Tokamak experiments provide unique data for validating spacecraft heat shield ablation models

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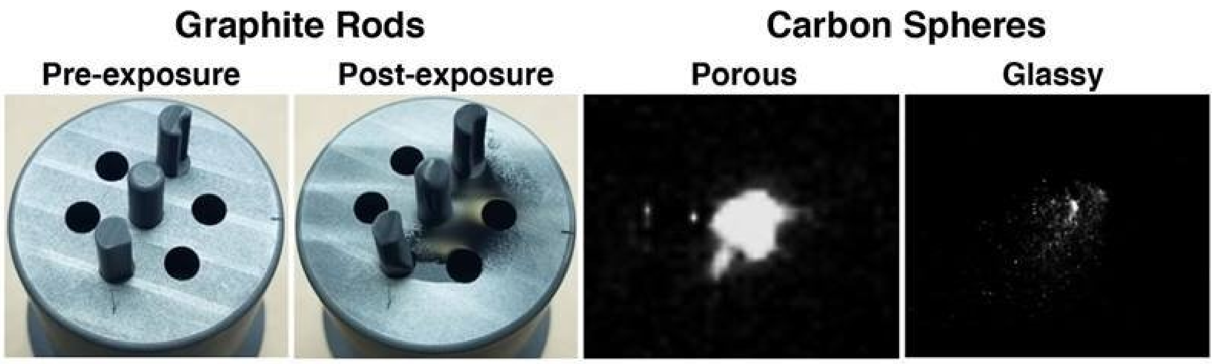

Ablation of three types of carbon studied in DIII-D experiments: graphite, porous, and glassy. All three samples erode with different characteristics when exposed to the high temperature fusion plasma. Credit: University of California, San Diego

When a spacecraft enters a thick atmosphere at a high velocity, it rapidly compresses the gas in front of it. This creates temperatures high enough to ionize the gas molecules into a hot, dense plasma. To protect against damage, spacecraft are typically covered by a heat shield material that burns in a controlled manner. This process is called ablation. Though current materials are effective for present-day missions, future missions require better heat shields.

To help develop them, scientists for the first time used a device known as a tokamak to study what happens to these materials in a hot plasma. In a series of experiments, the team exposed stationary graphite rods to the plasma near the floor of the tokamak. They then injected small carbon pellets deeper into the core of the plasma to observe how different carbon-based materials burn in conditions relevant to spacecraft entry into atmospheres.

Tokamaks are donut-shaped devices that can trap plasmas with strong magnetic fields. Scientists primarily use these devices for research into fusion energy. Conditions in a tokamak plasma can be similar to those experienced during some of the most challenging space missions ever attempted, such as the Galileo probe entry into Jupiter's atmosphere. Although the Galileo mission was successful, its heat shield occupied about half the mass of the probe. This left little capacity for scientific instruments.

Developing lighter and more advanced heat shields requires testing material destruction in extreme heating conditions. These conditions are challenging to reproduce on Earth. These first-of-a-kind experiments provided much-needed data for the advancement of heat shield materials.

Past heat shield testing approaches using lasers, plasma jets, and hypervelocity projectiles suffered from the problem that no single method could simulate the exact heating conditions present during a high-speed atmospheric entry. Consequently, past models of heat shield behavior have sometimes over- or under-predicted the rate at which a heat shield loses material, with potentially disastrous results.

Experiments at the DIII-D National Fusion Facility, a Department of Energy (DOE) user facility, demonstrated that the hot plasma created by a fusion reactor during operation offers a novel and potentially improved way of modeling heat shield behavior, especially for future entries into Venus or the gas giants. The team included researchers from the University of California San Diego, Auburn University, General Atomics, and Baylor University.

Because DIII-D is one of the most flexible and highly instrumented fusion facilities in the world, the team was able to gather a range of valuable data on the behavior of the samples and use it to improve theoretical models and numerical simulations. The DIII-D results show agreement with predictions from a semi-empirical model developed in the aerospace community for calculating the mass loss rate of carbon-based heat shields under extreme heat fluxes during entry into Jupiter's atmosphere.

Thus, the experiments both validated the use of this model in the design of future heat shields and demonstrated that the tokamak plasma can reproduce the extreme heating conditions during atmospheric entry in laboratory environment. The former will help improve spacecraft design for future missions to the gaseous planets in our Solar system. The latter will pave the way for studying experimentally a wide range of fundamental questions, including how meteorites deliver organic material to planet surfaces—an important question in the origin of life.

The research is published in *Volume 4: Advances in Aerospace Technology*.

More information: Dmitri M. Orlov et al, Design and Testing of DiMES Carbon Ablation Rods in the DIII-D Tokamak, *Volume 4: Advances in Aerospace Technology* (2022). DOI: 10.1115/IMECE2021-73326

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