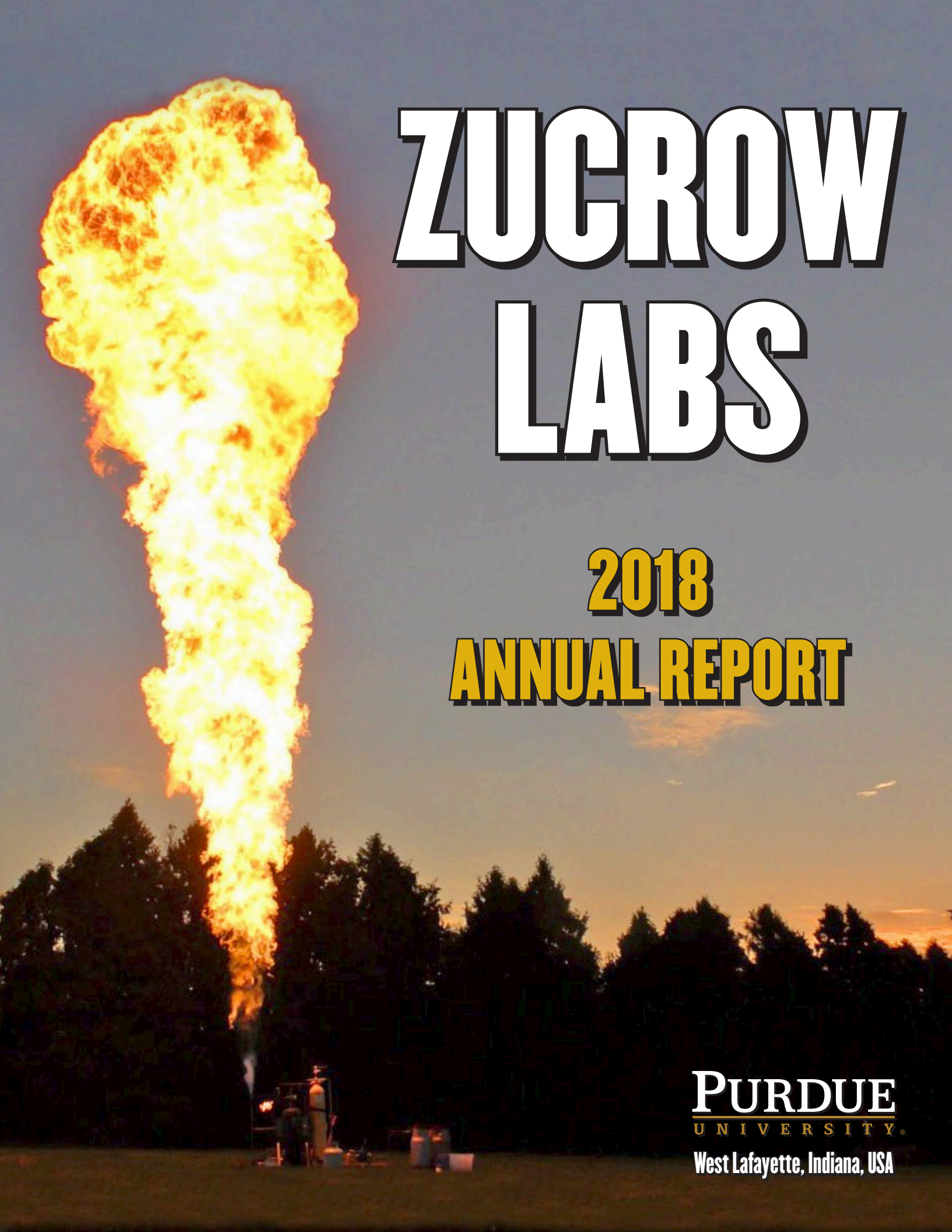

ZUCROW LABS

2018 ANNUAL REPORT

PURDUE UNIVERSITY®

West Lafayette, Indiana, USA

Zucrow Labs
2018 Annual Report

In 1967, Honeywell supplied Purdue the latest state-of-the-art data acquisition systems, including computer analysis. 50 years later, the names are the same, but the technology has advanced exponentially! Now Purdue researchers can instantly analyze millions of data points per second.

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.

PURDUE UNIVERSITY®

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Front and back cover photos: The "Big Friendly Flame" sculpture was built in Carson Slabaugh's Propulsion Design, Build, and Test class, for the annual Burning Man art festival in Nevada.

From the Director

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

The last year has again been a very exciting and rewarding one for me as the Director of Zucrow Labs. We continue to see strong growth in our research programs, improvements in our infrastructure, and increased interest in our activities both from Purdue University and the outside world. The new High Pressure Combustion Laboratory, designated ZL8, was dedicated on September 22, 2017. At the time of the dedication, there was still a tremendous amount of work to be performed to bring the building to operational status. After many months of bending and flaring tubing, installing fluid control and data acquisition systems, routing cables from the control rooms to the test cells, experimental activities have now commenced in all of the five test cells in ZL8, as well as the Tebbe TDI Laser Lab. Thanks again to the many donors who made this new addition possible.

As Zucrow Director, my main focus continues to be dealing with the current rapid growth in our research activities. Last year at this time we had 144 graduate students in residence, and it seemed that we were at capacity. However, we now have 163 graduate students in residence. Somehow Managing Director Scott Meyer and Administrative Assistant Jen Ulutas managed to find desks for all the incoming students, even though we did have to open a room with "hot desks" on the upper floor of Chaffee Hall. It is often very hard to find a parking space, and when this happens many cars can be seen parked on the grass.

The growth in research activity shows no signs of slowing, and may actually accelerate. The excellence of the faculty, staff, and graduate students, the unmatched experimental facilities, and the Zucrow culture which encourages collaboration between research groups, are powerful factors that are driving our current research growth. Zucrow research expenditures in CY18 totaled $14.05M. The turbomachinery programs of Profs. Nicole Key (compressors) and Guillermo Paniagua (turbines) accounted for a large fraction of this total. Our rocket propulsion programs, led by Profs. Bill Anderson, Steve Heister, Tim Pourpoint, Carson Slabaugh, and Managing Director Scott Meyer are extremely active, with intense interest in Zucrow facilities from numerous external companies and agencies. Rotating detonation engines are being investigated for both gas turbine engines and for rocket propulsion by Profs. Heister and Slabaugh. Prof. Sally Bane is investigating the use of plasmas to stabilize high-pressure combustion systems. Research efforts in propellants and energetic materials, led by Profs. Steve Son, Tim Pourpoint, Chris Goldenstein, Terry Meyer, and Davin Piercey, are growing very rapidly as part of the larger Purdue Energetics Research Center (PERC). Profs. Steve Heister, Tim Pourpoint, and Jay Gore continue their strong efforts in the Rolls-Royce-funded University Technology Center on Advanced Thermal Management Systems. The development of laser diagnostic methods for reacting flows (categorized under thermal sciences) is an active area of research for Profs. Terry Meyer, Mikhail Slipchenko, Paul Sojka, Jun Chen, Carson Slabaugh, and me. Profs. Meyer and Slipchenko are making notable strides in the development of femtosecond and picosecond versions of pulse burst laser systems. Prof. Slabuaugh and his group recently used a nanosecond pulse burst laser system to perform particle-imaging velocimetry measurements in the exhaust stream of a 20 MW rotating detonation engine. Profs. Li Qiao and Terry Meyer are developing new X-ray techniques for spray diagnostics.

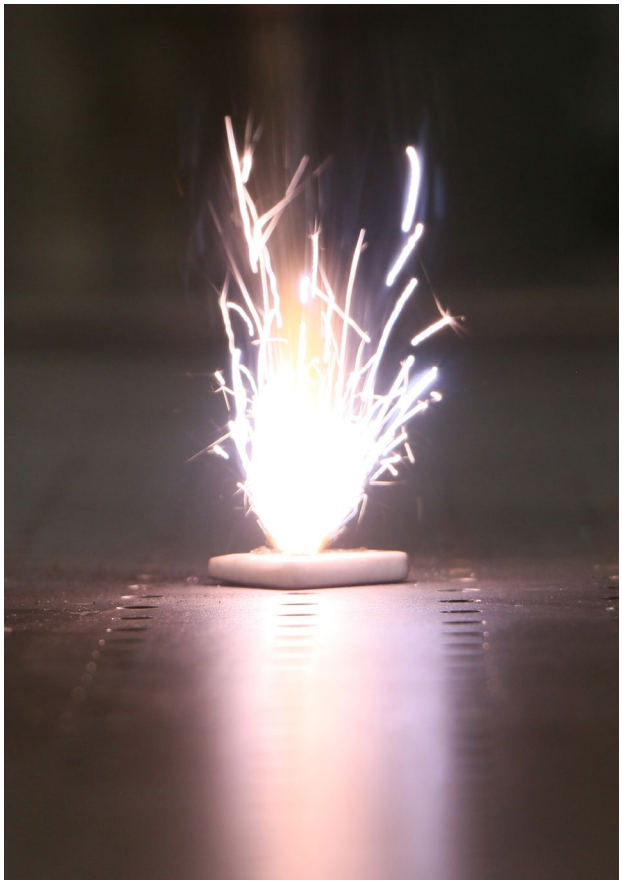
Davin Piercey is a new faculty member who started in January 2018. He is synthesis chemist who will be developing new types of energetic materials. At the present time he has set up his laboratory in Purdue's on-campus Flex Lab. The Propulsion Lab (ZL4) will be extensively renovated to make it suitable for his experiments. The renovation will include the installation of six sophisticated fume hoods so that his experiments can be performed with the required rigor and safety. He was hired as a member of Purdue's Preeminent Team on Energetic Materials, and is now part of the Purdue Energetics Research Center.

During 2017 we developed a strategic plan and shared it with the Schools of Mechanical Engineering and Aeronautics and Astronautics and with the College of Engineering. In 2018 we have been working with a team of experts from Jacobs on a long-term Master Plan for Zucrow Laboratories. The Master Plan will serve as a blueprint for future investment in facilities.

Finally, I'm sharing this photo of a sunset, taken from the roof of ZL8, to remind us all that what we are doing is not only important, but also beautiful and inspiring.

Robert Lucht
Director, Maurice J. Zucrow Laboratories

Piezoenergetics



Steve Son is leading a multi-disciplinary team which has received a $7.5 million grant by the Air Force Office of Scientific Research (AFOSR) to study **piezoenergetics**, which combines piezoelectric properties with energetic materials. Specifically, the team is interested in what happens when an external field, such as an electric voltage, is applied to the energetic materials; or in reverse, how the energetic materials themselves can generate voltages and act as embedded gauges.

"This is the first time that these two fields have been brought together in a thorough study," Son said. "We're excited about finally being able to fully understand the relationship between piezoelectric properties and reaction. This could open up a whole new area of material science."

The AFOSR grant is part of their Multidisciplinary University Research Initiatives program, which encourages collaboration with teams of researchers from several universities across several technical disciplines. For this project, Son is collaborating with colleagues from Case Western Reserve, Georgia Tech, Penn State, and the University of Maryland.

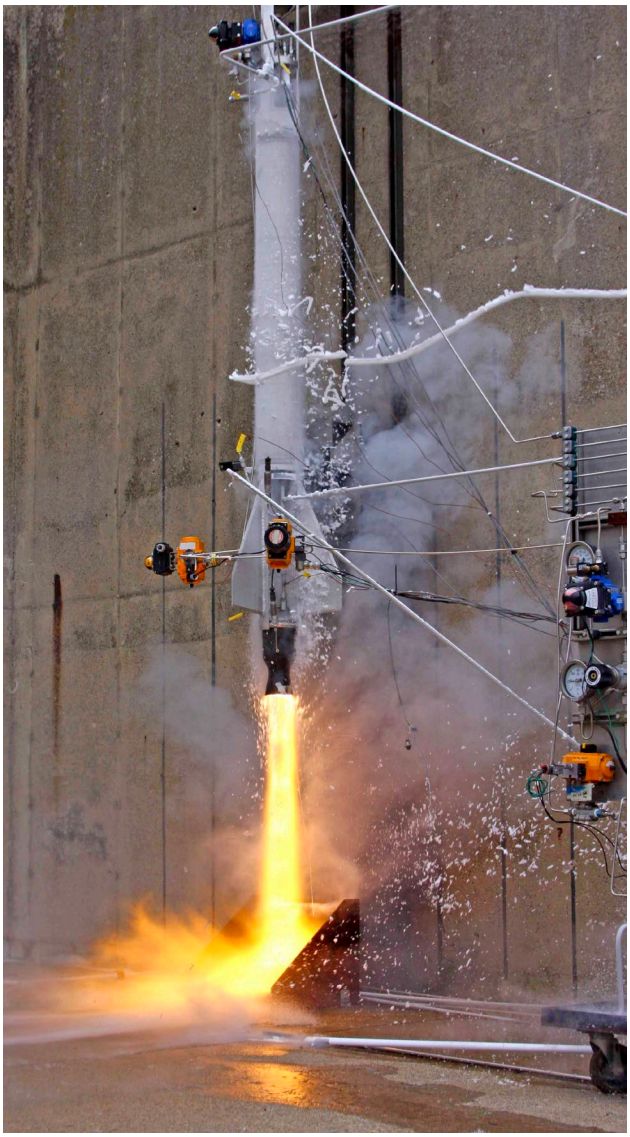
Rocket Test Group meets at Zucrow

In September, Zucrow hosted the **Rocket Test Group**, an organization of rocket test facility operators. More than 40 of our colleagues attended, from NASA, SpaceX, Blue Origin, Northrop Grumman, Stratolaunch, Air Force Research Lab, Aerospace Corporation, and more. They toured through the new ZL8 and laser lab, and shared their knowledge and experiences. We were also thrilled (but not surprised!) to see how many of them were Purdue alumni!

David Helderman and Tyler Sorchik are two of many Purdue grads that now work at Blue Origin.

SEDS team builds liquid methane rocket

Building a liquid-fueled rocket at the university level is extremely rare. But a functioning liquid methane rocket? That's unprecedented.



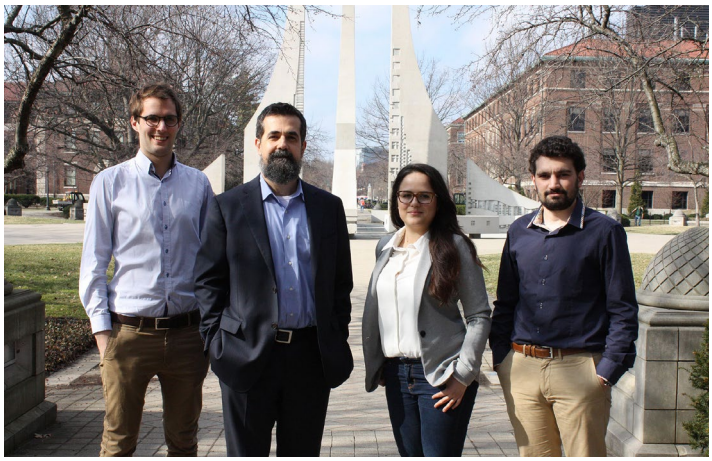
Purdue SEDS (Students for the Exploration and Development of Space) is led by senior Christopher Nilsen. His liquid rocket team shot for the moon (so to speak) by attempting to utilize liquid methane as fuel, developing a condenser system to generate their own liquid methane on the pad. Documenting the build on Instagram and Reddit, Nilsen and his team gained fans around the world. Hundreds tuned in live on YouTube for hotfire tests... at 2:30 in the morning!

With the help of Scott Meyer and the staff and facilities at Zucrow, the team (mostly made up of AAE undergraduates) pulled off a successful hotfire in June 2018. For their efforts, they won Technical Project of the Year from SEDS USA. The next feat? Become the first team ever with a successful launch. "It's just a matter of taking everything from the courtyard where we tested, to putting it on the trailer," says Nilsen, who plans for a March 2019 launch. "There's no great engineering feats left. There's just getting it all on the trailer and praying!"

Other Purdue rocket teams have also enjoyed success. At an event in New Mexico, the Solids team launched Purdue's highest flying rocket ever, reaching 41,000 feet and speeds of Mach 2.4.

Read the full story and watch video at purdue.edu...

Entrepreneurship updates



A new startup founded at Zucrow is developing instruments to precisely measure pressure, temperature and other analytics inside the harsh environments of rocket engines and gas turbines. **Petal Solutions LLC** was founded by professor Guillermo Paniagua, and doctoral research assistants Valeria Andreoli, David Cuadrado and James Braun. They decided to design their own instruments because they couldn't find conventional instruments that could survive the high temperatures of their engine tests.

They already have shown through simulations that their device, about 4 millimeters in diameter, works properly. They are working on a prototype that can withstand temperatures up to 1,300 degrees Fahrenheit. By next year they plan to have a prototype that can withstand temperatures up to 3,000 degrees. Their plans call for Petal Solutions to provide client-specific software to process sensor output, and certificates attesting to the calibration of the device. Learn more at www.petal-solutions.com

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Adranos Energetics received $800,000 to develop its high-performance environmentally friendly solid rocket propellant, developed at Zucrow Labs. Brandon Terry (Ph.D.'15) studied energetic materials under Steve Son, formulating an aluminum-lithium composite that dramatically reduces the amount of hydrochloric acid produced during a launch. Brandon formed a company, Adranos Energetics LLC, and has since once won numerous business and entrepreneurship awards.

Learn more at www.adranos.com

3D-printed solid rocket fuel? It's coming, thanks to **Next Offset Solutions**, a company founded by professor Jeff Rhoads and former research assistant professor Emre Gunduz. They have developed an array of technologies to safely and precisely print energetic materials using inkjet printing, 3D printing, and high viscosity 3D printing. This process allows users to customize the geometry of their fuels, so that one section burns at a different speed than another. It also reduces the chance of voids, which can lead to inconsistent (and sometimes catastrophic) burns. The high-viscosity printing technique is a unique breakthrough, using ultrasonic vibrations to snake clay-like material through a print head with minimal friction.

Learn more at www.nextoffset.com

“Big Friendly Flame” for Burning Man

“Burning Man” seems a totally appropriate name for an event involving Zucrow students! The weeklong art festival in the Nevada desert attracts 50,000 visitors every year. This year’s festival featured a Purdue-designed fire sculpture: **a 100-foot flamethrower** called the “Big Friendly Flame.” It was built by students in Carson Slabaugh’s AAE535 Propulsion Design, Build, Test class. Because they couldn’t spray liquid fuels in an environment filled with people, they pressurized propane to 500 PSI, vaporizing it instantly after ejection. A 10-member team perfected the kinetic fire sculpture at Zucrow Labs, before installing it on a firetruck called “Heathen.” Burning Man attendees could easily see the flame from miles around.
Learn more and watch the video at purdue.edu...

Carrying the torch

In 2016, a Zucrow team led by Timothee Pourpoint created the **Bicentennial Torch**, carried on a relay through all 92 counties of Indiana to celebrate the state’s 200th anniversary. Purdue’s College of Engineering has recognized them with the Team Award: “for their superb project management and technical contributions creating a lasting symbol, the bicentennial torch, which served as a centerpiece for student education and the State of Indiana’s bicentennial celebrations.”

Welcome back Scott Tingle!

Scott Tingle (MSME '88) spent six months on the International Space Station, returning to earth in June 2018. In addition to hundreds of scientific experiments (and an 8-hour spacewalk to repair the robotic arm), Scott participated in Purdue's commencement ceremonies live via satellite. **He also carried several Zucrow keepsakes into space**, which are now on display in Chaffee Hall.

Loral O'Hara continues astronaut training

Loral O'Hara (MSAAE '09) **has begun training as part of NASA's 22nd Astronaut Class.** O'Hara, who built sub-scale rocket engines at Zucrow Labs with Professor William Anderson, was selected from more than 18,000 applicants.

Her astronaut training had an inauspicious start, as Hurricane Harvey flooded Houston the week they began! But soon O'Hara and her cohort began learning the procedures and systems of NASA and the International Space Station. Her first year of training has included:

- Learning to fly T-38 jets
- Survival training in Maine
- Geology lessons in New Mexico
- Russian language classes
- Hypoxia training
- Learning the tools used on spacewalks

She'll complete her training in August 2019, and then be eligible for posting on future space missions.

Read more about Loral O'Hara at purdue.edu...

Let's throw back to: 1974

Good news: Creedence Clearwater Revival are touring again! Just kidding.

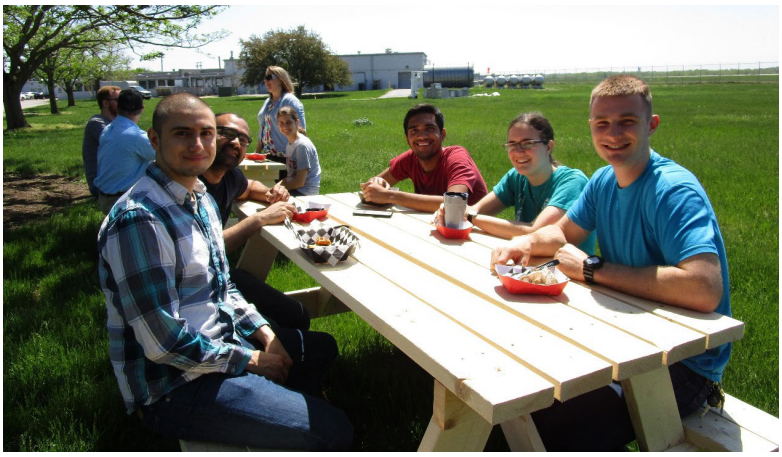
This photo was unearthed by Martin Mlynarik. It's from 1974, when Zucrow was called the Thermal Sciences and Propulsion Center (TSPC). People we know in the photo: Dan Hirleman, Steve Kenninger, Sigmar Wittig, Bob Rankin, and Jim Hoey. Do you know any others? Fill us in!

Remember that giant ugly tank?

Well, look at it now! Built in 1961 by the Chicago Bridge and Iron Company, this tank has a capacity of nearly 300 cubic meters (80,000 gallons). But it sat dormant for as long as anyone could remember. Last year it was moved, cleaned, repainted, and connected to Guillermo Paniagua's lab in the new ZL8 building, where they test turbine aerodynamics. Thanks to this **massive vacuum tank**, Paniagua's team can perform tests at very low pressure levels (to replicate high altitude testing), as well as high supersonic and eventually hypersonic conditions.

Zucrow Student Association

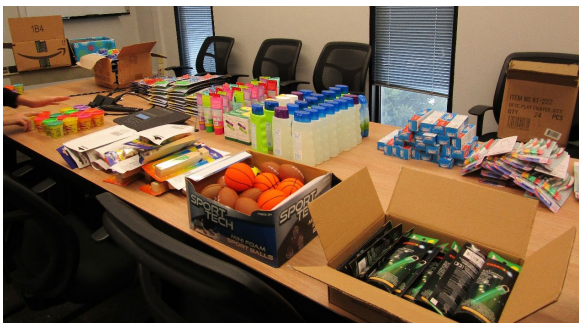
The Zucrow Student Association (ZSA) organizes educational and social events, promoting an inclusive lab for all Zucrow students. This includes group outings (canoeing on Wildcat Creek), post-exam celebratory dinners, and our frequent coffee & donut breaks!



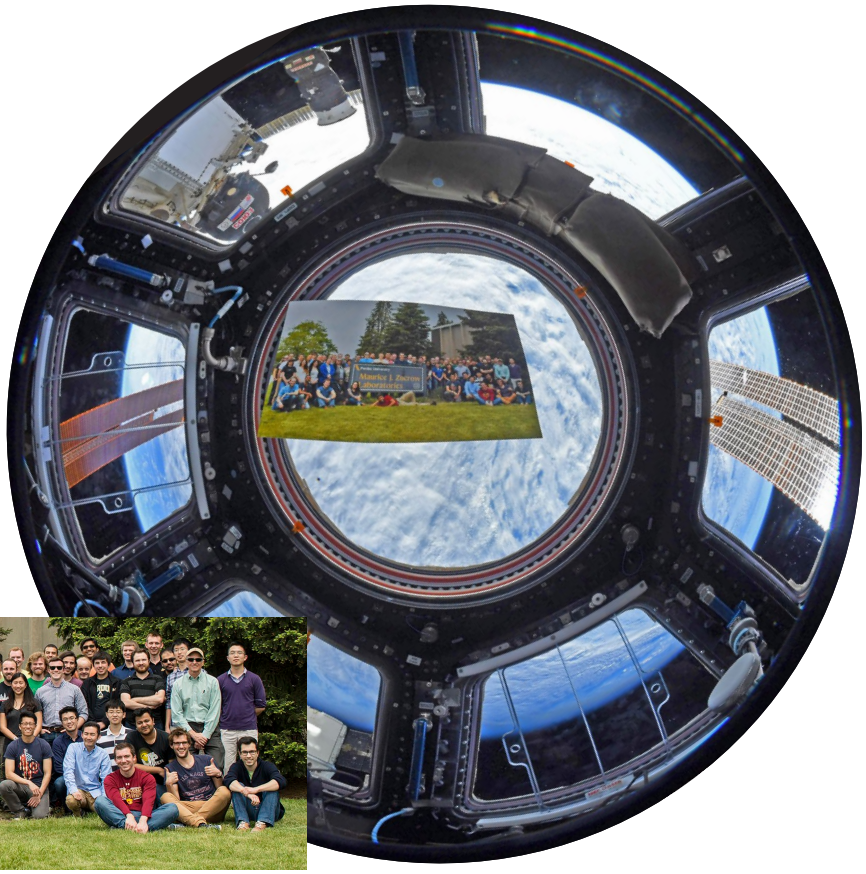
Sometimes, it's as simple as stepping outside the building. We built picnic tables this summer next to Chaffee, so that when food trucks come by, we can enjoy lunch out in the sunshine with our colleagues!

We are also involved in each other's academic success. We formed the Zucrow Council, with one representative from each research group, meeting regularly with Dr. Lucht. We continued our 5-minute lecture series, so that we get to learn about each other's research. And we give tours of the facilities, so that outside visitors can appreciate the jewel that is Zucrow Labs!

Here is the winner from our 2018 Zucrow pumpkin carving contest!



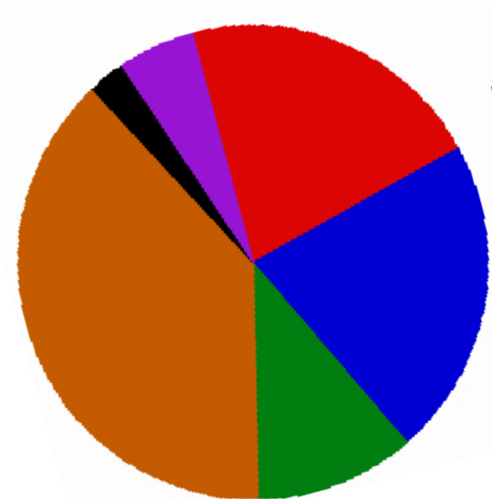
Zucrow students give back: we teamed up with Lafayette Food Finders Food Bank to create holiday gift bags that were distributed to Battle Ground Elementary School students.



We're in space! Astronaut Scott Tingle carried a group photo of Zucrow students and faculty onto the International Space Station in 2018.

Zucrow By The Numbers

Total expenditures at Zucrow for calendar year 2018: $14.05 million



Thermal Sciences:
$0.74M (5%)

Rocket Propulsion:
$2.96M (21%)

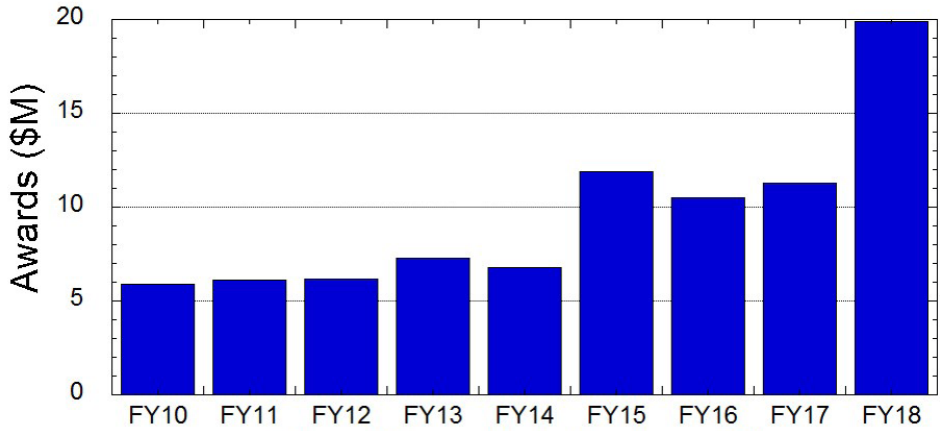
Thermal Management:
$0.36M (3%)

Energetic Materials:
$3.04M (22%)

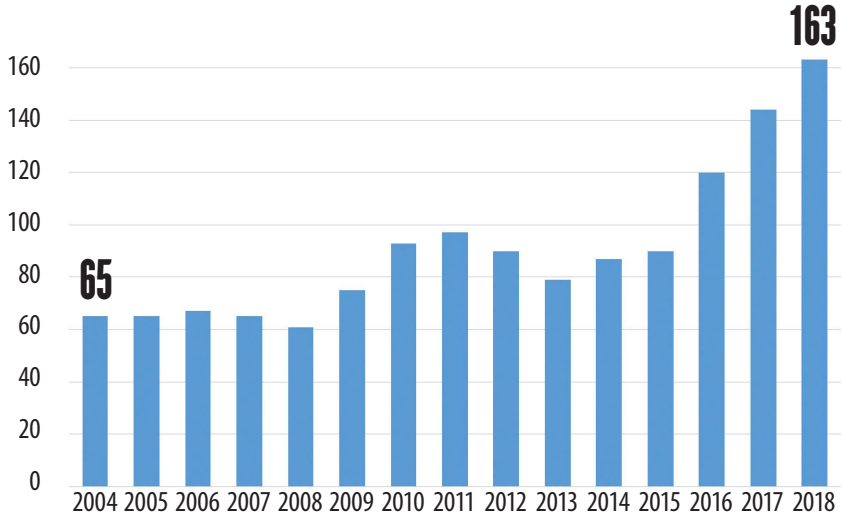
Turbomachinery:
$5.4M (38%)

Gas Turbine Combustion:
$1.56M (11%)

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.*

Fare Thee Well

Here's where our graduating students end up.

Dayle Alexander	Virgin Orbit (CA)
Ruben Adkins-Rieck	SpaceX (CA)
Wes Anderson	Arnold Engineering Development Center (TN)
Matt Beason	Los Alamos National Labs (NM)
Gabriel Diez	Northrop Grumman (UT)
Alber Douglawi	NASA Marshall Space Flight Center (AL)
Matt Elliott	Blue Origin (WA)
William (Zach) Hallum	Orbital Technologies (WI)
Shourya Jain	DuPont (DE)
Nitya Kamdar	Cummins (IN)
Ashwin Kumar	Virginia Tech (VA)
Shengqi Lu	Notre Dame- PhD (IN)
Alex Mastrean	Orbital ATK Northrop Grumman (AZ)
Andres Porro Carvalhar	
Vishnu Radhakrishna	Purdue University – PhD (IN)
Morgan Ruesch	Purdue University – PhD (IN)
Jorge Saavedra	Purdue University- Current Research Group
Ian Shelburne	Los Alamos National Labs (NM)
Forrest Son	Sandia National Labs (NM)
Matt Tanner	PLD Space, Spain
Jared Willits	SpaceX (CA)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