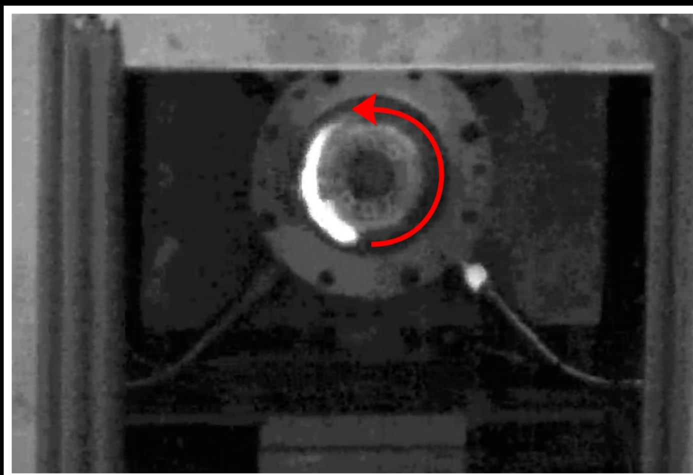
ZUCROW LABS 2023 ANNUAL REPORT



Rotating detonation engines (RDEs) are the holy grail of propulsion, and Zucrow Labs is helping to bring them to life. Terrence Meyer's lab hosts the THOR (Turbine-integrated High-pressure Optical RDE) test rig, allowing researchers to look inside the combustion chamber, and use laser-based imaging to characterize RDEs' complex dynamics with millions of data points a second.

Photo by Venkat Athmanathan

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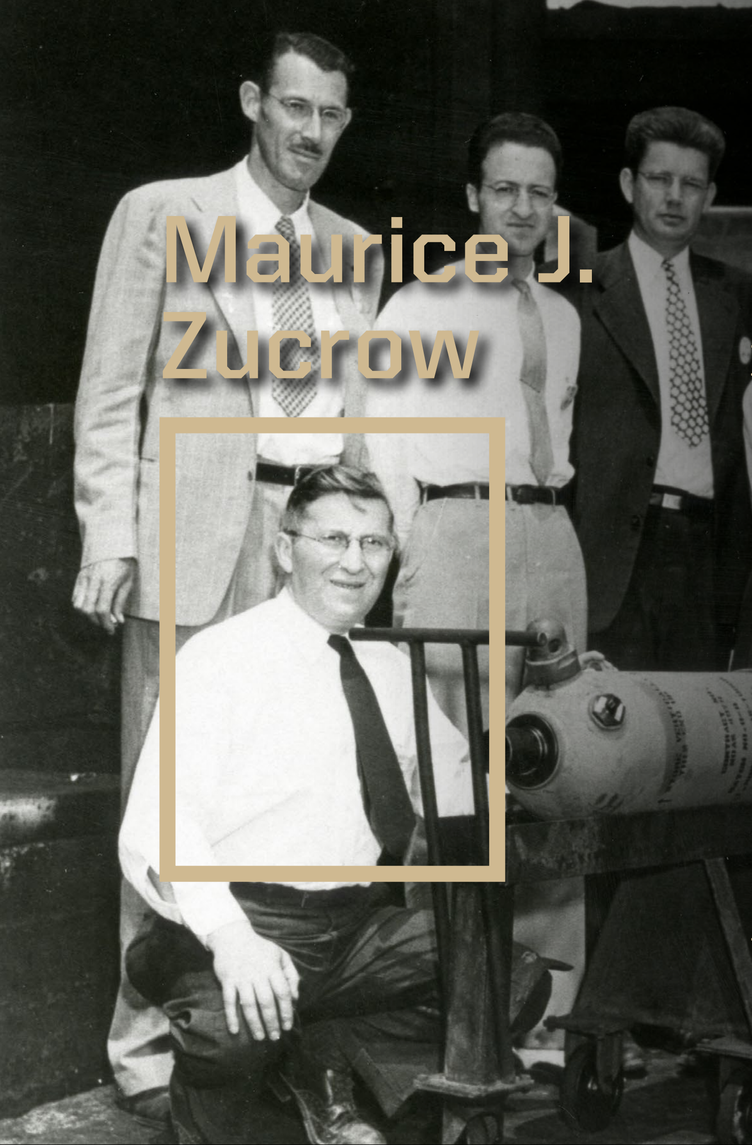
Maurice J. Zucrow



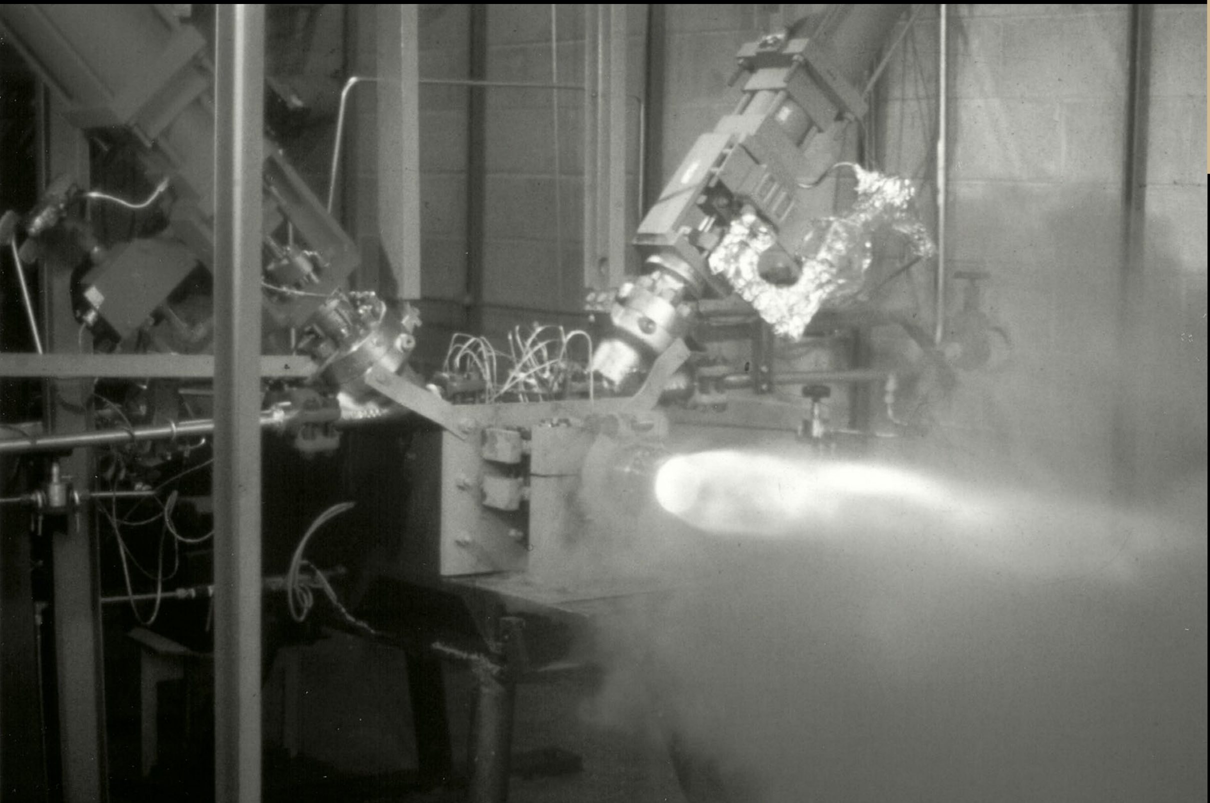
Our founder, Maurice J. Zucrow, is an unsung hero in the history of aerospace. After serving in World War I, he earned Purdue University's first ever Ph.D. in 1928 — and also earned his nickname, "Doc." He worked at Aerojet Corporation, advising the design of the Atlas rocket that would launch John Glenn into orbit. In 1946 he wrote the jet industry's first textbook: *Principles of Jet Propulsion and Gas Turbines*. The reputation of the book and its author is supposedly one of the reasons Neil Armstrong chose to attend Purdue.

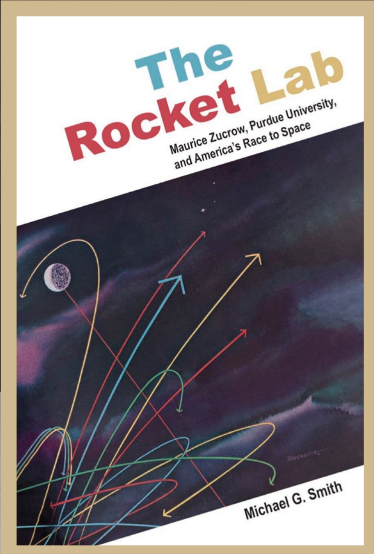
In 1948, Zucrow helped to design and build Purdue's first ever "Rocket Lab," located by Purdue Airport. His groundbreaking research in high-pressure combustion and film cooling contributed to the design of the RS-25 Space Shuttle Main Engines — which never once failed a mission, and are still being used to this day for the Artemis program.

Fifty years after its founding, Purdue renamed the "Rocket Lab" to honor its founder: the **Maurice J. Zucrow Laboratories**. The 24-acre complex is the largest academic propulsion lab in the world.

Above: *"Doc" Zucrow and his Aerojet team with a solid-propellant JATO (jet-assisted take-off) motor.*

Below: *an early 1960s high-pressure bi-propellant test at Purdue using* N_2O_4 *and Aerozine 50, with a ceramic-coated combustion chamber operating at 4,800 psia.*





Maurice J. Zucrow is the subject of a new book from Purdue University Press called ***The Rocket Lab***, which covers both "Doc" Zucrow's life and the lab's influence on aerospace history. You can buy the book at Amazon, or directly from ***press.purdue.edu***

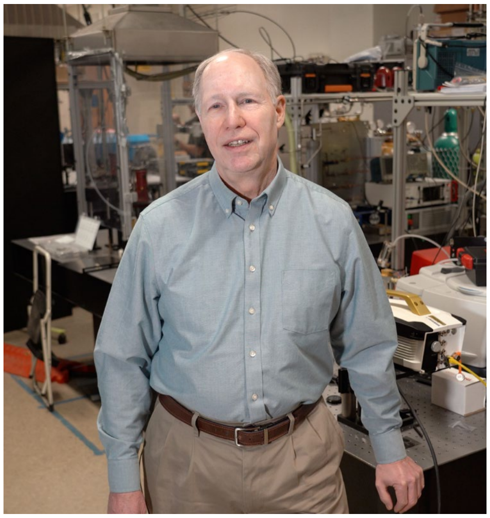
From the Director

This... is a parking lot. It may not seem like much, but this actually represents a quantum leap forward for Zucrow Labs. Let me explain.

When I first became director of Zucrow Labs, you had to drive under a one-lane railroad bridge and turn onto an unmarked dirt road to get here. **Starting in 2015, Zucrow became a permanent construction site.** The first thing we did was pave the road, and replace the railroad bridge so trucks could easily get in! This began a building spree that has continued right to the present day.

- In 2017 we opened the **ZL8** propulsion complex, with five state-of-the-art test cells and a climate-controlled 2,000-square-foot laser lab.
- In 2021, as part of the new **Discovery Park District**, Saab opened a factory right next door manufacturing fighter jet airframes. Rolls-Royce built an office building nearby, and also has a hybrid engine testing facility currently under construction.
- In 2023, we opened the **Hypersonics and Applied Research Facility (HARF)**, a first-of-its-kind $41 million research facility with hypersonic wind tunnels, shock tubes, manufacturing labs, and secure entry for national defense research.
- In 2024, we plan to open **ZL9**: the ultimate high-pressure combustion laboratory, a $73-million crown jewel for propulsion research at Purdue.

In short, the physical footprint of Zucrow Labs has been covered in dust ever since I arrived. Our heroic students, faculty, and staff have had to deal with it: parking their cars in the mud; jumping over puddles to get to their labs; wheeling their test rigs over gravel construction sites. And yet — in the midst of all this inconvenience, **they still find a way to conduct some of the most groundbreaking propulsion research on the planet**.



Which brings us back to this new parking lot. This humble stretch of asphalt means that our researchers will no longer have to park in the mud and jump over puddles to get to their labs. It's not just a nicety, it's a necessity — because ZL9 will bring nearly 100 additional graduate students to the 190 who are already working hard here every day.

So fasten your seat belts — because the world's largest academic propulsion lab is about to get even bigger and better!

Robert P. Lucht
Director, Maurice J. Zucrow Laboratories

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ZL9 takes shape

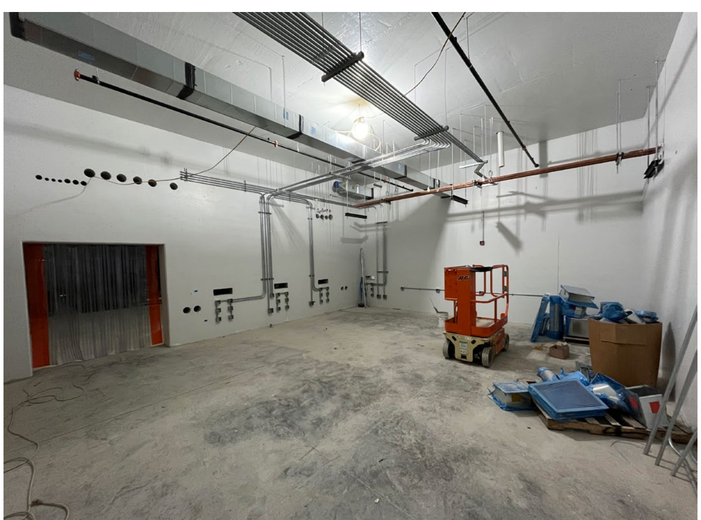
We've watched the $73 million **High-Speed Propulsion Lab**, otherwise known as ZL9, rise out of the ground this year, and I'm thrilled to share the progress. In addition to the massive test cells and individual laser labs, a new high-pressure heated air plant will reliably deliver conditions for any experiment imaginable. A new fabrication workshop enables almost any test rig to be designed, built, and operated all under one roof.

ZL9 also features all the intangibles that will make it a welcoming environment for the 100+ new researchers who will work there. Windows, conference rooms, kitchens, meeting areas, a lobby, and yes, even a parking lot with a paved walkway.

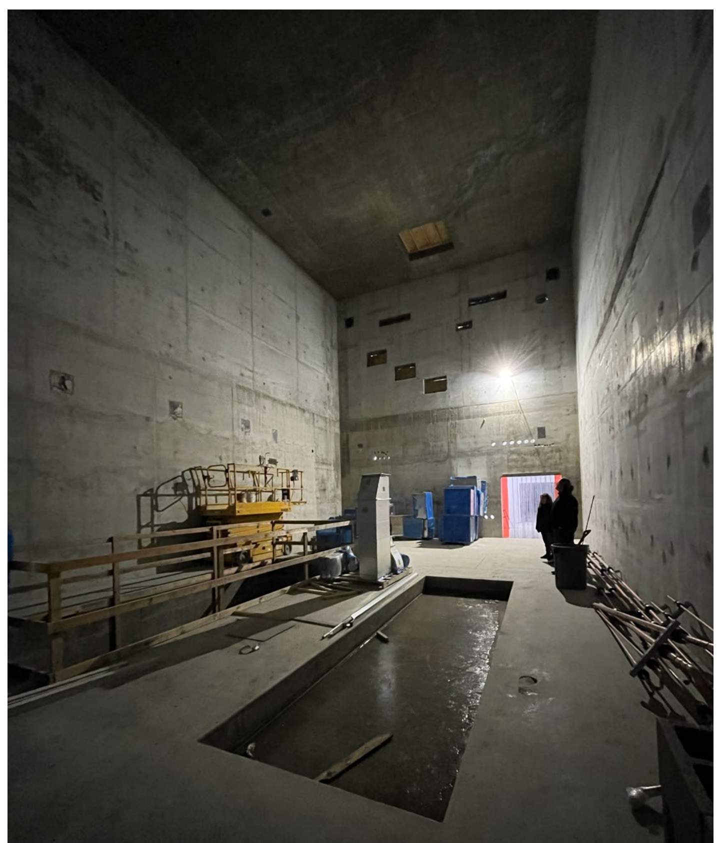
Opening later this year, ZL9 incorporates everything that makes Zucrow great, and takes it to the next level.

ZL9's features will revolutionize research, as well as create a better environment for researchers.

The 2nd floor adds 100 new desks, meeting rooms, kitchen, and other welcome features.



Each test cell hosts its own individual climate-controlled laser diagnostics facility.



ZL9's test cells are an astonishing 34 feet tall. The three rectangular inlets will deliver high-pressure heated air.

HARF ushers in hypersonic era

In June 2023, leaders from Purdue, federal government, and industry celebrated the opening of the **Hypersonics and Applied Research Facility (HARF)**, a $41 million, 65,000-square-foot building that is home to two cutting-edge wind tunnels – the only Mach 8 quiet wind tunnel in the world, and the hypersonic pulse (HYPULSE) reflected shock/expansion tunnel. It is also home to the Hypersonics Advanced Manufacturing Technology Center (HAMTC), a single location for industry partners to work on materials and manufacturing innovations and provide access to testing capabilities.

From left, Karen Plaut, executive vice president for research; Mark Lewis, CEO of Purdue Applied Research Institute; Mung Chiang, Purdue University president; and Scott Meyer, managing director, Maurice J. Zucrow Laboratories, celebrate the opening of the Hypersonics and Applied Research Facility. (Purdue University photo/Charles Jischke)

"The Hypersonic Applied Research Facility is an investment in test and evaluation and research capabilities that this country desperately needs," said Mark Lewis, chief executive officer for Purdue Applied Research Institute. "Through facilities such as HARF, we will help solve some of the most challenging and relevant problems in the field of high-speed flight while also building the future workforce."

The tunnels recreate different scenarios, such as spacecraft re-entry or missile flight through the atmosphere, as well as replicating unique engine conditions for extremely high-speed propulsion. The Mach 8 quiet wind tunnel and the HYPULSE tunnel offer controlled environments to research several facets of high-speed flight. The wind tunnel more closely simulates flight and provides more accurate data than conventional hypersonic wind tunnels.

The HYPULSE tunnel uses a shock wave of high-temperature air to recreate specific hypersonic flight conditions. It allows flight simulations at speeds ranging from Mach 5 to as high as Mach 40. Purdue is only the second U.S. university to offer HYPULSE test capabilities.

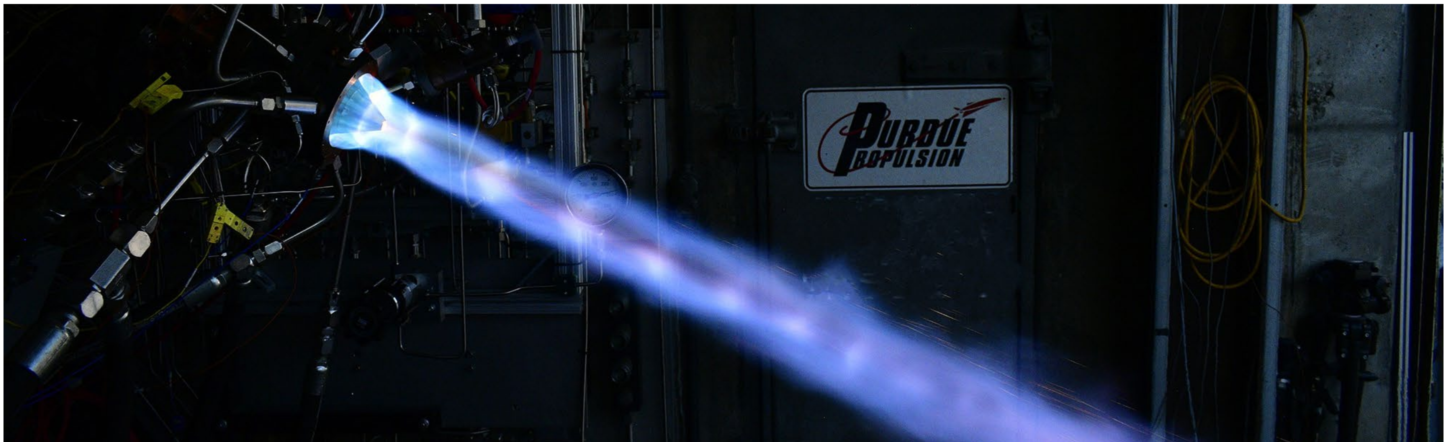
The HYPULSE hypersonic pulse shock tunnel, donated by Northrop Grumman, is one of several features that makes HARF a unique place to test hypersonic vehicles.

At HAMTC, located in HARF, researchers can collaborate with industry partners to develop materials and manufacturing innovations. HAMTC is the only vertically integrated prototyping center in the nation that enables the design, manufacturing, joining and testing of hypersonic components and subsystems in one location, speeding time from concept to full-fledged product.

"Flying is part of our Boilermaker DNA, from autonomous drones all the way to the moon, and in near space with hypersonics, too," Purdue President Mung Chiang said at the ribbon cutting. "This is a particularly transformational moment with the opening of HARF, and we are reaffirming here today our unwavering commitment to national security and defense, and to growing Purdue as the epicenter of hypersonic research, testing and talent development for the United States."

[Read the full story...]

Zucrow leads the RDE revolution

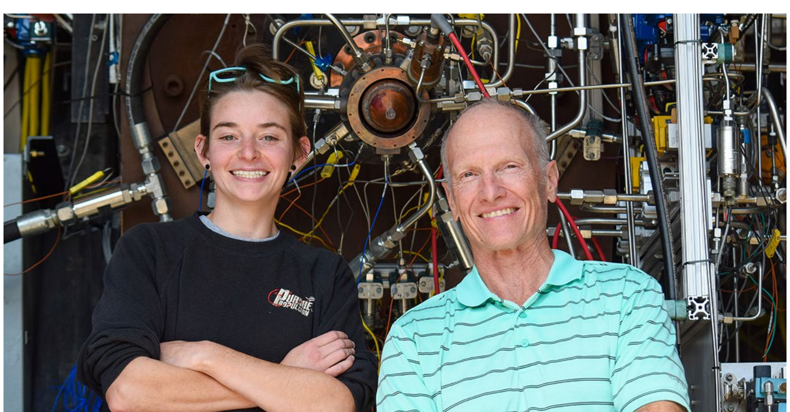


Purdue researchers are leading in study and design of 3D-printed rotating detonation rocket engines, which could transform spacecraft and hypersonic vehicles. (Purdue University photo/Ariana Martinez)

The next generation of propulsion is closer than ever. A revolutionary design, called a **rotating detonation engine (RDE)** has been the elusive "holy grail" of propulsion for decades. The supersonic dance happening inside an RDE promises to generate the same or more thrust as traditional rocket engine, but in a much smaller package. After years of slow but steady progress, RDE development is now blazing — and Purdue's early start, unique capabilities, and top-level expertise put Boilermakers at the forefront of this field. Purdue researchers even contributed to NASA's first full-scale test of a rotating detonation rocket engine in 2022.

Stephen Heister, the Raisbeck Engineering Distinguished Professor of Aeronautics and Astronautics, draws a comparison between a rotating detonation rocket engine (RDRE) and NASA's time-honored RL-10. Originally designed in the 1950s and used on countless satellite and deep space exploration launches, versions of that rocket engine are still part of satellite launch systems today. An RDRE that produces similar thrust to the RL-10 could be as much as 40 percent shorter in length. That factor alone could be transformational for spacecraft design. "If we do everything right, an RDRE with just a few percent more thrust could double the payload of the launch vehicle," Heister says.

The level of development and testing happening now at Zucrow Labs is unrivaled in academia, Heister says. Other universities running RDRE combustion experiments are burning gaseous fuel and oxygen, and with engines that use a solid metal center to absorb its copious heat energy. Those can only run for about a second before the metal reaches thermal capacity and begins melting away. While useful for research, it's far from the demands of a real-world engine that must run for minutes at a time. In 2022, while studying under Heister, then-student John Smallwood (PhD AAE '23) built and tested **Purdue's first water-cooled RDRE**. His design endured 120 hot-fires, some with 30-second runs, and still looked pristine when they cut it open afterward.



Ariana Martinez and Stephen Heister at a Zucrow test stand, in front of the RDE engine she designed. (Purdue University photo/Alan Cesar)

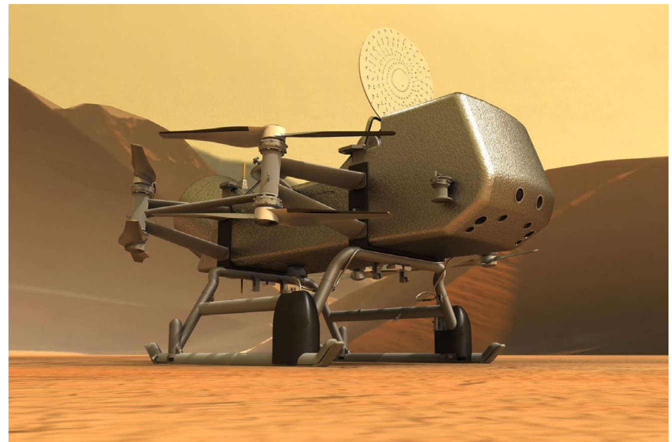
Encouraged by those results, AAE doctoral student Ariana Martinez had to push farther. She looked to NASA's success with 3D-printing an exotic copper alloy, called GRCop-42. She collaborated with NASA Marshall Space Flight Center to print the combustor. Over the spring and summer of 2023, she put it through 31 hot-fires for a total duration of 200 seconds. "The water-cooled hardware would survive if we could continue feeding propellant to it," Martinez says. "We could run it indefinitely."

***This story originally appeared in* Aerogram.**
Read the full story and watch video here...

Helping Dragonfly survive

Saturn's largest moon, Titan, is rich with organic substances and may contain clues to the chemical beginnings of life. NASA is planning to send a first-of-its-kind rotorcraft lander called Dragonfly to explore Titan's unique surface.

But before it begins flying, Dragonfly's entry capsule has to make it through Titan's dense atmosphere. That's where Chris Goldenstein comes in. His team are studying the chemistry that unfolds at extreme temperatures behind shock waves in Titan's atmosphere. This directly influences the amount of radiative heating impacting the vehicle's heat shield, which must withstand incredible temperatures to survive and allow for a successful landing of the Dragonfly rotorcraft on the surface of Titan.



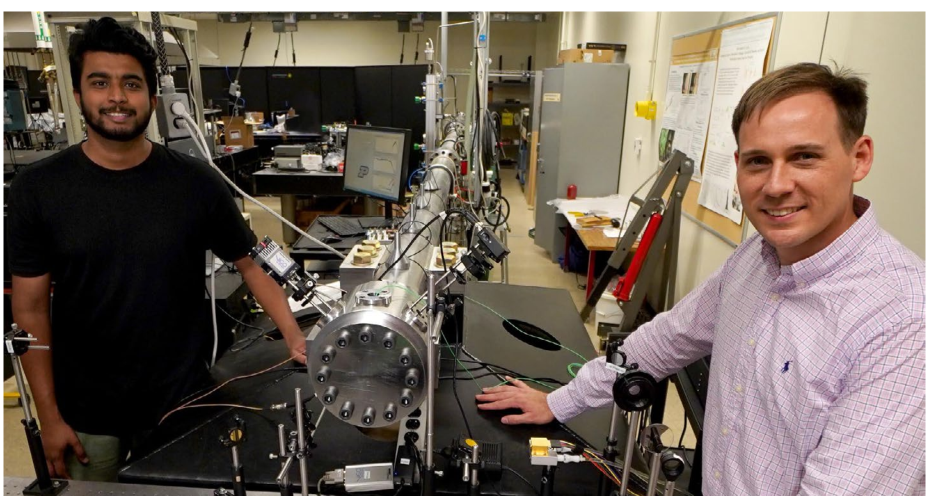
NASA's Dragonfly hopes to become the first aircraft to conduct scientific research on another planet. But first it has to survive atmospheric entry on Titan. (Photo courtesy NASA / Johns Hopkins APL)

"Titan's atmosphere is mostly nitrogen (like Earth's), with about 1.5% to 2.5% methane by volume," said Vishnu Radhakrishna, a Ph.D. student in Goldenstein's lab and lead author of a recently-published paper on detailed spectroscopy relevant to entry on Titan. "But it's about 4 times denser than Earth's — and hundreds of times denser than Mars' — which makes rotor-based flying easier."

"The vehicle will enter Titan's atmosphere at extremely high velocity, forming a shock layer with unique and highly non-equilibrium chemistry," Goldenstein said. "That will induce a significant amount of heat flux to the vehicle. It's our job to try to understand that chemistry and the interactions of the shock layer plasma, so that NASA can more accurately predict the radiative heat transfer and design an appropriate heat shield for Dragonfly."

Goldenstein's team developed a diagnostic called ultrafast laser absorption spectroscopy to study the chemical processes occurring behind shock waves. "This diagnostic has a unique ability to quantify the number of molecules in a huge number of energy levels and on a very short timescale, less than one nanosecond," Goldenstein said. "This results from using femtosecond laser pulses, which inherently possess many wavelengths of light."

"We're very proud of our shock tube facility here," Goldenstein said. "We can operate at burst pressures of over 200 atmospheres to produce very strong shock waves. There aren't many shock tubes in academia that can operate at such high pressures."



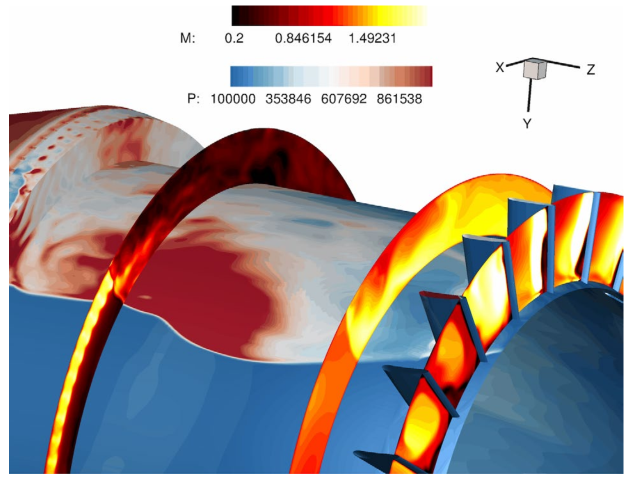
Vishnu Radhakrishna and Chris Goldenstein use a shock tube to recreate the extreme temperatures, pressures, and velocities of atmospheric entry on Titan. (Purdue University photo/Jared Pike)

As a result of their experiments, they witnessed cyanide (a compound with one carbon atom and one nitrogen atom) being created in high-energy quantum states, and surviving there longer than conventional models predict. "This is something that hadn't been conclusively observed previously," Radhakrishna said. "These results could help NASA develop improved radiative heat transfer models for Dragonfly."

Read the full story and watch video here...

Computing award for turbines

A team led by Guillermo Paniagua was honored with the "**Best High-Power Computing Collaboration**" award in HPCwire's 2023 Readers' and Editors' Choice Awards. The team used Purdue's Rosen Center for Advanced Computing (RCAC) Bell supercomputer to run simulations for its work developing novel engine components that will have implications for decarbonized power generation.



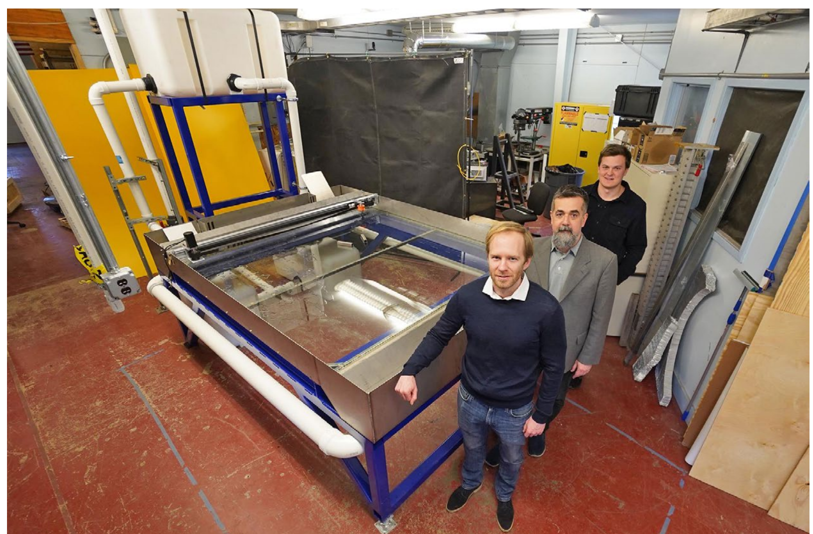
"We are honored to receive this recognition from HPCwire, and it reflects the hard work and dedication of the many people involved in this multi-institution collaboration," says Paniagua, a professor of mechanical engineering, who moved to Purdue in 2014 primarily so he could pursue research on advanced turbines for clean power and propulsion. "This award shines a light on Purdue's world-class experimental and computational resources, including our advanced turbine facilities tailored for pioneering small core clean aviation propulsion."

The team used Purdue's computing clusters to perform numerous computational fluid dynamic simulations of the combustor; optimize the design of the turbine, which involved running hundreds of direct evaluations of turbine geometries to maximize efficiency and reduce pressure distortion; and design the turbine's diffuser to ensure the correct temperature and pressure profile upstream of the turbine.

Read the full story...

Supersonic water table

There's no substitute for actually seeing supersonic flow in person, and being able to quickly iterate your designs as a result — without time-consuming wind tunnel tests or computer simulations. Paniagua's lab now has an alternative: **a water table which simulates supersonic flow**.



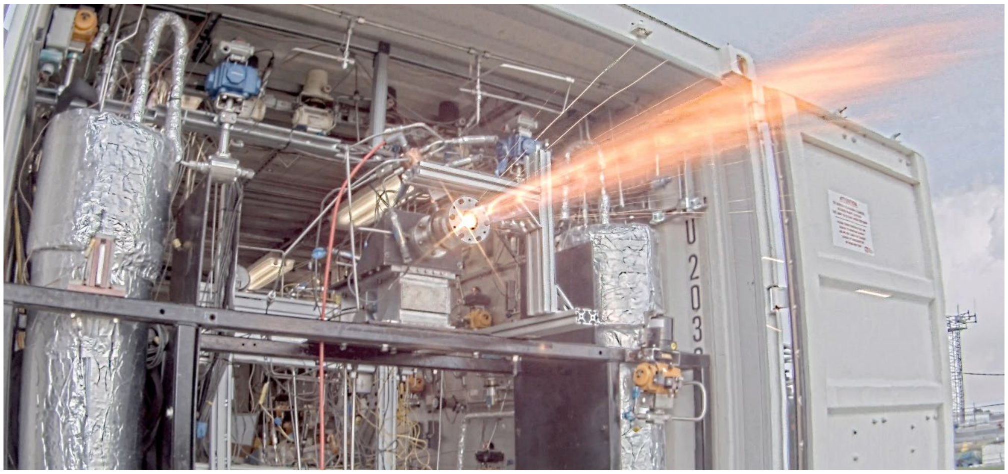
Bringing the water table to life was a group effort, led by (left to right) Dr. Lukas B. Inhestern, Dr. Guillermo Paniagua, and Kevin Boes. (Purdue University photo/Jared Pike)

"We can now easily experiment with different geometries for turbine blades," said Paniagua, "We create 2D representations of an airfoil, put them in the water, instantly see the results, and then use that analysis to refine the airfoil design."

The facility consists of a 2-meter-square pane of glass, set at a gentle slope. A reservoir of water at the top end feeds a thin film of water over the entire face of the glass, emptying into another reservoir at the bottom. A series of pumps and tanks keeps the flow continuously circulating. Placing airfoil shapes on the glass interrupts the flow of the water, creating visual patterns that simulate what might be seen experimentally in a wind tunnel test, or simulated in a computer model. They also designed a secondary gantry to sit at the top of the 2-meter glass field, with a pulley-driven arm that moves horizontally from one side of the tank to the other. By lowering a pointer that barely breaks the surface of the water, the back-and-forth motion creates the exact kind of shockwaves that they want to simulate.

Read the full story and watch video here...

Liquid-fueled rockets for $600?



In spring 2023, Purdue students split into two teams to see **who could design, build, and test the best rocket engine for less than $1,500.** Carson Slabaugh, the Paula Feuer Associate Professor of Aeronautics and Astronautics, called for a methane-oxygen engine capable of a steady 300 lbf of thrust for two seconds, and two hot fires.

“Cost overruns kill many programs and always leads to delays. Cost has significant effects on design decisions and, in many cases such as this, force engineers to get creative,” Slabaugh says.

The teams, made up of graduate and undergraduate students, set up and ran the tests themselves at Zucrow Labs.

Team *SpaceY* designed a single-element shear-coaxial injector and an innovative graphite nozzle to handle the heat, fabricating two copies for $1196.43. Thrust was just shy of target, producing an average 294 lbf on the best test.

Team *Frugal Fire* designed a multi-element, impinging injector and used fuel film cooling on the nozzle. To reduce cost, the team machined the injector plate themselves and used brass and carbon steel materials. Total cost: just $652.38. Their output, 307 lbf, was impressive, but fuel film cooling wasn’t enough: The nozzle melted down during its first run, leaving no time for a second test.

Team *SpaceY* was declared the winner on spec, but *Frugal Fire’s* experience was also an opportunity for rocket forensics. It led to in-depth discussions with Slabaugh on combustion instabilities — a lesson they wouldn’t have gotten with a successful test.

“It was a formative experience,” said Christina Huynh of the *SpaceY* team. “This class is why I came to Purdue.”

This story originally appeared in Aerogram.
Read the full story and watch video here...

Student teams Space Y (below) and Frugal Fire (right) competed in a frugal rocket challenge, each designing and building rockets for around $600.

Zucrow alum leads NASA Glenn

Zucrow alum **James "Jimmy" Kenyon** (MSE '98) has been appointed Director of NASA's Glenn Research Center in Cleveland, Ohio, with a staff of more than 3,200 people and an annual budget of approximately $900 million.

Jimmy Kenyon (MSE '98), Director of NASA's Glenn Research Center

"In the '90s, I studied with Sandy Fleeter, who was world-famous when it came to gas turbines," said Kenyon. "He was an interesting character, and it was fascinating to pick his brain about unsteady aerodynamics. I think he supervised 26 graduate students at the time, and boy did he work us hard. He used to drive out to Zucrow Labs late at night, just to see whose office lights were on!"

Kenyon said he learned a lot of lessons at Zucrow: "Sandy ended up being a great mentor. He taught me how to prioritize working with multiple stakeholders – industry, government, customers, co-workers. Those are lessons I still carry with me today here at NASA."

Kenyon says that his engineering background plays a huge role in his current success. "Someone once told me that getting an engineering degree is learning how to learn. That's true whether you're an undergraduate or graduate. Even if you get a Ph.D. like I did, you'll be the smartest expert on one narrow subject for a time – until someone else comes along and does more research! But when you're an engineer, you learn how to solve problems. And as you progress through your career, the problems become different – it's less about solving equations or conducting experiments, and more about leading a team and finding solutions together."

Read the full story...

O'Hara makes her first spaceflight

Loral O'Hara (MSAAE '09) launched on a Soyuz rocket from Kazakhstan to the International Space Station in September 2023. It's her first spaceflight since joining NASA's astronaut corps in 2017.

O'Hara was recruited to Zucrow Labs in 2007 by William Anderson, a professor in Purdue's School of Aeronautics and Astronautics. She had been a project manager at Rocketplane, integrating rockets into a suborbital launch vehicle, but wasn't sure that was her future. Coming to Purdue helped her find direction.

Loral O'Hara launched to the International Space Station in September 2023. (Purdue University photo/Rebecca Robiños)

"The work that I got to do at Zucrow designing, building and testing hardware was really the first time I got to do that – to take a project from the initial concept stage all the way through to test. All my work before that had been kind of analytical or more project management," she says. "Purdue set the stage for the rest of my career."

Since arriving at ISS, O'Hara has been busy conducting experiments, hosting media events, and joining fellow astronaut Jasmin Moghbeli for the fourth all-female spacewalk in history.

Read the full story...

Awards and honors

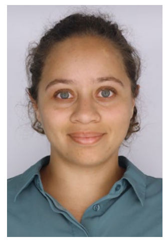
Kevin Boes, Ph.D. student in Mechanical Engineering, was appointed to serve a two-year term as student trustee for Purdue University's Board of Trustees. Kevin works with Guillermo Paniagua developing and testing turbines.

Jay Gore, the Reilly University Chair Professor of Mechanical Engineering, was chosen by Purdue to receive the Arden L. Bement Jr. Award for highly significant and impactful contributions to big data, artificial neural networks, machine learning and artificial intelligence in physics-based models of energy.

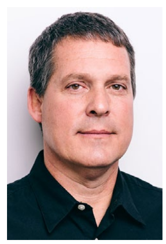
Daniel Guildenbecher has joined the School of Mechanical Engineering as an Associate Professor. His research interests include multiphase flows; energetic materials detection & combustion; sprays and atomization; and high-speed fluid mechanics. Both his B.S. and Ph.D. are from Purdue University, where he was advised by Paul Sojka. He has worked at Sandia National Laboratories since 2011.

Nicole Key, Professor of Mechanical Engineering, has been chosen for the ASME Fellow Review Committee.

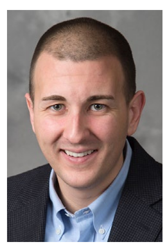
Kazuki Maeda has joined the School of Aeronautics and Astronautics as an Assistant Professor. He previously collaborated with Purdue on laser-based ignition through his large-scale turbulence simulation work at Stanford. His research interests are in rocket propulsion, hypersonics, and data assimilation. He has a PhD from CalTech.



Monique McClain, Assistant Professor of Mechanical Engineering, has been named to MIT Technology Review's Innovators Under 35 list for her work on additive manufacturing of energetic materials.



Scott Meyer, Managing Director of Maurice J. Zucrow Laboratories, has been elected as Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA), cited for "outstanding contributions to the development of sophisticated, state-of-the-art rocket and gas turbine test facilities and for rigorous training of numerous students in propulsion testing."



Carson Slabaugh has been named the Paula Feuer Associate Professor of Aeronautics and Astronautics.

Anduril Industries acquires Adranos

Purdue-originated startup **Adranos Inc. has been acquired by major defense products company Anduril Industries.** In 2015, then-Ph.D. student Brandon Terry worked with Steve Son at Zucrow Labs to develop a proprietary aluminum-lithium alloy solid rocket fuel called ALITEC, which significantly increases range, payload performance, and speed of defense and space systems. Terry later co-founded Adranos to market his invention.

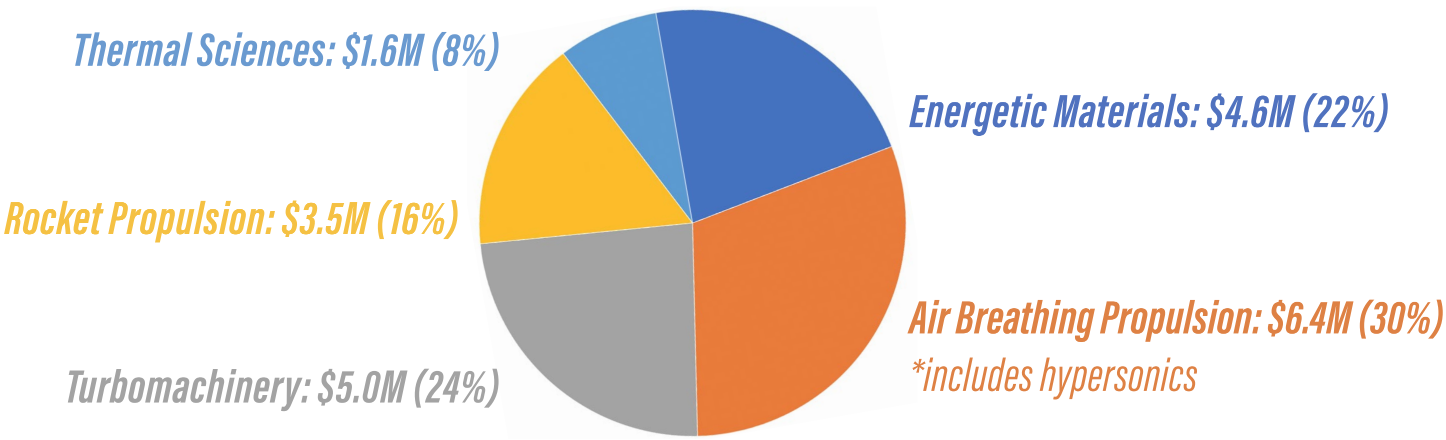
Based in Costa Mesa, California, Anduril will bring critical resources toward developing the Adranos Solid Rocket Complex production facility in Mississippi into a modern manufacturing facility, which will increase output of both standard and ALITEC solid rocket motors to thousands per year at much faster lead times than currently available.

[*Read the full story...*]

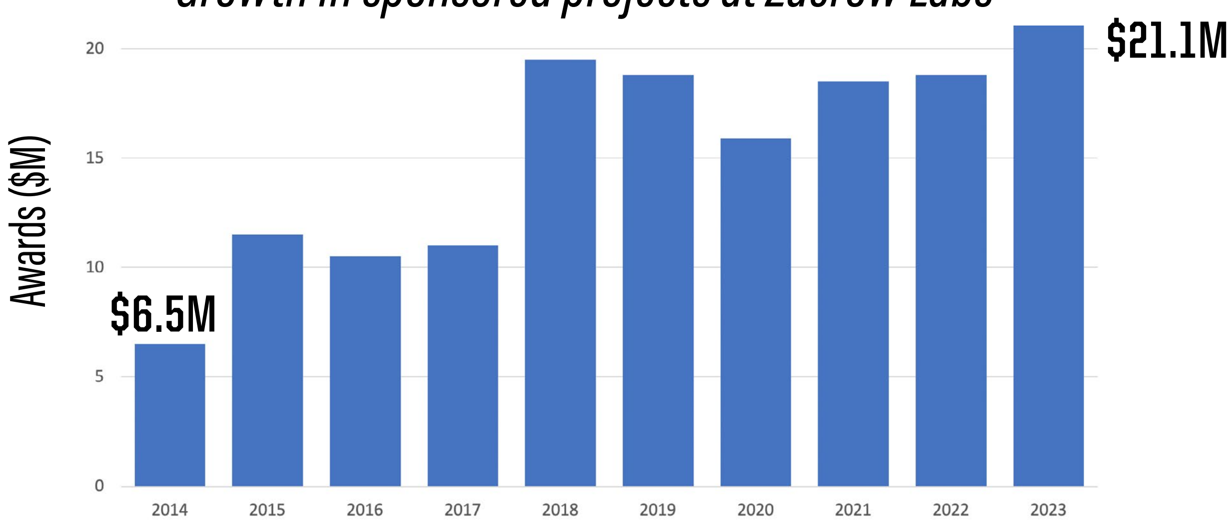
Adranos opens a manufacturing facility in Mississippi in 2022.

Zucrow by the numbers

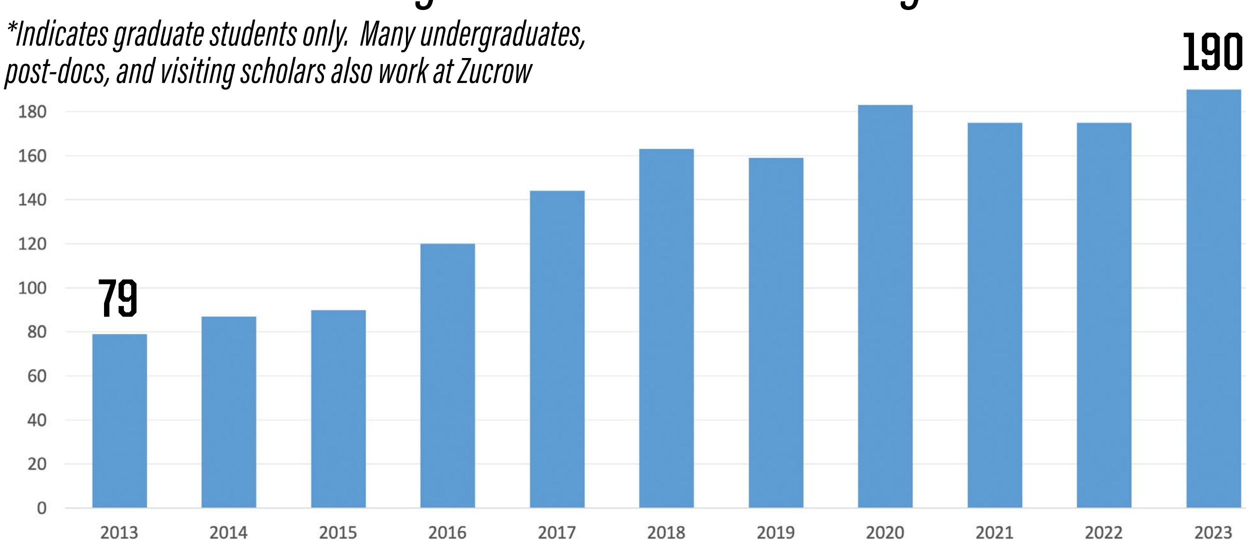
Total expenditures at Zucrow for calendar year 2023: $21.1 million



Growth in sponsored projects at Zucrow Labs



Growth in number of graduate students working at Zucrow Labs



HIGH SPEED PROPULSION LAB (ZL9) DEDICATION

AND

ZUCROW LABORATORIES 75TH ANNIVERSARY CELEBRATION

SAVE THE DATE!

Friday, October 4, 2024

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ROCKET LABORATORY

LAFAYETTE, INDIANA

EXPERIMENTAL PERFORMANCE AND HEAT TRANSFER OF A ROCKET MOTOR OPERATING ON WFNA-JP-3 AT 700 PSIA CHAMBER PRESSURE AND 500-LB. THRUST

Delbert E. Robison

This technical report from 1952 is one of hundreds of research papers originating from Purdue that contributed to furthering aerospace and national defense in the 20th century. It comes from a new book about Maurice J. Zucrow called "The Rocket Lab."

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