NASA Applications of Molecular Adsorber Coatings

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Code 546 Contamination and Coatings Engineering Branch

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Abstract

The Molecular Adsorber Coating (MAC) is a new, innovative technology that was developed to reduce the risk of molecular contamination on spaceflight applications. Outgassing from materials, such as plastics, adhesives, lubricants, silicones, epoxies, and potting compounds, pose a significant threat to the spacecraft and the lifetime of missions. As a coating made of highly porous inorganic materials, MAC offers impressive adsorptive capabilities that help capture and trap contaminants. Past research efforts have demonstrated the coating’s promising adhesion performance, optical properties, acoustic durability, and thermal stability. These results advocate its use near or on surfaces that are targeted by outgassed materials, such as internal optics, electronics, detectors, baffles, sensitive instruments, thermal control coatings, and vacuum chamber test environments. The MAC technology has significantly progressed in development over the recent years. This presentation summarizes the many NASA spaceflight applications of MAC and how the coatings technology has been integrated as a mitigation tool for outgassed contaminants. For example, this sprayable paint technology has been beneficial for use in various vacuum chambers for contamination control and hardware bake-outs. The coating has also been used in small instrument cavities within spaceflight instrument for NASA missions.
Introduction

- What are Molecular Adsorber Coatings?
- Why do we need them for spaceflight applications?
- What are the benefits of using this coating technology?
Introduction

- **Molecular Outgassing**

  *in Spaceflight Applications*

  - Significant threat to the spacecraft and the lifetime of NASA missions
  - Originates from materials that outgas or release molecules during orbit inside of the spacecraft (in vacuum)
    - **Examples:** plastics, adhesives, lubricants, silicones, epoxies, tapes, potting compounds, solvents, and other similar sources
  - On-orbit molecular contaminants from outgassed materials can deposit onto hardware and instrument components, and thereby, degrade the performance of highly sensitive surfaces
    - **Examples:** optics, electronics, laser systems, detectors, baffles, solar arrays, and thermal control coatings, vacuum chambers

Photo Credit: NASA, [https://en.wikipedia.org/wiki/Space_Shuttle#/media/File:STS120LaunchHiRes-edit1.jpg]
Introduction

- **Molecular Adsorber Coating (MAC)**
  - Developed by NASA Goddard Space Flight Center (GSFC) as a practical *low mass* and *cost effective* solution to address on-orbit contamination from molecular outgassing
  - Sprayable, patent pending paint technology comprised of *inorganic materials* made from:
    - Highly permeable, porous zeolite minerals
    - Inorganic, colloidal silica based binders
  - Available in both *white* and *black* variations for internal use only
    - White Molecular Adsorber Coating, GSFC MAC-W
    - Black Molecular Adsorber Coating, GSFC MAC-B
  - Successfully demonstrated its technology with development and testing efforts in relevant space environments
  - Ready for infusion and application specific advancement efforts for spaceflight projects and commercial markets that need to protect surfaces against the damaging effects of outgassing and/or molecular contamination

Photo Credit: NASA/Pat Izzo
Introduction

Molecular Adsorber Coating (MAC)

MAC serves as a dual purpose contamination control coating

<table>
<thead>
<tr>
<th>Type of Coating</th>
<th>WHITE THERMAL CONTROL COATING</th>
<th>WHITE MAC</th>
<th>BLACK MAC</th>
<th>BLACK THERMAL CONTROL COATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Contamination Control</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Thermal Control Properties</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Optical Stray Light Control</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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</table>

MAC provides several other advantages as an innovative coating technology:

- Easily spray applied onto most substrates (with optimal adhesion performance)
- Tailored to meet specific adsorption characteristics (thickness dependent)
- Low mass (adds very little additional mass to the spacecraft)
- Low outgassing (made from all inorganic materials)
- Cost effective (made from low cost materials)
- Limited particulation effects (with cleaning mitigation techniques available)

Provides thermal control characteristics for thermal surfaces (white and black)

Provides optical straylight control for baffles and optical surfaces (black)
Background

- What is the chemistry behind the MAC technology?
- What are its coating properties?
Background

Chemistry

- MAC is comprised of two key components: (1) **ZEOLITE** and (2) **COLLOIDAL SILICA**

**ZEOLITE**

- **Pigment** *(Molecular Sieve)*
  - Acts as the adsorbent material that captures and traps molecules due to its porous structure

- **Desired Characteristics**
  - Large open pores, or cavities, within crystal structure
  - Large surface area to mass ratio that maximizes available trapping efficiency

- **Chemical Composition**
  - $\text{Na}_{86}(\text{AlO}_2)_{86}(\text{SiO}_2)_{106} \cdot x\text{H}_2\text{O}$

Contaminant Molecules

Cavity

ZEOLITE STRUCTURE
Background

Chemistry

MAC is comprised of two key components: (1) ZEOLITE and (2) COLLOIDAL SILICA

Unlike colloidal silica, other silicate based binders that are commonly used in thermal control coatings, tend to wrap around the zeolite structure. This prevents access to the active pores, or adsorption sites.

3D network of silica

Nano-sized silica molecules (SiO₂)

COLLOIDAL SILICA

- **Binder (Suspensions of Colloidal Silica in Liquid Phase)**
  - Acts as the glue that holds the coating together and provides adhesion between substrate layers

- **Desired Characteristics**
  - Nano-sized silica molecules are not large enough to clog pores or prevent access to the adsorption sites on the zeolite structure. Instead, a 3-dimensional network of silica gels around the zeolite structure.

- **Chemical Composition**
  - SiO₂ · xH₂O · Stabilizers
Background

- **Surface Morphology**

**Confocal Imaging Microscope (CIM)**

<table>
<thead>
<tr>
<th>CIM Parameters</th>
<th>CIM Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olympus LEXT confocal laser scanning microscope producing 3D imaging of coating surface at 20X magnification</td>
<td>Image above illustrates high surface area and surface roughness of the coating</td>
</tr>
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**Scanning Electron Microscope (SEM)**

<table>
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<tr>
<th>SEM Parameters</th>
<th>SEM Analysis</th>
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<tbody>
<tr>
<td>Electron scanning microscope under 5 kilovolts (kV) at 636X magnification</td>
<td>Image above illustrates highly porous structure of zeolite materials in the coating</td>
</tr>
</tbody>
</table>

Photo Credit: NASA/Code 546

Photo Credit: NASA (SEM Analysis performed by Mollie Grossman/NASA GSFC Code 541)
# Background

## Thermal & Optical Properties

<table>
<thead>
<tr>
<th>COATING TYPE</th>
<th>COATING DESCRIPTION</th>
<th>COATING THICKNESS</th>
<th>SOLAR ABSORPTANCE</th>
<th>NORMAL EMITTANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Silicate</td>
<td>Alion Z-93P</td>
<td>4.0-5.0 mils</td>
<td>0.16</td>
<td>0.92</td>
</tr>
<tr>
<td>White Silicate</td>
<td>Alion Z-93C55</td>
<td>4.0-5.0 mils</td>
<td>0.13</td>
<td>0.92</td>
</tr>
<tr>
<td><strong>White MAC</strong></td>
<td><strong>GSFC MAC-W</strong></td>
<td><strong>4.0-5.0 mils</strong></td>
<td><strong>0.30</strong></td>
<td><strong>0.93</strong></td>
</tr>
<tr>
<td><strong>Black MAC</strong></td>
<td><strong>GSFC MAC-B</strong></td>
<td><strong>2.5-8.5 mils</strong></td>
<td><strong>0.97</strong></td>
<td><strong>0.92</strong></td>
</tr>
<tr>
<td>Black Polyurethane</td>
<td>Aeroglace® Z306</td>
<td>2.0-3.0 mils</td>
<td>0.96</td>
<td>0.91</td>
</tr>
<tr>
<td>Black Polyurethane</td>
<td>Aeroglace® Z307</td>
<td>2.0-3.0 mils</td>
<td>0.97</td>
<td>0.88</td>
</tr>
</tbody>
</table>

**Solar Absorptance** ($\alpha_S$) - The measure of the proportion of solar radiation the coating absorbs.

**Normal Emittance** ($\varepsilon_N$) - The measure of the relative ability of the coating to radiate absorbed radiation.

AZ Technology LPSR-300 Spectral Reflectometer

*Instrument measures reflectance from 0.25 to 2.8 microns at a 15° angle of incidence (ASTM E903-82)*

Gier-Dünkle DB-100 Infrared Reflectometer

*Instrument measures reflectance from 5 to 40 microns at room temperature (ASTM E408-71)*
Background

- **Adsorption Characteristics**
  - *Molecular capacitance* is the measure of the coating’s ability to adsorb or entrap outgassed materials
  - Adsorption characteristics are dependent on:
    - Coating Thickness
    - Surface Area Coverage
    - Type of Contaminant
    - Duration of Exposure
  - Main contaminant sources used for vacuum molecular capacitance testing have been *complex chemical constituents*, which are representative of the commonly outgassed materials in spaceflight applications
    - *Long Chain Hydrocarbons*
      - Example: *Stearyl Alcohol*
    - *Silicone Based Compounds*
      - Example: *DC704 Diffusion Pump Oil*
## Background

<table>
<thead>
<tr>
<th>Long Chain Hydrocarbon</th>
<th>Type of Contaminant</th>
<th>Silicone Based Compound</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stearyl Alcohol</strong></td>
<td></td>
<td><strong>Dow Corning® DC704 Diffusion Pump Oil</strong></td>
</tr>
</tbody>
</table>

- **Stearyl Alcohol**, comprised of volatile condensable materials that have a constant vapor pressure, provides a constant source rate for testing purposes.

- **DC704 Diffusion Pump Oil**, comprised of complex materials that have varying vapor pressures, does not provide a constant source rate for testing purposes.

<table>
<thead>
<tr>
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<th>Chemical Name</th>
<th>Molecular Capacitance</th>
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<tbody>
<tr>
<td>1-octadecanol</td>
<td><em>C_{18}H_{38}O</em></td>
<td><em>1.2 mg/cm^{2}</em>*</td>
</tr>
<tr>
<td>C_{18}H_{38}O</td>
<td><strong>C_{28}H_{32}O_{2}Si_{3}</strong></td>
<td></td>
</tr>
<tr>
<td>2.3 mg/cm^{2}</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>6.0 mils</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>~88 hrs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45 °C</td>
<td></td>
<td></td>
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</table>

- *Stearyl alcohol adsorption data is based on samples that have reached saturation at the coating thickness.*
- **Diffusion pump oil adsorption data is based on samples that have not reached saturation. The value listed is adsorption at a minimum at the coating thickness.*
Background

Effect of Coating Thickness on MAC Adsorption Capabilities

Molecular capacitance is a function of coating thickness. Ex: white MAC at 6 mils is projected to have a molecular capacitance three times greater than a 3 mil sample.

Contaminant Source
Stearyl Alcohol at 45 °C

Adsorption varies from 0.5 to 5.0 mg/cm² at thicknesses between 2 to 11 mils
Background

■ Structural Integrity

■ Performed vacuum thermal cycle tests at temperature extremes similar to those expected during spaceflight conditions to evaluate the thermal survivability and vacuum stability of the coating
  ■ MAC is anticipated to operate at temperatures that are representative of electronics boxes and other sensitive internal surfaces, which typically reach temperatures between -10 °C to 40 °C

■ Coating structural integrity was evaluated on its adhesion performance before and after exposure to vacuum thermal cycle test conditions
  ■ Favorable coating adhesion performance results were achieved

<table>
<thead>
<tr>
<th>Thermal Cycle Parameters</th>
<th>Expected Survivability Conditions</th>
<th>White MAC Test Conditions</th>
<th>Black MAC Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vacuum Duration</strong></td>
<td></td>
<td>50 cycles</td>
<td>100 cycles</td>
</tr>
<tr>
<td><strong>Cold Temperature Limit</strong></td>
<td>-10 °C</td>
<td>-40 °C</td>
<td>-60 °C</td>
</tr>
<tr>
<td><strong>Hot Temperature Limit</strong></td>
<td>40 °C</td>
<td>70 °C</td>
<td>90 °C</td>
</tr>
<tr>
<td><strong>Test Margin</strong></td>
<td></td>
<td>30 degrees</td>
<td>50 degrees</td>
</tr>
</tbody>
</table>

Photo Credit: NASA/Code 546
Applications

- *What are the NASA Applications of MAC?*
- *What is its scope for other applications?*
NASA Applications

- MAC has been proposed to be integrated as an innovative contamination mitigation tool on several NASA applications in the recent year(s).

- Current examples of these implementation efforts include:
  - Within vacuum chamber environments to protect test equipment from outgassed contaminants
    - **JWST**: Chamber A
  - Inside small, sensitive instrument cavities to reduce effects of on-orbit material outgassing
    - **ICON**: Far Ultraviolet Instrument
    - **GEDI**: Laser Components
  - For hardware bake-outs to reduce effects of vacuum material outgassing
    - **MMS**: Navigator Box
NASA Applications

**Project**

**James Webb Space Telescope (JWST)**
- Successor to NASA’s Hubble Space Telescope
- Most powerful infrared space telescope ever built with a 6.5 meter primary mirror and a tennis court sized five layer sunshield
- Expected launch date is 2018

**Application**

**Chamber A at NASA Johnson Space Center (JSC) in Houston, Texas**
- MAC was used to capture *vacuum chamber contamination* originating from persistent outgassing sources within Chamber A, such as silicone pump oil residue (and other hydrocarbons)
- MAC is expected to lower the contamination risk cost effectively and prevent harmful outgassed components within the chamber environment from migrating and depositing onto JWST’s highly sensitive *optical ground support equipment* surfaces during testing
NASA Applications

Problem

Chamber A’s Contamination

- Chamber A is a 55 ft diameter cryogenic optical vacuum chamber that has been upgraded to test JWST in a space stimulation environment.
- Prior to its upgrade, Chamber A was originally used for testing space capsules for NASA’s Apollo missions.
- Due to its history, DC704 oil residue (among other hydrocarbons) still remained within the chamber.
  - Silicone based contaminants are known to outgas and spread easily, even at ambient temperatures, and are extremely difficult to remove. Its outgassing effects can harm test equipment.

Solution

MAC Test Panels

- Much effort has been performed to remove these persistent contaminants.
  - Among one of the innovative contamination mitigation tools is through the use of MAC.
- MAC technology was tested during JWST’s Chamber A Commissioning Test in October 2014 for proof of concept prior to its first large scale vacuum chamber application in May 2015.

Chamber A Commissioning Test: MAC Proof of Concept

<table>
<thead>
<tr>
<th>Nonvolatile Residue (NVR) Materials Chemical Analysis</th>
<th>Pristine Sample 01</th>
<th>Contaminated Sample 04 (Loc 1, BD)</th>
<th>Contaminated Sample 05 (Loc 2, PL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Size: 700 cm²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NVR Adsorption</td>
<td>5.7 E-03 mg/cm²</td>
<td>1.7 E-01 mg/cm²</td>
<td>1.3 E-01 mg/cm²</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>4.0 mg (&gt;99 %)</td>
<td>103.1 mg (88%)</td>
<td>82.4 mg (89%)</td>
</tr>
<tr>
<td>DC704 Diffusion Pump Oil</td>
<td>0 mg</td>
<td>0.7 mg (0.6%)</td>
<td>4.0 mg (4%)</td>
</tr>
<tr>
<td>Methyl Based Silicones</td>
<td>0 mg</td>
<td>0.5 mg (0.4%)</td>
<td>1.4 mg (1%)</td>
</tr>
<tr>
<td>Other Contaminants</td>
<td>0 mg</td>
<td>12.4 mg (11%)</td>
<td>5.3 mg (6%)</td>
</tr>
</tbody>
</table>

Fourier Transform Infrared Spectroscopy (FTIR) and Gas Chromatography/Mass Spectrometry (GC/MS) Materials Chemical Analysis performed by Aparna Boddapati NASA/GSFC Code 541
NASA Applications

**Description of Task**

MAC was deployed for JWST’s first Optical Ground Support Equipment (OGSE-1) test effort in May 2015

- Several MAC panels were custom designed, fabricated, and installed in very strategic locations within Chamber A to capture vacuum chamber contamination and prevent them from entering the test environment where the OGSE is housed.

All Photo Credits: NASA/Chris Gunn
NASA Applications

Project

Ionospheric Connection Explorer (ICON)
- NASA explorer program, led by University of California-Berkeley (UCB), designed to study the boundary between Earth and space and to understand its physical connection
- Expected launch date is 2017

Application

ICON’s Far Ultraviolet (FUV) Imaging Spectrograph Instrument
- MAC is proposed to be used internally within the FUV instrument cavity to address on-orbit material outgassing concerns and to meet molecular contamination requirements
- This implementation will be MAC’s first flight mission application

Description of Task

Custom Fabricated MAC Plates
- UCB supplied hardware will be spray applied with MAC and installed in strategic locations within the instrument cavity of the spectrograph and imager
NASA Applications

Project

Global Ecosystem Dynamics Investigation Lidar (GEDI)

- NASA science program designed to characterize the effects of changing climate and land use on ecosystems, and to understand Earth’s carbon cycle and biodiversity
- Expected launch date is 2018

Application

GEDI’s Laser Electronics Components

- MAC is proposed to be used on the interior cover of a laser q-switch board to address on-orbit material outgassing from electronics cards and its conformal coatings, and to meet molecular contamination requirements

Description of Task

- MAC will be spray applied directly onto the laser cover hardware surface
Project

Magnetospheric Multiscale Mission (MMS)

- NASA mission comprised of four identical satellites flying in a tetrahedral formation designed to investigate how the magnetic fields of the Sun and Earth connect and disconnect
- Launched on March 2015

Application

Vacuum Bake-out of MMS’s Navigator Box Components

- MAC was used during a Navigator (NAV) box thermal vacuum test to reduce the effects of vacuum material outgassing from pre-baked components, such as electronic wires and harnesses

Description of Task

Custom Fabricated MAC Plates

- MAC coated plates were placed alongside the NAV box components during thermal vacuum test runs
- Quartz Crystal Microbalance (QCM) outgassing rates showed a significant reduction with the use of MAC
- Post analysis of MAC samples verified the adsorption of hydrocarbons, silicones, phenyls, and plasticizers from the NAV vacuum test environment

QCM OUTGASSING RATES

<table>
<thead>
<tr>
<th>Chamber Description</th>
<th>Outgassing Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty Chamber</td>
<td>No MAC ~575 Hz/hr</td>
</tr>
<tr>
<td>Chamber with NAV Box and pre-baked Components</td>
<td>No MAC &gt;~6000 Hz/hr</td>
</tr>
<tr>
<td>With MAC Plate, TR1</td>
<td>With MAC Plate, TR1 ~300 Hz/hr</td>
</tr>
<tr>
<td>With MAC Plate, TR2</td>
<td>With MAC Plate, TR2 ~675 Hz/hr</td>
</tr>
</tbody>
</table>

QCM Analysis performed by Glenn Rosecrans SGT/Code 546
Commercial Applications

NASA GSFC Innovative Technology and Partnerships Office (ITPO)

- We coordinate with ITPO for technology transfer licensing opportunities
  - ITPO facilitates creative collaborations between NASA Goddard technology researchers and external parties for mutual benefit. For more information, please visit [http://itpo.gsfc.nasa.gov](http://itpo.gsfc.nasa.gov)

- Commercial applications for MAC may include industries that require general gas adsorption, collection and containment of outgassed and/or offgassed contaminants and volatiles. Some of these potential applications may include but are not limited to:
  - Aerospace
  - Vacuum Systems
  - Laser
  - Optics
  - Electronics
  - Semiconductor
  - Manufacturing
  - Pharmaceutical
  - Medical
  - Food Industry
  - Chemical Processing
Conclusions
Conclusions

■ Summary

■ MAC is an innovative solution for molecular contamination control
  ■ Captures contaminants that otherwise can cause harm by depositing onto sensitive hardware
  ■ Helps meet mission molecular contamination requirements for hardware with outgassing components
  ■ Lowers pressures in vacuum chambers
  ■ Reduces outgassing rates during thermal bake-out times
  ■ Limits the use of cryogenic panels (i.e. liquid nitrogen scavenger cold plates) in vacuum chambers
  ■ Ideal within instrument cavities or hardware with electronics, optics, mirrors, telescopes, cameras, laser systems, detectors, baffles, solar arrays, etc

■ Future Plans

■ Continue with the advancement of the existing MAC technology with further qualification efforts and seek more infusion opportunities for future spaceflight mission applications
Acknowledgements

Our **MAC Technology Team** consists of

<table>
<thead>
<tr>
<th>Nithin Abraham</th>
<th>John Petro</th>
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<tbody>
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<thead>
<tr>
<th>Mark Hasegawa</th>
<th>Sharon Straka</th>
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<tbody>
<tr>
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Acknowledgements

Valuable support was provided by individuals from NASA GSFC and Stinger Ghaffarian Technologies, Inc (SGT):

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<thead>
<tr>
<th>BRANCH SUPPORT</th>
<th>THERMAL COATINGS SUPPORT</th>
<th>ITPO TECH TRANSFER SUPPORT</th>
<th>MATERIALS ENGINEERING SUPPORT</th>
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<tr>
<td>Randy Hedgeland</td>
<td>Alfred Wong</td>
<td>Dennis Small</td>
<td>Doris Jallice</td>
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<tr>
<td>Nancy Carosso</td>
<td>Kenny O’Connor</td>
<td>Alexson Harris-Kirksey</td>
<td>Mollie Grossman</td>
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<tr>
<td>Jack Triolo</td>
<td>Grace Miller</td>
<td></td>
<td>Aparna Boddapti</td>
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<tr>
<td>SGT/Code 546</td>
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<tr>
<td>Eve Wooldridge</td>
<td>Mark Secunda</td>
<td>David Hughes</td>
<td>Glenn Rosecrans</td>
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<td>Kelly Henderson</td>
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<td>Craig Jones</td>
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References

MOLECULAR ADSORBER COATINGS


NASA SPACEFLIGHT MISSIONS

- James Webb Space Telescope (JWST), <http://www.jwst.nasa.gov/>
- Ionospheric Connection Explorer (ICON), <http://icon.ssl.berkeley.edu/>
- Global Ecosystem Dynamics Investigation Lidar (GEDI), <http://science.nasa.gov/missions/gedi/>
- Magnetospheric Multiscale (MMS), <http://mms.gsfc.nasa.gov/>
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