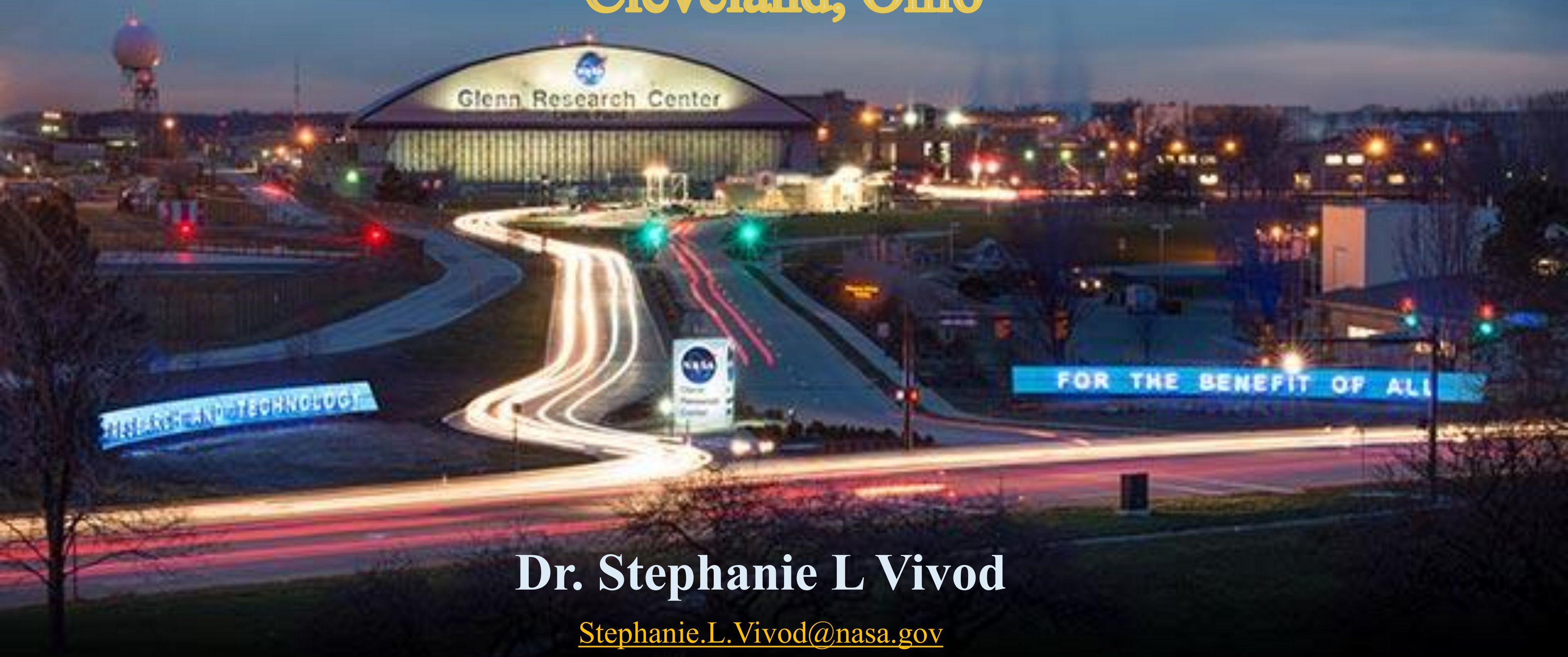
Polymer Aerogels for Lunar Applications and Beyond

Joint School of Nanoscience and Nanotechnology (JSNN)

NASA John H. Glenn Research Center at Lewis Field

Cleveland, Ohio



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Materials Chemistry and Physics Branch

Materials and Structures Division

National Aeronautics and Space Administration
NASA
NASA centers and facilities
NASA Headquarters
Ames Research Center
Dryden Flight Research Center
Glenn Research Center
Goddard Space Flight Center
Jet Propulsion Laboratory
Glenn Research Center
Cleveland, Ohio
Plum Brook Station
Sandusky, Ohio
Goddard Space Flight Center
Greenbelt, Maryland
NASA Headquarters
Washington, DC
Wallops Flight Facility
Wallops Island, Virginia
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Hampton, Virginia
Ames Research Center
Moffett Field, California
Dryden Flight Research Center
Edwards, California
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White Sands Test Facility

NASA Centers and Facilities

NASA consists of its Headquarters in Washington, DC, field centers, and facilities. Each center's Outreach and Educational programs have been assigned a geographic region of responsibility. On the reverse side is a map of the United States color coded to show the states and the assigned NASA center. For additional information go to http://www.nasa.gov/about/sites/index.html.

NASA Headquarters
NASA Headquarters, located in Washington, DC, exercises management over the space flight centers, research centers, and other installations that constitute NASA.

Ames Research Center
Ames Research Center specializes in research geared towards creating new knowledge and technologies that span the spectrum of NASA interests.
Alaska, Northern California, Hawaii, Idaho, Montana, Nevada, Oregon, Utah, Washington, Wyoming

Dryden Flight Research Center
As the lead for flight research, Dryden continues to innovate in aeronautics and space technology. The newest, fastest, and highest—all have made their debut in the vast, clear desert skies over Dryden.
Arizona, Southern California

Glenn Research Center
Glenn Research Center develops and transfers critical technologies that address national priorities through research, technology development, and systems development for safe and reliable aeronautics, aerospace, and space applications.
Illinois, Indiana, Michigan, Minnesota, Ohio, Wisconsin

Goddard Space Flight Center
The mission of the Goddard Space Flight Center is to expand knowledge of the Earth and its environment, the solar system, and the universe through observations from space.
Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont

Jet Propulsion Laboratory
The Jet Propulsion Laboratory, managed by the California Institue of Technology is NASA's lead center for robotic exploration of the solar system.

Johnson Space Center
From the early Gemini, Apollo, and Sky Lab projects to today's Space Shuttle and International Space Station programs, Johnson Space Center continues to lead NASA's effort in Human Space Exploration.
Colorado, Kansas, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Texas

Kennedy Space Center
Kennedy Space Center is America's Gateway to the Universe—leading the world in preparing and launching missions around the Earth and beyond.
Florida, Georgia, Puerto Rico, Virgin Islands

Langley Research Center
Langley continues to forge new frontiers in aviation and space research for aerospace, atmospheric sciences, and technology commercialization to improve the way the world lives.
Kentucky, North Carolina, South Carolina, Virginia, West Virginia

Marshall Space Flight Center
Bringing people to space; bringing space to people. Marshall Space Flight Center is the world leader in access to space and use of space for research and development to benefit humanity.
Alabama, Arkansas, Iowa, Louisiana, Missouri, Tennessee

Michoud Assembly Facility
Michoud Assembly Facility is a world-class manufacturing facility providing vital support to NASA exploration and discovery missions.

Plum Brook Station
Plum Brook Station facilities can simulate environmental conditions found on Earth, in low Earth orbit, on planetary surfaces, and in deep space.

Stennis Space Center
Stennis is responsible for NASA's rocket propulsion testing and for partnering with industry to develop and implement remote sensing technology.
Mississippi

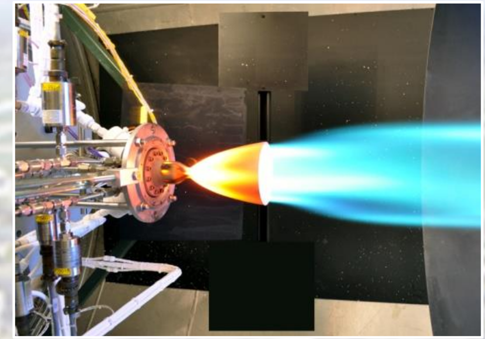
Wallops Flight Facility
Located on Virginia's Eastern shore, Wallops is NASA's premier site for sub-orbital and small orbital flight projects, Earth Science research, and technology development and is home to NASA's only owned and operated launch range.

White Sands Test Facility
White Sands Test Facility conducts simulated mission duty-cycle testing to develop numerous full-scale propulsion systems and evaluates upgraded or redesigned shuttle orbiter components to extend service life, enhance performance, and improve mission safety.

Research Centers

GRC Core Competencies

Air-Breathing Propulsion

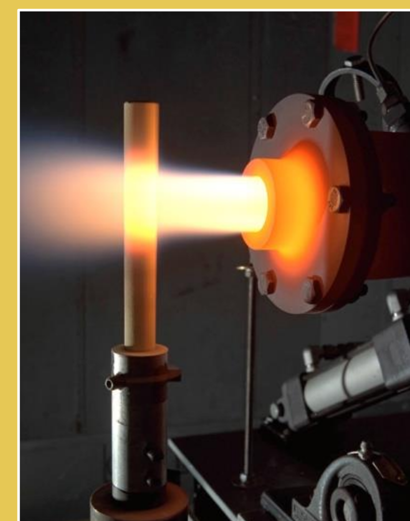


In-Space Propulsion and Cryogenic Fluids Management

Physical Sciences and Biomedical Technologies in Space

Communications Technology and Development

Power, Energy Storage and Conversion



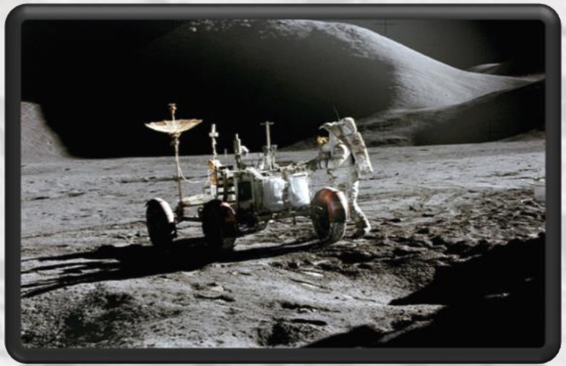
Materials and Structures for Extreme Environments

WE’RE GOING BACK!

Artemis Program: Return to moon-2026

https://www.nasa.gov/specials/artemis/

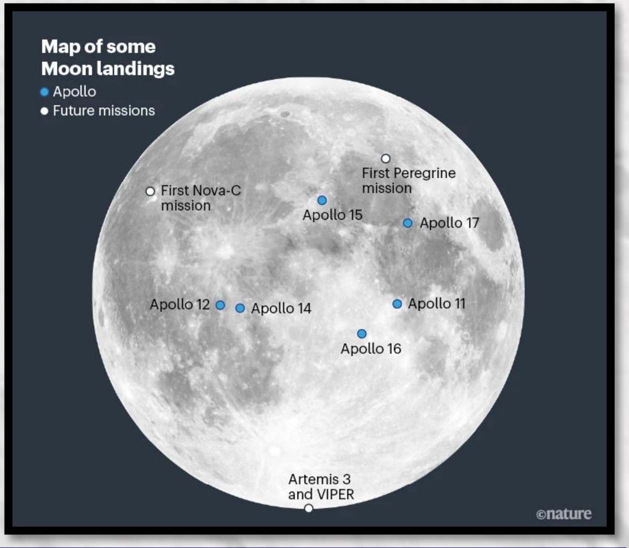
Apollo Program ran from 1961 to 1972



Apollo 15-Astronaut James B. Irwin, lunar module pilot, works on the Lunar Roving Vehicle

Moon Landing Missions:

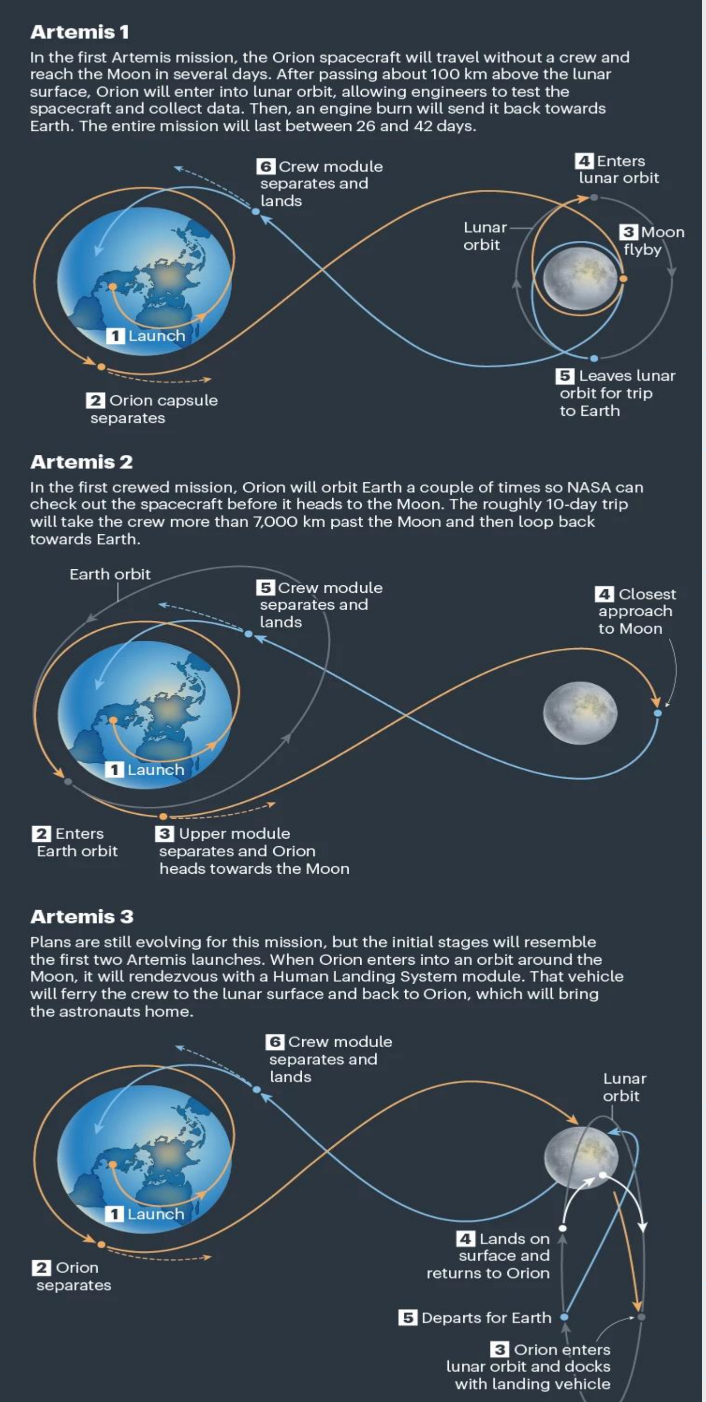
- **Apollo 11 (1969)** Neil Armstrong (Commander), Buzz Aldrin, Michael Collins
- **Apollo 12 (1969)** Charles “Pete” Conrad (Commander), Alan Bean, Richard Gordon
- ***Apollo 13 (1970)** James Lovell (Commander), Jack Swigert, Fred Haise
- **Apollo 14 (1971)** Alan Shepard (Commander), Edgar Mitchell, Stuart Rosa
- **Apollo 15 (1971)** David Scott (Commander), James Irwin, Alfred Worden
- **Apollo 16 (1972)** John Young (Commander), Charles Duke, Thomas Mattingly
- **Apollo 17 (1972)** Eugene Cernan (Commander), Harrison Schmitt, Ronald Evans



NASA is now preparing for an ambitious new era of sustainable human spaceflight and discovery

Nature | Vol 605 | 12 May 2022

*mission aborted

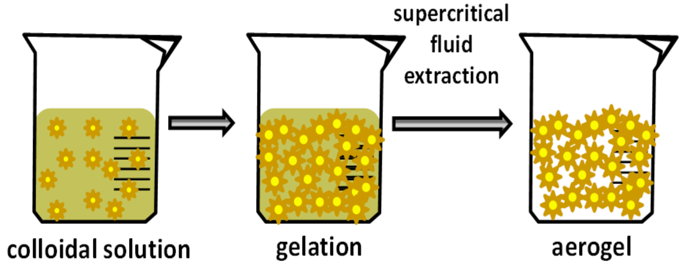


doi: https://doi.org/10.1038/d41586-022-01253-6

Issues and Concerns with Space Exploration

- Orbital debris
- Radiation
- Payload weight reduction
- Lunar dust
- Crew health and safety
- ISRU

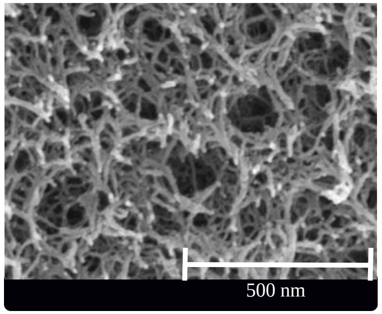
The Wonderful World of Polymer Aerogels!



Aerogels made using sol-gel synthesis and supercritical fluid extraction

What is an aerogel?

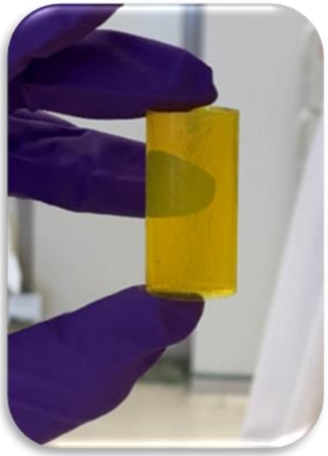
- An open-celled, light weight, porous material derived from a gel in which the liquid is replaced by gas while maintaining the self-assembled three-dimensional structure



Scanning Electron Micrograph of polymer aerogel matrix

Many characteristics of aerogels are tailored by using various chemistries; however, all aerogels have these Typical Properties:

- High porosity (> 90 %)
- Nano-scale pore sizes (10-40 nm)
- Low density (0.1-0.2 g/cm^3)
- Large surface areas (400 – 850 m^2/g)
- Low thermal conductivity (~20mW/m·K)
- Low dielectric (1.1)
- Low refractive index (1.02-1.09)


polymer aerogel cylinder (1g) (SA= 850 m2/g)

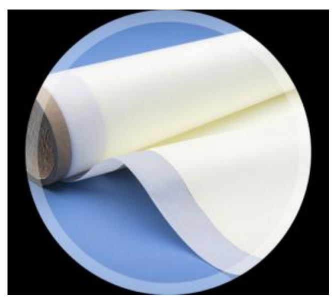
Current aerogel products and market

Cabot Lumira® Aerogel for daylighting applications

Aerogel Technologies Airloy® Fireproof aircraft panels/noise mitigation

Insulated portable living space by Nice Architects

Aspen Aerogels Spaceloft® insulation



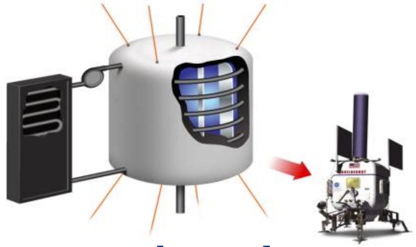
Blueshift AeroZero® thin film insulation

BASF Slentite© panels

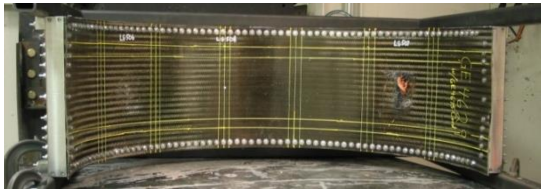
© Aerotherm thermal cooler

Outdoor gear/apparel

Applications for durable aerogels in aeronautics and space exploration

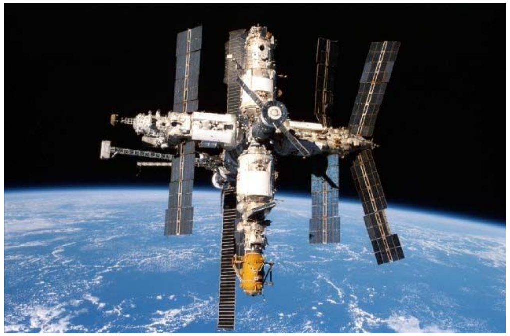


Cryotank Insulation

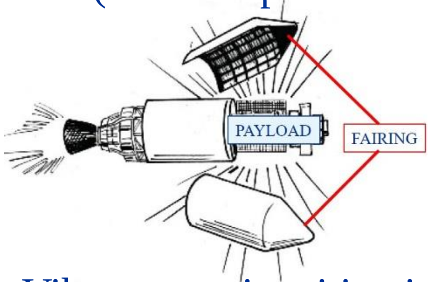


Fan engine containment
(Ballistic protection)

Inflatable aerodynamic decelerators



Light weight satellite ODC



Vibro-acoustic mitigation

Propellant tanks

Heat shielding

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

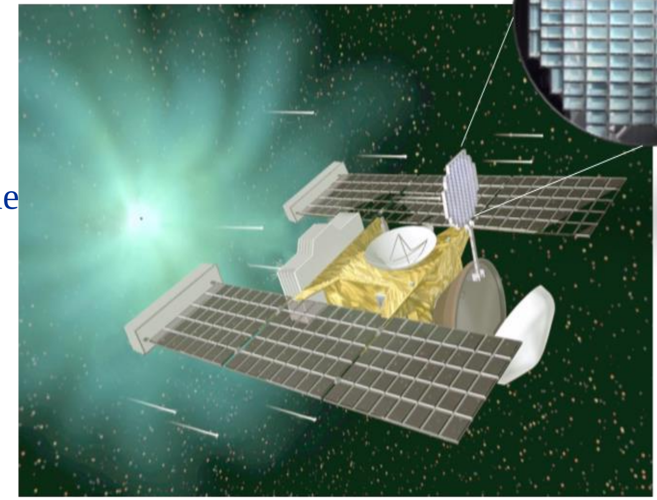
Improving on Previous Technology

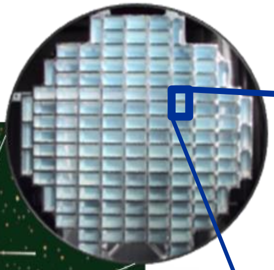
Rover Battery Insulation

- Sensitive internal components must not exceed extreme temperatures of -40° Celsius to +40° Celsius (-40° Fahrenheit to 104° Fahrenheit)
- Night temperatures on Mars can drop to -96° Celsius (-140° Fahrenheit).
- The rover is kept warm by a special layer of silica aerogel

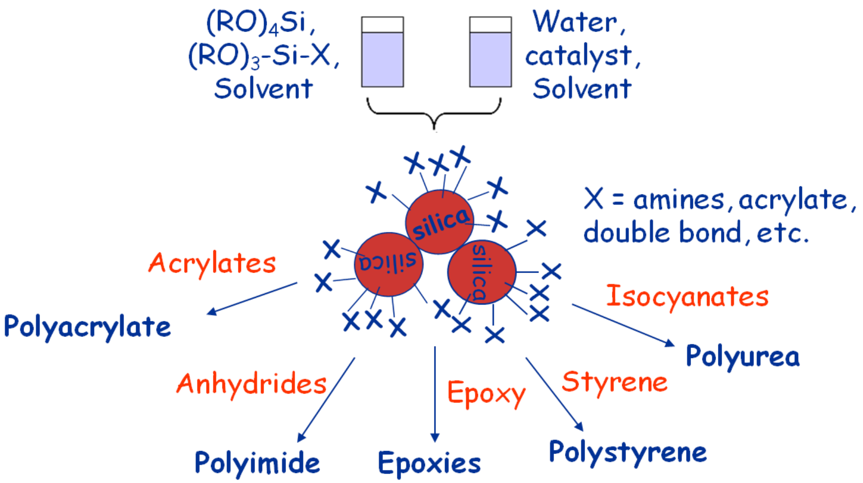
Stardust Mission

- NASA's Discovery Mission Stardust launched with the intention of performing a close (142 km) flyby of the comet Wild-2 in order to collect cometary samples embedded within an aerogel substrate.



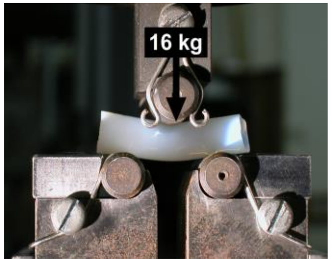


Durable aerogels by reinforcing silica aerogels with polymers



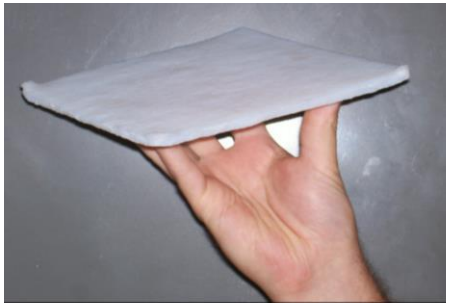
- Versatile: allows cross-linking with variety of polymers to tailor properties

Native

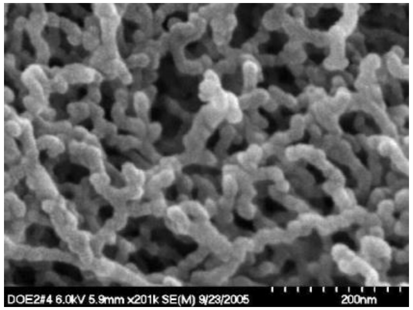


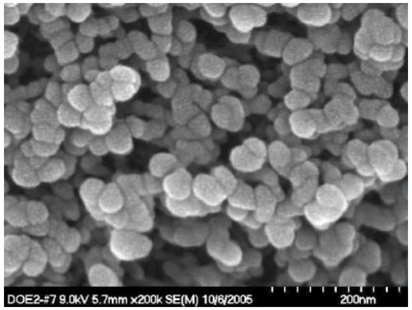
Cross-linked

- Polymer reinforcement ***doubles*** the density
- Results in ***two order of magnitude*** increase in strength
- Does not change pore structure



Polymer reinforced silica batting



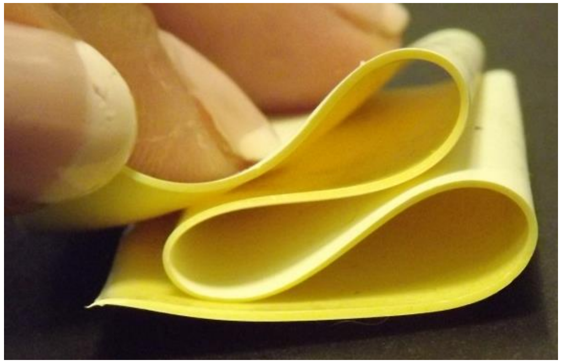


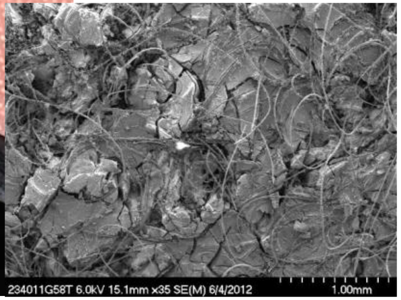
Low density... to higher density, same aerogel pore structure

Meador, et al. ACS Applied Materials and Interfaces, 2009, 1 (4), pp 894–906

Flexible insulation layer for thermal protective system (TPS)

- Developed as flexible improved insulation for hypersonic inflatable decelerators for entry descent and landing (EDL) applications
- Improvement over Pyrogel 3350—less dusty, onset of decomposition 550-600 ^{o}C
- PI aerogels stable up to temperatures of 400 ^{o}C



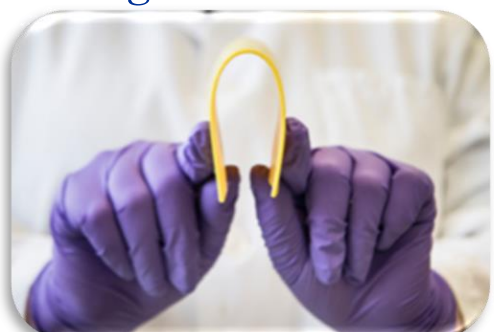


Why polyimide aerogels?

Polyimides

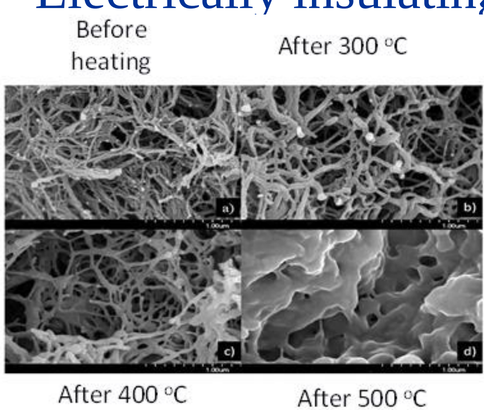
- DuPont-high temperature engineering polymers
- High glass transition (Tg) temp
- Thermal stability (>500 °C)
- Mechanical strength –toughness, flexibility, high tensile strength
- Chemical resistance
- Transparency
- Electrically insulating

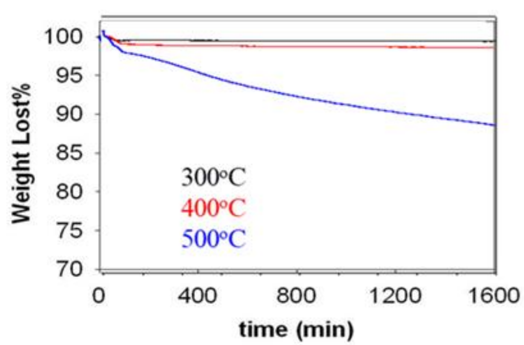
Strong and Flexible

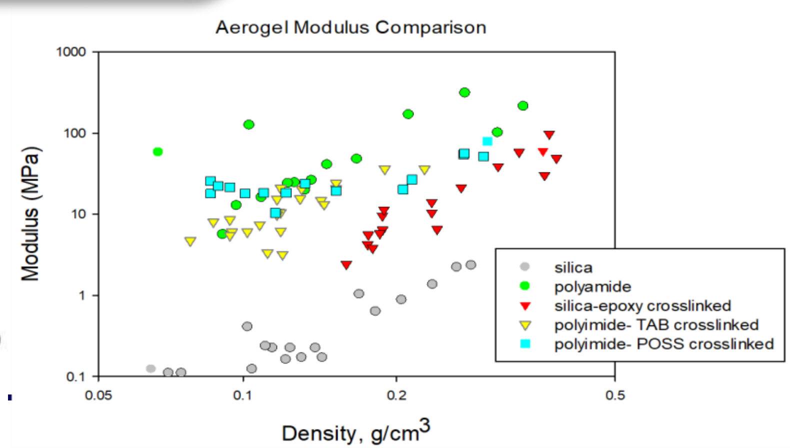


Aerogels

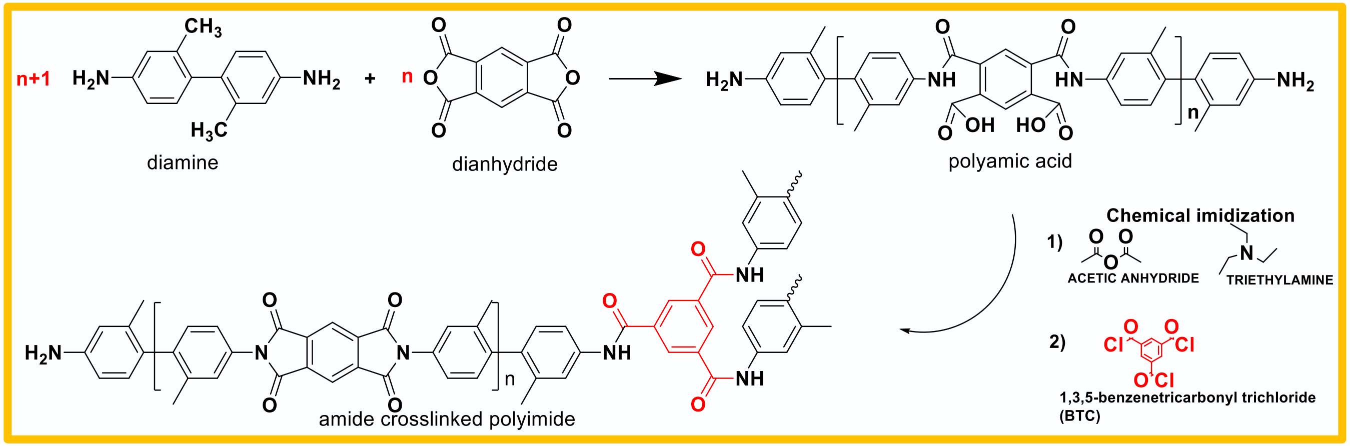
- Low density
- High porosity
- High surface area
- Low Tc



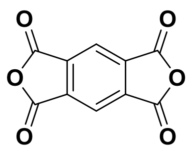




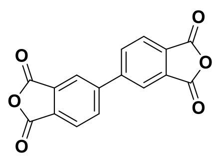
Polyimide Synthesis Mechanism and Monomers



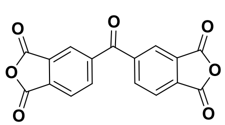
Dianhydrides



Pyromellitic dianhydride (PMDA)

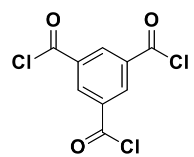


3,3’,4,4'-biphenyltetracarboxylic dianhydride (BPDA)

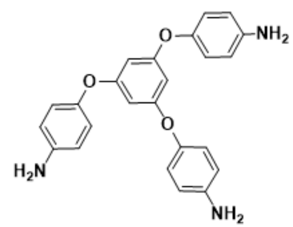


Benzophenone-3,3’,4,4'-tetracarboxylic dianhydride (BTDA)

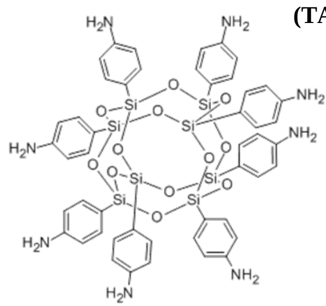
Cross-linkers



1,3,5-benzenetricarbonyl trichloride (BTC)

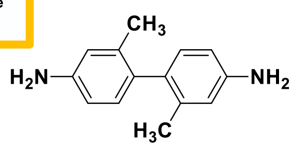


Tris-1,3,5-aminophenoxy benzene (TAB)

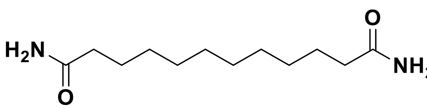


octa(aminophenyl)polysilsesquioxane (OAPS)

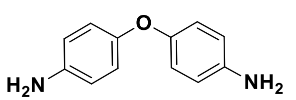
Diamines



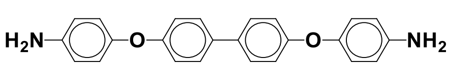
2,2"-dimethylbenzidene (DMBZ)



1,12-dodecyldiamine (DADD)

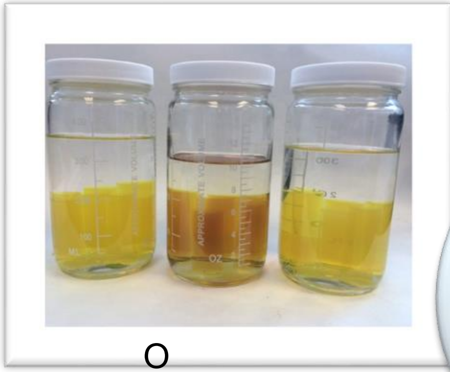


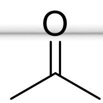
4,4'-oxydianiline (ODA)



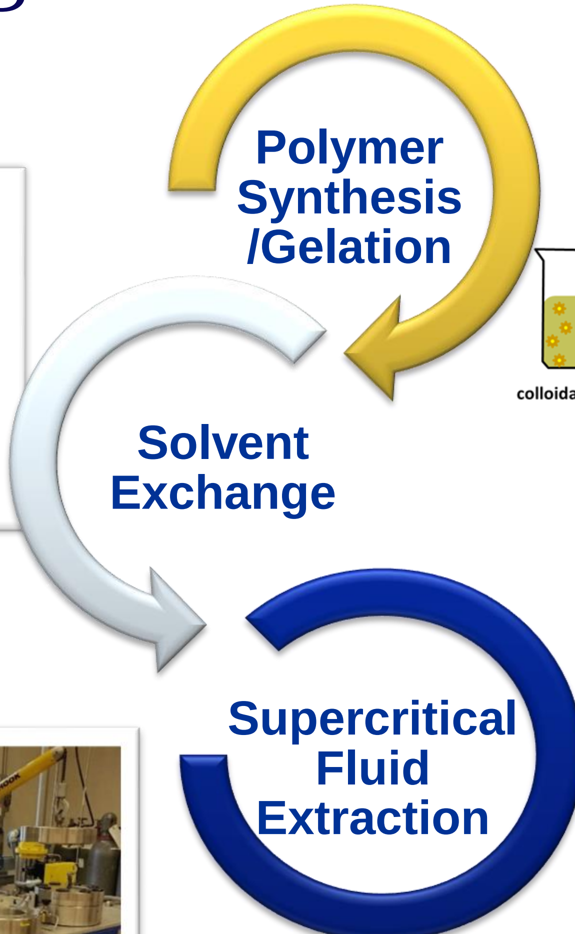
4,4'-Bis (4-aminophenoxy) biphenyl (BAPB)

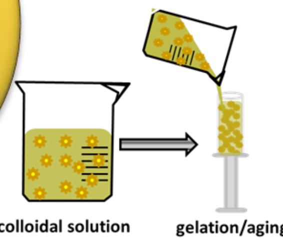
Aerogel Fabrication Process

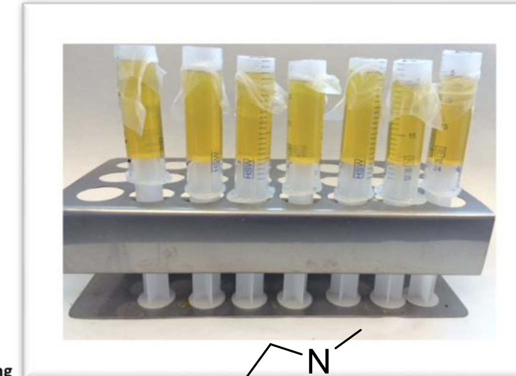


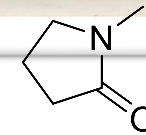


acetone

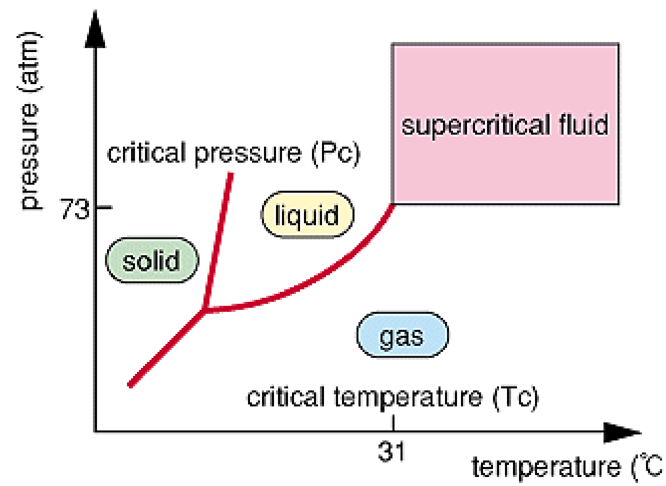






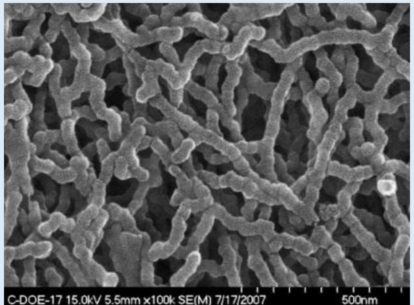


n-methylpyrrolidone (NMP)

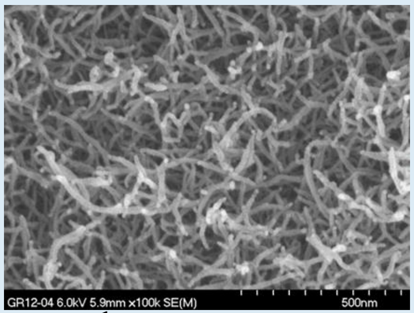


Aerogel Properties

Structure
Typical in all aerogels



silica

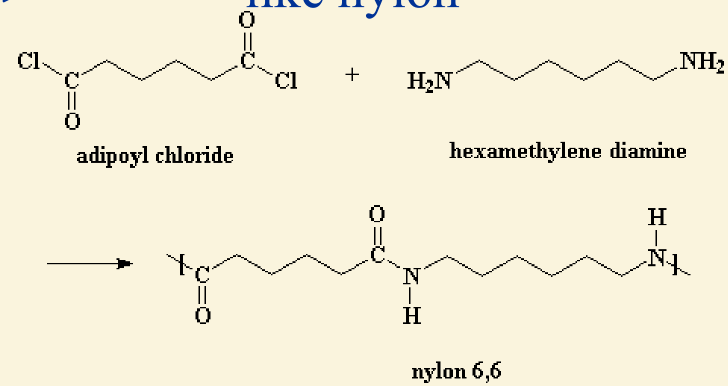


polymer

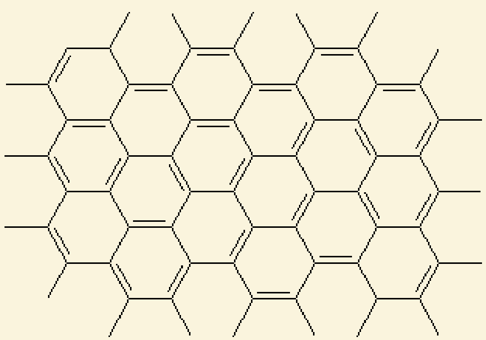
- High porosity
- Nano-scale pore size
- Low density
- High internal surface area
- Low Tc and dielectric

Chemistry
Varies in all aerogels

- Aliphatic in backbone increases flexibility like nylon

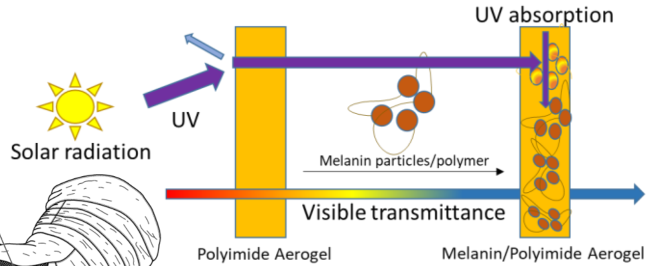


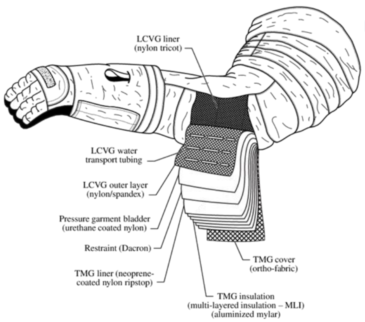
- Aromatics in backbone increases strength and temperature resistance like graphite



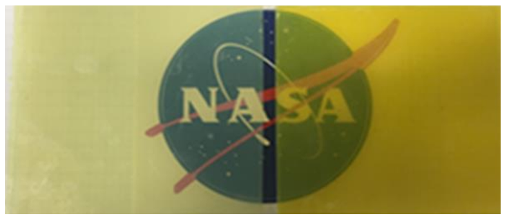
a section of a sheet of graphite

Polyimide Aerogel Development

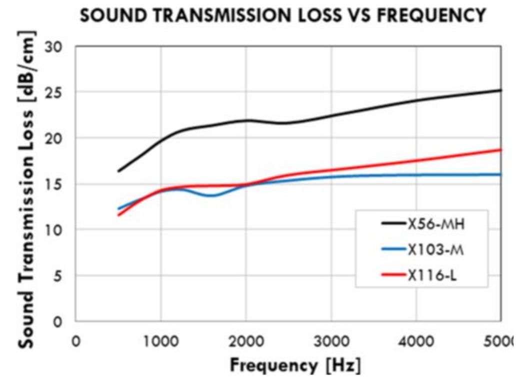




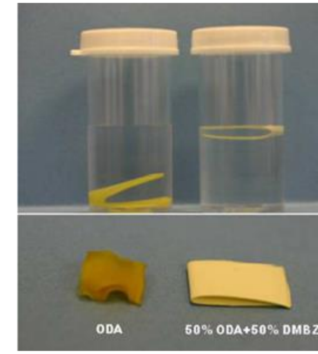
Radiation mitigation



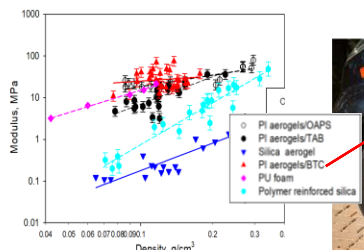
Tunable Transparency



Acoustic impedance



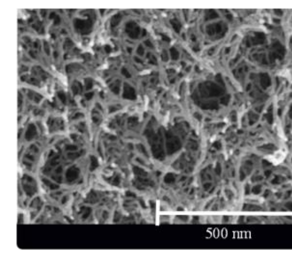
Tailored Hydrophobicity



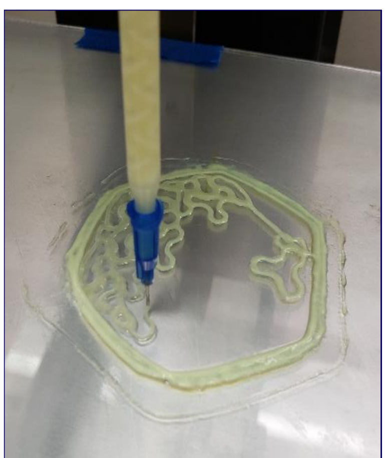
Improved mechanical properties

Baseline MLI (Mylar + scrim)

Pi aerogel + Mylar

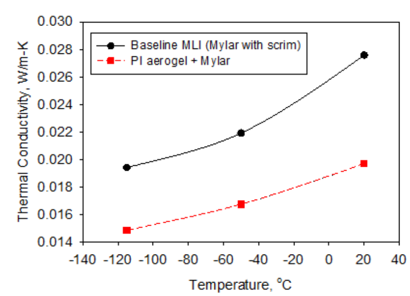


Tunable pore structure

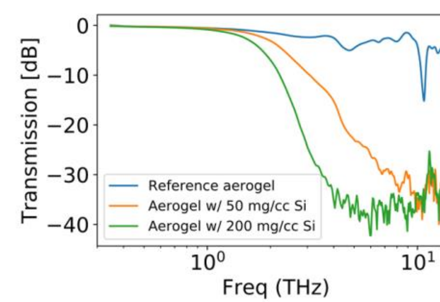


3D printing

Orbital debris containment



Enhanced thermal impedance



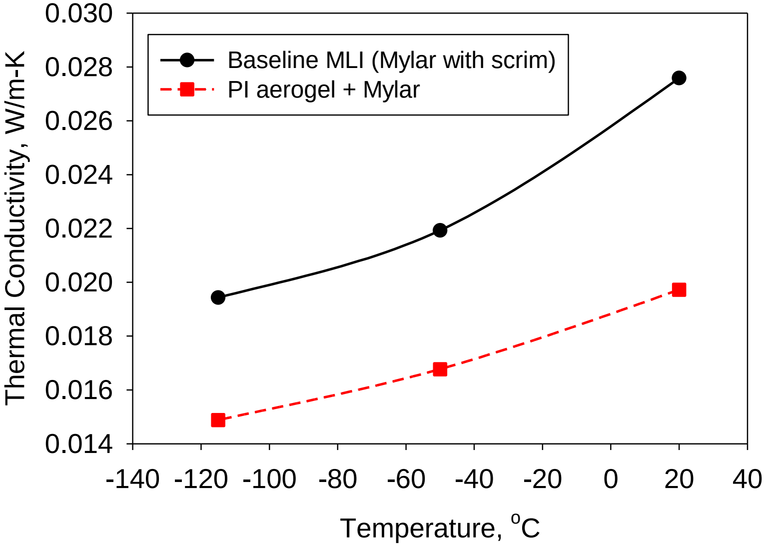
IR filtration

Multifunctional, Universal Thermal Insulation System

- Current multilayer insulation (MLI) only functions in vacuum
  - Layers of Mylar separated by scrim layers
- MLI incorporating aerogel in place of scrim reduces TC by 23-37%

Baseline MLI (Mylar + scrim)

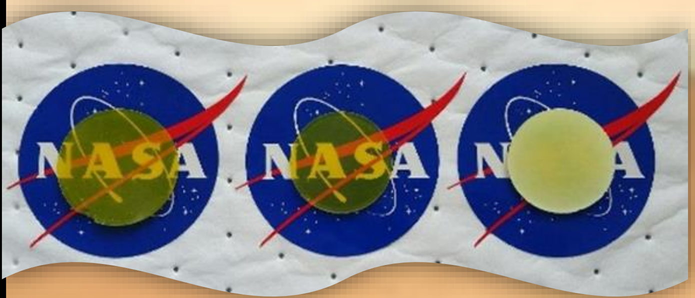
Pi aerogel + Mylar



MLI with and without aerogel tested under simulated Mars atmosphere (8 Torr Argon, -120 to 20 °C)

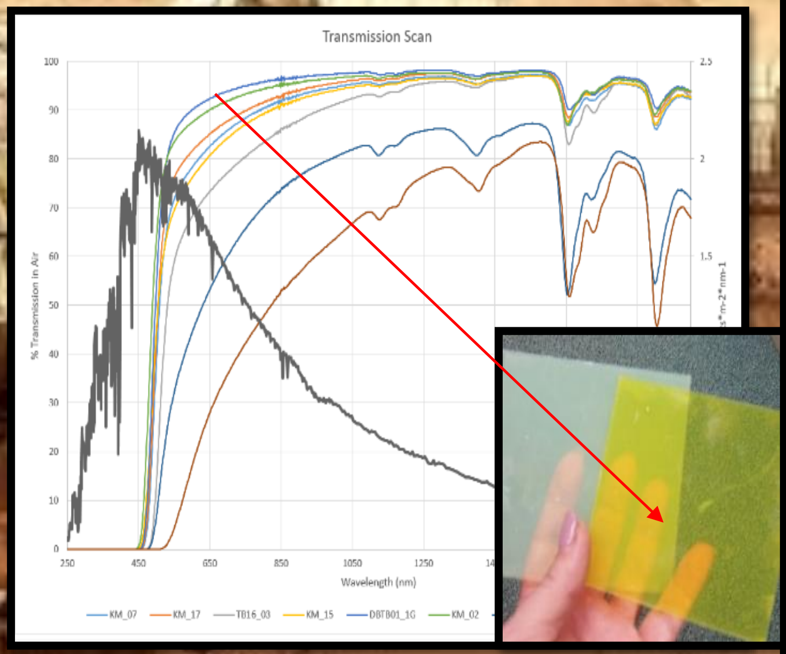
Polymer Aerogels for Passive Thermal Containment

Aerogels for Surviving the Lunar Night (ASLAN)



Tunable opacity

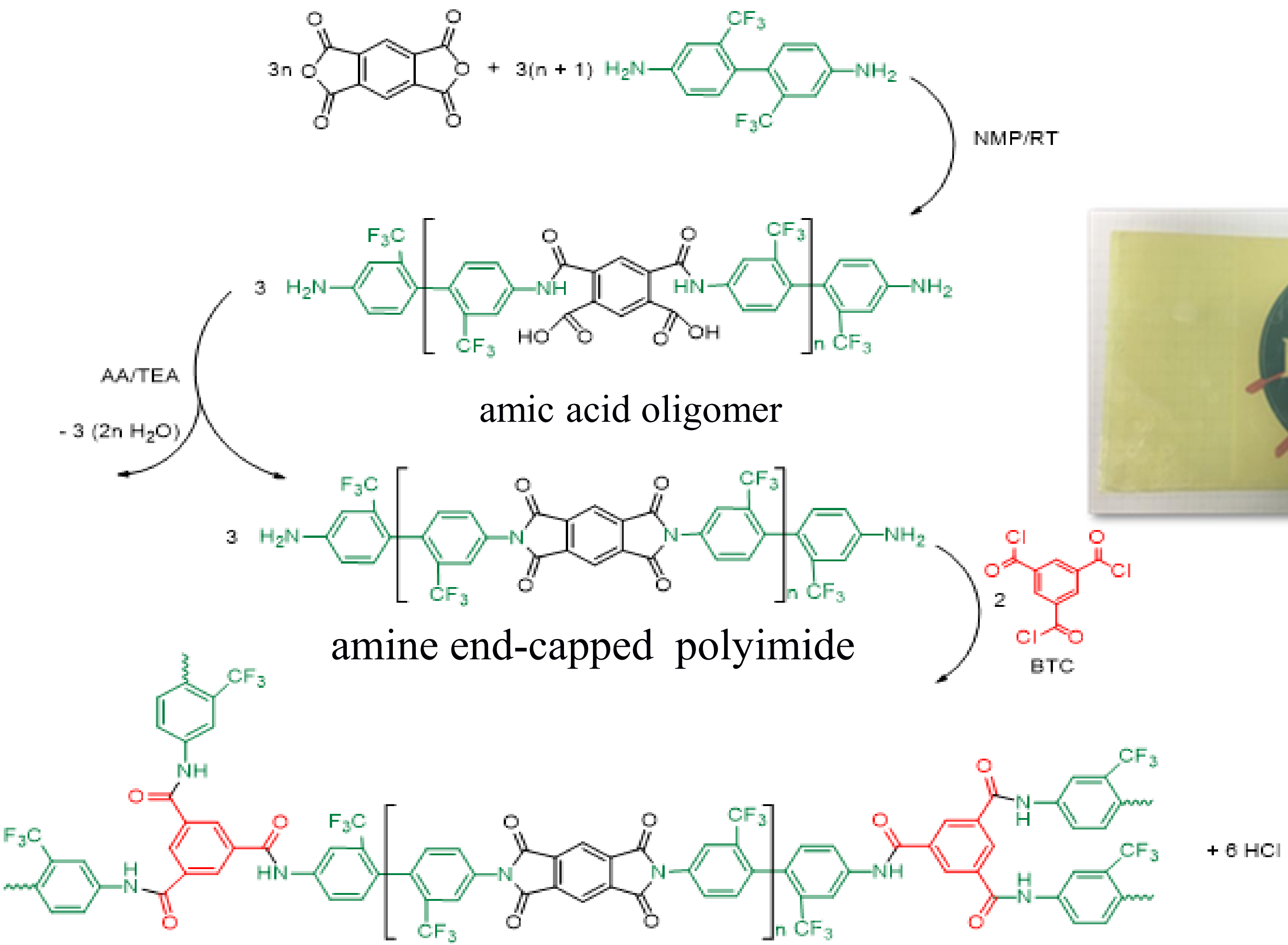
PTC for habitats, greenhouses, terraforming



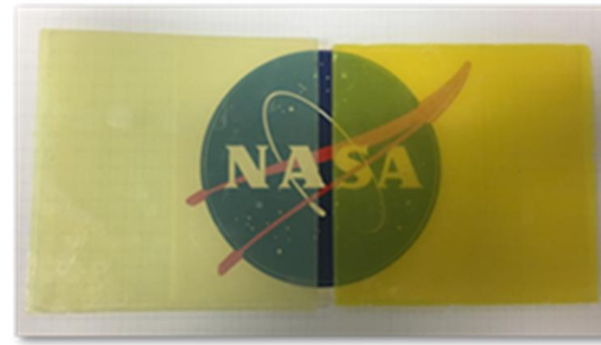
Higher transmissivity and optical clarity with fluorinated monomer

Vivod, et al. ACS Appl. Mater. Interfaces 2020 (7) 8622-8633

Fluorinated Monomer Incorporation

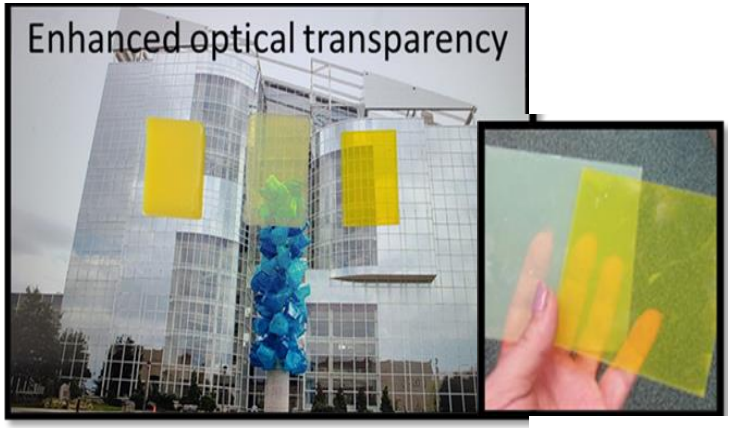


Crosslinked polyimide

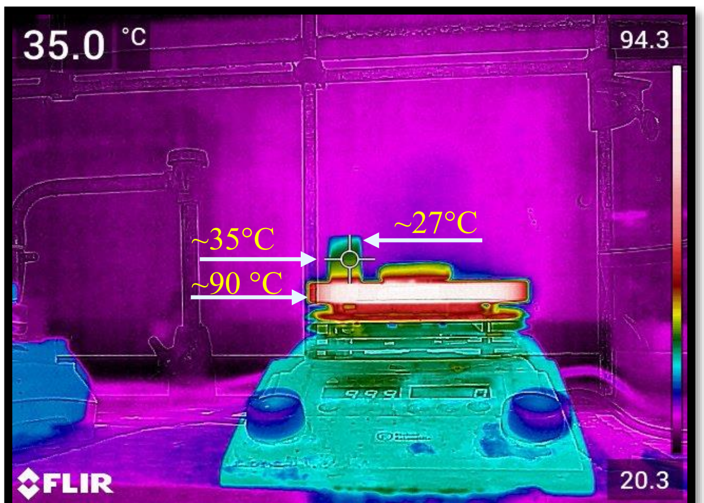


$3(n+1)$ diamine + $3(n)$ dianhydride + 2 trifunctional crosslinker - $6n\ H_2O$ - 6 HCl

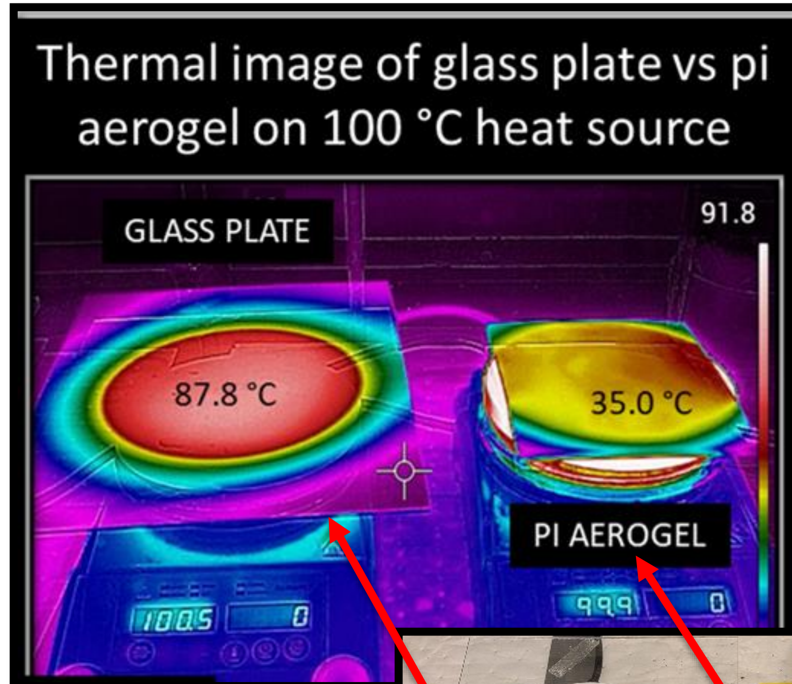
Thermal imaging of aerogel vs plate glass

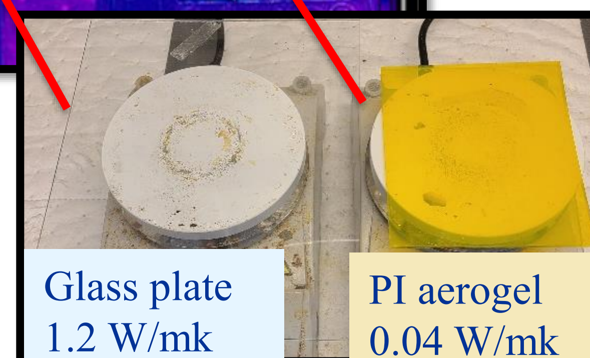


Improved transparency



Heat transfer through a pi aerogel cylinder (left) and block (right)-30 min





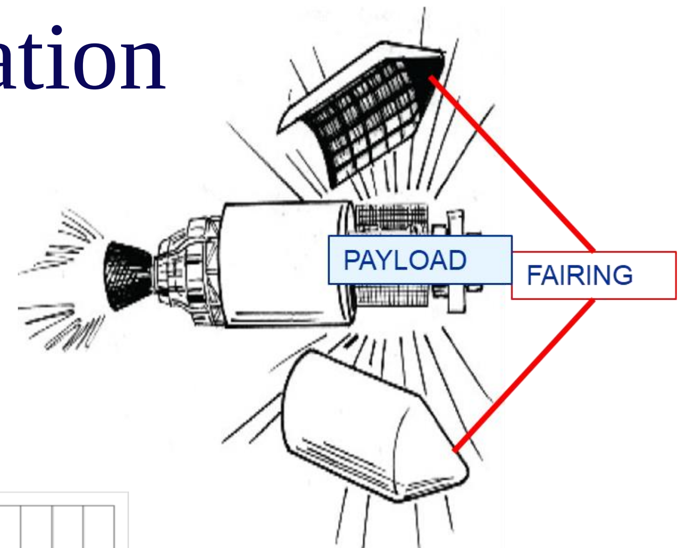
Polyimide aerogel is 30-60 times more thermally insulating than glass plating at room temperature and ambient pressure

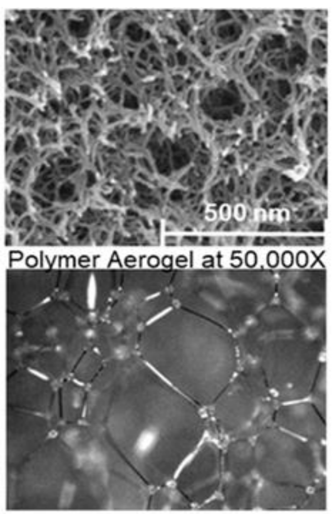
Thermal resistance = thickness/area*thermal conductivity

$$\frac{t_{aerogel}}{A * \lambda_{aerogel}} = \frac{t_{glass}}{A * \lambda_{glass}} \rightarrow \frac{t_{glass}}{t_{aerogel}} = \frac{\lambda_{glass}}{\lambda_{aerogel}} = 30$$

Advanced Acoustic Materials for Noise Mitigation

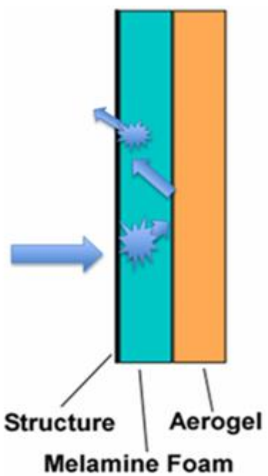
- Vibro-acoustic loads pose threat to payload launch survivability
- Aerogels will add damping to the structure, which reduces the amplitude of the vibration and noise transmission in addition to weight reduction



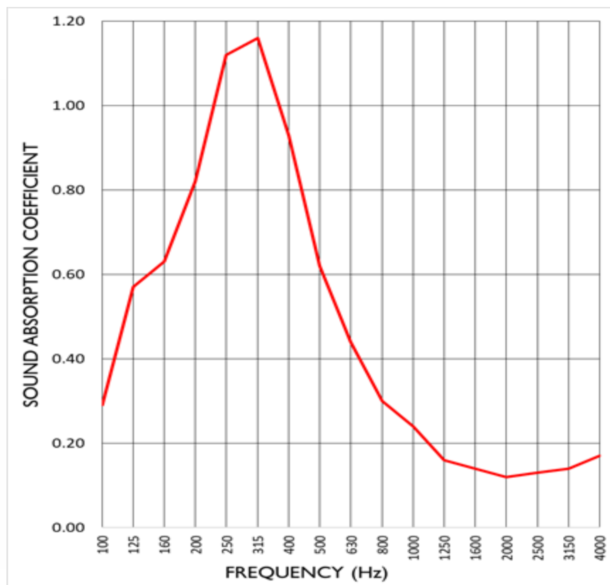


Polymer Aerogel at 50,000X

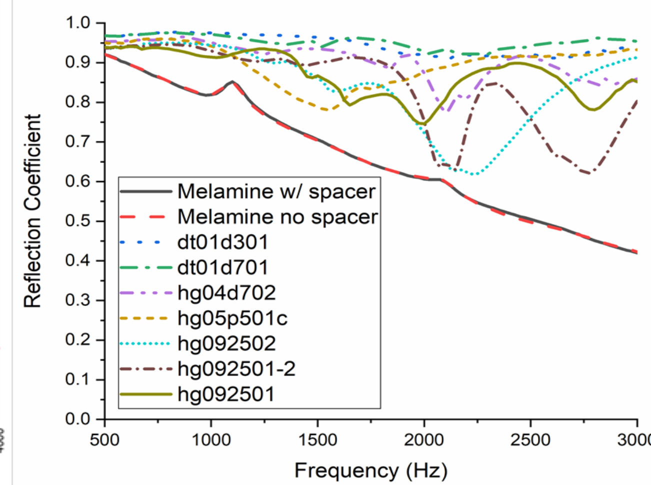
Melamine Foam at 80X



Absorbing material with aerogel as reflective backing

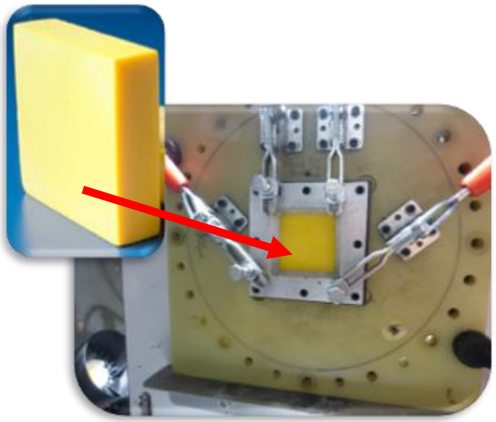


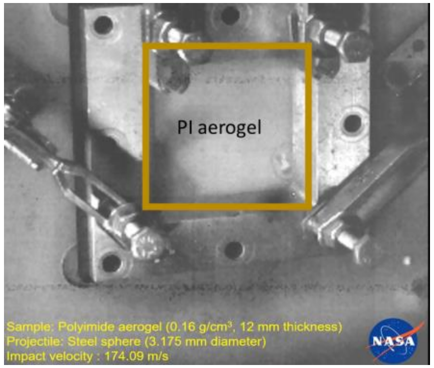
Absorption coefficient of polyimide aerogels/melamine foam composite



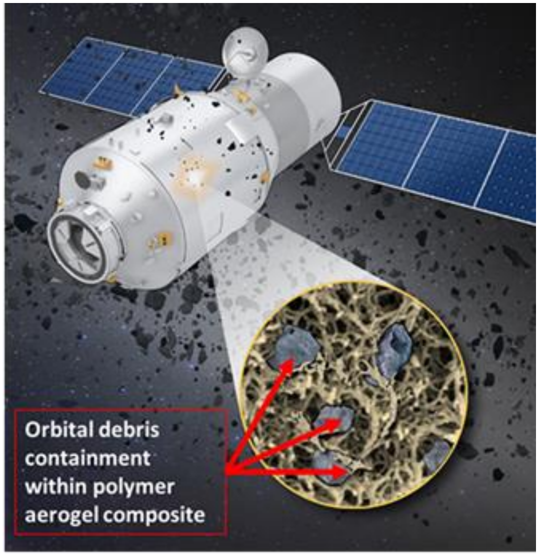
Reflection coefficient of polyimide aerogels vs melamine foam

Orbital Debris Remediation and Energy Absorption

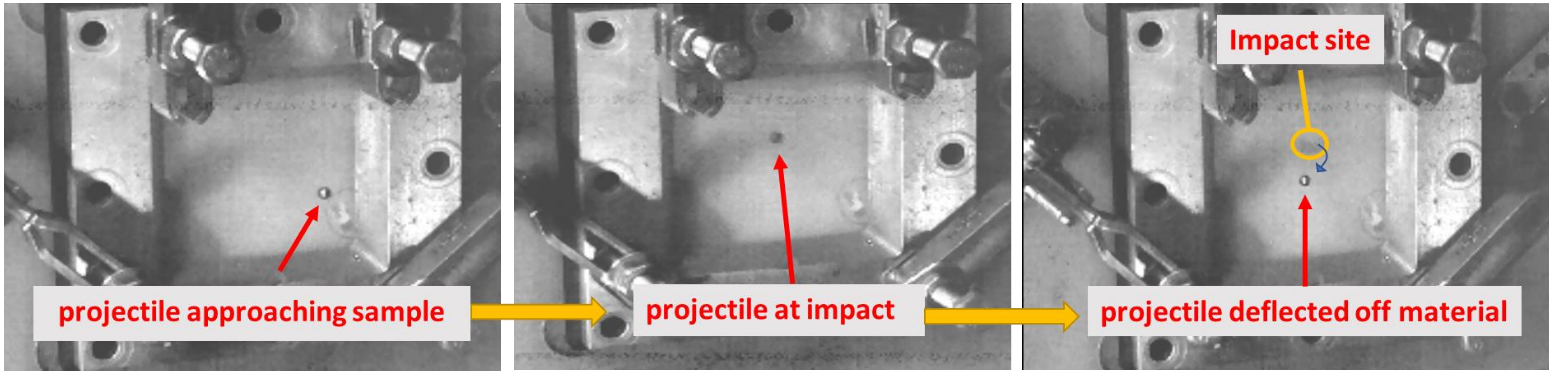




name	areal density, ρ_a (g cm^{-2})	impact velocity, v_i (m s^{-1})	exit velocity, v_e (m s^{-1})	absorbed energy, (%)
PI-1	0.22	1283.05	1160.18	18.24
PI-2	0.19	1091.16	1018.95	12.80
PI-3	0.23	1237.40	1145.32	14.33
PI-4	0.20	466.24	369.21	37.29
PI-5	0.19	435.22	371.63	27.09
PI-6-A	**0.19**	**160.92**	**0**	**100**
PI-6-B	**0.19**	**174.09**	**0**	**100**
PI-7	0.17	179.21	31.61	96.89
PI-8	**0.23**	**171.53**	**0**	**100**

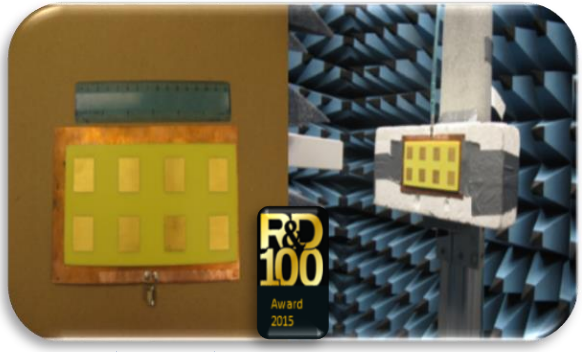


Polymer aerogel acts as an energy dissipating barrier



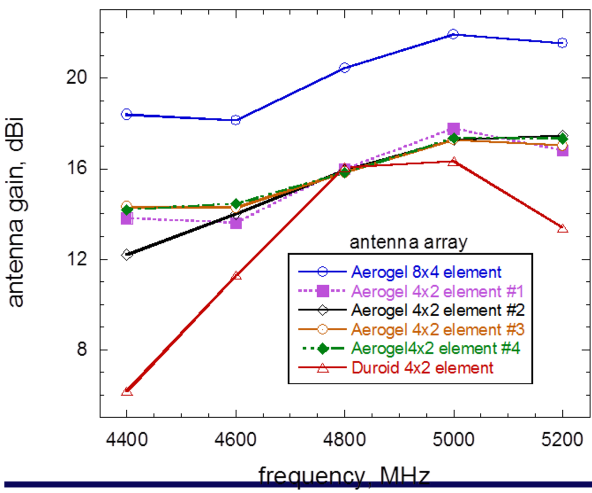
Malakooti S, et al. Polyimide aerogels for ballistic impact protection. Sci Rep. 2022 12(1):13933

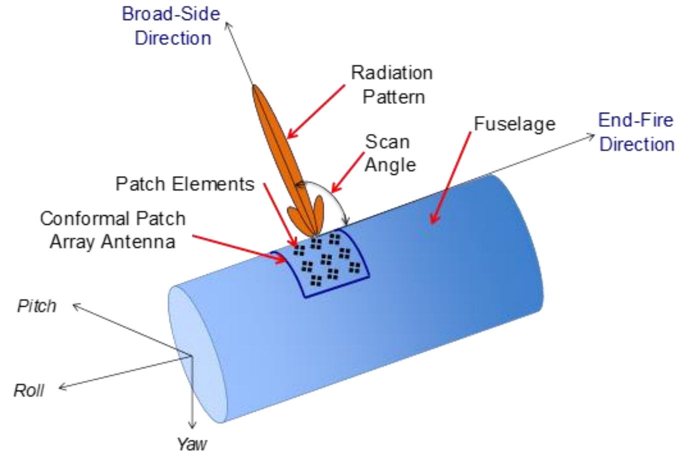
Low dielectric properties of PI aerogel



Phased array antennas

- Improved gain and efficiency 77 % lighter in weight
- Broader bandwidth allowing for reduced number of antennas





Beyond line of sight (BLOS) coverage for UAS

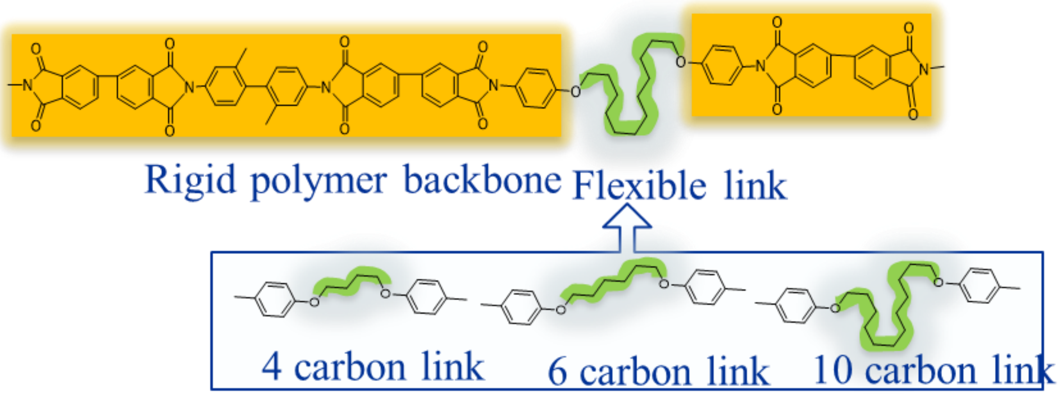
Global Hawk/Northrop Grumman

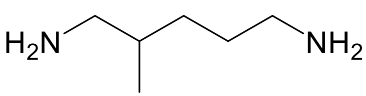
- Electronically attenuated ultra low side lobes to avoid interference with ground
- Build out of ultra-lightweight, low dielectric polymer aerogels
  - Up to 80% weight savings by using unconventional materials
- Reduced drag through use of conformal designs

Meador, et al. ACS Appl. Mater. Interfaces 2012, 4, 11, 6346–6353

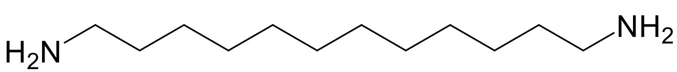
Approach to more flexible aerogels

- Utilize aliphatic diamines to replace up to 75 % of aromatic diamine

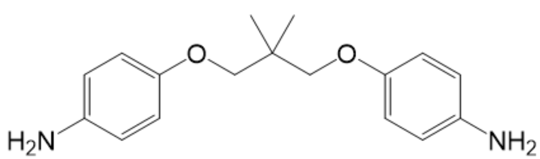




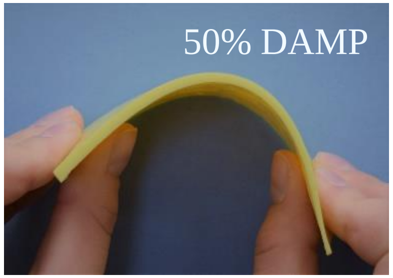
1,5-diamino-2-methylpentane (DAMP)

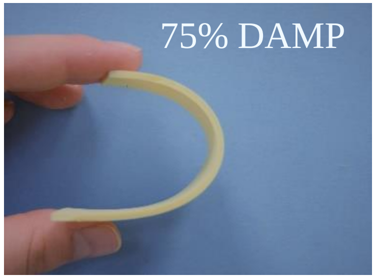


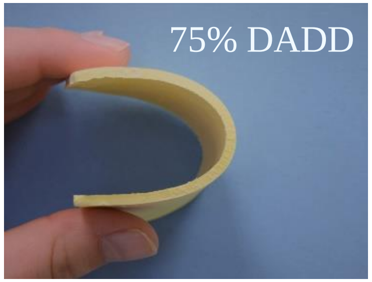
1,12-diaminododecane (DADD)



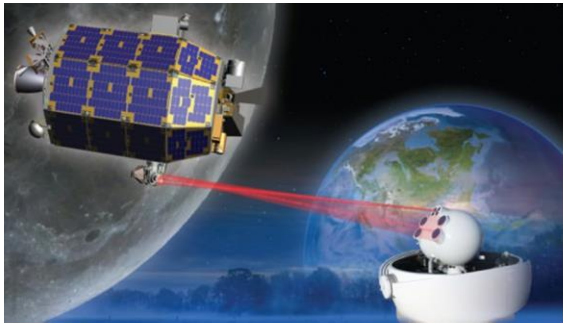
1,3-Bis(4-aminophenoxy)neopentane (BAPN)



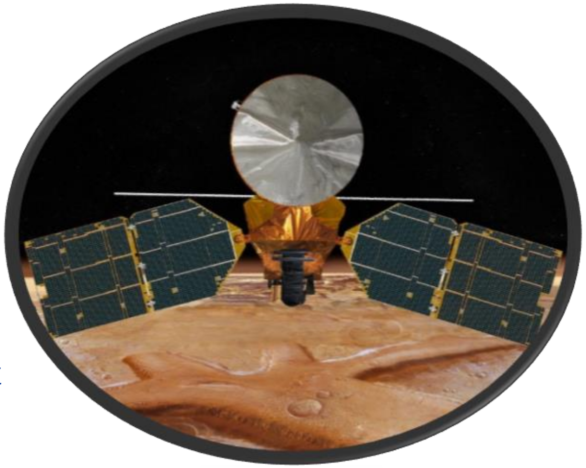




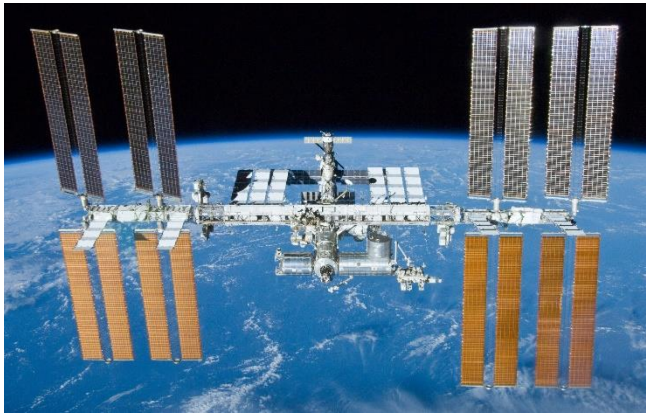
BLOS Communication for Space Applications



Lunar Atmosphere and Dust Environment Explorer (LADEE) satellite in lunar orbit



Mars Reconnaissance Orbiter Mission

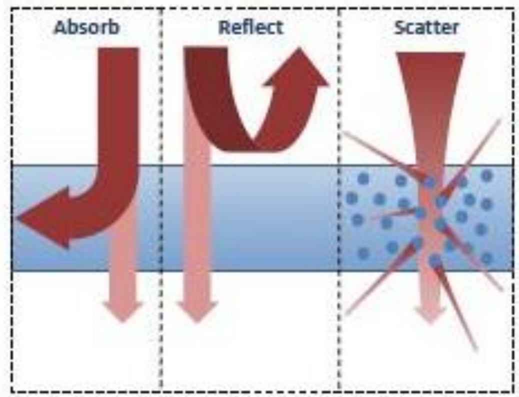


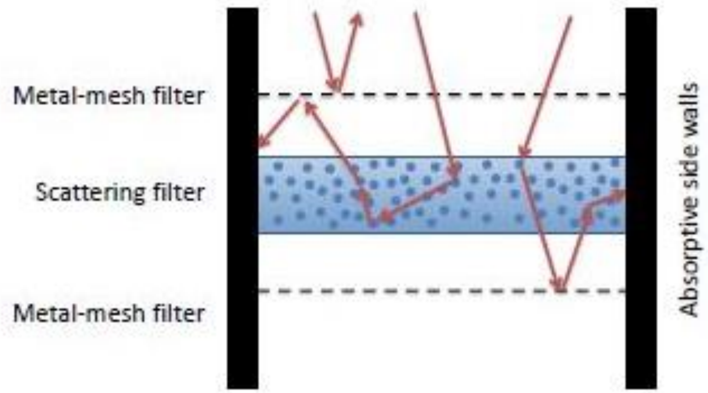
International Space Station

https://www.nasa.gov/sites/default/files/atoms/audio/ep157_gateway.mp3

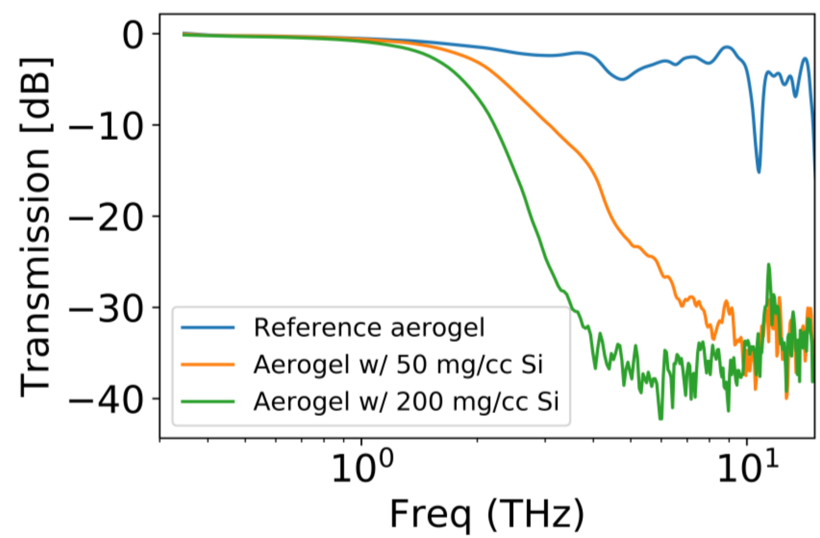
The Deep Space Network (DSN): NASA's international array of giant radio antennas that support interplanetary spacecraft missions

Aerogel IR Scattering Filters for mm and Sub-mm Astrophysics (Origin of Life Studies)





- IR blocking filters made by embedding scattering particles in an aerogel substrate
- Maximizing the sensitivity of millimeter and sub-millimeter instruments requires rejection of infrared (IR) light.



T. Essinger-Hileman,et al. Appl. Opt. 59, 5439-5446 (2020)

M16 ▪ Eagle Nebula

Hubble Space Telescope ▪ WFC3/UVIS/IR

NASA and ESA

STScI-PRC15-01c


The Southern Ring Nebula
Webb's Near-Infrared Camera (NIRCam)
Webb's Mid-Infrared Instrument (MIRI)
"planetary nebula" - vivid shells of gas and dust expelled into space by a dying star some 2,000 light-years away

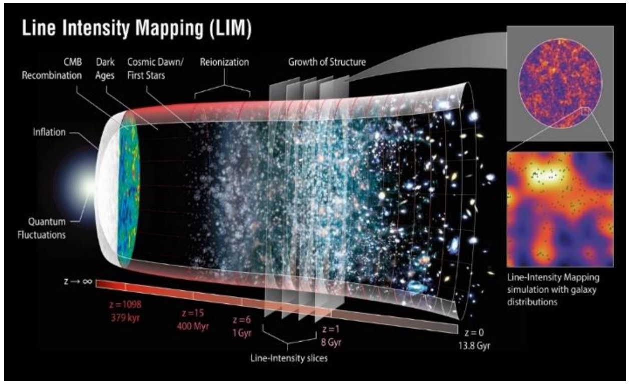

Carina Nebula
edge of a nearby, young, star-forming region

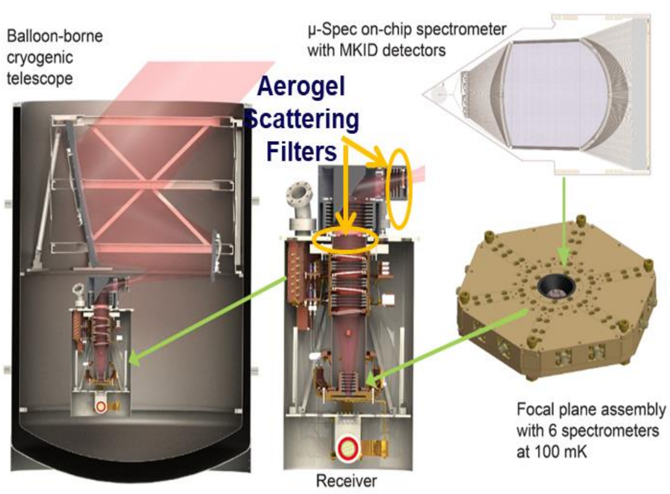

Stephan's Quintet
a cluster of five galaxies between 40 million -290 million light-years away


SMACS 0723
Near-infrared image of galaxy cluster

EXCLAIM:
The EXperiment for Cryogenic Large-Aperture Intensity Mapping

EXCLAIM will map CO and ionized carbon [CII] at redshifts of $0 < z < 3.5$ (depending on the line) to try to understand star formation over cosmic time



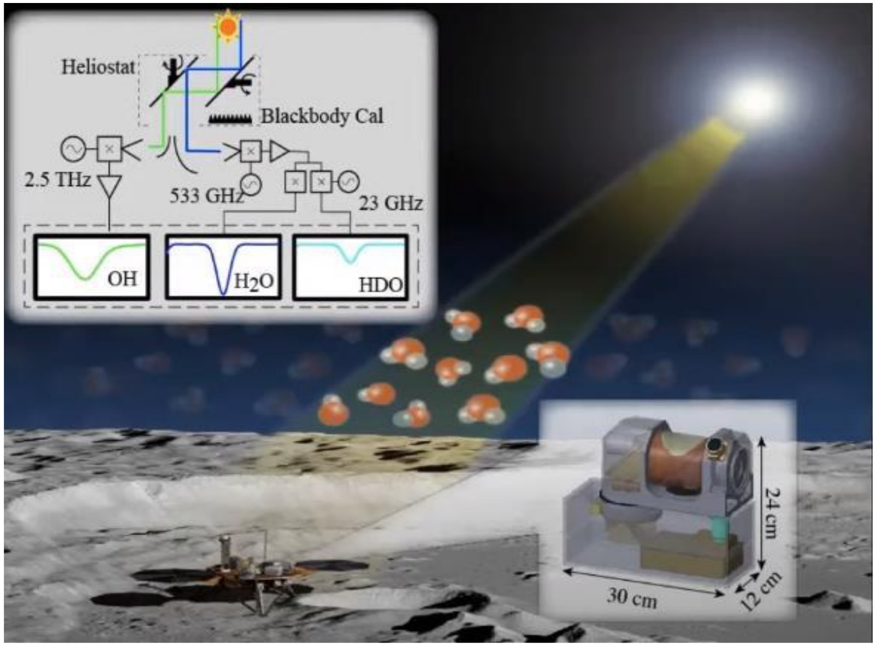


Aerogel scattering filters are the baseline infrared-blocking filter for EXCLAIM

The EXCLAIM band is 420-540 GHz and the filters should effectively block radiation above 1 THz

PI: Eric Switzer (GSFC)

SSOLVE:
Submillimeter Solar Observation Lunar Volatiles Experiment

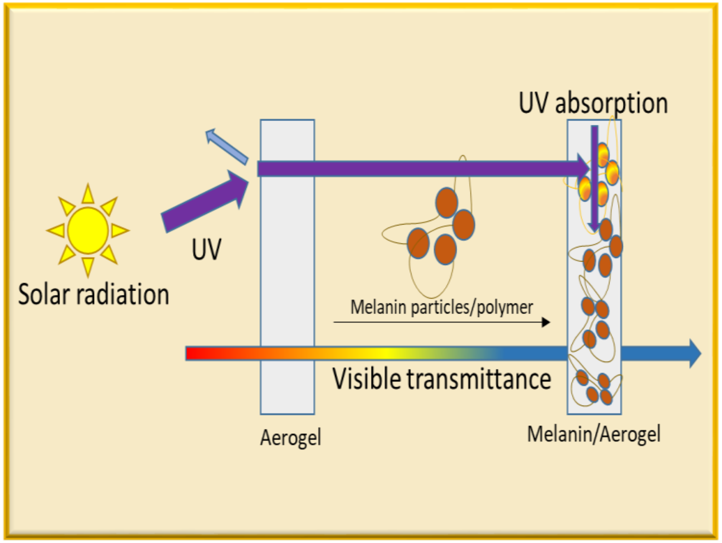


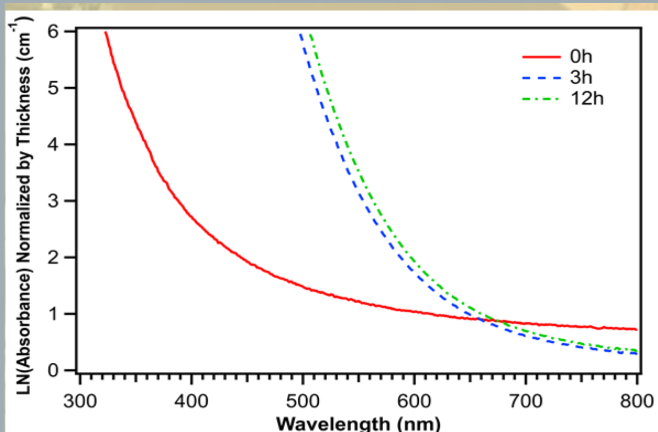
- SSOLVE will measure water vapor to learn which source(s) of water dominates the lunar atmosphere.
- Operate submillimeter spectrometers from a lander, using a heliostat to target the Sun and to measure the column abundance of H2O, OH, and HDO in the lunar atmosphere

EPSC Abstracts, Vol. 13, EPSC-DPS2019-1173-1, 2019

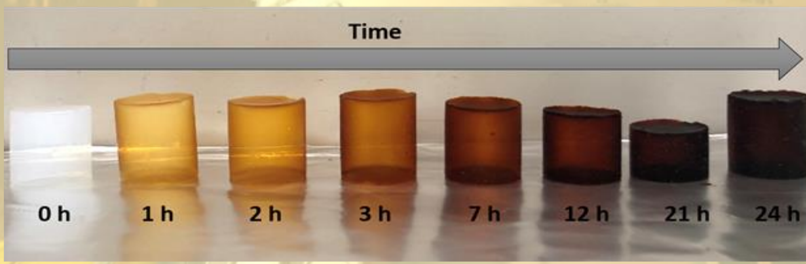
PI: Berhanu Bulch (GSFC), Tim Levingood (University of Maryland)

Melanized Aerogel for Radiation Mitigation

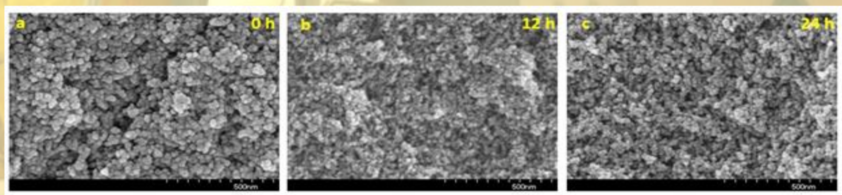




Representative UV-vis spectra for PDA-coated aerogels at t=0, 3,12



PDA-coated silica aerogels at coating time (t) t=0, 1, 2, 3, 7, 12, 21, 24 h.



SEM images of the surface morphology of native aerogel (a) and PDA coated aerogel at t=12 h (b) and t=24 h (c)

Melanized aerogels exhibit higher absorption over native aerogel with little to no effect on surface area, density, shrinkage, and porosity

***G.Rey, et al. ACS Appl. Mater. Interfaces* 2021 *13* (34), 41084-41093**

Aerogel applications with Industry, Academia, and OGA's

- **Aerogel Technologies, LLC:** Holds the highest number of licenses for NASA aerogel technology
- **UT Austin/NSF:** ultralight carbon aerogel electrodes to increase energy density of rechargeable batteries
- **Scintilex,LLC/DoE: Highly** transparent aerogel - high energy particle detection
- **Aspen Aerogel-SBIR with NASA**: Thin Aerogel as a Spacer in Multi-Layer Insulation. Fixed-Wing and Rotary-Wing Aircraft Thermal, Acoustic, IR & Fire Protection
- **US DoD/ Lockheed Martin**: Nanocellulose Aerogels for UAV applications
- **Washington State University**: 3D-printed LH2 Tank-Aerogel Insulation
- **Bremont Watch Co(UK)/Boeing**: Wristwatches and chronometers featuring Boeing aeroplane material (aerogel)
- **Designer Claire Choisne**: Boucheron's Goutte de Ciel, which translates as "taste of the sky."


Acknowledgments

–Anne McNelis, Lucas Shearer, Dr. Chris Johnston, Dr. Maria Kuzmarski, Dr. Tom Essinger- Hileman, Dr. Berhanu Bulcha, Dr. Theresa Benyo (NASA)

–Linda McCorkle, Dan Scheiman Frank Bremenour, Spyro Efpraxias (NASA)

–Dr. Ali Dhinojwala, Gabrielle Rey, Saranshu Singla (University of Akron)

–Dr. Stephen Steiner, Justin Griffin, Ryan Moriah Buckwalter (Aerogel Technologies)

Collaboration with Aerogel Technologies

NASA GRC AEROGEL TEAM

Dr. Stephanie Vivod

Dr. Haiquan Guo

Dr. Sadeq Malakooti

Ariel Tokarz

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SMD Astrophysics Research and Analysis (APRA) Program

STMD Game Changing Development Program (GCDP) ACO

NASA Center Innovation Fund (CIF)

NASA Independent Research and Development (IRAD) Program

RSSA-Launchspace Technologies

Partnering with NASA
Strategic Partnership Office

License NASA's Patents

- NASA's patents can be browsed on the Technology Transfer Program website: technology.nasa.gov
- Patents are sorted into industrially relevant categories
- Licenses come with a variety of terms depending on intended use:
  - Research license: allows licensee to "test drive" commercial viability of NASA's technologies with minimal risk
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NASA Spin-off Technology

CMOS IMAGE SENSOR

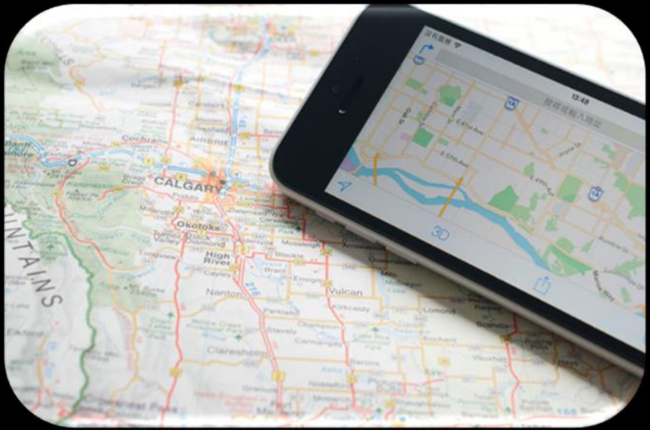
When NASA needed miniature cameras for interplanetary missions, they created the CMOS active pixel sensor.

MEMORY FOAM

Originally designed by NASA-funded researchers to keep test pilots cushioned during flights.

SCRATCH-RESISTANT SUNGLASSES

NASA's Ames Research Center conducted research on ways to protect astronaut helmet visors from scratches, as well as increase their ability to filter out UV-rays and enhance colors.



GLOBAL POSITIONING SYSTEM (GPS)

NASA's Jet Propulsion Laboratory (JPL) developed a software in the 1990s to correct errors in the data from their global network of receivers.

And don't forget about these:

- Anti-corrosion coating
- Cordless vacuums
- Arterio vision
- Cochlear implants
- Insulin pump
- Charge coupled devices
- Water filters

https://spinoff.nasa.gov/

https://spinoff.nasa.gov/sites/default/files/2022-01/Spinoff.2022.pdf

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