Polymer Aerogels in Space:
How Low Earth Orbit Shapes Advanced Materials

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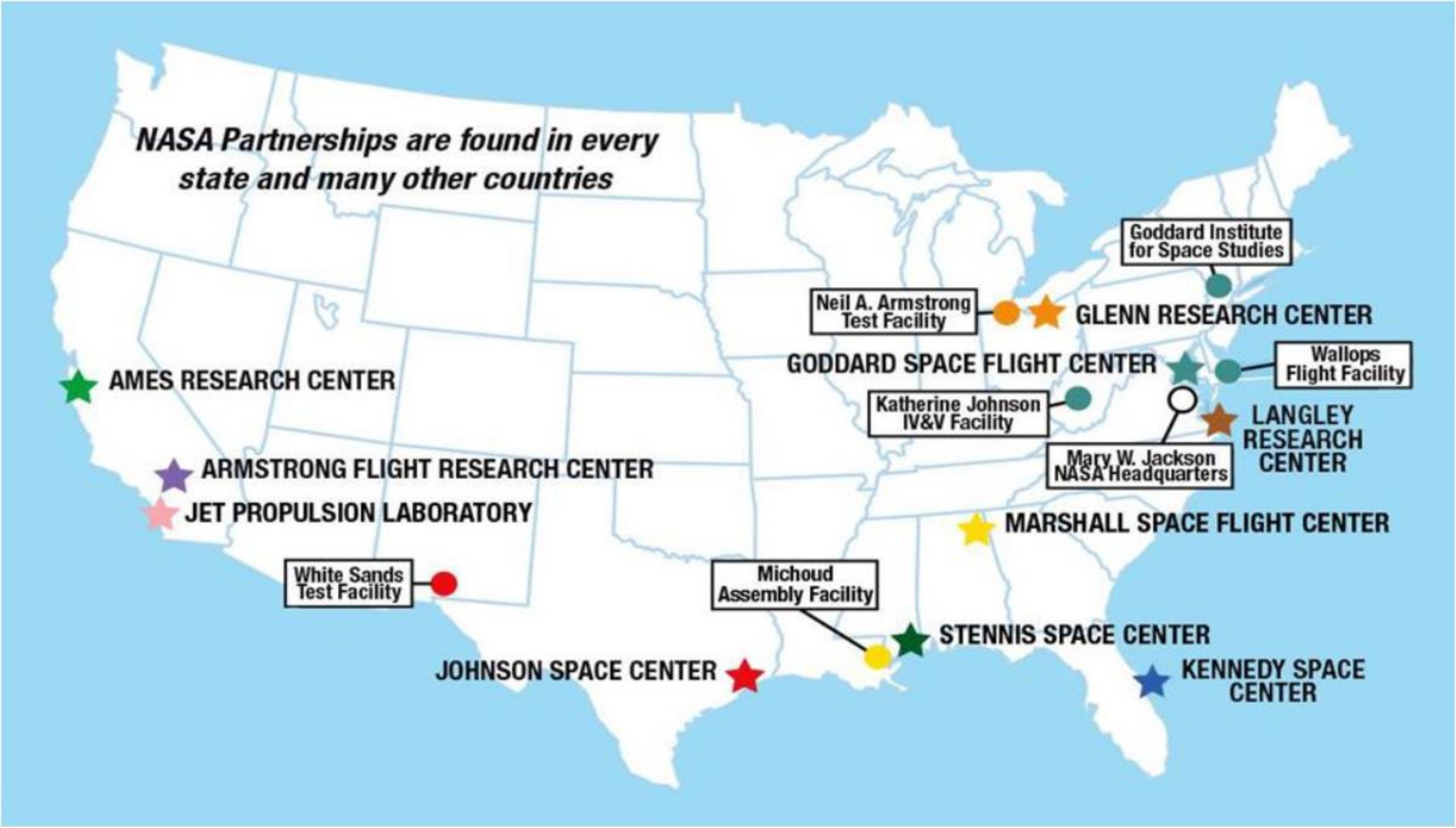
Spring 2025 Colloquium Series, Depart. of Physics and Astronomy, Ball State University, Muncie, IN

Centers and Field Sites



Center Specialties

NASA Headquarters
Agency leadership
Washington D.C.

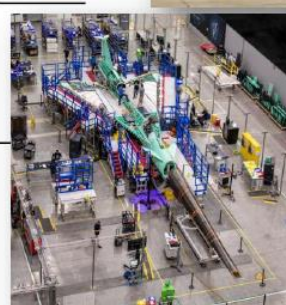
Ames Research Center
Aeronautics & astrobiology research
Moffett Field, California

Armstrong Flight Center
Flight research
Edwards, California

Glenn Research Center
Aero propulsion & communications technology
Cleveland, Ohio

Johnson Space Center
Human space exploration
Houston, Texas

Kennedy Space Center
Launch missions
Merritt Island, Florida



Goddard Space Flight Center
Universe observations, space communications & navigation
Greenbelt, Maryland

Jet Propulsion Laboratory
Robotic exploration of the solar system & earth observations
Pasadena, California

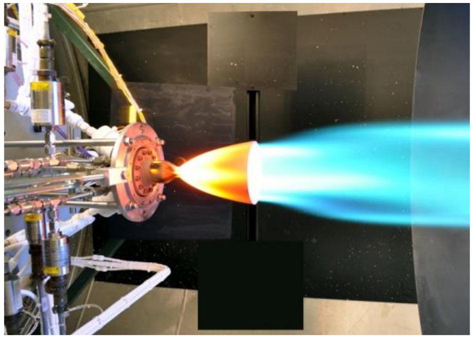
Langley Research Center
Aviation, space technology & earth science
Hampton, Virgina

Marshall Space Flight Center
Space transportation & propulsion technologies
Huntsville, Alabama

Stennis Space Center
Rocket propulsion testing & remote sensing technology
Mississippi

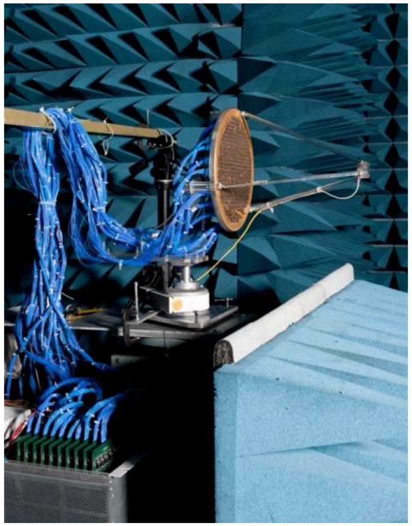
GRC Core Competencies

Air-Breathing Propulsion



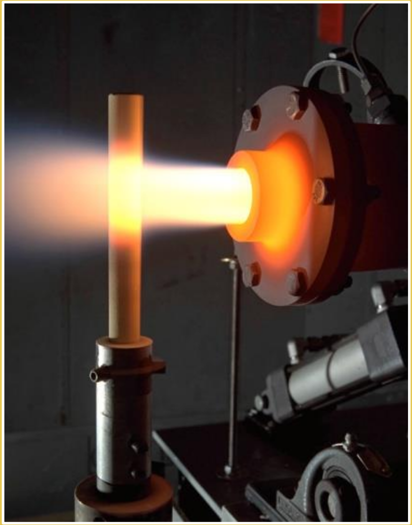
In-Space Propulsion and Cryogenic Fluids Management

Physical Sciences and Biomedical Technologies in Space



Communications Technology and Development

Power, Energy Storage and Conversion

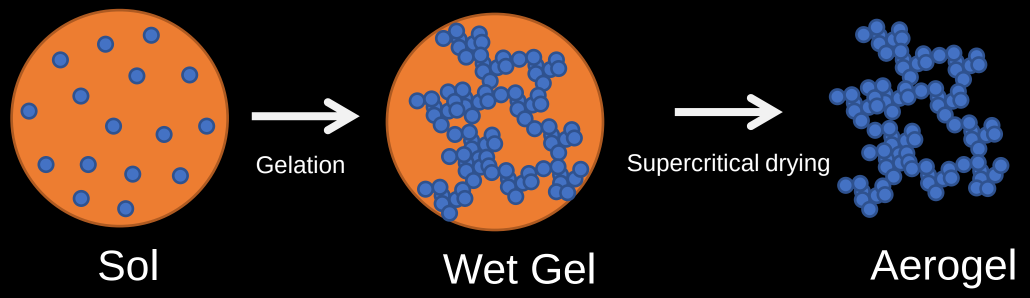


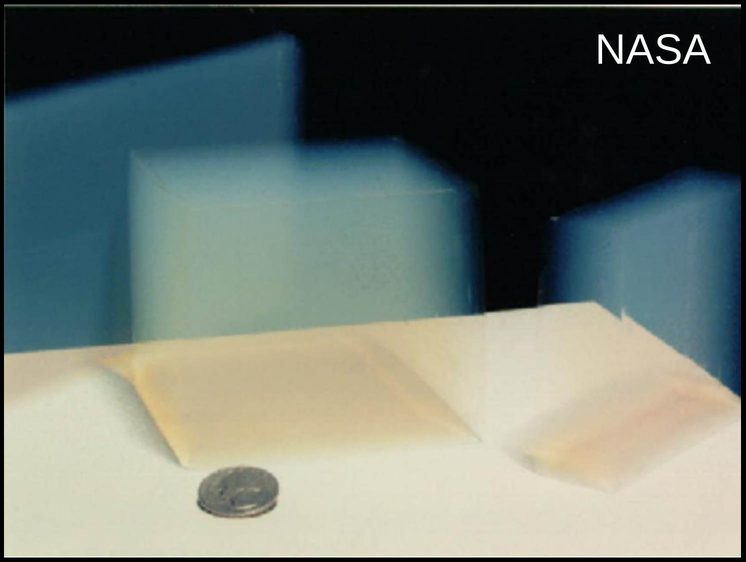
Materials and Structures for Extreme Environments

Aerogel: Solid Blue Smoke

Aerogel definition: Highly porous solids made by drying a wet gel without shrinking

- Silica Aerogel or just simply Aerogel
  - Lowest density of any solid known to man (1.1 mg cm^{-3})
  - Lowest optical index of refraction (1.002)
  - Lowest thermal conductivity (16 mW/m.K)
    - 2-4 times better than fiberglass under ambient pressure, 10-15 times better in light vacuum
  - Lowest speed of sound through a material (70 m/s)
  - Lowest dielectric constant from 3-40 GHz (1.008)

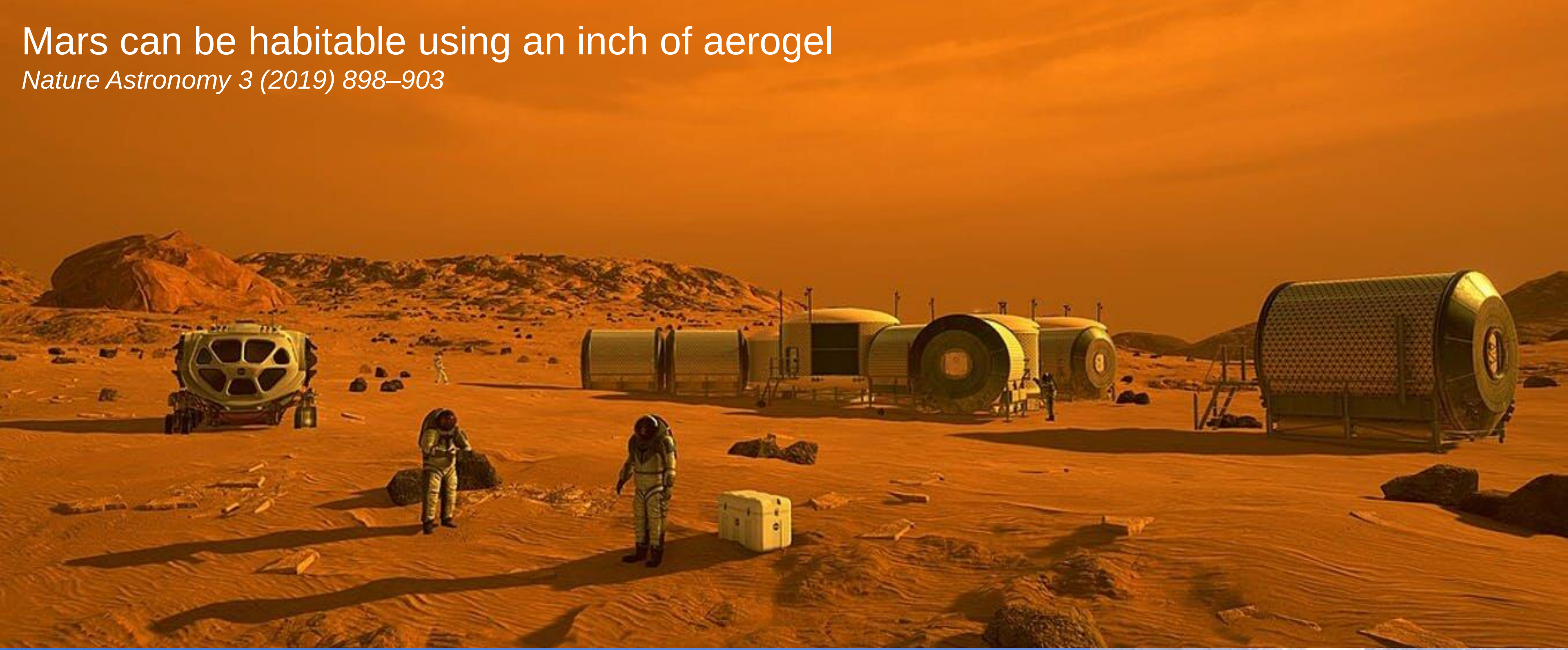




Typical monolithic silica aerogels

Mars can be habitable using an inch of aerogel

Nature Astronomy 3 (2019) 898–903

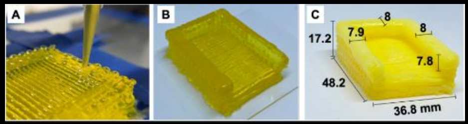


Aerogel in oil industry

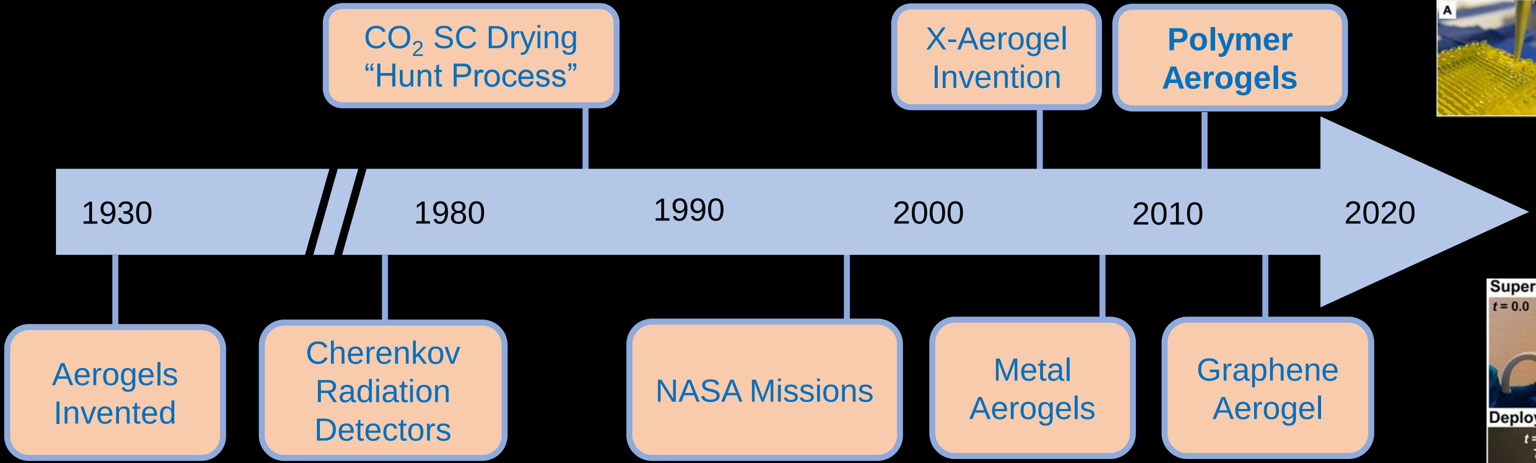
Aerogel clothing

Brief history of aerogel

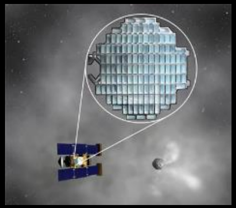
Polyimide Aerogel
(*ACS Appl. Mater. Interfaces* 2012)



3D-printed Aerogel
(*RSC Appl. Polym., 2024*)



Prof. S. Kistler

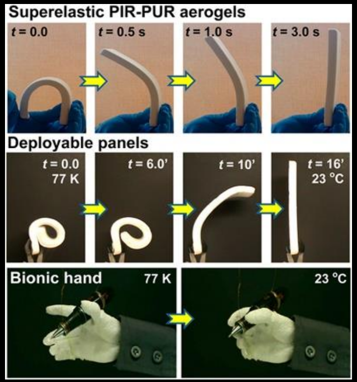


NASA

NASA

Gold Aerogel
(phys.org)

Aerographite
(extremetech.com)



Shape Memory
Polyurethane Aerogel
(*Chem. Mater.* 2017)

From inorganic to purely organic aerogels

Native

Cross-linked

Diverse range of polymers and diverse potential applications

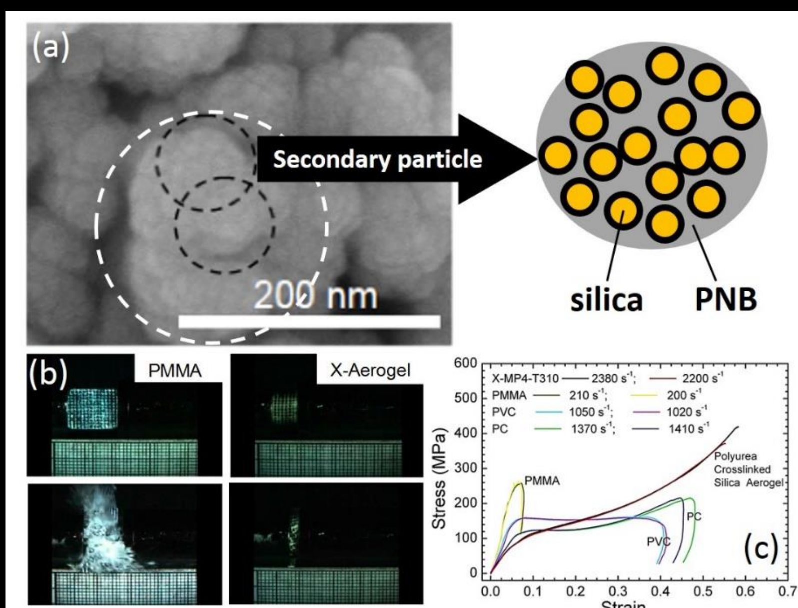
- Such as polyimide, polyurea, polyurethane, polyamide, phenolic, polyacrylate, PBO and many others.

Lower production costs and so easier commercialization

- One pot synthesis

Excellent properties

- High ductility and strength
- Super strong (90 J/g)
- Density gradient possibility
- Still excellent thermal insulators (20 mW/m.K)
- Flame retardant



High impact energy absorption properties in X-Aerogels
Aerogels Handbook (2024)

Malakooti et. al., *RSC Advances* (2018)
Taghvaee et. al., *ACS Nano* (2019)
Malakooti et. al., *ACS Applied Polymer Materials* (2019)

Polyimide Chemistry

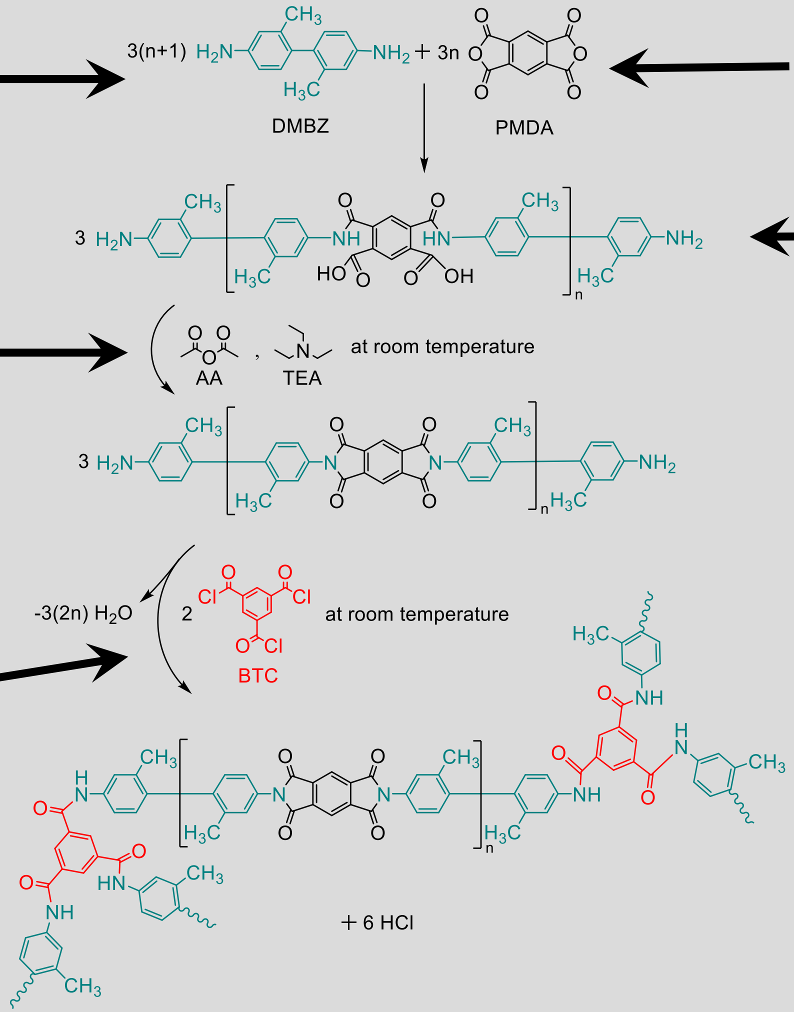
Diamine

Dianhydride

Poly(amic) acid

Catalysts for chemical imidization

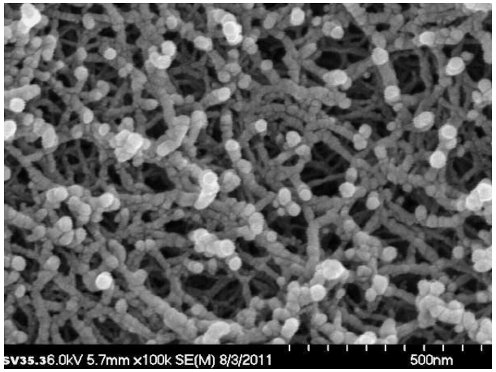
Cross-linker

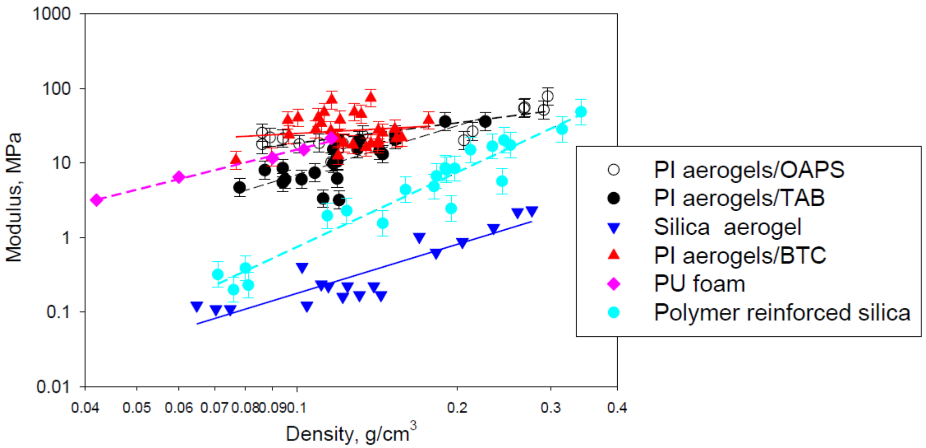


Why polyimide aerogels?

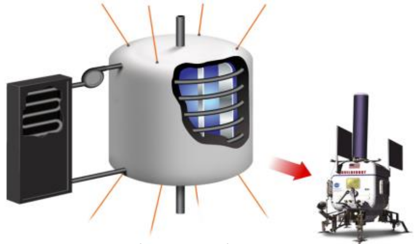
Typical properties

- High porosity (>85%)
- Pore size 10-40 nm
- High specific surface area
- Open-cell fibrillar architecture
- High thermal stability
- Tunable hydrophobicity
- Tunable mechanical properties
- Can be cast into flexible thin films

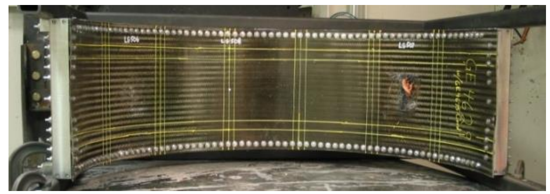




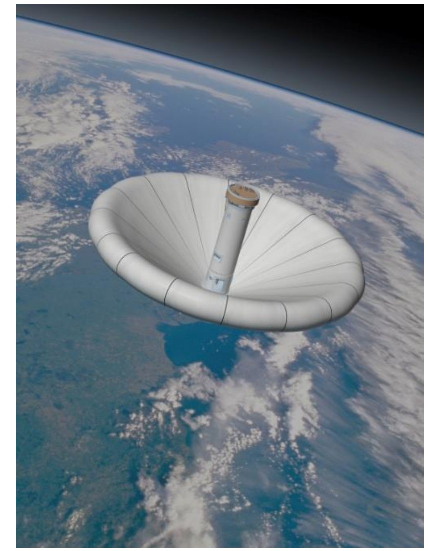
Applications for aerogels in aeronautics and space exploration



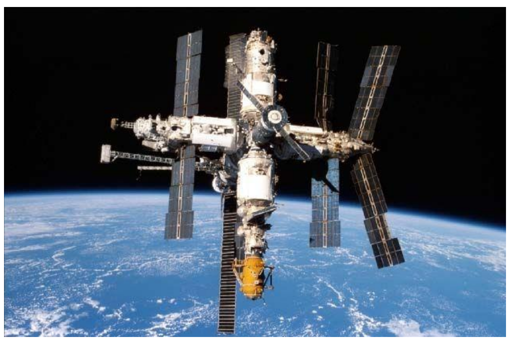
Cryotank Insulation



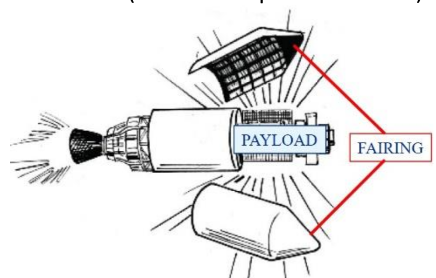
Fan engine containment
(Ballistic protection)



Inflatable aerodynamic decelerators



Light weight satellite ODC



Vibro-acoustic mitigation

Propellant tanks

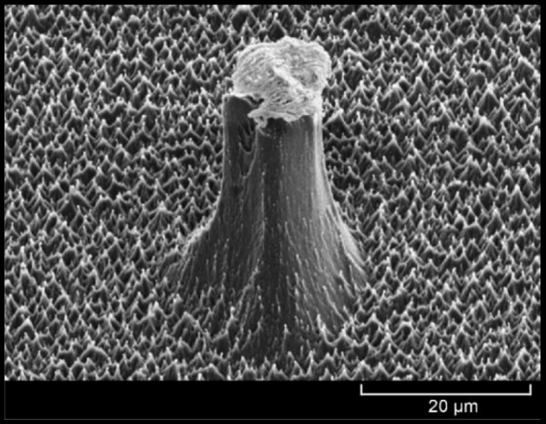
Heat shielding

Ultra-lightweight, multifunctional structures for habitats, EVA suits, rovers

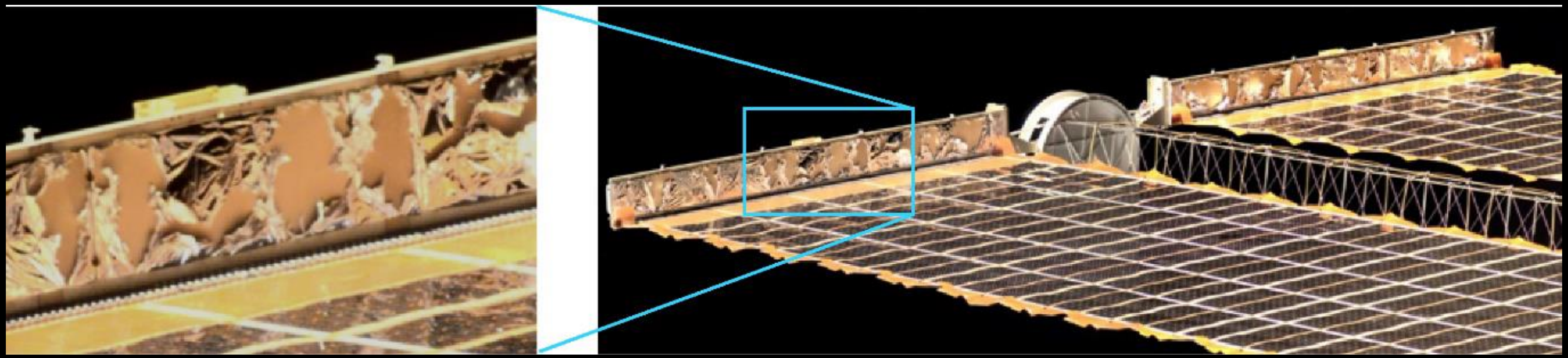
The Space Environment

In low Earth orbit environmental threats include:

- Solar radiation (ultraviolet, x-rays)
- "Solar wind” particle radiation (electrons, protons)
- Cosmic rays (energetic nuclei)
- Temperature extremes & thermal cycling
- Micrometeoroid & orbital debris (space particles)
- Atomic oxygen (reactive oxygen atoms)



Atomic oxygen erosion of Teflon FEP after 5.8 years of space exposure



Atomic oxygen undercutting degradation of the P6 Truss solar array wing blanket box cover on the ISS after only 1 year of space exposure

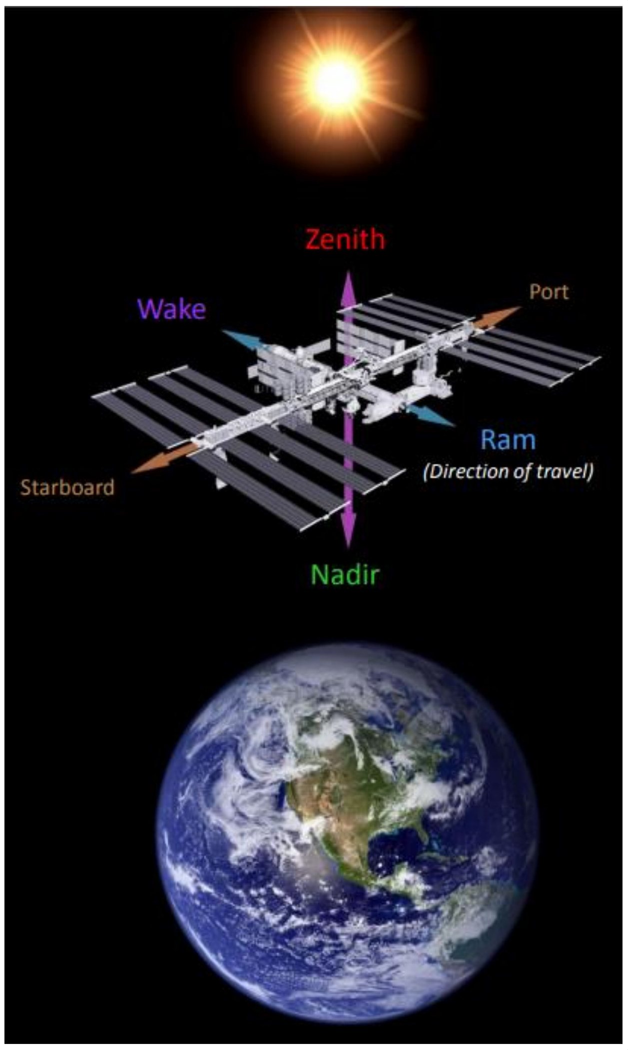
de Groh, K. K. and Banks. B. A., MISSE-Flight Facility Polymers and Composites Experiment 1-4 (PCE 1-4). TM-20205008863, 2021.

Materials International Space Station Experiment (MISSE) missions

- MISSE is a series of materials flight experiments consisting of trays of samples that are exposed to the space environment on the exterior of the International Space Station (ISS).

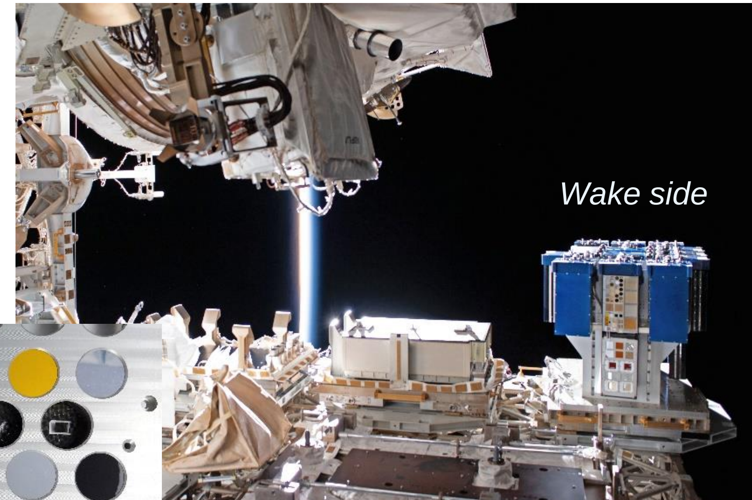
- The sample trays are positioned in either a *ram/wake orientation* or a *zenith/nadir orientation*.

Objective:
To test the stability and durability of materials and devices in the space environment



MISSE Missions 9, 12 and 15

Polyimide Aerogel Samples



MISSE-FF Experiment	Flight Direction	MISSE Sample Carrier (MSC)	Launch Mission	Installed on MISSE-FF	Retrieved from MISSE-FF	Return Mission	Time on MISSE-FF (Years)	Direct Space Exposure Duration (Years)	Atomic Oxygen Fluence (atoms/cm^2)	Mission Equivalent Sun Hours (ESH)^
MISSE-9 PCE-1	Ram	R2 (MSC 3) MS	SpaceX-14 April 2, 2018	April 18, 2018	Nov. 11, 2019	SpaceX-19 Jan. 7, 2020	1.57	0.77	3.44E+20	952.3
MISSE-12 PCE-3	Ram	R2 (MSC 4) SS	NG-12 Nov. 2, 2019	Nov. 11, 2019	Nov. 25, 2020	SpaceX-21 Jan. 13, 2021*	1.04	0.89	2.97E+20	1104.0
	Wake	W3 (MSC 6) MS			Nov. 27, 2020		1.05	0**	0	0
MISSE-15 PCE-3 Wake Re-flight**	Wake	W1 (MSC 10) MS	SpaceX-23 Aug. 29, 2021	Dec. 28, 2021	Aug. 2, 2022	SpaceX-25 Aug. 20, 2022	0.60	0.44	4.77E+18	511.7

MS: Mount side deck; SS: Swing side deck

*January 13, 2021 EST (January 14, 2021 UTC)

**The PCE-3 wake samples were re-flown as part of the MISSE-15 mission

^ Mission Equivalent Sun Hours (ESH) is from Aegis Aerospace's "MISSE MSC UV Equivalent Sun Hours Calculation" Report (A. Goode, August 17, 2022-C03)

Erosion Yield (E_y) and Erosion Depth (E_d)

$$E_y = \frac{\Delta M_s}{A_s \rho_s F}$$

(cm³/atom)

$$E_d = \frac{\Delta M_s}{A_s \rho_s}$$

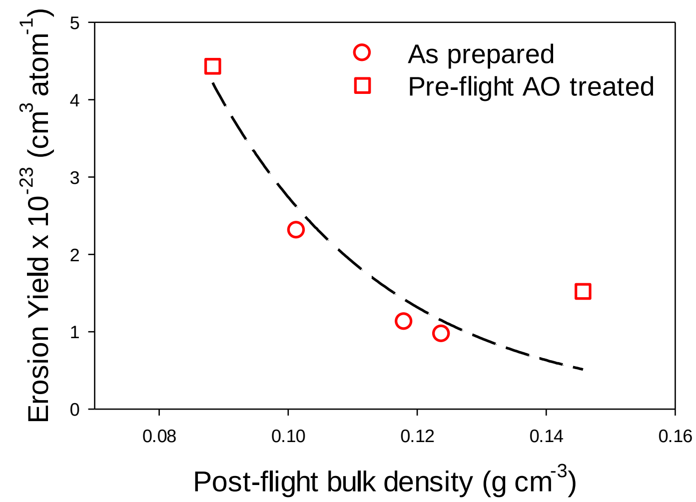
(cm)

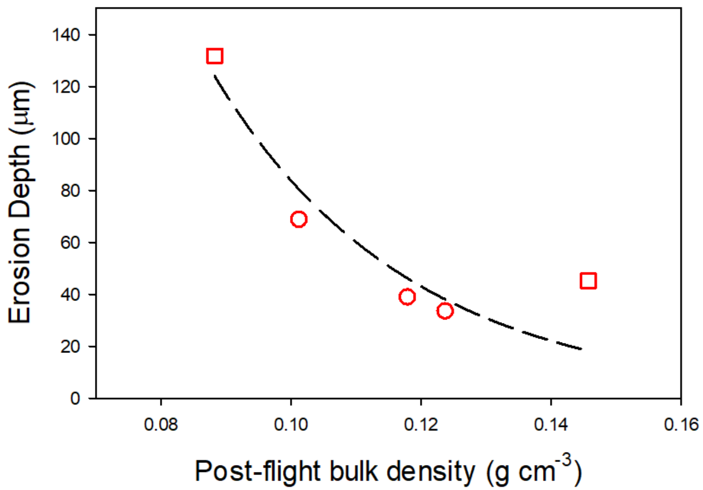
- ΔM_s is the dehydrated mass loss (g)
- A_s is the exposed surface area (cm^2)
- ρ_s is the pre-flight bulk density (g/cm^3)
- F is the low Earth orbit AO fluence of the MISSE experiment (cm^3/atom).

Note: The value of the F during a MISSE experiment is determined from the AO erosion yield of a Kapton H witness sample (3.0 E-24 cm^3/atom) flown on the same MISSE experiment.

Erosion Yield and Erosion Depth data

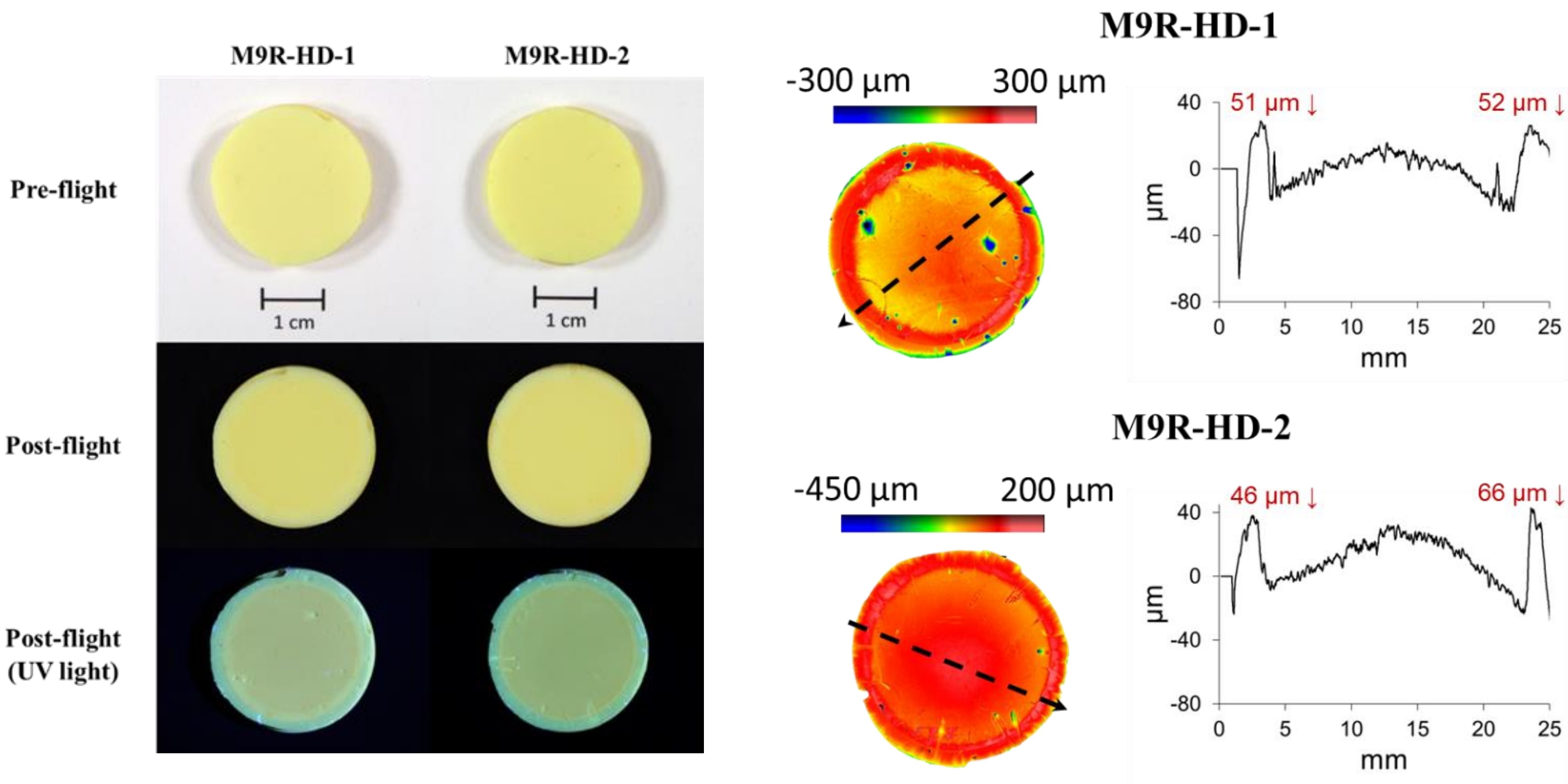
Sample name	Density (g/cm^3)[a]	Mass loss (mg) [%]	Erosion yield × 10^{-24} (cm^3/atoms)	Erosion depth (µm)
M9R-Kapton H	1.427	5.27 [5.55]	3.00	10.35
M9R-Kapton H	1.427	5.35 [5.76]	3.00	10.28
M9R-Kapton HN	1.435	5.32 [5.76]	3.03	10.43
M9R-HD-1	0.153	1.79 [0.93]	9.69	33.31
M9R-HD-2	0.153	2.08 [1.09]	11.27	38.73
M12R-Kapton H	1.427	4.45 [4.79]	3.00	8.91
M12R-HD	0.153	-1.47 [-0.62]	N/A	N/A
M12R-LD	0.087	2.09 [1.47]	23.10	68.63
M12R-HD-AO	0.153	2.42 [1.63]	15.21	45.20
M12R-LD-AO	0.087	4.01 [3.45]	44.30	131.66
M15W-Kapton H	1.427	0.07 [0.08]	3.00	0.14
M15W-HD	0.153	-10.94 [-4.58]	N/A	N/A
M15W-LD	0.087	-7.45 [-5.35]	N/A	N/A





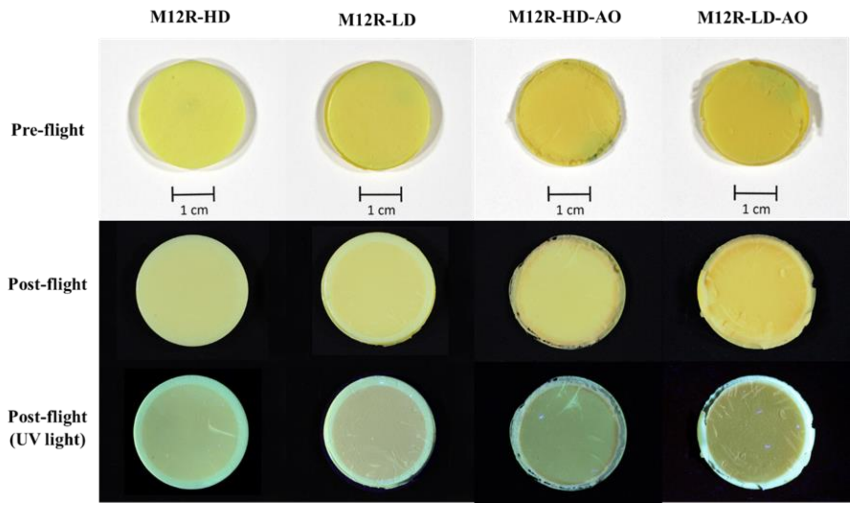
[a]Pre-flight data; MXR: MISSE-X, ram direction; MXW: MISSE-X, wake direction; LD: Low density; HD: High density

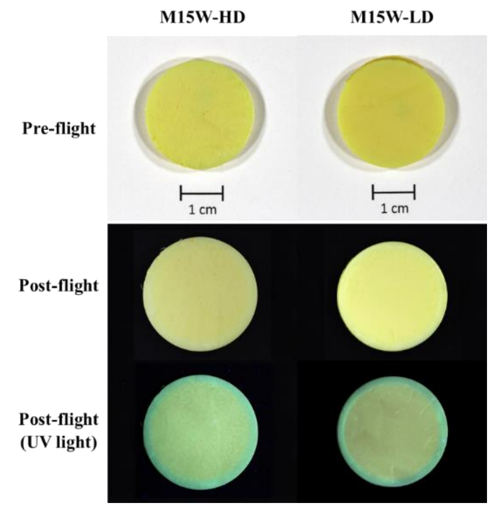
Optical images and the 2D topographic profiles M-9 ram flight samples

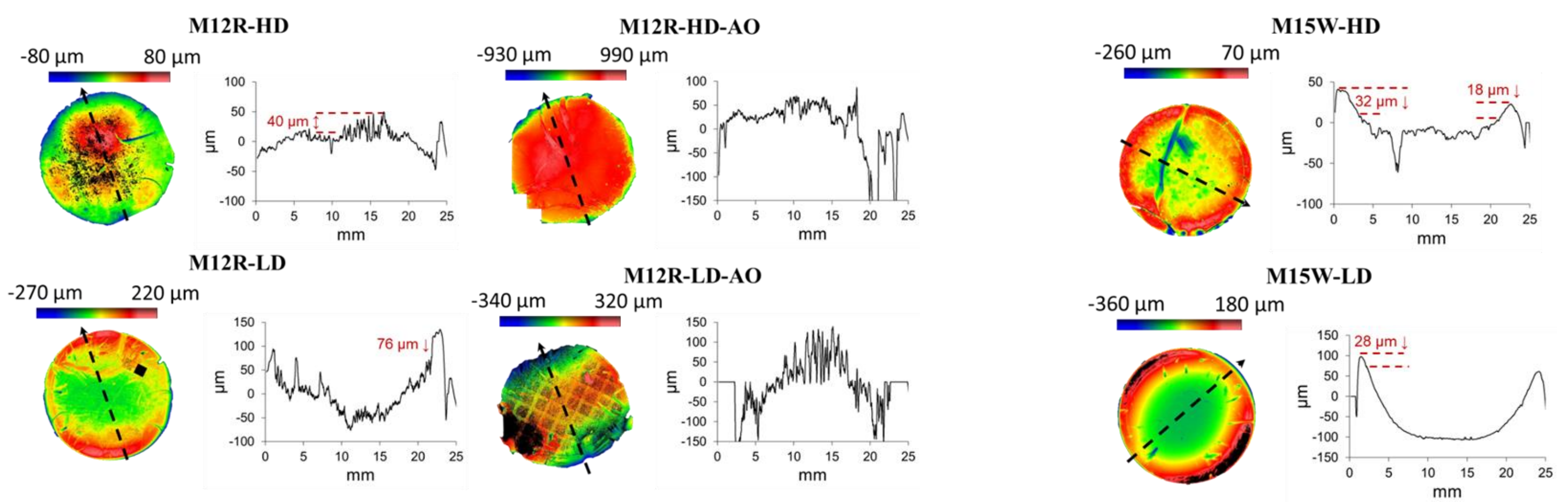


365 nm UV flashlight

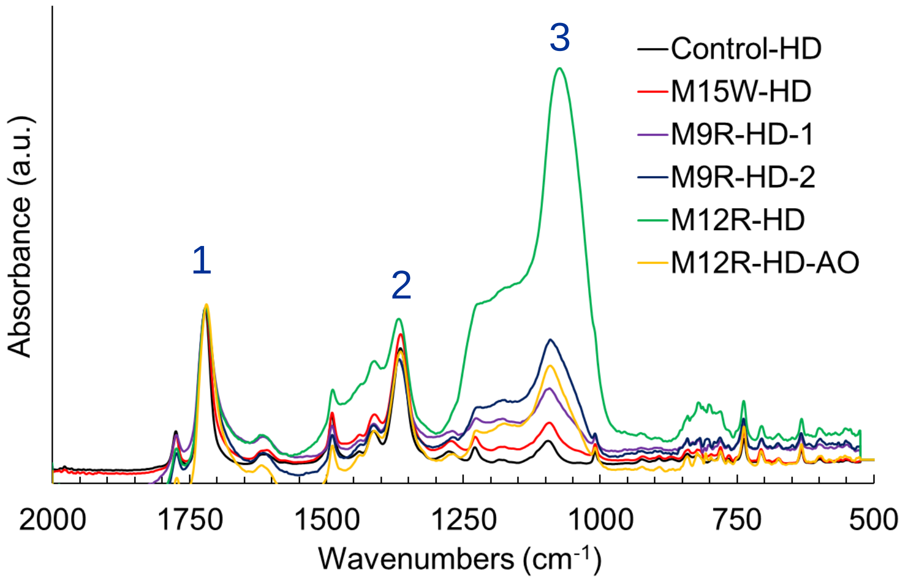
Optical images and the 2D topographic profiles M-12 ram and M-15 wake flight samples

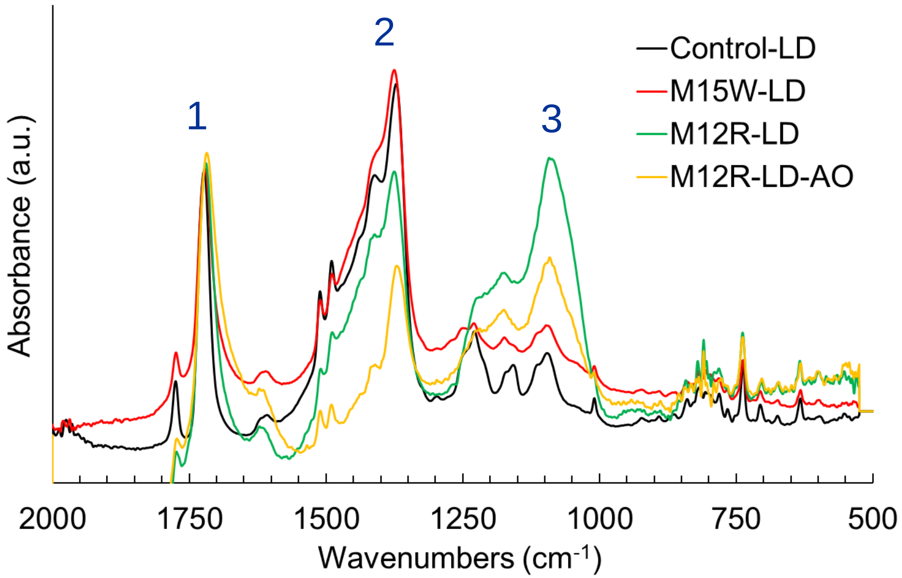




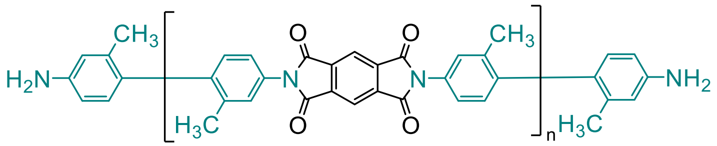


Surface Chemistry



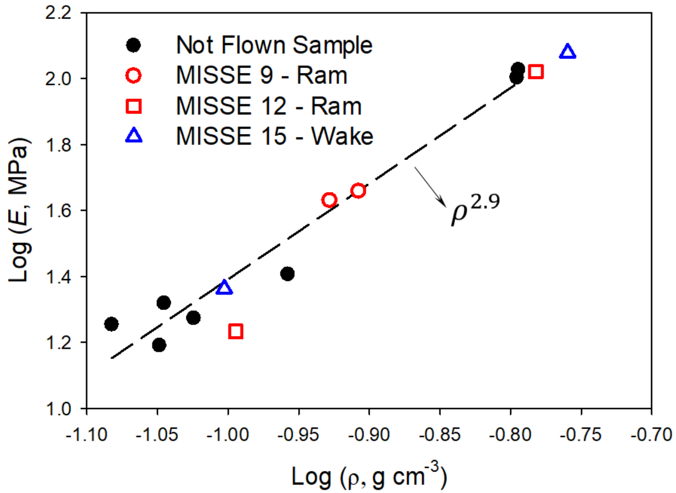


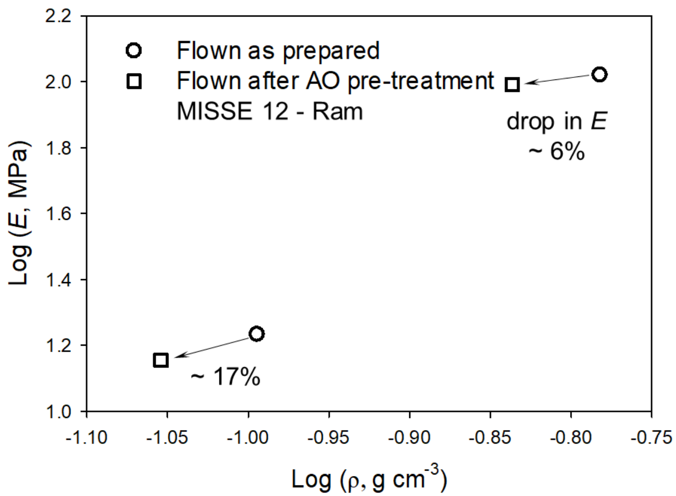
1: Imide carbonyl (C=O)
2: Imide C-N degradation (ring opening)
3: Potential silicon contamination related with some ether linkage growth (C-O-C)



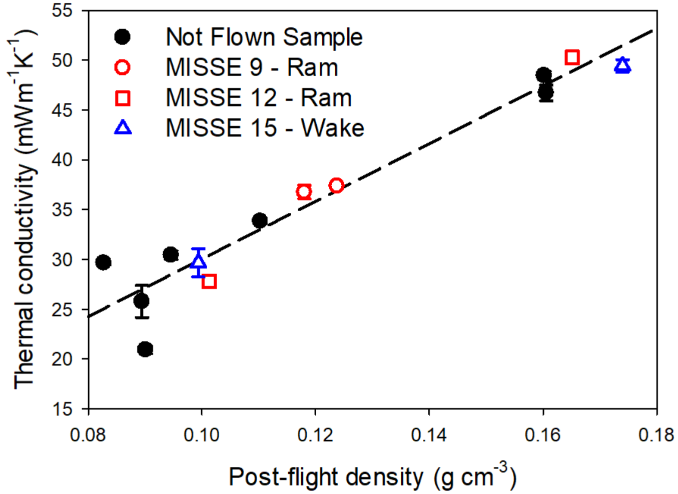
Attenuated total reflectance (ATR) infrared spectroscopy using a Nicolet Nexus 470 FT-IR spectrometer

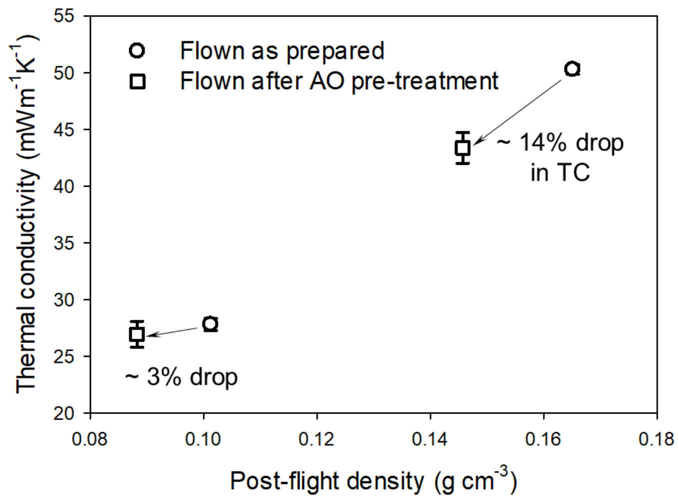
Elastic Modulus and Thermal Conductivity





Impulse Excitation Technique
(ASTM E1876-22)





Modified Transient Plane Source
(ASTM D7984-21)

Summary

- Low Earth orbit exposure effects on NASA GRC polyimide aerogels have been studied.
- Erosion depths were measured by optical profilometry.
- High density aerogels had an erosion depth of ~ 50 µm, 1.5% of initial thickness.
- Low density aerogels had an erosion depth of ~ 150 µm, 5% of initial thickness.
- Infrared spectroscopy provided some insights on the AO chemical effects by the formation of new aliphatic ether linkages (C-O-C) on the exposed aerogels.
- The impact of the erosion was not detrimentally high as the post-flight aerogel material properties did not significantly change.
- Pre-flight AO skin removal (oxygen plasma etching) made aerogels more susceptible to AO degradation effects.

NASA Aerogel Lecture Series - |

https://www.nasa.gov/glenn/aerogel-lecture-series/

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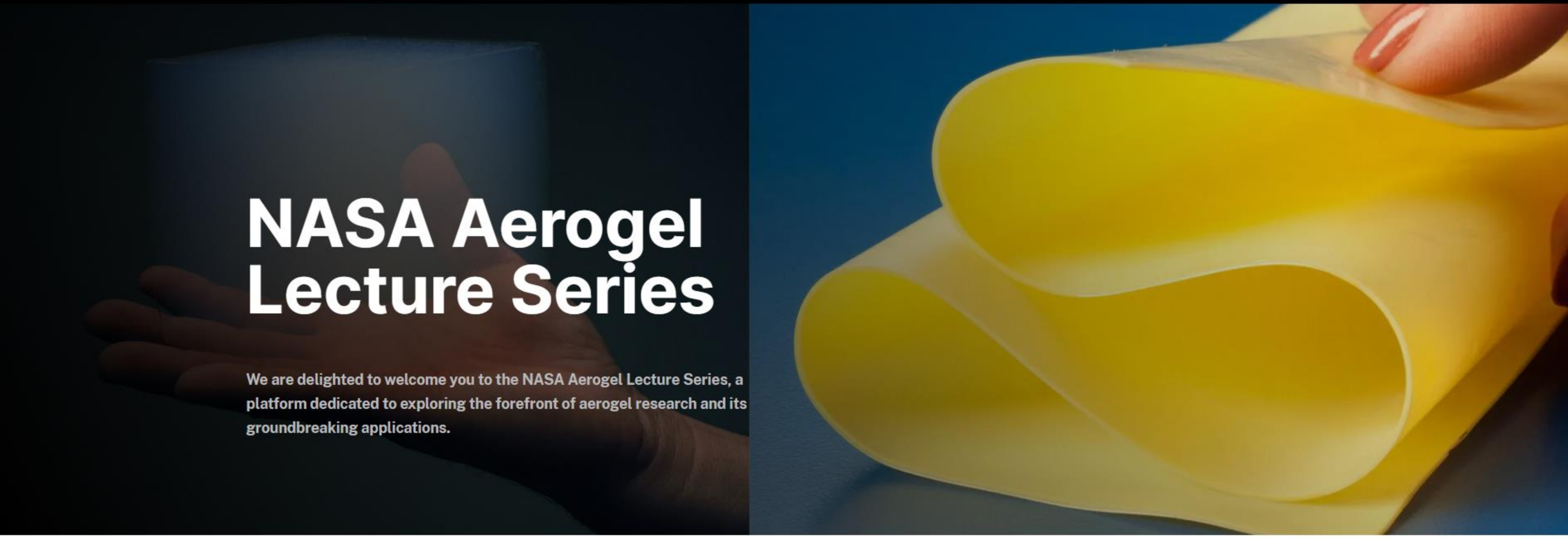

Hosted by Dr. Sadeq Malakooti from the Materials and Structures Division at the NASA Glenn Research Center, the Aerogel Lecture Series unveils the extraordinary potential of aerogels — a class of highly porous solid materials derived from a gel in which the liquid is replaced by gas while maintaining the self-assembled three-dimensional structure.

Upcoming Lectures

Bio-aerogels: materials born in the 21st century

Date: Thursday, May 15, 2025, at 10 a.m. ET

Location: Virtually via Microsoft Teams.

Speaker: Dr. Tatiana Budtova, MINES ParisTech, Sophia Antipolis, France

Registration is required to attend. Event link will be included in the registration email.

Register Now

Internships for all majors

What Majors Does NASA Look For?

Accounting
Business Administration
Communications
Contracts
Economics
Education
Finance
Graphic Design
Human Resources
Industrial Management
Journalism
Public Affairs
Purchasing
Quantitative Methods
Supply Chain Management

Aerospace Engineering
Biomedical Engineering
Chemical Engineering
Computational Engineering
Computer Engineering
Computer Science
Electrical Engineering
Environmental Engineering
Industrial Engineering
Materials Engineering
Mathematics
Mechanical Engineering
Physics
Software Engineering

Some skills that NASA routinely needs:

Programing:

C++ CAD
Java Pro-E
HTML Matlab
3D Modeling

Networking

3D Printing

Social Media

Technical Writing

Database Administration

Machine Shop
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Prototyping

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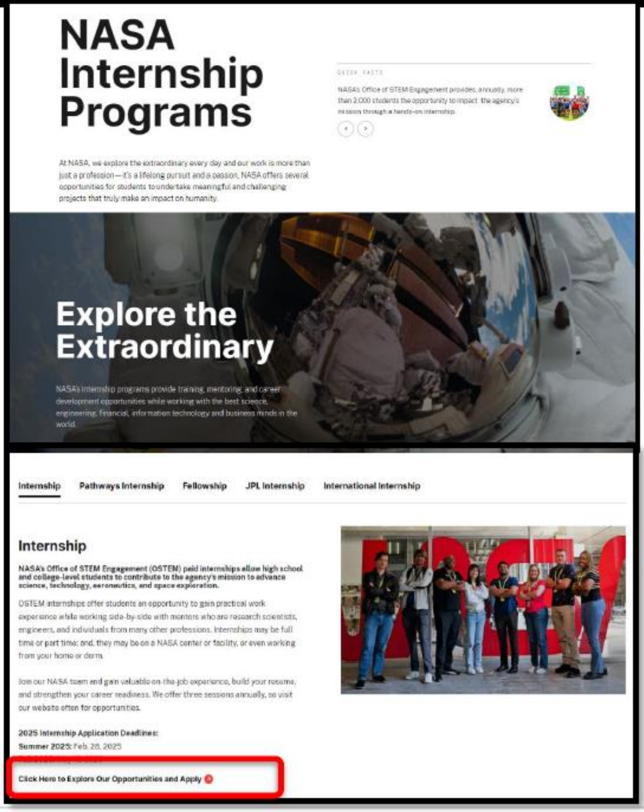
2. Create an account
3. Set up a profile
4. Explore opportunities
5. Apply!



Acknowledgments

<u>NASA GRC Aerogel Team (Left to right)</u>:
- Dr. Sadeq Malakooti
- Dr. Stephanie Vivod (Team lead)
- Bilal Hasan (Spring-25 intern)
- Dr. Michael Chauby

NASA GRC
- Kim de Groh

- NASA Flight Opportunities Program
- The International Space Station Program Office
- NASA Biological and Physical Sciences Division
- Aegis Aerospace, Inc.

For more information: sadeq.malakooti@nasa.gov