuing, let’s do a quick test. The paint industry uses TiO2 particles to scatter visible radiation, allowing “items” to look white. Let’s put 6 mm of TiO2 powder into a 1 inch diameter cell and hold it in place with two glass windows, as shown below.

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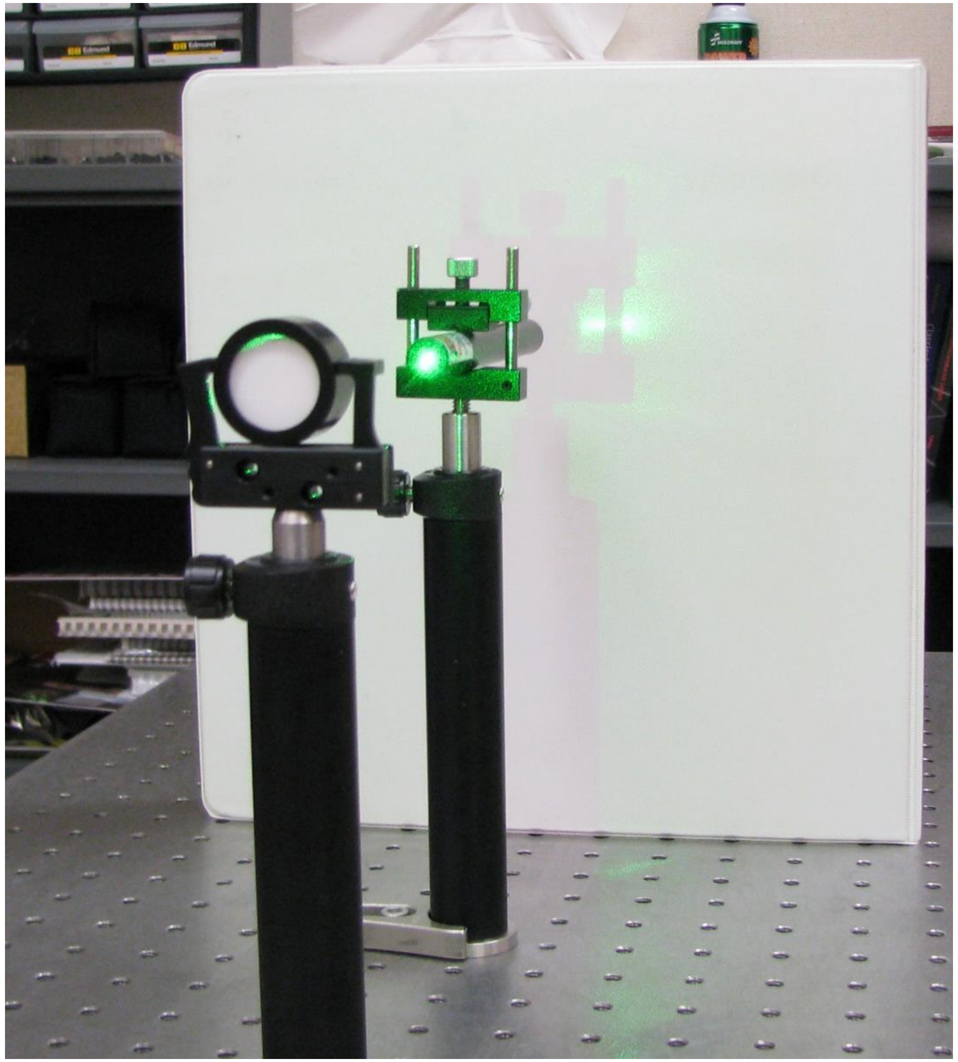
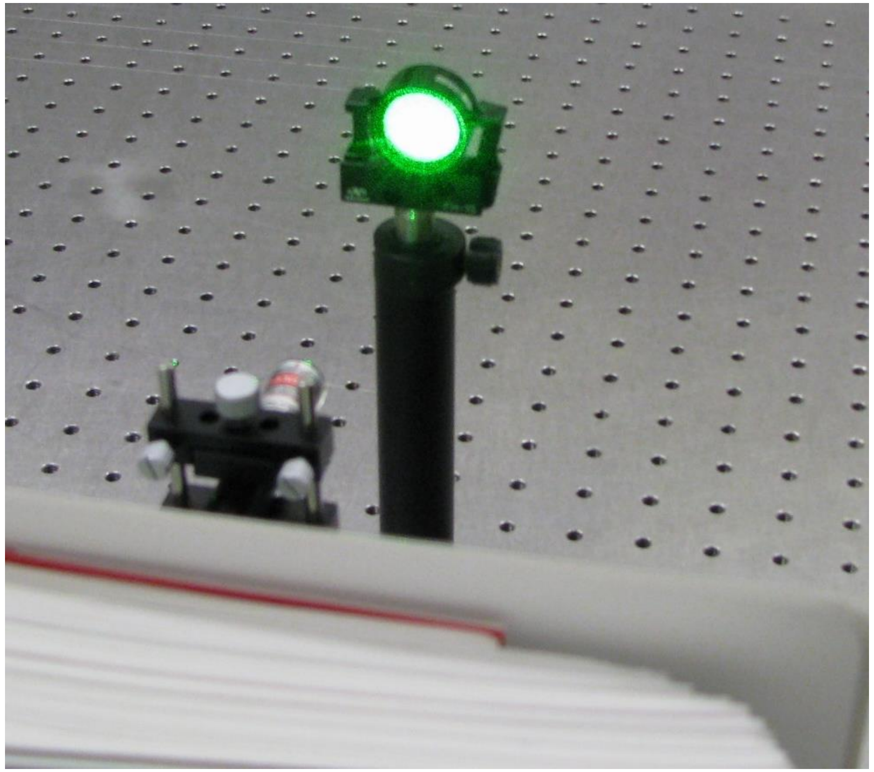


If we launch a 5 mW green laser at this layer essentially no light gets through, most being scattered backward.



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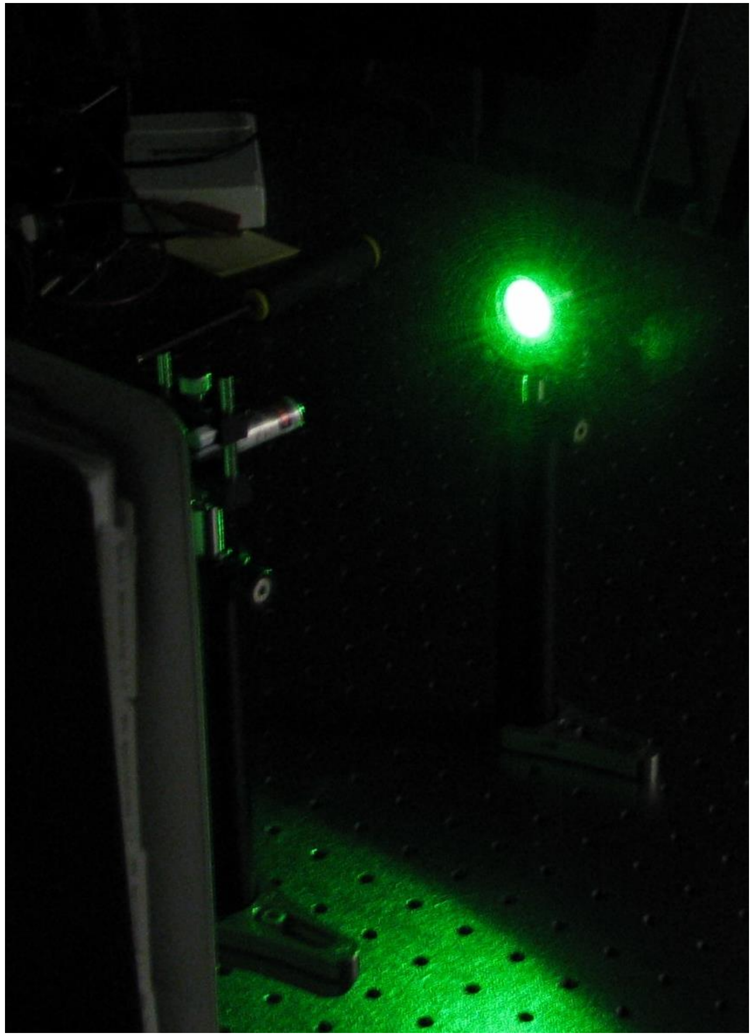
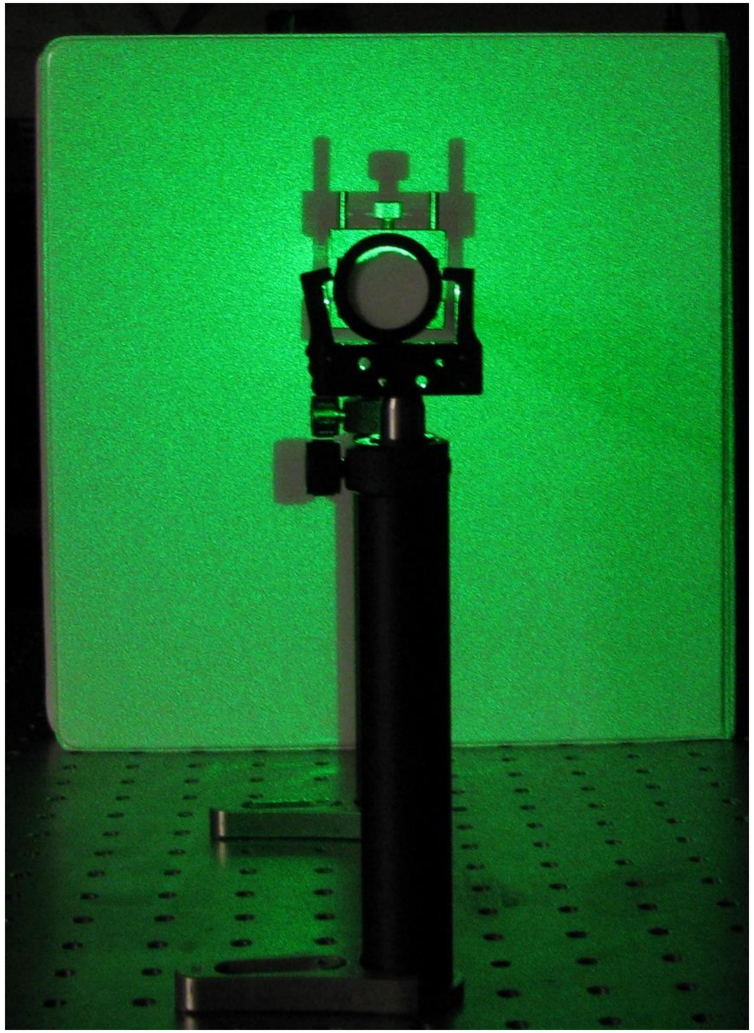
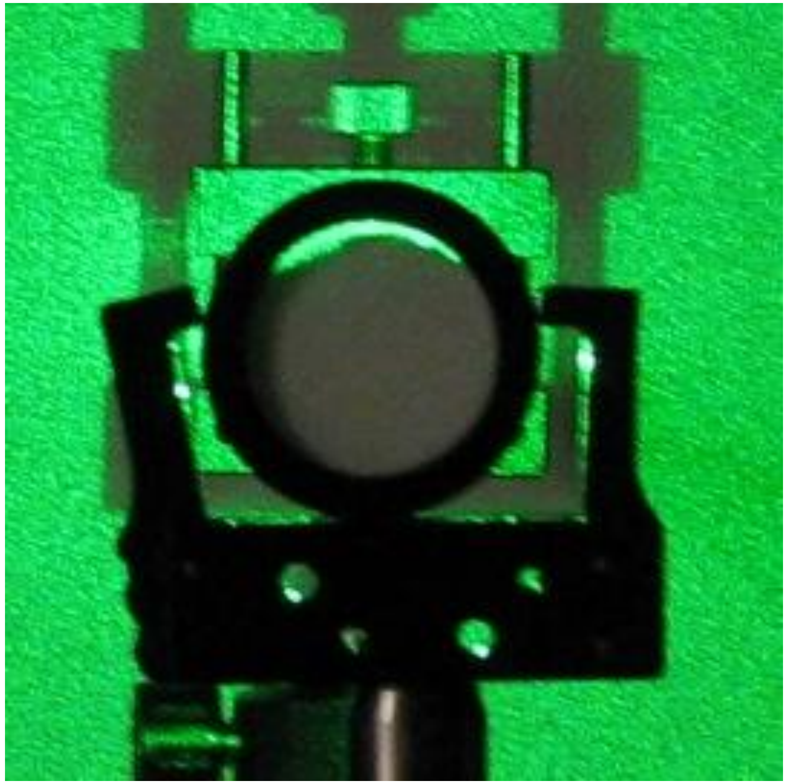




This is even more apparent if we turn out the lights.



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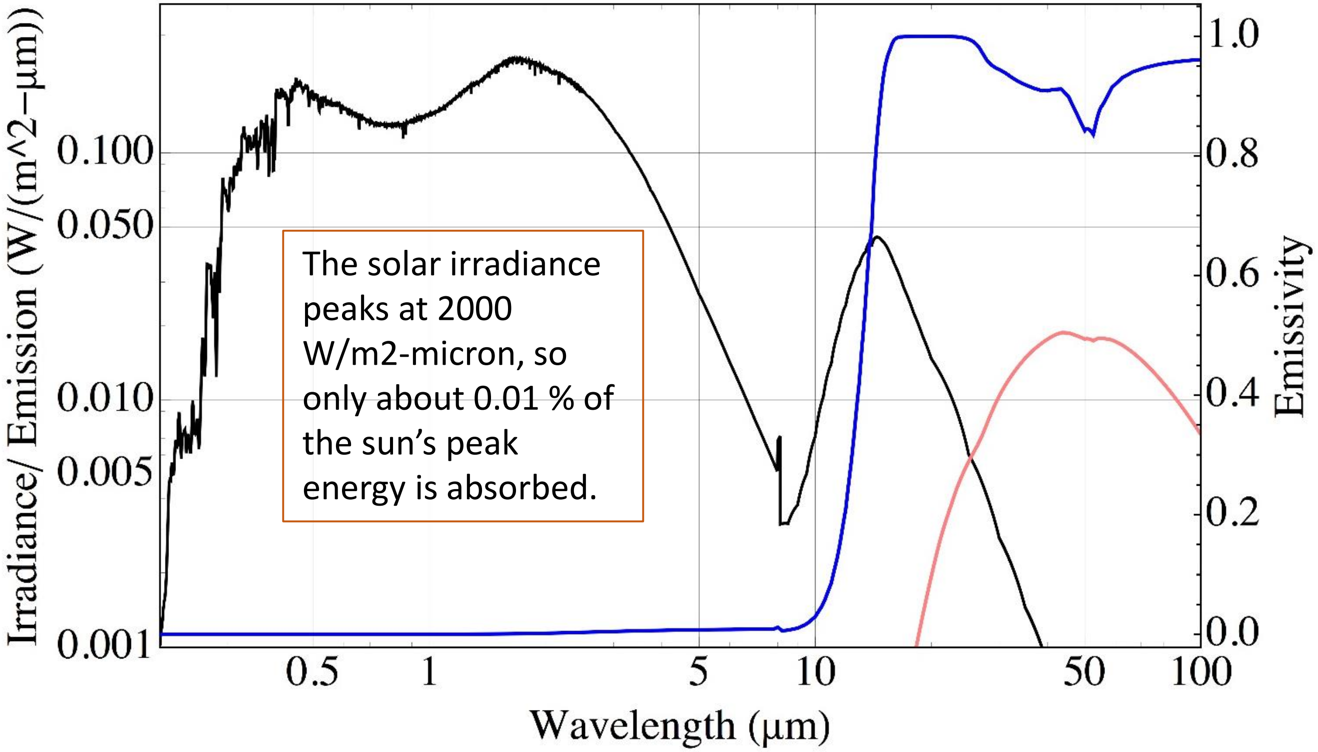
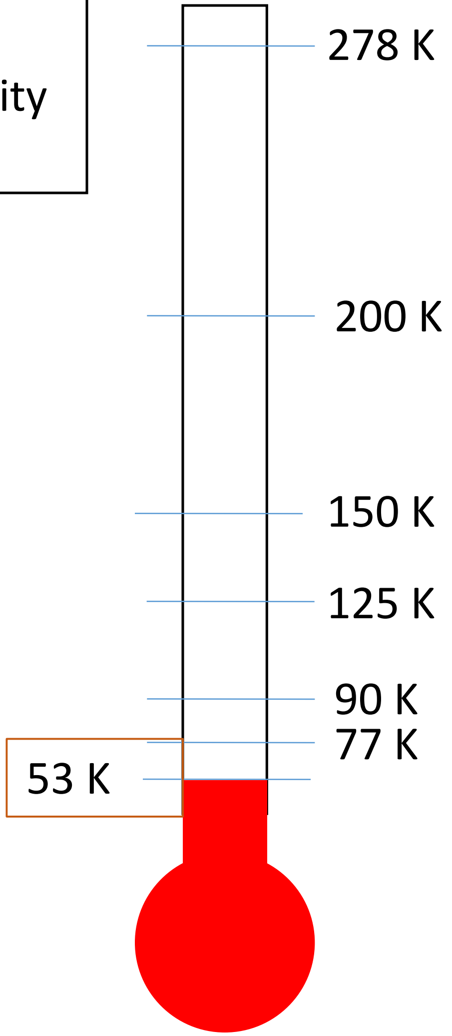
We developed models—identical to published paint theory models—and coupled these to Mie scattering models, to predict the performance of our new coating.
The plots below show the solar absorbed spectrum, the emitted power spectrum, and the emissivity for a 5 mm thick layer of BaF2 on silver on a flat plate facing the sun, coated on both sides.



The solar irradiance peaks at 2000 W/m2-micron, so only about 0.01 % of the sun's peak energy is absorbed.

A 1 m radius sphere would only absorb about 3.5 Watts of the 4300 Watts of solar power hitting it and would reach a predicted temperature of about 53 K !!



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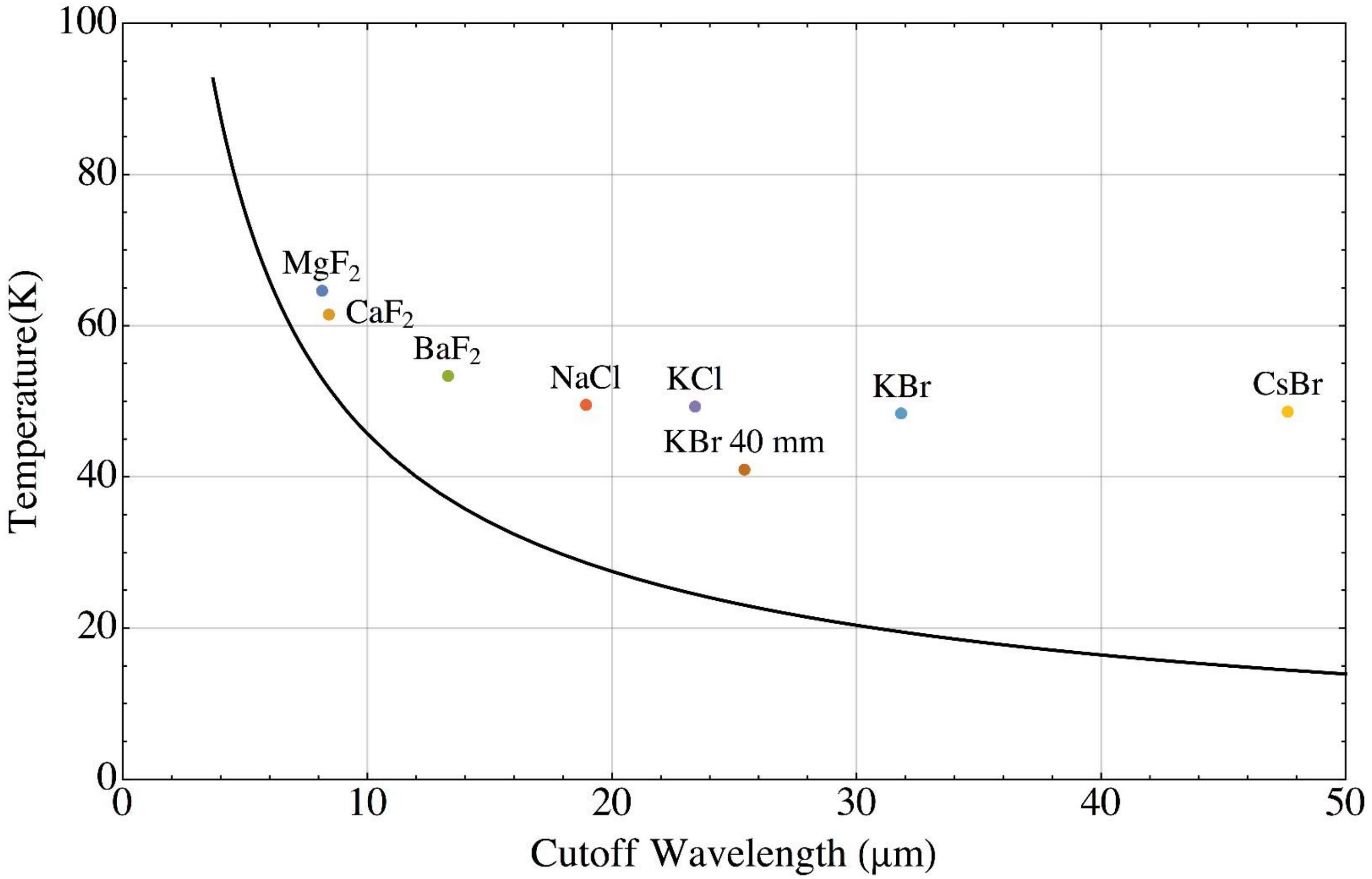
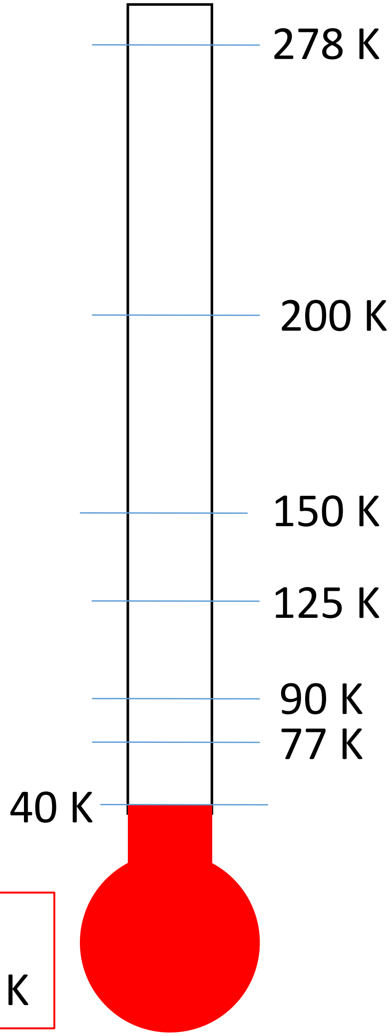
How close are we to the Ideal Hibbard Selective Surface?



For a Hibbard Selective Surface, light below the cutoff wavelength is perfectly reflected and above it is completely absorbed.

We modeled 5 mm coatings on silver on our 1 m radius sphere for seven materials used as broadband spectroscopy windows.

The predicted temperatures, compared to that achieved by a Hibbard selective surface are shown to the left.



The freezing point of LOX is about 50 K

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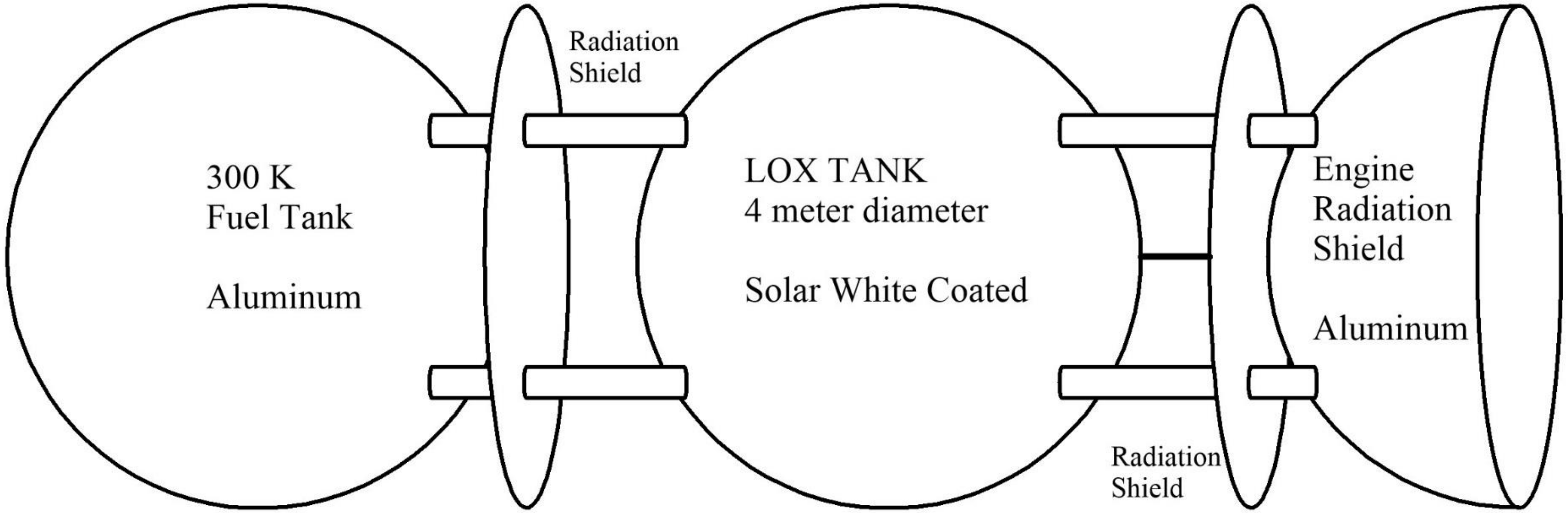
Our Mission goal was to determine if Solar White could allow LOX to be carried on a Mars Mission.



Here is a possible configuration where a LOX tank is located between a warm fuel tank and warm engine/nozzle.

Solar White does not effectively reflect long wave infrared radiation, so radiation shields are needed to block that radiation from the warm portions of the vehicle and from nearby planets, such as the Earth.

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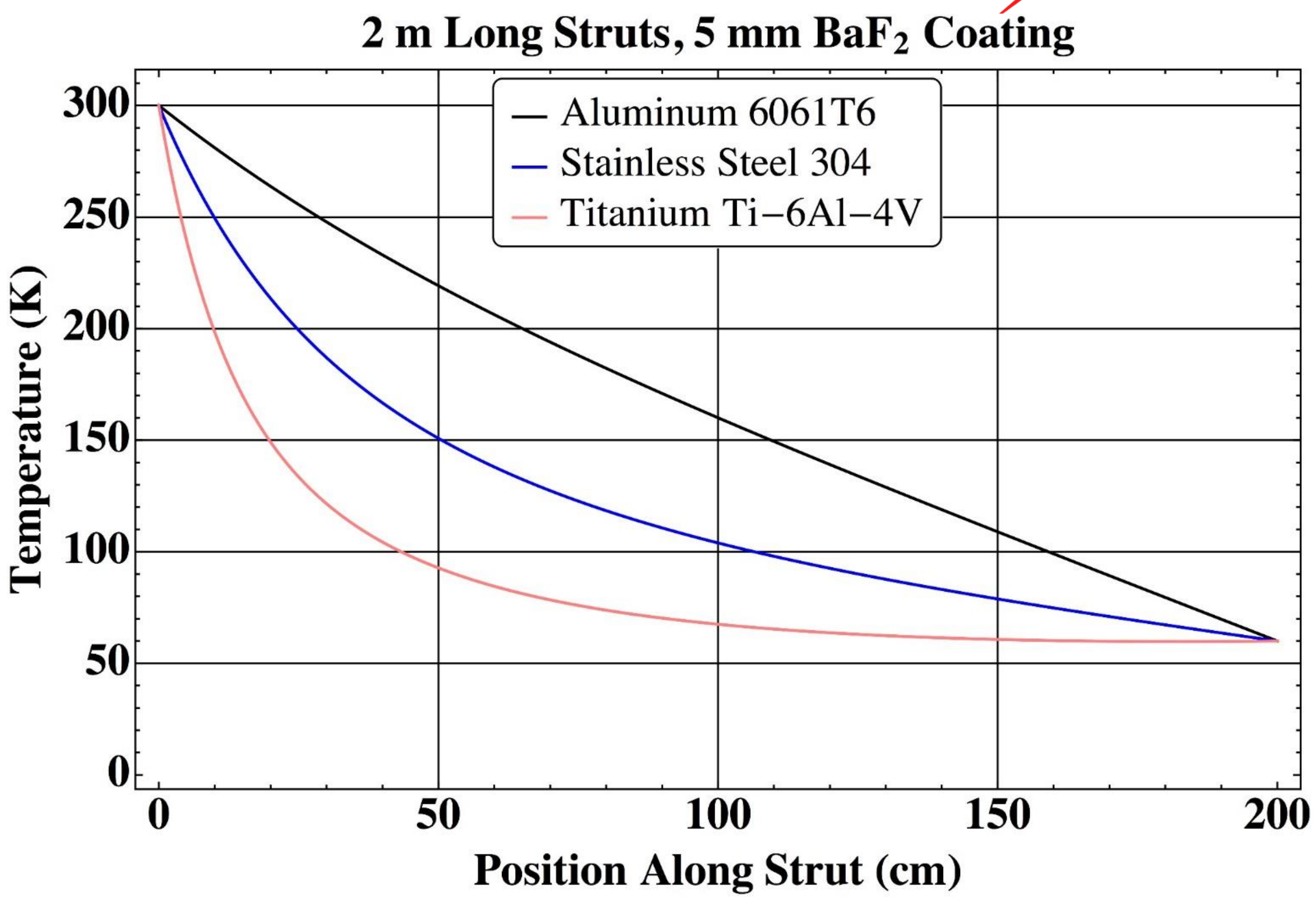
Heat can also reach the LOX tank by conduction along support struts.

Assume a strut is coated with Solar White and is in full sunlight, attached to a 300 K object on one end and a 60 K object on the other end.

The temperature along the strut is calculated for three different metals, showing that substantial heat will be carried to the LOX tank for aluminum struts, but that for titanium struts a small amount of heat will be pulled away from the LOX tank.



Struts are hollow cylinders 2 m long, 0.25 m OD, wall thickness 8.2 mm for Al, 7.1 mm for stainless, and 2.4 mm for titanium (220 kN per strut, 1.4 safety margin).

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Mission Goal: To transport LOX to Mars

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Power Budget with radiation shields for a 5 mm BaF2 Solar White Coating

Solar Irradiance	13.5 Watts
IR Load from the shields	10 Watts
Struts	0 Watts
Fuel line	3 Watts
Total	**26.5 Watts (63 K)**

On a trip to Mars via Venus the total heat load can rise to about 54 Watts (70 K).

Planetary infrared radiation can raise these values.
Using a thicker coating or switching to KBr can lower these values.

Our “simplistic” analysis has demonstrated that not only can LOX be taken to Mars by using Solar White, there is a possibility that the LOX will freeze at distances far from the sun.

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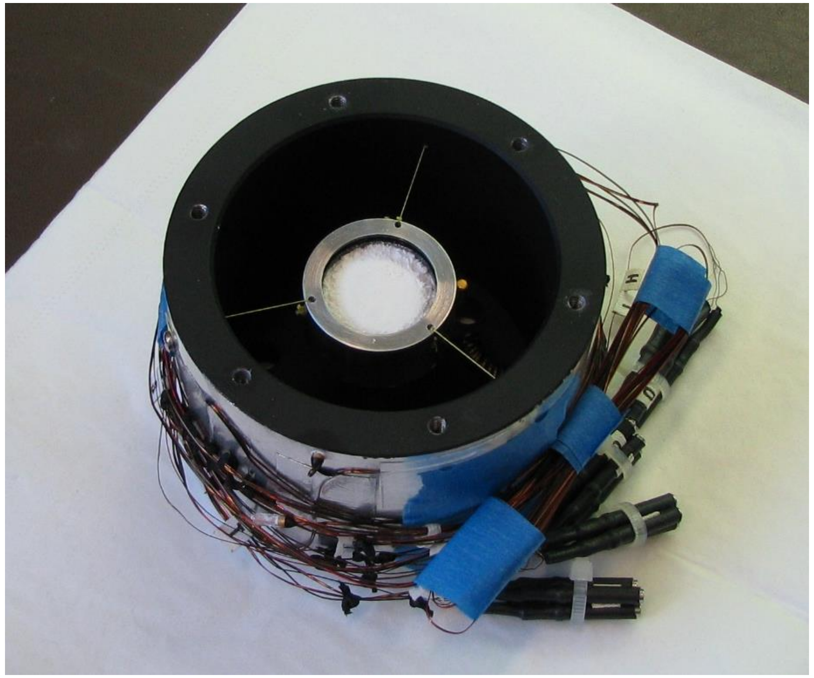
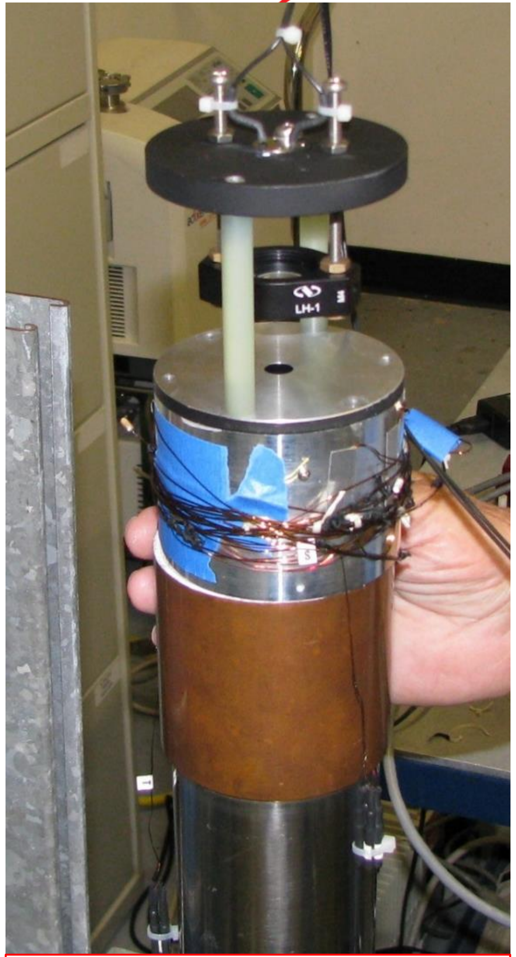
We’ve begun experimental testing on powder versions of Solar White.

Samples will be suspended in a simulated deep space environment (cold vacuum) and then irradiated while their temperature is monitored.



Solar White sample suspended in a cold cell.

Light source and lens launching radiation into the cold cell



These assembly on top of a cryo-cooler.

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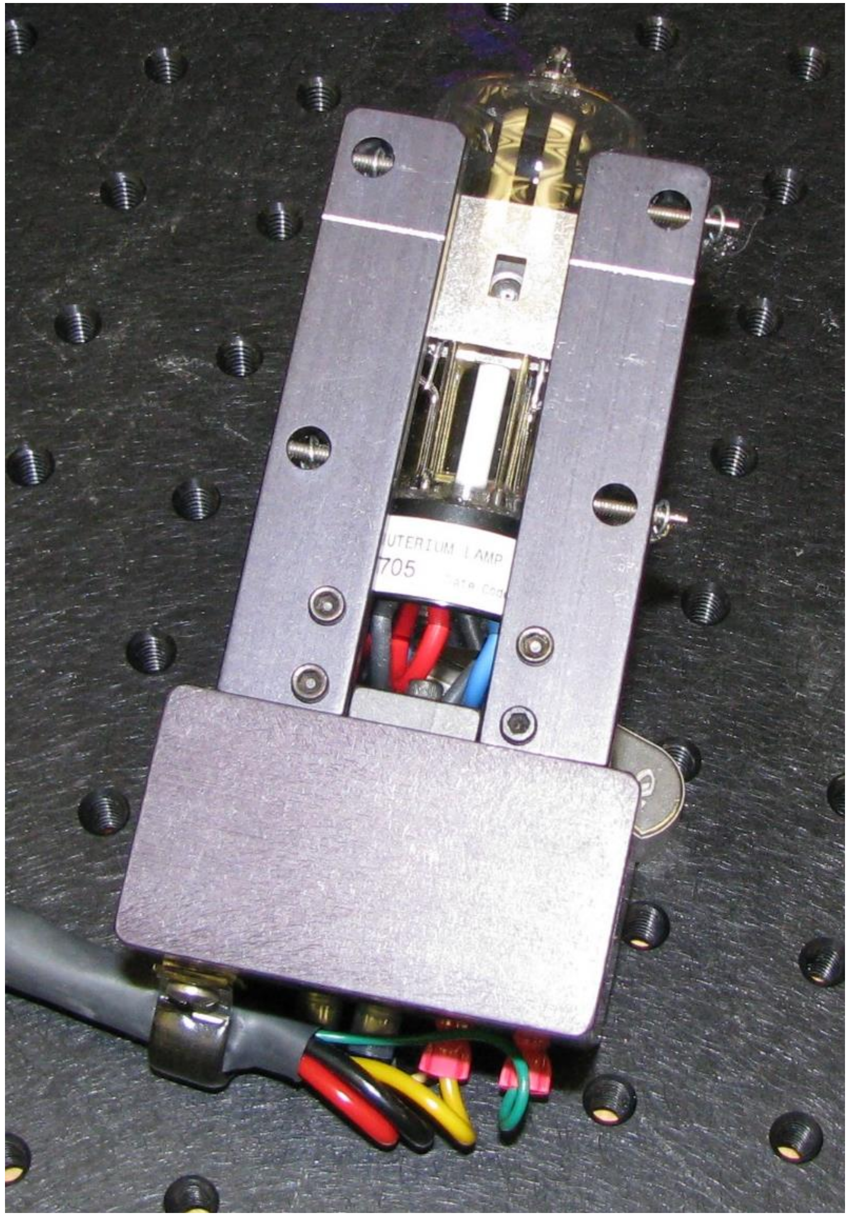

Testing is starting with 1000 K blackbody sources, i.e. in the infrared.

After this we will move to a calibrated deuterium lamp to test in the ultraviolet region.

Comparing the relative performance of Solar White to other approaches will help to solidify its advantages.

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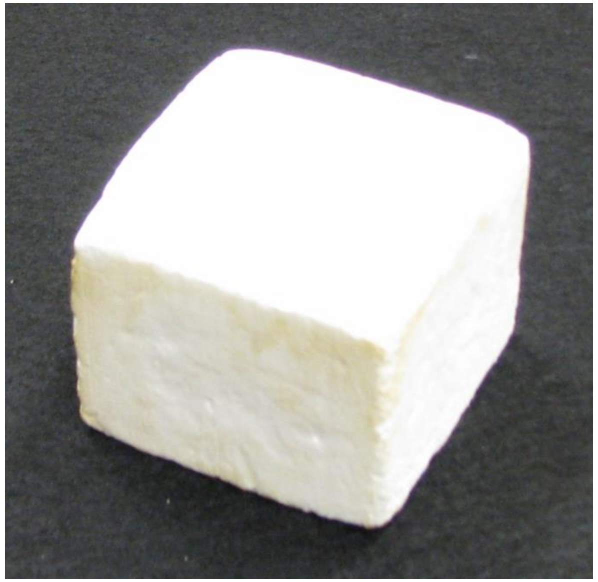
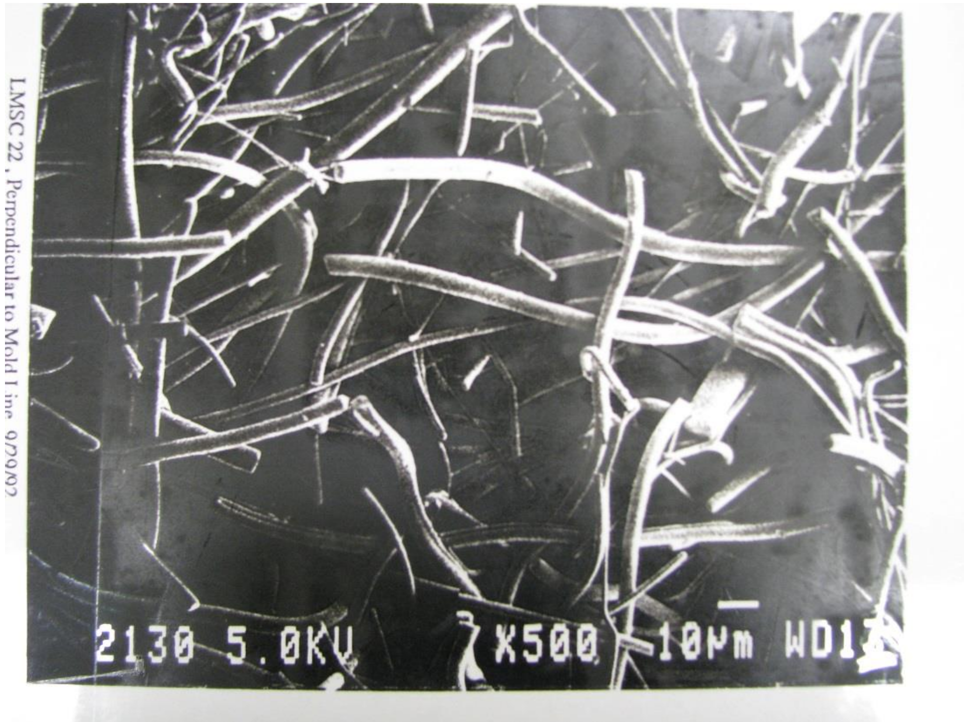
But this is still powder testing. We need to develop a rigid version of Solar White. So we need a particle like scatterer, composed of one material, that has structural strength. A close example of such a material is the Space Shuttle Tile.



This is a cube of Shuttle tile material, 2 inches on a side.

It is composed of nearly pure glass which has essentially no absorption in the visible spectrum. Note how white it is.



This is an SEM image of the tile, showing the glass fibers that make up about 6% of its volume.

For our purposes we want much smaller fibers and a higher fill factor, but this shows the possibility.

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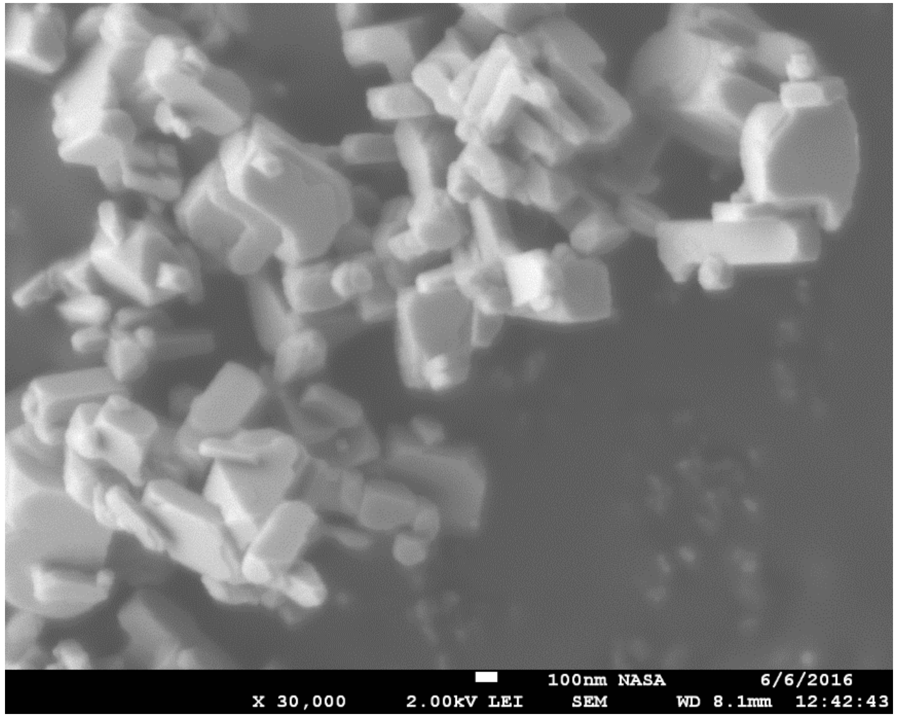
The Shuttle tiles are made by sintering glass fibers. Can we do that with BaF_2 powder to make a rigid coating?

Here is BaF_2 powder placed on a 25 mm diam. 3 mm thick BaF_2 window.



The SEM shows particles about 200-300 nm in size (perfect) and a reasonable fill factor!

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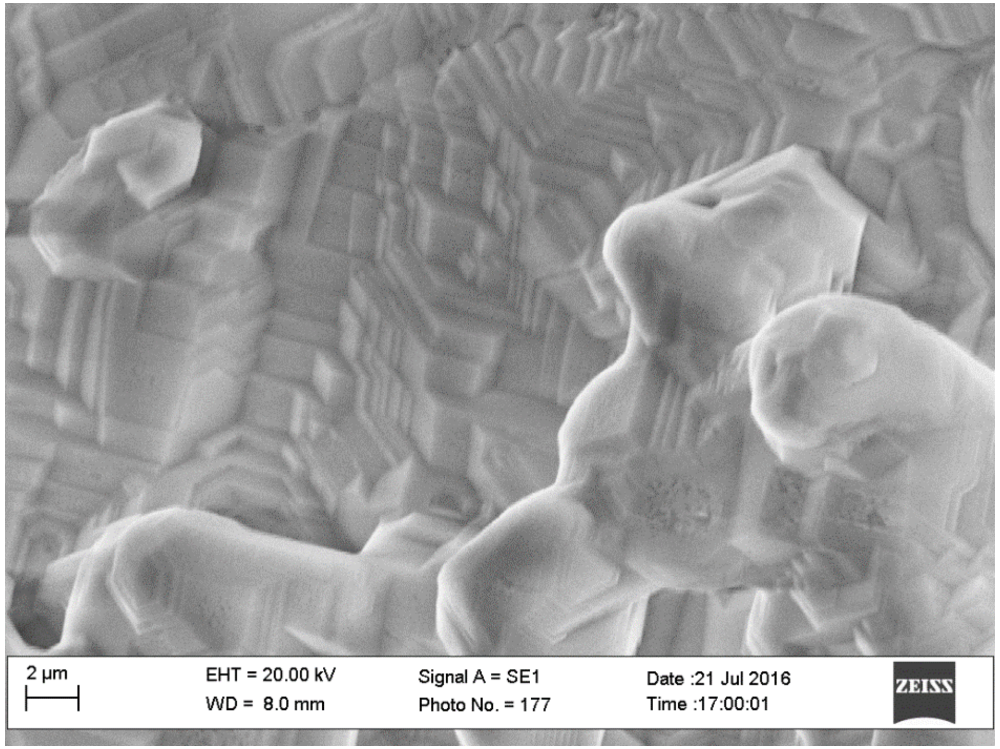

If we place the BaF2 powder in an oven the powder sinters and sticks to the BaF2 window.

But under the SEM we've lost the particles. Perhaps too long in the oven or too hot. Will be trying again.

We plan on exploring several methods for fabricating a rigid solar white coating using different materials.

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Solar White Selective Surfaces—Potential Uses.

Superconductor Operation

If we can reach 40-50 K, then superconductors with a 90K critical temperature can be used for magnetic energy storage.

We could use superconductors for power delivery or to generate magnetic fields over large distances.

A large scale, but relatively weak, magnetic field can provide GCR radiation protection.

Cryogenics

LOX and LN2 storage on long duration space flights, in space depots, or on the Moon.

Solar Shielding

A new generation of solar electro-magnetic radiation shields could be developed.

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Future Plans

1. Improve our solar white models
2. Expand our mission models—working with Wesley Johnson at GRC
3. Test powder and rigid versions of solar white in a simulated deep space environment.
4. Explore different fabrication methods for rigid solar white—working with Sylvia Johnson at ARC.
5. If all goes well, start looking at flight tests.

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In Closing:

We are excited by this new “Solar White” coating and the possibilities it represents.

We have filed a provisional patent on this novel concept.

We have co-funding support from KSC and from the Launch Service Program.

We have published the concept in Optics Letters.

We have started discussions with STMD’s Game Changing Development Program, with Glenn Research Center, with the John Hopkins’ University Applied Physics Laboratory, with the Florida Institute of Technology, and with the International Space Program about the impact of this breakthrough concept and potential flight tests.