Cryogenic Thermal Control Coatings
An Overview

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Presentation Outline

- Concepts and Goals
- Partners/Funding Sources
- Game Changing Development work
- Other work
- Publication/Patents
A black body (perfect emitter and absorber) in space absorbs UV, Visible, and Near-IR radiation and emits long-wavelength radiation resulting in an equilibrium temperature (1 AU from the sun) of 280 K

If we can create a coating that reflects, instead of absorbs, the shorter wavelengths, and still emits in the longer wavelengths, how much can the equilibrium temperature of a body in space drop?
A Body in Space

In equilibrium, an object radiates (R) the same power it absorbs (B), so R=B where;

Stefan-Boltzmann Law: \[ R = \sigma e A T^4 \]

\( \sigma \) = Stefan-Boltzmann constant
\( e \) = emissivity
\( A_T \) = total area of radiating body
\( T \) = temperature

AND

(solar heat source only): \[ B = \frac{p}{1} I A C S \]

\( p \) = percentage of available power absorbed
\( I \) = Irradiant power of the Sun
\( A_{CS} \) = cross sectional area of the absorbing body

For a sphere, the total area (radiating surface = \( 4 \pi r^2 \)) is 4 times the cross sectional area (absorbing surface = \( \pi r^2 \)), so a factor of 1/4 replaces \( A_{CS}/A_T \).

Solving for \( T \):

\[ T = \sqrt[4]{\frac{p I}{4 \sigma e}} \]

Substituting:

\( I = 1366 \text{ W/m}^2 \) (at 1 AU – Irradiance decreases as distance from the sun increases)
\( \sigma = 5.67 \times 10^{-8} \text{ W/(m}^2 \text{ K}^4) \)
\( e = 0.9 \) (value based on emissivity data of other similar substances and is consistent with test data)
\( p = 1\% \) (goal value)

Solving yields \( T = 90 \text{ K} \)

Therefore, a spherical body in space, approximately 1 AU from the Sun, coated in a material that absorbs 1% of the suns power and has emissivity of 0.9, will come to equilibrium at 90 K (LOX temp), assuming no heat sources other than the sun.
Thermal Control Coatings

- Coatings that reflect some wavelengths and emit others are referred to as thermal control coatings

Current State of the Art

AZ-93 White Paint
Absorbs 15% Solar Spectrum*

Single layer silver based TCC
Absorbs 10% Solar Spectrum*

Qioptiq quartz on silver TCC
Absorbs 6% Solar Spectrum*

*Absorption numbers are based on industry standard reflectance measurements using a spectrophotometer, with reference to NIST standard Spectralon
Solar Spectrum

Ranges and percentages are approximate

<table>
<thead>
<tr>
<th>Description</th>
<th>Range</th>
<th>Solar Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultraviolet</td>
<td>0 – 400 nm</td>
<td>7%</td>
</tr>
<tr>
<td>Visible</td>
<td>400 – 700 nm</td>
<td>44%</td>
</tr>
<tr>
<td>Near Infrared</td>
<td>700 – 1400 nm</td>
<td>37%</td>
</tr>
<tr>
<td>Short wave IR</td>
<td>1400 – 2400 nm</td>
<td>8%</td>
</tr>
<tr>
<td>Mid/Long wave IR</td>
<td>2400+ nm</td>
<td>4%</td>
</tr>
</tbody>
</table>
Scattering White Powder (Y2O3)

• Many different scattering white powders considered
• Yttrium Oxide (Y2O3) reflects UV above 0.235 microns through IR up to 8 microns
• This equates to 0.2% solar absorption
• If solar absorption is limited to 0.2%, the equilibrium temperature of a body in space drops to 60 K!
• Yttrium Oxide is also hydrophobic and chemically stable.
Cryogenic Thermal Control Coating

- Y2O3 scattering layer reflects UV, Visible, and Near to Mid-IR radiation
- A thin silver (or other) backing will reflect Far-IR radiation
- A metallic backing also allows for easy application
- Vapor deposition chamber 5 microns thickness
Funding Sources/Projects/Interest

- **Game Changing Development** – process development and performance testing
- Launch Services Program - Cube sat
- Materials International Space Station Experiment (MISSE) - space environment testing
- Northrop Grumman - reflectance testing
- Blue Origin - sample testing capability
- Nuclear Thermal Propulsion – system integration
- United Launch Alliance – spray on coating development
- Launch Services Program - Superconductivity
- NASA Innovative Advanced Concepts (NIAC) – Initial concept funding and Solar Surfing
GCD Project Objectives

• Optimization of powder sintering pressure and temperature (thermal properties & tile strength)
• Reflectance measurements using industry standard tools and techniques
• Absolute performance data using NASA designed deep-space simulator
• Application of a metallic backing (silver preferred)
• Engagement of KSC’s Thermal Protection System Facility expertise for large scale fabrication
• Atomic oxygen degradation characterization
• Electromagnetic charging characterization
Fabrication (Tile Samples)

- Compress the yttrium oxide white powder, then sinter it in an oven to make a “tile”
- Pressure used in compression and oven temperature impact tile strength and these parameters are currently being optimized
Fabrication (Spray-on Coating)

- Dissolve potassium bromide (KBr) in water
- Mix in Yttrium Oxide particles (which will not dissolve in water)
- Spray the desired surface using a paint sprayer
- After drying, the KBr forms sheets that hold the Y2O3 particles in place
- Multiple layer may be applied

This is a very similar process to making white paint, except with the use of a broadband optical material (KBr) as the binder in order to avoid UV absorption

Continuing work to enable more uniform application, increase adherence, maximize thickness, and minimize flaking
Reflectance Testing

• Jasco V-770 Spectrophotometer
AZ-93 (white paint) – Solar absorption: 15%

Reflectance plots like this are made measuring the material against the NIST standard reference material, Spectralon
CTCC Reflectance Plot

Yttrium Oxide Tile (Y2O3) – Solar absorption: -0.004% over this range

We are not making light... the Yttrium Oxide tiles are performing better than the Spectralon reference material!
Spray-on Yttrium Oxide Reflectance Plot

The bare stainless surface was cleaned with solvent and lightly scuffed.

The estimated solar absorbances are:
1. bare stainless *47%
2. painted steel (matte white finish) 26%
3. one coat of spray 15%
4. two coats of spray 10%.

(note 4% of the Sun’s irradiance is beyond 2.4 microns, but is not included in most alpha calculations. Qioptiq goes from .25 to 2.5 microns).

Coated 1 Weight: 0.165 g
Surface Area: 0.0027m²
Weight/SA: 0.061kgm⁻²

Coated 2 Weight: 0.316 g
Surface Area: 0.0027m²
Weight/SA: 0.117kgm⁻²

*The bare stainless surface was cleaned with solvent and lightly scuffed.
Deep-Space Simulator

- Reflectance testing shows **relative** improvement over existing coatings using the industry standard testing approach.
- The deep-space simulator is intended to provide an **absolute** measure of absorption.
- Deep-space simulated environment testing using a vacuum chamber, cryo-cooler, and solar simulator.

**Diagram:**
- Cryomech AL230 cold head (20 K)
- Two-part vacuum chamber with feed-throughs
- Black painted test chamber, mounted to cold head
- Test sample hanging from Kevlar thread
Solar Simulator

- Fiber optic quartz light source provides a good solar simulation from 255 nm to 2200 nm
- Short wave UV and long wave IR are difficult to simulate

The total intensity of light hitting the sample is adjusted to best match the same total intensity it would see in deep space at 1 AU from the Sun.
Deep-Space Simulator
Testing (Deep-Space Simulator)

- Promising data, but refinement still needed in the test set-up
- MLI blankets have to be undone and re-wrapped for each test
- Fiber must bend to illuminate the sample, and thermally strapped to the cold head each time
- A new vacuum chamber design has recently been completed
- Multiple runs have sample temps ranging from 102 – 125 K (1.2% – 2.7% absorption)

\[ T_{\text{max}} = 110 \text{ K, corresponding to 1.6\% light absorption} \]

\[ T_{\text{max}} = 107 \text{ K, corresponding to 1.5\% light absorption} \]
Other Heat Source Examples

- Silicon Diode, barrel style, wrapped in foil
- Aluminum “tank” with chip style sensor varnished inside
- Thick layer of black coating to absorb long-wave IR
- Kevlar strings
- Dark temp sensor wires
New Vacuum Chamber for KSC’s Deep-Space Simulator

- improve repeatability
- minimize time required between testing runs
- eliminate bends in the fiber optic cable
- allow for better chilldown of the fiber
- apply lessons learned to minimize parasitic heat leaks
GRC’s Deep-Space Simulator

Newport LCS-100 Solar Simulator

Optical Set-up
Vacuum Chamber
Cryomech PT805 cold head
Test sample in holder
GRC’s Deep-Space Simulator

- Promising data, but lacks consistency
- Changes from Run 1 to Run 2:
  - Orbital light spectrum filter decreased light intensity from 100 -180 mW/cm² to 85-164 mW/cm² (137 mW/cm²)
  - Adjusted sample holder to increase length of Kevlar string
- Modifications to the chamber have been recently completed, testing to follow

\[ T_{\text{max}} = 90 \, \text{K}, \text{corresponding to 0.67\%} \text{ light absorption} \]

\[ T_{\text{max}} = 135 \, \text{K}, \text{corresponding to 3.8\% light absorption} \]
In-Space Environment Testing

A Y2O3 sample is currently flying on ISS thanks to MSFC’s MISEE 11 panel (as of Feb 2019)
Cube Sat for In-space performance testing

- The Launch Services Program is developing a 3-U cube sat through the University of Florida
- The top sample holder will be thermally isolated and designed to always point away from the Earth
- It will hold 4 sample, 2 Y2O3 tiles and 2 Y2O3 tiles painted with an AZ-93 overcoat for comparisons
Patents/Papers

- Patent application “Method of Fabrication a Rigid Radiation Reflector – filed 9/18
- Patent application “Reflective Paint for Cryogenics Applications” – filed 9/19