New X-ray Detectors to Provide Unprecedented Vision of the Invisible Universe

Project: Advanced Magnetic Microcalorimeter development

Snapshot: A new class of X-ray detector with unprecedented energy resolution and array size could help transform our understanding of the cosmos through unparalleled vision into the otherwise invisible universe.

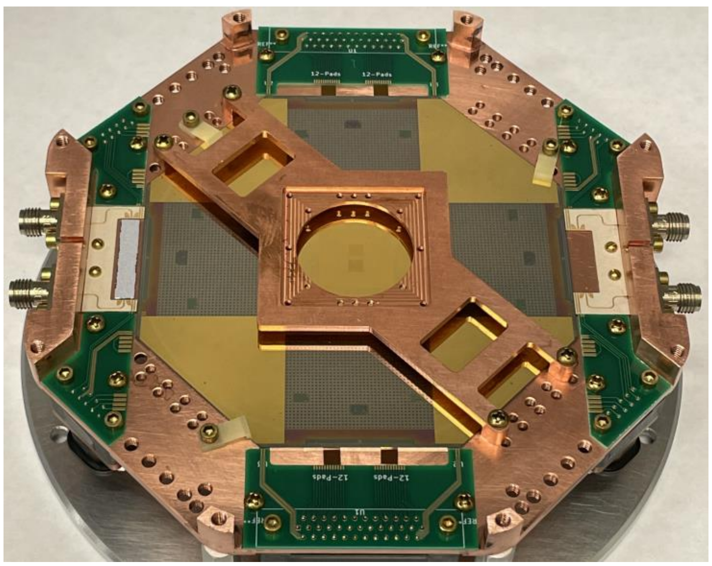


Figure 1: Prototype 100,000-pixel magnetic calorimeter array developed via collaboration between NASA GSFC and MIT Lincoln Laboratory. (Image credit: NASA GSFC)

Very detailed information is now available from ultraviolet, optical, and submillimeter observations of the stellar, dust, and cold gas content of galaxies, and yet there is a dearth of understanding about the mechanisms that formed these galaxies. To truly understand how galaxies form, X-ray observations from high energy resolution imaging spectrometers are needed to see the cores of the galaxies themselves.

New large-area, high-angular-resolution, imaging X-ray spectrometers will expose the essential drivers of galaxy evolution, which leave imprints in the warm-to-hot plasma that cosmologists believe exists in the spaces between galaxies. These intergalactic spaces contain 40–50% of the 'normal matter' in the universe and extend well beyond the currently visible size of galaxies.

A class of X-ray spectrometers called microcalorimeters operate at a very low temperature—a few tens of milli-Kelvin above absolute zero. Over the past five years, the X-ray Microcalorimeter Group at NASA's Goddard Space Flight Center (GSFC), the Advanced Imager Technology Group at Massachusetts Institute of Technology's Lincoln Laboratory (MIT/LL), and the Quantum Sensors Group at the National Institute of Standards and Technology (NIST) in Boulder, Colorado have been collaborating on the development of an ambitious new X-ray camera with unprecedented imaging and spectroscopic capabilities.

This camera is based on a new type of X-ray microcalorimeter called a magnetic microcalorimeter. This NASA/MIT/NIST effort significantly extends the capabilities of the technology. For example, the X-Ray Imaging and Spectroscopy Mission (XRISM) mission, which is a collaboration between JAXA and NASA scheduled to launch in 2023, consists of a microcalorimeter array with 36 pixels. An ESA flagship mission currently in formulation (the Advanced Telescope for High Energy Astrophysics, or ATHENA) will have a microcalorimeter array with about two-thousand pixels. The arrays under development by the NASA/MIT/NIST collaboration have around *one-hundred thousand pixels or more*, reaching the angular scales and array sizes normally only associated with charged-coupled device (CCD) cameras.

Figure 2 shows one of the 100,000-pixel arrays the team has developed. The pixels are designed to have energy resolution that is about two orders of magnitude greater than that of an X-ray CCD camera. This exquisite high-energy resolution is critical to measure the abundances, temperatures, densities, and velocities of astrophysical plasmas. Such measurements will expose the essential drivers of galaxy evolution that are hidden in the plasmas of the universe.

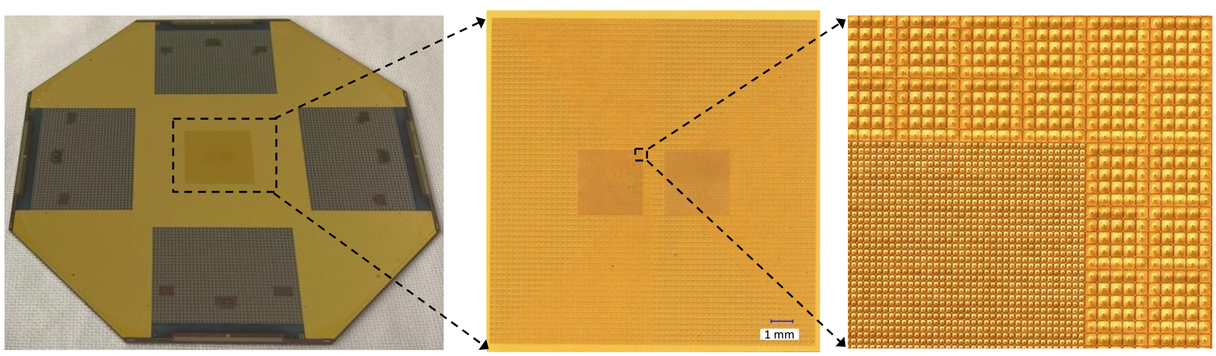


Figure 2: Zoom-in of prototype 100,000 -pixel magnetic calorimeter array showing the three different pixel types in this array. (Image credit: NASA GSFC)

When an incoming X-ray hits the microcalorimeter's absorber, its energy is converted into heat, which is measured by a thermometer. The temperature rise is directly proportional to the X-ray's energy. The thermometers employed with magnetic microcalorimeters use paramagnetism to enable high-precision temperature sensing. In a paramagnet, the magnetization is inversely proportional to temperature, making it very sensitive to small changes at the low temperatures (at or below 50 milli-Kelvin) at which these devices operate.

In addition to single-pixel sensors, it is possible to design position-sensitive magnetic microcalorimeters in which a sensor is attached to multiple X-ray absorbers with different thermal conductance strengths. The unique temporal response of the different pixels to X-ray events allows the pixel event location to be distinguished. Due to the many heads in the sensor, this kind of thermal multiplexing device is often called a `Hydra,' after the multi-headed serpentine water monster in Greek and Roman mythology. An example of a magnetic calorimeter `Hydra' sensor is shown in Figure 3.

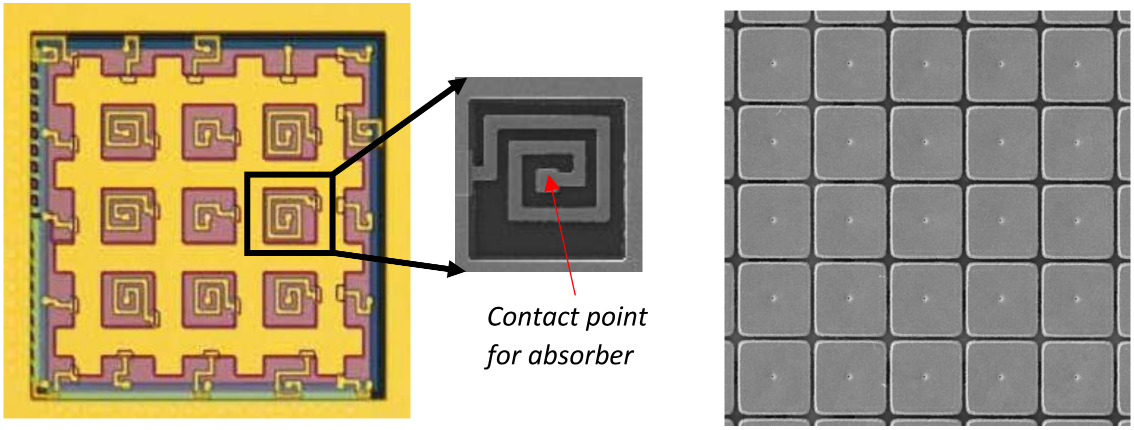


Figure 3: Photograph of a 25-pixel thermally multiplexed Hydra sensor. The waffle-shaped gold region is the magnetic sensor (left). The thin meandering lines emanating from the sensor are the different thermal links that go to 25 different contact points from which 25 independent X-ray absorbers can be suspended on top of the sensor, as shown in the electron micrographs (center, right). (Image credit: NASA GSFC)

The main factors limiting the development of microcalorimeter arrays with the desired size and angular resolution (the distance from the center of one pixel to the next, or "pitch") are the challenges involved in fabricating high-density, high-yield, microstrip superconducting wiring to connect all the pixels in the array. The major innovation employed to overcome this difficulty is to incorporate many layers of buried wiring underneath the top surface of detector chips on which the microcalorimeter arrays are then fabricated. Through an investment in technology for superconducting electronics, MIT/LL developed a process that allows over eight layers of superconducting wiring with high yield. The array shown in Figure 2 uses four layers of superconducting wiring, and the next generation of devices currently in fabrication utilizes seven layers of buried wiring. By combining this buried wiring process with the 25-pixel, 'thermally multiplexed,' microcalorimeters developed at NASA GSFC, the team has been able to produce large-format arrays of wires with pitch as fine as 25 microns.

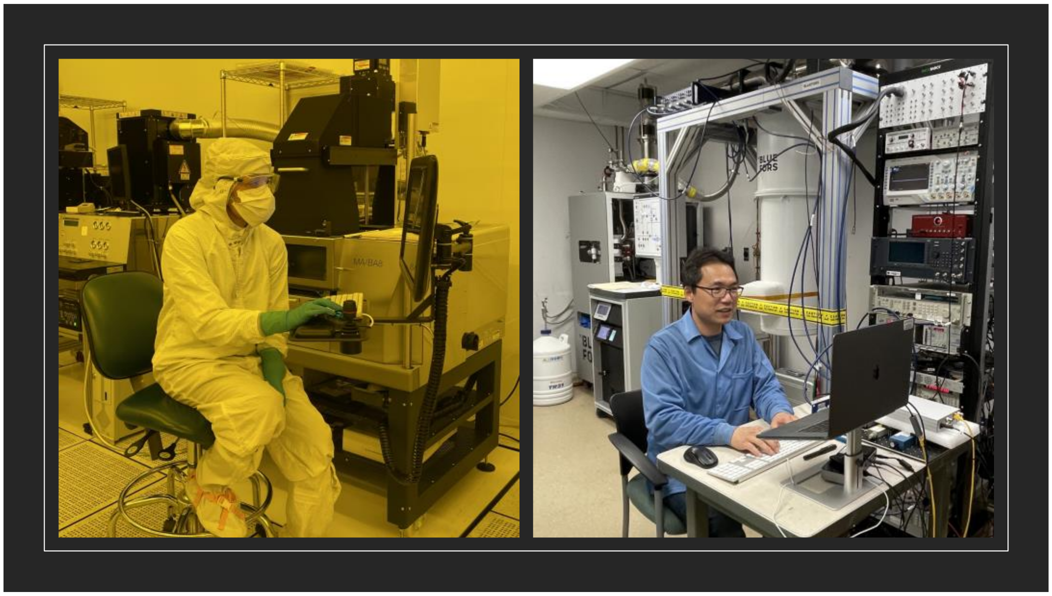


Figure 4: The magnetic calorimeter being fabricated by Dr. Archana Devasia (left) and tested by Dr. Wonsik Yoon (right). (Image credit: NASA GSFC)

The final key development needed to make this detector suitable for future astrophysics missions is the multiplexed read-out needed for such large arrays of pixels. With NASA funding, NIST is developing a microwave-multiplexer superconducting quantum interference device (µ-MUX SQUID) read-out in a form-factor suitable for direct integration with this detector. Four two-dimensional chips carrying this read-out will be bump-bonded to the four large green rectangular areas in the outer regions of the detector shown in Figure 1. NIST has recently demonstrated low-noise µ-MUX SQUIDs, in small one-dimensional resonator arrays suitable for the new magnetic calorimeters. These µ-MUX SQUIDs measured magnetic flux noise that corresponds to just 20 quanta (or photons) at signal frequencies, meeting the challenging design requirements. In the near future, two-dimensional versions of this read-out will be bump-bonded to the detector shown in Figure 1, and the team hopes to demonstrate a ground-breaking new astrophysics instrumentation capability.

NASA's Astrophysics Division has invested in magnetic calorimeter development at GSFC since 2008, most recently in this collaborative effort with MIT/LL. This type of device is under consideration for use in several potential future missions.

Project Lead(s): Dr. Simon Bandler, Dr. Thomas Stevenson, Dr. Archana Devasia and Dr. Wonsik Yoon (GSFC), Dr. Kevin Ryu (MIT/LL), Dr. Joel Ullom, Dr. Benjamin Mates (NIST).

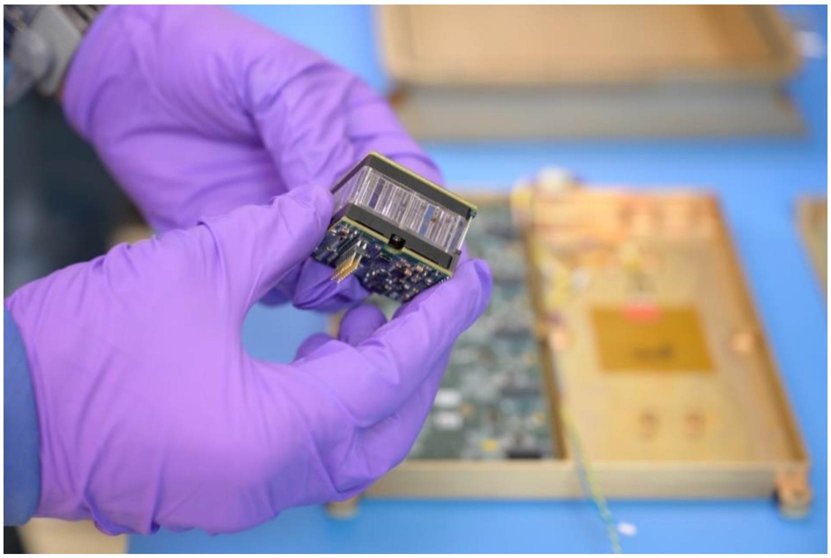
Sponsoring Organization(s): Astrophysics Division Internal Scientist Funding Model (ISFM) and Astrophysics Research and Analysis (APRA) Programs

Key terms: X-ray detector, imaging spectrometer, cryogenic sensor, microwave multiplexing

Growing Yeast on the Moon to Study Radiation Risks to Human Explorers

Project: Lunar Explorer Instrument for space biology Applications (LEIA)

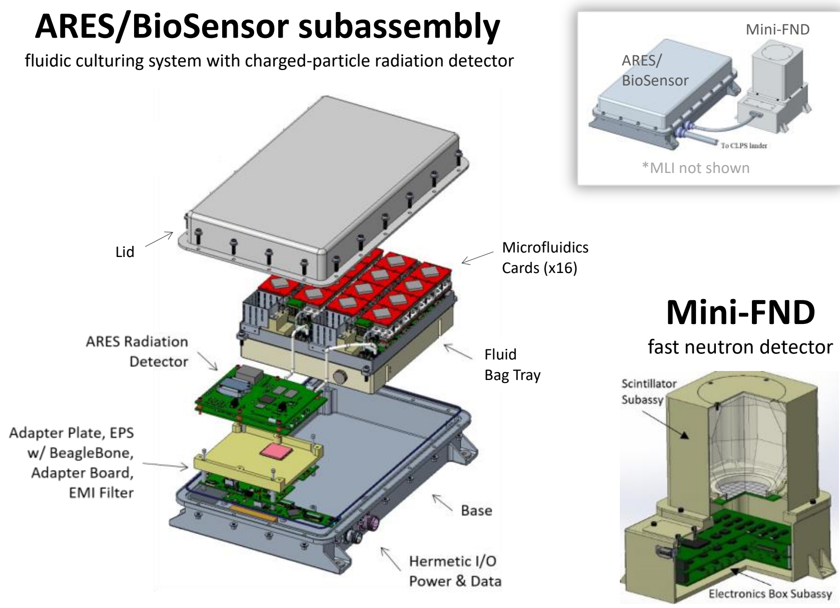
Snapshot: An autonomous microfluidic culturing system with CubeSat heritage teams up with two state-of-the-art radiation detectors to measure how biology responds to the radiation and reduced gravity environment on the lunar surface.



A LEIA card stack: a fluidic card with microwells for yeast growth, sandwiched by the electronics that control temperature and optics.

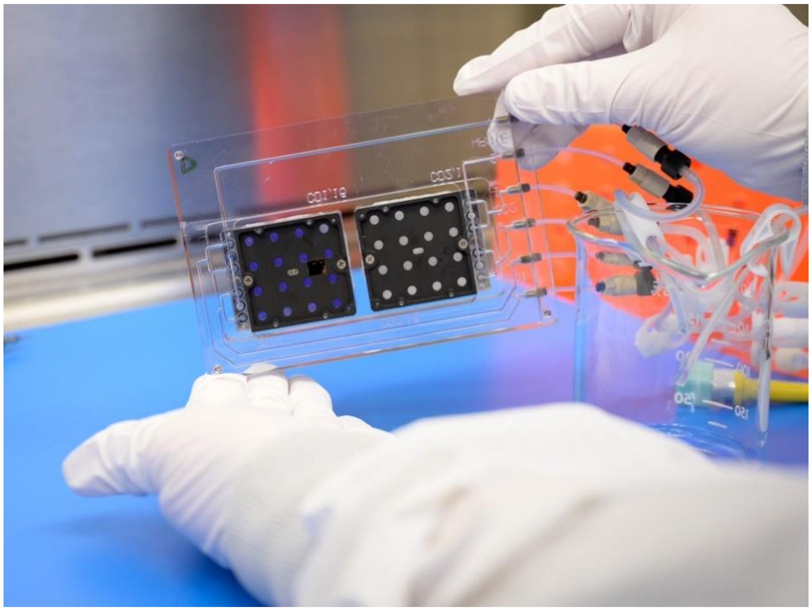
Humans are returning to the Moon for the first time in decades, and we intend to stay. NASA's Artemis missions are preparing for a sustained human presence on and around the Moon, with the ultimate goal of sending humans to Mars. These deep-space destinations present health risks to astronauts that are qualitatively and quantitatively different from those associated with stays on the International Space Station (ISS). One of the most significant risks for astronauts venturing outside the protection of Earth's magnetic field is ionizing radiation: Galactic Cosmic Rays (GCR), Solar Particle Events (SPE), and the "albedo" radiation produced by the interaction of space radiation with the lunar surface. Exposure to ionizing radiation can result in an increased risk of cancer, cardiovascular disease, and neurological impairment.

The Lunar Explorer Instrument for space biology Applications (LEIA) aims to provide empirical data to help define these risks by measuring the biological effects of lunar radiation and reduced gravity using a well-studied microbe whose DNA has a lot in common with ours: baker's yeast. Remarkably, yeast and humans have hundreds of similar genes, including those important to DNA damage responses, so understanding the effects of stress on yeast in space will help us develop countermeasures to protect humans. As an added dividend, LEIA will obtain precise measurements of the radiation environment on the lunar surface at the South Pole, near the anticipated landing site for Artemis III—the mission that will return humans to the Moon's surface.



Drawings of the hardware components comprising LEIA—the ARES/Biosensor subassembly and the Mini-FND. The image at the top on the right depicts how these two components are connected to form LEIA. (ACRONYM KEY: MLI = Multi-Layer Insulation, EPS = Electrical Power System, EMI = Electromagnetic Interference)

LEIA is a suite of instruments that work together to characterize the lunar radiation environment and the biological response to it. The biological instrument, the BioSensor, is based on the BioSentinel CubeSat developed at Ames Research Center as part of the Artemis I mission. The BioSensor has an autonomous microfluidic system in which yeast cells, kept in a dry dormant state for transit, are activated by adding a liquid culture medium to stimulate growth and metabolism over several days. The LEIA version of the BioSensor has 16 fluidic cards, each with 16 culture microwells, so the instrument can accommodate 256 samples and calibration standards. Each well is equipped with three Light-Emitting Diode (LED) lights, as well as a photodiode sensor to measure cell growth via optical density and metabolic activity using a color-changing oxidation-reduction (redox) indicator dye. Chronic, sublethal radiation damage to cells is a significant concern for astronaut health. The BioSensor detects these effects through changes in rates of metabolism and cell growth in the yeast.



A pair of fluidic cards mounted in a manifold, being filled with growth medium containing blue redox indicator dye.

Two radiation detectors will accompany the BioSensor as part of the LEIA suite. The Airborne Radiological Enhanced-sensor System (ARES), a radiation detector slated for use on the Artemis II and III missions, will measure time-resolved dose, dose rate, and energy deposition by charged particles from the solar wind and GCR. The Mini-Fast Neutron Detector (Mini-FND) will measure high-energy neutrons, which are a substantial component of lunar surface radiation and a significant risk to quantify for crewed missions. The Mini-FND is a miniaturized version of the International Space Station (ISS) Radiation Assessment Detector (ISS-RAD) FND. ARES was developed at NASA Johnson Space Center (JSC), and the Mini-FND is being developed by the Southwest Research Institute (SwRI) in Boulder, CO.

LEIA technology has roots in instruments with extensive flight heritage, yet several developments distinguish it from its predecessors. One example is the introduction of a “late-load” capability, enabling investigators to integrate the fluidic cards containing the yeast cells into the BioSensor at the end of the payload assembly. Late load allows fresh yeast cells to be flown, which mitigates the cell damage that occurs when yeast cells are stored in suboptimal environmental conditions during integrated lander testing and potential launch delays. This improvement ensures more direct measurements of the effects of the lunar surface environment.

Members of the LEIA biology team using custom-built ground support hardware for testing yeast growth in fluidic cards.

The LEIA yeast strains, currently being developed by Principal Investigators (PIs) Mark Settles and Sergio Santa Maria at NASA Ames Research Center (ARC), represent a biotechnological development central to achieving the scientific aims of the mission. The LEIA experiments will include both strains flown on BioSentinel and additional strains engineered with modifications to DNA repair pathways, to provide data on how different components of cellular machinery interact to fix radiation-induced damage. In addition, LEIA will include yeast strains from the BioNutrients experiment, a project to develop microbial food sources that could provide astronauts with nutritional supplements produced on-demand during long-duration missions. Specifically, LEIA will study whether yeast engineered to produce antioxidants such as beta-carotene can maintain antioxidant production in the lunar environment. LEIA will also test yeast strains that include genes introduced to increase radiation resistance. Extensive research is underway to select flight strains that are robust enough to withstand pre-flight storage, launch, and transit, but sensitive enough to provide a measurable biological response to the lunar environment.

LEIA is supported by a Payloads and Research Investigation on the Surface of the Moon (PRISM) Grant and is scheduled for delivery to the Moon by the Commercial Lunar Payload Services (CLPS) program in 2026.

Project Leads: Dr. Mark Settles and Dr. Sergio Santa Maria (PIs), NASA Ames Research Center (ARC)

Sponsoring Organizations: NASA Biological & Physical Sciences (BPS) Space Biology Program; Exploration Science Strategy and Integration Office (ESSIO)

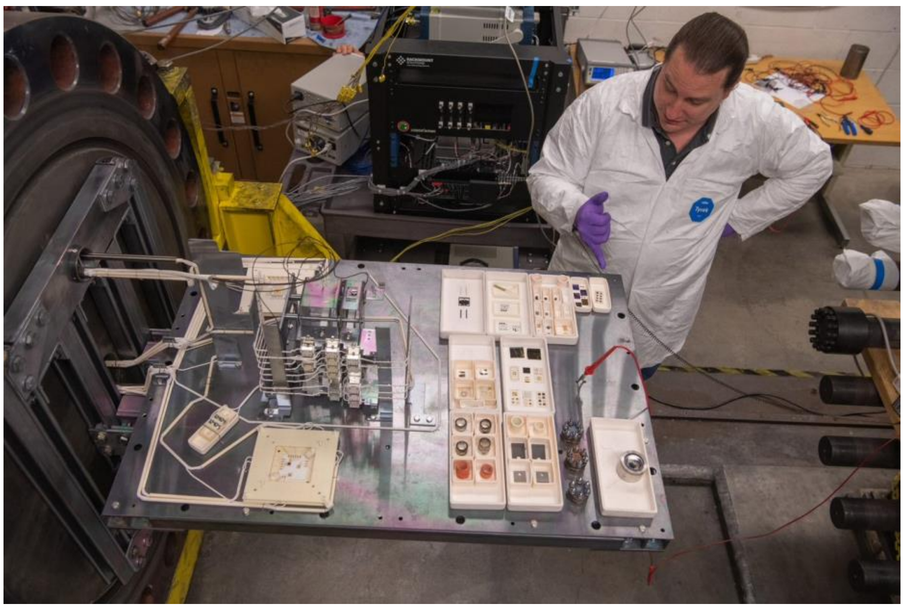
Key terms: CLPS, lunar environment, space radiation, radiation detectors, CubeSats, yeast

HOTTech Attempts to Tackle Venus

Specialized test rig determines how new technologies fare in extreme conditions

Project: Hot Operating Temperature Technology (HOTTech) Program; NASA Glenn Extreme Environment Rig (GEER)

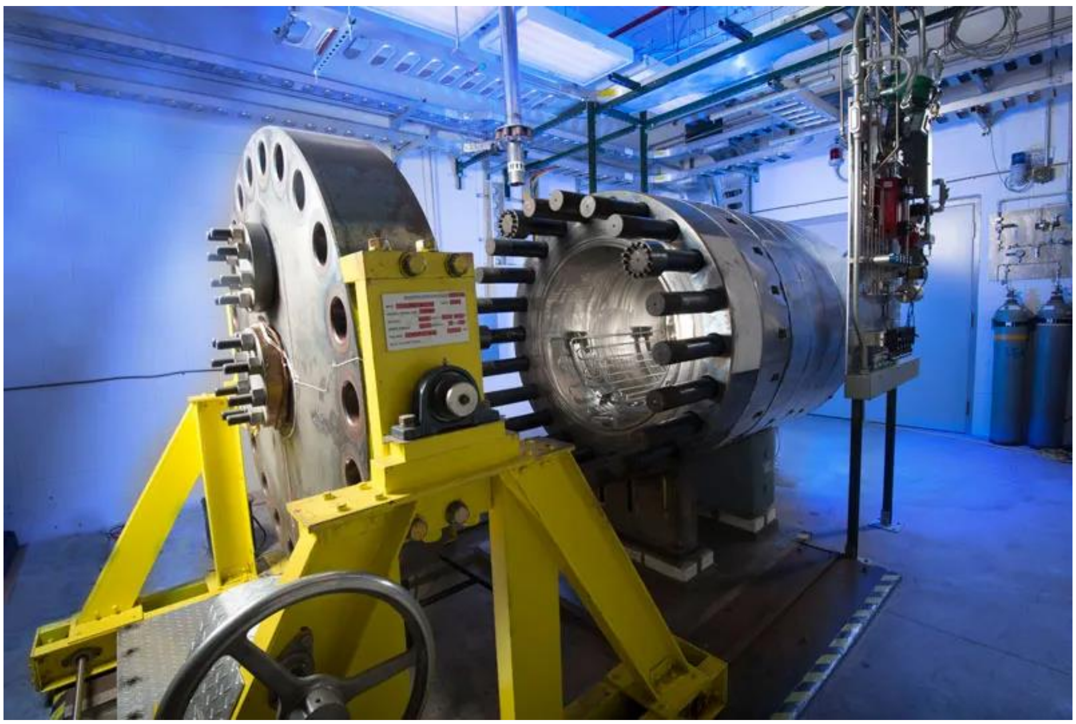
Snapshot: Projects in NASA's HOTTech Program are developing technologies that will operate on the surface of Venus for at least 60 days. Since previous Venus landers have only survived for several hours, long-duration operation represents a paradigm shift in landed spacecraft technology. The GEER chamber at NASA Glenn Research Center simulates Venus conditions and acts as a testbed for materials, electronics, sensors, and power technologies for future long-duration exploration.



HOTTech test articles being prepared for insertion into the GEER chamber by Mark Sprouse, GEER Test Ops Team Electrical Engineer (Image credit: NASA GRC)

As far as solar system exploration goes, the surface of Venus is an inhospitable place for technology. The average temperature is almost 900°F, high enough to melt metals like lead; the atmospheric pressure is over 90 times that of Earth; and the atmosphere contains highly corrosive chemicals. Previous Venus landers subjected to these harsh environmental conditions have only survived for several hours. To overcome this challenge, the HOTTech Program is developing core technologies including electronics, batteries, power systems, and actuators that will be able to operate on the Venus surface for at least 60 days.

The teams working on these technologies have been iteratively building and testing in laboratories throughout the US over the last several years, but eventually the big question is: How would these technologies fare on Venus? Enter the Glenn Extreme Environment Rig (GEER), a nearly 20-ton chamber at the NASA Glenn Research Center designed to simulate the conditions on the surface of Venus. The chamber is massive to safely contain the Venus pressure. The GEER end cap, which slides opens on railroad-like rails to enable set up of experiments, is subject to two million pounds of force as the Venus surface pressure is simulated. Heaters keep the chamber and everything inside at the extreme temperature of almost 900°F. Furthermore, GEER can insert and monitor corrosive gases in the chamber and 'boost' them as needed to match conditions expected on the Venus surface (these gases may react with the technologies being tested!). Finally, the GEER team has incorporated electrical feedthroughs to allow power and electrical signals to be transferred between the HOTTech technology inside the chamber and external test equipment.



The GEER chamber (Image credit: NASA GRC)

Several HOTTech project teams formed a community of practice to collaborate with each other and the GEER team to improve and optimize their technologies. The goal is to eventually combine successful individual components into increasingly capable systems. The technologies listed below were recently tested together in GEER to learn how they might fare during long-term operations on Venus:

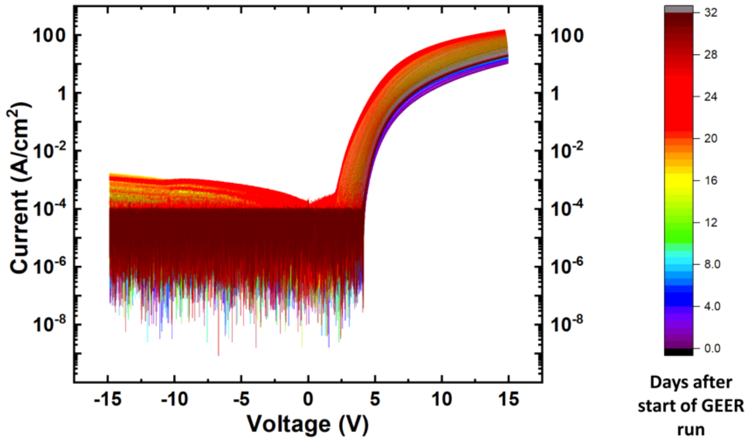
HOTTech program technologies recently evaluated in GEER	
Principal Investigator/Institution	**Technology**

Jitendra Kumar/University of Dayton	Battery technology
Darby Makel/Makel Engineering, Inc.	Silicon carbide electronics for chemical sensors
Alan Mantooth/University of Arkansas	Electronics packaging
Robert Nemanich/Arizona State University	Diamond electronics
Phil Neudeck/NASA GRC	Silicon carbide RAM Memory
Leora Peltz/Boeing	Field emission electronics
Alex Rattner/Penn State University	Seals for power production
Debbie Senesky/Stanford University	Gallium nitride clock circuits
Yuji Zhao/Arizona State University	Gallium nitride electronics

The GEER test of these technologies ran from December 2022 through February 2023. Although the technologists are still performing post-test analyses to evaluate how their technologies performed, some encouraging initial results have already been noted.

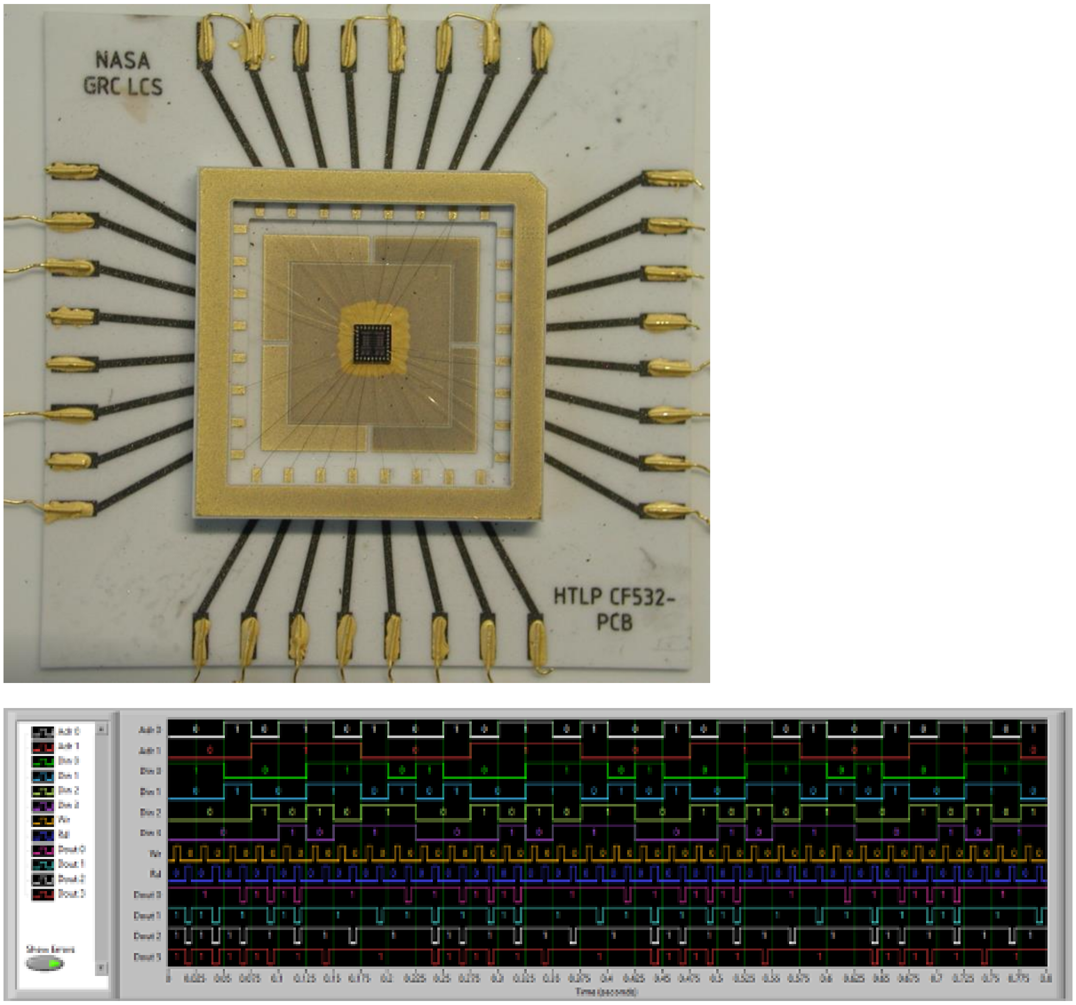
Gaskets are critical components that seal the various mechanical and electrical systems on a spacecraft or lander, preventing the ingress of dust, gas, and other contaminants. While developing a power system for a future Venus lander, the Penn State team identified vermiculite as a potential gasket material capable of surviving the extreme Venusian conditions. “Vermiculite is a mineral with excellent thermal stability, a low coefficient of thermal expansion, and a great resistance to most corrosive environments” said Dr. Christopher J. Greer, Assistant Research Professor Mechanical Engineering, Penn State University. The GEER tests determined the ability of this vermiculite sealing material to hold back the high pressure and temperature and withstand the corrosive conditions on Venus.

In a collaborative effort, three different groups tested electronic devices packaged by a fourth group in this recent GEER test. One of those devices was a diamond diode provided by Dr. Nemanich, a member of the Arizona State University team. He explains “Each hour, the computer-controlled system turned the diamond diode on and recorded the current density (vs. voltage) in the forward and reverse directions. The figure below presents a composite plot of all measurements during the 30 days. Throughout the test, the diode showed a high rectification ratio (forward vs reverse current density), which is consistent with the theoretical simulations.” This GEER test represents the first demonstration of diamond-based electronics operating in simulated Venus surface conditions for an extended time, and provides a foundation for a new type of electronics for future missions



Composite plot of the electrical characteristics of a diamond diode during the HOTTech GEER test. The Current-V curves were recorded during the 30-day test, and the color scale on the right indicates the day the specific scans were recorded (Image credit: Dr. Robert Nemanich/Arizona State University)

A notable "first" achieved in the GEER test was the successful operation of electronic memory, which allows scientific data to be stored until it can be transmitted using silicon carbide (SiC) electronics. The picture below shows the pristine condition of the memory chip and packaging after the GEER test was completed, as well as a snapshot of the electrical performance during the test. Dr. Phil Neudeck, NASA GRC, remarked, "Even though this early prototype chip is just 16 bits, it nevertheless represents the first random access memory ever to demonstrate successful operation for days while exposed to the insanely harsh temperature, pressure, and reactive chemical environment found on the Venus surface. The chip outlasted the Venus environment test duration. Such capability represents another step in the march towards opening the Venus surface to the kind of prolonged robotic exploration that has proven so scientifically fruitful on the surface of Mars."



Silicon Carbide RAM memory chip after exposure to simulated Venus surface conditions in GEER (above) and electrical signals (below) showing the memory working flawlessly, unsheltered from Venus surface conditions in GEER. (Image credit: Dr. Liangyu Chen, OAI)

Other technologies were also tested in this latest GEER run. Results are still being analyzed and will be the subject of future presentations and publications. As a whole, a wide range of technologies and materials of differing levels of maturity were, in some cases, given their first GEER-simulated Venus surface exposure. Some technologies gained a new level of demonstrated maturity, while developers of others gained valuable lessoned learned about the harsh environment on the surface of Venus. This collaborative GEER testing effort provided a foundation for future technology advancements that will enable extended missions on the surface of Venus.

Project Lead(s): Dr. Michael Lienhard (GRC), PSD HOTTech program officer; Dr. Gary Hunter (GRC), HOTTech GEER coordinator; and the HOTTech Principal Investigators listed above

Sponsoring Organization(s): NASA SMD Planetary Science Division HOTTech Program

Key terms: Extreme environment technology, high temperature technology, high temperature electronics, high temperature batteries, high temperature sensors, high temperature actuators