Development of a space irradiance simulator for advanced studies and materials research

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Abstract. A lab-scale experimental apparatus that mimics the solar-thermal environment of space has recently been developed and tested at NASA Kennedy Space Center in support of novel materials research for future space science and exploration applications. The Space Irradiance Simulator (SIRS) apparatus exposes specimens up to roughly 61 mm in diameter to a similar thermal environment that exists at distances as close as 0.4 AU from the Sun. This includes a high vacuum environment, access to a deep cryogenic background temperature with optical properties that closely imitate a blackbody, and irradiance from a broadband solar “point” source at fluxes as high as 9300 W/m². Cooling is provided by a Gifford-McMahon cryocooler capable of 25 W of cooling power at 20 K, with a base temperature of 14 K. A commercially available Xenon lamp acts as the solar source, creating broadband electromagnetic radiation with a spectrum similar to that of the Sun. Light is beamed through the vacuum chamber and onto a sample suspended within the cold-mass via a flexible quartz fiber bundle in conjunction with a custom vacuum feedthrough. The system design, fabrication, and operation are discussed; and results from the initial checkout testing of the system are presented.

1. Introduction

Future spacecraft and lunar facilities will need better solar reflectors than those currently available to achieve long duration storage of cryogenic propellants. If a solar reflector can be fabricated with a solar absorptivity of 1% and infrared emissivity of 90%, a tank of liquid oxygen (LOX) could be passively stored indefinitely (assuming no other sources of heat) at 1 AU from the Sun. Work is underway to develop solar reflectors that should achieve this [1-4], but the concern is accurately characterizing their performance, as measuring such a low level of reflectivity, as well as the corresponding emissivity, is extremely difficult using standard experimental techniques. The accepted approach for measuring solar absorptivity is described in ASTM E903, “Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres”. A beam of light is aimed at the sample, varied in wavelength from the ultraviolet to the mid-infrared (a typical range would be 250 nm to 2400 nm), and a portion of the reflected light is captured by an integrating sphere and measured. The measured radiation is then compared with a reflectance standard, such as Spectralon®, to determine the reflectivity of the sample.

ASTM E903 has several shortcomings, including being a relative instead of an absolute measurement; ignoring solar energy outside of the integration band; and introducing errors based on the
scattering angle, depth of scattering of the sample, and the reference material. For example, a National Institute of Standards and Technology (NIST) traceable reflectance standard (Spectralon® serial number 3153) was obtained and its supplied reflectivity curve is shown in Figure 1 below. Using a Jasco V-670 reflectance spectrometer with an ISN-723 integrating sphere accessory, the reflectance versus wavelength of a disk of sintered Yttrium-Oxide (Y2O3) was measured and its spectral reflectivity calculated by comparison with the measured reflectance of the Spectralon® standard using its NIST data. The result is also shown in Figure 1 and yields a broad region with reflectivity greater than one, which is not possible. The calculated solar absorptivity of the Spectralon® standard is 1.16% and -0.68% for the Y2O3, a negative absorptivity, demonstrating the measurement problem in using ASTM E903.

![Figure 1. Comparison of NIST Spectralon Data and ASTM A903 Testing of Y2O3 Material](image)

Consequently, it was decided that a direct measurement of solar absorption was needed to assess the performance of highly reflective materials. This would entail creating an environment similar to that of deep space: a high vacuum environment, access to a deep cryogenic background temperature with optical properties that closely imitate a blackbody, and a light source providing a spectral irradiance similar to that of the Sun. Referred to as the Space Irradiance Simulator (SIRS), this paper discusses the design evolution of SIRS at NASA Kennedy Space Center, and details the fabrication and testing of the current and most advanced version of the apparatus.

**2. Evolution of the SIRS**

Two previous iterations of SIRS apparatuses were developed and tested in-route to the current unit. Each utilized the same Gifford-McMahon AL230 cryocooler sourced from Cryomech company, custom-built 2-piece vacuum chamber assembly, and commercially available Xenon light source; however, where SIRS-1 beamed light vertically through the vacuum chamber and onto the cold sample via a series of windows and lenses, SIRS-2 accomplished this through a custom, commercially available, flexible quartz fiberoptic cable. Each version used an 82.5 mm diameter aluminum sample cup affixed to the cryocooler cold head, and a removable lid where light entered and irradiated the test specimen. Samples were horizontally oriented inside the cup and suspended at three points via thin strings to limit the solid conduction heat load. Silicon diode temperature sensors were used to monitor the sample and cup temperatures during testing. Figure 2 shows details of the SIRS-1 and SIRS-2 configurations.
Procedurally, both SIRS-1 and SIRS-2—and later, SIRS-3—began with a pump-down to high vacuum, usually overnight, followed by startup of the cryocooler and a multi-day cooldown phase. When the sample and cold assembly reached steady state, the lamp was switched on and the temperatures monitored while the sample warmed, usually reaching maximum within about 4 hours. A test was terminated once the temperatures peaked; the lamp and cryocooler were switched off and the system was allowed to warm back to ambient temperature under vacuum.

2.1 SIRS-1 Influence on SIRS-2
Although the SIRS-1 configuration afforded simpler vacuum sealing by beaming light through an off-the-shelf sapphire window at the top of the chamber, it also relied on a relay of lenses inside the chamber to focus light on the sample. Due to the nature of the particular test specimens examined, these lenses needed to be cooled to prevent them from emitting infrared radiation and affecting the test results. The
aluminum lens tube design shown in Figure 2 housed the lenses and was cooled by the coldhead, however, there was no practical way to directly monitor lens temperatures. Therefore, it was impossible to know if infrared light had led to inaccurate test results.

Beaming light through the chamber and onto the sample via a quartz fiberoptic cable was a potential solution to the infrared issue. It allowed for more options to couple the coldhead to the cable and directly cool the quartz fibers in-route to the cup. However, it also required a penetration through the vacuum boundary, for which a custom feedthrough had to be developed. Various versions of the feedthrough were tested, all of which relied on Stycast 2850FT epoxy to form the seal. Ultimately, a design was found that allowed for high vacuum (i.e. <10⁻⁵ torr) to be achieved and tests of SIRS-2 to be successfully conducted, but vacuum leaks were always a concern with the setup.

2.2 SIRS-2 Influence on SIRS-3
Testing of the fiberoptic setup of SIRS-2 was extremely informative and lent confidence that solar spectrum light can be successfully transported into the cryostat in this way. However, two primary issues were found with the particular configuration: 1. The fiber had to be bent sharply at 90° after entering the vacuum chamber, and again at 180° to enter the top of the cup, which caused concerns of breaking the quartz fibers; and 2. There still was no effective way to thermally link the quartz fibers to the coldhead (the copper foil shown in SIRS-2 setup in Figure 2 was an early attempt to address this issue). Due to #2, the concern for infrared contamination still existed, and destructive examination of the cable revealed a multitude of broken fibers at bend locations. Therefore, a wholly new design for SIRS-3 was embarked upon that attempted to capture all of the lessons learned in SIRS-1 and SIRS-2.

3. Design & Assembly of SIRS-3
Two primary guiding principles drove the design of SIRS-3: 1. The fiberoptic cable must have minimal or no bends; and 2. The individual quartz fibers must be cooled directly and efficiently. After exploring numerous options, it was decided that the fiber should be kept completely straight, which meant that it was more practical to have it penetrate the vacuum chamber and interface to the sample cup horizontally instead of vertically as with the SIRS-1 and SIRS-2 setups. Ramifications of this decision were that the sample cup became a box, as having flat vertical surfaces provided a simpler means of interfacing the fiberoptic cable, and the specimen had to be oriented vertically and suspended from the lid of the box. The walls and lid of the box were constructed from 101 copper, and high emissivity Metal Velvet black foil from Edmunds Optics company was applied to the inner surfaces. A sample cradle was designed to be affixed to the bottom of the lid at one of six discrete locations at increasing distances from the aperture to vary the spot diameter on the specimen, and the sample was suspended in the middle of the cradle using thin string as in the previous setups. Figure 3 shows the box and lid configurations.

Figure 3. SIRS-3 Sample Box Affixed to Coldhead with Lamp On (left); Test Sample in Cradle (right)
The configuration changes described above were relatively straightforward to execute from a design and fabrication standpoint; the more difficult challenge was how to effectively link the quartz fiber bundle, which was oriented horizontally, to the vertically oriented, round AL230 coldhead, and to achieve the maximum heat removal possible. Maximum heat transfer meant maximizing the surface area in contact between the quartz fiber bundle and coldhead mount; a challenging problem given the bundle consisted of roughly 500 individual, 0.22 mm diameter, fragile fibers. A new, larger upper vacuum chamber was designed that provided more internal space for mounting the fiber and used an offset coldhead penetration to create even more distance between the chamber wall where the fiber entered, and the sample box. An L-shaped copper mount was designed that interfaced the fiber to the coldhead, and a series of three mounting blocks were secured around the circumference of the coldhead using two stainless steel band clamps to anchor the L-shaped mount. On the opposite end, a copper thermal anchor block was designed to link the fiber bundle to the L-shaped mount. A U-shaped channel was machined length-wise into the anchor block to house the bundle, and a lid was bolted to the top to form a tunnel. Part of the stainless steel outer sheath was removed from the fiberoptic cable, exposing the individual quartz fibers where the anchor was to be placed. The bundle was carefully positioned into the channel, expanded PTFE gaskets were positioned at the ends and held in place by copper end plates, the lid was secured, and Stycast 2850FT epoxy with copper powder filler was injected into the tunnel to completely fill-in the space around the fibers. This created a solid conductive mass that completely encapsulated the fiber bundle and provided an efficient heat transfer path to the L-shaped mount. Figure 4 shows the various stages of fabrication and assembly of the fiber anchor and SIRS-3 (note: the copper cables seen on the L-shaped mount were introduced as a way to gain back some of the heat transfer area lost due to machining of the brackets at the coldhead and fiber anchor points).

Figure 4. Exposed Fiber Bundle (upper left); Fiber Bundle Positioned in Thermal Anchor Prior to Epoxy Filling (upper right); Completed SIRS-3 Assembly (lower)
The final significant change to the SIRS-3 setup was the custom vacuum feedthrough for the fiberoptic cable. Due to the aforementioned persistent leakage concerns, it was desired to move away from the previous designs that relied solely on epoxy filler to form the vacuum seal. As such, for SIRS-3 a new method was devised that used Swagelok compression fittings and stainless steel tubing to form the primary seals. Since the endcap of the cable was already stainless steel and had a standard diameter (12.7 mm), a readily available compression fitting could be swaged directly to the termination and transition to a larger diameter tube. At the other end, this tube penetrated a bored-through 40 mm NW-style vacuum blank and welded compression fitting to form the final seal. The entire fiberoptic cable was routed through the feedthrough assembly with minimal modifications and need for epoxy sealant—a small amount of epoxy was used on the backside of the fiber end cap where the swaged compression fitting was located to ensure no air could leak through the fiber bundle termination. Upon pumping down the chamber the entire feedthrough was also evacuated all the way up to the end cap at the interface to the Xenon lamp, and vacuum levels below 10⁻⁶ torr were easily attained using the setup. Figure 5 shows the completed feedthrough assembly and Xenon lamp interface to the cryostat.

Figure 5. SIRS-3 Vacuum Feedthrough Assembly (left); SIRS-3 Cryostat with Xenon Lamp (right)

4. Results & Discussion of Initial Checkout Testing of SIRS-3

Three silicon diode temperature sensors were placed at various locations on the cold-mass for initial checkout testing of the SIRS-3 setup to understand the cooldown behavior of the system, and to capture the response when the lamp was switched on. Figure 6 below shows the results of the checkout testing and reveals a cooldown of the entire cold-mass to almost the base temperature of the cryocooler in just over an hour. Additionally, very little ΔT existed between the four sensors during the cooldown phase, and even less once steady state was achieved (0.44 K average ΔT across all sensors at 120 min), which was almost certainly due to the use of highly conductive oxygen free copper throughout the design, but also lent credibility to the design approach and assembly procedures.

At roughly 124 minutes into the test the lamp was switched on, initiating an almost instantaneous increase in temperatures on all four sensors. This response can be seen in the expanded region in Figure 6 from about 110 minutes to 150 minutes (values within this region correspond to the right-most y-axis). Two notable features of the lamp-on data are that the temperatures stabilize quickly at the new higher temperature, within roughly 12 minutes, and the total rise in temperature was relatively small, 0.61 K for T1 and 0.50 K for T2 & T3. Prior to the test, the total radiative power being emitted by the fiber was measured with a Thor Labs PM100D digital power meter with a broadband detector and found to be 1.11 W. Using the T1 measurement and the published data for the AL230 capacity as a function of coldhead temperature, the 0.61 K increase with the lamp on equates to an additional 2.46 W heat load on the cryocooler. The difference between this estimate and that found with the PM100D was primarily
due to T1 being located a non-trivial “thermal distance” away from the actual coldhead, resulting in a larger $\Delta T$ than would be expected on the coldhead itself when the lamp was turned on. During subsequent testing, the $\Delta T$ directly on the coldhead was found to be roughly 0.3 K, which equates to an additional 1.21 W heat load on the cryocooler; much closer to the PM100D measurement.

![Figure 6. SIRS-3 Initial Checkout Test Results](image)

The test was terminated around 155 minutes when the cryocooler was turned off, and the system was allowed to warm back to ambient under vacuum. The results presented in Figure 6 are of a single test, however, the trends and behavior were duplicated on numerous occasions. This effectively validated the overall design and setup, and allowing the SIRS-3 system to transition into an operational testing phase pending a final test to determine if there was any attenuation of the light through the fiber after it was cooled down to the operational temperature, as this would decrease the 1.11 W output measured at ambient temperature and lead to misinterpretation of the test results.

4.1 Attenuation Testing

To determine the difference, if any, in power emitted by the fiber when cold versus at ambient, an array of four Thor Labs FDS100 photodiodes was positioned inside the sample box at differing radial distances from the fiber centerline. The diodes were secured into a G-10 backing plate using Stycast 2850FT epoxy, and a small flexible heater and type-E thermocouple were adhered to the back of the plate to maintain its temperature at ambient so the diode readings would not be skewed when the system was cooled down (the only desired change was to be in the intensity of the light coming from the fiber; holding the diode temperature constant between the two measurements ruled them out as a possible source if any differences were found). The plate was affixed to the box lid and multi-layer insulation was applied to it and the inside walls of the box to reduce the infrared heat load associated with maintaining it at ambient temperature throughout the test.
Diode measurements, in the form of milliamp DC outputs, were taken using a multimeter with the system at ambient temperature, and then the lamp was switched off and cryocooler turned on to chill the system down to the operational temperature range seen in Figure 6. During cooldown, the heater was controlled manually via a power supply to keep the plate at 296 K. Once cold, the lamp was switched back on and the second series of measurements were taken. Figure 7 shows the attenuation setup during fabrication and prior to final install.

Figure 7. G-10 Backing Plate and Single Photodiode (left); Attenuation Setup Final Installation (right)

Results of the attenuation testing showed a 15.9% average reduction in emitted power across all photodiodes, with a standard deviation of 0.03, between ambient and the SIRS-3 operational temperature. Accounting for this reduction means that roughly 0.93 W of broadband solar power is available to irradiate a sample during testing.

5. Conclusion
A Space Irradiance Simulator (SIRS) that mimics the solar-thermal environment of space has been successfully designed, fabricated, and tested at NASA Kennedy Space Center. The SIRS utilizes a Gifford-McMahon cryocooler to create cryogenic background temperatures down to roughly 15 K, and a Xenon light source to beam around 1 W of broadband solar radiation via a quartz fiberoptic cable to a sample housed within the cryostat. The SIRS was designed to provide a new capability beyond established standard test methods, and to provide a relatively straight-forward means of characterizing the in-space performance of materials and systems. SIRS is currently being used by NASA for research and technology development of highly reflective materials for future space missions.

6. References
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