NASA Applications of Molecular Adsorber Coatings

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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

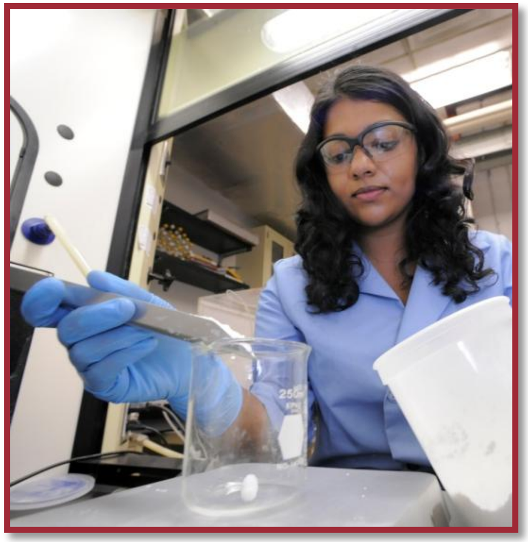


Photo Credit: *NASA/Pat Izzo*

Introduction

- **Molecular Adsorber Coating (MAC)**
  - MAC serves as a dual purpose **contamination control** coating

Type of Coating	WHITE THERMAL CONTROL COATING	WHITE MAC	BLACK MAC	BLACK THERMAL CONTROL COATING
Molecular Contamination Control		✓	✓	
Thermal Control Properties	✓	✓	✓	✓
Optical Stray Light Control			✓	✓

- Provides **thermal control** characteristics for thermal surfaces *(white and black)*
- Provides **optical straylight control** for baffles and optical surfaces *(black)*

  - 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)*

Background

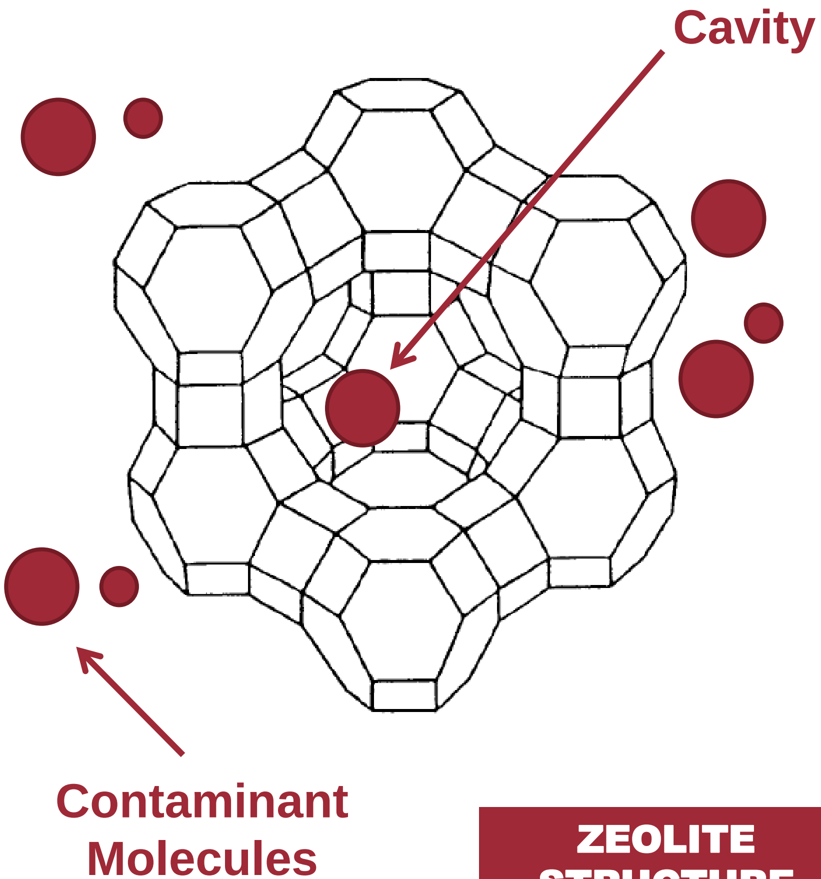
- *What is the chemistry behind the MAC technology?*
- *What are its coating properties?*

Background

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

ZEOLITE

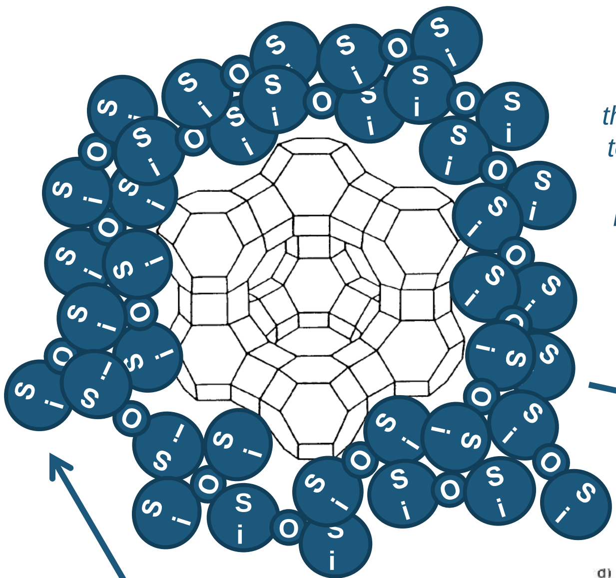
- **Pigment *(Molecular Sieve)***
  - Acts as the adsorbent material that captures and traps molecules due to its porous structure
- **Desired Characteristics**
  - Large open pores, or cavities, within crystal structure
  - Large surface area to mass ratio that maximizes available trapping efficiency
- **Chemical Composition**
  - $Na_{86}[(AlO_2)_{86}(SiO_2)_{106}] \cdot xH_2O$



ZEOLITE STRUCTURE

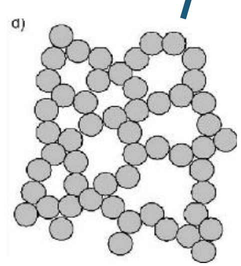
Background

- **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 (SiO_2)

BINDER NETWORK SURROUNDING ZEOLITE

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**
  - $SiO_2 \cdot xH_2O \cdot$ Stabilizers

Background

▪ Surface Morphology

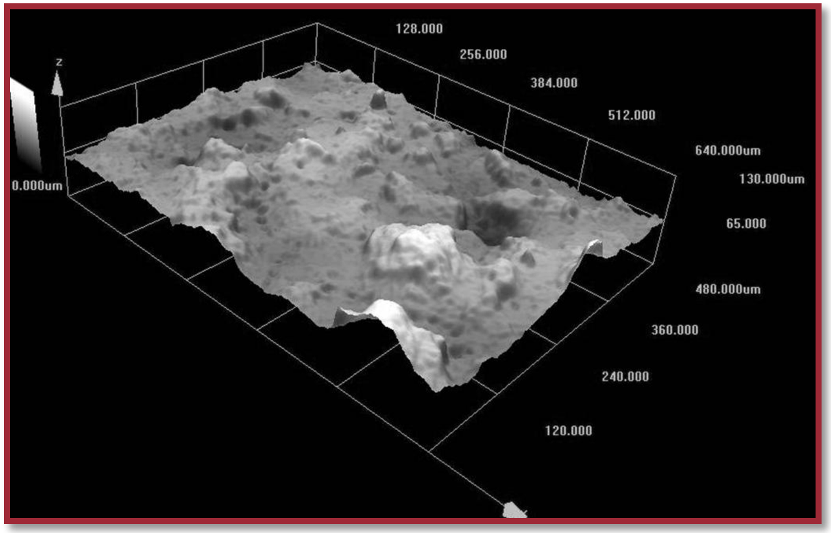


Photo Credit: *NASA/Code 546*

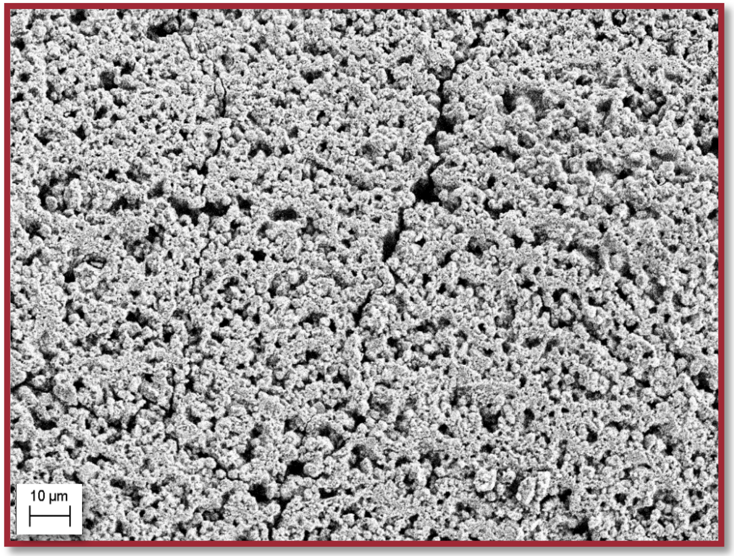


Photo Credit: *NASA (SEM Analysis performed by Mollie Grossman/NASA GSFC Code 541)*

Confocal Imaging Microscope (CIM)

CIM Parameters	CIM Analysis
Olympus LEXT confocal laser scanning microscope producing 3D imaging of coating surface at **20X** magnification	Image above illustrates **high surface area** and **surface roughness** of the coating

Scanning Electron Microscope (SEM)

SEM Parameters	SEM Analysis
Electron scanning microscope under 5 kilovolts (kV) at **636X** magnification	Image above illustrates **highly porous structure** of zeolite materials in the coating

Background

▪ Thermal & Optical Properties

Solar Absorptance (α_S)	Normal Emittance (ε_N)
The measure of the proportion of solar radiation the coating absorbs 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)*	**The measure of the relative ability of the coating to radiate absorbed radiation** Gier-Dünkle DB-100 Infrared Reflectometer *Instrument measures reflectance from 5 to 40 microns at room temperature (ASTM E408-71)*

COATING TYPE	COATING DESCRIPTION	COATING THICKNESS	SOLAR ABSORPTANCE	NORMAL EMITTANCE
White Silicate	Alion Z-93P	4.0-5.0 mils	0.16	0.92
White Silicate	Alion Z-93C55	4.0-5.0 mils	0.13	0.92
White MAC	GSFC MAC-W	4.0-5.0 mils	0.30	0.93
Black MAC	GSFC MAC-B	2.5-8.5 mils	0.97	0.92
Black Polyurethane	Aeroglaze® Z306	2.0-3.0 mils	0.96	0.91
Black Polyurethane	Aeroglaze® Z307	2.0-3.0 mils	0.97	0.88

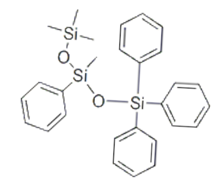
Background

- **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*

Photo Credit: *NASA/Pat Izzo*

  - 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

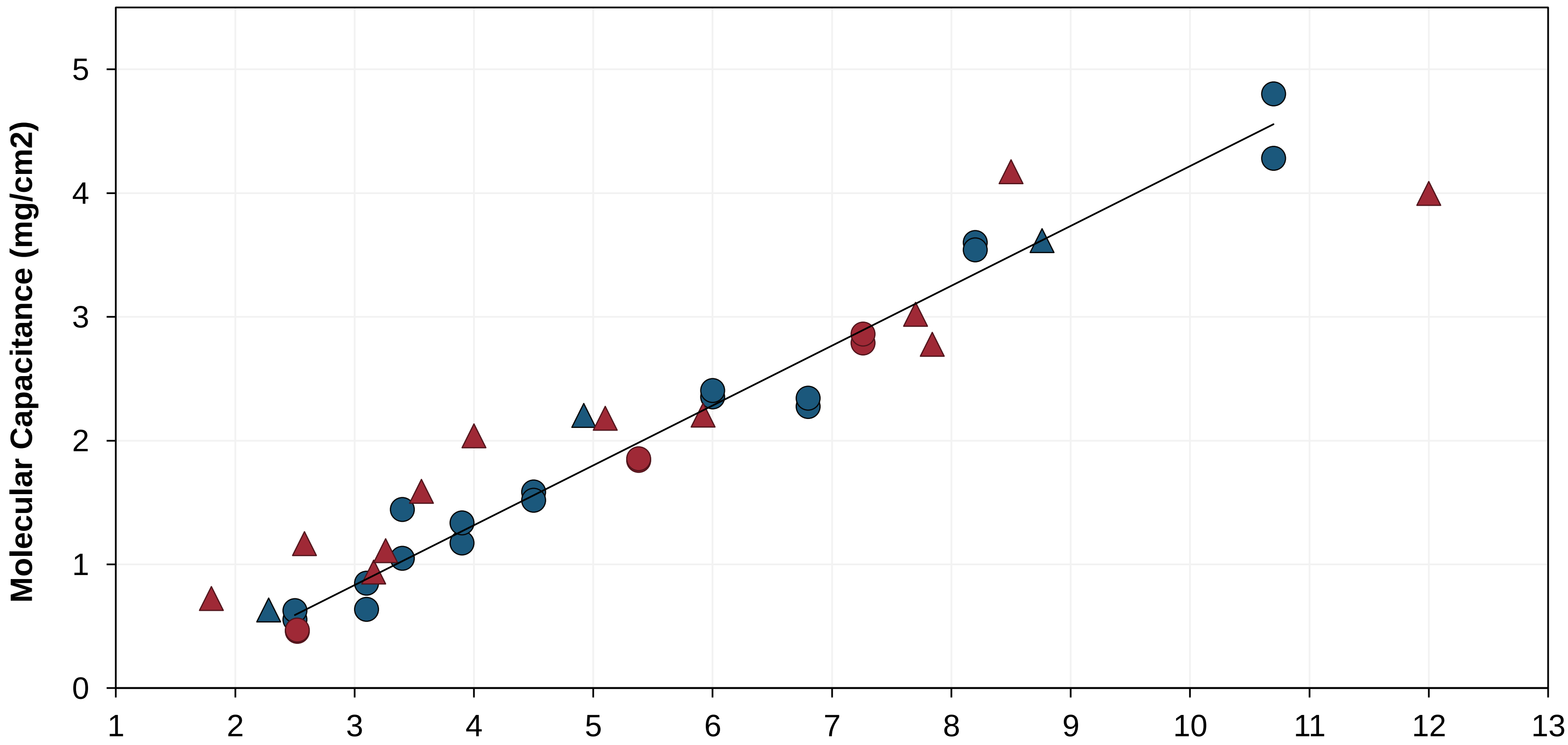
Long Chain Hydrocarbon	*Type of Contaminant*	Silicone Based Compound
Stearyl Alcohol  *Stearyl Alcohol*, comprised of volatile condensable materials that have a constant vapor pressure, provides a constant source rate for testing purposes.	*Contaminant Source*	**Dow Corning ® DC704 Diffusion Pump Oil**  *DC704 Diffusion Pump Oil*, comprised of complex materials that have varying vapor pressures, does not provide a constant source rate for testing purposes.
1-octadecanol	*Chemical Name*	tetramethyl tetraphenyl trisiloxane
$C_{18}H_{38}O$	*Chemical Formula*	$C_{28}H_{32}O_2Si_3$
2.3 mg/cm^2 *	*Molecular Capacitance*	**1.2 mg/cm^2** **
6.0 mils	*Coating Thickness*	6.0 mils
~88 hrs	*Exposure Time*	~115 hrs
45 ˚C	*Source Temperature*	70 ˚C

* *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.*

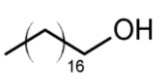
Background

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.



- ● WHITE MAC (Formula B-TRL6) at 88 hr exposure
- ▲ WHITE MAC (Formula B-TRL6) at 160 hr exposure
- ▲ BLACK MAC (Formula 2-ML-H75) at 160 hr exposure
- ● BLACK MAC (Formula 2-ML-H75) at 155 hr exposure



Contaminant Source

Stearyl Alcohol at 45 ˚C

Adsorption varies from 0.5 to 5.0 mg/cm^2 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

Thermal Cycle Parameters	Expected Survivability Conditions	White MAC Test Conditions	Black MAC Test Conditions
Vacuum Duration		50 cycles	100 cycles
Cold Temperature Limit	- 10 ˚C	- 40 ˚C	- 60 ˚C
Hot Temperature Limit	40 ˚C	70 ˚C	90 ˚C
Test Margin		30 degrees	50 degrees

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:

Photo Credit: NASA <http://www.nasa.gov/content/goddard-implementation-plan-in-response-to-the-2014-nasa-strategic-plan>

Goddard SPACE FLIGHT CENTER

- 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

Photo Credit: *NASA/ Chris Gunn < http://www.nasa.gov/content/space-simulation-chamber-prepared-for-testing-webb-telescope>*

Photo Credit: *NASA/Chris Gunn <https://www.nasa.gov/ multimedia/imagegallery/image_feature_2467.html>*

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

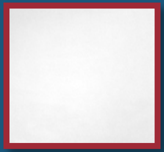
Photo Credit: NASA, http://grin.hq.nasa.gov/ ABSTRACTS/GPN-2001-000013.html

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

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

Photo Credit: NASA/UC Berkeley <http://icon.ssl.berkeley.edu/>

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

Photo Credit: *NASA <http://science.nasa.gov/missions/gedi/>*

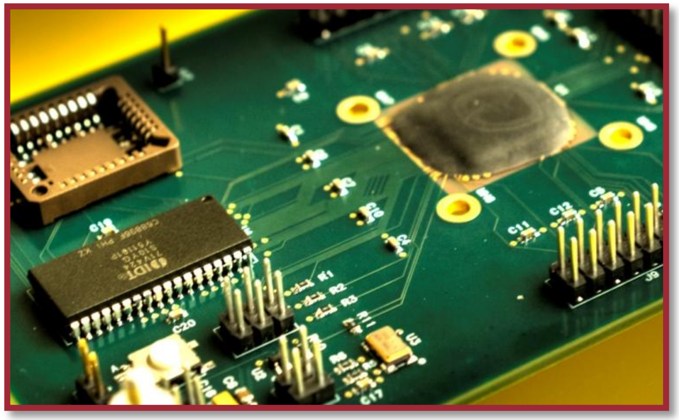


Photo Credit: *NASA <https://www.nasa.gov/sites/default/files/paquettes_device_0.jpg>*

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

NASA Applications

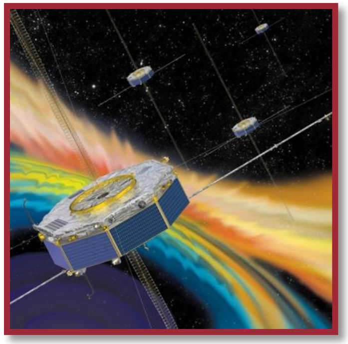


Photo Credit: NASA <http://mms.gsfc.nasa.gov/index.html>

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

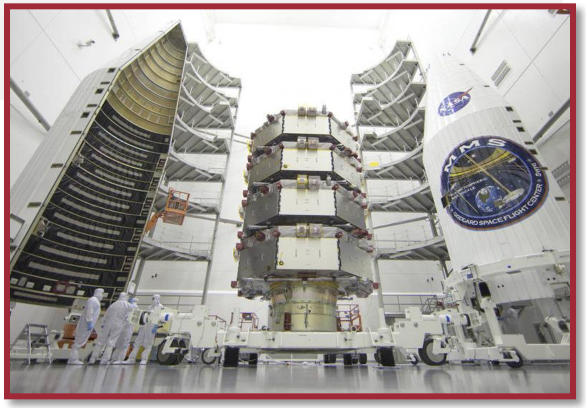


Photo Credit: NASA <http://mms.gsfc.nasa.gov/index.html>

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

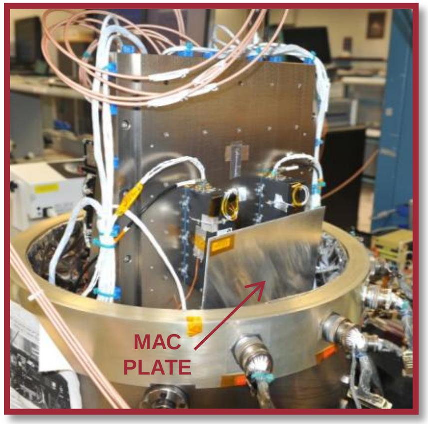


Photo Credit: NASA/MMS

Description of Task

Custom Fabricated MAC Plates

- MAC coated plates were placed along side 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	
Empty Chamber	No MAC ~575 Hz/hr
Chamber with NAV Box and pre-baked Components	No MAC >~6000 Hz/hr
	With MAC Plate, TR1 ~300 Hz/hr
	With MAC Plate, TR2 ~675 Hz/hr

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
  - 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

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Kelly Henderson *SGT/Code 546*	**Evelyn Lambert** *Intern/Code 546*		
Joseph Ward *SGT/Code 546*			
Niko Stergiou *SGT/Code 546*			
Craig Jones *SGT/Code 546*			

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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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