Heating Things Up in Microgravity

Experiments in Space Answer Burning Questions About Fire Behavior

BY STEPHENIE LIVINGSTON, *Staff Writer*

European Space Agency astronaut Alexander Gerst removes the BASS hardware from the Microgravity Science Glovebox onboard the space station. NASA astronaut Reid Wiseman looks on.

NASA

Ya-Ting Liao has always been fascinated by fire. Even as a child growing up in Taiwan, she was interested in the science that makes flames possible. Later, as a scientist, she wanted to understand the mysteries behind flame behavior and how to control it to improve fire safety on Earth and during future space missions. In the vastness of space, where the physics behind flames are in some ways simplified and easier to study, fire itself can still prove equally deadly.

After finishing college in Taiwan, Liao moved to the United States to pursue her Ph.D. at Case Western Reserve University in Ohio. She developed numerical solutions of equations using computer models based on data collected in space by her mentor James T'ien, whose early fire research in microgravity inspired her interest in performing experiments on the International Space Station (ISS). On Earth, gravity-driven forces like buoyancy and convection make it difficult to observe the underlying physics of flame behavior. But scientists can study fire without gravity's masking effects in a microgravity environment.

"When you look at a flame, you don't just see a flame—you can see all the physics on Earth," said Liao, an associate professor of mechanical and aerospace engineering and director of the Computational Fire Dynamics Lab at Case

Western Reserve University. "What is fire? What is a flame? You have thermal fluid processes, transport phenomena, chemistry, and so on. So, if you study fire, you can study just about everything in science, and I love science."

In 2019, Liao decided to take her fascination with flames to space and watched anxiously as the rocket carrying her ISS National Laboratory-sponsored experiment disappeared into the clouds. The investigation, funded by the U.S. National Science Foundation, was designed to study how flames behave in confined spaces—specifically, how solid materials burn in confined spaces and the interaction of fire with surrounding walls. It was the first study on the space station to directly investigate the underlying physics of how confined flames behave in microgravity to improve fire safety models for buildings and other structures.

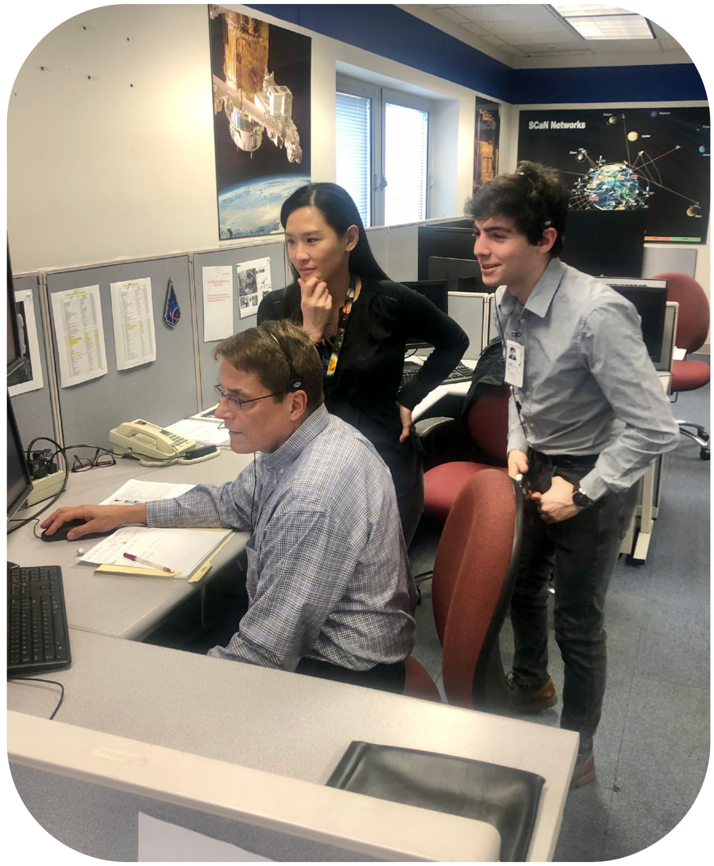
"Currently, we do not usually consider confinement when designing fire-safe structures, so I'm interested in raising awareness by showing how important it is to saving lives," Liao said. "I hope this is just the starting point, and as we move forward, eventually, we will have a complete understanding of how fire behaves under confinement."

Investigating Flames in Space and Within Spaces

In the summer of 2017, faulty electrical components in a refrigerator ignited a fire in London's Grenfell Tower, a 24-floor high-rise in North Kensington. The flames spread to confined spaces in the exterior walls where aluminum cladding and combustible insulation were recently added during renovations. The materials exploded into a raging fire that spread unusually fast to all floors, giving little time for evacuation. Seventy-two people died, and many more were injured.

Liao emphasized that how materials burn when the aerodynamics and thermal effects of confinement influence fire behavior has yet to be well studied, with most fire safety codes needing more guidelines for confined spaces. She noted that the Grenfell fire is an example of what can happen when flames behave entirely differently under confined conditions than in the open air. In some instances, such as when confined flames experience chimney effects and a limited amount of oxygen, flames can burn faster, generate more smoke, and survive longer, which is a dangerous combination.

"Grenfell inspired our hypothesis that confined conditions determine how fire behaves and the rate at which flames spread," said Liao. "The idea is that confinement can be extremely dangerous under some conditions, accelerating how quickly flames spread and how long they burn. We want to understand and predict under what conditions worst-case scenarios occur so that they can be prevented."



Ya-Ting Liao, a researcher at Case Western Reserve University, is shown during operations at NASA Glenn Research Center as her experiment was underway onboard the space station. NASA researcher Paul Ferkul (left) and Jonah Sachs-Wetstone (right), a then-undergraduate student in Liao's lab, are also shown.

Courtesy of Case Western Reserve University

On Earth, confinement is easy to visualize. Just picture a fireplace. A self-sustaining hot region is created thanks to radiating heat between the logs and the inner walls of the fireplace, with rising, flickering flames. A gravity-driven force called buoyancy gives a flame its rise on Earth, but fire burns differently in space. Gravity and the forces driven by it are effectively eliminated, meaning hot gas does not rise. Instead, most flames in space move outward in an otherworldly dome-shaped flame rather than the typical candle flame shape.

Buoyancy and other gravity-driven forces make it challenging to study the fundamental nature of fire in a controlled way on Earth. With many interconnected forces acting on the flames, isolating a single factor on Earth is very difficult. So, to study these gaps in our knowledge of fire physics, Liao needed to strip fire of its gravity-driven forces so she could simplify it and better understand the physics.

"The problem with buoyancy flow is it's very messy," Liao said. "It varies as your fire grows, is hard to characterize, and masks the underlying physics we want to investigate. That is why we brought fire to space."

Removing interferences from buoyancy-induced convection that are nearly impossible to separate from flames on Earth allowed Liao's team to better study the physics behind fire's behavior—knowledge they, in turn, are using to develop improved models and theories.

"These models and theories could lead to the development of safer structures, especially for high rises and spacecraft, where escaping from a window is not an option," said mechanical engineer James Quintiere, who is retired from the National Institute of Standards and Technology, where he led fire protection research for more than 20 years.

"One reason Ya-Ting's research is important is a pure science reason—it builds on fundamental physics knowledge that will help us understand fire behavior, which, in turn, could help us live more safely on Earth," Quintiere said. He also highlighted another important motivation for studying confined flames. "We need to know how fire behaves differently in space than on Earth. Otherwise, we cannot safely live there."

Breathing New Life into Old Hardware

Liao knew the space station was ideal for testing her fire behavior and confinement hypothesis. The microgravity environment would allow for long-duration, more extensive experiments than the reduced gravity options she utilizes on Earth, like parabolic flights and drop towers.

Additionally, a facility and hardware already existed on the space station for performing confined flame experiments. The toaster-sized Burning and Suppression of Solids (BASS) hardware is housed within the Microgravity Science Glovebox (MSG), which allows for the safe observation and burning of solid materials onboard the orbiting laboratory by creating multiple ways the flames are contained.

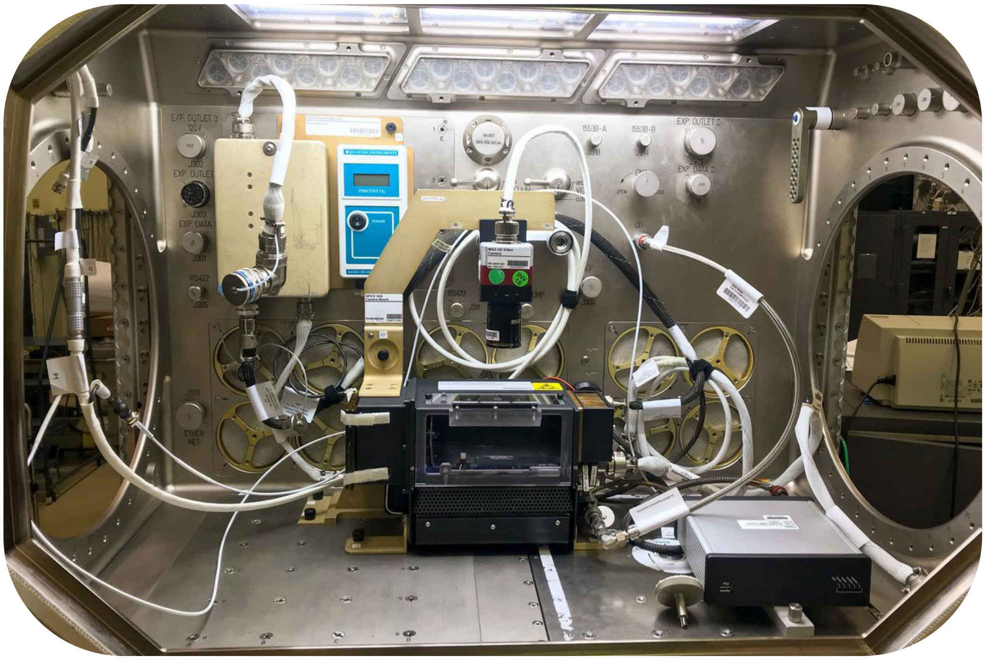
BASS ON THE SPACE STATION

The Burning and Suppression of Solids (BASS) hardware operates within the MSG for experiments that require observing burning solid materials onboard the ISS. It allows researchers to safely study factors like flame shape, how fast flames develop, and their dynamics. A pioneer of microgravity research using BASS on the space station was Liao's mentor James T'ien, a professor in the mechanical and aerospace engineering department at Case Western. Liao, NASA, and ZIN Technologies modified the BASS hardware for a new generation of experiments.

"The hardware was already there, and it was not being used then, but it had been flown for fire experiments many times before in different guises," said co-principal investigator Paul Ferkul, a project scientist with NASA's Glenn Research Center in Cleveland, who helped design modifications to the BASS hardware for the project's specific needs.

"Simple hardware modifications allowed Liao's experiments to be done relatively cheaply compared with most of our flight experiments," said Michael Johnston, a project scientist at NASA's Glenn Research Center, who was also part of the confined combustion research team.

The main feature of BASS is the small wind tunnel that allowed the researchers to impose airflow on the burning material sample. Liao's team retrofitted BASS with baffling to simulate walls in confined spaces that could be adjusted to test different levels of confinement. These interchangeable simulated walls with three different surface treatments (reflective, translucent, and black) were designed to test how flames react to surrounding structural material. With



The configuration of the Microgravity Science Glovebox for the confined combustion experiment is shown here before launch.

NASA

buoyancy and other effects of gravity eliminated, Liao could impose this flow in a controlled manner, allowing the team to investigate different parameters independently, which made it easier to interpret the experiment's outcome.

Within a year, the modified BASS hardware was ready for testing. From there, Liao and her team worked tirelessly for months to prepare for the launch. They spent hours in the lab, testing and re-testing the equipment, ensuring everything was ready for the journey into space.

NASA astronaut Christina Koch installs samples for experimental burning in the Microgravity Science Glovebox during the confined combustion investigation onboard the space station.

NASA

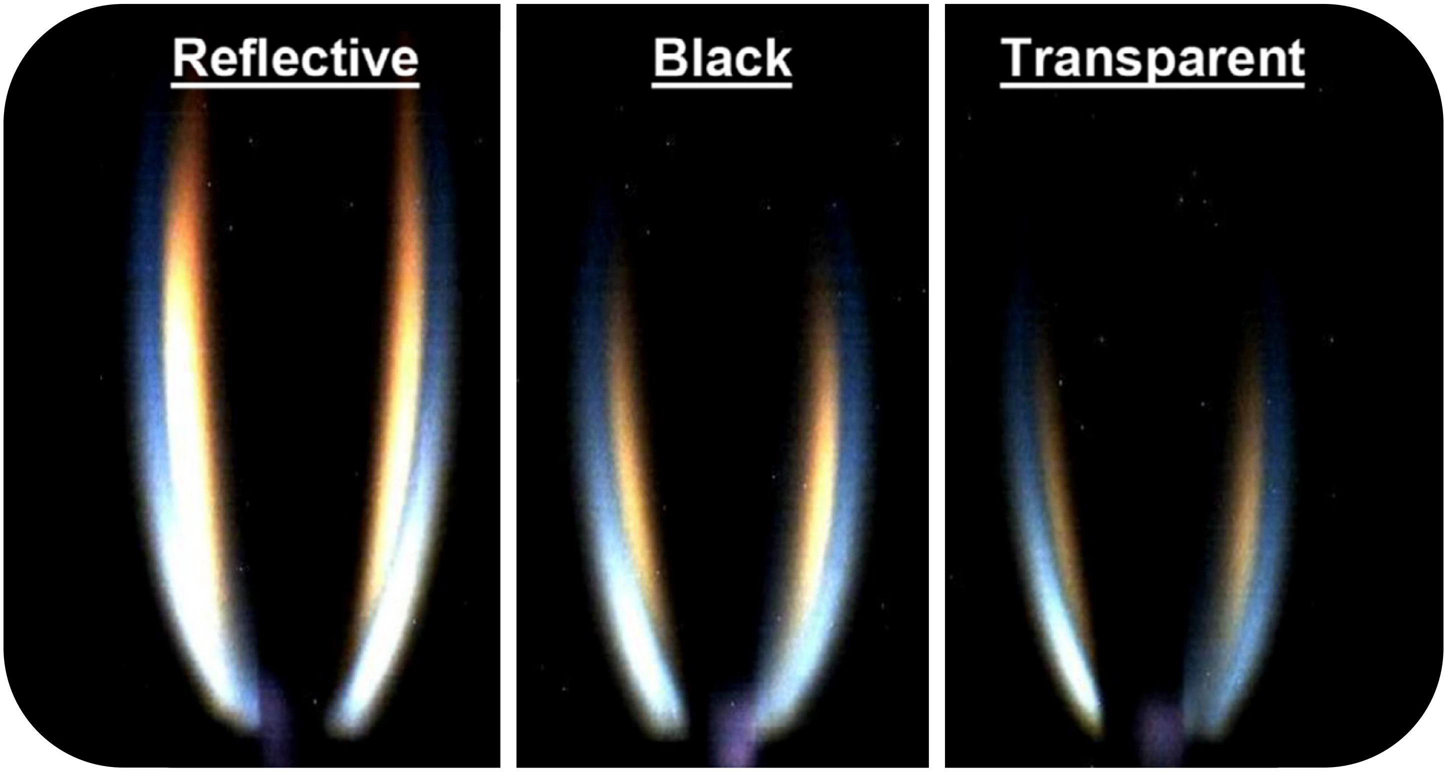
Testing Flames on an Orbiting Lab Takes Time

Once their payload was on station, Liao and her team waited patiently for experiments to begin as the equipment was installed and samples unpacked. They sent two sample materials for the investigation, a clear acrylic plastic known as Plexiglass and a cotton-fiberglass fabric. It all felt real when the team watched from a monitor at Glenn Research Center as NASA astronaut Christina Koch set fire to the first cotton sample material inside the MSG.

The team studied various parameters to test their hypothesis about the behavior of flames under confinement. They examined how the confinement distance between the simulated walls and the degree of airflow affected flame growth and how radiative properties were affected by different types of confinement and different treatments to the simulated walls.

By changing the airflow speed and confinement conditions, the team observed under which conditions flames grow, spread, or are extinguished—pinpointing scenarios that caused flames to grow faster and get hotter. For example, when they burned the cotton-fiberglass material, its flame grew largest when confined by reflective walls.

The space station crew of six astronauts performed 63 tests under 100 different conditions over 18 days. It was time-consuming work, but the crew did not mind, Ferkul said.



This image shows flames during the confined combustion experiment, which used simulated walls with reflective, black, and transparent treatments to study how flames behave in different types of confinement.

Courtesy of Case Western Reserve University

"The astronauts really loved doing this experiment," he said. "With many of the experiments they do up there, the astronauts don't see the results immediately. But with ours, they saw when something big happened, and we talked to them during the process. It was exciting and interactive."

Liao said data drawn from the experiments are being used to build numerical models, which is the first step before applying it to real scenarios. Once Liao and her team received all the data from the investigation, they used a state-of-the-art combustion computational fluid dynamics (CFD) model they developed to study the various parameters numerically. The team also conducted numerical simulations during tests back on Earth to complement the experiments.

"Liao's team is trying to lay a rock-solid foundation for the modeling work that's needed before a true application can happen," said chemical engineer Randall McDermott, a principal developer of the Fire Dynamic Simulator at the National Institute of Standards and Technology. "We've had the pillars of theory and experiment in science, but nowadays, it's common to think of modeling as another pillar of science. Sometimes the actual application is more complicated than a single theory or experiment, and models are a way of packaging it all together to be applied in the real world."

Translating Space Station Experiments into Fire Safety at Home

Four years and several scientific journal articles later, the project continues to yield results. The investigation supports Liao's hypothesis that solid materials burn differently in confined versus open spaces. While the results are limited to the materials and parameters tested, her investigation shows that flame spread in confined spaces can continuously accelerate and pose an even more severe fire hazard than fires in open spaces.

The project's results suggest that this acceleration in confined spaces is due to the radiative heat feedback from the surrounding walls and the tunnel flow acceleration effect. This means that walls that reflect the heat back to the flames help to feed their growth. Similarly, the shape of confined spaces helps direct hot air flow and spread flames.

Because the experiments also demonstrate that materials burn differently within different types of confinement, the results offer evidence for making structures more fire safe. Liao said it is essential to look beyond a material's flammability and determine how the geometry of the surrounding environment will influence how it burns.

"Our experiments supported our hypothesis, showing that flames spread quickly when the confined space is moderately large and slowly when the confined space is very narrow, due to heat loss," Liao said. "But perhaps even more interesting, the investigation identified confinement 'sweet spots,' where the parameters we tested worked together to cause a fire to spread at increasing speed and burn for longer before consuming the material."

As the project is providing new insights into the physics of flame behavior, Liao and her team are looking to the future. Eventually, she hopes to build a complete understanding of the effects of confinement on fire. Additionally, the data Liao's team collected on the space station is already helping researchers interested in fire behavior better understand how confinement determines how fast fires travel, McDermott said.

"Her work is a reminder of the power of human and scientific ingenuity to overcome the challenges of exploring the unknown," he said.

THE FUTURE OF FLAMES ON THE SPACE STATION

"I have a lot of wild ideas," Liao told the audience at the 11th annual International Space Station Research and Development Conference in 2022. During a panel discussion at ISSRDC, Liao said she has ideas for fire experiments on the ISS that would test new materials and environments, such as batteries, and experiments that would aim to understand how fire will behave in environments reached during long-duration space missions and on other planets. Determining how to do even more innovative flame tests safely is the biggest hurdle to overcome, she said. As capabilities for in-space experimentation progress, though, what is currently impossible could become possible.

For Liao, the ISS National Lab project was an exploration of fire and a way to unravel one mystery within the unknown. But when she reflects on the importance of the work, her thoughts return to the tragedy that inspired it. The Grenfell Tower fire exposed the vulnerabilities and limitations of modern construction and fire safety. Liao's research was a step toward addressing these challenges and preventing future tragedies.

She envisions a growing body of fire research in microgravity that continues to fill gaps and inform new structure designs and innovative fire suppression technologies. In the future, the work she's initiating now has the potential to revolutionize fire safety in confined spaces and save countless lives, both on Earth and in space.