UPWARD

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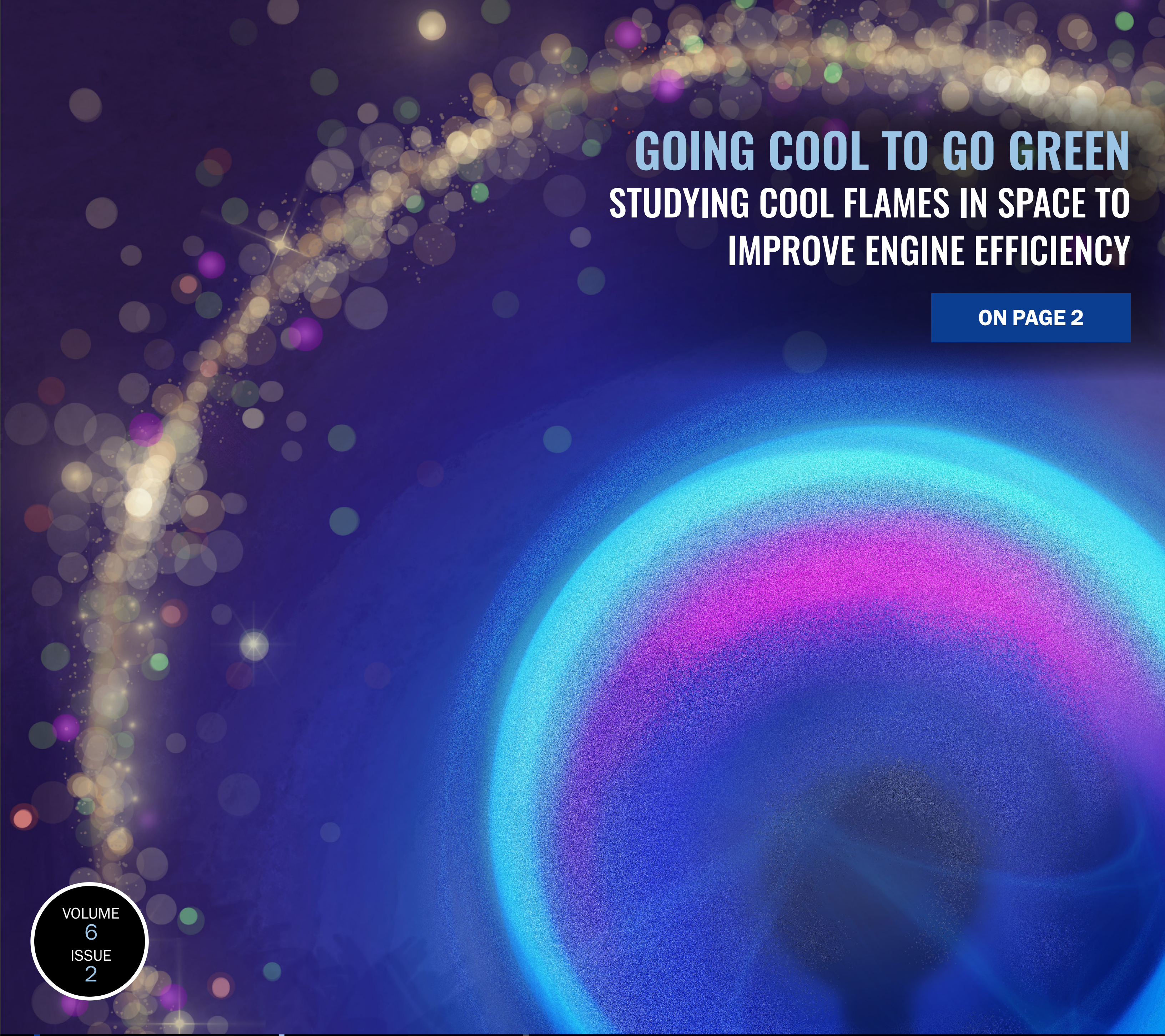

GOING COOL TO GO GREEN

STUDYING COOL FLAMES IN SPACE TO IMPROVE ENGINE EFFICIENCY

ON PAGE 2

VOLUME 6 ISSUE 2

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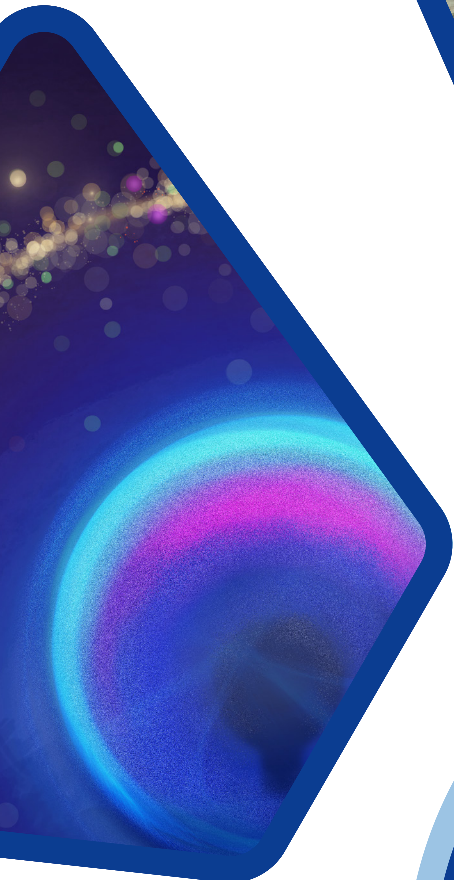

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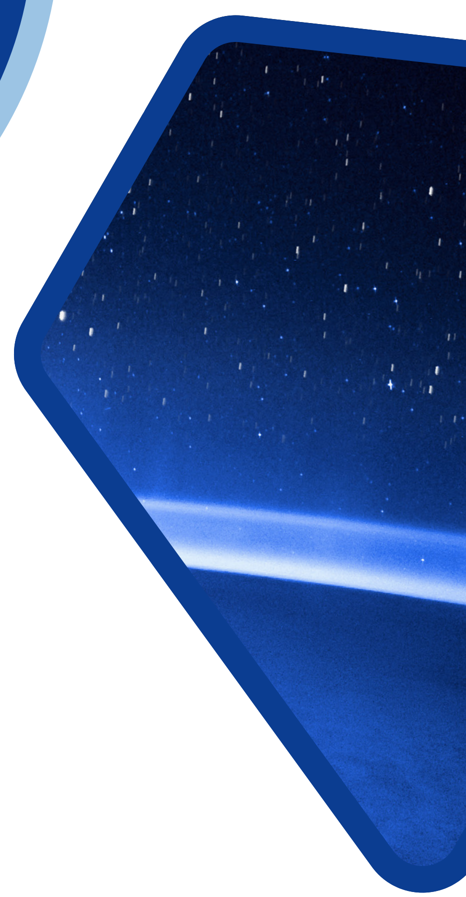

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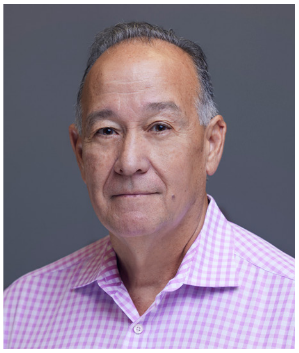
VIEW FROM THE CUPOLA

BY RAY LUGO, CASIS CEO



Ray Lugo is chief executive officer of the Center for the Advancement of Science in Space, Inc., manager of the ISS National Lab.

In 1994, as a much younger self, I had the opportunity to work with a team at NASA's Johnson Space Center (JSC) on the redesign of a space station that would serve as the world's first orbiting laboratory. At that time, it was called Space Station Freedom, later to become the International Space Station (ISS). During this period, Henry Pohl was the director of engineering at JSC, and although he was a much more senior employee, he always made time to meet with younger staff.

I can recall a team meeting Henry joined, where, as always, we were trying to improve our space station design. He implored us not to create a space station merely as a "science project" but to design a space station to do science. That distinction sticks with me today as we take advantage of the International Space Station as a valuable platform for science to benefit humanity and look toward future commercial space stations.

What we are doing today is similar to seeding a field in the spring and harvesting the crop in the fall. The science we are doing now is an important element of securing our future. The experiments we perform today will lead to new knowledge and products that will improve life on Earth for future generations.

In this issue of Upward, you will have the chance to read about some of the groundbreaking science being done on the space station. While the results may not become commercial products in the next year, this science is crucial to increasing our understanding of the world and the physical, chemical, and biological processes underlying everything.

I find the research on the physics of flames and fire propagation fascinating. As a child, I was always interested in fire, and that curiosity continues today. Cool flames are always "cool," but in the investigation highlighted in our cover story, "Going Cool to Go Green," they're very cool. Understanding the chemistry of cool flames may be the key to improving the efficiency of internal combustion engines and reducing air pollution—no small feat. Transitioning from cool flames to hot flames, this issue's second feature on confined combustion, "Heating Things Up in Microgravity," showcases how space station research provides valuable insight into how fire spreads. This knowledge could lead to breakthroughs in fire safety for people in confined spaces on Earth, like buildings and airplanes, as well as astronauts in spacecraft and onboard space stations.

Our third feature, "Stem Cells and Space," tells the story of how heart cell studies in space are helping people on Earth. According to the Centers for Disease Control and Prevention, around 1.5 million people in the U.S. have a heart attack or stroke each year, and we spend nearly $314 billion annually treating cardiovascular disease. More importantly, most of us have at least one family member affected by heart disease, connecting this critical area of research to all of us. The use of stem cells to regenerate the heart may sound like science fiction, but results from this space station research could lead to therapies that reverse heart damage, improving the lives of patients across the globe.

These are three very different and exciting projects that represent just a small sample of the incredible work supported by the ISS National Laboratory—science in space that benefits all of us on Earth.

Going Cool to Go Green

Studying Cool Flames in Space to Improve Engine Efficiency

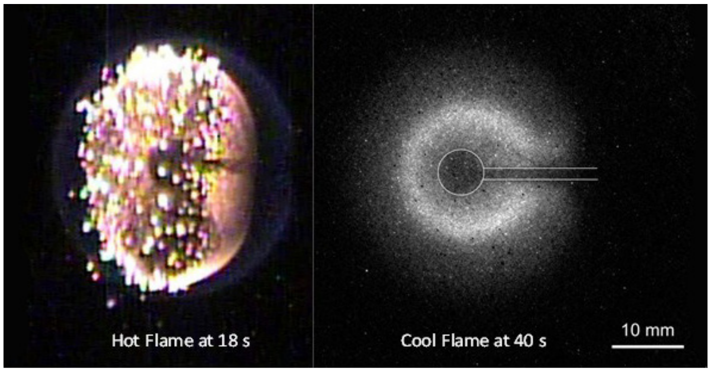
BY AMELIA WILLIAMSON SMITH, *Managing Editor*

Transportation is crucial to our society, yet it is something most of us take for granted. There are more than 1.4 billion cars worldwide and approximately 100,000 flights that transport people and goods around the globe each day. People can get in their cars or hop on an airplane and travel wherever they want without really thinking about it. It's hard to imagine life without the freedom of transportation.

It was a revolutionary invention in the late 1800s—the internal combustion engine—that forever changed how we travel and ushered us into the modern world of transport we enjoy today. However, it also brought with it the modern-day problem of pollution. With the climate change crisis we now face, there is an emerging need for new technology that makes internal combustion engines run more efficiently and reduces our carbon footprint.

To improve the efficiency of internal combustion engines and decrease pollutant emissions, scientists are turning to something that at first may seem like a contradiction of terms: cool flames. When you think of flames, the first thing that probably comes to mind is heat. Hot flames like those on a natural gas stove reach 3,100 degrees Fahrenheit. Cool flames, however, burn at much lower temperatures that typically do not exceed 1,000 degrees Fahrenheit.

For internal combustion engines, temperature plays a key role in both engine efficiency and the production of pollutants. If engines could be designed to incorporate aspects of cool flame chemistry, they would run cooler, meaning they could run cleaner and much more efficiently. But this requires an in-depth understanding of cool flame chemistry, which is difficult to study on Earth. Cool flame chemistry is slow, and gravity-driven buoyancy moves fast, extinguishing cool flames before they can fully establish.



A hot flame (left) gives way to a cool flame (right).

University of Maryland/Peter Sunderland

To better study cool flames, scientists needed an environment where gravity, and thus buoyancy, is removed. This means they needed a laboratory not on Earth but in space. Leveraging the International Space Station (ISS) National Laboratory, a team of researchers led by Peter Sunderland, a professor of fire protection engineering at the University of Maryland, set out to do something that couldn't be done on the ground. In an investigation funded by the U.S. National Science Foundation, the team aimed to use microgravity to produce a new type of cool flame never before seen that would provide valuable data to improve cool flame combustion models.

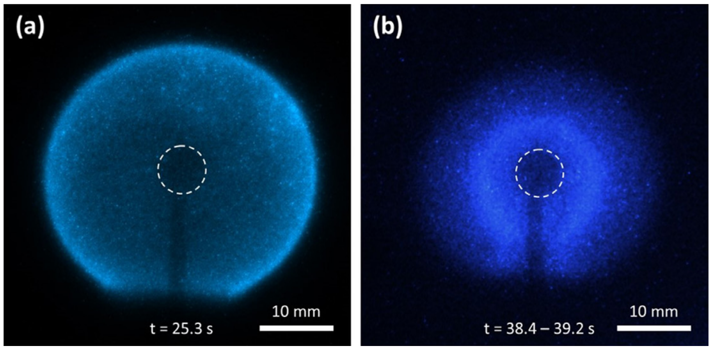
"On Earth, as soon as you have a flame, you get buoyancy, and the gases move so fast that the slow chemical processes can't be observed," Sunderland said. "But in space, you have a better environment where the molecules will hang around for a second or more inside the flame, and that's when you can get this really slow, rare type of chemistry and record it and learn about it."

It All Comes Down to Temperature

Most cars with internal combustion engines burn gasoline at 35% efficiency. This means the average car is powered by only about one-third of the energy produced from engine combustion. What happens to the rest of the energy produced? The answer: it is lost to heat.

This loss from heat happens in two ways—hot exhaust that goes out of the car's tailpipe, which not much can be done to avoid, and engine heat, which engine manufacturers are now focusing on. Current internal combustion engines run very hot, and a cooling system is required to lower the engine's temperature for safe operation. High combustion temperatures also produce more nitrogen oxide (NOx) pollutants. If high combustion temperatures are the problem, cool flame chemistry could provide a solution, but not in the way you are probably thinking.

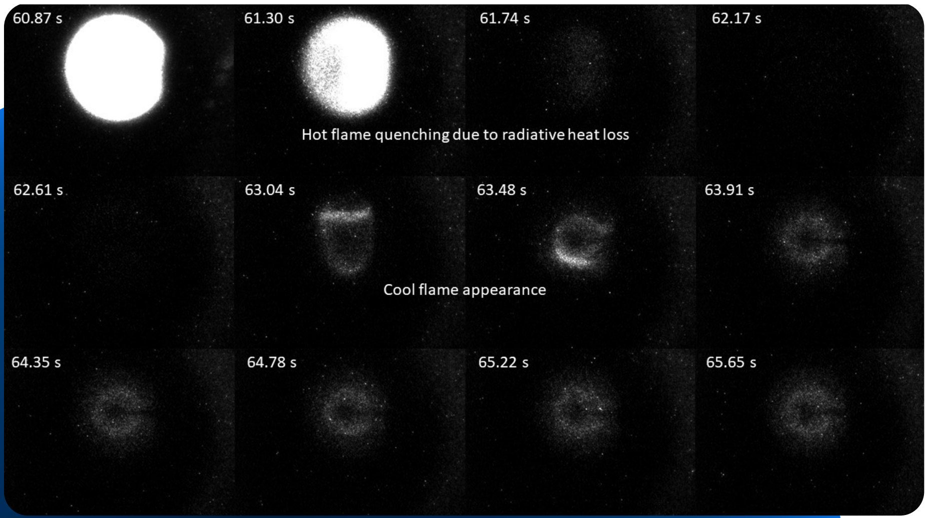
Cooler combustion temperatures could be achieved not from cool flames themselves—the engine would still run on hot flames—but from incorporating cool flame chemistry that allows extra air to be added to the combustion.



Intensified camera images from an n-butane hot flame on the space station (a) that transitioned to a cool flame (b). The original grayscale images have been converted to their expected blue colors. The times after ignition are shown. The dashed circles indicate the burner location. Image (b) is an average of images from the times shown and has an exposure 50 times as bright as that of (a).

University of Maryland/Peter Sunderland

In internal combustion engines, fuel is mixed with air at precise ratios and compressed, and a spark plug ignites the fuel-air mixture for combustion. If engine manufacturers could run the same amount of fuel through the engine but with twice the amount of air, it would run much cooler—so much cooler, in fact, that a cooling system may not be needed at all. Less energy would be lost to engine heat, and fewer NOx pollutants would be emitted.



Multiple images pulled from an intensified camera filtered to look for the very faint emissions of a cool flame during a run of the experiment show the hot flame going out and a cool flame appearing.

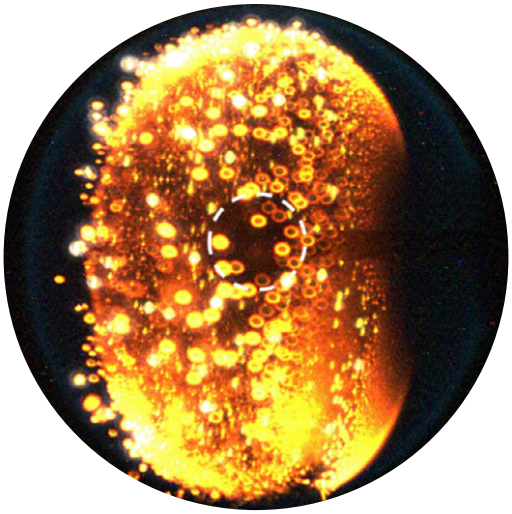
NASA

However, for engines running with twice as much air, ignition with a spark plug would no longer work because the flames would extinguish or propagate through the fuel-air mixture too slowly, Sunderland explained. Instead, ignition would need to be through compression alone, which requires cool flame chemistry.

"In engines, ignition timing is essential," Sunderland said. "With spark-ignited engines, the ignition timing can be controlled precisely if the flames are hot and strong. In future ultra-lean compression-ignition engines, the first reactions will involve cool flame chemistry, which will ignite the hot flames that propel the car."

Currently, cool flame chemistry is poorly understood, and better computational models of cool flame chemistry are needed for engine manufacturers to be able to design compression-ignition engines.

"If we can master this cool flame chemistry, we could theoretically improve internal combustion engine efficiency from 35% to as high as 60%," Sunderland said. "Many major car companies are now trying to understand cool flames to improve their technology."



An image from the color camera on station showing an n-butane hot flame soon after ignition. The yellow regions are glowing soot.

University of Maryland/Peter Sunderland

Discovering Cool Flames

The first detection of cool flames dates back to 1810 when British chemist Sir Humphry Davy accidentally discovered them while studying combustion to design safer lamps for coal miners. Two centuries later, in 2012, another accidental discovery—this time on the International Space Station—uncovered a different type of cool flame: cool diffusion flames.

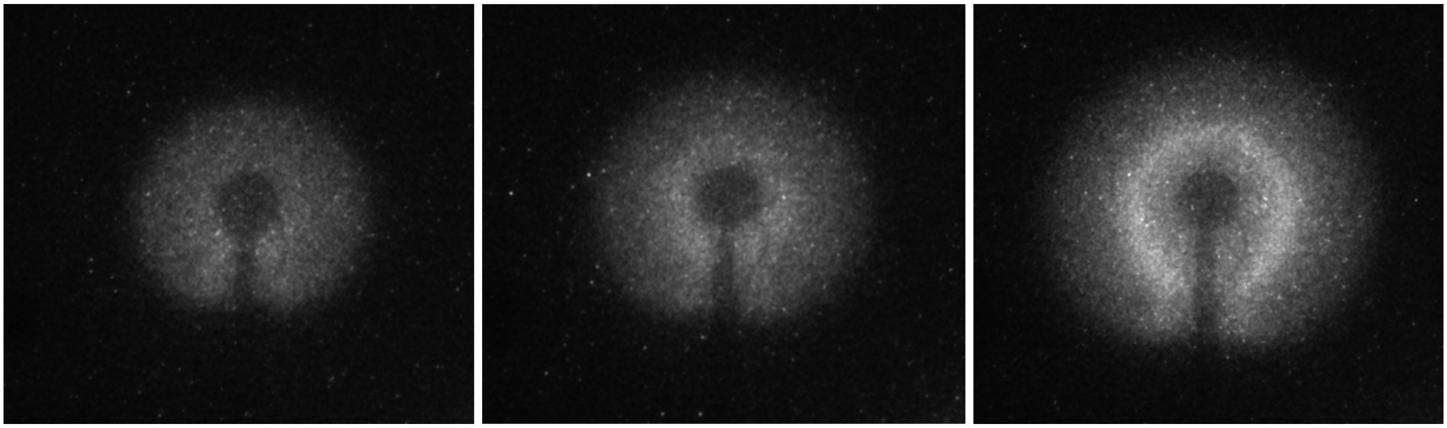
Cool diffusion flames occur in systems where the fuel and oxidizer (oxygen or other oxidizing agent) are not premixed like the cool flames from 1810 were. Instead, the fuel and oxidizer diffuse toward each other, and the flame occurs at the place where they meet.

In the 2012 experiment, Forman Williams, professor of mechanical and aerospace engineering at the University of San Diego, was producing hot flames using liquid fuel droplets to study combustion in microgravity. When the hot flame went out, Williams and his team noticed the fuel droplet kept shrinking, which did not make sense. After much head-scratching, they realized that the hot flame had transitioned to a cool flame. Cool flames are so weak that they are barely visible and require a special intensified camera, which is why the researchers had not initially noticed them.

Building on the 2012 discovery, Sunderland had an idea. He joined forces with Williams and Richard Axelbaum, professor of energy, environmental, and chemical engineering at Washington University in St. Louis, who led a previous space station hot flames experiment Sunderland had worked on. Together, this power team of combustion researchers aimed to use the ISS National Lab to produce cool diffusion flames—not from liquid fuel like in the 2012 experiment—but from gaseous fuel.

Cool flames are prone to form with liquid fuels, which contain large molecules. But Sunderland and his team wanted to push cool flames to their limit. They wanted to find the smallest-molecule fuel that could be used to create a cool flame, which meant they had to go to gaseous fuels, Axelbaum said.

The investigation used three gaseous fuels of decreasing molecular size: butane, propane, and ethane. These smaller-molecule fuels also make it easier to study cool flame chemistry, Sunderland explained.



Intensified camera images from an n-butane cool flame onboard the space station. After the hot flame extinguished there was barely any luminosity (left). Then the glowing increased (center) until a steady cool flame was established (right).

University of Maryland/Peter Sunderland

Collaborating Separately

The research team spent months collaborating on their cool flames investigation but never actually met in person during the project. The team is scattered across the U.S.: Sunderland and Kim in Maryland, Axelbaum in Missouri, and Williams in California. They designed the whole investigation, watched their project launch, monitored the flames and sent commands to control the experiment while it was on station, and analyzed the results all from their individual locations, meeting only on Zoom.

"With big molecules, it's much harder to understand the fundamental chemistry," he said. "Smaller-molecule fuels like butane and propane provide a simpler system to work with. Gasoline is a really complex fuel, so getting a good understanding with the lighter hydrocarbons is the first step."

What's Gravity Got to Do With It?

Most people do not realize that gravity is critical to utilizing combustion on Earth. Think of a hot candle flame. When you light the candle, the flame establishes quickly and immediately travels upward to make the typical teardrop-shaped flame. This is because gravity-driven buoyancy causes the hot products of combustion to rise and this pulls in fresh air. It is this flow that keeps the flame going, and the process is very fast.

In contrast, cool flame chemistry is very slow, producing a weak flame that takes longer to establish. On Earth, buoyancy moves so quickly that it snuffs out cool flames almost immediately.

But in microgravity, flames burn much differently. Instead of taking on a teardrop shape, flames in space can be spherical. This happens because the only mechanism for the oxidizer to get to the flame is diffusion, which is weak and slow. In fact, it can be challenging to sustain hot flames in microgravity because there is no buoyancy to feed the flames quickly. But this is what makes space an ideal environment to study cool flames.

"If we have an environment where gases are moving quickly, and the chemistry is slow, it's going to put out the flame," Axelbaum said. "Cool flames involve really weak reactions, but in our microgravity experiments, we don't disturb the flames at all, so that gave us hope that we could establish cool flames with our apparatus."

Microgravity is beneficial for not only establishing cool flames but also sustaining them long enough for researchers to examine them.

"Without gravity, the flames don't accelerate with buoyancy, so it can give you a longer time to study flame chemistry," Williams said. "The International Space Station is a laboratory for learning more about the chemical kinetics of combustion that's difficult to learn in experiments on the ground."

The Search for a New Type of Cool Flame

On the space station, the experimental setup involved a sealed combustion chamber (about the size of a small office trashcan) filled with an oxygen and nitrogen mixture. Inside was a one-quarter-inch sphere made of sintered metal filings that allowed gas to flow through, and an igniter was used to start the combustion. The team tested the three fuels using different fuel and oxygen concentrations and different pressures. Their goal was to find the precise conditions needed to produce a cool diffusion flame from gaseous fuel.

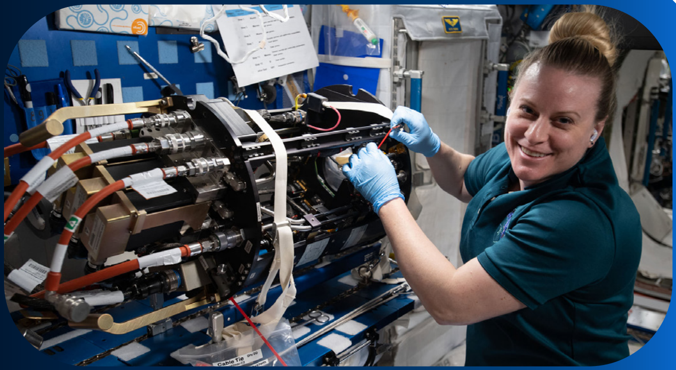
While the experimental runs were happening on the space station, Sunderland and his graduate student, Minhyeng Kim, anxiously watched the flames from the ground through live video. "Watching the burning processes in the real-time videos was amazing," Kim said. "It's kind of beautiful—the colors, the shapes—and the flame glows bigger and bigger, and then suddenly it oscillates a little and is gone."

Day after day, they watched the video and looked at the data, expecting to find hot flames transitioning to cool diffusion flames. In the first set of runs, they used ethane. In the next set, they used propane and, finally, butane. Each time, they watched the hot flame go out, waited several seconds, and then sent the command to stop the fuel flow. But day after day, run after run, the data showed no cool flames. By the time the butane experimental runs were nearly over, the team was discouraged.

"We thought we would easily get hundreds of cool flames, but we found that it was difficult," Sunderland said. "I got home that night and went to bed feeling disappointed."

Bothered by the fact that they had still not detected any cool flames, Kim did not go to bed. Instead, he poured through the day's data. "I was reviewing the data and found that after the normal hot flame extinguished, there was still a little bit of signal coming from the heat sensor," Kim said.

In the morning, Sunderland saw an email from Kim that was really exciting. "He had stayed up looking at the data and found the signature of a cool flame," Sunderland said. "When



NASA astronaut Kate Rubins working on the cool flames investigation preparation.

NASA

NASA astronaut Shane Kimbrough completing the Multi-user Droplet Combustion Apparatus reconfiguration for the cool flames investigation setup.

NASA

we had stopped the butane flow, there had been a cool flame and we didn't know it. It took us a few days to get the intensified camera images and the full data, but we were celebrating from then on—we had our first cool diffusion flame from gaseous fuel."

Creating Higher-Accuracy Models

The ultimate goal of the investigation was to improve computational and numerical models of cool flame chemistry so engine manufacturers can design better internal combustion engines, Sunderland said. After successfully demonstrating cool diffusion flames using butane, the complex models had to be adjusted to account for smaller-molecule fuels.

Publishing data from the investigation allowed Williams and others to refine the chemistry in their models, adding important details that increased model accuracy. The data is helping to improve not only cool diffusion flame models but also premixed cool flame models.

"We had published the simplified chemistry, and now because of our results, we're doing calculations with augmented simplified chemistry," Williams said. "The new calculations point out that I had overlooked an important step that makes my published paper on premixed cool flame chemistry wrong, and I am correcting that."

According to Axelbaum, the most exciting aspect is that the ISS National Lab allowed them to do something no one had ever done before and demonstrate that these types of flames can exist. "We gained a lot of knowledge we didn't anticipate," he said. "It's wonderful to realize there are things you didn't know, and you would never have known, if not for the unique opportunity to do these experiments in this novel environment."

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Stem Cells and Space

What Microgravity Can Teach Us About the Human Heart

BY AMY THOMPSON, *Staff Writer*

NASA Astronaut Kate Rubins examines iPSC-derived cardiomyocytes grown within a fully enclosed cell culture plate.

NASA

The musical "Rent" famously calculated 525,600 minutes in a year, but how do you measure a year in heartbeats? The human heart is a small but mighty muscular organ that sends oxygen-rich blood throughout the body as it beats more than 30 million times a year. But not all our hearts function as they are supposed to. When you measure a year in terms of lives lost to cardiovascular disease, the number is staggering. With nearly 18 million people dying from heart disease each year, the World Health Organization says this condition is the number one cause of death globally.

Cardiovascular disease damages heart muscle; once this tissue is damaged, there's no cure or means to restore its function. But what if the affected tissue could be fully regenerated? Induced pluripotent stem cells (iPSCs), which can transform into many different cell types—including heart cells, are at the forefront of regenerative medicine research. A team of investigators from Stanford University took cardiac iPSC research where it had never gone before: the International Space Station (ISS).

The team sent human cardiac cells derived from iPSCs to space to study heart function at the cellular level. Previous experiments have shown that spaceflight induces physiological changes in cardiac function, including reduced heart rate, lowered arterial pressure, and increased cardiac output. But most cardiovascular studies in space have been at the organ level, with little data on how microgravity affects the heart and its functionality at the cellular level.

Arun Sharma explains his experiment ahead of its launch on the SpaceX CRS-9 mission.

Arun Sharma

Joseph Wu of Stanford University's School of Medicine and Arun Sharma, a former Stanford graduate student and current assistant professor at the Cedars-Sinai Medical Center, set out to change that. As part of their ISS National Laboratory-sponsored investigation, they transformed iPSCs into specialized heart muscle cells called cardiomyocytes and examined microgravity-induced changes in those cells' contraction, growth, and gene expression. Through their findings, published in Stem Cell Reports, the team sought insights that could improve cardiovascular disease modeling and drug screening and lead to new cell replacement therapies to treat damaged heart muscle tissue.

"Our study is unique because it is the first to use human induced pluripotent stem cells to study the effects of spaceflight on human heart function," Wu said. "Space-based research may provide insight into cellular mechanisms that could not only benefit astronaut health during long-duration spaceflight but also lay the foundation for new insights into improving heart health on Earth."

From a Dream to Reality

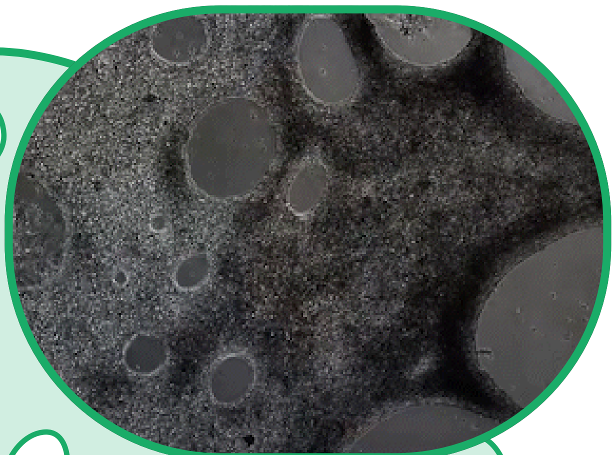
Growing up as a child in Huntsville, Alabama, Sharma's head was among the stars as he dreamt of exploring space. Today, he has his own research lab at Cedars-Sinai, where he creates models of the heart using iPSCs to study cardiovascular disease. A few years ago, an opportunity to leverage the ISS National Lab for cardiac stem cell research brought his childhood dreams of space to life.

When Sharma was a graduate student, he worked in Wu's lab at Stanford. As stem cell biologists, the researchers were pioneering new ways to use stem cells to study the heart when they heard about an opportunity to design stem cell experiments to send to the space station. The space station is home to a cutting-edge research laboratory that enables science not possible on Earth, and the two jumped at the chance to advance their research using this unique platform.

Microgravity induces changes in living organisms, and it is well documented that spaceflight can adversely affect cardiac function. Researchers have also found that long-term exposure to microgravity leads to the weakening of heart muscle tissue and other changes in cardiac function seen in patients with cardiovascular disease. These changes happen more quickly than on Earth, providing an accelerated model of disease progression.

"We wanted to answer the fundamental question of what exactly happens to the cells of the human heart in microgravity," Sharma said. "We had an idea of what happens on the organ level but not on the cellular level."

To this end, Wu and Sharma sought to examine microgravity's effects on the structure and function of cardiomyocytes derived from iPSCs. The benefit of using iPSCs is that they can easily be produced from donor blood or skin samples, and once they are transformed into cardiomyocytes, they are comparable to and share the same DNA as cells from the donor's heart.



A view of the cardiomyocytes beating under a microscope onboard the ISS.

NASA

"Induced pluripotent stem cells can transform into nearly any other cell type in the body, which means they are a prime resource for regenerative medicine because they serve as a single source of cells that could be used to replace those lost to damage or disease," Wu said.

Arun Sharma, NASA astronaut Kate Rubins, and Sarah Wallace of NASA's Johnson Space Center speak with CNN correspondent Rachel Crane at the 2017 International Space Station Research and Development Conference.

ISS National Lab

For the investigation, peripheral blood mononuclear cells from three donors were collected and converted into stem cells that were differentiated into cardiomyocytes before they were sent to space. The team cultured the iPSC-derived cardiomyocytes onboard the space station for a little more than a month and analyzed cellular structure, function, and gene expression.

"We used induced pluripotent stem cells—blood cells that have been reprogrammed—and turned them into beating human heart cells," Sharma said. "And we're hoping to use these cells to predict what's going to happen to a real patient in a clinic who has heart disease."

Long-Duration Cell Culture in Space

Wu and Sharma served as trailblazers in studying iPSC-derived cardiomyocytes in space, but they also paved the way for future long-duration cell culture on the space station. Researchers have been doing cell culture in space for decades, but they were limited by how long a space shuttle could remain in orbit for its mission—typically no longer than two weeks.

With the advent of the International Space Station and the commercial cargo program, researchers could grow cells in space for longer than ever, enabling more in-depth studies into how cells behave in microgravity. But first, facilities, hardware, and processes were needed to keep cells alive in space for more than a month.

"We think of the International Space Station as this permanent presence in low Earth orbit with this state-of-the-art science lab, but at first, we didn't necessarily have the proper cell culture facilities and all the equipment needed to support it," said NASA astronaut Kate Rubins, who worked on Wu and Sharma's investigation while on station. "One of the key things this experiment did was to really pioneer ways to keep the cells in culture long term."

According to Rubins, many technologies supporting the investigation, from the carbon dioxide incubator that housed the cells to the special dishes that the cells would grow on to even the method Rubins used to feed the cells, all needed to be created specifically for this project.

"Coming up with all the equipment and procedures needed for growing these cells for 30 days, it's really quite pioneering and will be the foundation for future stem cell investigations," she said.

While the team's cardiomyocytes were on the orbiting laboratory, Rubins was charged with their care. She ensured they were fed and documented their growth through photos and video captured with a special microscope she installed on station. Rubins said that, terrestrially, most cell culture is not all that thrilling. On Earth, the cells are settled on a plate, and they just sort of stick there and grow, but watching the cardiomyocytes growing and beating in space was more exciting.

"My crewmates laughed at me every time I raved about the microscope I got to use for this experiment as I was installing it," Rubins said. "But then when I was doing the actual imaging, they all came and floated down, huddled around the screen to get a glimpse of the cells beating."

Rubins said the microscope allowed her to document what was going on with the cells during the process, providing a wealth of data for the researchers to analyze spaceflight's effects on the growing cardiomyocytes.

NASA astronaut Kate Rubins examines heart cells onboard the ISS as part of the Effects of Microgravity on Stem Cell-Derived Heart Cells investigation.

NASA

"Through the video microscopy, we can record the images and learn a lot about the cells: cell size, cell morphology, and how it's changing over time," she said. "We could also quantify the strength of the contractions and the timing to compare to ground-based cells."

Understanding Spaceflight-Induced Changes

After the samples returned to Earth, the researchers looked for changes in cell morphology and structure and found no clear differences between the flight and ground control samples. However, functional changes within the cells remained even after the cells were returned to a normal gravity environment. The team also assessed the calcium-handling of the cells as part of their analysis.

Calcium plays a key role in regulating cardiac contractile function. The team discovered that the spaceflight cells not only displayed decreased calcium recycling but also beat irregularly. Additionally, the team performed RNA-sequencing analysis on the samples both during spaceflight and after their return to Earth. Among spaceflight, postflight, and ground control samples, the team discovered changes in the level of gene expression among more than 2,600 genes.

According to Sharma, the changes indicated that the cells adopted a unique gene expression signature while in space, which means they appear to be able to adjust to their environment. What's more, once the cells returned to Earth, they appeared to return to a pattern more similar to ground controls, despite having spent more than a month in space.

"We're surprised about how quickly human heart muscle cells are able to adapt to the environment in which they are placed, including microgravity," Wu said. "Microgravity is an environment that is not very well understood in terms of its overall effect on the human body, and studies like ours could help shed light on how the cells of the body behave in space."

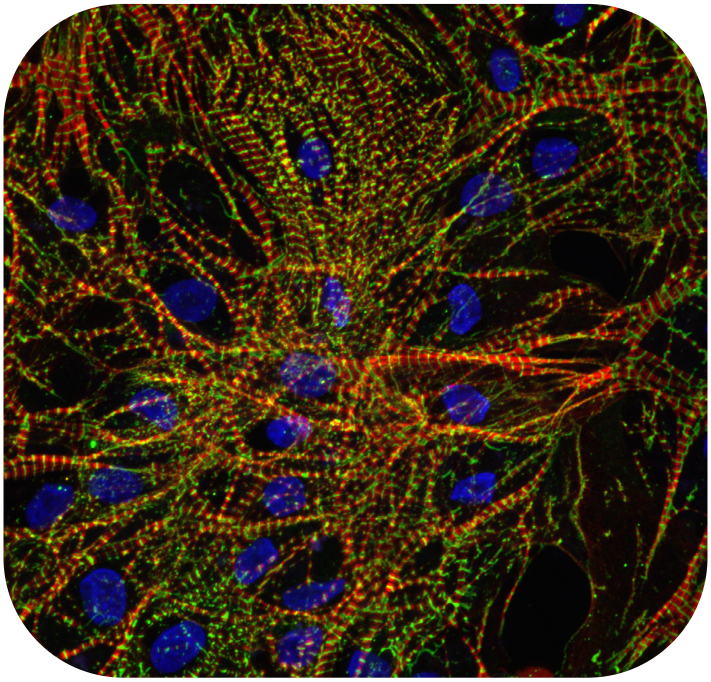
A view of the biocell that housed the heart cells on the space station.

Stanford University

Wu noted that while the changes observed were subtle, they were statistically significant. Additionally, it was difficult to say for sure whether the changes would affect how the heart functioned.

"Keep in mind our study was only five weeks—it's a short time. I don't know what gene changes would be if it was six months," Wu said. "I'm sure if the experiment ran for a longer period, you would see more changes."

But the biggest takeaway from this experiment is that it established the use of iPSCs as an accurate model to study cardiac function in microgravity. "This investigation laid the groundwork for future experiments that can utilize next-generation technologies to make the leap from 2D cells to 3D tissues and even organoids to further improve disease modeling and cardiac function in space," Wu said.



An image of heart cells grown in microgravity onboard the space station.

Stanford University

The project also helped set the stage for more complex types of stem cell experiments in space, including the burgeoning field of tissue chip research. Using iPSCs as a base model, researchers can design experiments to study other organ systems like the brain, kidneys, and more.

"This may seem like science fiction, but we're enabling real science, and other researchers are taking notice, which will hopefully initiate an influx of these types of experiments on the space station," Sharma said. "There are lots of different scientists that are thinking about how to use iPSC-derived cells in space to advance their research."

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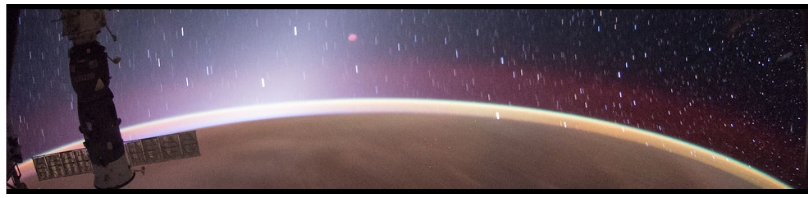

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Heating Things Up in Microgravity

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.

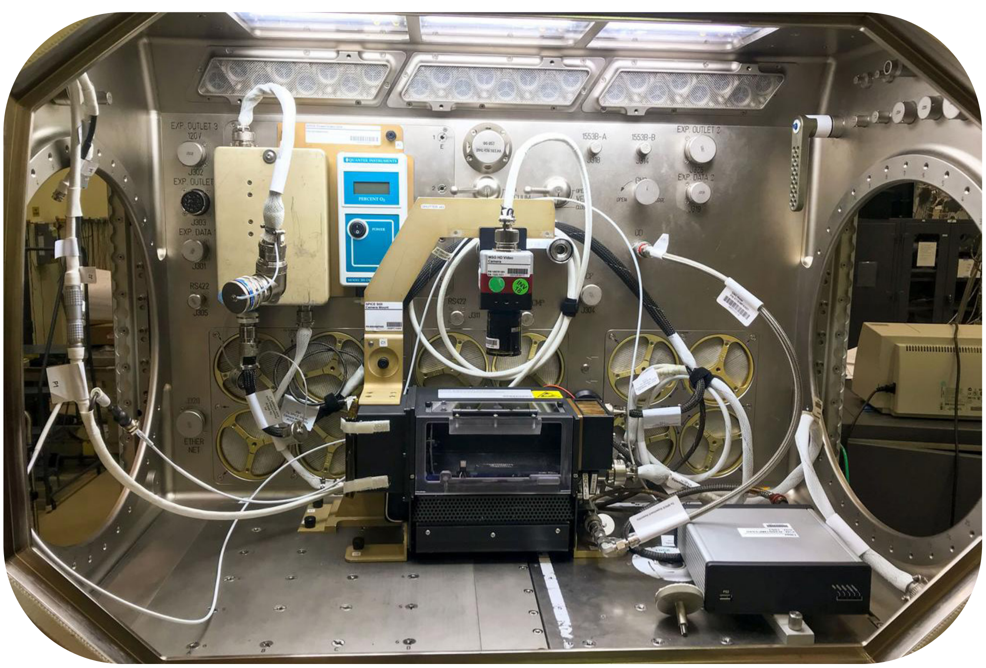
BASS ON THE SPACE STATION

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.

Testing Flames on an Orbiting Lab Takes Times

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.

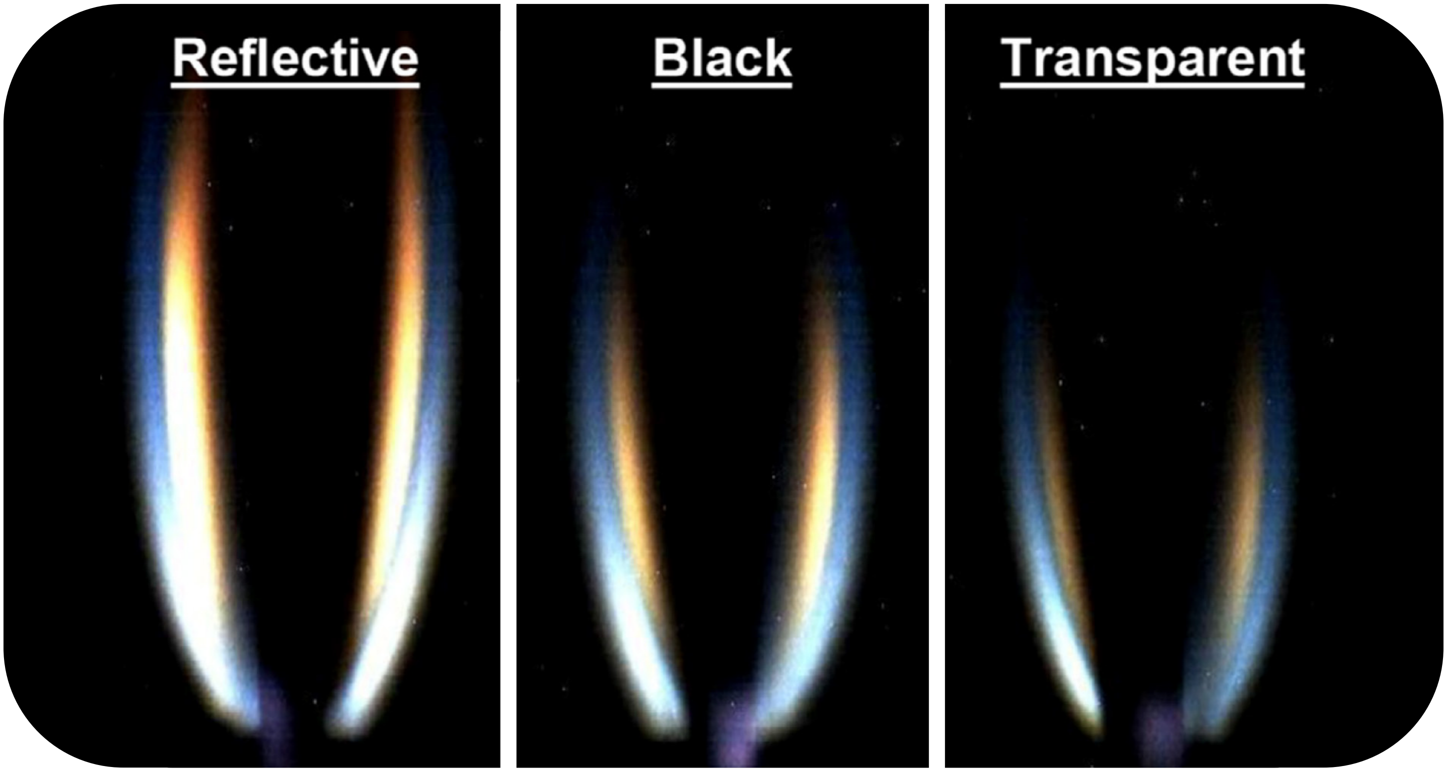
The team studied various parameters to test their hypothesis about the behavior of flames under confinement. They examined how the confinement distance between the simulated walls and the degree of airflow affected flame growth and how radiative properties were affected by different types of confinement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

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

NASA

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.

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