
ZUCROW LABS
2021
ANNUAL REPORT
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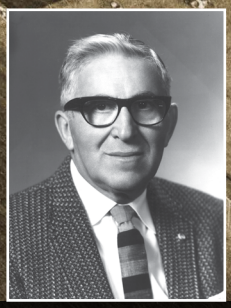
The Legend Grows



Dr. Maurice J. Zucrow *joined Purdue University in 1946 to teach jet propulsion and gas turbines. He soon established a physical facility, adjacent to Purdue Airport, to run propulsion experiments. In the decades since, the "Rocket Lab" has expanded to more than 24 acres, including research on compressors, high-pressure combustion, thermal sciences, fluid mechanics, and energetic materials. Now bearing his name, the* ***Maurice J. Zucrow Laboratories*** *have become the largest academic propulsion lab in the world.*

Front cover photo: *In Steve Son's research group, they have developed an electric match composed of a lead-free nanoscale thermite.*

Rear cover photo: *Nicole Key studies 3-stage axial compressors, visualizing flow using fluorescent tempera paint, which highlights secondary flows and boundary layer separations near the stator trailing edge.*

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PURDUE UNIVERSITY

From the Director

One of the new additions in our office is a poster of all the former directors of Zucrow Labs, going all the way back to Maurice J. Zucrow himself in 1946. I've had the pleasure of knowing many of these colleagues personally – from Joe Hoffman, who we just lost (*see below*), to my immediate predecessor Stephen Heister (*see story on page 8*), who truly set Zucrow on the upward trajectory it's on today. Like most academics, I stand on the shoulders of those who came before me, and I aspire to make equally "giant leaps" for our faculty, staff, students, and collaborators.

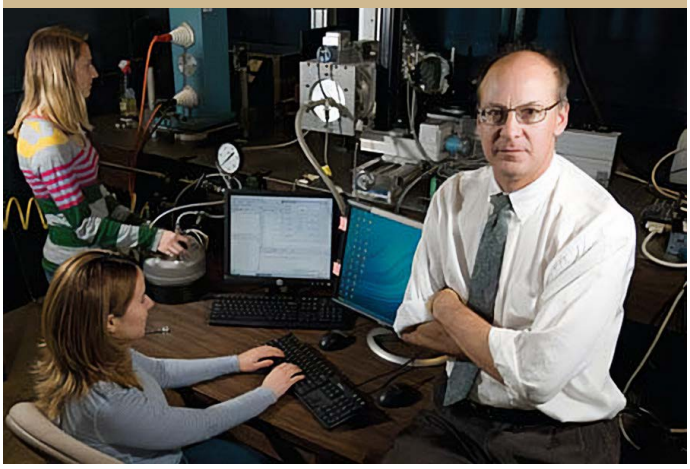
That's why I'm so excited to announce several major construction projects happening at Zucrow (*see story on page 4*). We've begun building one of the first facilities in the nation specifically devoted to hypersonics research. We're planning a new complex of high-pressure combustion test cells, ZL9, based on the incredible success of ZL8. We're also taking the opportunity to address our infrastructure: building sidewalks, parking lots, sewer lines, and a new high-pressure air plant.

COVID threw us all for a loop, but we didn't let it sway us. Because much of our research is "essential," our students and faculty never stopped doing their amazing work. As you can see in the census at the end of this report, both our student population and our funding have fully recovered, as we return to "normal" operations.

One last reminder of Purdue's place in propulsion history came during the recent renovation of our main offices in Chaffee Hall. On a backroom shelf, we found every thesis and dissertation in Zucrow history, going back to the 1940s. We had to temporarily relocate them to prepare for the newly-renovated space. In the same way, we'll never forget the past, but we will build upon it to create an even more exciting future.

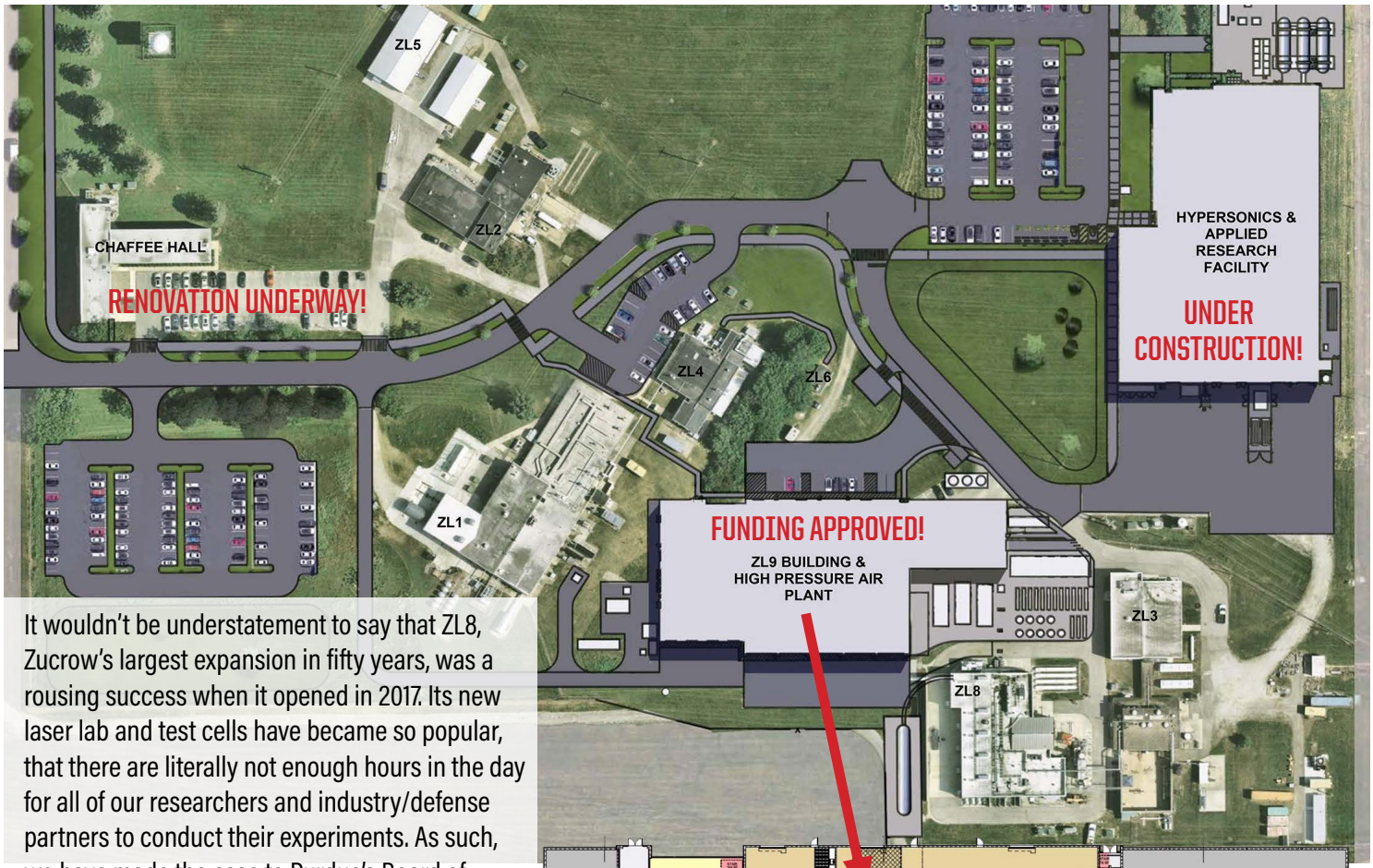
Robert Lucht
Director, Maurice J. Zucrow Laboratories

Paul Sojka has retired from Purdue, after 38 years as a professor of mechanical engineering. His research focus was on fluid mechanics; specifically, sprays and spray measurements. He said his work spanned from "dessert to defense" and "agriculture to airplanes." ***More about Paul...***



Joe Hoffman passed away February 13, 2021. He taught mechanical engineering for 38 years, specializing in computational fluid dynamics, gas dynamics, and numerical methods. He served as lab director from 1989 to 2001, overseeing its transition from the "Thermal Sciences and Propulsion Center" to "Zucrow Labs." ***More about Joe...***

New buildings under construction



It wouldn't be understatement to say that ZL8, Zucrow's largest expansion in fifty years, was a rousing success when it opened in 2017. Its new laser lab and test cells have became so popular, that there are literally not enough hours in the day for all of our researchers and industry/defense partners to conduct their experiments. As such, we have made the case to Purdue's Board of Trustees to build **ZL9**, a new facility adjacent to ZL8 that would add 5 new test cells, each with their own individual laser lab and control room. In addition, we will add a much-needed new high-pressure air plant, to replace the aging system which we have heroically kept operating for all these years. All together, it's a $70 million project, which will add the capacity for Zucrow to conduct even more of the world-class research that our partners have been asking for.

ZL9 FLOORPLAN AND RENDERING

But those aren't the only new developments to Zucrow's site plan. The 65,000-square-foot **Hypersonics and Applied Research Facility (HARF)** is currently under construction *(see story on next page)*, and we hope to begin one-of-a-kind hypersonics research there next year.

Chaffee Hall is receiving a well-deserved renovation, specifically to the 2nd floor where many of our grad students have their offices and study spaces. In addition, Zucrow will be adding many more parking spaces, upgrading its sewer system, and adding proper sidewalks between buildings for the very first time.

Hypersonics trifecta

Three big stories in 2021 illustrate how Purdue University and Zucrow Labs are becoming one of the most prestigious destinations for hypersonics research in the world.

The planned 65,000-square-foot **Hypersonics and Applied Research Facility (HARF)** will house two cutting-edge wind tunnels, enhancing Purdue's world-leading capabilities in hypersonics evaluation and testing. The $41 million facility will house the only Mach 8 quiet wind tunnel in the world, as well as a hypersonic pulse (HYPULSE) shock tunnel, which will allow flight simulations at speeds ranging from Mach 5 to as high as Mach 40. Purdue will be only the second university in the U.S. to offer HYPULSE test capabilities.

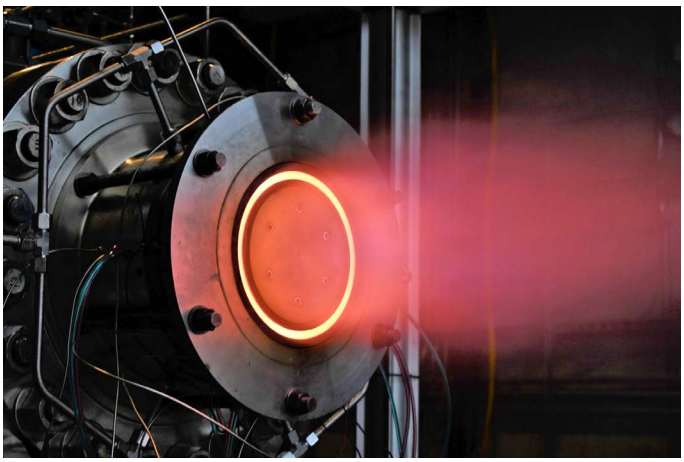
"Purdue's rich hypersonics program includes both a broad bench of more than 40 experts and unique capabilities that allow the university to play an important role in the security of our nation," said Theresa Mayer, Purdue's executive vice president for research and partnerships. "This first-of-its-kind facility will further Purdue's capacity to conduct research including tests and evaluations under real-world conditions for faculty, industry partners, federal agencies and other stakeholders."

HARF will also include the new Hypersonics Advanced Manufacturing Technology Center (HAMTC), an industry-focused center focused on developing high-temperature materials and creating new manufacturing processes to build and join these materials , which will extend hypersonic vehicles' capabilities. Primary partner GE Additive joins a list of industry partners planned to test their materials here, including, Dynetics, Lockheed Martin, Aerojet Rocketdyne, GE Edison Works, and Boeing.

In the nearby Purdue Aerospace District, a new facility will focus on more defense-oriented research. The **Hypersonic Ground Test Center (HGTC)** was announced in August 2021 during a two-day Hypersonics Summit hosted by Purdue and the National Defense Industrial Association. "At Purdue, we're committed to research at the very frontiers of science, especially when it can contribute to the national security of Americans," Purdue President Mitch Daniels said. "Becoming home to the nation's premier hypersonics facilities can make such a contribution, while providing enormous new opportunities for our researchers, aspiring entrepreneurs, and job seeking graduates."

The HGTC will be administered by a new nonprofit consortium of national defense industry partners that will manage capital and operational costs; Rolls-Royce North America is the first aerospace industry member. The HGTC facility will house two separate testing streams; partners can conduct tests in the 3.5-5.0 Mach range or the 4.5-7.5 Mach range. Multiple companies can undertake work simultaneously on site, while being ensured full protection of intellectual property and sensitive work.

Finally, HySonic Technologies LLC, a company founded by associate professor of mechanical engineering **Carlo Scalo**, has received a $140,000 grant from the Office of Naval Research's Small Business Technology Transfer program. They have joined forces with assistant professor of aeronautics and astronautics **Carson Slabaugh** to focus on modeling and experimentation of new propulsion systems specifically designed for future hypersonic vehicles.



"This is an exciting time for propulsion technologies," said Slabaugh. "We have built and tested several rotating detonation engines here at Zucrow Labs. I'm excited to work with Carlo and the US Navy on the potential uses for this engine in hypersonic vehicles."

NASA funds Zucrow initiatives

Purdue University has received funding for two new projects as part of the University Leadership Initiative, a NASA program that gives the academic community an opportunity to support the agency's aeronautical research goals and provide students with experience solving real-world technical challenges.

Timothee Pourpoint is the principal investigator for a team selected to receive a three-year, $3.2-million grant from the highly prestigious and competitive program. Purdue's team will refine techniques and hardware associated with a particular set of optical and laser sensors that can be used in examining the surfaces and flow of a hypersonic vehicle in a way that can help that aircraft maintain control in flight. Hypersonic flight is flight at speeds of Mach 5 and beyond — more than 3,500 mph at sea level. The Purdue team includes Christopher Goldenstein, Robert Lucht and Terrence Meyer, as well as members from the University of Virginia, Hampton University, Sydor Technologies, and Innoveering, LLC. "Our ULI team has a highly relevant and rich track record of teamwork with NASA, both in the aeronautics arena and the space arena," Pourpoint said.

In parallel with the optical and laser-based sensors development, the team will use and continue to build its capabilities to test the sensor suite and demonstrate control in realistic flow fields. The sensors will be designed and evaluated over a range of experimental conditions and will be integrated into closed-loop feedback control systems for internal and external hypersonic flow paths.

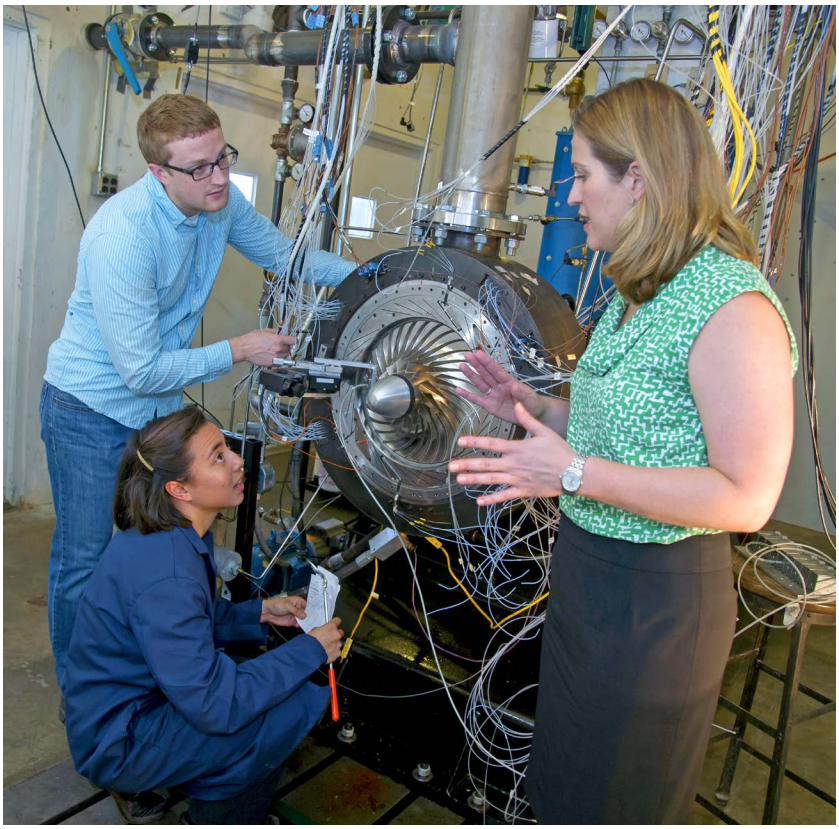
Terrence Meyer and Guillermo Paniagua are part of a $10 million five-year project selected by NASA's University Leadership Initiative, to explore using liquid ammonia as a potential carbon-free jet fuel.

For this project, Purdue is teaming up with the University of Central Florida, who are proposing using liquid ammonia (NH3) as a fuel for aircraft. Upon combustion, liquid ammonia produces harmless carbon-free emissions, while still providing enough power to keep the aircraft aloft. It also provides cooling for the engines, while not requiring the special handling of cryogenic fuels.

Both Meyer and Paniagua work on propulsion and aerothermal flows at Zucrow Labs, the largest academic propulsion lab in the world (Paniagua is currently on a Humboldt Fellowship, conducting research in Germany). Meyer will be responsible for experimental validation of NH3 combustion at engine representative conditions, while Paniagua will be responsible for the development of supercritical CO2 turbomachinery and heat exchangers, and overall engine modeling.

Other partners include Georgia Tech, GE, Boeing, ANSYS, Southwest Research Institute, and the Greater Orlando Aviation Authority.

Stall warning for gas turbines



Gas turbine engines often are considered the "heart" of airplanes and ships. Now, Purdue researchers have developed an electrocardiogram-type technology for gas turbine engines to monitor rhythms and warn of potential compressor stall.

"An effective stall warning and avoidance technique is of great value to gas turbine engines used in aviation and land-based applications," said **Nicole Key**, professor of mechanical engineering. "Stall is a type of flow instability in compressors that sets the low-flow limit for gas turbine engine operation. When the compressor stalls, it can cause severe damage to gas turbine engines. Like a heart attack in humans, compressor stall can happen without apparent precursors."

The Purdue compressor stall warning technology uses sensors to record the data during operation and then uses a novel signal processing procedure to determine the engine's status. "It is hard to identify the small disturbances associated with compressor stall from the ones associated with turbulent flow," said Fangyuan Lou, a researcher in Key's lab. "When evident precursors occur, the gas turbine engine runs into stall within a few milliseconds. That is not enough warning time for action." The team used a nonlinear feature extraction algorithm to extract the early and small stall precursors, providing enough warning time for action to correct the situation.

Hyperspectral imaging

En'Urga Inc., which develops and commercializes innovative diagnostic equipment for use in the manufacturing, research and consumer arenas, has received a six-month, SBIR Phase I grant from NASA. The $125,000 grant will be used to design and evaluate a hyperspectral imager, a diagnostic tool to be used at ground test facilities at NASA's John C. Stennis Space Center in Hancock County, Mississippi. The primary commercial application of the hyperspectral imager will be to obtain validation data from the plumes of all types of propulsion devices. Phase I experiments will be carried out at Zucrow Labs under the guidance of **Jay P. Gore**, the Reilly University Chair Professor of Mechanical Engineering at Purdue. "We are probably the best-recognized group in infrared sensing and diagnostics, a part of the hyper spectrum that is of key interest to NASA," Gore said. "Further, En'Urga and Purdue have partnered over two decades in educating our students while serving sponsors like NASA."

Professor Gore's team are also using **machine learning** to solve issues related to thermodynamics, combustion, and CO2 recycling. They have published research about early detection of lean blowout, and about using big data to model thermodynamic properties of a steam generator under cycling operation.

Faculty profile: Stephen Heister

The Thermal Sciences and Propulsion Center wasn't dying, but it desperately needed a revitalization. The propulsion research that the lab's founder, Maurice J. Zucrow, was known for largely had fizzled by the late 1980s. Only one professor in the School of Aeronautics and Astronautics was teaching propulsion, and he was set to retire. All of Purdue's propulsion classes at the time were in combination with the School of Mechanical Engineering, and ME professors ruled the rocket lab. Alten "Skip" Grandt, Jr., the head of AAE at the time, was searching for a professor to spur the department's propulsion major.

He found the answer in 1990 in **Stephen Heister**, fresh out of the aerospace industry, whose background and qualifications ideally matched what Osborne wanted in a successor and the kind of innovative and progressive mind Grandt needed to propel the research area. Heister embarked on a research program that was based on computational modeling of injectors, but student interest soon started tugging him into the experimental realm. "Certainly there were faculty with strong research programs, but for Zucrow Labs to be recognized nationally as a center for propulsion was all facilitated by Steve," said Scott Meyer, who has been Zucrow Lab's managing director since 2009.

Heister would never say that, of course. His colleagues and friends call him humble almost to a fault, never taking credit even when it's warranted. "We can all claim that our research is what defines us. But it's not," Heister said. "It's the people that define us and the accomplishments of those people and what small impact we might have had on those people during their small time that they spend here with us. That's the thing that certainly gives me the most pride."

He also enjoys teaching. Whether it be in a classroom full of undergrads, or in the day to day with his graduate students. He's a five-time winner of the School's Elmer F. Bruhn Award for teaching, via a vote of the undergraduate student body in AAE. Those are badges of honor. He has developed new courses and opportunities, whether it be receiving a grant to build a rocket engine test stand and to procure hardware to launch model rockets, or adding a hypersonic propulsion course in 2002. Heister was able to leverage relationships that were being fostered with Rolls-Royce to create new opportunities, and, ultimately crafted a path toward developing the nation's first University Technology Center. "There was a bit of a void," said Heister. "We had a course in gas turbines, kind of conventional gas turbines, but we didn't have one that talked about ramjets and scramjets and turbo ramjets and things like the SR-71, we hadn't really touched on. So the course grew out of those interests."

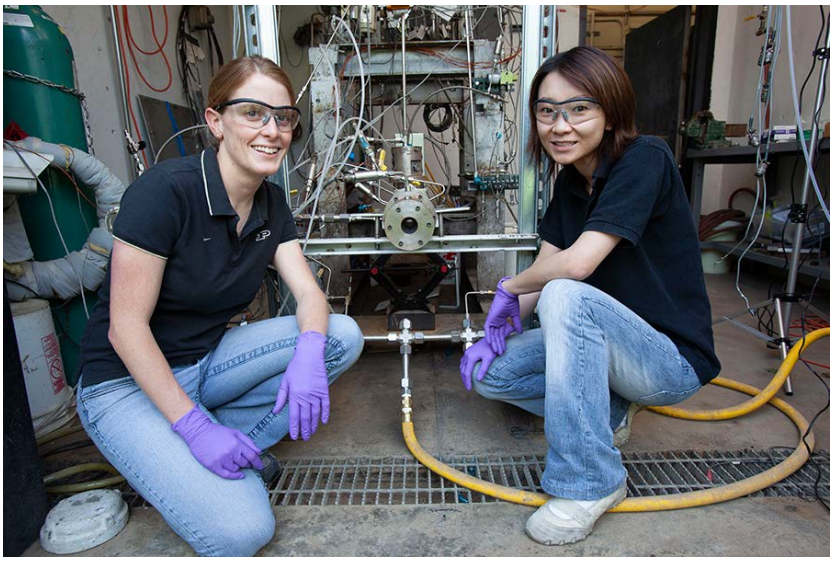
Since 2014, a major focus of his research has been related to rotating detonation engines (RDEs). The RDE is a device that exploits continuous detonative combustion in a thin annular channel and has the potential to advance aerospace propulsion performance significantly. "That's the neat thing about being a professor, you're able to steer things and work on things that truly interest you," Heister said. "Especially in these new areas, RDEs, very unique dynamic injection environment. There's no reason why the injectors should look the same as they do for a conventional engine, so that's captivating to me. 'OK, it's a new clean sheet of paper. Let's think about new ways to solve this problem.' "

In 2011, Heister was named director of Maurice J. Zucrow Labs. "When he became lab director, we'd done about as much as we could with our existing infrastructure," Meyer said. "With a vision for our first new building since 1965, Steve was like, 'We need to do something. Everyone is out of space. We need more capability.' He wasn't saying, 'We should do this.' He was saying, 'What should we do?' That engaged everyone to bring in ideas and requirements, and in 2012 we developed the design of what would become ZL8."

Heister can reel off stories endlessly. In his 31 years as a professor in AAE, he has impacted hundreds of undergrads and has been thesis advisor for more than 100 graduate students, both Ph.D. and master's. "I hope they appreciate that I provided some guidance and education. Inspired them. That's all a teacher or a professor could want," Heister said.

Click here to read the full-length profile story of Stephen Heister online

Space leaders bonded at Zucrow



Could have been any Friday night in 2008. **Yen Yu** and fiancé Yu Matsutomi squeezed around a table with fellow School of Aeronautics and Astronautics graduate student **Loral O'Hara** making dumplings, with Loral dialed in, getting the folds just-so, filling the pockets with engineer-type efficiency. They talked about their hometowns, their families, their goals and their failures. They laughed 'til their faces hurt and their sides prickled, Loral throwing in what Yen calls "composed sarcasm without a flinch," and playful Yen mixing in self-deprecating humor. Then they said good night, with an expectation of seeing each other again soon.

When Yen and Loral finished their studies at Zucrow, they separated and pursued passions on opposite sides of the country. Yen went to Washington State to join Blue Origin; Loral to Massachusetts and Woods Hole Oceanographic Institute. A decade later, Loral had completed astronaut training at NASA, and Yen had risen to become Blue Origin's senior director of the Engines Design Office. In 2021, both women were selected as Outstanding Aerospace Engineers in the same class.

None of it surprised Bill Anderson, the graduate advisor to both. "It's an even more interesting story than if they were to come together and follow the same path. They came together and took very different and very remarkable paths," said Anderson.

Yen and Loral became the first all-female rocket propulsion team at Zucrow Labs, Anderson said, and, at the time, they formed one of the few all-female rocket propulsion teams in the country. They conducted subscale rocket engine experiments for NASA's Marshall Space Flight Center. Yen built a model rocket, and for each test, the pair measured temperature and pressure under different configurations, injector sizes, combustor sizes, operating chamber pressure and other propellant combinations. The goal: To establish predictive capability and gain fundamental understanding toward rocket engine combustion instability that could be applied to next-generation rocket engines. They also co-authored papers based on their work.

"She's just so matter of fact about it. You would never know talking to her that she's a brilliant engineer," Loral said of Yen's humility. "I kind of ping-ponged around in my own interests so much, I very much admire people who can dive into a subject and study it with such intent."

Yen was also impressed with Loral's adventurous nature. "She was telling me she signed up to be one of the few researchers out in Antarctica. She was going through selections for that (while at Purdue) and describing to me what that life would be or what the research would be. I seriously thought she was joking. She went after it anyway."

Having witnessed Yen's dogged determination and relentless pursuit of excellence, Loral knew Yen would impress with technical prowess and leadership ability. "Even at Purdue as a Ph.D. student, she was just a good role model and a leader in our lab. Overall, the kind of person you'd want to put in charge of a lot of people and run a program," Loral said. "She's just really impressive."

"When it was announced, it wasn't a surprise to me," Yen said of Loral's selection to NASA's 2017 astronaut class. "I've heard so many people say, 'I want to be an astronaut.' But Loral is somebody I've seen that actually applied and did all the skill-building to get there. I'm so thrilled for her and so proud."

Click here to read the full-length profile story of Yen and Loral online

The glue that holds Zucrow together

As Laboratory Coordinator at the world's largest academic propulsion lab, **Michelle Moody** has a big job. But her efforts have made Zucrow Labs a better place for everyone. Purdue's College of Engineering recently recognized Michelle with their Support and Customer Service staff award.

At Zucrow Labs, hundreds of students and faculty conduct research in rockets, turbines, energetic materials, and other propulsion technologies. It's a 24-acre complex with nearly a dozen buildings, shared by the schools of Mechanical Engineering and Aeronautics and Astronautics. As such, there are a lot of moving parts to coordinate - and working with potentially dangerous or hazardous materials and equipment brings its own layer of safety concerns and protocols.

Michelle brought her industry background to Zucrow five years ago in a part-time capacity, and last year was hired full-time as Laboratory Coordinator. She is in charge of much of the shared equipment and infrastructure, and oversees many of the processes and protocols students work with every day. She makes sure that tools get properly used and returned. She trains people to use forklifts, cranes, and other machinery, and is OSHA certified to oversee Zucrow's safety needs.

"Michelle is great at working with students, other staff members, and the faculty," said Robert Lucht, Director of Zucrow Labs. "She brings a level of professionalism to her work that actually serves as a great example for our graduate students."

There are multiple examples of her streamlining processes and spaces at Zucrow Labs. If there's a room being unused, she'll set up tables and chairs for students to study. If there's an unclaimed pile of scrap metal, she'll find a way to recycle it, to save the students money on material costs. She makes sure spaces are clean, organized, and stocked with everything that researchers need.

"Michelle has great organization skills, a 'can-do' attitude, and a strong work ethic," said Carson Slabaugh, Associate Professor of Aeronautics and Astronautics. "She has taken an active role in important, but often unglamorous tasks that have made a tremendous difference to others."

Michelle worked to add artwork onto the plain gray walls of ZL1, just one of numerous initiatives she has undertaken to make Zucrow a nicer place to work.

But she doesn't stop there. Many Zucrow buildings date back to the 1940s, and their battleship-gray decor could potentially be a depressing environment to spend hours in. Michelle took her own initiative to decorate the building with new posters, artwork, and signage. When the Grounds Department was short-staffed, she brought in plants from her own garden, and coordinated student volunteers to help beautify the grounds, to make Zucrow a more pleasant place to visit.

"She is not bound by her job description – if Michelle sees a need, she fills it!" said Michelle Kidd, Zucrow's Operations Administrator. "Those qualities mean she is great at her job, but it's her dedication to the success of Zucrow that sets her apart from the rest."

Zucrow alumni at Virgin Orbit

Virgin Orbit's air-dropped LauncherOne rocket reached space during the company's second launch demonstration on January 17, 2021. It was a culmination of nearly nine years of intense, relentless, thorough work – much of it undertaken by Boilermakers. Nearly a dozen Purdue alumni work at Virgin Orbit, many of them Zucrow veterans.

Some of Virgin Orbit's Purdue alumni include (left to right) Matt Wierman, Steven Hunt, Nick Zarbo, Giovanny Guanche Silva, Jamie Eckstein, Eric Briggs, Dayle Alexander, and Tony Gingiss

"Within my first couple of weeks, I was given responsibility of a really important combustion device on the engine," said **Dayle Alexander** (BSAAE '16, MSAAE '18). "That was really cool for me, that I was given so much responsibility off the bat. It taught me a lot because that part, it's actually a 3D-printed part, so there was a bunch of materials research that had to go into it and development with the printer and everything like that. So I've had to learn a lot of stuff. This is the first thing I've ever touched that has made it to space! When you started to see on the livestream that the sky was black instead of blue, that was just really, really cool. Then you heard it on the comms system that we were in space, that part was unforgettable."

Alexander worked at Zucrow, advised by AAE Professor Stephen Heister. "There are some things you can't get in a classroom," Alexander said. "Just the fact that you know what a turbopump looks like and know how to calibrate a pressure transducer. Or you know what to look for in the plume of the engine or the data you're looking at. Seeing that not for the first time when you start your first job is just so important."

Steven Hunt (PhD AAE '16) works as a senior propulsion engineer. He also sat on console during the launch and monitored the second stage propulsion systems in real time. That included monitoring the liquid-oxygen systems, the propulsion systems during the "captive carry" when the rocket is aboard CosmicGirl, the 747 carrier plane, and the propulsion systems after LauncherOne was dropped and the first stage was lit. "For Virgin Orbit, this was important because we transitioned from a field of companies with rocket concepts, which is honestly a crowded field, to a field of companies that have a working rocket and have made it to orbit. That's a very small field," Hunt said.

"Any school can have good theoretical education if they have a good faculty, but to have the hands-on experimental testing opportunity, they need to invest the infrastructure. I would dare anybody to find a better rocket testing facility or aerospace experimental facility than Zucrow labs at Purdue," said Hunt, whose advisor was Heister. "That's not normal. It's a unique place. I was really fortunate to have been able to go there. "I'm understating that it was huge for my career."

Matthew Wierman (MSAAE '10, PhD AAE '14) started at Virgin Orbit in 2015, when it still was conducting activities as a division of Virgin Galactic. As a senior propulsion design and analysis engineer, Wierman works on the NewtonThree engine, going to the Mojave test site to direct engine test operations.

He also ran a test cell at Zucrow, working under advisor Bill Anderson. "Having that experience at Zucrow of being the person who is not only analyzing the data but also running the test and getting yourself up under the test articles to fix them, it makes you appreciate not only the high-level design work but also the boots on the ground, of turning the wrenches," he said. "One of my main responsibilities as a responsible engineer is just writing work instructions and saying, 'OK, we need to replace this transducer, and that means you need this part number, it needs to be checked out to this standard ...' and understanding the technicians, they have to take my instructions and do them. I need to be able to communicate the exact way I want them to do it. The experience at Zucrow was helpful because I had to do that myself."

Click here to read the full-length profile story of Virgin Orbit alumni online

PSP had a blast in 2021

Purdue Space Program (PSP) is the Purdue chapter of Students for the Exploration and Development of Space (SEDS). Nearly 400 students participate in six different teams, building rockets and satellites.

The biggest highlight of the year was the successful launch of Boomie Zoomie Beta (BZB), the second version of Purdue's LOX/Methane rocket – one of the first undergraduate-developed liquid bipropellant rocket engines in the world. In fall 2021, the team conducted two full-stack hotfire tests at Zucrow, reaching a peak thrust of 975 lb-ft and an average tank pressure of 490 psi. Then in 2022, they took their equipment to the Mojave desert for the first ever successful launch. Due to valve issues, they only hit 65% of their target thrust and 70% of their target burn time. Undeterred, they successfully recovered the rocket, recycled it, and had a second successful launch the next day – one of the few times any liquid methane rocket of any size has ever been reflown!

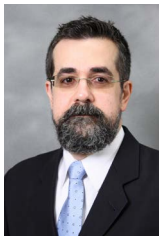
Learn more at PurdueSEDS.space

Faculty honors

Stephen Heister was selected as the 2021 American Institute of Aeronautics and Astronautics (AIAA) Wyld Propulsion Award winner. The award is presented for outstanding achievement in the development or application of rocket propulsion systems.

Nicole Key has been appointed to a two-year term of the NASA Advisory Council, as part of the Aeronautics Committee, which advises the NASA Administrator on commercial air transportation, advanced air vehicles, aviation safety, and air transportation system technology. She was also recognized by Purdue in 2021 as a Distinguished Woman Scholar.

Terrence Meyer has been elected as a Fellow to Optica (formerly the Optical Society of America).



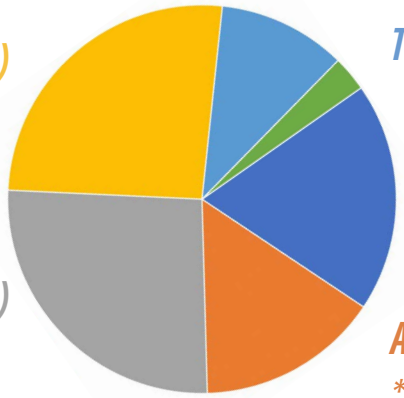
Guillermo Paniagua received the prestigious Humboldt Research Award, moving to Germany for six months to research at Technical University of Darmstadt. He also was elected as a Fellow of the American Institute of Aeronautics and Astronautics (AIAA), and chosen by Purdue's Provost as a University Faculty Scholar.

A paper by **Timothée Pourpoint** and his team was selected for the 2021 AIAA Liquid Propulsion Best Paper Award from the Propulsion and Energy Forum. Pourpoint's team also received a group achievement award from the NASA Engineering & Safety Center, for his combustion modeling of pressure spikes in hypergolic engines.

Steve Son was recognized by Purdue's College of Engineering with the Excellence Award for Research.

Zucrow by the numbers

Total expenditures at Zucrow for calendar year 2021: **$18.5 million**



Energetic Materials: $4.8M (26%)

Thermal Sciences: $2.0M (11%)

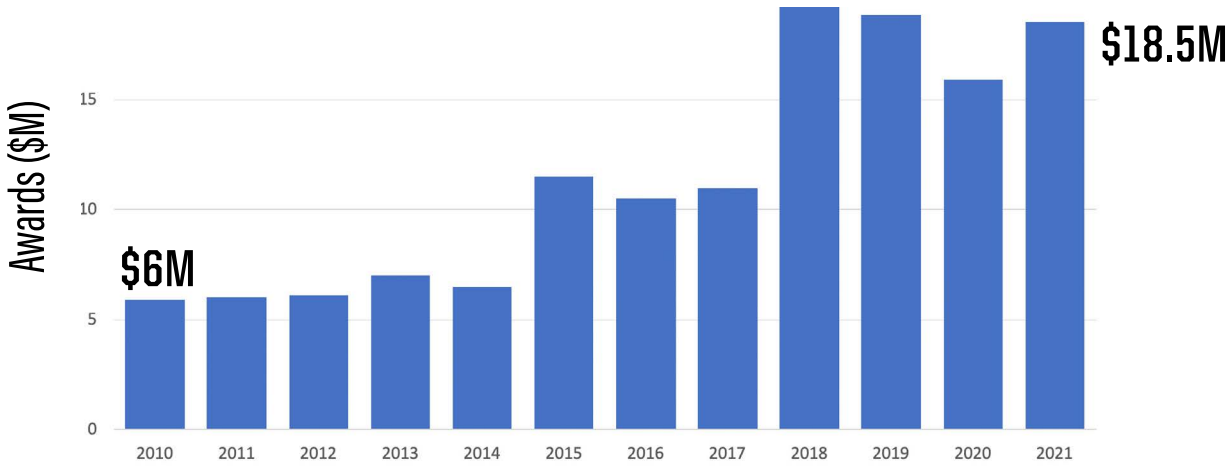
Thermal Management: $0.5M (3%)

Rocket Propulsion: $3.5M (19%)

Turbomachinery: $4.8M (26%)

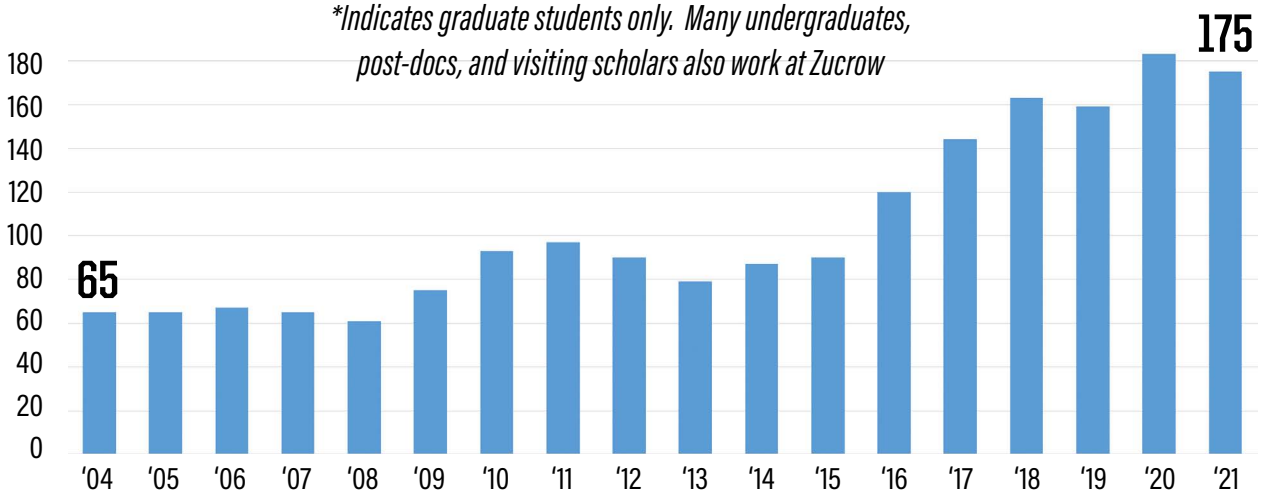
Air Breathing Propulsion: $2.8M (15%)
*includes hypersonics

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



ZUCROW LABS

2021

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