

# SOLAR WHITE THERMAL COATING FOR CRYOGENIC PROPULSION SYSTEMS

Jarred Wilhite, Jason Wendell

NASA Glenn Research Center, Cleveland, OH 44135

## ABSTRACT

NASA is currently conducting research into the potential of storing cryogenic fluid in low Earth orbit (LEO). Having cryogenic propellant readily available for high-performance propulsion systems can be very beneficial for deep space missions in the near future. One of the key challenges to storing cryogenic fluid in LEO is minimizing boil-off. To address the challenge, NASA is evaluating new concepts in thermal insulation. One recent experimental study evaluated the feasibility of using yttrium oxide ( $Y_2O_3$ ), formed into tiles or spray coating that can potentially be used as a thermal coating for cryogenic propellant storage applications in deep space. Due to its temperature and wavelength dependent optical properties, this “solar white” material can reflect a vast majority of the Sun’s radiative energy while having a very high infrared emissivity for rejecting heat to deep space.

As a part of the material development and proof of concept testing, multiple tests have been run at KSC and GRC to demonstrate the performance of the material. At GRC, the tests were run using the Deep Space Solar Simulator (DS<sup>3</sup>) which contains a thermal vacuum chamber in which the solar white sample was exposed to a deep space environment (< 10 K, optically dense walls) while under full illumination via solar lamp. In order to improve the use of the test results and apply them to spacecraft, there is a need to be able to model the material properties within NASA’s standard thermal modeling tools. As such, it was set out to verify a thermal model of one of the experiments using Thermal Desktop with Sinda. The thermal model of the DS<sup>3</sup> test setup includes the solar white sample along with a solar lamp simulator capable of outputting heat at varying wavelengths. The model was developed in order to validate the test results and also to help predict results that will be obtained in future tests. This paper will review the modeling methods and thermal analysis results for various test cases that were run within the DS<sup>3</sup> facility.

## NOMENCLATURE, ACRONYMS, ABBREVIATIONS

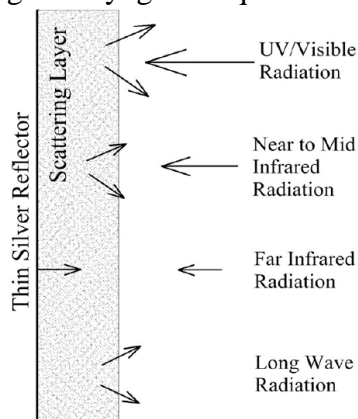
CTCC	Cryogenic Thermal Control Coating
DS <sup>3</sup>	Deep Space Solar Simulator
NIAC	NASA Innovative Advanced Concepts
IR	infrared radiation
UV	ultraviolet
$Y_2O_3$	yttrium oxide
$\alpha$	absorptivity
$\varepsilon$	emissivity

## INTRODUCTION

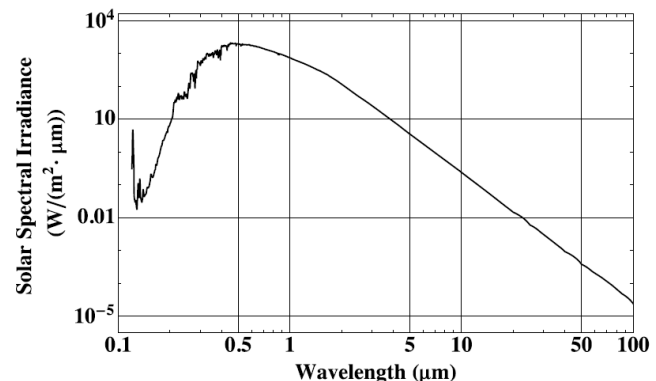
In spacecraft applications, thermal control coatings are often used to reduce external heat absorption and to regulate radiant heat exchange between onboard spacecraft components<sup>1</sup>. These coatings are designed to have specific radiative properties, absorptivity  $\alpha$  and emissivity  $\epsilon$ , which vary depending on the desired application. For instance, black coatings (high  $\epsilon$ , high  $\alpha$ ) may be required for high temperature applications within the spacecraft, while the external surfaces may require a white coating (lower  $\alpha$ , high  $\epsilon$ )<sup>1</sup>. A recent NIAC study developed a thermal coating that has low absorption of solar radiation and high emittance of infrared (IR) energy, which can enable cryogenic storage and superconductor operation in space<sup>2-3</sup>. In order to support such applications, this coating would need to reflect a vast majority of the Sun's irradiance at lower wavelengths while emitting radiation in the longer wavelengths. This would be an improvement over current state-of-the-art thermal coatings (i.e. AZ-93 white paint) which absorb significant ultraviolet (UV) and long wave infrared energy<sup>3</sup>.

Fig. 1 shows the concept used to develop a cryogenic thermal control coating (CTCC) which includes covering a thin layer of silver with a layer of scattering particles<sup>3</sup>. This scattering layer is composed of "solar white" material, which is a broadband material that has minimal absorptivity within the solar spectral irradiance (from 0.2-10  $\mu\text{m}$ ) as shown in Fig. 2. Since solar white has low absorption within the solar spectrum (see Fig. 2), the particles in the scattering layer reflect UV/visible radiation and near to mid-IR, while the thin silver backing reflects the far-IR radiation (5-10  $\mu\text{m}$ ). The scattering material becomes emissive at the longer wavelengths and radiates energy, thus providing cooling<sup>3</sup>.

The combination of the thin silver layer with the scattering layer of solar white material results in a solar reflector that can theoretically reflect 99.9% of the Sun's energy when used in deep space. An analytical model in Phase I of this NIAC study showed that a sphere in deep space can reach cryogenic temperatures ( $< 50 \text{ K}$ ) when covered with a 10 mm thick coating of solar white material, located 1 astronomical unit (1 AU) from the Sun. Thus, application of this solar white coating has far-reaching benefits, with the most significant being the long-term, deep space storage of cryogenic liquids for future lunar and planetary missions (i.e. liquid oxygen)<sup>3</sup>.



**Fig. 1** – Schematic of CTCC composed of a scattering layer on a thin silver reflector.<sup>2</sup>

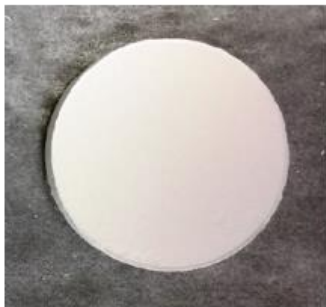


**Fig. 2** – Deep space solar irradiance spectrum, solar power density vs. wavelength.<sup>3</sup>

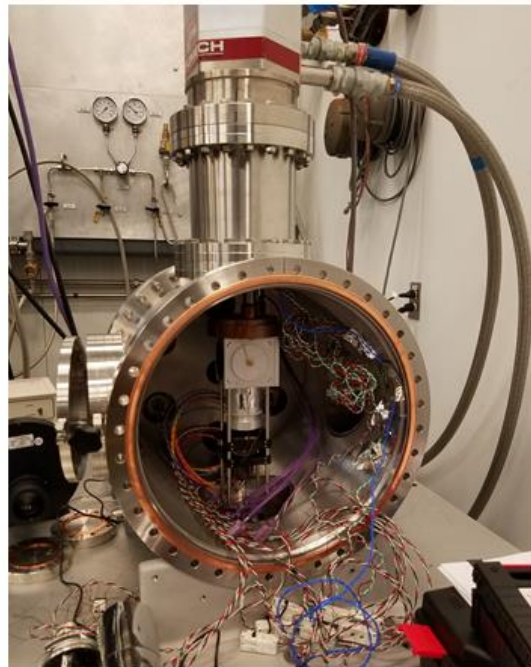
## APPROACH

The NIAC project involved extensive studying and testing of many different scattering white powders for utilization as the solar white material. Yttrium oxide ( $Y_2O_3$ ) was ultimately selected due to its ability to reflect UV above  $0.235\ \mu\text{m}$  through IR up to  $8\ \mu\text{m}$ , which equates to only 0.2% solar absorption (see Appendix for calculation)<sup>4</sup>. Yttrium oxide is also lightweight, hydrophobic, and chemically stable, which are all good properties for this type of application. Phase II of this NIAC project first included fabricating rigid versions or samples of the solar white coatings. This was done by compressing the yttrium oxide powder at high pressures, and then sintering it in an oven to make a disk-shaped tile as shown in Fig. 3. In addition to fabrication, KSC also conducted reflectance testing of the samples using a spectrophotometer, which showed relative improvement over thermal coatings that are currently in use.

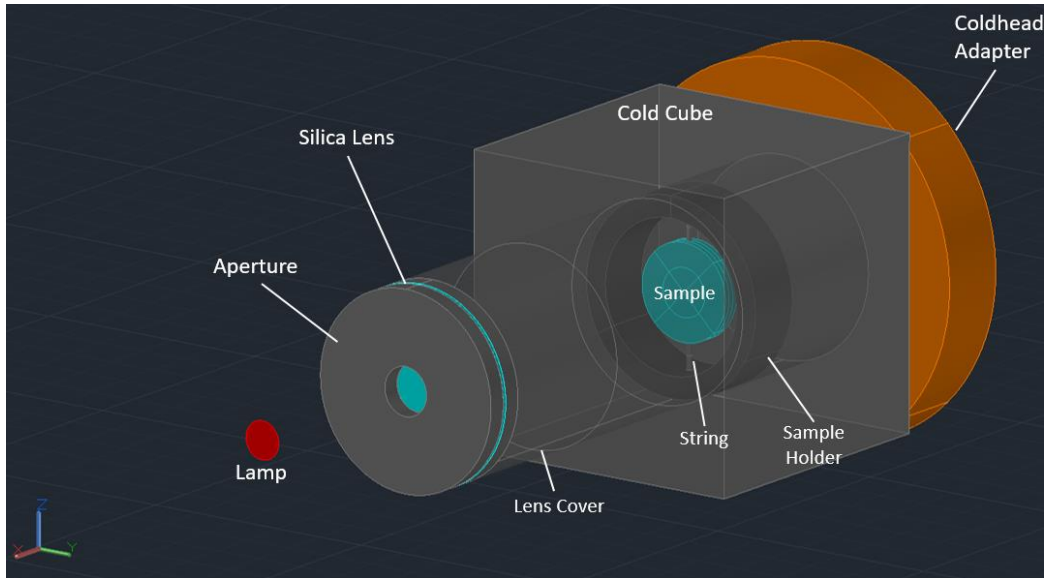
The samples were then sent to NASA GRC for further testing in the Deep Space Solar Simulator, or DS<sup>3</sup>, which is a facility designed to test CTCCs in a simulated deep space environment. DS<sup>3</sup> consists of a thermal vacuum chamber with optically dense walls and a cryocooler coldhead adapter to maintain temperatures at  $\sim 12\ \text{K}$ . DS<sup>3</sup> also includes a Xenon solar lamp simulator, which serves as a solar irradiance source and is equipped with an optical setup to direct light energy to the sample. Silicon diodes are used to measure the simulator environment temperatures and the sample temperature, while a light energy measurement technique is used to measure the energy input at the sample. Since its inception, eight test series have been completed at DS<sup>3</sup>.



**Fig. 3** – Sintered yttrium oxide sample.



**Fig. 4** – DS<sup>3</sup> facility.



**Fig. 5** – Thermal Desktop model of DS<sup>3</sup> facility.

Fig. 5 shows the thermal model of the DS<sup>3</sup> facility. The main objective of the thermal modeling and analysis is to help understand the energy inputs of the sample and to evaluate ways to remove parasitic IR heat loads from the simulator environment. Not pictured in Fig. 5 is the vacuum chamber, which encompasses the entire setup.

This model includes the solar white sample held by Kevlar strings within the sample holder, all of which are contained within the cold cube. The lens cover contains a thin fused silica lens, which has indium foil (not pictured) and aperture on both sides. The solar lamp is modeled as a thin surface with a single node, and has the “NORMAL” optical property on the active side so that light leaving the surface is collimated with an emissivity of 1.

This model also includes two different radiation analysis groups, with the first group containing all of the components except for the solar lamp surface. The other group includes only the lamp, the solar white sample, and the silica lens, which allows the lamp to radiate light energy only to the sample and silica lens. The lamp surface is also set up to output radks as heating rates, which enables it to radiate a specific amount of light energy through the ½” diameter viewport in the aperture, transmitting light downstream through the silica lens to the sample.

Two different types of tests were run at DS<sup>3</sup>, which involved the solar lamp being on or off. “Light On” cases were run with the solar lamp turned on, while the solar lamp was turned off for “No Light” cases. No Light cases were run in order to have a 100% deep space cold cube with no light source. However, initial test data from the No Light cases showed that the sample still reached a temperature of about 40 K, which is greater than the ~12 K background established by the coldhead adapter. This implies that there are IR leaks present within the DS<sup>3</sup> setup, which causes the temperature of the sample to increase despite there being no light source present.

The thermal model was used to investigate these two cases. The No Light case was modeled to simulate an ambient, emissive environment in which the inside surfaces of the chamber were set to 300 K, in addition to a lower light intensity setting for the solar lamp. Although the solar lamp is turned off for the No Light case, a value still needs to be entered into the model to account for the IR contribution. Source emittance analysis was used to calculate this IR contribution to be equal to 43.1 mW/cm<sup>2</sup>. This calculation was based on radiative parameters and size of components within DS<sup>3</sup>. The light intensity during most of the tests with the solar lamp turned on was 180 mW/cm<sup>2</sup>. Thus, a value of 223.1 mW/cm<sup>2</sup> was used in the Light On case, which includes the solar lamp intensity with the light on plus the ambient IR contribution.

Wavelength dependent properties are another important TD feature used in this analysis. Both solar white and silica have optical properties that vary with wavelength, including emissivity and transmissivity as shown in the Appendix. This feature is mainly used for the radiation analysis tasks, in which wavelength dependent properties were enabled for a range of 0-25 μm for this study.

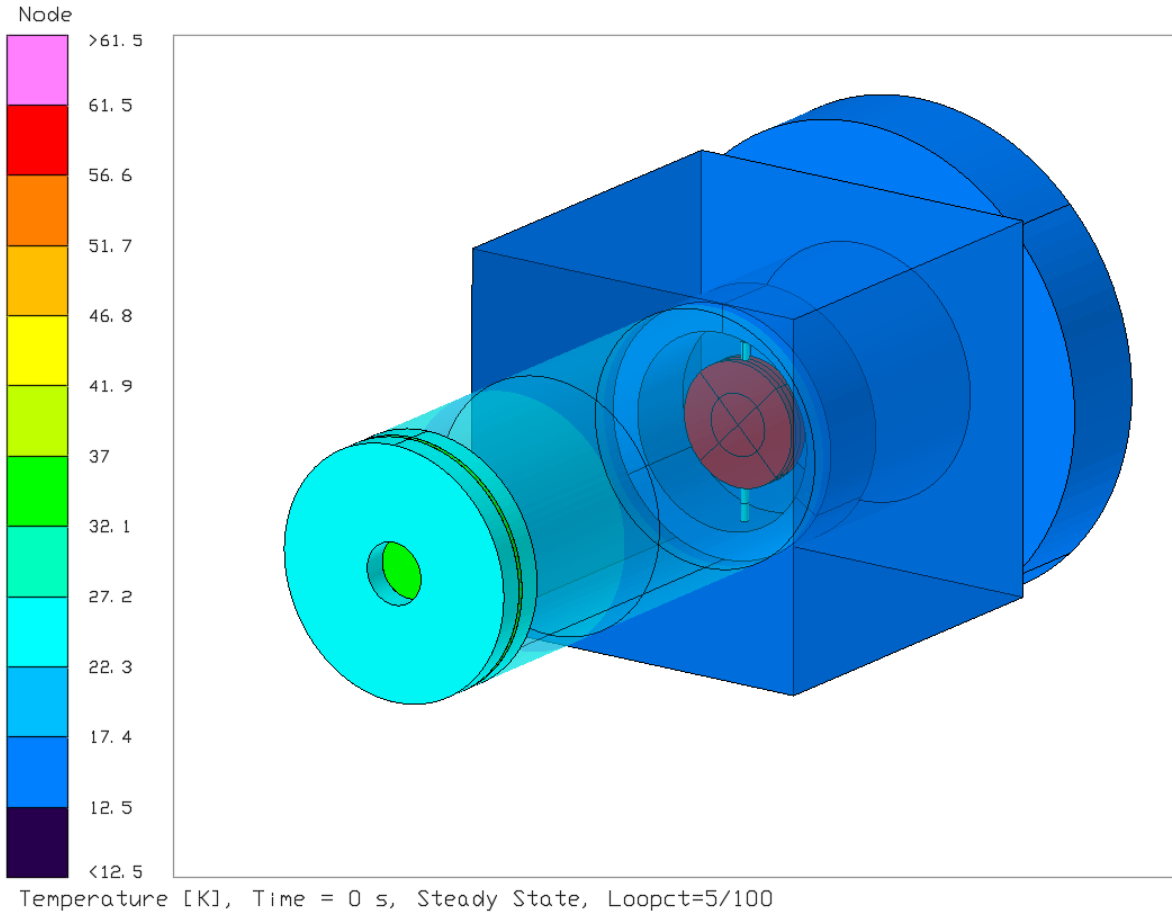
## RESULTS

The thermal analysis results for the No Light case are outlined in Table 1 and Fig. 6. The cold cube and sample holder both reached temperatures of 12.5 K due to the boundary condition of the coldhead adapter. The temperatures of the aperture, indium foil, and lens cover are slightly higher due to the chamber walls being held at 300 K, which is done to help establish the ambient, emissive environment for this case. However, conduction from the cold cube to the lens cover keeps the temperatures of these components within the 20 K range. The silica lens and the solar white sample are the only components that are at relatively higher temperatures due to radiative exposure from the solar lamp.

As previously mentioned, only the calculated ambient IR (43.1 mW/cm<sup>2</sup>) is emitted from the lamp surface for the No Light case. Although the silica lens was initially expected to absorb a significant amount of IR coming from the lamp surface, the results show that the sample is considerably warmer than the silica lens for this case.

**Table 1 – Component Temperatures for No Light Case**

Steady State - No Light Temperatures (K)										
Light Intensity (mW/cm <sup>2</sup> )	Aperture	Indium Foil	Silica Lens (ID)	Silica Lens (OD)	Sample	String	Sample Holder	Lens Cover (avg.)	Cold Cube	Coldhead Adapter
43.1	23.1	23.1	35.8	34.6	61.5	27	15.3	19.5	12.5	12.5



**Fig. 6** – Results from No Light case.

This is mainly due to the wavelength dependent transmissivity of the silica lens, which fluctuates from 1.4 to 5  $\mu\text{m}$  (shown in Appendix)<sup>5</sup>. The silica lens is also in direct contact with the aluminum lens cover and indium foil, which are much colder components. The model also accounts for potential IR leaks into the facility as well as the 10  $\mu\text{W}$  heat load generated by the diodes that measure the sample temperature, which further explains the sample being at a greater temperature than the silica lens.

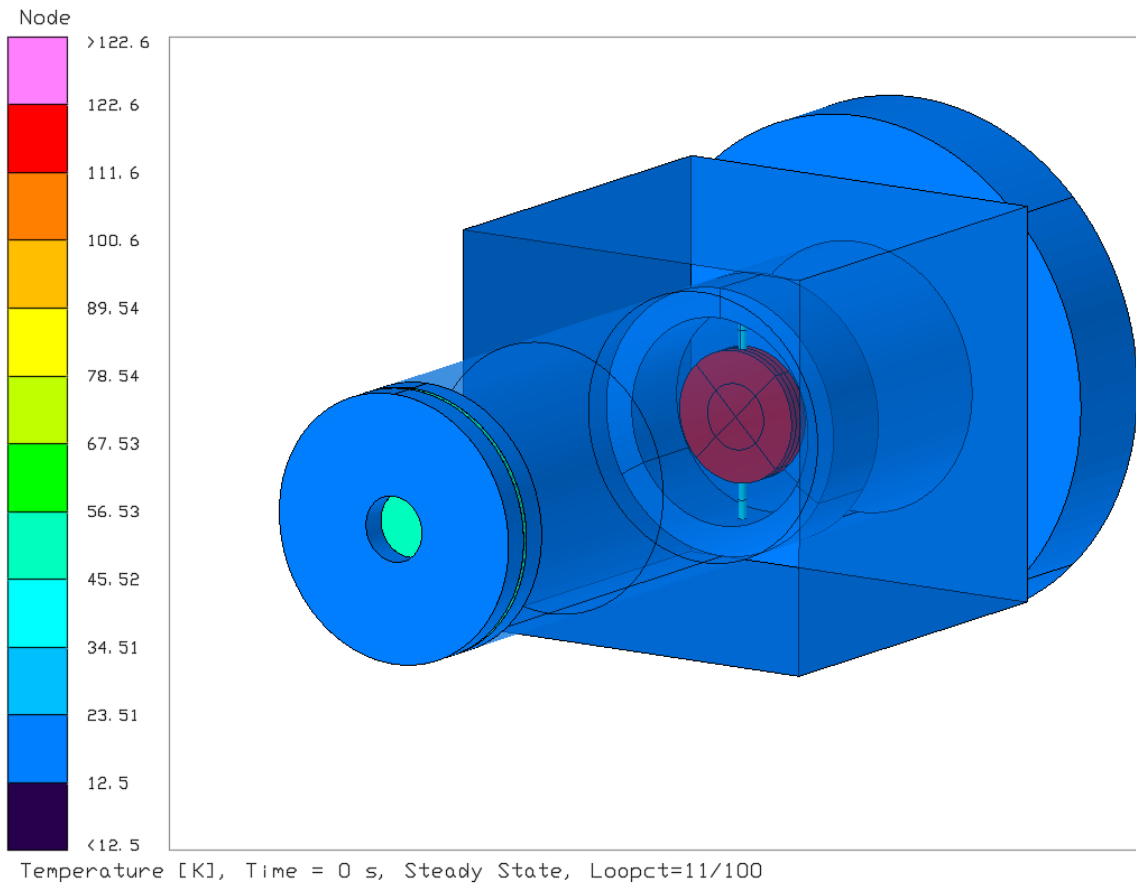
**Table 2** – Component Temperatures for Light On Case

Steady State - Light On Temperatures (K)										
Light Intensity (mW/cm <sup>2</sup> )	Aperture	Indium Foil	Silica Lens (ID)	Silica Lens (OD)	Sample	String	Sample Holder	Lens Cover (avg.)	Cold Cube	Coldhead Adapter
223.1	14	14	53.4	51	122.6	39.1	12.8	13.4	12.8	12.5

The Light On case has very similar trends to the No Light case. All parts that are in direct contact with the coldhead adapter remain near 12.5 K, and both the sample and silica lens temperatures

are greater due to the increased light intensity from the solar lamp being turned on. In addition, both cases show the temperature of the silica lens at the inner diameter to be slightly greater than that near the outer diameter. This is a result of the light energy being directed through the viewport where the inner diameter of the silica lens is located. However, the temperature gradient across the lens stays relatively low for both cases as expected.

Not shown in the results is the temperature of the lamp surface. This is because the surface is not generated when the model runs; therefore, it is not entirely part of the model. The purpose of the lamp is only to emit radiation via light energy to the sample and the silica lens, which is set up in the radiation analysis tasks.



**Fig. 7** – Results from Light On case.

## CONCLUSIONS

This NIAC study involved the development of the solar white material, which has the potential to be used as a thermal coating for cryogenic propellant storage for deep space missions. Yttrium oxide was selected for this study due to its ability to reflect most of the Sun's irradiance at lower wavelengths while emitting long wave radiation. After fabrication and proof of concept testing at KSC, the solar white samples were tested at GRC's DS<sup>3</sup> facility in which the samples were exposed to a deep space thermal environment while under illumination via solar lamp.

The thermal model of DS<sup>3</sup> helped to gain a better understanding of energy inputs of the sample by determining how the IR contribution affects temperatures of the components within the setup. The model results showed temperatures for the sample and other components that were close to temperature data obtained during testing. However, the temperatures obtained for the silica lens were lower than expected due to the effect of its wavelength dependent optical properties as well as conduction to nearby components that reached much lower temperatures. Overall, the thermal model helped to validate the results obtained during tests and will be used to help predict results that will be obtained in future DS<sup>3</sup> tests. Next steps will include utilizing these modeling strategies and properties for other deep space models where the solar white coating can be applied.

## ACKNOWLEDGEMENTS

We would like to acknowledge Dr. Robert Youngquist (KSC), who is the principal investigator and leader of the NIAC project, Cryogenic Selective Surfaces. We also acknowledge the project manager, Michael Doherty (GRC) as well as Dr. Tracy Gibson (KSC), Angela Krenn (KSC), Wesley Johnson (GRC), Dr. Mark Nurge (KSC), and Sarah Snyder (KSC) who continue to make significant contributions to this project.

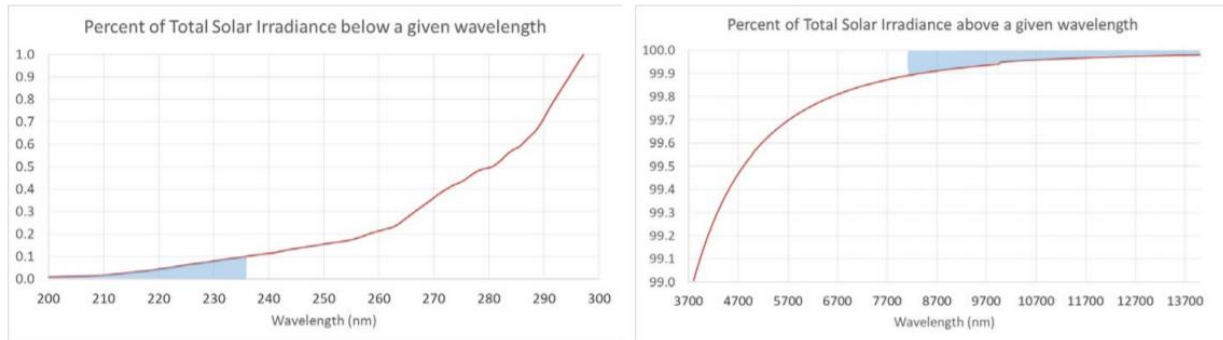
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- <sup>3</sup>Youngquist, R., et al., "Cryogenic Selective Surfaces, NIAC Phase II Study Final Report." NASA. 2018.
- <sup>4</sup>Krenn, A., et al. "Cryogenic Thermal Control Coatings, An Overview", NASA Technical Review Presentation. 2020.
- <sup>5</sup>"Silica Glass (SiO<sub>2</sub>)". Crystran. <https://www.crystran.co.uk/optical-materials/silica-glass-sio2>



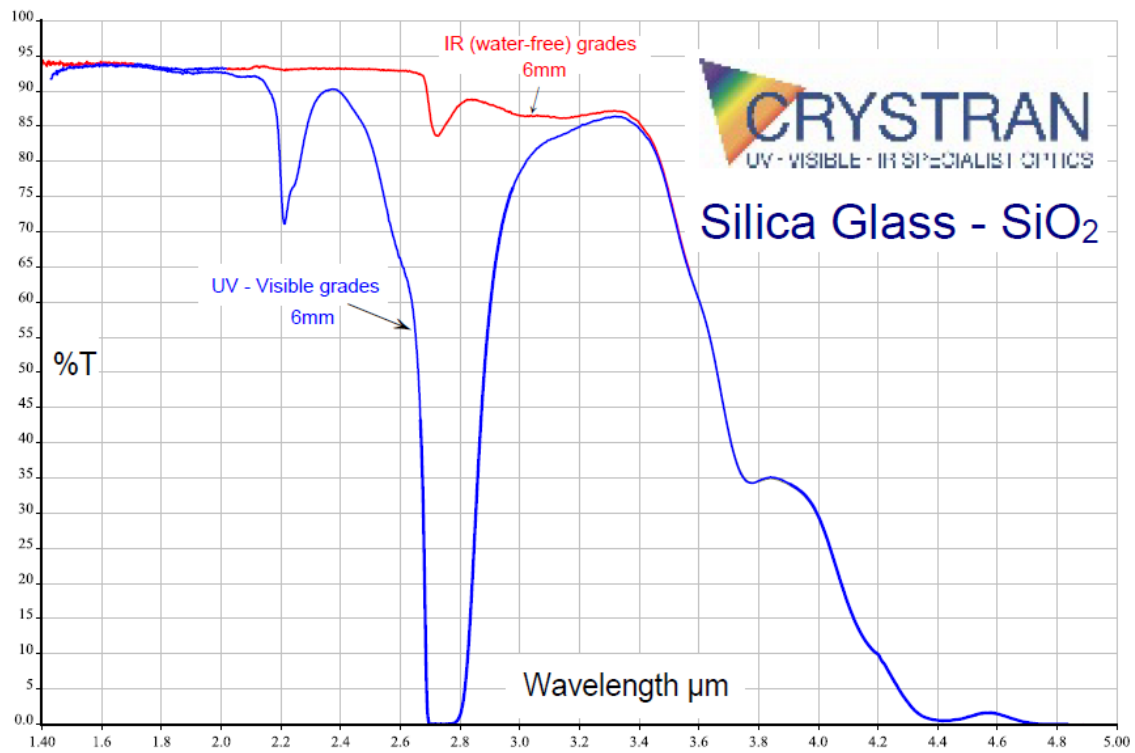
## APPENDIX

Fig. 8 shows the percent of total solar irradiance below 0.235 microns (UV) and above 8 microns (IR). The blue shaded region is the solar absorption by  $Y_2O_3$ , which equates to only 0.2%.



**Fig. 8** – Percentage of total solar irradiance absorbed by  $Y_2O_3$  across varying wavelengths

Fig. 9 shows the wavelength dependent transmissivity for the silica lens obtained from Crystran<sup>5</sup>.



**Fig. 9** – Transmissivity vs. wavelength of silica glass.