PURDUE
UNIVERSITY

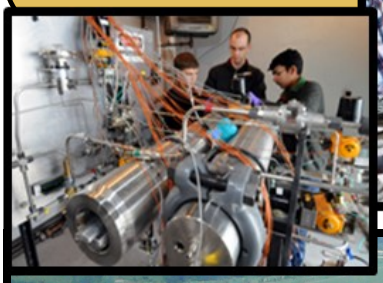
# 2010-2011 ANNUAL RESEARCH REPORT

## MAURICE J. ZUCROW LABORATORIES

**School of Mechanical Engineering**

**School of Aeronautics and Astronautics**

Wind Engineers: (from left) Doug Adams, professor of mechanical vvengineering, Sanford Fleeter, the McAllister Distinguished Professor of Mechanical Engineering, Brandon Ennis (MSME '09) and Jonathan White (PhD '09) at the Benton County Wind Farm in Fowler, Indiana.



PURDUE ENGINEERING



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# ….from the DIRECTOR

Colleagues, Alumni, and friends of the Maurice J. Zucrow Labs:

I am pleased to provide my initial input to you in this annual report. As many of you know, it has been over a decade since we have had a lab director at MJZL and I am honored to be chosen to serve in this role as of 1 April of 2011. As you might imagine, there are many things to report to you and I hope that you find this document informative and rewarding. Those who are alumni will be proud to know that the lab is doing very well with over 100 current students pursuing degrees in diverse areas including wind energy, rocket propulsion, gas turbine propulsion, blood flow in heart valves, energetic materials, coal gasification, bio-inspired air vehicles and numerous other diverse topics as outlined in the student section of this report.

The MJZL has had a busy year that featured visits from NASA Chief Administrator, General Bolden and Purdue President France Cordova. The lab has become a shining example of multidisciplinary research as affiliated faculty from seven different schools of engineering and also from the school of science pursue collaborative work with MJZL faculty and staff. Scott Meyer continues as the MJZL Managing Director and has made numerous upgrades to both office and lab spaces and Rob McGuire continues as our Technical Services Supervisor helping out with many machinist and technician functions. Charlotte Bell is our Administrative Assistant and we owe her great gratitude for all her efforts for the lab (including preparing this report). Our business services staff, Starr Crystal, Joan Jackson and Michelle Kidd provide tremendous support to the team as they process 30-40 purchase orders per day and help us spend over $8M this year in research funds.

My main job over the past 8 months has been in developing a strategic plan for the laboratory and I wish to thank all our faculty and some of our alumni for helping me in this capacity. The lab is in need of additional test cell and general lab space as all our cells are presently occupied and quite busy. Chaffee Hall is also quite full as every desk is now assigned at present. We hope that we can refine this plan and secure funding for additional lab space; perhaps some of you are excited about the prospects of partnering with us in this regard.

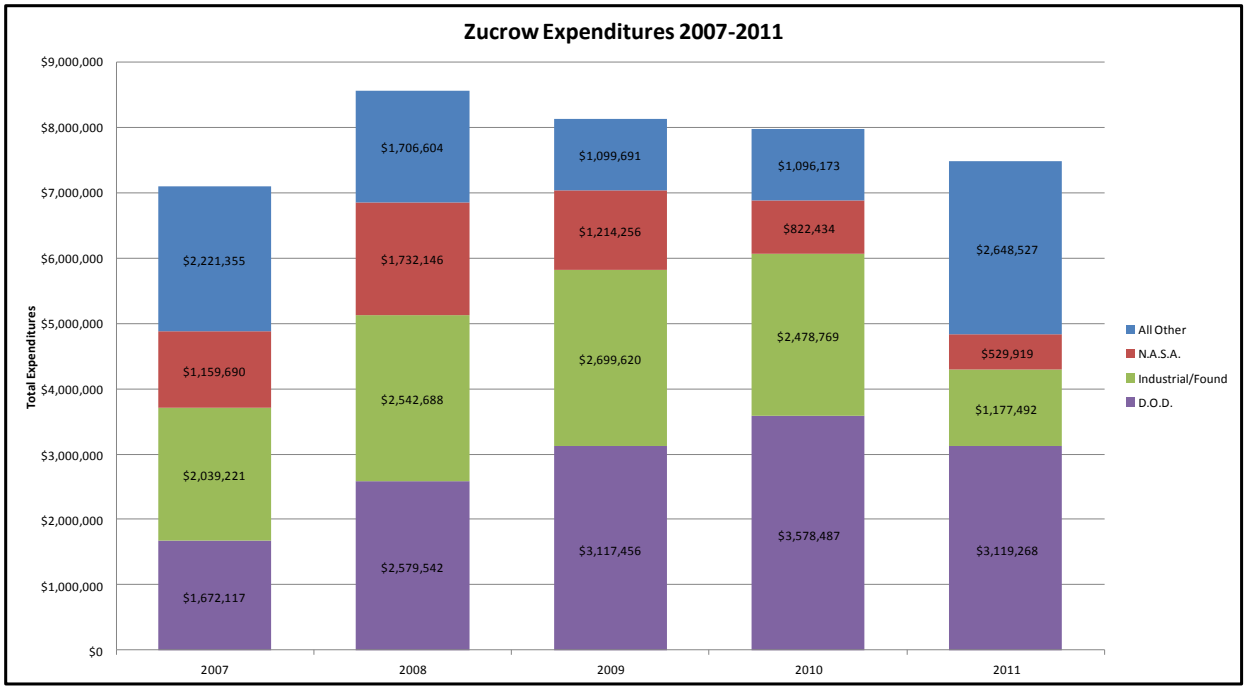
As a final word, I have a request for you. We have begun the arduous task of assembling an alumni database from a lab that is over 60 years old and fear that we have missed many in this process. Please help us if you would to identify alumni who may not be included in our database. If you wish to help in this regard, please send email to Charlotte (bellce@purdue.edu) and she can share the current database with you.

Thanks and best regards, and of course Hail Purdue!

Stephen (Steve) Heister, Raisbeck Distinguished Professor
Schools of Mechanical Engineering and Aeronautics and Astronautics

# 2010-2011 Research Highlights

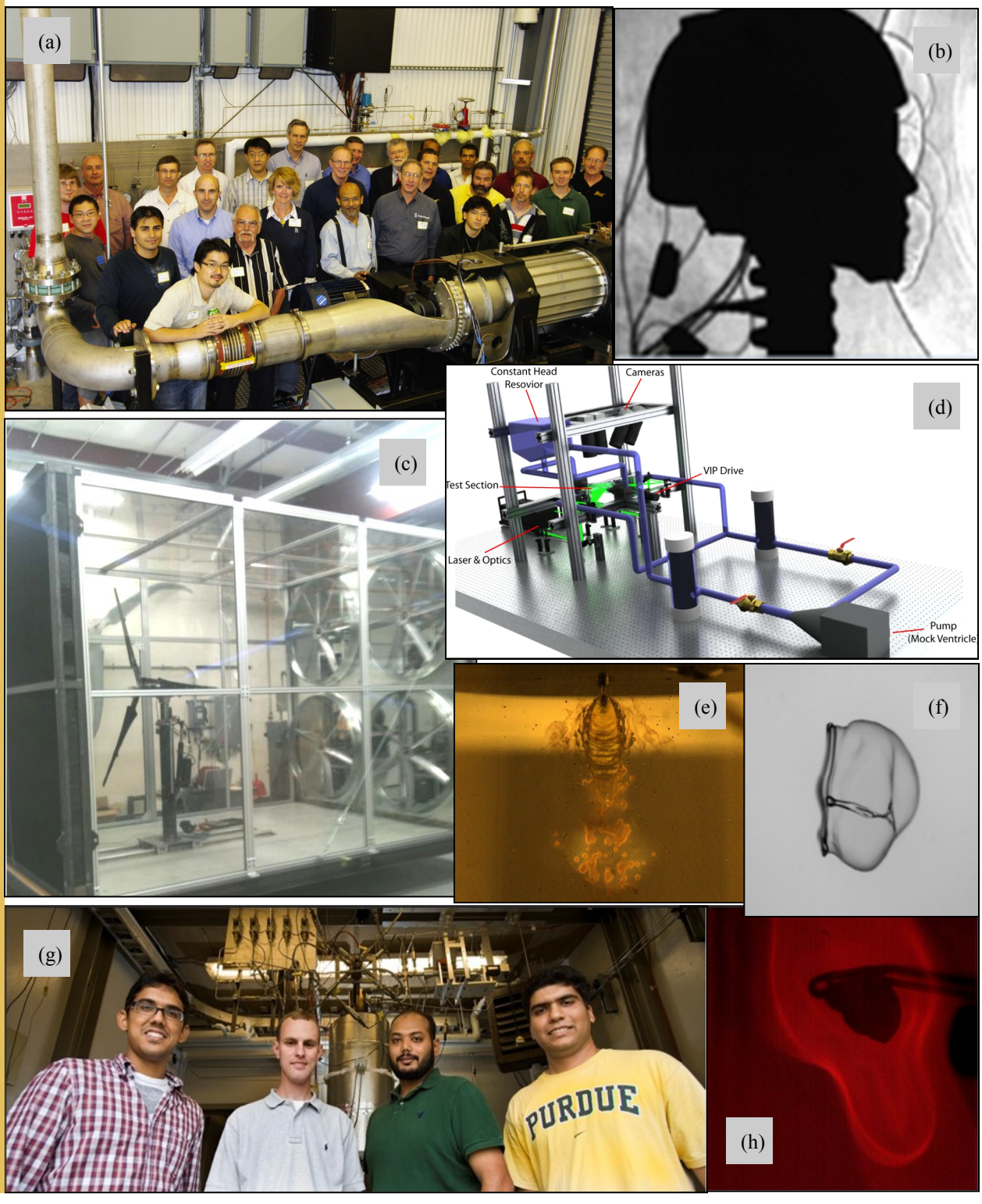
MJZL Research expenditures are summarized in the chart and table below. The lab continues to be very active, and a global view shows heavy funded activity in 15 of our 16 test cells and high utilization of general lab space as well. In rough measure the lab is spending about $8M in research funds per year. Major programs are highlighted in the table below. Other significant sponsors include: NIH, MDA, Sandia, GM, GE, Caterpillar, CCTR, and ONR. The following page provides some highlights of recent research results from some of the programs. The ARO MURI project necessitated the development of a new lab. Our Gelled Propellants Lab, GPL, housed within the Propulsion Lab took shape in 2009 and is a unique facility designed for evaluation of toxic hypergolic propellants monomethyl hydrazine and red fuming nitric acid. Professor Pourpoint was the chief designer and developer of this unique capability.




| Project | Sponsor | MZL PIs | Annual Budget |
|---|---|---|---|
| Gelled Propellant MURI, Droplet Energetics | ARO | Anderson, Sojka, Son, Lucht, Merkle, Pourpoint, Heister, Qiao | $1.5M |
| Biomass Gasification Studies | AFOSR | Agrawal, Gore, Lucht, Qiao, Ribeiro, Delgass | $1M |
| Rockets, Biomass Reactors | AFOSR | Anderson, Heister, Son, Pourpoint | $900K |
| Various Rocket Projects | NASA | Anderson, Merkle, Lucht, Heister, Son, Pourpoint | $750K |
| Hydrogen Storage, Wind Turbines | DOE | Gore, Pourpoint, Fleeter | $750K |
| Comb. Lasers, Low Reflight | NSF | Lucht, Qiao, Deng | $750K |
| High Mach UTC, Compressors | Rolls-Royce | Sojka, Heister, Key | $600K |
| Gas Turbine Combustion | Siemens | Anderson, Lucht | $300K |
| Energetic Materials | DTRA | Son | $300K |
| Carbon Nanotubes | NSF | Lucht, Fisher, Gore | $150K |
| Graduate Student Salary Support | Cummins | Gore | $50K |
| Graduate Student Salary Support | Crane | Gore | |

# MJZL Highlights (cont.)

**Research Collage**: (a) - Wave Rotor Combustion Rig team, (b) - Prof. Son's blast injury mitigation work, (c) - Wind turbine in Prof. Fleeter's tunnel, (d) - Index-matched mock loop for blood pump experiment in Prof. Chen's lab (funded by NIH and collaborated with Prof. Frankel), (e) - Prof. Pourpoint's gelled hypergol combustion rig, (f) - Prof. Sojka's work on gelled drop atomization, (g) - Prof. Gore's coal gasification rig and team, (h) - Prof. Anderson's work on gelled drop combustion



# Zucrow Students Association (ZSA)

In September of 2011, Professor Heister solicited inputs from students in forming a local association at MJZL. Student interest was high and current M.S. student Andrew Rettenmaier and Ph.D. student David Reese agreed to head up formation of the new student group. The ZSA has been created to serve and represent the interests of Zucrow students and faculty by providing historical context to lab activities, organizing social events, and maintaining resources for all students consistent with the research and development mission of our historic laboratory.

PhD student Matt Wierman chats with NASA Chief Administrator General Bolden

As part of this mission, ZSA intends to begin by building an outreach program and a student development program. Planned outreach efforts include:

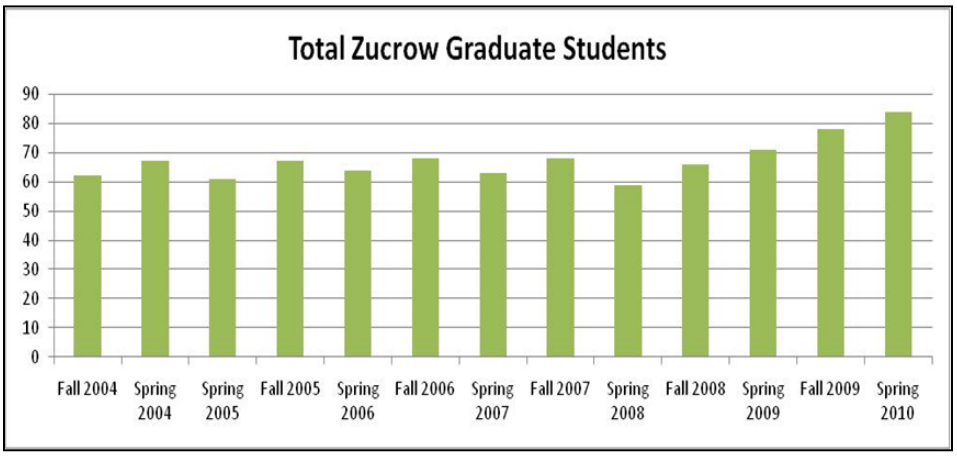
- Obtain a Purdue "Service Learning Grant" in the Spring 2012 semester to fund outreach programs with local schools.
- Arrange lab tours for undergraduates to excite/encourage them to attend grad school.
- Arrange workshops with local STEM teachers to supplement their teaching/lessons.
- Present a community outreach day.

Supersonic Combustor/Afterburner Rig (SCAB) Designed and Built by Ph.D. Student Adam Trebs

In general, ZSA envisions reaching out to local grammar schools to encourage students to pursue STEM related careers, undergraduates to pursue a higher education, teachers to supplement their curriculum, and the community to increase our exposure as a group doing cutting edge research. The student development program will focus on monthly presentations. Each month, 3 students will present a 5-10 minute topic related to their current work. This will offer students the ability to practice in front of an audience of their peers for conferences with feedback to strengthen their speaking ability. Consequently a new forum for the exciting research being done at Zucrow will be created.

Professor Key's Students Natalie Smith and John Brossman with 3-Stage Axial Compressor Hardware

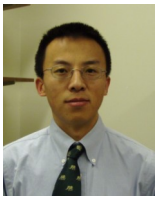
In addition to these efforts, an alumni group has been created to help preserve the rich history of Zucrow and its former students and faculty. Students have catalogued all alumni from existing theses dating back to the late 1940's thesis of the late Walter Hesse.



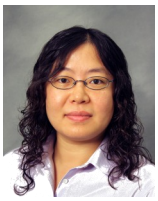
# ZUCROW LABS FACULTY

**John Abraham**, Professor of Mechanical Engineering Research Interests: Multiphase Flows, Combustion, Internal Combustion Engines, Computational Fluid Dynamics. Areas: Combustion, Energy Utilization, and Thermodynamics.

**Bill Anderson,** Associate Professor of Mechanical Engineering (by courtesy), Associate Professor of Aeronautics and Astronautics. Research Interests: Chemical Propulsion and Design Methodoligies. 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.



**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.



**Xinyan Deng,** Assistant Professor of Mechanical Engineering. Research Areas: Systems, Measurement, and Control.

**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.

**Stephen Frankel,** Professor of Mechanical Engineering. Research Interests: Combustion, Turbulent reacting flows, Computational fluid dynamics, Aeroacoustics, Multiphase flow. Research Areas: Combustion, Energy Utilization, and Thermodynamics. Bioengineering.

**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.

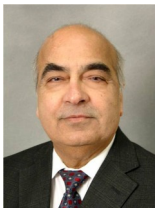
**Lori Groven,** Senior Research Scientist. Research Interests: Combustion—specifically in the areas of synthesis and materials processing for improvement of energetic materials (propellants, pyrotechnics, explosives). Electromagnetic and acoustic effects in reactive materials. Nanoscale energetic. Advanced energetic materials. Hydrogen generation.

# ZUCROW LABS FACULTY (cont.)

**Nicole Key,** Assistant 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.

**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.

**Charles Merkle,** Professor Emeritus, Reilly Professor of Engineering. Joint appointment with Mechanical Engineering. Research interests: Computational Fluid Dynamics and Mechanics. Two Phase Flows. Propulsion Components and Systems.



**Hukam Mongia,** Professor of Mechanical Engineering. Research Areas: Combustion, Energy Utilization, and Thermodynamics.

**Tim Pourpoint,** Research Assistant Professor. Research Interests: Aerospace propulsion systems,. Rocket engine combustors. Liquid propellant injection systems. Hypergolic propellants. High pressure and hydrogen storage systems.

**Li Qiao,** Assistant Professor, 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.

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

**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 AFFILIATE FACULTY

**Doug Adams**, Kenninger Professor of Renewable Energy and Power Systems, Mechanical Engineering; Affiliate of the Division of Environmental and Ecological Engineering. Research Areas: Mechanics and vibrations. Research Interests: Nonlinear structural dynamics and vibration. Structural diagnostics/health monitoring and prognostics. Applications in aerospace and automotive systems. Applications in energy systems including wind turbines and batteries. Noise and vibration control.

**Gregory Blaisdell**, Associate Professor for the School of Aeronautics & Astronautics. Research Interests: Computational fluid mechanics. Transition and turbulence.

**Osvaldo Campanella**, Professor of Agricultural & Biological Engineering. Research Interests: Biological engineering. Food process engineering. Food safety.

**Carlos Corvalan**, Associate Professor of Mechanical Engineering (by Courtesy), Associate Professor of Food Science. Research Interest: Food process engineering.

**Timothy Fisher**, Professor of Mechanical Engineering. Research Areas: Heat Transfer. Nanotechnology. Research Interests: Nanoscale energy transport and conversion. Synthesis of nanomaterials. Cooling of microelectronics. Microfluidics.

**Klein Ileleji**, Associate Professor of Agricultural & Biological Engineering. Research Interests: Bioenergy. Food process engineering.

**Anastasios Lyrintzis**, Associate Professor of Aeronautics and Astronautics. Research Interests: Computational Aeroacoustics. Aerodynamics for rotorcraft and jet flows.

**Fabio Ribeiro**, Professor of Chemical Engineering.

**P. Veeraragha Ramachandran**, Professor of Chemistry.

**David Stanley**, Associate Professor of Aviation Technology

**Alejandro Strachan**, Associate Professor of Materials Engineering

**John Sullivan**, Professor & Director of the Center for Advanced Manufacturing

**Jerry Woodall**, Barry and Patricia Epstein Distinguished Professor of Electrical and Computer Engineering. Research Interests: Exploratory compound semiconductor materials and devices. Research Areas: Microelectronics and Nanotechnology.

**F. Zhao**, Assistant Professor of Mechanical Engineering. Research Interests: Environment friendly design and life cycle engineering. Applications of bio-based materials in manufacturing. Fast and los-cost detection of pathogenic microorganisms. Biomass thermo-chemical upgrading for liquid and gaseous fuel. Research Areas: Design. Manufacturing and Materials Processing.

# ZUCROW LABS STAFF

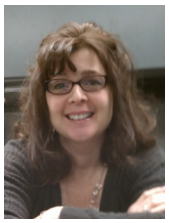
**Steve Heister,** Director Maurice J. Zucrow Laboratories. Raisbeck Engineering Distinguished Professor

**Scott Meyer,** Managing Director Maurice J. Zucrow Laboratories

**Rob McGuire,** Supervisor of Technical Services

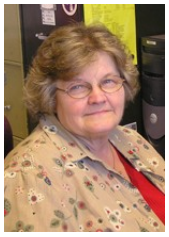
**John Fizel,** Machine Shop Coordinator / Building Deputy

**Charlotte Bell,** Administrative Assistant to the Director



**Michelle Kidd,** Business Services

**Starr Crystal,** Business Services



**Joan Jackson,** Business Services

## Faculty and Staff in Transition:

Merkle

We have had several changes in the composition of the MJZL leadership team over the past year. Most notably, we were sad to learn of Dr. Merkle's retirement that was announced in July and took effect in August of 2011. As many of you know, Dr. Merkle is a world leader in computational modeling of reacting flows. He served as the inaugural Director of the Propulsion Engineering Research Center at Penn State and worked with literally hundreds of graduate students over his successful career. We wish him the best in retirement and note that he is sorely missed.

Nugent

In addition, we note the departure of Senior Engineer Nick Nugent to a position at NASA Stennis Space Center. We are sure Nick will enjoy working the large liquid rocket engine test stands at Stennis. In September of 2010, Mark Bass retired after 34 years of service to the lab. In January of 2011, Ron McGuire retired after 19 years at MJZL. We wish our retirees Dr. Merkle, Mark and Ron the best in retirement.

Bass

McGuire

Finally, we wish to welcome Mr. John Fizel to the staff of MJZL. John has recently joined us as Machine Shop Coordinator/Building Deputy, effective last December. He will be assisting with building deputy functions and will be responsible for our compressed air plant. He also will take on technician and machining duties as time permits.

Fizel

# ZUCROW LABS HISTORY

**John Norberg**

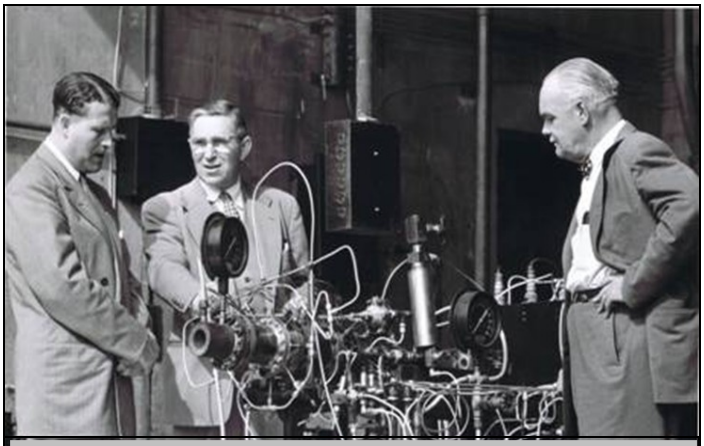
At the close of World War II, Purdue University was positioned to play a leading role in one of the most incredible periods of technological development in human history. Some of the most exciting work was taking place in jet propulsion and rockets. There were implications for industry along with national defense, and the consensus was that American universities needed to educate engineers for these critical fields.

According to Purdue Mechanical Engineering Professor Emeritus Charles Ehresman, by the end of the war "a new era had dawned in the propulsion of vehicles in the earth's atmosphere." And the idea of exploring space beyond earth's atmosphere was becoming a distinct possibility rather than science fiction. The essentials for jet propulsion and rockets were known before 1941, but their real potential was realized during the war. And the post-war period brought about incredibly fast developments.

In 1946, Purdue's new President Frederick Hovde, along with Dean of Engineering A.A. Potter, decided the University needed to be a leader in jet propulsion and rocket development. They launched an industry-wide search for a person qualified to establish and teach graduate-level courses in gas turbines and jet propulsion, coupled with developing a supporting fundamental research program.

The best person they could find was one of Purdue's own, **Maurice Zucrow,** who was working as an engineering technical assistant to the executive vice president of Aerojet in Pasadena, California.

Zucrow was born in Kiev, Russia in 1899. His family came to the United States in 1912. A gifted student, he enrolled at Harvard University and received his bachelor's degree in Mechanical Engineering in 1922 and his master's in 1923. In 1928 he became the first student to receive a Ph.D. in engineering from Purdue. Zucrow's thesis, titled *Discharge Characteristics of Submerged Jets,* foreshadowed the outstanding contributions he would make in industry and as a Purdue professor and researcher.



**Dr. Wernher von Braun and Commander White (ONR) visit with Doc Zucrow at Propulsion Lab (1953)**

After receiving his degree, Zucrow left Purdue in 1929 and acquired an outstanding reputation in industry, particularly in the areas of gas turbines and rocket propulsion. He played an important part in the research and development of the nation's first gas turbine built by the Elliott Company in 1942. During World War II he also helped develop Aerojet Engineering Company's JATO rocket, used by seaplanes to assist take-off under adverse conditions.

In April 1946, Zucrow accepted Purdue's offer to return to West Lafayette and he immediately began setting up a course in jet propulsion. He also published his groundbreaking text, titled *Principles of Jet Propulsion and Gas Turbines*. The first textbook in the field, it extended Zucrow's influence to engineering students throughout the world.

It soon became evident that a major physical facility was needed to provide adequate space for research by Zucrow and others he would recruit. Space was made available in the east hangar of the Purdue Airport with a limited experimental area adjacent to the offices. Zucrow's work involved rocket engine firings, and the hangar was not set up for hazardous projects. Zucrow discussed this problem with the Office of Naval Research (ONR), which requested a proposal to fund construction of a liquid rocket test facility. ONR awarded Purdue a $20,000 grant for the facility, and those funds were matched by the Purdue Research Foundation. With that money, a rocket facility went up on a plot of land at the northwest corner of the Purdue Airport.

**The Rocket Propulsion Laboratory,** (now termed the **Propulsion Laboratory**) completed in 1948, provided space for two rocket motor firing cells, a common control and instrument room, a small machine shop for rocket motor construction, a chemistry laboratory, and space for three onsite graduate student desks used on a first come first served basis. It was a simple beginning. But -- "it was at this laboratory that one of the most significant liquid rocket research programs began," said Ehresman, a Purdue graduate who went to industry and later returned to the University to work with Zucrow.

Zucrow recruited Cecil Warner during the earliest days of work. In 1949 Warner became a general assistant to Zucrow and remained on the staff until 1973 when he became a full time teacher in Mechanical Engineering. According to Warner the first building was small and accommodations very simple for the advanced and important research that was taking place.

# ZUCROW LABS HISTORY (cont.)

"Electric power was supplied by a four cylinder diesel generator set obtained as war surplus from the Navy," Warner said. "A small gasoline engine electric generator unit provided electric power at night. No telephone service to the remote location of the laboratory was available. To provide emergency communication . . . an army field telephone operated by a hand crank was obtained as war surplus. Lines were strung on existing fence posts. Needless to say, this system was subject to numerous failures during heavy winter snows."

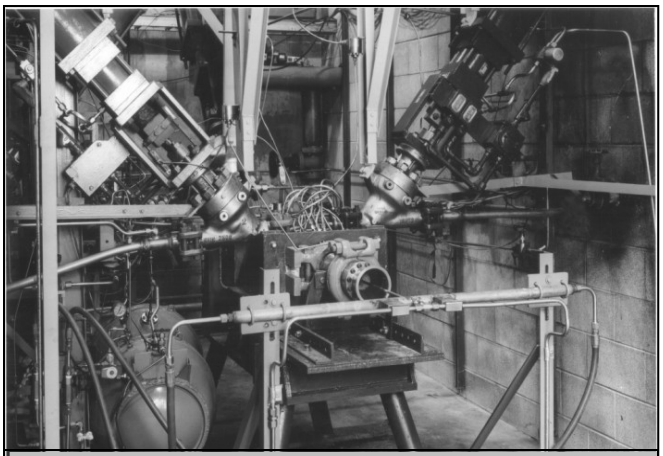
The research area was gradually expanded, year-by-year. In 1951 the machine shop was enlarged and Zucrow added an instrument storage room and graduate student offices. Space was provided for two additional rocket motor cells and control rooms.

After a failure in the war surplus electric generator, the Jet Propulsion Center, as it became known, was connected with Purdue University power, water, and telephone service in 1951. At the same time, the additional test cell space allowed expansion of the rocket research. Techniques for obtaining rocket propellant ignition delays developed at Purdue became the industry standard for many years.

In 1953 a **Combustion Laboratory** was added to provide much needed on-site office space for Zucrow, his assistants, two secretaries, and several graduate students. Space for three component test cells and control rooms was also provided. Due to the growing number of graduate students in the program, an instructional classroom was completed. To provide for the design of research rigs, a drafting room was also included in the building. Extensive expansion of the Combustion Laboratory was completed in 1955. The test cell wing was extended by the addition of four test cells and control rooms. Two large rooms with high ceilings formed a new wing of the building.

In 1954 a **Gas Turbine Laboratory** (now called the **Gas Dynamics Lab**) was added at the site to provide space for an enlarged machine shop, three gas turbine component test cells and control rooms, two Navy surplus high-pressure air compressors, a welding shop, and an experimental equipment assembly room. Following many years of use, the two surplus high-pressure air compressors outlived their life expectancy and were replaced by four new air compressors in space provided in a new addition to the original Gas Turbine Laboratory building. Ingersoll Rand and Purdue University provided funds for the improved air facility.

"Due to the vision and understanding of Professor Zucrow, the early work during the later 1940s and early 1950s involved the entire scope of problems involved with liquid rocketry performance, and heat transfer," Ehresman said.



**Testing of SSME Narloy-Z Liner Material at High Pressure Lab (circa 1970)**

A major impact of the Center derived from early studies that established the relationship between rocket power and high combustion-chamber pressure. Results of this research have been of particular value to the U.S. SpacePprogram and were most recently applied in the design of the space shuttle's main engine. Combustion-chamber pressure on the space shuttle main engine (SSME) reached 3,000 pounds per square inch. When Zucrow began his investigations, conventional chamber pressure was 300 pounds per square inch.

Researchers focused other major work on the development of liquid film cooling for rocket motor parts. These findings have also been applied to turbine engine cooling.

The construction of an administrative center was started in 1965. It was later named **Chaffee Hall** in honor of Purdue graduate Roger Chaffee who died in an Apollo I accident at the Kennedy Space Center in January of 1967. The new hall was designed to provide office space for Dr. Zucrow, twelve teaching staff members, thirty graduate students, and three secretaries.

The **High Pressure Laboratory**, built in 1965, was designed to accommodate experimental rocket motors operating at 5000-psi chamber pressure. The control room housed the experimental system control and instrumentation systems required to operate the two rocket motor test cells. Remote controlled TV cameras were used to monitor rocket motor firings.

Zucrow retired from Purdue in 1968. He died in 1975. In 1998, on the occasion of the 50th anniversary of the then-named Thermal Sciences and Propulsion Center, the research complex was renamed in honor of its founder, The Maurice J. Zucrow Laboratories.

"Professor Zucrow was not only able to contribute greatly to the understanding and solution of many of the early problems, but he also contributed greatly by training outstanding young men who left Purdue for other universities, industry or government," Ehresman said. "His impact in that regard is still significant as the many 'Sons of Zucrow' remain active in responsible positions in the research and development community."

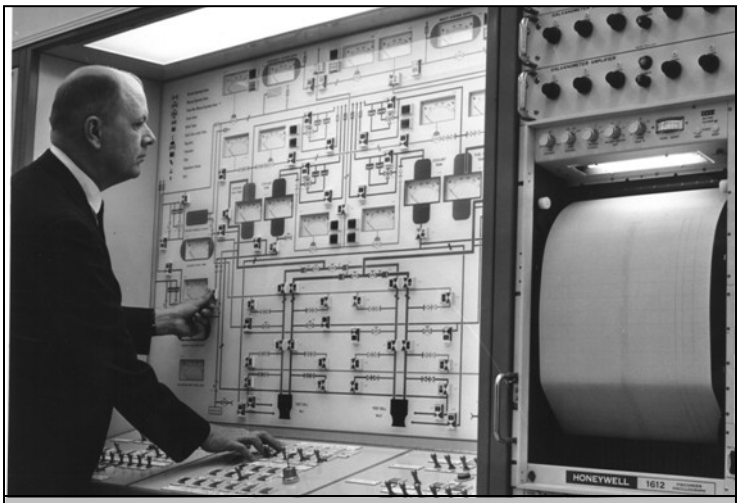
# ZUCROW LABS HISTORY (cont.)

Keith Hawks, retired assistant head of Mechanical Engineering, served for a time as acting director of Zucrow Labs until December 2010. He has been at Purdue, first as a student and later as a faculty member, since 1960. "I only knew Dr. Zucrow for a short period after the high pressure lab was opened in the late 1960s," Hawks says. "I was impressed with him. He was an excellent researcher. He really knew the rocket propulsion field. I did enjoy talking with him briefly about NASA and rockets and his vision for rocket research at Zucrow. Of course, that was before the labs were named for him. He was always taking care of business; however, he would take the time to talk with you and explain what was going on."

Among those who did graduate work at Zucrow and received a master's degree in 1972 was Jerry Ross, who became a NASA astronaut and holds the record (tied with one other person) for most launches by any human being.

The Center that eventually bore Zucrow's name established Purdue as an international leader in combustion and attracted many outstanding students and faculty, including Professor Bruce A. Reese. Reese received his Ph.D. under Zucrow in 1953 and was appointed an assistant professor of Mechanical Engineering. He later served as director of the Jet Propulsion Center and subsequently head of the School of Aeronautics and Astronautics.

Ehresman received his master's degree working under Zucrow in 1951. He went to Aerojet General Corporation in California before being recruited back to Purdue in 1964. He initially was a visiting assistant professor and in 1966 was promoted to associate professor of Mechanical Engineering and had already been given responsibility for the design and construction of the High Pressure Rocket Laboratory. From 1977 to 1981 he served as Operations Manager of the Thermal Sciences and Propulsion Center. He retired in 1992.




Chuck Ehresman at HPL Control Panel (circa 1965)

Other faculty recruited by Zucrow included John Robert Osborn, S.N.B. Murthy, Joe Hoffman, Mel L'Ecuyer, Doyle Thompson, James Skifstad, and Arthur Mellor.

During its history, Zucrow directors have been: Maurice J. Zucrow (1946-1966), Bruce A. Reese (1966-1973), Douglas Abbott (1973-1977), Charles M. Ehresman (1977-1981), Sanford Fleeter (1981-1989), Joe D. Hoffman (1989-1999), and Stephen D. Heister (March 1, 2011-present).

The facilities now occupy a 24-acre site adjacent to the Purdue Airport with research including unsteady aerodynamics of turbo machinery, aeroacoustics, combustion, measurement and control, computational fluid mechanics, particle flow heat transfer and atomization processes. The Zucrow Labs consists of six buildings housing twenty-two individual laboratories, a computer lab with two server clusters on site, a professional machine shop, and air compressors and air tanks capable of delivering 3300 cubic feet of air at 2200 psi. Associated with eight of the twenty-two individual labs are a total of eighteen "hazard" test cells and four "high hazard" test cells.

Sixteen faculty are active at Zucrow and another comparable number affiliated with the center. One hundred graduate students are currently involved in Center work. "It's an exciting and busy place," Heister says. "We are much more than rockets. Historically, Dr. Zucrow built the lab to study the emerging fields of jet and rocket propulsion in post World War II Era. Today we have a number of projects related to energy and much more, but our rocket and jet propulsion work continues.

"This center has had a huge impact on the U.S. Space Program. A large number of our alumni worked in the Space Shuttle Program. Virtually all the shuttle and propulsion prime contractors have graduates from Zucrow Labs."

Among Zucrow faculty is Steven Son whose research activities are primarily focused on multiphase combustion phenomenon. Using unique facilities available at Zucrow, Son's research group has also started small-scale explosive blast loading studies to understand and mitigate blast injury.

# ZUCROW LABS HISTORY (cont.)

Paul Sojka is a Zucrow researcher working with sprays formed from rheologically complicated (non-Newtonian) fluids, in particular those for rocket injection. Applications include: consumer products, paints/coatings, spray drying of foods and detergents, spray formation in pharmaceutical manufacturing, gas turbine engines, rocket motors, and internal combustion engines.

Professor Xinyan Deng's research is centered around biological locomotion and bio-inspired robots, from investigating the underlying principles of animal locomotion to the construction and control of intelligent machines for similar tasks or environments. Her group is particularly interested in insect flight and fish locomotion. They use experiments and mathematical analysis to reveal the physical principles of flapping flight, its fundamental fluid mechanism, and flight dynamics and control. Sample projects include: aerodynamics of flexible wings; passive stability in insect flight; wing-wing interaction in dragonflies; insect robot development; sensory feedback control of robotic fish.

Zucrow researcher Steven Frankel worked with Mark Rodefeld, an associate professor of surgery and medical doctor at the IU School of Medicine, to develop a new heart pump that can significantly reduce open-heart surgeries and increase the lifespan of children.

Jay Gore, the Reilly Chair Professor of Engineering works at Zucrow researching sustainable energy and environment, combustion and turbulent reacting flows, combustion and heat transfer in materials, biomedical flows and heat transfer and global policy research.

Nicole Key's research areas include fluid mechanics and propulsion. Engineers continually strive to design more efficient gas turbine engines of low specific fuel consumption and high thrust-to-weight ratios. This requires low-weight, highly efficient compressors. Compressor weight reduction is accomplished by a decrease in the number of stages and axial gap between blade rows. This results in blade rows with higher loading and increased blade row interactions. Thorough understanding of blade row interactions is required to design efficient compressors for long duration of operation.

Research in the Purdue High Speed Compressor Research Laboratory is aimed at understanding the effects of blade row interactions on compressor performance and durability. Steady and unsteady aerothermal measurements acquired in the compressor test facilities illuminate flow physics relevant to today's high performance compressors.

Robert Lucht is the Ralph and Bettye Bailey Professor of Combustion in Mechanical Engineering. His research areas include combustion, energy utilization and thermodynamics; fluid mechanics and propulsion; systems, measurement and control.

John Abraham is researching combustion, energy utilization and thermodynamics.

Jun Chen is researching fluid mechanics and propulsion.

Hukam Mongia is researching combustion, energy utilization and thermodynamics.

Sanford Fleeter, the McAllister Distinguished Professor of Mechanical Engineering at Zucrow is an expert in gas turbine engines. He became interested in wind power not just because he thought he could "really make a contribution" to the rapidly advancing science, but also because he recognized its commercial potential.

"When I looked at wind power, I saw a growing business," Fleeter said. "With energy costs going up, wind power is not only a green alternative." It also makes sense economically, since it is not subject to supply-and-demand fluctuations of the marketplace. Fleeter notes that "when you put in a wind farm, you know what the power from that farm will cost in 20 years."

**Author John Norberg is also a weekly columnist for Lafayette Journal & Courier**

Zucrow also intersects with Aeronautics and Astronautics. Two faculty from that school are particularly active in Zucrow research – William Anderson and Timothée Pourpoint. Anderson studies combustion instability in both liquid rocket engines and gas turbine combustors. He also studies heat transfer in liquid rocket engines. Professor Pourpoint studies advanced propellants for rocket applications and hydrogen storage for automotive applications.

Looking ahead, Heister sees a lot of research at Zucrow focusing on alternative energy and rockets.

"We have the infrastructure one needs to study advanced energy generation concepts," he said. "We're moving to those areas. The faculty really decides what the new areas will be, but we're moving into bio fuels bioreactors, wind turbines and coal gasification

"At the same time, we still serve the propulsion community, and we have a very strong program in rockets and gas turbine combustion."

"I'm very excited about the future," he said. "It's a wonderful crew, a great group of faculty and students. The students are really hard working and energetic, and it's just a joy to be around them. It all comes down to the faculty as the key. We have some very accomplished faculty and as a result they're winning lots of research grants."

# MJZL CURRENT STUDENTS

| Student | Advisor | Email ....@purdue.edu | Thesis Topic |
|---|---|---|---|
| Ameen, Muhsin | J. Abraham | mameen | Simulations of Reacting Jet at High Temperature and High Pressure Conditions |
| Anderson, Eric | X. Deng | eanders | non-thesis |
| Bajaj, Chetan | J. Abraham | bajajc | Near-field Diesel Spray and Flame Lift-off |
| Ball, Patrick | N. Key | prball | Inlet Distortion Considerations for Multistage Compressor Performance |
| Bangar, Devashish | R. Lucht | dbangar | Subject: Laser diagnostics in combustion |
| Barbera, Giovanni | X. Deng | gbarbera | |
| Bedard, Michael | S. Meyer | mbedard | Fiber Optic Spectroscopy of High Frequency Combustion Instability |
| Berdanier, Reid | N. Key | rberdani | Design of a Multistage Research Compressor for Cantilevered Stator Hub Leakage Flow Investigaztion |
| Bhattacharya, Sayantan | X. Deng | bhattac3 | |
| Black, Will | S. Frankel | wblack | Subject: Modeling turbulent reacting flows and supersonic combustion for scramjets using high-order finite-volume methods |
| Brossman, John | N. Key | jbrossman | The Effects of Large Rotor Tip Leakage Flows in the Rear-Block of a Multistage Compressor |
| Buckley, Joey | W. Anderson | jrbuckle | non-thesis |
| Camel, Rozzerio | J. Gore | rcamel | Numerical Simulations of High Speed Nonreacting and Reacting Jet Flows |
| Chang, May Lin | S. Fleeter | changm | An Interactive Tool to Predict VAWT Performance Using Streamtube Models |
| Chandra, Rishabh | S. Frankel | chandr11 | Developing Quantum Computing Algorithms for CFD |
| Cheng, Bo | X. Deng | bcheng | The Mechanics and Control of Flapping in Flight |
| Cho, Kevin | S. Son, R. Lucht | kycho | Optical Diagnostics of Gelled Hypergolic Bipropellants |
| Dadson, Jennifer | S. Son | jdadson | (undecided) |
| Daily, Megan | S. Son | daily2 | Subject: Electromagnetic properties of energetic materials |
| DeGan, Jonathan | S. Frankel | jedegan | Subject: Analysis of powered Fontan hemodynamics using computational fluid dynamics |
| Delorme, Yann | S. Frankel | ydelorme | Subject: LES code to simulate blood flow in a total cavopulmonary connection to improve Fontan circulation |
| Dennis, Jacob | S. Son, T. Pourpoint | dennis4 | Subject: The ignition and combustion of advanced hypergolic propellants |
| Ennis, Brandon | S. Fleeter | bennis | Subject: Aerodynamics and aeromechanics of wind turbines and wind farms |

# MJZL CURRENT STUDENTS (cont.)





| Student | Advisor | Email ....@purdue.edu | Thesis Topic |
|---|---|---|---|
| Feldman, Thomas | W. Anderson | tfeldman | Hydrogen addition effects on combustion instability in a continuously varying resonance combustor |
| Fey, Brittany | W. Anderson | bfey | Mechanistic Combustion Response Model For An Unstable Model Rocket Combustor |
| Fineman, Claresta | S. Son | cfineman | High Shear Rheology of Hypergolic Gelled Propellants |
| Finney, Heather | P. Sojka | hfinney | Subject: Fluid dynamics of deep water multiphase jets |
| Firehammer, Stephanie | P. Sojka | sfireham | Subject: Size and velocity distributions for secondary atomization fragments |
| Forness, Jordan | S. Heister | jforness | Injector Concepts for Hypergolic Propellants |
| Fugger, Chris | W. Anderson | cfugger | Subject: A reacting jet in an unstable crossflow |
| Gao, Jian | J. Chen | gao53 | Application of Digital Holography to Spray Diagnostics and Zebrafish Embryonic Development Imaging by Digital Holographic Microscopy |
| Gejji, Rohan | W. Anderson | rgejji | Investigation of Combustion Instability in a Lean Direct Injection Gas Turbine Combustor |
| Hallum, W. Zach | S. Meyer | whallum | The Use of Proper Orthogonal Decomposition to Develop a Response Function During Combustion Instability |
| Hedman, Travor | S. Son, R. Lucht | hedman | Study of Ammonium Perchlorate Based Solid Propellants Using High Speed PLIF |
| Heinz, Nick | Sullivan | nheinz | Experimental Investigation of an Ejector Nozzle Using Forced Mixing Tabs for Supersonic Business Jet Applications |
| Kan, Brandon | S. Heister | bkkan | Pulse Detonation Rocket Engines |
| Kerlo, Anna-Elodie | J. Chen, S. Frankel | akerlo | Development of a Circulatory Support for the Univentricular Fontan Circulation |
| Kittell, David | S. Son | dkittell | A Water-Based Rocket Propellant Utilizing Aluminum Nanopowder with a Protective Hydrophobic Coating |
| Kulkarni, Guarav | J. Gore | gkulkar | Subject: Combustion and heat transfer |
| Kulkarni, Mayuresh | J. Gore | mkulkar | Improved stoves for Grain Drying |
| Kulkarni, Varun | P. Sojka | vkulkarn | Secondary Atomization of Non Newtonian Drops at High Weber numbers |
| Lamont, Warren | R. Lucht, W. Anderson | wlamont | Experimental Study of a Distributed Combustion System for Stationary Gas Turbines |
| Leng, Yujun | S. Fleeter | leng | Multistage interaction in axial and centrifugal compressors |
| Liu, Yun | X. Deng | liu739 | |
| Lou, Fangyuan | N. Key | louf | Inlet Distortion Effects on a High Speed Centrifugal Compressor |

# MJZL CURRENT STUDENTS (cont.)

| Student | Advisor | Email ....@purdue.edu | Thesis Topic |
|---|---|---|---|
| Mallory, Jennifer | P. Sojka | jamallor | Jet Impingement and Primary Atomization of Non-Newtonian Fluids |
| Mares, Jesus Jr. | S. Son | maresj | Response of Energetic Materials Under Acoustic Energy Insult |
| Mason, B. Aaron | S. Son | bamason | Impact Ignition of Intermetialic Materials |
| Massaro, Matt | S. Son | mmassaro | Coal Fine Utilization and Analysis Using Municipal Solid Waste (MSW) Plastics and Other Binders |
| McKinney, Emerald | W. Anderson | mckinnee | non-thesis |
| Miklaszewski, Eric | S. Son, L. Groven | emiklasz | Oxy-fuel Combustion: Laboratory Experiments and Pilot Scale Tests |
| Miller, Keith | N. Key | keithmiller | On the Design of a Centrifugal Compressor Research Facility for Low Specific Speed Applications |
| Morgan, Collin | W. Anderson | morgancj | Subject: Testing a shear coax gas-gas injector in a transverse instability field at similar conditions to the Hydrocarbon Boost engine |
| Musick, Stephen | X. Deng | smusick | Subject: Design of a Cable-Driven Manipulator for Flapping Flight Simulation |
| Neal, Jarad | | jcneal | non-thesis |
| Nellums, Robert (Ross) | S. Son | rnellums | Subject: Desensitization of nanothermites using flouropolymer binders |
| Nielsen, Tanner | S. Frankel | nielsent | Subject: CFD studies for optimization of high-speed flows |
| O'Neil, Patrick | S. Heister | oneil | Study of Composite Propellants using Dicyclopentadien Binder |
| Park, Sunny | S. Heister | park199 | Modeling Two-phase flow with stochastic coalescence/breakage model |
| Patrick, Catherine | R. Lucht | patrickc | Subject: Emissions reduction in gas turbine engines with TAPS combustion technology |
| Pfeil, Mark | S. Son, S. Heister | mpfeil | MS: Effects of Ammonia Borance on the Combustion of Ethanol |
| Pfeil, Teandra | T. Pourpoint | tlevans | Subject: Solution combustion synthesis to create nano -foam cobalt oxide powders to catalyze hydrolysis of sodium borohydride for hydrogen storage |
| Pinnola, Marissa | N. Key | mpinnola | Characterizing the Forcing Functions and Response of an Embedded Rotor at Resonance Conditions |
| Pomeroy, Brian | W. Anderson | bpomeroy | Transverse Combustion Stability of Hydrocarbon Liquid Fuel Injectors |
| Rankin, Brent | J. Gore | brankin | Spatiotemporal Radiation Properties and Planar Emission Tomography of Tuburlent Reacting Flows |
| Reddy, Harinath | J. Abraham | reddyh | Numerical Studies of Turbulence Effects on Developing Flames in Lean Methane/Air Homogeneous Mixtures |
| Reese, David | S. Son | reesed | MS: Inclusion of Nanostructured Materials in Composite and Double Base Propellants |

# MJZL CURRENT STUDENTS (cont.)





| Student | Advisor | Email ....@purdue.edu | Thesis Topic |
|---|---|---|---|
| Rettenmaier, Andrew | S. Son, S. Heister | arettenm | Erosive Burning of Composite Propellants |
| Reuter, Bryan | S. Frankel | breuter | Uncertainty Quantification for Powered Fontan Hemodynamics |
| Roa, Mario | R. Lucht | mroa | Subject: Laser diagnostic techniques for distributive combustion with applications to gas turbines |
| Roll, Jesse | X. Deng | jroll | Subject: Design and Control of Bio-Inspired Micro Air Vehicles |
| Rosen, Stan | W. Anderson | srosen | Combustion Instabilities in the Transition Region of an Unstable Model Rocket Combustor |
| Sane, Anup | J. Gore | asane | A Numerical and Experimental Study of Solid Carbon Conversion Processes in Energy Systems and Combustion |
| Sane, Mugdha | J. Gore | msane | Subject: Combustion |
| Seebald, Paul | P. Sojka | pseebald | Subject: Transcritical Injection |
| Shark, Steve | S. Son, S. Heister | sshark | Hybrid Rocket Combustion: Advanced Fuel Additives and Mixing Studies |
| Sippel, Travis | S. Son | tsippel | Hypergolic Ignition and Stabilization of Metal Hydride-based Propellants |
| Sircar, Indraneel | J. Gore | isircar | Subject: Experimental investigation of coal and biomass gasification for liquid fuel synthesis |
| Slabaugh, Carson | R. Lucht, S. Meyer | cslabau | High-Pressure TAPS Flame Visualization |
| Smith, Natalie | N. Key | smith773 | Experimental Investigation of Vane Clocking Effects on Stall Performance and Unsteady Boundary Layer Development in a Multistage Compressor |
| Snyder, Sharon | P. Sojka | snyder22 | Secondary Atomization of Elastic Non-Newtonian Liquid Drops |
| Solomon, Yair | W. Anderson | ysolomon | Combustion of Gelled Hypergolic Fuel Droplets in Oxidizing Atmosphere |
| Sullivan, Andrew | W. Anderson | sulliva | |
| Sun, Lijian | S. Fleeter | lsun | CFD Modeling of Wind Turbine Wake in Wind Farms |
| Terry, Brandon | S. Son | terry13 | Subject: Nanoscale silicon composite energetic materials. |
| Thompson, Andrew | S. Heister | thomps79 | Flashing of High Temperature Fuels in Internal Flow Passages |
| Trebs, Adam | S. Heister, S. Meyer | atrebs | The Effect of Boundary Layer Variability on Compression Ramp Injector Functionality |
| Troiani, Alex | S. Son | atroiani | Effects of Fuel Additives on Combustion Distribution and Stability |

# MJZL CURRENT STUDENTS (cont.)

| Student | Advisor | Email ....@purdue.edu | Thesis Topic |
|---|---|---|---|
| Voskuilen, Tyler | J. Gore, T. Pourpoint | tvoskuil | A Study of Hydriding Kinetics of Metal Hydrides Using a Physically Based Model |
| Wang, Yi | X. Deng | wang1332 | Subject: Bio-inspired robotics |
| Whitson, Bryce | J. Gore | whitsonl | non-thesis |
| Wierman, Matt | W. Anderson | mwierman | Subject: Nonlinear predictive model of rocket engine combustion instability |
| Wiest, Heather | S. Heister | hwiest | Subject: Testing nozzle performance for supersonic business jet applications |
| Xu, Duo | J. Chen | xu95 | Experimental Study of Turbulent Stratified Jet |
| Zakrajsek, Andrew | S. Son | azakrajs | Water Blast Mitigation |
| Zaseck, Chris | S. Son | czaseck | Development of High Performance Paraffin-Based Hybrid Fuels |
| Zhang, Jiang | X. Deng | zhang699 | Subject: Bio-inspired Mechatronics and Control |

# MJZL RECENT GRADUATES





| Student | Degree/Yr | Advisor | Thesis Title |
|---|---|---|---|
| Basu, Sumit | PhD 2010 | J. Gore, Y. Zheng | A Study of Hydrogen Generation and Storage in Ammonia Borane Based Systems |
| Bluestone, Stephen | MS 2010 | S. Heister | Development of Composite Solid Propellant Using Dicyclopentadiene Binder |
| Blunck, David | PhD 2010 | J. Gore | Radiation Diagnostics of High Temperature High Speed Flows |
| Bode, Martin | MS 2011 | Pourpoint | non-thesis |
| Chang, May Lin | MS 2011 | S. Fleeter | |
| Cummings, Chase | MS 2010 | S. Heister | BiAnnular Nozzle Rig (BANR) Facility Checkout and Plug Nozzle Performance Data |
| Dambach, Eric | PhD 2011 | S. Heister | Hypergolic Ignition of Monomethyl Hydrazine with Nitric Acid |
| Dechelette, Alexis | PhD 2011 | P. Sojka | Predicting drop size distributions for transient sprays |
| Deshpande, Kedaresh | MSME 2011 | J. Gore, Y. Zheng | An Experimental Study of Ammon ia Borane Based Hydrogen Storage Systems |
| Finney, Heather | MS 2011 | P. Sojka | Deep Water Crude Oil/Natural Gas Jet Flows |
| Fisher, Travis | MS 2010 | S. Frankel | |
| Hinkelman, Matthew | MS 2011 | S. Heister | Development and Testing of Dicyclopentadiene Based Solid Composite Propellants |
| Janesheski, Robert | MS 2011 | T. Pourpoint, S. Son | Detonation Failure Characterization of Non-Ideal Explosives |
| Kennington, Jeff | MS 2011 | S. Frankel | Design and Optimization of a Novel Cavopulmonary Assist Device for Fontan Circulation: CFD and PIV Studies |
| Kou, Nannan | PhD 2011 | F. Zhao | |
| Kubal, Travis | PhD 2010 | S. Son | Characterization of Rheological and Ignition Properties of Hypergolic Propellants |
| Lastufka, Arin | MS 2011 | W. Anderson | Effect of Diluent on Gelled Monomethylhydrazine Ignition and Dual Flame Behavior |
| Lee, Andrew | PhD 2011 | P. Sojka | High-shear granulation |
| Lopez-Rivera, Celienid | PhD 2010 | P. Sojka | Secondary Breakup of Inelastic Non-Newtonian Liquid Drops |
| Luk, Wai-Chak | MS 2010 | S. Heister | Plume Mixing Characteristics of a Round-to-Rectangular Transition Nozzle |
| Manship, Tim | MS 2010 | S. Heister, S. son | High Burn Rate Solid Composite Propellants |
| McPherson, Paul | MS 2011 | S. Fleeter | |
| Miklaszewski, Eric | MS 2011 | S. Son | Oxy-fuel Combustion: Laboratory Experiments and Pilot Scale Tests |
| Mitchum, Greg | MS 2011 | H. Mongia, R. Lucht | |
| Moore, Joseph | MS 2010 | S. Son | The Experimental Characterization of Particle Dynamics of Solid Composite Propellants |

# MJZL RECENT GRADUATES (cont.)

| Student | Degree/Yr | Advisor | Thesis Title |
|---|---|---|---|
| Mukhopadhyay, Saumyadip | PhD 2011 | J. Abraham | Ignition and Early Flame Development in Stratified-charge Mixtures |
| Owston, Rebecca | PhD 2010 | J. Abraham | Modeling of Combustion in Stratified Hydrogen-Air Mixtures |
| Reeves, Robert V. | PhD 2011 | S. Son | Control of Ignition and Reaction Behavior in Gasless Reactive Systems Via Microstructural Modification |
| Salontay, Jonathan | MS 2010 | N. Key | A Computational Investigation of Vane Clocking Effects on Compressor Forced Response and Performance |
| Seshadri, Priya | MS 2011 | S. Son, S. Heister | Combustion Characteristics of Nanoenergetic Materials Composed of Aluminum, Nickel Oxide and a Fluoroelastomer |
| Shetty, Dinesh | PhD 2010 | S. Frankel | Numerical investigations of subgrid-scale mixing models for large eddy simulation of turbulent racting flows via the filtered mass density function approach |
| Slaby, Justin | MS 2010 | S. Heister | Experimental Investigation of Erosive Burning in Solid Propellant Motors |
| Snyder, Sharon | MSME 2011 | P. Sojka | Secondary Atomization of Elastic Non-Newtonian Liquid Drops |
| Strohm, Gianna | MS 2010 | S. Son | The Viability and Performance Characterization of Nano Scale Energetic Materials on a Semiconductor Bridge (SCB) |
| Talalayev, Anton | MSME 2011 | N. Key | On the Renovation of the Three-stage Axial Compressor Research Facility for Compressor Performance Research |
| Thariyan, Mathew | MS 2010 | J. Gore, R. Lucht | Coherent Anti-Stokes Raman Scattering for Quantitative Temperature and Concentration Measurements in a High Pressure Gas Turbine Combustor Rig |
| Wood, Tyler | MS 2010 | S. Son | Feasibility Study and Demonstration of an Aluminum and Ice Solid Propellant |
| Williams, Shae | PhD 2011 | I. Hrbud | On the Performance of Radio-Frequency (RF) Electric Propulsion Thrusters |
| Yan, Allen | MS 2011 | S. Son, S. Heister | Validation of Numerical Simulations for Nano-Aluminum Composite Solid Propellants |
| Yarrington, Cole | PhD 2011 | S. Son | Combustion Characterization and Modeling of Novel Energetic Materials: SI/PTFE/VITON and AL/PTFE/VITON |
| Yilmaztuerk, Ali | MS 2011 | P. Sojka | Transient supercritical injection |