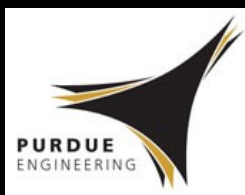
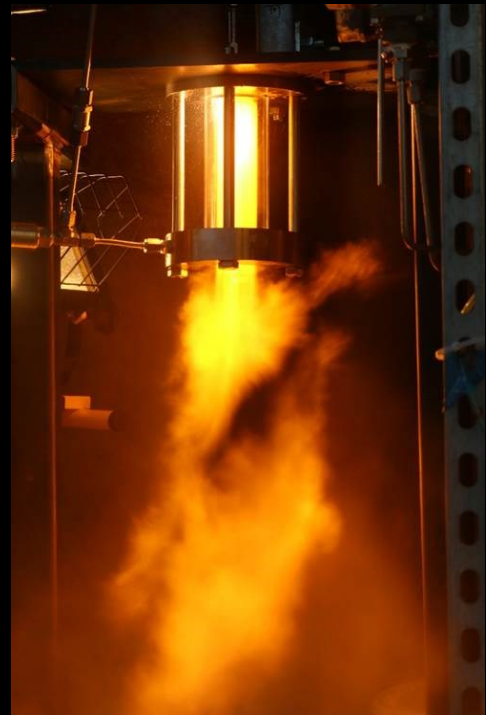




2015 ANNUAL RESEARCH REPORT

Maurice J. Zucrow Laboratories

School of Mechanical Engineering/School of Aeronautics and Astronautics



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From the Director.....

Greetings from Chaffee Hall to all alumni and friends of the Zucrow Labs. I have much to report from our growing laboratory and I do encourage you to look to details in the remainder of this report. As with any organization, our people are our most important resource and we have had numerous changes over the past year. Our electronics technician Jared Neal left us for an exciting position developing flight hardware for Blue Origin. Recently, we have filled this position with Shawn Swindle who joins us from Purdue's physical facilities organization as an expert in electrical systems. Our administrative assistant Charlotte Bell also left us early in 2015 for a part-time position within Purdue. We are pleased that Jen Ulutas has taken on this important role (after all she compiles the lion's share of this report). Finally, in the business services area Sheri Dill joined us in January of this year after Matt Singleton departed in mid-2015.

We have also had several additions to our faculty ranks over the past twelve months. Dr. Terry Meyer joined as a Full Professor in Mechanical Engineering. Terry's research focuses on laser diagnostics of reacting and non-reacting flows with recent emphasis of ballistic imaging of high pressure sprays. Dr. Mikhail Slipchenko has also joined us as a Research Associate Professor. Mikhail's will be working closely with Dr. Meyer and his research. We also added Assistant Professor Dr. Carson Slabaugh to Zucrow staff from AAE department. Carson's interests are in turbulent combustion and optical diagnostics. It is noteworthy that both Dr. Meyer and Dr. Slabaugh are former students of Prof. Lucht; a testament to his impact and leadership in laser diagnostics area.

Zucrow students have been in the news this year having won all of the AIAA Liquid Propulsion Technical Committee student awards. Eric Meier (now at Blue Origin) won the student award for his work with Profs. Anderson and Heister in controlling combustion instabilities in liquid rocket engines. Drs. Jacob Dennis (now at China Lake NAWC) and Brian Pomeroy (now at Aerojet-Rocketdyne) won the young professionals awards. Congrats to Eric, Jacob, and Brian! Our Zucrow Student Association (ZSA) has also been active in the past year (see their page in body of this report) and have coined a new term, "Zucropians", to identify folks at the lab. In August, ZSA helped organize our semi-annual -when-we-remember-to-do-it golf outing at the Ravines country club just west of the laboratory.

On a more serious note, Zucrow students have figured prominently in a high profile project to design a torch to commemorate the State of Indiana's Bicentennial celebration. Professor Pourpoint led a multidisciplinary team that included several MZL students that successfully designed the torch to some arduous requirements (such as staying lit while riding along in an Indy car). The torch will traverse all 92 counties in Indiana over the course of 2016 and Prof. Pourpoint has even arranged to have the torch relay route pass by the Zucrow Lab this summer!



Torch for State of Indiana Bicentennial Celebration – designed by MZL students & Prof. Pourpoint

We continued our MZL History Lecture series in April of 2015 with wonderful lectures from Dr. George Schneider and Dr. Lynn Snyder. Dr. Schneider spent the bulk of his career in Washington DC as an authority on ballistic missile systems while Dr. Snyder spent his career in the gas turbine industry at Pratt & Whitney and Allison (Rolls-Royce, Indianapolis). It is always interesting to get perspectives on our laboratory during the “Doc” Zucrow days. In a related note, Dr. Michael Smith, Professor of History here at Purdue, is currently working on a new book that will detail Dr. Zucrow’s career from mid-1940’s (when he joined Purdue) to mid-1960’s. We are all thrilled that Professor Smith, an expert in cold war and Soviet Union rocketry developments, has decided to take on this exciting task. Stay tuned for publication in the next year or so.

As I wrap up this lengthy letter, I return to the subject that I have bored you with over the past five years – namely, our new building. On February 18, 2015 we celebrated the Lilly Foundation’s largest cash donation in Purdue’s history, \$5M of which was designated to Zucrow Labs to completely fund our new building and High Pressure Lab renovation project that I have described to you in prior reports. I want to highlight the sponsorship from numerous Zucrow, ME, and AAE alumni that provided the impetus for our Dean Leah Jamieson to include the Zucrow request in the major “ask” to the Lilly Foundation. We all should recognize that bubbling to the top of our Dean’s list of highest priorities is a great testament to the incredible efforts of our faculty, staff and students who are contributing to what is quite arguably the finest propulsion and thermal sciences laboratory in the world. With our new building addition, this claim will be perhaps more obvious.

Best wishes to all for a prosperous and healthy 2016.



Steve Heister, Director, Maurice J. Zucrow Laboratory



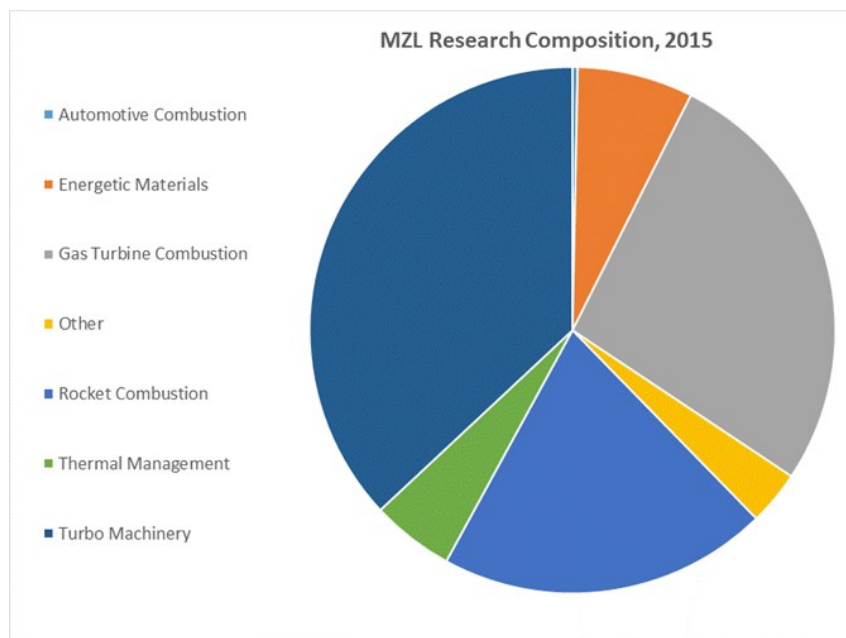
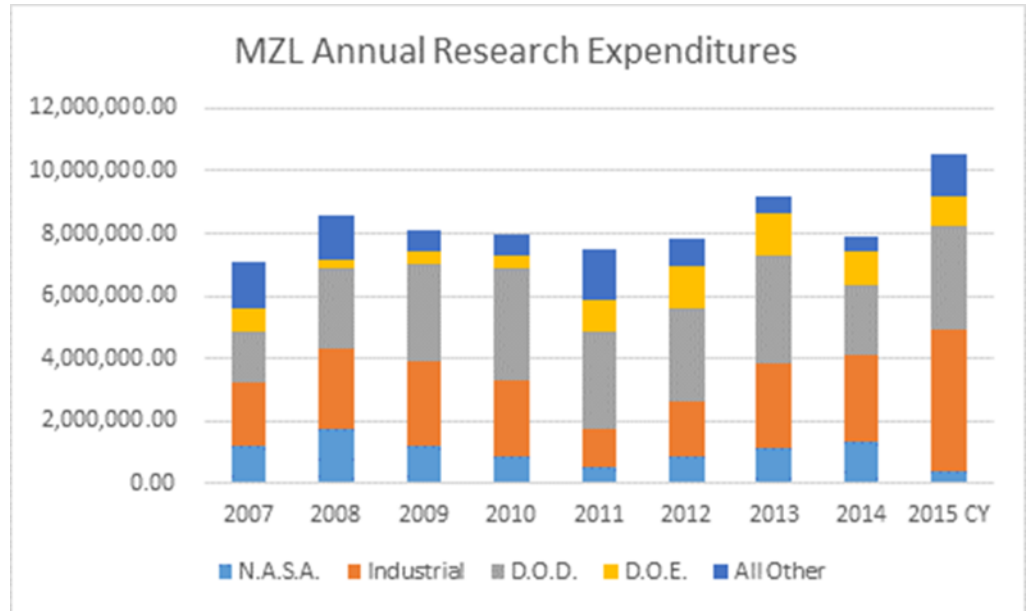
Sarah B. Cobb, Vice President of Education for Lilly Endowment discussing the Purdue gift

Maurice J. Zucrow Laboratories

Zucrow Lab Finances

The lab research expenditures grew substantially last year with the bulk of the increase attributed to expansion of industrial sponsored work in both tur-

bomachinery and combustion. Currently, we support roughly 85 graduate students. We are seeing additional interest in the new facilities that are currently under construction. This factor, combined with the increases in productivity of new faculty as they settle into MZL bodes well for continued growth in 2016-17 timeframe. Regrettably, our continued reductions in NASA funding appears to be part of a national trend.



The chart at the left shows the composition of MZL research by area. With dramatic growth of Prof. Key's work in compressors, turbomachinery now represents the single largest sector in terms of research expenditures. Gas turbine combustion, rocket combustion, and energetic materials also represent

major areas of emphasis as in the recent past. Prof. Fishers Center for Integrated Thermal Management (CITMAV) located their capstone facility at MZL this past year and this project now represents a significant portion of the MZL research landscape.

ZUCROW LABS FACULTY

PAGE 7



Bill Anderson, Associate Professor of Mechanical Engineering (by courtesy), Associate Professor of Aeronautics and Astronautics. Research Interests: Chemical Propulsion and Design Methodologies. Research Areas: Systematic and careful combination of analysis and experimentation on injectors, combustors, nozzles, and propellants for both rocket and air-breathing propulsion. Specific research areas include ignition, non-toxic propellants, combined cycle propulsion, combustion stability, fuel cooling, and life prediction.



Sally Bane, Assistant Professor of Aeronautics and Astronautics, PhD 2010, Caltech. Research Interests: gaseous combustion dynamics, detonations, plasma control of combustion instability, hypergolic combustion, pressure-gain combustion, energetic materials, electrostatics and ignition, experimental fluid mechanics and aerodynamics, active flow control/plasma flow control. Research Areas: Combustion, Propulsion, Fluid Mechanics, Aerodynamics.



Jun Chen, Assistant Professor of Mechanical Engineering. PhD 2004, Johns Hopkins University. Experimental fluid dynamics; development of flow diagnostic techniques; flow dynamics in stratified environment; and turbulent flow measurements and modeling.



Sanford Fleeter, McAllister Distinguished Professor of Mechanical Engineering. Research Interests: Turbomachinery fluid dynamics, Aero-mechanics, Aero-acoustics, Computational fluids. Research Areas: Fluid Mechanics and Propulsion.



Jay Gore, Reilly University Chair Professor of Engineering and Jefferson Science and Technology Fellow; Research Interests: Combustion, Turbulent reacting flows, Combustion and heat transfer in material processing, and Pollutant reduction. Research Areas: Combustion, Energy Utilization, and Thermodynamics. Bioengineering.



I. Emre Gunduz, Research Assistant Professor. Research Interests: Nanostructured energetic materials, high performance solid and hybrid propellants, near-net shape fabrication, high-power ultrasonics, advanced imaging and characterization.



Steve Heister, Raisbeck Engineering Distinguished Professor for Engineering and Technology Integration, Director Maurice J. Zucrow Laboratories. Research Interests: Aerospace propulsion systems; Airbreathing and rocket engine combustors; Liquid propellant injection systems; Two-phase and capillary flows.



Nicole Key, Associate Professor of Mechanical Engineering, by courtesy in Aeronautics & Astronautics. Research Interests: Aerothermal Aspects of Turbomachinery. Axial and Radial Compressor Performance. Experimental Methods in Fluid Mechanics. Research Area: Fluid Mechanics & Propulsion.

Maurice J. Zucrow Laboratories

ZUCROW LABS FACULTY (cont.)



Robert Lucht, Ralph and Bettye Bailey Professor of Combustion in Mechanical Engineering. Research Interests: Laser Diagnostics. Diode-laser-based Sensors. Gas Turbine and Internal Engine Combustion. Materials Processing and Synthesis. Combustion Science. Fluid Mechanics and Heat Transfer. Research Areas: Combustion, Energy Utilization, and Thermodynamics. Fluid Mechanics & Propulsion.



Terrence Meyer, Professor of Mechanical Engineering. Research Interests: Laser spectroscopy and imaging for combustion, sprays, energetics, hypersonics, plasmas, and non-equilibrium flows. Applications to gas-turbine, rocket, internal combustion, and scramjet engine performance, efficiency, and emissions. Research Areas: Combustion, Energy Utilization, and Thermodynamics. Fluid Mechanics & Propulsion.



Guillermo Paniagua, Associate Professor of Mechanical Engineering. Research Interests: Compact high speed turbomachinery: Design, analysis (experimental-numerical), cavity and tip flows, flow control. High speed propulsion: Novel cycle development, intakes, boundary layer transition, combustion. Development of measurement techniques and data processing. Research Areas: Fluid Mechanics & Propulsion.



Tim Pourpoint, Associate Professor of Aeronautics and Astronautics. Research Interests: Aerospace propulsion systems. Rocket engine combustors. Liquid propellant injection systems. Hypergolic propellants. High pressure and hydrogen storage systems. Research Areas: Propulsion, Energy Storage and Experimental Testing Facilities.



Li Qiao, Assistant Professor of Aeronautics and Astronautics. Research Interests: High-performance fuels for high-speed propulsion systems, alternative and synthetic fuels, fuel synthesis by coal/biomass gasification, endothermic fuels, nanoscale energetic materials, laser diagnostics, experimental fluid dynamics, supersonic and hypersonic combustion, and advanced propellant and propulsion concepts.



Carson Slabaugh, Assistant Professor of Aeronautics and Astronautics. Research Interests: Turbulence-chemistry interactions, swirl combustion, detonation, and thermo-acoustic instability, with an ancillary emphasis on high-bandwidth measurement technique development. Research Areas: Physics of turbulence and combustion in the operating regimes of advanced propulsion and energy systems.



Paul Sojka, Professor of Mechanical Engineering. Research Interests: Spray and spray measurements. Fluid mechanic instability. Research Areas: Combustion, Energy Utilization, and Thermodynamics.



Mikhail Slipchenko, Research Associate Professor of Mechanical Engineering. Research Interest: Methods and instruments development for linear and nonlinear optical spectroscopy and microscopy. Application of high-speed, hyperspectral imaging to nonreacting and reacting flows. Research Areas: Combustion, Energy Utilization, and Thermodynamics. Fluid Mechanics & Propulsion. Nanotechnology.

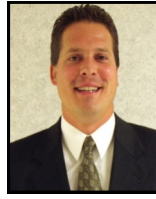


Steve Son, Professor of Mechanical Engineering. Research Interests: Multiphase combustion, particularly related to propellants, explosives, and pyrotechnics. Nanoscale composite energetic materials. Advanced energetic materials. Microscale combustion. Research Areas: Combustion, Energy Utilization, and Thermodynamics.

ZUCROW STAFF



Steve Heister
Director and Raisbeck Engineering
Distinguished Professor



Scott Meyer
Managing Director



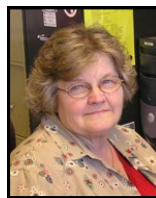
Jennifer Ulutas
Secretary



Edie Moffitt
Business Services



Sheri Dill
Research Account Specialist



Joan Jackson
Building Deputy



Rob McGuire
Supervisor of Technical Services



Shawn Swindle
Electrical & Computer Engineering
Tech

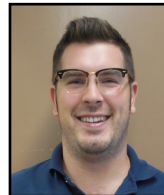
ZUCROW ENGINEERS



Michael Bedard
Propulsion Engineer



Jason Gabl
Test Engineer



Andrew Pratt
Propulsion Engineer

ZUCROW RESEARCH SCIENTIST AND POST DOC



Reid Berdanier
Post Doc



John Fabian
Senior Research Scientist



Swan Sardeshmukh
Post Doc
Research Associate



Natalie Smith
Post Doc



Brandon Terry
Post Doc

Progress on New Infrastructure

Our vision for a new laboratory is being realized thanks to contributions from alumni, Purdue, and the Lilly Endowment. This past summer, our new air heater was installed and is now fully functional. We still have the matter of installing piping (some very expensive piping I might add) to the test cells, but we thank the university for the nearly \$2M investment in MZL infrastructure.

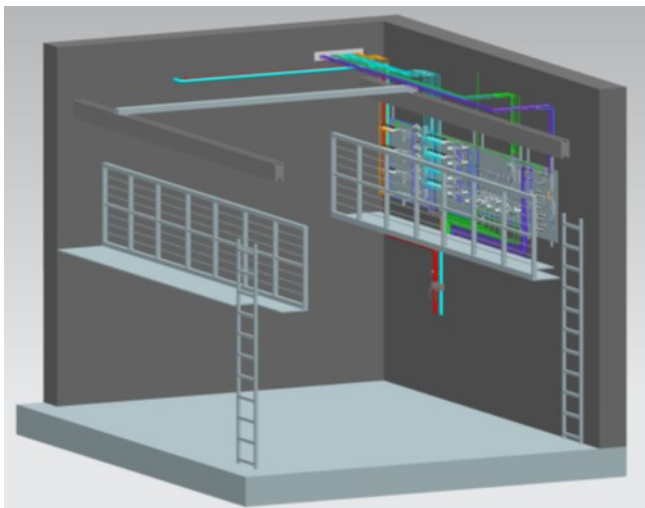


New MZL air heater can deliver 1500 deg. F air at 8 lbm/sec providing capability to simulate compressor exit conditions of most advanced engines

On 8 November, 2015 the construction firm J.R. Kelly provided the low bid of \$5.65M for the construction of the new building and office/control room additions to the existing HPL. We have moved the HPL office spaces to temporary trailers and demo work has already begun in HPL office area as shown in above photo. Prof. Slabaugh and his students are working on the layout for some of the new test cells at our new lab.



Panoramic view of HPL control room/electrical room areas after demolition of all interior walls. Photo taken about 20 January, 2016.



Test cell layout prepared by Prof. Slabaugh's students. Fluid and electrical system panels will be placed overhead in order to maximize floor space. Overhead bridge crane will be used to change rigs as required

Our experience in the current building is helping tremendously here as we try to seamlessly integrate fluid and electrical systems while maintaining floor space. Photo at right shows CAD of current concept.

The university has scheduled a formal ground breaking ceremony for February 22. Too many people were invited to hold the event at Zucrow, so it will be held in the Armstrong Hall atrium instead.

A Special Thanks to AAE, ME, and MZL Alumni Who Made our New Building a Reality

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Purdue alumni contributed over \$2M to the \$8.2M development project that is bringing a new world-class capability to our own Zucrow Lab. We are indebted to the following alumni for their generosity and vision in helping us realize our goals. The faculty, staff, and students of our current MZL want all to know of our deep appreciation for this support.



Trailer that houses current HPL offices and rocket control room (1-30-16)



Water line installed for modified HPL. Amazingly, test operations are still going on. (1-30-16)

Summary of Major Alumni Donations

Test Cell – Terry and Marianne Murphy
Test Cell – Dunville Family
Test Cell – In Memory of Bob Andresen
Test Cell – Ron Kerber
Laser Lab – Stan Tebbe
Conference Room – Tom and Joan Maxwell
Faculty Office – In Honor of Prof. Normand Laurendeau (Gift by Ragnar Avery)
Faculty Office – In Honor of Mr. Thomas Gates (Gift by Ragnar Avery)
Faculty Office – Jeffrey Homsher
Faculty Office – In Memory of Bob Osborn (Ron Derr and Mike Murphy led)
Faculty Office – In Honor of Joe Hoffman (Ron Derr led)
Faculty Office – In Honor of Bruce Reese (Mike Murphy led)
Faculty Office – Bob and Ellen Hostetler
Break Area – Daryl Anderson and Juana Quinones
Control Room – Steve and Susie Baranyk
Control Room – Mike and Sandi Corso
Control Room – Ken and Ann Miller
An anonymous donor \$21K for Building Fund

Maurice J. Zucrow Laboratories

Zucrow's Expansion

Written by Mary C. Nauman, Director of Strategic Initiatives, Corporate and Foundation Relations—Purdue Research Foundation

Fueling New Insights through State-of-the-Art Technology

Although the Maurice J. Zucrow Laboratories expansion begins in February, Zucrow researchers and their collaborators recently celebrated the commissioning of a \$1.1 million combustion rig for advanced diagnostics. This advanced experiment platform will be central to the expansion's new Laser Diagnostics Lab.

"This is an entirely new class of a device," said Prof. Steve Heister, director of Zucrow Labs. "With the Laser Diagnostics Lab, we will be conducting research no one else can do in a way no one else can do it." The Laser Diagnostics Lab is at the "heart" of Zucrow's new test cells. It runs adjacent to each of the five test cells, providing Zucrow's researchers with access to the most advanced optical diagnostics to their experiments. With careful temperature and humidity control, this room will be amenable to the most sensitive laser sources and photonics.

Purdue professors Robert Lucht and Carson Slabaugh designed and developed the combustion rig in collaboration with a major corporate partner, and work was completed in December. Prof. Slabaugh emphasized that the challenge to this project was creating a test article in which advanced measurements (velocity, temperature, chemical species, and pressure) can be conducted from the inside.

"We built the experiment with optical windows that allow us to send the laser light into the flame. In doing so, we can measure the properties of the flame exactly as they are found in real engines. That is very unique," said Prof. Slabaugh. "There are perhaps two other experiments in the world that offer this capability – one is at [the German Aerospace Institute] and one is at the Wright Patterson Air Force Base – both are roughly 20 years old and remain extremely important fixtures in combustion R&D. We are very excited about what we can do here and, as an early career faculty, I am really looking forward to what is ahead."

Zucrow Labs: Expanding Zucrow, Expanding Opportunities

Once the Lilly Endowment announced in January that it will provide the final funding for Maurice J. Zucrow Laboratories' five much-needed test cells, activity at Zucrow hit jet speed.

While finalizing construction plans, the Zucrow research team members' talks with potential funders increased – all eager to discuss the opportunities for collaboration once the test cells are constructed. As of April, Zucrow also became an anchor for the newly established 980-acre Purdue Research Park Aerospace District. The district – which encompasses the Purdue University Airport, Lafayette Aviation and Zucrow Labs – is a unique opportunity for aerospace companies that wish to collaborate with Purdue to build research and development facilities. The site has already been named an Indiana Certified Technology Park by the Indiana Economic Development Corporation.

The Purdue Research Park Aerospace District is owned by the Purdue Research Foundation and will be operated similarly to the foundation's four Purdue Research Park sites around the state where more than 260 research, education and high-tech companies currently employ more than 4,500 people. Parks are located in West Lafayette, Indianapolis, Merrillville and New Albany.



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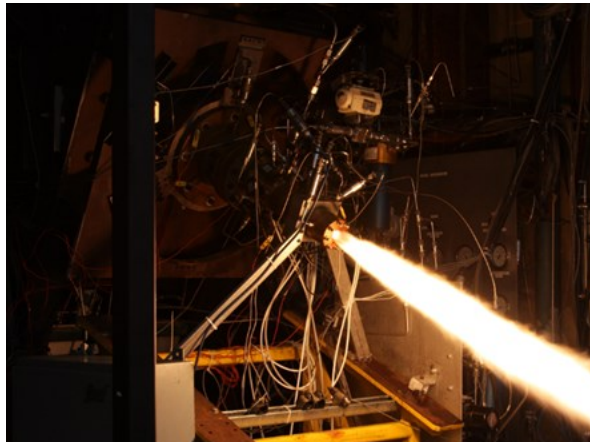
In September, Rolls-Royce announced it will be the first corporate partner to develop a building in the Purdue Research Park Aerospace District. Rolls-Royce will develop a 40,000-square-foot facility that will house its research and development group for its jet engine component research. This marks a new phase in a long-term, strategic relationship for the university, said Purdue President Mitch Daniels.

"Rolls-Royce and Purdue have a deep history of collaboration. Over the years, the company has invested more than \$17 million in collaborative research and development activities at Purdue," said President Daniels. "The company also has nearly 600 Purdue graduates working for it, making it a strong recruiter of Purdue talent. That Rolls-Royce is our first partner in our newly created aerospace district marks a new era in our history with the company." Article was written by Mary Nauman, Director of Strategic Initiatives, Purdue Research Foundation.

Air Force Space and Missile Command Awards Zucrow \$2.1 Million Grant

Prof. William Anderson, professor of Aeronautics and Astronautics, is leading a team of Purdue researchers that was awarded \$2.1 million to help develop design tools that can be used by the United States to predict and prevent combustion instability in its advanced rocket engines.

Prof. Anderson conducts research at Maurice J. Zucrow Lab, specializing in chemical propulsion, design methodologies, and concurrent simulation and experiment. The award from the Air Force Space and Missile Command is part of a two-year collaborative project with Georgia Tech Research Institute, the Air Force Research Laboratory and the NASA Marshall Space Flight Center. It complements other work underway at the lab also funded by the Air Force and directed by Prof. Anderson to provide validation data for advanced, high-fidelity predictions of combustion instability. Other members of the Purdue team include professors Steve Heister, Timothee Pourpoint, Carson Slabaugh, and senior engineer Michael Bedard.



The Purdue research group was awarded \$2.1 million to develop suite of software-based design tools that will improve the stability characteristics in advanced rocket engines.

The goal is to develop a suite of software-based design tools for predicting and analyzing stability characteristics of combustion devices used in hydrocarbon-fueled, oxidizer-rich staged combustion engine cycles with an expected completion date of 2017.

Labs Timeline

Description	Adjusted Projected Dates	Implemented / Scheduled
Board of Trustees Approval	May 2014	May 2014
Hire Architect/Start Design	February 2015	March 2015
Design	February – September 2015	March - October 2015
Construction Bid Award	October - November 2015	December 2015
Construction	December 2015 - March 2017	January 2016 - January 2017
Occupancy	May 2017	February 2017

ZSA (Zucrow Student Association)

President – Jeanne Methel

Treasurer – Alicia Benhidjeb-Carayon

Professional Development Chair – Trey Harrison

Zucrow Student Association (ZSA) is celebrating its fifth anniversary since its inception in 2011 to help build a support network for all people working at Maurice Zucrow Laboratories (MZL) and create a historical context to all activities involved in the research and development mission of our lab. ZSA promotes professional development, outreach and social activities for students, staff and faculty and raise awareness between labs of the different research projects going on.

One of the main activities sponsored by ZSA is the bi-monthly “Lunch and Learn”. Students

are welcome two Thursdays every month to enjoy a free lunch and enrich their professional development. The main purpose of this event is to give students the opportunity to practice giving technical presentations in a relaxed and inclusive atmosphere. Additionally, students are familiarized to the other research projects going on around the different laboratories at MZL. This year, ZSA also invited guests from outside MZL such as Professor Dumbacher from the School of Aeronautics and Astronautics to engage students in a discussion about what the future could hold for engineers, technical communication specialist Joanne Lax to present the basics of academic paper writing and Nicole Barr from the Graduate School to explain the process of graduation.



Purdue campus and smoke stack 1960 with vintage autos

ZSA also organizes social events to encourage students, faculty and staff to mingle and spend time with each other in an informal setting. During the annual Maurice J. Zucrow History Lectures, where distinguished alumni share their stories of their time at the lab, ZSA also organized the lunch cookout party so that the officers' grilling skills were put to the test under Rob McGuire's intense supervision.

For the Purdue vs. Virginia Tech game, ZSA also put together one of the tastiest tailgate parties ever with homemade pulled pork and chicken, the whole of it topped off with a flyby of two F-18s. Finally, ZSA held its main fundraising campaign by selling Purdue Pro-

pulsion apparel, including mugs, caps, jackets and polos so current students and alumni can proudly wear their MZL colors.



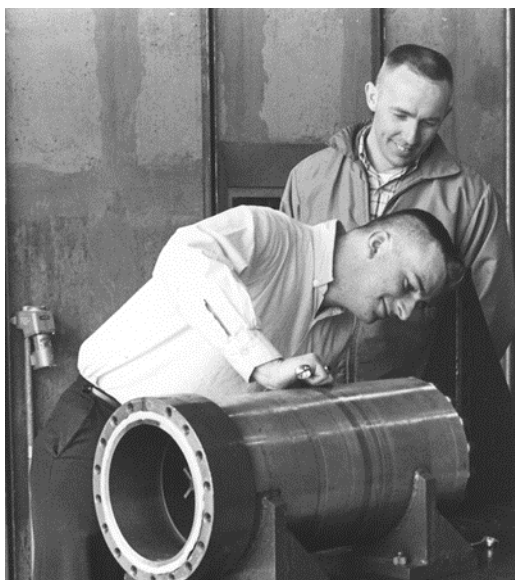
Zucrow Lab History Lectures

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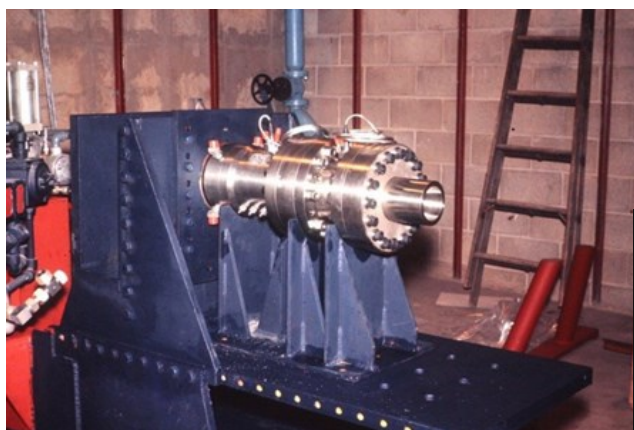
In 2015, MZL held two sets of History Lectures. On April 10th, Drs. Robert Strickler and Walter O'Brien gave lectures entitled, "If you come to a fork in the road, take it", and "It started at the Lab", respectively. Due to illness, Dr. O'Brien's talk had to be given via speakerphone, but the audience got to learn first hand about life at Purdue and at the lab in the early 1960's. Dr. Strickler's talk focused not only on his experiences at Purdue in the "The Rocket Lab" in the 1960's, but also on his career decisions that ultimately led him to Vice President-level positions at TRW. Dr. Strickler also explained his role as key designer of the high pressure lab and showed hardware from our highest pressure rocket test ever conducted (3600 psi chamber pressure).



Dr. O'Brien (and dog), circa 1960



Dr. Strickler (in foreground), circa 1960



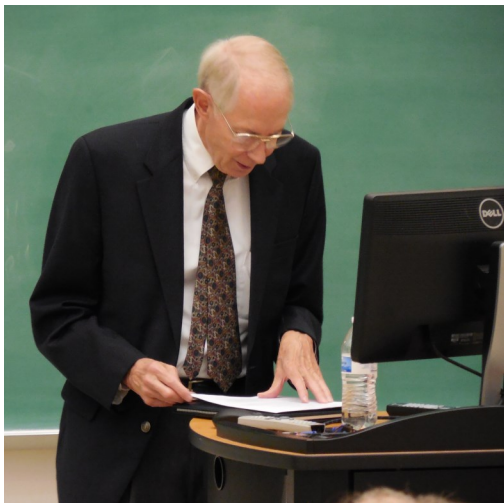
Nitrogen tetroxide ox-rich gas generator with chamber pressure of 3600psi. Designed and operated by Dr. Strickler in mid-1960's



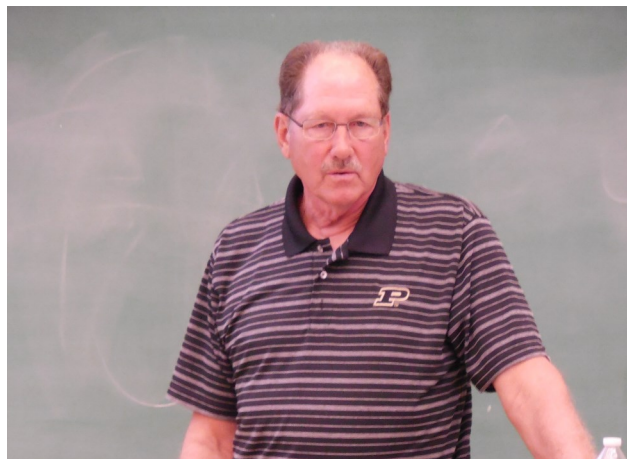
Data acquisition circa 1960

Maurice J. Zucrow Laboratories

On October 9th, we had two other contributions to the MZL History Lecture series. Dr. George Schneider described his days at the lab in the 1960's and his career in the ballistic missile defense field, eventually as a participant at the famous Strategic Arms Limitations Talks (SALT) in the early 1970's. Dr. Lynn Snyder then described his time at the lab and his career in the gas turbine industry at Pratt & Whitney, and mainly at Allison (now Rolls-Royce Liberty Works) in Indianapolis.



Dr. George Schneider



Pictured : Dr. Lynn Snyder



Invited Lecturers

April 10, 2015– Dr. Walter O’Brien– *“It Started at the Lab”*

April 10, 2015– Dr. Bob Strickler– *“When You Come to a Fork in the Road, Take It!”*

May 14, 2015– Dr. John Bennewitz *“High Frequency Combustion Instability Control through Acoustic Modulation at the Inlet Boundary”*

June 29, 2015—Professor Fei Qi *“Recent Advances of Synchrotron VUV Photoionization Mass Spectrometry in Combustion and Energy Researches”*

July 18, 2015—Michael Oschwald *“The DLR Institute of Space Propulsion, Lampoldshausen, Germany”*

September 14, 2015—Dr. Dave McGrath *“Controllable Solid Propulsion at Orbital ATK Elkton”*

October 9, 2015– Dr. George Schneiter *“MJZL History Lectures”*

October 9, 2015– Dr. Lynn E. Snyder *“MJZL History Lectures”*

November 10, 2015—Dr. Steven J. Beresh *“Pulse-Burst PIV in High-Speed Flows”*

November 16, 2015– Dr. Daniel R. Guildenbecher *“Digital Inline Holography as a Multi-phase Flow Diagnostic”*

December 10, 2015– Dr. Steve Heister *“Confessions of a Schizophrenic Pyromaniac– A Career in Aerospace Propulsion”*

*This is not an all-inclusive list

Maurice J. Zucrow Laboratories

2015 Zucrow Social Events

Zucrow's Semi Annual, "when-we-remember-to-do-it" Golf Outing
August 7, 2015



ZSA Tailgating before the Purdue vs. Virginia Tech game.



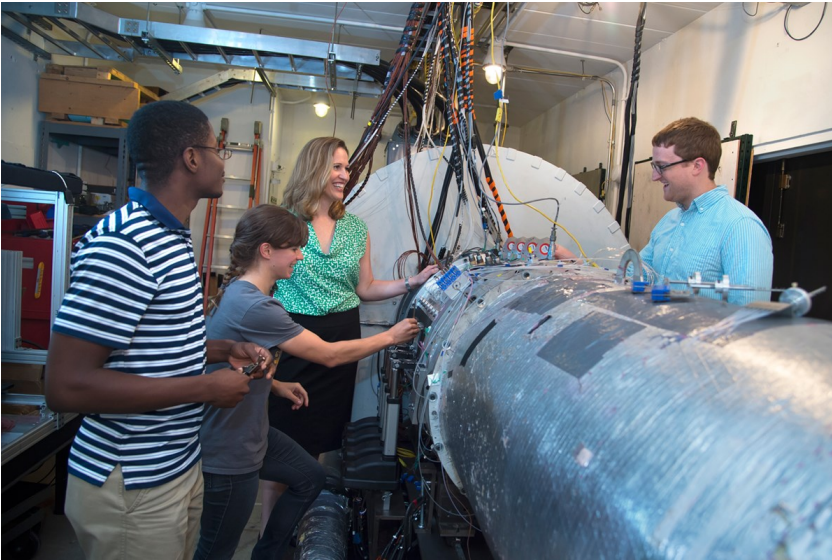
Zucrow Christmas Party
December 11, 2015
West Lafayette Golf and Country Club



Research Advancing Next-Generation Compressor Technologies

By Emil Venere

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Researchers check the instrumentation on Purdue's current three-state axial compressor before a test. (From left) Nyansafo Aye-Addo, PhD student in AAE; Natalie Smith, postdoctoral research associate who completed her master's and PhD AAE degrees in this lab; Professor Nicole Key; and Reid Berdanier, graduate research fellow who completed an MSME and is completing a PhD in this lab. Purdue University photos/Mark Simons

Rolls-Royce is developing high-performance compressor technologies for next-generation jet engines, and much of the research to develop the enabling technology is based at Purdue's Maurice J. Zucrow Laboratories.

"This work will immediately impact the industry because the data are getting folded into design methods and future engine concepts currently being developed at Rolls-Royce," says Nicole Key, associate professor of mechanical engineering. "We have a good team in place."

Her group has two grants from Rolls Royce — one each for axial and radial compressor research — totaling several

million dollars. The team includes four graduate students, a postdoctoral researcher and a research scientist. Because of a tight timetable, the researchers will have the test rigs fabricated by a vendor. "It's a really aggressive program but an amazing opportunity," Key says. "The good thing is we've already been running similar kinds of rigs for Rolls-Royce, and we have an excellent capability as far as taking measurements with high accuracy and good resolution."

An important challenge facing engine manufacturers is how to design the rear stages of a "small core" compressor. "The rear stages become physically small, and this makes the losses associated with endwall regions more significant," Key says.

She and her group have been studying the effects of relatively large rotor tip clearances for NASA the last four years.

"Through the NASA project, we invested in hardware and instrumentation that allows us to better understand the development of these flows and how they affect the losses in the downstream stages," Key says. "I'm excited to extend this work to a current state-of-the-art compressor design."

The current three-stage axial compressor utilized in the laboratory has been operating for about 15 years with the majority of its funding from Rolls-Royce. The compressor is being re-designed to match Mach numbers and Reynolds numbers and blading styles consistent with next-generation engines. This is possible because of a lab renovation led by Key in 2009, where 1,400-horsepower electric motors were installed in the test cells, allowing operation of compressor research vehicles with higher pressure ratios and higher speeds.

"Purdue is one of the few places in the world where this kind of research can be performed and that is thanks to the investment the university has made in critical infrastructure," she says.

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Cont.....

A long history of collaboration

The compressor lab at Purdue has been working on centrifugal compressors with Rolls-Royce since 2009. More recently, researchers in the lab have been studying the effect of tip clearance size and diffuser design on the overall compressor performance.

The new centrifugal compressor facility will incorporate inlet flow features that mimic the engine transition duct between the axial stages and the centrifugal stage providing an opportunity to understand the impact of these non-uniform inlet flows on impeller performance.

The new centrifugal compressor facility is a researcher's dream — it is always challenging to get flow-field measurements in these machines, but a close collaboration between Purdue, Rolls-Royce, and the rig supplier ensures that instrumentation access will be excellent," Key says.

The team utilizes standard probes to measure temperature and pressure, but fast-response transducers that can track the passing of the individual blades are also used in the lab. Additionally, plans for laser-based velocimetry measurements ensure that the team will understand the flow field without the effect of probe interference.

"This research is satisfying on many levels. We know we are impacting a the future of engine design and yet we are able to simultaneously investigate many fundamental questions associated with these complicated flow fields."

The ultimate goal of this research is to advance the state of the art in performance and operability for next-generation axial and centrifugal compressors.

"The test and measurement capabilities being developed by Dr. Key at Zucrow and implemented on our compressor rigs will be the cornerstone of future compressor design methods and have far reaching impact across Rolls-Royce business units and future products," says Nate Cooper, chief of Compressor Sub-System, AES Tech Demo at Rolls-Royce.

He says the rigs at Purdue are in the process of being upgraded with the latest design methodologies and engine representative features that will ensure developed technology will transition into future products.

"Technologies developed will increase the power-to-weight of next-generation engines while increasing component efficiency," Cooper says. "Novel blade and vane profiles that increase the compressor's loading (pressure ratio / stage) will be evaluated using the latest in non-intrusive measuring techniques to validate and update computational models."



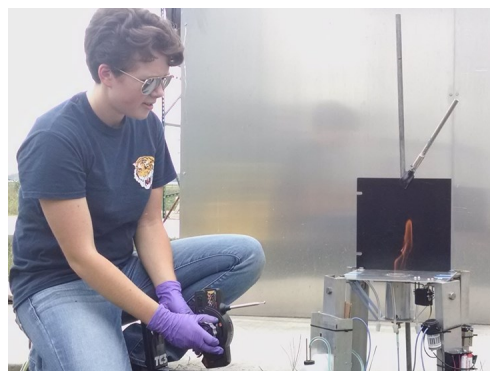
Jeanne Methel, an AAE master's student, calibrates a tip clearance measurement probe for the current centrifugal compressor CSTAR facility. Purdue University photos/Mark Simons

The 2016 Indiana Bicentennial Torch is, truly, a Hoosier Made High-tech Torch!

Designed by a team of Purdue Engineering students, staff, and faculty led by AAE and Zucrow Laboratories Associate Professor Timothée Pourpoint, the torch is inspired by the Indiana State Flag. It will be carried by more than 1800 people during a five-week relay in September and October 2016.

At just under 24 inch tall, the torch is made out of an aluminum shell and includes many unique features. For example, AAE students developed an E-85 burner and feed system capable of sustaining a flame for 45 minutes. With their ABE and ECE counterparts, they designed a system that provides a rich and highly visible flame that can be automatically shut-off based on an internal electronic gyroscope. The torch is also fitted with a GPS for high accuracy and near real-time positioning and tracking and an HD camera for photos and videos connected to social media.

The final torch design was unveiled by Governor Pence on Statehood Day, December 11, 2015. The detailed specifications can be found at: <http://www.in.gov/ibc/torchrelay/index.htm> and <http://www.in.gov/ibc/torchrelay/3150.htm>



Gabby Feldman - Purdue Undergraduate in AAE works on an experimental burner for the Indiana Torch – Zucrow Laboratories,

Among the many press releases about this symbol of Indiana:

<http://www.indystar.com/story/news/2015/12/11/bicentennial-torch-tour-indiana/77111532/>

<http://www.insideindianabusiness.com/story/30727869/purdue-teams-bicentennial-torch-unveiled>

The following YouTube video is also a great way to learn more about this project:

https://www.youtube.com/watch?v=ZB_TvgxDbZg

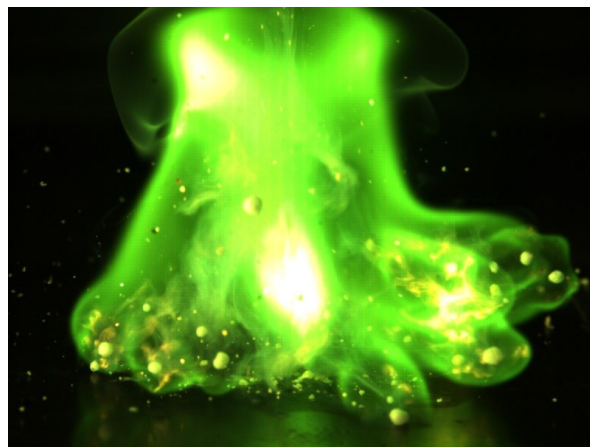


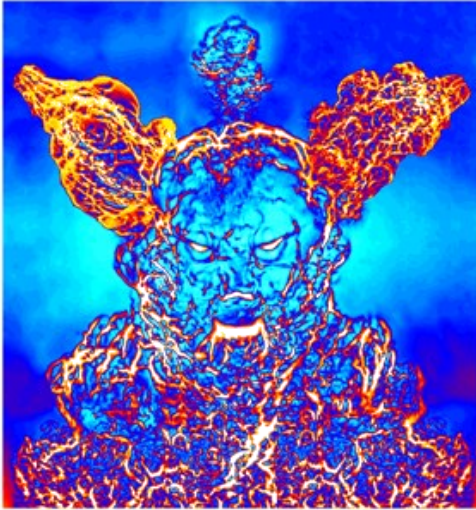
Purdue students from the College of Engineering bring a very special package to the Indiana Bicentennial Kickoff Event at the Indianapolis State House. (Statehood Day, December 11, 2015) Photo by: Karen Marais



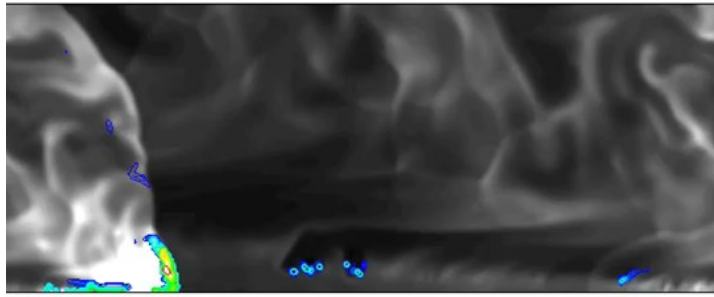
Purdue team discusses the design of the Indiana Bicentennial Torch with Governor Pence on December 11, 2015. Photo by: Indiana Statehouse Staff

ROTC Internship at Zucrow

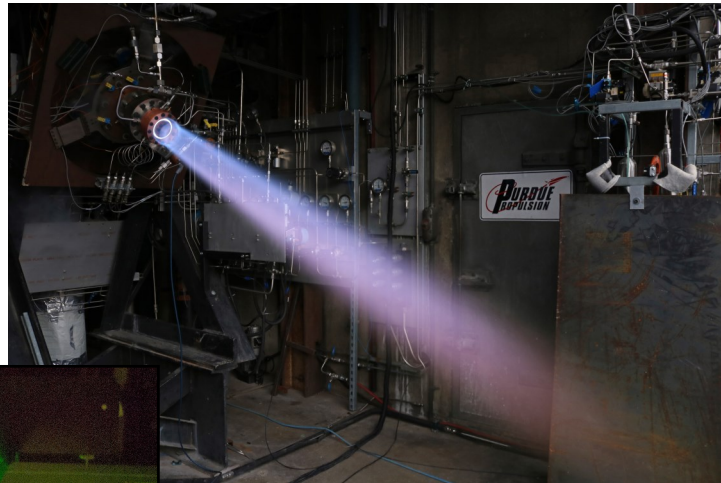




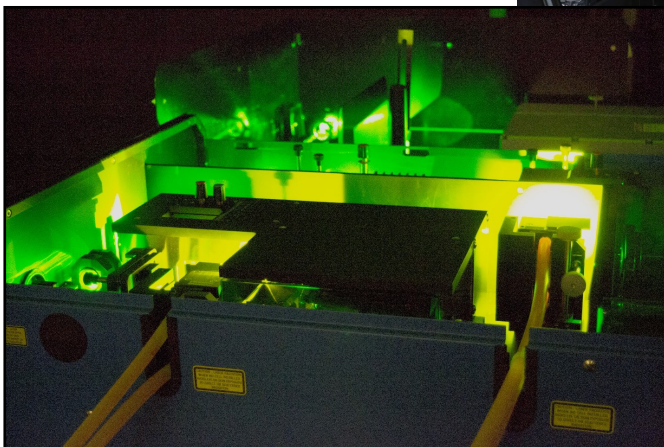
Graduate student Sayan Biswas won the 2015 Combustion Art Competition award from the Combustion Institute for his work
“Afrit (Arabian mythology) - The Fire Monster



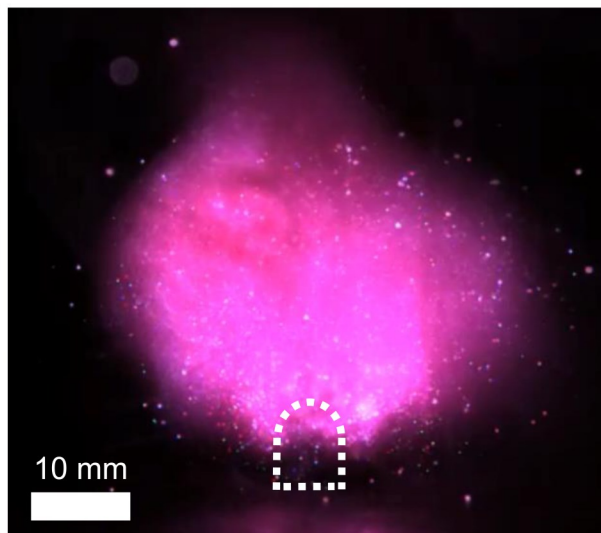
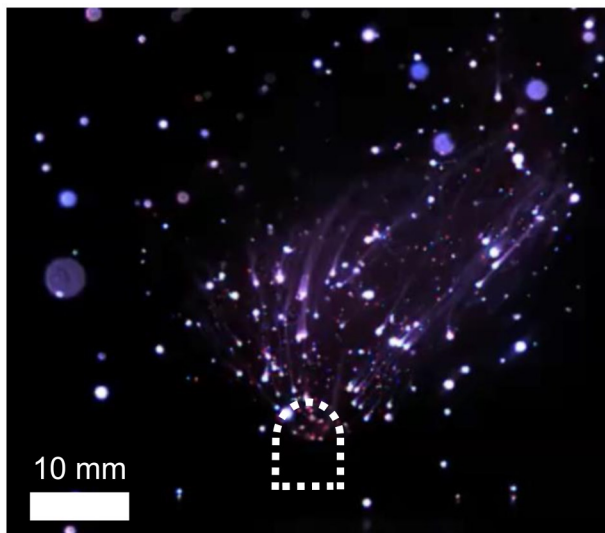
Top: Simulation of combustion in rotating detonation engine



Top: Pulse detonation rocket engine combustion



Left: Green laser is pumping a tunable dye laser system to produce a specified wavelength based on the dye and solvent selection. In this case 566nm beam for OH PLIF for propellant combustion experiments



Left: Traditional solid rocket propellant vs. on the right Aluminum lithium alloy-higher performance/ environmentally cleaner.

MJZL Current Graduate Students

Maurice J. Zucrow Laboratories

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Adams, Zachary	J. Chen	adams31
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Athmanathan, Venkat	J. Gore	vathmana
Atyam, Deepak	T. Pourpoint	datyam
Aye-Addo, Nyansafo	N. Key	payeaddo
Back, Cory	W. Anderson	backc
Baier, Michael	S. Son/R. Lucht	mbaier
Bangalore, Prashanth	S. Bane	pbangalo
Basak, Prithviraja	J. Gore	pbasak
Beason, Matthew	S. Son	mbeason
Bedard, Michael	S. Son	mbedard
Belal, Hatem	S. Son/ V. Ortalan	hbelal
Benhidjeb-Carayon, Alicia	T. Pourpoint	abenhidj
Bishop, Gina	S. Heister/T. Fisher	bishop25
Biswas, Sayan	L. Qiao	biswas5
Black, Ariel	T. Pourpoint	ablack
Bokart, Andrew	R. Lucht	abokart
Braun, James	G. Paniagua	jbraun
Brooks, Amelia	N. Key	brooks
Busari, Tobi	R. Lucht	tbusari
Buschhagen, Timo	R. Lucht	tbuschha
Casey, Alex	S. Son/T. Meyer	caseya
Cummock, Nick	S. Son	ncummock
D'Antuono, Domenico	W. Anderson	ddantuon
Davis, Cameron	N. Key	davis916
De Maesschalck, Cis	G. Paniagua	cdemaess
Engerer, Jeff	T. Fisher	jengerer
Fuller, Tristan	W. Anderson	fuller27
Gejji, Rohan	W. Anderson	rgejji
Gonzalez Cuadrado, David	G. Paniagua	gonza279
Gooding, William	N. Key	wgooding
Goyal, Vikrant	J. Gore	goyal21
Graziano, Tyler	S. Bane	tgrazian
Griffin, Ryan	C. Slabaugh	griffi29
Hallum, Zach	W. Anderson	whallum
Han, Dong	J. Gore	han193
Harry, Jacob	T. Pourpoint	jharry
Hasti, V. Raju	J. Gore	vhasti
Huang, Shouyuan	Xu/S. Heister	huang706
Hunt, Steven	S. Heister	hunt54
Juangphanich, Paht	G. Paniagua	nsa
Justice, Andrew	Son/Gunduz	justicea
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MJZL Current Graduate Students (cont...)

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Leng, Yujun	S. Fleeter	leng
Lim, Dasheng	S. Heister	lim37
Liu, Thomas	W. Anderson	liu1657
Liu, Zhe	G. Paniagua	liu1752
Lou, Fangyuan	N. Key	louf
Mares, Jesus Jr.	S. Son	maresj
Mathews, Joshua	T. Pourpoint	mathew15
Matthews, Doug	N. Key	dmatthews
Methel, Jeanne	N. Key	jmethel
Mikoshiba, Kota	T. Pourpoint	kmikoshi
Miller, Jacob	S. Son	mille411
Mishler, Luke	S. Son	lmishler
Mugenda, Angela	S. Bane	amugenda
Nur, Mononita	T. Pourpoint	mnur
Orth, Michael	T. Pourpoint	orthm
Powell, Michael	S. Son	powell84
Rahman, Kazi Arafat	T. Meyer	rahman34
Ramachandran, Raghav	S. Son	raghav
Roberts, Zane	S.Son/Rhodes	robertsz
Rocha, Jonathan	P. Sojka	rocha0
Saavedra, Jorge	G. Paniagua	saavedra
Schwinn, Kyle	S. Slabaugh	kschwinn
Shang, Weixiao	J. Chen	shangw
Shao, Jiayun	J. Gore	shao22
Sousa, Jorge	G. Paniagua	fernan57
Stechmann, David	S. Heister	dstechma
Vaughn, Nicole	C. Slabaugh	nvaughn
Vuppuluri, Vasant	S. Son	vvuppulu
Wallace, James	N. Key	wallacej
Whitehead, Benjamin	T. Pourpoint	whitehe3
Wiest, Heather	S. Heister	hwiest
Willits, Jared	T. Pourpoint	jwillits
Zhang, Robert	R. Lucht	zhan1599
Zheng, Yutao	G. Paniagua	zheng277

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MJZL Recent Graduates

Graduate	Advisor	Thesis Title	Career Destination
Adams, Jesse	J. Gore	Minimum Hot Surface Ignition Temperature Diagnostics Including Infrared Imagery.	
Berdanier, Reid	N. Key	An Experimental Study of Tip Clearance Effects in a Multi-Stage Axial Flow Compressor	Purdue– Post Doctoral Research Associate
Buschhagen, Timo	J. Sullivan	Performance Analysis of Vortex Based Mixers for Confined Flows	Continuing on towards PhD
De, Narendra	S. Son	Photoflash and Laser Ignition of High-Nitrogen Materials.	SpaceX
Dolan, Matthew	N. Key	Establishing Repeatable Operation of a Centrifugal Compressor Research Facility for Aerodynamic Investigations	Alambic Investment Management
Dubitsky, Andrei	S. Heister/ X. Xu	Performance Evaluation of an Automotive Thermoelectric Generator	Aerospace Corp.
Fugger, Chris	W. Anderson	Experimental Investigation of a Reacting Transverse Jet in a High Pressure Oscillating Vitiated Crossflow	AFRC, Dayton OH
Fuller, Tristan	W. Anderson	Review of Chemiluminescence as an Optical Diagnostic Tool for High Pressure Unstable Rockets	Continuing on towards PhD
Gao, Xiangyu	J. Chen	Characterization of Wake Effects and Loading Status of Wind Turbine Arrays under Different Inflow Conditions	PhD Program at the University of So. Cal.
Hey, Joel	T. Fisher	Testbed Design, Implementation, and Model-Based Validation for Aircraft Thermal Management Systems	Sandia National Laboratory
Huang, Cheng	W. Anderson/H. Wang	Fundamental Insights into Combustion Instability Predictions in Aerospace Propulsion	Post Doc
Iser, Sarah	S. Son/ R. Lucht	In Situ Flame Structure Imaging of Composite Propellants using High-Speed Planar Laser-Induced Florescence	Army Research Laboratory
Kumar, Nitish	J. Gore	Role of Catalysts in Biomass Gasification with Carbon Dioxide	PhD Program at Georgia Tech
Lim, Dasheng	S. Heister	Transient Response of a Liquid Injector to a Steep-Fronted Transverse Pressure Wave	Continuing on towards PhD
Lou, Fangyuan	N. Key	A Study on Flow Development in an APU-Style Inlet and its Effect on Centrifugal Compressor Performance	Continuing on towards PhD
McBain, Andrew	S. Son	Laser Ignition of Select Hexanitrohexaazaisowurtzitane (HNIW or CL-20) Cocrystals	Chrysler
Meier, Eric	S. Heister	Investigation of Combustion Control in a Dump Combustor Using the Feedback Free Fluidic Oscillator	NASA Kennedy Space Center
Panda, Pratikash	R. Lucht	Structure and Dynamics of a Reacting Jet Injected into a Vitiated Crossflow in a Staged Combustion System	Sandia National Laboratory
Pratt, Andrew	R. Lucht	The Application of Stereoscopic PIV in a Liquid-Fueled Gas Turbine Combustor.	Purdue– Propulsion Engineer
Schenk, Matthew	S. Heister	Non-Thesis	Valley Tech Systems, Inc.
Smith, Natalie	N. Key	An Experimental Study on the Effects of Blade Row Interactions on Aerodynamic Loss Mechanisms in a Multistage Compressor	Southwest Research Institute

MJZL Recent Graduates (cont.)

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Snyder, Sha- ron	P. Sojka	Spatially Resolved Characteristics and Analytical Model- ing of Elastic Non-Newtonian Secondary Breakup	Raytheon– Missile Systems
Steiner, Matt	T. Pourpoint	The Development of Reactive Fuel Grains for Pyrophoric Relight of In-Space Hybrid Rocket Thrusters	SpaceX
Stoot, Ste- ven	S. Bane	Combustion Characteristics of Hypergolic Microdroplets	SpaceX
Tamanampudi, Gowtham	W. Anderson	Reduced Order Modeling and Analysis of Combustion Instabilities	Continuing on towards PhD
Tian, Shengguang	J. Gore	Non-Thesis	F. Tech R&D North America Inc.
Terry, Bran- don	S. Son	Alerted Combustion Characteristics of Metallized Energet- ics Due to Stable Secondary Material Inclusion	Post Doc.- Purdue University
Wang, Weichao	J. Gore	An Experimental Investigation of a Premixed Laminar Flame Using Tunable Diode Laser and Quantitative Imag- ing of Radiation Intensity	Cummins
Waters, Es- sene	T. Pourpoint	Development of a Component Design Tool for Metal Hy- dride Heat Pumps	Post Doc
Zarbo, Nick	T. Pourpoint	Characterization of Moisture and Water Content on Ignition and Combustion of Hypergolic Propellants	Virgin Galactic
Zaseck, Chris	S. Son/T. Pourpoint	Development of High Performance Paraffin-Based Hybrid Fuels	Blue Origin

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