ZUCROW LABS
2022
ANNUAL REPORT

Terrence Meyer's research group studies turbulence-chemistry interactions of high-speed reacting flows. The image is a piloted CH4/air jet diffusion flame operating at Re = 45,000 (Sandia Flame-F). Photo by Brandon Yant

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Control Rooms

THEN AND NOW

In 1967, Honeywell outfitted Purdue's "Jet Propulsion Center" with a complex data acquisition system to observe critical data from rocket engine tests, storing the data for future analysis. More than a half-century later, **Zucrow Labs is now academia's largest propulsion lab**, and data acquisition is just as important... but orders-of-magnitude more capable!

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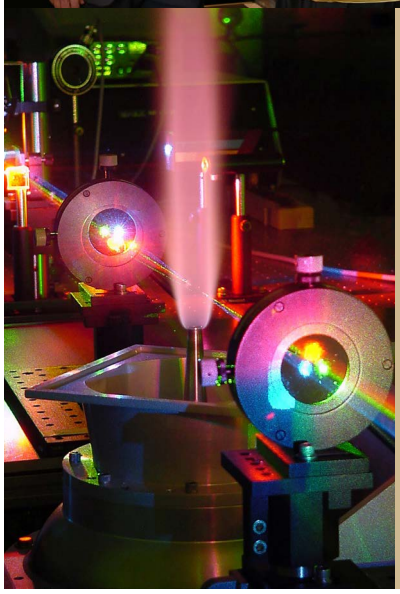
From the Director

In 2022, my colleagues at the School of Mechanical Engineering surprised me with the Outstanding Mechanical Engineer award, given to notable Purdue alumni (my undergrad degree is in Nuclear Engineering, but I also have my MS and PhD in Mechanical Engineering from Purdue). One of the aspects they highlighted was my two-fold job: I direct Zucrow Labs as an administrator, but I'm also still a dedicated researcher. Every day, my team is making breakthroughs in laser diagnostics and other combustion measurement tools. **One-of-a-kind research is the core of what we do here at Zucrow.**



Bob Lucht *(left) accepts the 2022 Outstanding Mechanical Engineer Award from the head of Purdue Mechanical Engineering, Eckhard Groll.*

Below: Lucht's coherent anti-Stokes Raman spectroscopy (CARS) research.

It's gratifying to know that Purdue University recognizes this, and that's why they continue to ramp up their support of Zucrow Labs:

- This year will see the opening of the $41 million **Hypersonics Applied Research Facility (HARF)**. This 65,000 square-foot facility houses two hypersonic wind tunnels found nowhere else in academia, as well as a full laboratory focused on high-temperature materials and manufacturing.
- We are starting to clear land for **ZL9, our newest $73 million high-speed propulsion laboratory**. Not only will it dramatically expand our testing capabilities, it will also include a new high-pressure heated air plant, to replace the aging system which we have heroically kept operating for all these years.
- Purdue's Board of Trustees have also included capital requests for a $15 million **Energetics Research Lab**. Our energetic materials research is spread throughout the campus – some in original buildings from the 1940s. This new state-of-the-art facility will be comprised of research lab space and support rooms, all specifically focused on fabricating, testing, detecting, deploying and defeating next-generation energetic materials. Pending approvals, construction could begin in spring 2024.

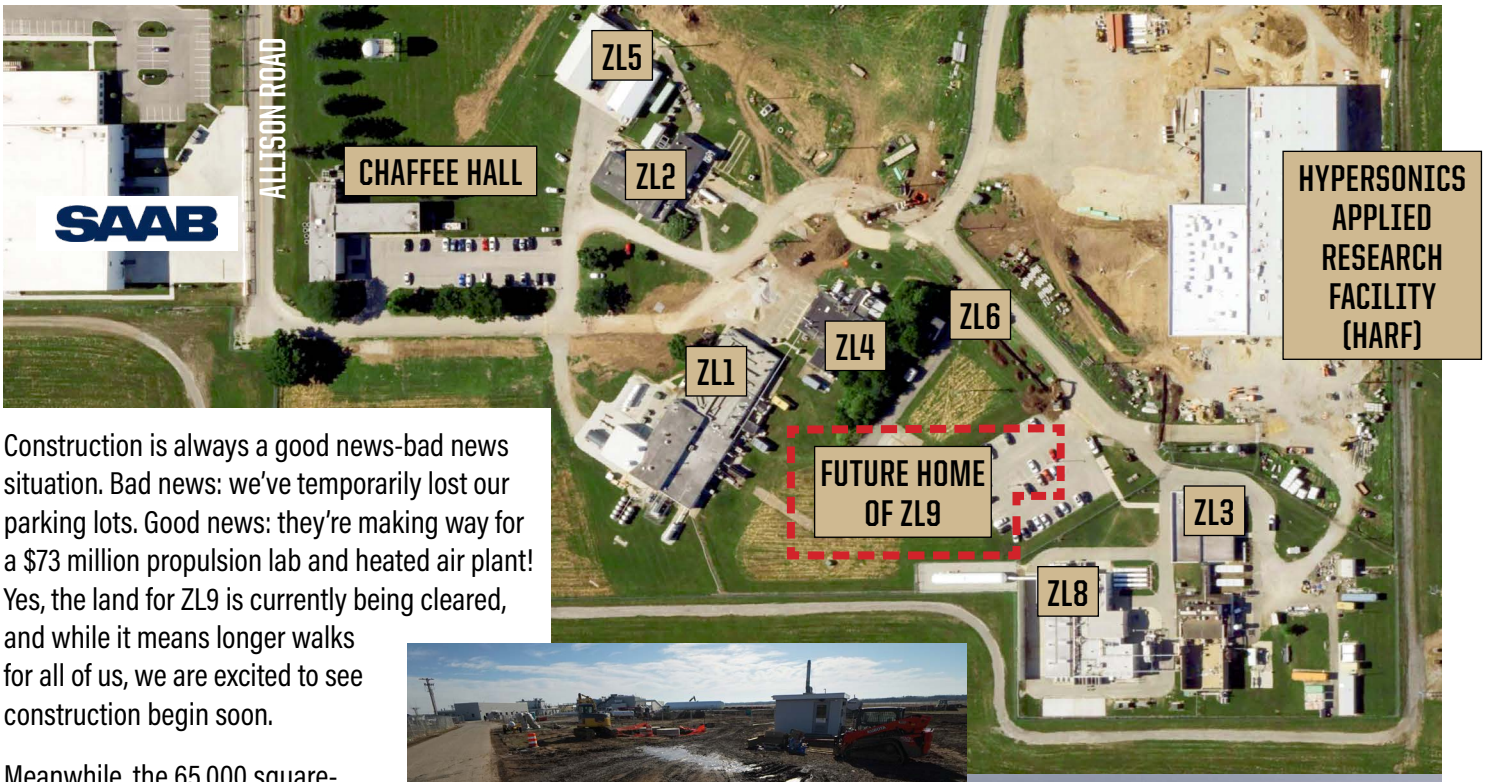
While new buildings are exciting, it's the people conducting world-changing research inside those buildings that really makes Zucrow Labs special. We look forward to seeing many breakthroughs from our team members and partners in the coming years!

Robert P. Lucht
Director, Maurice J. Zucrow Laboratories

Arthur McLeod (Mac) Mellor passed away in January 2022. A well-known figure in combustion and propulsion, he served as a professor of mechanical engineering at Purdue from 1967 to 1975, recruited by Maurice Zucrow himself. ***More about Mac...***

This photo is from 1978, and includes (left to right) unknown, Bill Wyatt, Jim Peters, Roy Washam, "Mac" Mellor, Steve Plee, Colin Ferguson, Jim Clark, John Stefucza, and Dave Smith. Photo courtesy of Jim Clark

Construction updates

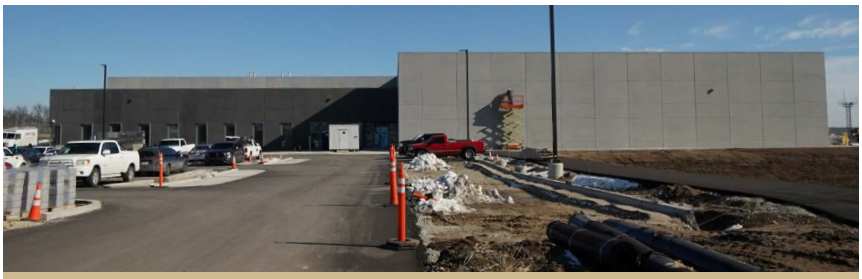


Construction is always a good news-bad news situation. Bad news: we've temporarily lost our parking lots. Good news: they're making way for a $73 million propulsion lab and heated air plant! Yes, the land for ZL9 is currently being cleared, and while it means longer walks for all of us, we are excited to see construction begin soon.

Meanwhile, the 65,000 square-foot Hypersonics Applied Research Facility (HARF) has been completed; we expect research to begin there this year. Also, upgrades have been completed in Chaffee Hall, both for our main office and the 2nd floor grad student offices.

Oh, and the Saab factory next door has begun building jet frames for the T-7A Red Hawk. As if the neighborhood weren't busy enough!

This mudpit may not look like much now, but it's the foundations of our $73 million high-speed propulsion lab, ZL9.



Don't let the battleship gray fool you: behind these walls is a game-changing $41 million Hypersonics Applied Research Facility (HARF).

***NEW!** You can now **tour Zucrow Labs** with 360-degree imagery! Explore the test cells, laser lab, control rooms, and more! Just visit tour.purdue.edu/zucrow*

The offices in Chaffee Hall have received a much-needed upgrade.

Rotating detonation engines

This rotating detonation rocket engine (RDRE), jointly developed by NASA and Purdue University, was test fired in August 2022 at NASA's Marshall Space Flight Center in Alabama. ***Watch video of the testfire!***

As NASA takes its first steps toward establishing a long-term presence on the Moon's surface, a team of propulsion development engineers at NASA have teamed up with Zucrow Labs to develop and test **NASA's first full-scale rotating detonation rocket engine**, or RDRE. The RDRE differs from a traditional rocket engine by generating thrust using a supersonic combustion phenomenon known as a detonation. This design produces more power while using less fuel than today's propulsion systems, and has the potential to power both human landers and interplanetary vehicles to deep space destinations, such as the Moon and Mars.

Engineers at NASA's Marshall Space Flight Center in Huntsville, Alabama collaborated with IN Space LLC (Purdue faculty Stephen Heister and Carson Slabaugh, Purdue grad BJ Austin, and Zucrow Managing Director Scott Meyer). They are confirming data from RDRE hot fire tests conducted in 2022 at Marshall's East Test Area. The engine was fired over a dozen times, totaling nearly 10 minutes in duration.

The RDRE achieved its primary test objective by demonstrating that its hardware – made from novel additive manufacturing, or 3D printing, designs and processes – could operate for long durations while withstanding the extreme heat and pressure environments generated by detonations. While operating at full throttle, the RDRE produced over 4,000 pounds of thrust for nearly a minute at an average chamber pressure of 622 pounds per square inch, the highest pressure rating for this design on record.

The RDRE incorporates the NASA-developed copper-alloy GRCop-42 with the powder bed fusion additive manufacturing process, allowing the engine to operate under extreme conditions for longer durations without overheating.

Additional milestones achieved during the test include the successful performance of both deep throttling and internal ignition. This successful demonstration brings the technology closer to being used with future flight vehicles, enabling NASA and commercial space to move more payload and mass to deep space destinations, an essential component to making space exploration more sustainable. Because of NASA's recent success with the RDRE, follow-on work is being conducted by NASA engineers to develop a fully reusable 10,000-pound class RDRE to identify performance benefits over traditional liquid rocket engines.

Read the full story from NASA and watch the video...

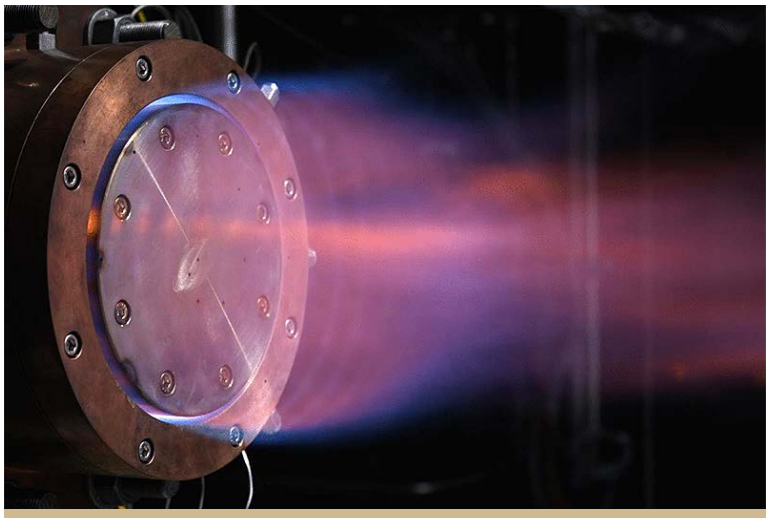
Rolls-Royce signs $75 million agreement

Purdue University and Rolls-Royce officials have signed a research and testing agreement that will bring $75 million over 10 years to the West Lafayette campus. **It is the largest deal with an industry partner in Purdue history.**

The Purdue and Rolls-Royce relationship has thrived for more than 70 years, highlighted by millions of dollars invested in aerospace testing technology, sponsorship of graduate student research fellowships, and more than 600 Purdue graduates among the company's current workforce in Indianapolis. Purdue is designated among the top class of partners as a Rolls-Royce University Technology Center, recognizing their collaborations on research, including advanced engine technology, materials, and testing capability. The relationship has expanded to include significant work on initiatives in hypersonics, cybersecurity and digital technology.

The newly signed agreement will fund testing and research with a focus in the areas of gas turbine technology and electrical and digital technology. Rolls-Royce already boasts some of the most efficient and capable power systems in the world across a suite of civil and defense applications. This investment will be focused primarily at Zucrow Labs for research in sustainable power systems through advanced technology in electrification, turbines, compressors and combustion with sustainable fuels.

Read the full story...



Purdue University and Rolls-Royce officials have signed a research and testing agreement for $75 million over 10 years, focused primarily at Zucrow Labs. (Photo courtesy Carson Slabaugh)

Adranos continues solid rocket success

West Lafayette startup **Adranos Inc. has closed on a $20 million Series A funding round** to help the company continue development of solid rocket fuel and motors for long-range missiles and space systems. Zucrow alum Brandon Terry developed a proprietary aluminum-lithium alloy fuel called ALITEC, which significantly increases the range, payload performance, and speed of defense and space systems.

The company currently employs about two dozen workers between its facilities in West Lafayette (which can produce 50,000 kilograms of ALITEC per year), and its new 450-acre manufacturing facility in Mississippi. Co-founder Chris Stoker expects the staffing size will double by the end of 2023.

Read the full story...

Adranos co-founders Chris Stoker (third from right) and Brandon Terry (far right) attend the ribbon cutting of their manufacturing facility in Mississippi, alongside U.S. Sen. Roger Wicker (second from right) and state representatives.

Undergrads love Zucrow Labs

A common thread of persistence and innovation ties all Boilermakers together, from the small steps of incoming freshmen to the giant leaps of successful alumni. **Tarun Prakash**, a sophomore studying mechanical engineering, is already well on his way to an exciting career filled with both small steps and giant leaps.

Tarun Prakash conducted research at Zucrow Labs while still a sophomore. "When it comes to engineering connections, resources, and opportunities, there is no other school that has what Purdue has."

During his first month on campus, Prakash got involved with the Purdue Space Program, an interdisciplinary team of students within the national Students for the Exploration and Development of Space (SEDS-USA) organization. The program offers students opportunities to design, build and fly experimental rockets while working with the guidance of more experienced mentors and faculty members, including Scott Meyer, his primary advisor. Meyer says that both undergraduate and graduate students who work at Zucrow are involved in the design of experimental test apparatuses. "It's always interesting to see the evolution of their skills, because they transfer when they are searching for their first job out of school," Meyer says.

"It was hard at the beginning, but I eventually started picking things up and succeeding," Prakash says. "Having a strong team helps a lot. Without the people I worked with, I definitely couldn't have done what I did."

His latest giant leap? A summer internship at Tesla.

Read Tarun's full story...

Rocketeers featured in commercial

In 2022, the undergraduate students of Purdue Space Program accomplished an unprecedented feat. First, they spent years at Zucrow Labs designing and testing a liquid methane rocket, which they jokingly called "Boomie Zoomie." They also built all the ground support equipment. After successful several cold flows and hotfires at Zucrow, they travelled to the Mojave Desert, **successfully launched the rocket – recovered it – and launched it again, all in one weekend.**

This remarkable accomplishment was noticed by Purdue University, who featured the intrepid rocketeers in their latest 30-second TV commercial, entitled "This is Persistence."

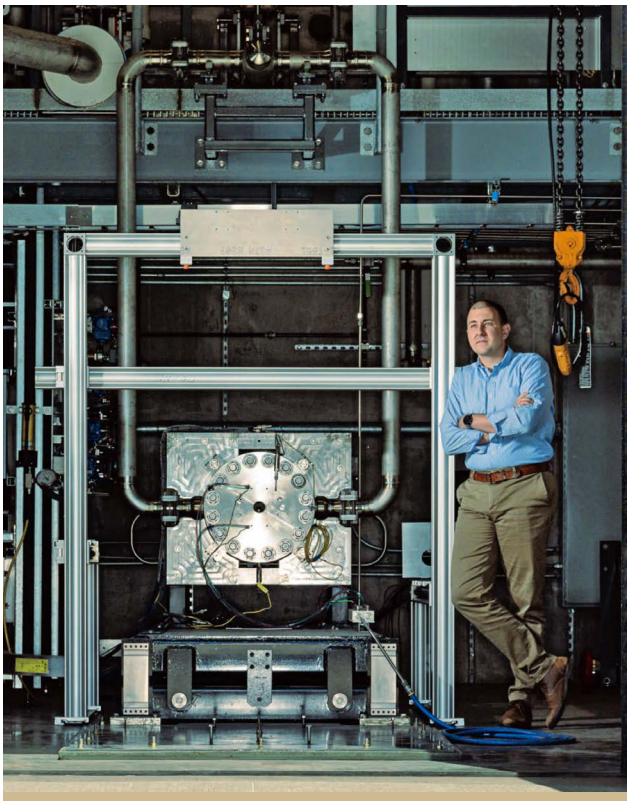
Watch the commercial...

Read the full story...

Purdue's latest commercial features Purdue Space Program, who built their liquid methane rocket at Zucrow Labs. ***Watch the commercial...***

Hypersonic scramjets

A new test rig at Purdue is set up to **fire rocket exhaust into the inlet of a hypersonic scramjet engine**. This capability — a first of its kind at any university — is one of a series of platforms at the Maurice J. Zucrow Laboratories that enable the rapid development, integration and operation of new propulsion concepts.



"There's a national need for these facilities," says Slabaugh. "We can now support critical programs here, including priority efforts for national security."

In order for a vehicle to go hypersonic with an air-breathing engine, aerospace engineers turn to scramjets, where the air and fuel travels through the combustor at a supersonic rate. The main challenge in improving these engines is that there's a very small window of time to complete the burn before the air and fuel has exited the engine. That's why the advanced tools available at Zucrow Labs are so important to further development. Carson Slabaugh, a leader in the field of laser-based combustion diagnostics, helped develop Purdue's portfolio of laser sources and high speed detection equipment. Quartz-based windows replace a portion of the combustor shell, allowing researchers to directly observe the combustion happening inside an engine.

But before Slabaugh could test a scramjet, he needed something that would simulate its operating environment. To test hypersonic engines, you need to feed it with a rocket.

In a direct-connect rig like the kind at Purdue, researchers test just the internal scramjet engine components by connecting the rocket, called a vitiating air heater, into the engine's air inlet. "Our direct-connect system allows us to replicate hypersonic conditions in a much smaller configuration, so we don't have to run a facility that's quite as large as a free jet wind tunnel," Slabaugh says. "As a way to build confidence in your propulsion system design without having to run tests that are that expensive, we extract the isolator, combustor, and expansion sections and we effectively replicate the flow that's going in and the flow that's going out."

Slabaugh had the chance to showcase his test rig to U.S. Deputy Secretary of Defense Kathleen Hicks when she visited Zucrow in August 2022.

Read more about Dr. Hicks' visit...

They use a vitiator, which works like a rocket by reacting hydrogen and oxygen and producing high-temperature water vapor. That rocket exhaust is supplemented with enough nitrogen and oxygen to simulate atmospheric air before it enters the scramjet combustor. A vacuum system, called an ejector, is attached downstream of the combustor to replicate the exhaust-side airflow at high altitude.

This rig, like the other propulsion test stands at Zucrow, lives in an isolated test cell with 20-inch-thick reinforced concrete walls and steel explosion-proof doors. Purdue is the only academic institution to offer this type of testing capability. Despite the challenges, Slabaugh is excited to have the scramjet test stand operating. "Our team always finds a way forward, because we are committed to working these fundamental, relevant problems at scale."

"I come to work and shoot lasers at fire," he says with a smile. "I can't complain."

Read the full story in the Fall 2022 Aerogram...

Monique McClain: Air Force grant

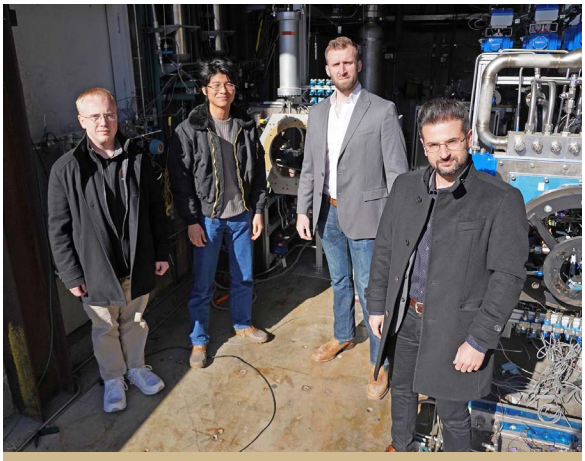
The U.S. Air Force Office of Scientific Research (AFOSR) has announced the latest group of grant recipients as part of its Young Investigator Research Program (YIP). Among the 2023 recipients is assistant professor of mechanical engineering Monique McClain, who will receive $450,000 over three years.

McClain studies additive manufacturing, especially in specialized areas such as energetic materials. Her project is entitled "**Enhanced Microstructural Control of Plastic Bonded Explosives via Additive Manufacturing**." It's an advancement of the research she started as a Ph.D. student at Purdue, studying how to 3D print extremely viscous materials.

"Traditionally manufactured energetic materials have tiny variations in their microstructure, which are challenging to control," said McClain. "I have proposed a new manufacturing method to more precisely control the microstructure, so that the sensitivity and performance is more predictable. By characterizing the manufacturing process and relevant material science phenomena, we will gain more understanding on how such defects form and how to control them."

Read the full story...

Carlo Scalo: DARPA Phase II award



HySonic Technologies is working to improve the aerodynamic and propulsive performance of hypersonic vehicles. (Left to right) Nathan Ballintyn, Forrest Lim, Karl Jantze, Carlo Scalo (not pictured: B.J. Austin, Stephen Heister, Scott Meyer)

HySonic Technologies, LLC, founded by associate professor of mechanical engineering Carlo Scalo, **recently received an award from DARPA to further develop its propulsion technologies.**

"This is a critical milestone for our company," said Scalo, whose academic research focuses on nonlinear acoustics, compressible turbulence, and hypersonics. "Starting a small business is always a challenge. But this award allows us to step up to the next level."

In 2018, he founded HySonic Technologies, LLC, to develop technologies to improve the aerodynamic and propulsive performance of hypersonic vehicles. With the help of the Purdue Foundry, he applied for and successfully received Phase I SBIR awards from the U.S. Navy in 2019 and 2021. Each of these $140,000 awards enabled Scalo to develop his small business in its early stages. With this newest two-year, $1.8 million Phase II award from DARPA (Defense Advanced Research Projects Agency), HySonic is growing closer to delivering a viable product.

"This is a stepping stone to achieving our dream," said Scalo. "Now there's a lot more to do."

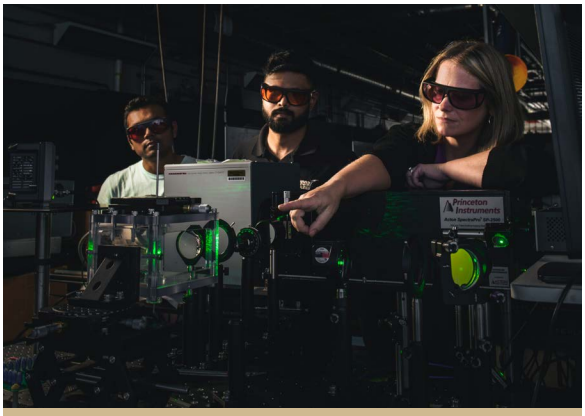
Under this DARPA funding, HySonic will continue to develop technologies for stabilizing the operation of high-speed propulsion systems, in collaboration with B.J. Austin at IN Space, LLC and Purdue colleagues Stephen Heister and Scott Meyer.

"We have a strong vision for HySonic Technologies," said Scalo. "It took a lot of effort to make it this far, and now with even more opportunities for growth coming our way, and I'm excited for the future."

Read the full story...

Sally Bane: Nanosecond Plasmas

Sally Bane, associate professor of aeronautics and astronautics, is taking a unique approach to getting a **deeper understanding of why plasmas behave the way they do**. "On a baseline level, we don't completely understand the underlying physics of these plasmas yet, particularly at high pressures, and so we can't predict them with our numerical models. We are trying to bridge the gap with measurements that have not been done before," she says.



(Left to right) Anup Saha, Karna Patel, Sally Bane

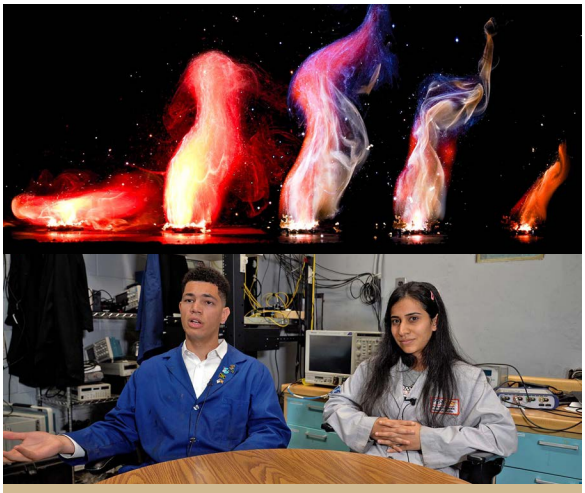
The fastest high-speed cameras available at Zucrow labs can capture an image in a bit less than a microsecond, or 10^{-6} seconds. But even those aren't sensitive or fast enough for Bane's needs. A streak camera, on the other hand, records the intensity of light over time, which allows it to capture light data in picoseconds — or 10^{-12} seconds. She is collaborating with Terry Meyer, who works on laser diagnostics for high-speed, turbulent flow and combustion. "He and I are working to adapt some of his methods to this streak camera device that I've been working with."

Though the tools individually aren't groundbreaking, combining them to achieve these results certainly is. "We're measuring a bunch of very important parameters, and we're measuring them with unprecedented temporal resolution, which you need because these plasmas are so short-lived," Bane says.

Read the full story...

Rocket propellant from Martian soil?

NASA's 2008 Phoenix Mars Lander discovered that Martian soil had a significant amount of molecules called perchlorates. "When I hear 'perchlorates,' my rocket scientist mind immediately goes to solid propellants," said Alex Hoganson, who got his master's degree at Zucrow Labs under Steve Son. "Ammonium perchlorate was used as the oxidizer on the Space Shuttle's solid rocket boosters. If there are perchlorates on Mars, my first question is: can I light them on fire?"



Alex Hoganson, Hetal Rathore, and Chase Wernex (not pictured) worked on a project at Zucrow Labs to make solid rocket propellant out of analog Martian soil. ***Watch the video...***

No one had yet studied the feasibility of using Martian perchlorates as solid rocket propellant. Hoganson and his colleagues determined that the chemical composition of Martian soil at the Phoenix Lander site was 60% calcium perchlorate and 40% magnesium perchlorate. "We can actually go online and buy those perchlorates," said Hoganson, "and make our own analog of a Martian solid propellant."

The initial results were encouraging. "The propellants behaved like propellants," said Hoganson. The 60/40 Mars blend was extremely hygroscopic, meaning it eagerly absorbed water from the air. That's a problem for earthbound propellants, but in the arid environment of Mars, it may not be as significant a hurdle.

The future goal is *in situ resource utilization*: manufacturing propellant *in situ* on the surface of Mars could enable missions to send a payload back without having to carry extra propellant all the way from Earth. "I can foresee a future where we have colonies and mining operations on Mars," he said. "Robots and industrial machines can scrape the soil and harvest these perchlorates en masse, creating their own rocket propellant to get back to Earth. Having that much oxidizer readily available in the Martian soil is a resource we should definitely take advantage of."

Read the full story...

Zucrow alumni at Blue Origin

More than 25 Purdue alums are writing new chapters in space at Blue Origin, which operates the reusable suborbital launch vehicle *New Shepard*, and is developing the heavy-lift rocket *New Glenn*.

David Helderman (BSAAE '06, MSAAE '09) caught the space bug early. "I have always loved space and problem solving," Helderman said. "My parents still have pictures of me drawing spaceships from when I was 5. It's something that has been a passion of mine for as long as I can remember."

He's director of Alabama Test Operations, responsible for all operations at the historic Test Stand 4670 in Huntsville; the test stand was built in 1965 during the Apollo space program to develop and test the Saturn V rocket, which first launched humans to the Moon. "The most satisfying part of my job is taking a group of talented individuals and enabling them to become a high-performing unit," Helderman said. "Driving a strong technical team to confront the extensive engineering challenges within a spaceflight arena is something that truly excites me every day."

David Helderman (BSAAE '06, MSAAE '09)

Heather Wiest (MSAAE '13, PhD AAE '17) joined Blue in 2017. The Purdue graduate is a mechanical engineer in Blue Origin's Launch Facilities Development Group in Cape Canaveral, Florida. She designs launch pad fluid systems that will be used to support the launches of New Glenn, which has twice the payload capacity of any existing launch vehicles, and a reusable first stage designed for a minimum of 25 flights.

"I chose Purdue to work at Zucrow Laboratories," she said. "I completed my master's and PhD while doing experimental gas turbine combustion research under Stephen Heister in the High Pressure Laboratory (ZL3). The hands-on experience I had in designing, building, operating and analyzing data for my own combustion experiment at HPL shaped me into the engineer I am today."

Wiest cited the satisfaction gained from taking a job from start to finish. "I have been at Blue for almost five years, and I have had the opportunity to watch LC-36 [Launch Complex 36 at Cape Canaveral Space Force Station] go from piles of strategically placed dirt to a substantially complete launch pad," she said. "I can't wait to start my transition from design to operations and be part of launching New Glenn."

Wiest has a personal recollection of an earlier New Shepard success. "I remember watching the New Shepard in-flight escape test in October 2016 from a conference room in Armstrong Hall at Purdue," she said. "It was the fifth successful launch and landing for that booster, and it occurred around the same time I accepted my full-time offer from Blue Origin. That flight confirmed I was making the right decision to join Team Blue."

Heather Wiest (MSAAE '13, PhD AAE '17)

Read the full profiles of Purdue grads working at Blue Origin...

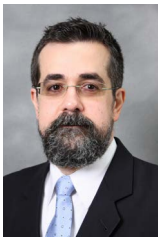
Awards and honors

Veeraraghava Raju Hasti has been elected an Associate Fellow of American Institute of Aeronautics and Astronautics (AIAA).

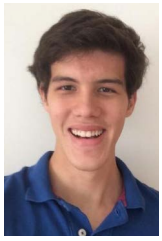
Stefannie Morales Jiménez was awarded a NASA Space Technology Graduate Research Opportunities (NSTGRO) fellowship. She is a Ph.D. student researching green hypergolic propellants with Timothee Pourpoint. ***More about Stefannie...***

Nicole Key has been appointed to the Fellow Review Committee for ASME (American Society of Mechanical Engineers), serving alongside dozens of past presidents.

Scott Meyer was recognized by Purdue's College of Engineering with their Research Staff Excellence Award for 2022 "for his revitalization of propulsion activities and outstanding leadership approach to the development of exceptional experimental facilities."



Guillermo Paniagua received the Fulbright Distinguished Scholar Award in Alternative Energy Technology. He will be teaching and researching at Chalmers University of Technology in Gothenburg, Sweden.



Roy Ramirez received the G.A. Ross Award, presented annually to one outstanding male senior in honor of his contributions to Purdue University. After conducting undergraduate research at Zucrow, Roy graduated in 2022 and is starting an aerospace company in his native Costa Rica. ***More about Roy...***

Carson Slabaugh has been elected an Associate Fellow of American Institute of Aeronautics and Astronautics (AIAA).

Mikhail Slipchenko accepted the 2023 Aerodynamic Measurement Technology Innovation Award from AIAA for "advancement and commercialization of pulse-burst laser technology, innovations in high-speed laser diagnostics, and applications in hypersonic ground test facilities" on behalf of his co-winners: Sukesh Roy, Terrence Meyer, Jason Mance, Naibo Jiang, and Paul Hsu.

Logan Tuite has been awarded the Rolls-Royce Chairman's Farewell Ph.D. Bursary Award, for engineering which benefits the environment. Logan is a Ph.D. student researching turbine blade optimization with Guillermo Paniagua.

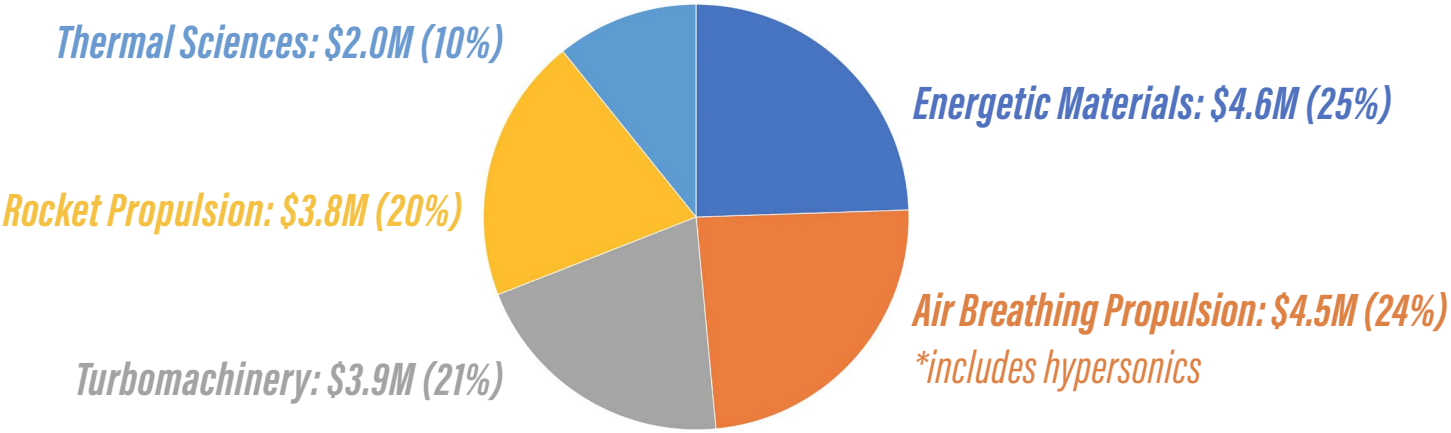
Two Zucrow alumni are headed to space in 2023!

Scott Tingle *(MSME '88) will serve as Commander of Starliner-1, the first operational flight of Boeing's new crew capsule (pending the launch of a successful crewed test flight first). Scott previously spent six months on the International Space Station in 2018.*

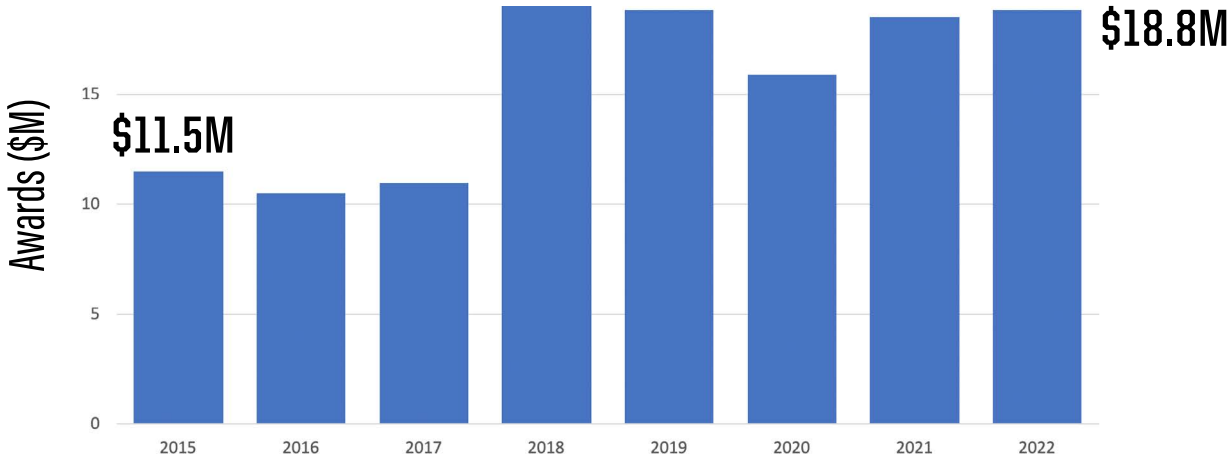
Loral O'Hara *(MSAAE '09) is scheduled to launch to ISS as part of Soyuz MS-24. This will be her first spaceflight since joining NASA's Astronaut Corps in 2017.*

Zucrow by the numbers

Total expenditures at Zucrow for calendar year 2022: **$18.8 million**

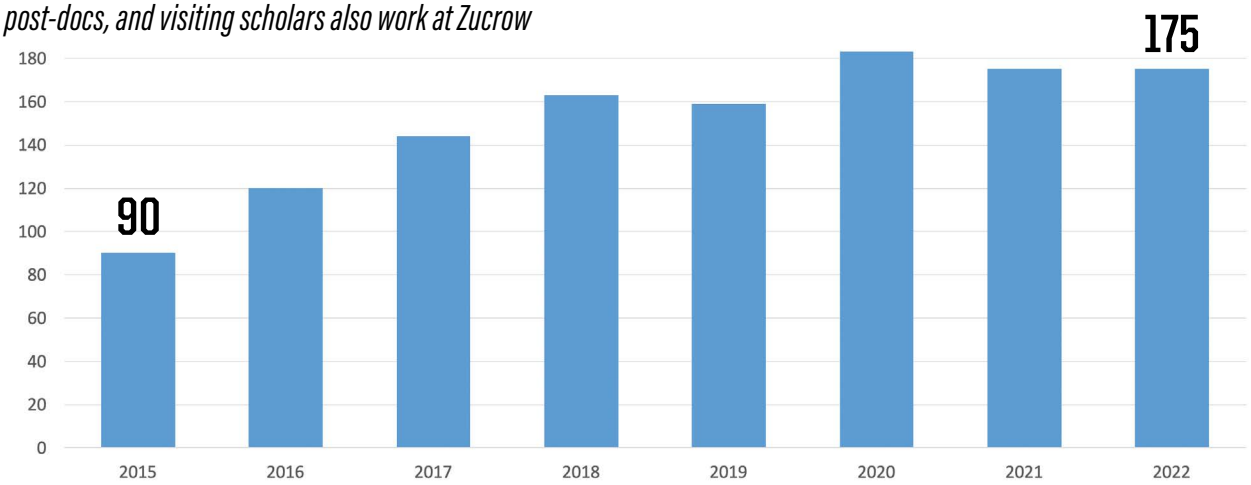


Growth in sponsored projects at Zucrow Labs



Growth in number of graduate students working at Zucrow Labs

**Indicates graduate students only. Many undergraduates, post-docs, and visiting scholars also work at Zucrow*



NTO/MON-3 and MMH are commonly used as a point of comparison in order to evaluate the relative performance of novel hypergolic propellants. The image sequence from Timothee Pourpoint shows a drop test: from drop release, to the initial contact and gas production, to ignition. This is the first step in evaluating the feasibility of use in a hypergolic propellant system.

PURDUE UNIVERSITY | Zucrow Labs