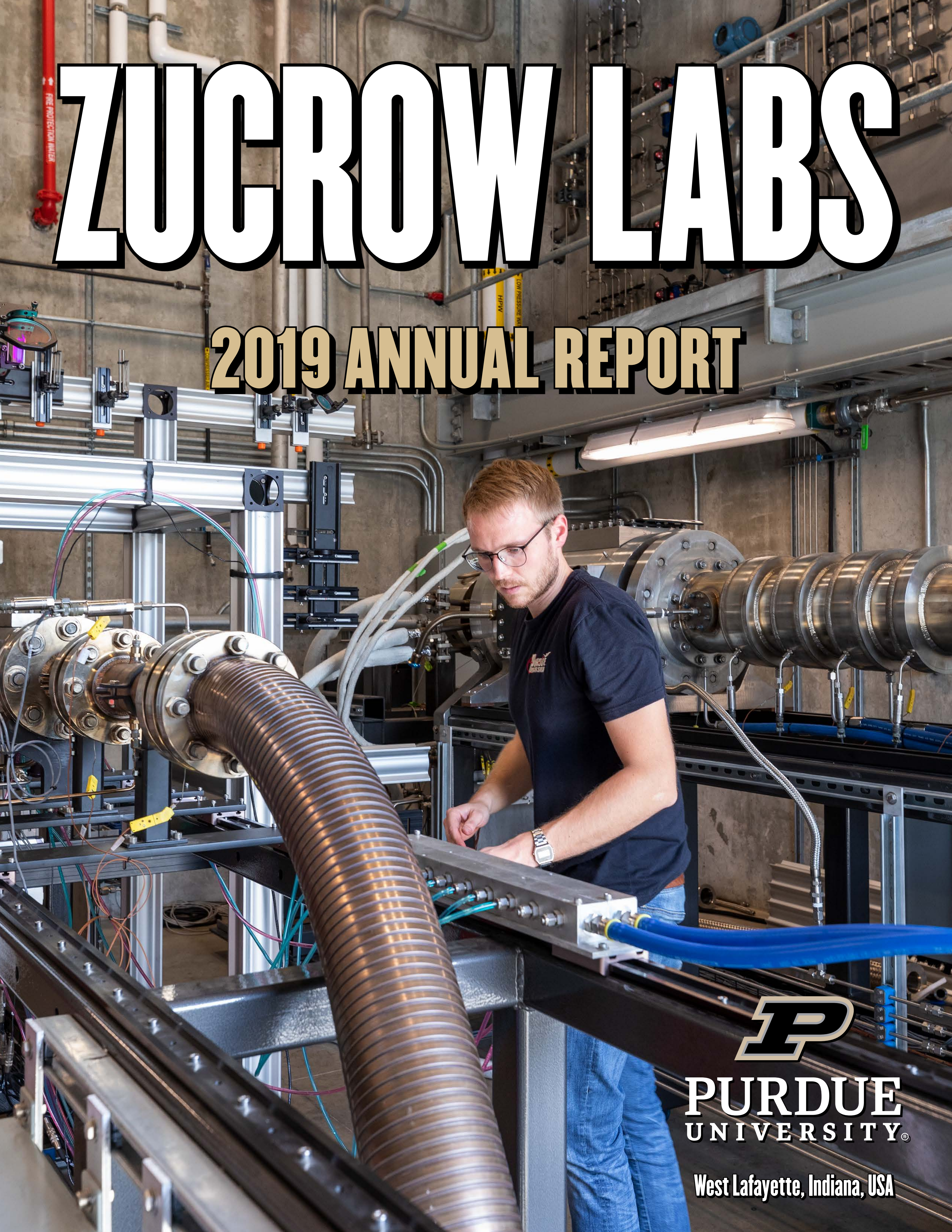
ZUCROW LABS

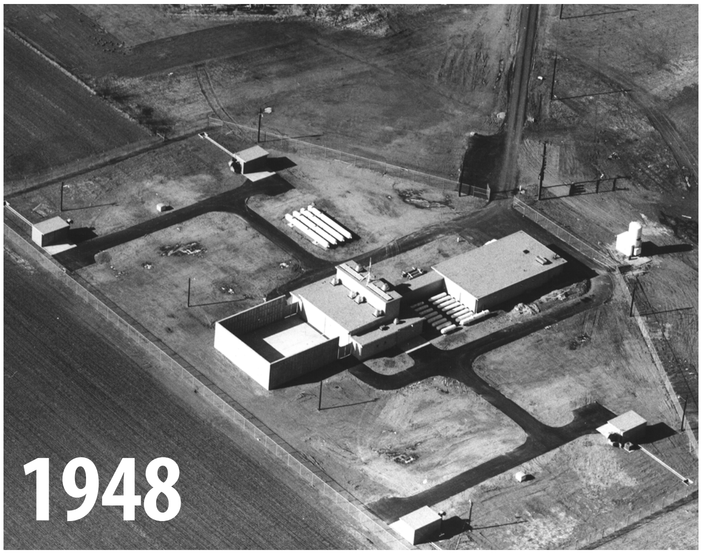
2019 ANNUAL REPORT



PURDUE
UNIVERSITY®

West Lafayette, Indiana, USA

Zucrow Labs
2019 Annual Report



The first "rocket lab" at Purdue didn't even have electricity. They used a Navy surplus diesel generator for power, and a hand-cranked WWII field telephone to communicate with the closest office building a mile away. Today, the Zucrow Labs complex hosts more than 160 graduate students, dozens of faculty, and millions of dollars of research.

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 24 acres, including research on compressors, high-pressure combustion, thermal sciences, fluid mechanics, propellants and fuels, instrumentation and data collection. Now bearing his name, the **Maurice J. Zucrow Laboratories** have become the largest academic propulsion lab in the world.

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Front cover photo: Ph.D. candidate Timo Buschhagen researches combustion dynamics in turbine engines, under assistant professor Carson Slabaugh. In their test cell at the ZL8 High Pressure Combustion Lab, he studies flow-flame-acoustic interactions in highly turbulent jets.

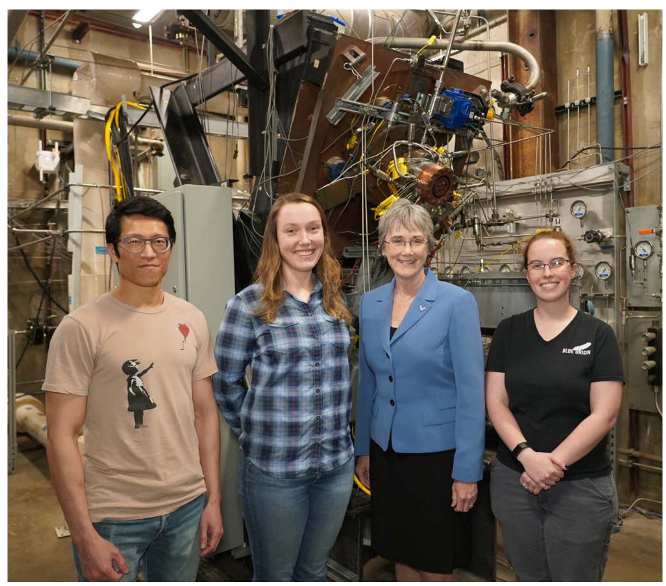
From the Director

Dear colleagues, alumni, friends, and supporters of Zucrow Laboratories,

What an exciting year it's been at the largest academic propulsion lab in the world. It seems like only yesterday we were driving under a one-lane railroad underpass (holding our breath to see if anyone was coming the other way!) and turning down a dirt road to get our laboratory. The dirt road was paved years ago, and now the railroad underpass is undergoing a major upgrade so that trucks and buses can actually get through.

With the advent of Purdue's Discovery Park District Aerospace *(see separate article below)*, we'll be welcoming many new friends and neighbors to our little corner of the cornfields. And they'll all need roads that an 18-wheeler can easily navigate. So our main entrance off Newman Road has been shut down this year, while the City of West Lafayette and the State of Indiana undertake a $12.5 million infrastructure overhaul. Taking a temporary detour through Purdue Airport has been an adjustment for all of us, but the end product means that Zucrow will be at the center of a bustling aerospace district, which already features Rolls-Royce and Saab, and will continue to expand throughout the years.

As for our own labs, we've never been busier. As you'll read in this annual report, our faculty from the schools of Aeronautics & Astronautics and Mechanical Engineering are blazing new trails (so to speak) in combustion, jet propulsion, rocketry, turbomachinery, and energetic materials. The number of students and faculty that conduct research at Zucrow is at an all-time high, as is the number of sponsored projects from industry, defense, government, and space.



As such, in the past year we've entertained some pretty important guests here on our campus. The Secretary of the Air Force, Dr. Heather Wilson *(right)*, toured many of our Air Force-sponsored projects (Wilson has since become the President of the University of Texas at El Paso). Many other defense and industry leaders joined us for our first ever Purdue Energetic Materials Summit, held in May 2019. And in October 2019, many of our Purdue astronaut alumni returned to campus for a reunion and celebration of Purdue's 150th anniversary. It was so great to see many of them visit the same test cells where they worked as students, now having put their research into practice in this golden age of space exploration.

On a sadder note, we said goodbye this year to Patrick Lawless, former associate professor at Zucrow Labs, who passed away in California. Patrick got his Ph.D. in mechanical engineering from Purdue in 1993, studying under Dr. Sanford Fleeter. He then became an associate professor, conducting research in turbomachinery aerodynamics, unsteady aerodynamics, and transient performance. He served as Ph.D. advisor to current professor Nicole Key. He also taught courses in fluid mechanics and gas turbine propulsion. He left Purdue in 2006 to become VP of Engineering at Xcelaero Corporation, a company in California making industrial fans.

Thank you so much for being part of the Zucrow family, and we can't wait to share with you all the breakthroughs that are coming in the 2020s!

Robert Lucht
Director, Maurice J. Zucrow Laboratories

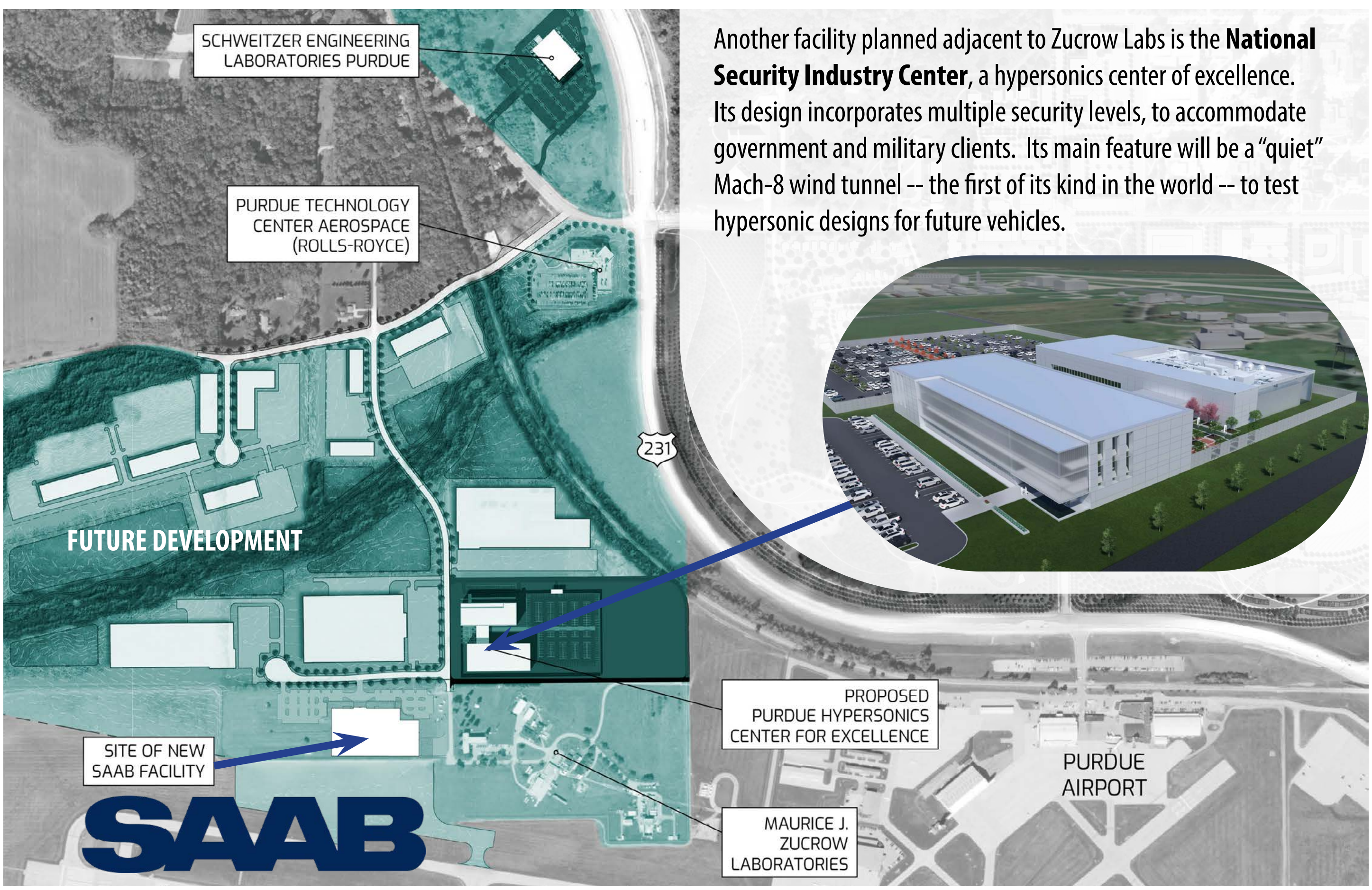
Saab factory is coming to Purdue

Indiana Governor Eric Holcomb speaks at the groundbreaking of Saab's new manufacturing facility in West Lafayette on May 8, 2019.

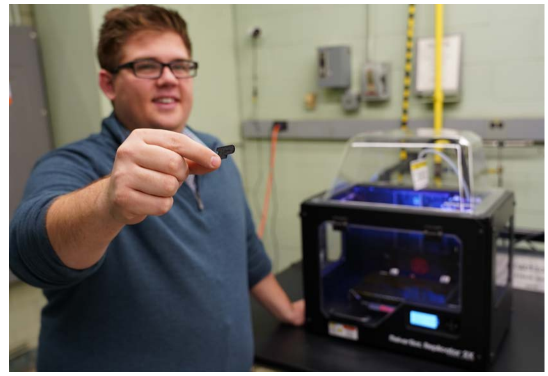
For the first time in 70 years, Zucrow Labs is welcoming new neighbors. **Saab** has announced that it is investing $37 million to build a manufacturing facility adjacent to Zucrow Labs. The Stockholm-based company teamed up with Boeing to create the T-7 Red Hawk supersonic jet, which was chosen by the US Air Force to replace the T-38 as the next generation of pilot training aircraft. Major aero structures for the T-7 will be built in the new West Lafayette facility, employing more than 300 people. Construction on the facility is currently underway.

This expansion is part of Purdue's Discovery Park District Aerospace: 176 acres on the west side of Purdue's campus, master-planned to attract aerospace-related industries and facilities. **Rolls-Royce** opened the first Aerospace building in 2017, and an electrical engineering research facility called the **Schweitzer Engineering Laboratory** opened in 2020. (The anchor of the district, Purdue Airport, opened in 1930 as the first university-owned airport in the United States; Zucrow Labs was established in 1948.) Learn more about Saab and the Discovery Park District...

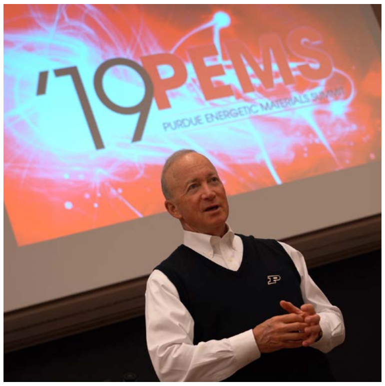
Another facility planned adjacent to Zucrow Labs is the **National Security Industry Center**, a hypersonics center of excellence. Its design incorporates multiple security levels, to accommodate government and military clients. Its main feature will be a "quiet" Mach-8 wind tunnel -- the first of its kind in the world -- to test hypersonic designs for future vehicles.



Energetics have an explosive year



The **Purdue Energetics Research Center** (PERC) is a new organization that consolidates the expertise of two dozen Purdue faculty who specialize in energetic materials (explosives, propellants and pyrotechnics). In addition to collaborating on research at Zucrow Labs and elsewhere on campus, PERC has successfully launched several companies like Next Offset Solutions *(right)*, which has devised a method for safely 3D printing energetic materials with fine geometric features.

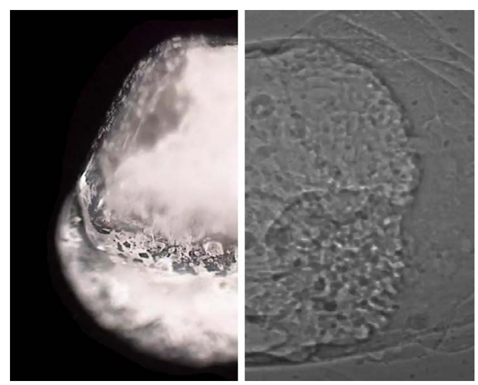


In May 2019, PERC also hosted the first ever Energetic Materials Summit on Purdue's campus, bringing together titans of industry, academia, government, and defense *(Purdue president Mitch Daniels, left, spoke at the summit)*.

Learn more about PERC...

Seeing inside explosions with high-speed X-rays

Zucrow researchers have studied energetic materials for years. Now, for the first time ever, they have used **high speed x-rays to look inside energetic materials during an actual explosion**, to determine exactly what causes them to react. Prof. Wayne Chen is the principal investigator of a 5-year multidisciplinary project sponsored by the Air Force Office of Scientific Research, determining exactly what causes certain explosives to react, and then observing the reaction itself in unprecedented ways.



So how do you test potent explosives without blowing up your lab? Chen's solution is to start at the mesoscale, working with a single grain of energetic material, suspended in a plastic binder to prevent it coming in contact with other crystals (creating a polymer-bonded explosive, or PBX). Chen's team then subjects the crystals to various conditions, including heat, vibration, and low-speed impact. They know that it only takes a small "hotspot" to trigger a reaction, so what has the potential to cause these hotspots? "My area of expertise is impact damage of materials," said Chen. "So we expose the samples to impact loading -- as if they had been dropped by someone handling them -- and observe exactly where the cracks form in the energetic materials."

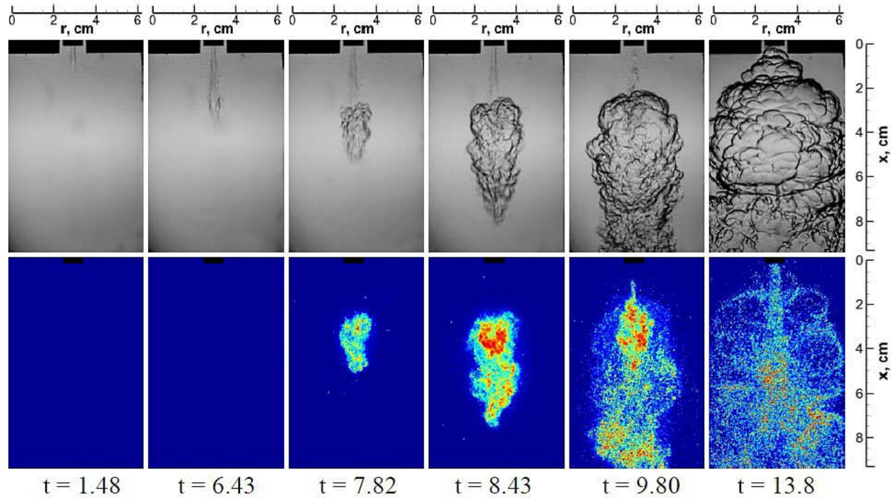
This creates two more big challenges. How do you observe a reaction that occurs in mere nanoseconds; and how do you look inside the particle to observe how the damage occurs? To solve these problems, Chen's team utilized a unique technology: high speed X-ray cameras. By using the Advanced Photon Source synchrotron at Argonne National Laboratory in Illinois, the team have recorded groundbreaking high speed X-ray videos at five million frames per second, showing exactly what happens to an energetic crystal as it explodes. Chen described what they observed when exposing a sample to ultrasonic vibration: "The crystal changed its shape first, so we knew something was about to happen. Then it changed its phase, and became a pool of molten crystal, sloshing around. Then, it quickly became a gas, which is what happens when something explodes. But we were able to experimentally observe this process for the very first time."

"That's the best joy as a scientist," said Chen. "We have seen something totally new. People have hypothesized about this for years, but no one has actually seen it until now! We've chased this for years, and finally we've recorded it." The team includes professors Steve Son, who creates the energetic material samples; Jeff Rhoads, whose team focuses on vibration; Terry Meyer, who measures the temperature response of the samples; Marisol Koslowski, who uses computer models to measure the forces exerted on the particles; and Marcial Gonzalez, who uses particulate science to extrapolate the results to a larger scale.

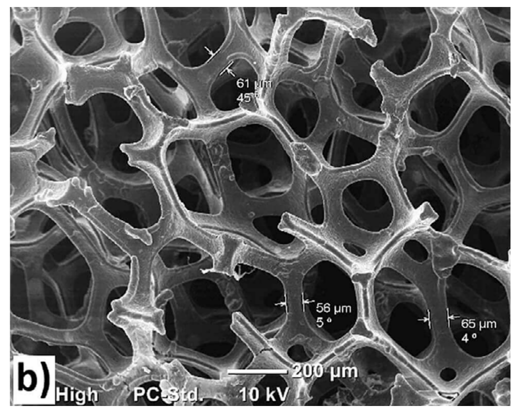
Watch the video...

Advances in jet ignition and graphene foam

Associate professor Li Qiao is developing **pre-chamber ignition technology, which may eventually replace sparkplugs** on traditional automobile engines. The pre-chamber is filled with a mixture of fuel and air, ignites, and tiny holes in the bottom of the chamber release the hot combustion products in the form of powerful jets, which penetrate into the main chamber and cause ignition. Compared with traditional spark ignition, this method provides a large surface for multiple-site ignition and fast flame propagation and enhances the overall combustion efficiency.



Jet engines have used pre-chambers for years, but the technology is new to gasoline engines. "The auto industry is feeling the pressure to optimize these engines because of the competition from electric vehicles," Qiao said. "Several automotive engine companies have started exploring pre-chamber technology for passenger cars."



Qiao is also working on a separate project involving graphene foam. This nanomaterial is now being used to help stabilize solid propellants. Because of its porous structure, graphene foam propellants have demonstrated improved burn rate, thermal stability, and reusability.

Read more about graphene foam...

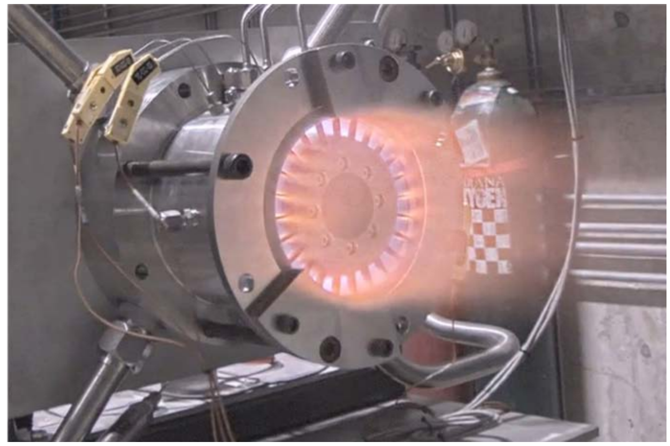
"Listening" to turbine blades stops failures

Zucrow researchers have developed a monitoring system to detect one of the most common causes of premature blade failure in gas turbine engines – rotor forced response vibration. These vibrations can be so intense at times that they affect the ability of the engine to function correctly. "Our technology is a blade vibration monitoring system using multiple unsteady pressure sensors to listen to the specific sound signature of gas turbine engine blade vibration," said research scientist Yujun Leng. "The flow field inside a gas turbine engine is very complicated and noisy. **The key challenge is how to filter out all the noise and just listen to the sound produced by the blade vibration**."

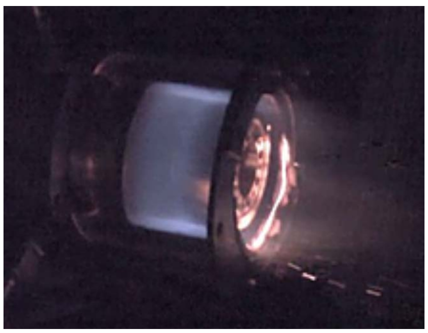
Gas turbine blades are usually very lightly damped and can act like a tuning fork. They have a specific frequency or tone when they resonate. The Purdue technology uses multiple unsteady pressure sensors to detect the pressure waves associated with blade vibration. "With the help of big data analytics, the blade vibration information can be used to predict the possible engine failure and optimize preventive maintenance schedules," said Prof. Nicole Key. "This technique has great potential to be used as a real-time blade vibration health monitoring system for the gas turbine engines used in both aviation and power generation."

Read the full story...

Seeing inside a rotating detonation engine



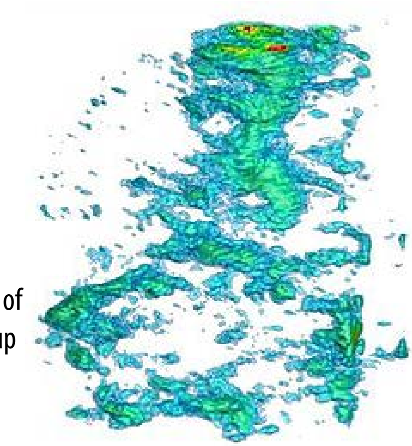
The research teams of Profs. Terry Meyer and Guillermo Paniagua joined efforts with private research firm Spectral Energies, LLC to build a **fully optically accessible rotating detonation engine**, to enable detailed investigation of the internal detonation dynamics. Due to high reaction rates and non-uniform combustion, imaging at rates of 100 kHz to 1 MHz is needed capture the mixing of fresh reactants, local detonation structures, reflected shocks, and deflagration within previous cycle products. Dubbed the Turbine-Integrated High-Pressure Optical RDE (THOR), the test facility was commissioned in mid-2019, and early results have been presented conferences of the American Institute of Aeronautics and Astronautics. Comparisons with modeling work by Post-Doctoral Researcher James Braun and Prof. Paniagua have led to deeper understanding of the underlying flowfield.



In addition, the device is highly modular and is designed to couple with and to test critical components in preparation for integration with a turbine for power generation. Combining efforts with Profs. Carson Slabaugh and Chris Goldenstein, this team has won grants from the AFRL and NASA to develop advanced diagnostics to assess performance metrics, improve thermodynamic efficiency, and reduce weight and cost of propulsion and power generation systems. Future work includes laser diagnostics of species, temperature, and density fields for comparison with numerical models.

Imaging sprays with high-speed 4D X-rays

X-ray imaging can readily penetrate optically dense regions of sprays and multiphase flows, but has typically been limited to low repetition rates. The research team of Profs. Terry Meyer and Mikhail Slipchenko, in collaboration with the AFRL, Spectral Energies, LLC, two visiting SURF students, and a professor from Fort Lewis College, have demonstrated **high-speed 4D X-ray imaging of dense spray for the first time**. In an article in *Optics Letters*, an X-ray system with three lines of sight were used to collect multiple views simultaneously, followed by tomographic reconstruction. The 3D images from a spray show the swirl motion and shedding of liquid layers as the flow propagates downstream. Ongoing and future plans include extending the high-speed X-ray imaging system to in-situ evaluation of alternative propellant formulations and additive manufacturing, in collaboration with the research group of Prof. Steve Son.

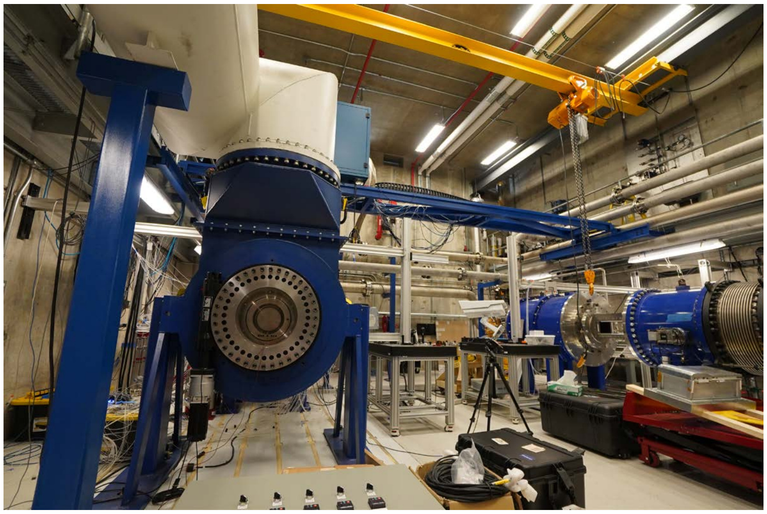


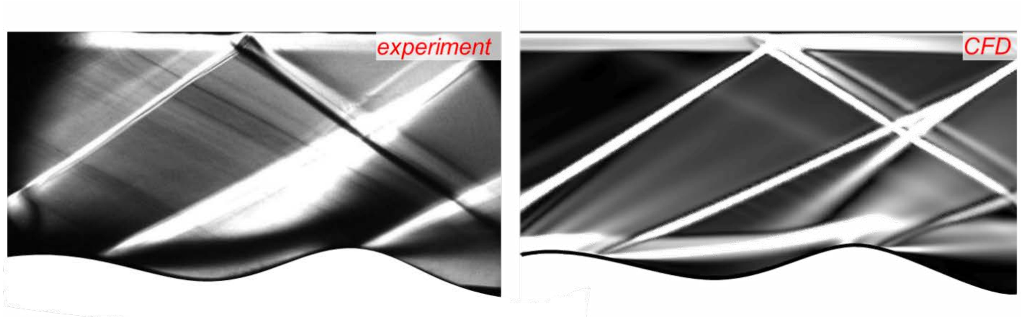
Prof. Mikhail Slipchenko and graduate research assistant Michael Smyser working on the development of the first MHz-rate burst-mode laser for measurements in hypersonic flows.

Graduate research assistants Diane Collard and Vaishnavi Radkar pitch in to help build up data acquisition systems for work in the ZL8 test cell.

Turbine breakthroughs

In Prof. Guillermo Paniagua's Purdue Experimental Turbine Aerothermal Lab (PETAL), **subsonic, transonic and supersonic testing was performed** in the modular tri-sonic facility, equipped with three different test sections. In the Linear Experimental Aerothermal Facility (LEAF), a compact transonic intake was tested for a micro-turbofan engine via pressure measurements, skin friction measurements and high-frequency Background Oriented Schlieren (BOS). The bladeless turbine concept was demonstrated at Mach 2; this turbine is capable to extract power from high-speed flows without airfoils. High frequency pressure measurements, Femtosecond Laser Electronic Excitation Tagging, 10 kHz Schlieren and atomic layer thermopiles were used to fully characterize the low and high frequency phenomena of the shock-wave boundary layer interactions



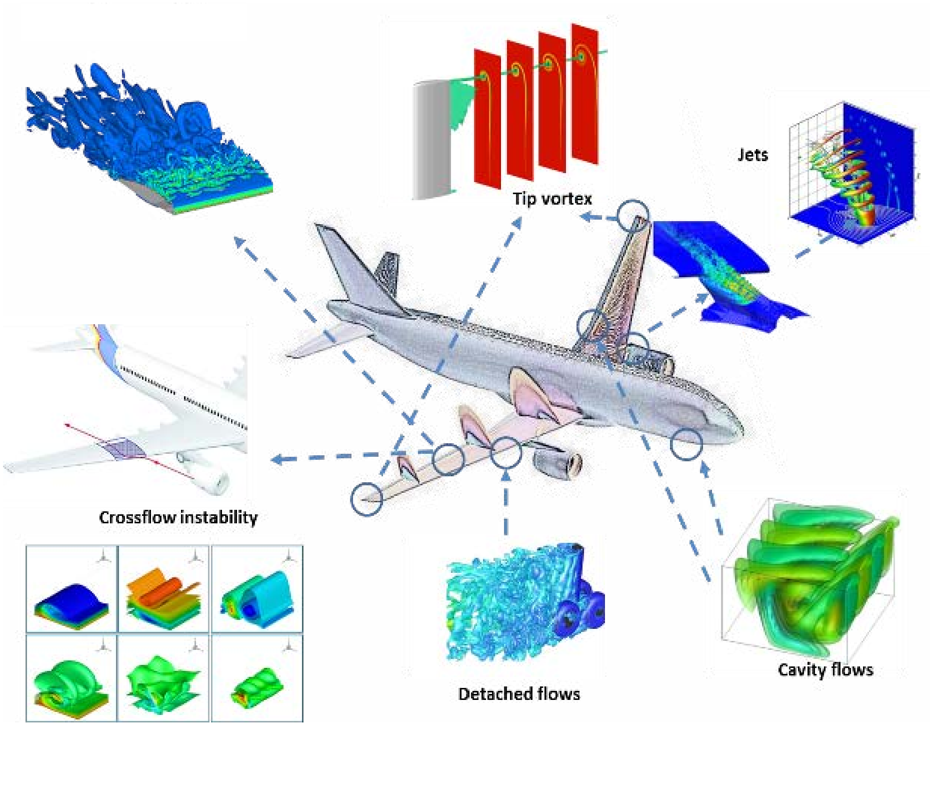


Left: Visualization of shock-boundary layer interactions at Mach 2 (Schlieren visualization)

Right: Reynolds averaged Navier-Stokes simulations

In the Big Rig for Aerothermal Stationary Turbine Analysis (BRASTA) a high subsonic turbine stator was investigated in a rainbow configuration. The stator was fully characterized with static pressure tappings, Pressure Sensitive Paint, total pressure contours with custom-made in-house Kiel head rakes and velocity and flow angle contours using PIV and 5-hole probes. All measurement techniques were developed and calibrated in our laboratory, increasing the degree of integration from TRL 1 to TRL4. The Small Turbine Aerothermal Rotating Rig (STARR, TRL6) has been assembled, including the cooling system. The team is focused on the commissioning phase to ensure safety, while developing the first high speed rotating two-stage turbine at Purdue.

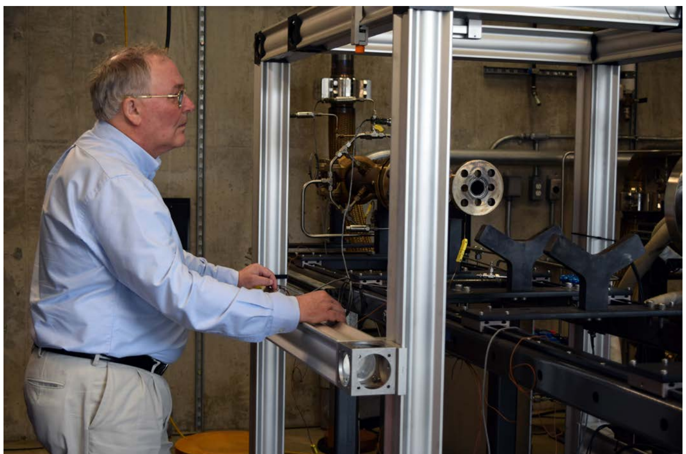
Finally, Prof. Paniagua's lab participated in a collaborative program with the European Union. Stability and Sensitivity Methods for Industrial Design (SSeMID), which finished in December 2019, received almost 4 million euros from the European Union's Horizon 2020 research and innovation program, aimed at improving the current aerodynamic performances of existing aircraft by developing new innovative methods and tools for modern airplane's design. Purdue participated in the experimental program by welcoming students from the Universidad Politecnica de Madrid and the von Karman Institute, focusing on the use of Coanda flows for turbine flow control.



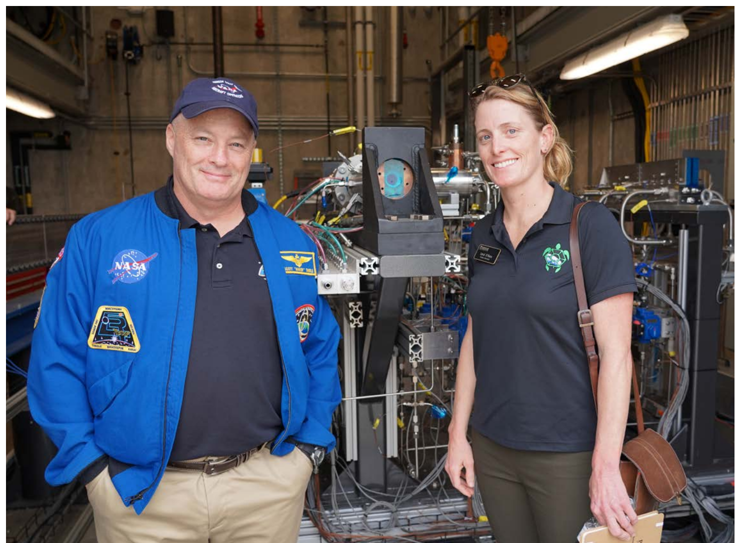
Astronaut reunion

As part of Purdue's 150th anniversary "Giant Leaps" celebration, **13 of Purdue's 25 astronaut alumni returned to campus** for a reunion in October 2019. Several other NASA VIPs were also in attendance, including Mark Geyer (BSAAE '82, MSAAE '83), the director of Johnson Space Center. They spoke to Purdue classes, visited local schools, attended a meet and greet with the public at Homecoming Tent Row, and were recognized on the field during halftime of the football game. The astronauts toured through Zucrow Labs, where several of them had studied propulsion during their time as Purdue students. See more Purdue astronaut photos...

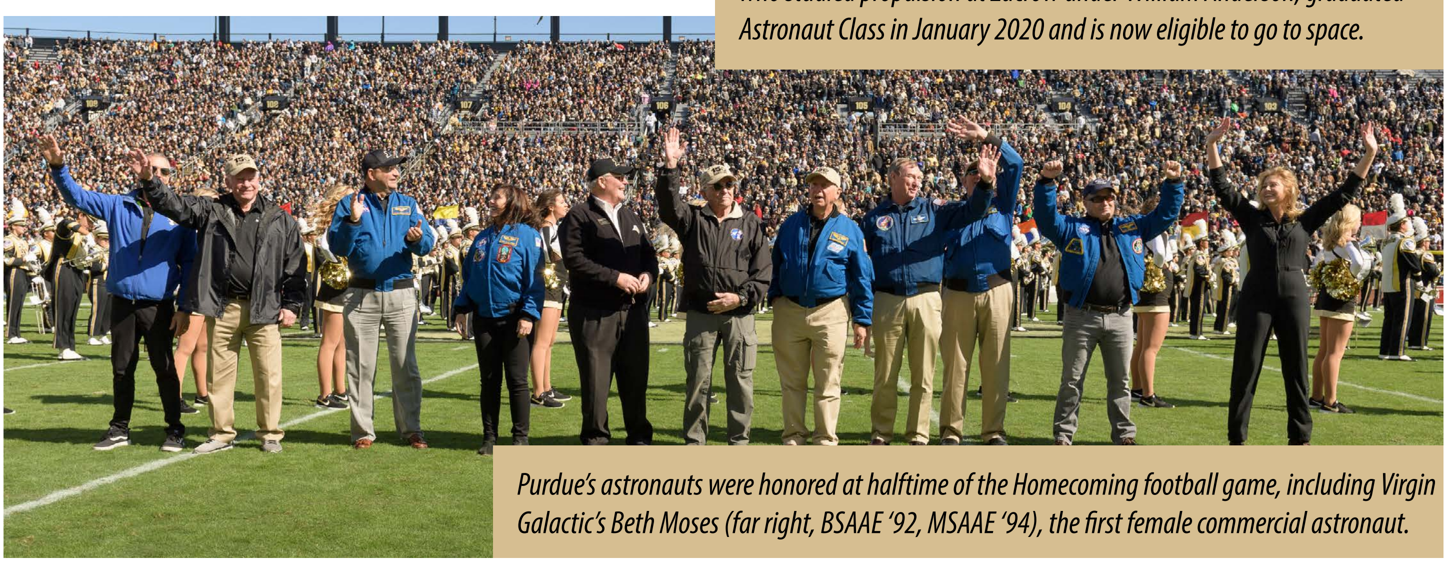
Chris Nilsen of Purdue's SEDS chapter shows off the mobile launch platform for their liquid methane rocket.



Jerry Ross (BSME '70, MSME '72) studied thermodynamics at Zucrow Labs before becoming a test engineer for the Air Force. He became a record-setting astronaut, embarking on seven Shuttle missions and nine spacewalks.



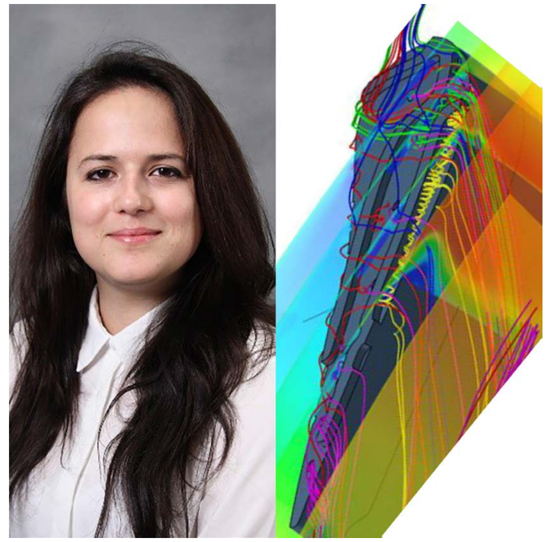
Purdue's two newest astronauts! Scott Tingle (MSME '88) spent most of 2018 on the International Space Station. Loral O'Hara (MSAAE '09), who studied propulsion at Zucrow under William Anderson, graduated Astronaut Class in January 2020 and is now eligible to go to space.



Purdue's astronauts were honored at halftime of the Homecoming football game, including Virgin Galactic's Beth Moses (far right, BSAAE '92, MSAAE '94), the first female commercial astronaut.

Awards

Valeria Andreoli, Ph.D. candidate at Purdue, has received the 2019 Howse, Ruffles, and Parker Award from Rolls-Royce, for the Best Doctorate Paper. The paper, "Aerothermal optimization of fully cooled turbine blade tips," discusses how changing the geometry of the tips of turbine blades can enhance their aerodynamic performance, while also reducing the thermal loads. It summarizes a Purdue-Rolls Royce collaboration that resulted in a new technology, now protected by US patent: "Tip structure for a turbine blade with pressure side and suction side rails."



Valeria conducts her research at the Purdue Experimental Turbine Aerothermal Lab (PETAL), under the supervision of Guillermo Paniagua, professor of mechanical engineering. The paper was presented at the ASME Turbo Expo in Oslo, Norway in June 2018, and subsequently published in the Journal of Turbomachinery.

Read the paper here...

The **Base 11 Space Challenge** is presenting the task for a student-led university team to design, build and launch a liquid-propelled, single-stage rocket to an altitude of 100 kilometers by Dec. 30, 2021. Purdue was approached to participate in the competition, based on the reputation built by its Students for the Exploration and Development of Space (SEDS) chapter. The work accomplished on its "Boomie Zoomie" rocket drew attention; they built the first liquid-liquid rocket designed entirely by Purdue students for a competition with a goal of reaching 45,000 feet. But that feat is not quite like reaching the Karman line, at the edge of space, 328,000 feet away.

"It's extremely ambitious," said former SEDS president Chris Nilsen, now a Zucrow propulsion engineer and the student interface on the project. "Whether we hit the altitude goal or not, the opportunity to get hands-on learning experience to test these high-pressure, high-flow systems is incredibly valuable."

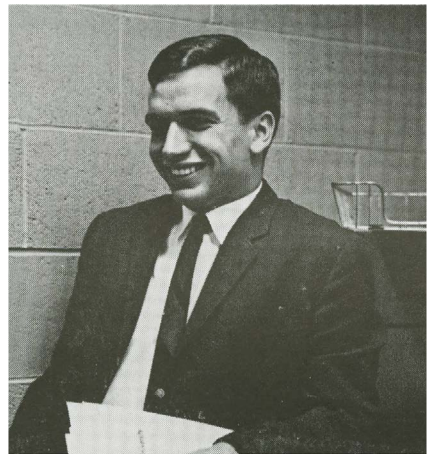
"There's tremendous enthusiasm for it," said Scott Meyer, the managing director at Zucrow Labs. More than 60 students are involved in the work, and professors Stephen Heister, Li Qiao, Scott Sudhoff, James Goppert, and Carson Slabaugh are all advising different aspects of the team. "We think it is important for Purdue to support this competition due to our reputation in propulsion and the great learning opportunities it provides our students," Heister said.

Read more about the Base 11 Challenge...

Adranos Inc., a Purdue-affiliated company developing a new high-performance solid propellant, has won the US Army's inaugural xTechSearch competition, besting more than 350 other companies. Company founder Brandon Terry (Ph.D. '15) developed the solid propellant working under Steve Son at Zucrow Labs. Using an aluminum-lithium additive, Adranos' fuel produces more thrust and is less corrosive than any other solid propellant. It also can be manufactured and processed using already-existing facilities and equipment. Adranos proved their fuel's superior performance in a recent demonstration for the Army, where their rocket and its signature magenta flame outperformed rockets using traditional fuels.

Watch the video...

Stan Tebbe's Zucrow gift inspires others



The largest expansion in Zucrow's history opened in 2017, and one key component is the **Stanley G. Tebbe TDI Laser Laboratory**. "My contributions to Purdue are all about people," says Tebbe (BSME '67, MSIA '68). "My motivation dates to my experience growing up on a farm in Greensburg, Indiana. I want to be an example, and I hope to inspire other alums to follow to invest in people, think big and give back to make the world a little better."

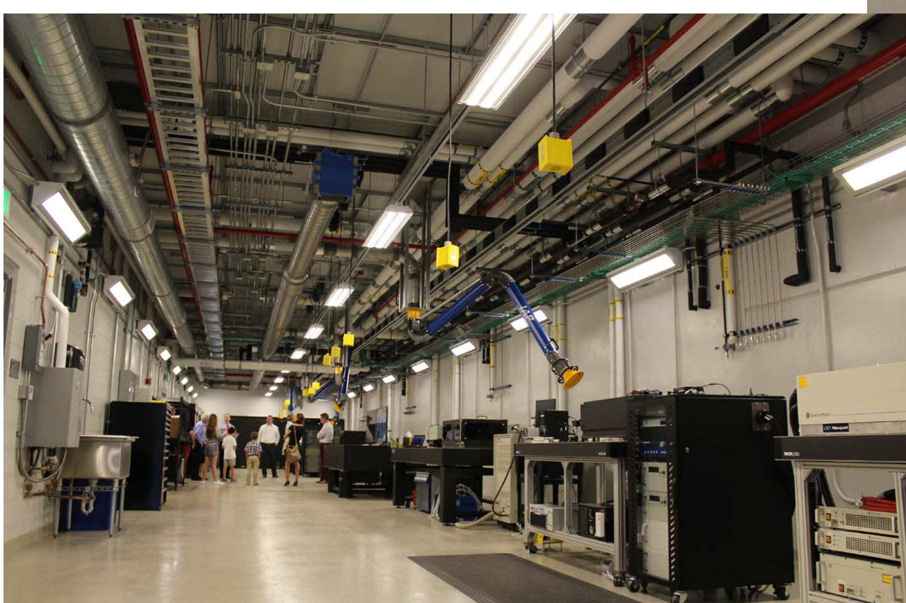
As a kid, Tebbe dismantled the family's toaster to see what was inside. After his mother warned him to wait until something broke to take it apart, the future engineer reassembled the toaster. Tebbe eventually attended Purdue Engineering, and later got his business degree from Purdue as well. Tebbe became a groundbreaking team leader at ExxonMobil, where he was one of their youngest executives. He also had tremendous success overseas, converting a non-ExxonMobil plant in the Netherlands to a successful plant, and engineering a successful joint venture in China.

Tebbe and his grandkids toured the lab in 2017.

Tebbe provided the lead gift that resulted in $1 million in contributions and secured commitments toward the 2017 expansion of Zucrow Labs, the world's largest academic propulsion research facility. The centerpiece of the addition is the Tebbe TDI Laser Lab, a 2,000-square-foot, climate-controlled laser diagnostics facility within the new High-Pressure Combustion Laboratory (ZL8).

The Tebbe lab is pushing boundaries in collecting and analyzing large amounts of data in short time frames to advance gas-turbine combustion research, chiefly for jet engines. Connected directly to five new test cells, the lab includes control, instrumentation and mechanical rooms, as well as a fabrication shop. The facility expansion was needed to retain and attract leadership people, faculty and students. Results have exceeded expectations.

"TDI" in the laser lab's name stands for "Teamwork, Discovery and Innovation – the three words that have guided me throughout my career and hold the key for the next generation of engineers," Tebbe says. "Purdue today exemplifies all the elements of TDI, and I see those strengths carrying the university forward. I'm proud to be helping Purdue sustain and enhance its world-class educational and research leadership, particularly to benefit first-generation college students. Purdue keeps educating people and making discoveries. We all win!"

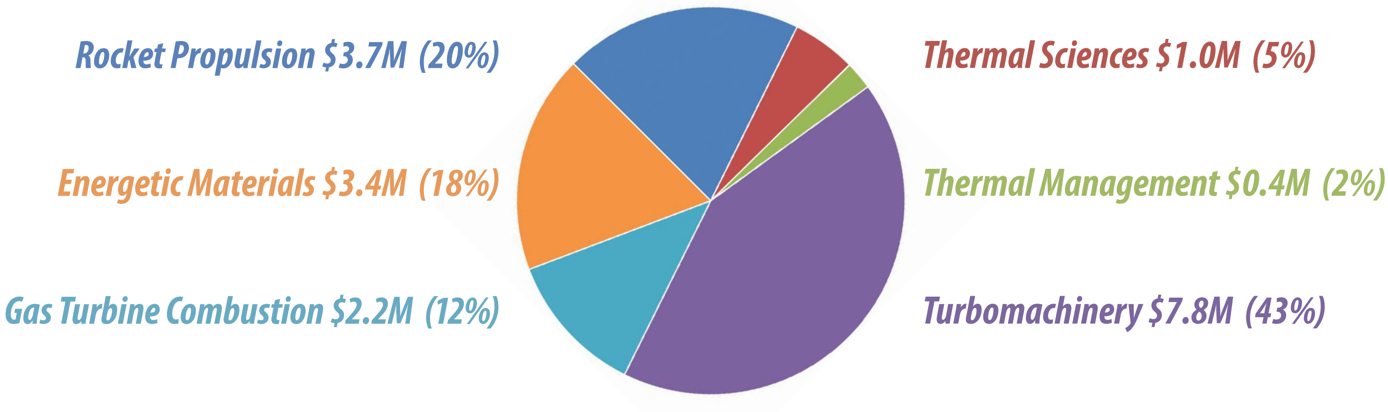


The laser lab is adjacent to five high-pressure combustion test cells.

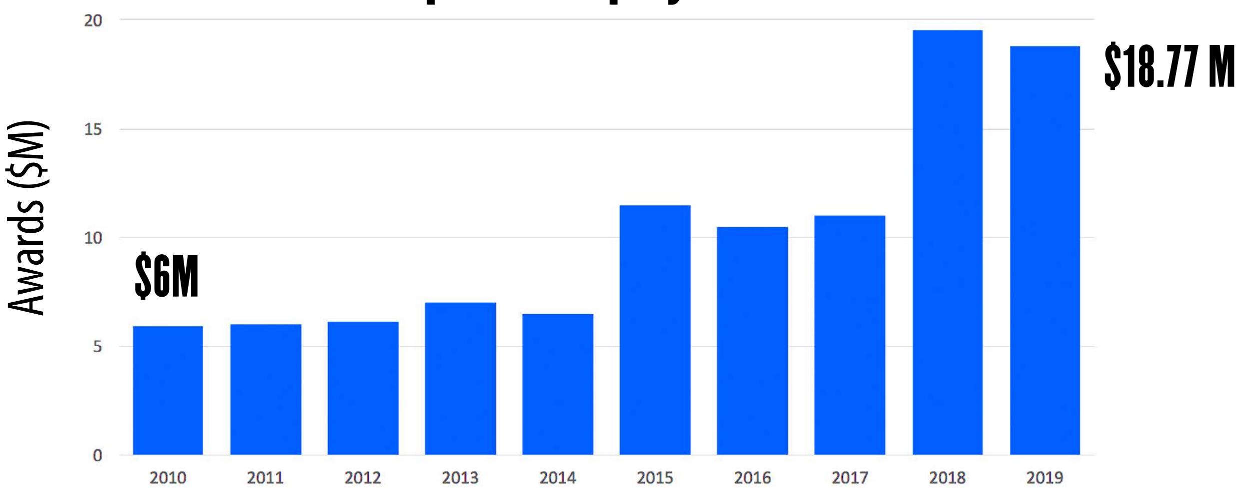
Learn more about Stan Tebbe's story...

Zucrow By The Numbers

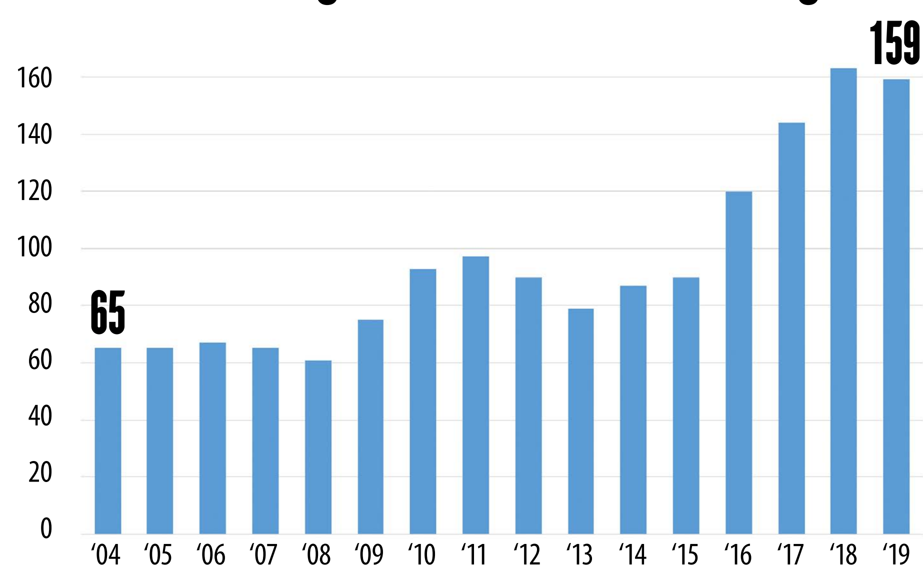
Total expenditures at Zucrow for calendar year 2019: $18.77 million



Growth in sponsored projects at Zucrow Labs



Growth in number of graduate students working at Zucrow Labs



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

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