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UAH Propulsion Research Center – 25th Anniversary Highlights

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The University of Alabama in Huntsville founded the Propulsion Research Center in 1991. The mission of the Propulsion Research Center is to provide an environment that connects the academic research community with the needs and concerns of the propulsion community, while promoting an interdisciplinary approach to solving propulsion problems. This paper documents the foundational ideals and goals of the center. It highlights the student production, funding history, and current status of laboratories developed over the past 25 years. Over that time the center faculty and staff have mentored students who have been awarded over 230 advanced degrees and have been supported by sponsors who provided over 35 million dollars of external funding. Current operations involve over 60 faculty, staff, and graduate/undergraduate students working in interdisciplinary research teams using 10 different laboratories to support external sponsors. Faculty of the UAH College of Engineering have developed 17 propulsion and energy related courses that are taught on a regular basis that support the PRC mission. The center continues to be a resource for both fundamental and applied research as well as workforce development for the propulsion and energy field.

I. A Propulsion Research Center is Born

SINCE the 1950s, Huntsville, Alabama has been at the forefront of America's rocket propulsion research, so much so that it is often called the Rocket City. The University of Alabama in Huntsville (UAH) was founded, to a great extent, because of the vision of Dr. Wernher von Braun. During his 1961 address to the Alabama Legislature, he said, "It's the university climate that brings the business. Let's be honest with ourselves. It's not water, or real estate, or labor or cheap taxes that brings industry to a state or city. It's brainpower." He added during his address to the legislature, "opportunity goes where the best people go, and the best people go where good education goes. To make Huntsville more attractive to technical and scientific people across the country - and to further develop the people we have now - the academic and research environment of Huntsville and Alabama must be improved." The presentation convinced the Alabama legislature to grant $3 million to seed the UAH Research Institute which grew into the University of Alabama in Huntsville. Presently, UAH graduates over 40 Ph.D.s

Figure 1. Initial Propulsion Research Center Team: Dr. Hugh W. Coleman, Professor of Mechanical Engineering and Eminent Scholar in Propulsion, Dr. Clark W. Hawk, Professor of Mechanical Engineering and PRC Director, and Dr. Robert A. Frederick, Jr., Assistant Professor of Mechanical and PRC Associated Faculty (August, 1991).

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and 350 master's students annually. A number of UAH's programs are ranked in the top 10 in the nation including, federally-funded research and development in aeronautical/astronautical engineering.

UAH's emerging Research Institute and Academic Colleges successfully supported local propulsion programs and workforce development for NASA and the Army indirectly for the first 30 years of its operations until a more focused strategy was implemented. The Propulsion Research Center (PRC) then came into existence on February 1, 1991 under the directorship of Dr. Clark W. Hawk. At that time, there were no associated faculty, students, or facilities connected with the PRC. The issue of focused faculty support was addressed immediately in August of 1991. Dr. Hugh W. Coleman was recruited and appointed as the Eminent Scholar in Propulsion and added to the faculty at the rank of Professor of Mechanical Engineering in the College of Engineering. Dr. Robert A. Frederick, Jr. joined the PRC to initiate experimental research in solid and hybrid propulsion and was appointed at the rank of Assistant Professor of Mechanical Engineering. Figure 1 shows a photo of the initial PRC team in August of 1991.

It is also significant to note that Dr. Hawk joined the Mechanical Engineering Faculty as a Professor and was put on a tenure track, meaning he would be called on to lead the center and establish an academic record that would be reviewed by his university peers for the award of tenure in the subsequent years. The Eminent Scholar in Propulsion was endowed in part by Rocketdyne, Aerojet, Martin-Marietta, Thiokol, and Lockheed Missiles and Space Company, which showed strong industry support for the endeavor. An agreement was also put in place to have Dr. Naminosuka Kubota from the Japan Defense Agency serve as a Visiting Scholar in Propulsion in 1992.

With Drs. Hawk, Coleman, and Frederick in place, an overall strategy to build the PRC was then implemented. Dr. Hawk had program management strengths and connections with the professional community from his 31 years of experience in propulsion research and technology with the Air Force. Dr. Coleman brought more than 25 years of experience in research fields related to rocket propulsion; he also brought a wealth of experience in working inside of academic intuitions which would prove valuable for integrating the PRC into the academic world. Dr. Frederick had four years of industrial experience as a solid rocket combustion researcher. Dr. Kubota had over 20 years of experience in solid rocket combustion studies and would become an integral part of building joint programs and bringing students to the university. By the end of the first year, the PRC had recruited five full-time graduate students and three part-time graduate students to engage in initial research programs. The PRC was off to an exceptionally fast start, but there would be many challenges ahead.

II. A Mission, a Strategy

The mission of the PRC was established to provide an environment that connects the academic research community with the needs and concerns of the propulsion community, while promoting an interdisciplinary approach to solving propulsion problems. Collaborating individuals and groups were envisioned as part of the PRC's research goals. This mission would be further accomplished though cooperation with researchers from government laboratories, other universities, and the aerospace industry. The result of this environment would be leading-edge research and scholarly activity in the pursuit of advanced technologies and their applications.

These endeavors were also envisioned as a means by which students associated with the PRC could achieve a high-quality education in engineering and related fields. The PRC committed to being an integral part of the UAH academic program. The PRC also declared at its founding that it would only seek those externally funded efforts that would provide graduate students with material for theses and dissertations, or provide supplemental support for undergraduate students. This was a departure from the more classical model of some research centers that sought to maximize research funding through the hiring of professional staff.

A major focus of the PRC would be to provide hands-on research opportunities for the students. Emphasis would be placed on building appropriate experimental facilities in which the students could gai n that experience. Upon founding the center, the initial staff had a great city and university, but little tangible on-site to work with. Dr. Frederick started some experimental work on hybrid propulsion as a NASA summer faculty using their facilities. This was followed by a grant Thiokol Corporation to provide support for a graduate student to research combustion instability in hybrid rockets. Later, in this paper, a brief summary of the many research capabilities and 10 on-campus laboratories that have emerged in the past 25 years of the PRC will be described to show how these foundational ideals have developed into the current capabilities.

It is also significant to note administratively, how the PRC was placed in the University - a position that the PRC still holds today. The director of the PRC reports to the Vice President for Research (Fig. 2). The director of the PRC is responsible for the technical and fiscal management of the research accomplished under the auspices of the PRC. Thus, the PRC is essentially an umbrella organization under which faculty members and students from all disciplines can voluntarily associate their research. The PRC also assists the faculty in marketing their research programs, creates

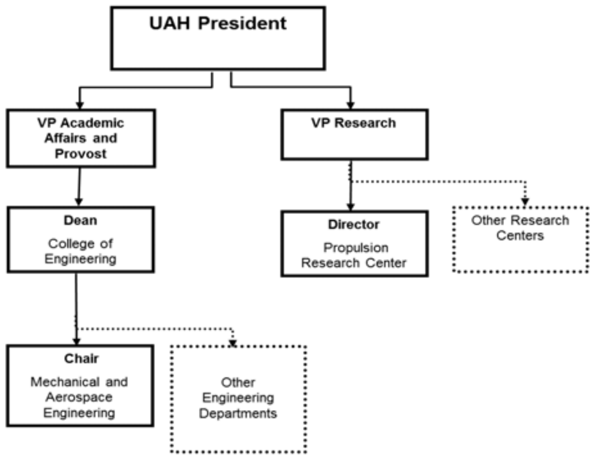

Figure 2. Administrative Organization of the Propulsion Research Center within the University

interdisciplinary teams, provides office space for associate faculty and students, and provides/maintains laboratories and equipment to support their research. This administrative structure, while efficient for business operations, creates separate administrative accounting, rewards, and communication lines from the academic parts of the university. Placing a new research center with three new faculty (reporting through a different two different chains of command) poses some unique challenges.

So 30 years after its founding, the University of Alabama, with the support of the industry and influential local agencies such as NASA Marshall Spaceflight Center and the U.S. Army Missile Command (MICOM) established a new Propulsion Research Center at The University of Alabama in Huntsville in 1991. In 2005, Drs. Hawk and Frederick[1] wrote a summary of the activities of the first 13 years of the UAH Propulsion Research Center. The current paper will highlight the history of the student production, external support, academic programs, and the laboratory capabilities that have developed over the past 25 years. As the details of research accomplishments are well documented in the literature, this paper will focus on the environment and capabilities that have emerged. The paper will finish up with an overview of our current organization and some thoughts for the future. A few of the significant milestones and challenges that were met, and sometimes overcome, along the way will be mentioned as well.

"*Aerospace is not for the faint of heart,*" author unknown.
"*I have an opportunity for you*," Dr. Clark Hawk

III. A Record of Students Achieving Advanced Degrees

Figure 3 shows the cumulative production of advanced degrees from students associated with the PRC from its inception in 1991. The total master's degree production is approaching 200 and the total Ph.D. production is approaching 40. as the center marks its 25th anniversary. As it takes some time to complete an advanced degree, the numbers do not begin immediately in 1991. The first seven master's degrees appear in 1993. The first four Ph.D. degrees registered in 1997. It is also apparent from the graph that over 80% of the degrees are master's theses. This is partially due to the dynamic nature of the funding over the years. It has been more difficult to sustain funded research over the duration of a Ph.D. program in the propulsion area.

It should be noted that the PRC itself does not grant academic degrees. The participating faculty in the various departments chair and participate in the students' committees and the degrees are conferred by the colleges and graduate school. Therefore, this graph shows the students who have been supported by the PRC faculty who participate in the PRC.

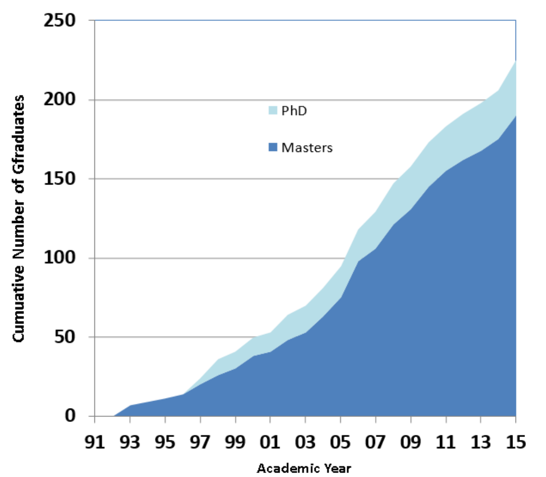

Figure 3. Cumulative Production of Advanced Degrees Associated the PRC.

IV. A Variety of Externally Supported Propulsion and Energy Research Sponsors

Figure 4 shows the annual expenditures from external customers of the Propulsion Research Center since its inception. These annual figures reflect the amount of money spent on research each year and not the total amount of awards from each year. The center has grown from essentially nothing to a cumulative level of expenditures totally over $35 million - averaging $1.4 million per year.

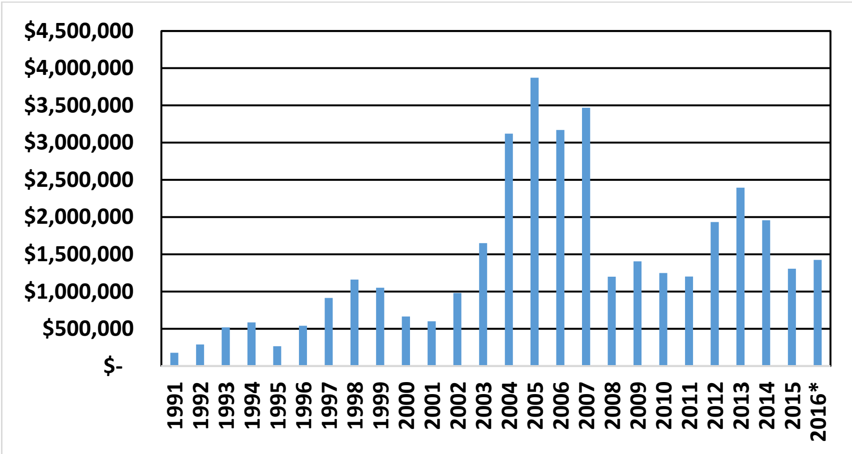

Figure 4. Annual Research *Expenditures* Associated the PRC.

Support has included a broad range of customers including NASA, DoD, DoE, and many others in industry. Significant rises in the annual expenditures come from a variety of sources. Early on in the 1990s, UAH participated in a DoD Ducted Rocket Engine Research program with The U.S. Army at MICOM. During this timeframe there was also a significant Office of Naval Research MURI program where the PRC was a member of a Cal Tech. university consortium. These two programs helped establish the solid propellant experimental capabilities.

NASA provided significant support in the 2000s that established liquid rocket laboratory capabilities. A significant NASA program called the Rocket Engine Advancement Program (REAP) was established in 2004 in which UAH lead a consortium of Universities including Purdue, Penn State, Auburn, and Tuskegee. This transitioned into the NASA Constellation University Institutes Project (CUIP) in which three PIs from UAH were awarded ongoing support in the areas of solid propellants, liquid injector instability, and computational fluid dynamics. Additional NASA and state funding were invested adding a new propulsion test facility and benchtop experiments for unit physics studies in combustion instability.

The 2010s have been marked by significant support from the Missile Defense Agency. The PRC has provided support for new technology assessments to fill requirements gaps, independent laboratory-based evaluation of emerging technologies, and physics-based modeling and simulation to provide tools for understanding the behavior of promising emerging technologies. Participation with small businesses in SBIR and STTR programs has also provided significant ongoing support particularly in our Propulsion Test Facility.

On a personal note, it is interesting to see the level of diligence, focus, and optimism required to sustain this type of operation over the past 25 years. The center had an annual external review for the first 15 years. In the second annual review, one reviewer commented, "*The PRC must, as a practical matter, be opportunistic, but not lose sight of what it wants to be when it grows up*." When first starting and maintaining a research center one must balance between "getting money" and pressing toward your mission.

Also, there is the ever-present need for "more external funding" from the university. In the report from the third annual external review, one reviewer noted, "*At our dinner meeting before the review…," [a university leader], " … provided an unexpected impetus for this review by stating that the university research organization was under considerable financial stress and he was weighing whether the Propulsion Research Center (PRC) should continue to be supported*." Over the years these kinds of pressures do not go away, and the business plan and academic benefits of a research center must be periodically reviewed in order to justify its continued presence and internal financial support of the university.

V. A Significant Academic Infrastructure in Propulsion and Energy

The science and engineering academic programs at UAH have grown significantly in the past 25 years. The PRC most closely associates with the Department of Mechanical and Aerospace Engineering (MAE) within the College of Engineering. That department has progressed from starting as a Mechanical Engineering Department and growing into a Mechanical *and* Aerospace Engineering Department having ABET accreditations in both Mechanical and Aerospace Engineering. The department also awards advanced degrees to the Ph.D. in Mechanical Engineering and Aerospace Systems Engineering.

The MAE Department currently has over 950 undergraduates. About one third of these are Aerospace majors. The program currently has 170 Mechanical and Aerospace graduate students. Many are working full-time at the Redstone Arsenal or for government contractors in the area. The MAE department has 18 tenure track faculty and 4 non-tenure track faculty members. The instructional load is supplemented by several part-time instructors from the area who have advanced degrees and excellent experience in aerospace topics.

The PRC also collaborates with other academic units on the campus. Faculty from the Departments of Chemical Engineering, Electrical and Computer Engineering, Industrial and Systems Engineering, Civil Engineering, Physics, Chemistry, Mathematics, Music, and others have collaborated on projects with the PRC. As mentioned before, the PRC has also been involved with teams or consortiums of universities on projects as well. Universities such as Alabama, Auburn, Georgia Tech., Maryland, MIT, Penn State, Purdue, Stanford, Tuskegee, UIUC, and others have been collaborators on proposals, funded research, and workshops.

A final unique aspect of the UAH Academic program that has been developed in conjunction with the propulsion focus is a significant number of propulsion and energy courses in the academic curriculum. Table 1 lists the 16 current offerings. These courses are taught regularly with the largest spacing being a two-year cycle for the more specialized courses. One course of note is the Advanced Solid Rocket Propulsion Course[2] in which 13 mentors from industry participated to develop the course.

Table 1. UAH Undergraduate and Graduate (Dual Level) Academic Courses Related to Propulsion and Energy

Undergraduate and Dual-Level Graduate Courses
MAE 420/520 – Compressible Aerodynamics
MAE 440/540 – Rocket Propulsion I;
MAE 441/541 – Airbreathing Propulsion
MAE 444/544 – Intro. To Electric Prop.
MAE 468/568 – Elements of Spacecraft Des.
MAE 493/593 – Rocket Design
MAE 495/595 – Intro. To Nuclear Propulsion

MAE **Graduate-Level**
MAE 640 – Rocket Propulsion II
MAE 633 – Tactical Missile Design I
MAE 644 – Adv. Solid Rocket Propulsion
MAE 645 – Combustion I
MAE 681 – Missile Trajectory Analysis
MAE 745 – Combustion II
MAE 795 ST – Intro to Fusion Propulsion;
MAE 695/795 – ST Adv. Readings in Prop.
MAE 695 – Comb. Instability in Solid Rockets
MAE 695 – Liquid Rocket Engineering

VI. An Environment for People and Research

A core value of the Propulsion Research Center is that *relationships are more important than tasks or problems.* While we strive to achieve technical excellence in our research, we also actively promote and maintain our relationships with each other. Building trust and friendship is something to value and enables us to achieve great things together. The PRC organization is here to enable the researchers and students to collectively have the opportunity to succeed.

From day one, over twenty five years ago, our founding center director, Dr. Clark Hawk, envisioned a positive and supportive community where students were at the center of research activities. Faculty and staff who participate in our research center value mentoring students in the classroom and in research; they are proud of their student's achievements. This enables students to become proficient in evaluating propulsion research hardware and provides them with a keen theoretical understanding of the physics.

A. UAH Propulsion Research Center Organization Chart

Figure 5 shows the current PRC "Organization Chart." Each box represents a functional area in the organization. Currently, there are over 60 faculty, staff, and students associated with the research activities of the PRC. The overall activities are managed by a director supported by staff that manage programs, advise in technical matters, and oversee laboratory operations. Faculty members serve as principal investigators and seven technical focus areas are shown in Fig. 5. The next sections will briefly describe some our current activities and capabilities as outlined in the organizational chart.

B. Director/Administration

The PRC Center Director has fiscal responsibility for overseeing all of the projects operating through the center, overseeing safety, and promoting the projects of the associated faculty staff and students in the organization. The director also provides overall strategy, marketing, and a point of contact for speaking with potential customers to the university. The director has a small number of direct reports including a Research Program Administrator/Budget Analysis, two Research Engineers, a Facilities Engineer, and part-time office assistants. It is significant to note that the director also has an academic faculty appointment and regularly teaches graduate and undergraduate course, serves on student committees, and supervises graduate students in their research. All the other participants associate with the PRC on a voluntary basis to benefit from the environment, focused support, and PRC laboratory facilities provided in the areas of propulsion and energy. When researchers associate with the center, some of the indirect overhead dollars returned from their funded work comes back to the PRC for investment into the organization.

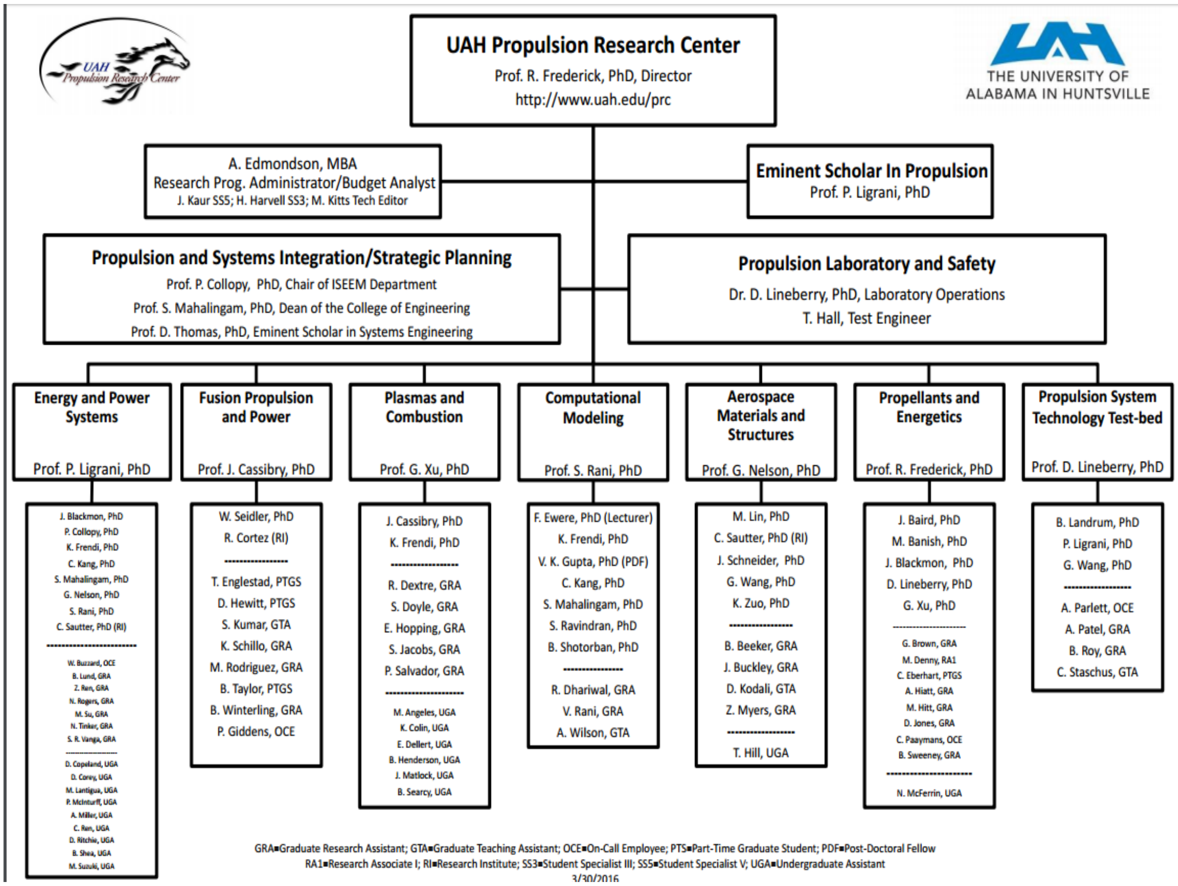

Figure 5. Current PRC Organizational Chart

C. Eminent Scholar

The Eminent Scholar in Propulsion is an academic appointment in the college of engineering. Currently, Dr. Phillip Ligrani, Professor of Mechanical and Aerospace Engineering holds this chair. Eminent Scholars perform research in their areas of expertise and also offer mentoring to the younger faculty. Dr. Ligrani's research expertise is in the areas of experimental heat transfer for air-breathing propulsion and supersonic shock wave boundary layer interactions. Dr. Ligrani was selected to join the university because of the excellence of his academic credentials and, in part, to diversify the research within the PRC into areas broader than rocket propulsion. Dr. Vladimir Bazarov, from the Moscow Aviation Institute, was Dr. Ligrani's predecessor, and led a significant increase in capability in liquid rocket combustion instability for the PRC. Dr. Hugh Coleman was the first Eminent Scholar and contributed in the areas of experimental uncertainty analyses.

D. Propulsion and System Integration/Strategic Planning

The Propulsion Integration and Strategic Planning group provides guidance on emerging critical areas of research and integration of the center activities within the university. Currently the Dean of the College of Engineering, the Chair of the Industrial and Systems Engineering department, and the Eminent Scholar in Systems Engineering comprise this team. Strategic plans are formalized on a five year cycle to adjust the direction of the center as needs and opportunities emerge.

The technical scope of this focus area is the integration of innovative propulsion technologies into total aerospace systems including: structures, aerodynamics, controls, power,

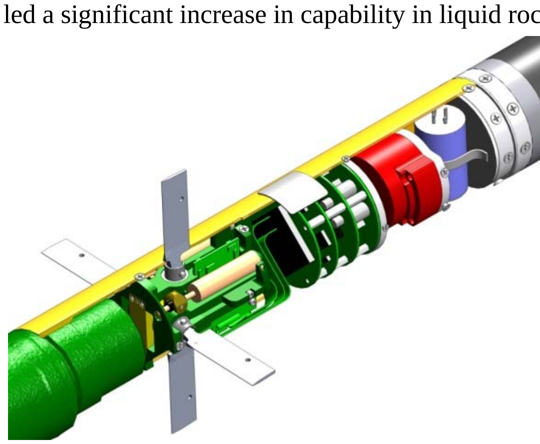

Figure 6. UAH Design Study on A Guided 2.75-in. Rocket Missile System

manufacturing, and power systems to achieve cost-effective, reliable, next-generation aerospace systems. Technical activities in this area have included: technology gap assessments, missile system designs, guided bullet designs, patents for new propulsion system concepts, advanced power systems, launch vehicle trade studies, and developing technically-based cost simulations for advanced propulsion systems.

Figure 6 shows the results of a missile system design for a guided 2.75-in. rocket motor concept. A new propulsion system was integrated with a forward canard aerodynamic control. Closed loop guidance algorithms in simulations evaluated how well the various concepts met overall mission requirements.

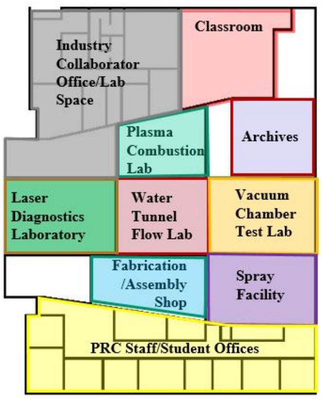

Figure 7. Johnson Research Center

E. Propulsion Laboratories

The PRC has approximately 15,000 square feet of laboratory space on the UAH campus. The majority of test operations are conducted at the Johnson Research Center (JRC) (Fig. 7), on the south side of the UAH campus. Within the JRC, the PRC has six primary facilities:

- The Plasma Combustion Laboratory
- Laser Diagnostics Laboratory
- Water Tunnel Flow Laboratory
- A Large Scale Vacuum Chamber
- A Fabrication/Assembly Shop
- The High Pressure Spray Facility

Student and staff offices allow interactions and work areas for the students, faculty, and staff. A classroom/conference center is used for lunch meetings, conferences, and classes. The industry collaborator space is currently occupied by Aerojet/Rocketdyne who perform their own independent research and collaborate with members of the research center.

Injector spray dynamics are evaluated under inert conditions in the High Pressure Spray Facility. The facility allows for injector characterization under relevant operating conditions (up to 500 psig) using conventional measurements and optical diagnostic techniques. In the Plasma Combustion Laboratory and Laser Diagnostics Laboratory, the behaviors of plasmas exposed to electric fields are investigated under atmospheric and vacuum conditions. The Water Tunnel Flow Facility provides the capability to investigate fundamental fluid dynamics of internal flows using Reynolds and geometric scaling similarity. The Large Scale Vacuum Chamber can create a hard vacuum environment (down to 10^{-5} Torr) for evaluation of propulsion devices (chemical and electric) in relevant atmospheres.

Behind the Johnson Research Center is a Propulsion Test Facility (Fig. 8) with two test bays containing:

- The Hot Fire Test Cell
- Supersonic Wind Tunnel / Thermal-Fluid Sciences Laboratory

Rocket engines (<500 *lbf*) are operated in the Hot Fire Test Cell. The PRC has tested solid, hybrid, and liquid (storable and cryogenic) engines over a range of engine pressures and propellant flow rates. The opposite bay houses a supersonic wind tunnel and other fundamental heat transfer experiments. The Supersonic Wind Tunnel Facility is a blow down facility which can generate supersonic flow (up to Mach 3) for evaluation of high speed flow phenomena like shock wave/boundary layer interaction. The two bays are connected by a diagnostics bay that holds specialized instrumentation. The rocket facility is operated remotely for the Johnson Research Center for safety.

Additionally, in other locations the PRC operates are the following laboratories:

- The High Pressure Combustion Laboratory
- The Solar Thermal Test Laboratory
- The Charger 1 Pulse Power laboratory

High Pressure Combustion Laboratory allows ballistic characterization and X-Ray radiography of energetic materials and

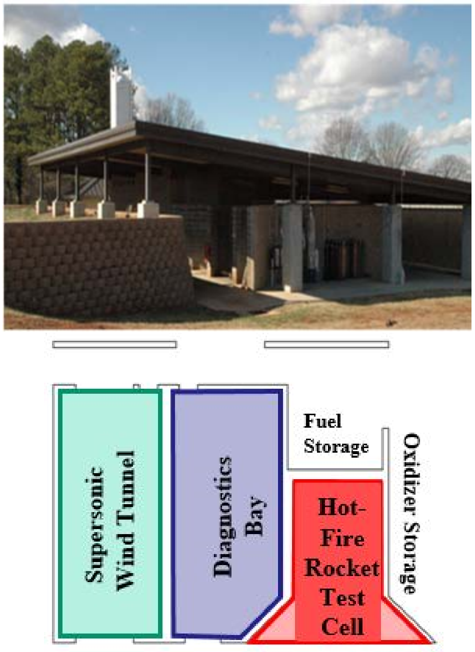

Figure 8. Propulsion Test Facility

solid propulsion devices. The Solar Thermal Test Facility is for high temperature experimentation in a high vacuum environment. The Charger One Facility (located on Redstone Arsenal), a is a state-of-the-art pulsed power facility with a focus on fusion propulsion research.

Current information on the capabilities of each one of these facilities can be assessed online along with relevant technical information. After the safety section, several of these facilities will be mentioned in the context of their use in current and past research studies.

F. Safety

Propulsion system testing involves inherent risks. While important in any environment, within the framework of a university, safety is paramount to any research center's continued existence. Testing failures in experiment with energetic materials can lead to significant facility damage and/or significant personal injury, both of which could result in a shutdown of all test operations. As a non-profit, the type of losses resulting from these failures cannot always be recovered from quickly, if at all. Over the years, the PRC has strived to maintain an impeccable safety record through the implementation of practices and processes to reduce the risk of equipment damage and prevent injury of our personnel.

The first step of the PRC safety policy is ensuring that no personnel are conducting hazardous operations alone. The "Buddy System" is strictly enforced for all testing operations in the PRC. Training plays an important role in the university environment where the average turnover of student workers is approximately 4 years. All personnel working on experiments are required to complete Red Cross First Aid, CPR/AED training. Additional training on experiment hazards is provided through mentorship with experienced students, PRC staff, and associated faculty.

Whenever necessary, hazardous test operations are conducted remotely. The PRC test facilities have controlled access to eliminate uninvolved personnel from being present during testing. When remote operations are not possible, procedural controls are relied on to ensure safety. All testing involving hazards require an approved operating procedure. These procedures are designed to ensure safe and successful execution of the experiment, . Operating procedures also outline the necessary steps to take in the event of an off-nominal event. Procedures are developed by test team members and are reviewed and approved by PRC staff prior to conducting test operations.

Additionally these procedures include hazard tables which outline the expected hazards, categorize them by severity and likelihood, and identify the steps taken to reduce the risks associated with those hazards to an acceptable level. During any test operations, all personnel involved are empowered, and expected, to voice any test related concerns. Operations are paused until any concerns can be resolved.

In the event of unexpected test incidents, the PRC has implemented an accident investigation procedure. The first step in the procedure, after any hazardous situations have been resolved, is to communicate the occurrence to PRC and University officials. This process must be completed within 24 hours of the incident. An incident investigation team is then established to evaluate the failure and identify the likely causes. All other test operations under the domain of the PRC are temporarily suspended and then reviewed for similar operations until the incident investigation is concluded. Once the likely cause(s) have been determined, external reviewers are brought in to review the findings and work with the team to recommend changes to eliminate the possibility of future occurrences. These recommendations are implemented in all PRC operations where similar failures could occur, and after implementation test operations are brought back online.

G. Energy and Power Systems

The Thermal-Fluid Sciences Laboratory (TFSL) capabilities include a facility investigation of impingement cooling with impingement jet Reynolds numbers up to 100,000, Mach numbers up to 0.8, and coolant to surface temperature ratios as low as 0.6. Another facility is employed for double wall cooling investigations over a wide range of flow conditions, and has provision to include the simultaneous effects of impingement jet array cooling, cross-flow coolant supply, full coverage effusion cooling, and conjugate heat transfer phenomena. The effusion cooling is provided with a full-coverage array of holes. One unique aspect is a main flow mesh heating system, which allows for transient heat transfer measurements, which, when employed with infrared thermography,

Figure 9. UAH Supersonic Wind Tunnel Test Section

provides simultaneous spatially-resolved distributions of surface heat transfer coefficients and surface adiabatic temperature (from which, distributions of adiabatic film cooling effectiveness are determined).

The new supersonic wind tunnel (Fig. 9) has three parallel test sections which provide means to investigate transonic and supersonic flow phenomena, either with or without heat transfer. Figure 9 shows the supersonic test section that has optical access for Schlieren diagnostics. The high speed flows are provided using an elaborate air pressure tank supply system with specially provisioned flow and pressure control regulating valves. Test section Mach number capabilities range from values as low as 0.2 to 3.0, with current test sections designed to operate at an inlet Mach number of 1.6. Unique capabilities include apparatus to investigate SWBLI – Shock Wave Boundary Layer Interactions, and other aerodynamics phenomena (as applied either to aero-propulsion, aerodynamic, aerospace, or turbomachinery components) with high-speed, compressible flows at transonic and supersonic Mach numbers. The laboratory also has capabilities for investigations of micro-fluidic and millimeter-scale-fluidic phenomena, including micro-pump flows, and the effects of slip phenomena on gas and liquid flows in micro-scale passage flows with and without surface roughness, including the effects of hydrophobic surfaces and elastic turbulence. Experimental techniques include a variety of devices for measurements of pressure, velocity, temperature, mass flow rates, and heat transfer characteristics, using a variety of devices, including millimeter-scale multiple-hole pressure probes, hot-wire anemometry sensors including subminiature sensors, and infrared thermography. Also available are a variety of flow visualization technologies and apparatus, including smoke wires, dye injection in liquids, and Schlieren systems for visualization of shock wave phenomena.


Figure 10. UAH Charger 1 Facility

H. Fusion Propulsion and Power

The PRC is pursuing pulsed fusion research for advanced interplanetary propulsion. If successful, fusion will enable round trips to Mars with 7 months or less total mission duration, roughly the same time as astronaut durations on the International Space Station. Controlled thermonuclear fusion is extremely challenging, with over 50 years and billions of dollars spent trying to develop reactors for terrestrial power. The PRC is researching z-pinch fusion with fiber and liquid targets, in which 2 million amps will be driven through 2 cm long wires about the thickness of a human hair. Success will increase understanding the maximum limits in fusion reaction yield with a sub-Megajoule pulsed power system and developing scaling laws for a breakeven system using these wire targets. The parameters studied will include fuel type, target radius, initial conditions including pre-ionization, and pulse width.

The PRC's pulsed power machine, Charger 1 (shown in Fig.10), is unique among universities worldwide because it is the largest machine in academia, and it enables varying the pulse width (100 ns to 1 microsecond) by controlling the timing on the output line switches. This provides the ability to study the effects of pulse width on performance and its effects on instabilities. Controlling and exploiting these instabilities may be key to success, as the high temperatures are always reached when the pinch goes unstable, usually near peak current.

I. Plasmas and Combustion

Researchers at the plasma and electrodynamics research lab conduct experimental work on miniature plasma propulsion systems, atmospheric pressure flames and microplasmas[3,4,5]. The lab can generate plasmas from high vacuum (Fig. 11) to atmospheric pressure with DC, AC, RF, microwave, and pulsed DC power sources. A Princeton Instruments ICCD spectrometer, a TSI PLIF laser system, and lab built probes are used to characterize flame and plasma properties[3,4]. The software CFD-ACE+ is also used to conduct comparison computational modeling of the combustion and plasma physics.

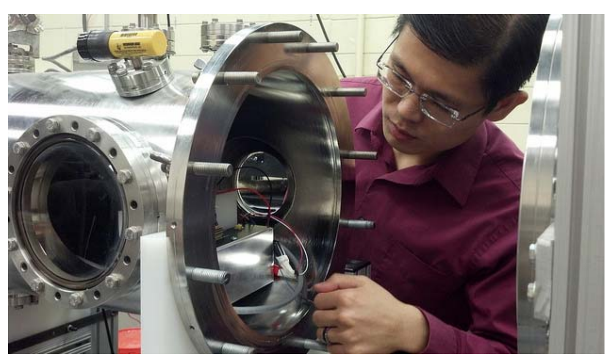
Figure 11. Vacuum Test Chamber in Plasma and Combustion Laboratory

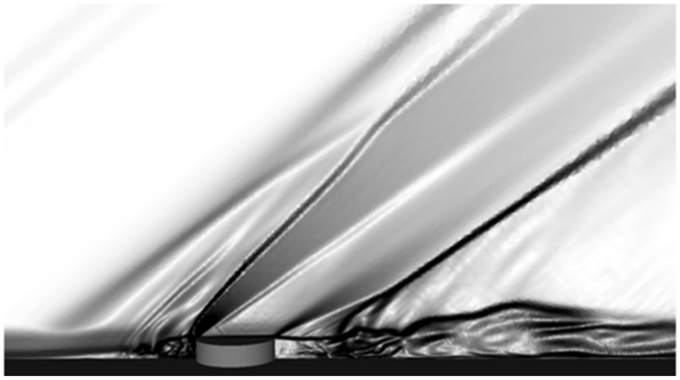

Figure 12. Example CFD Calculations of Supersonic Flow Past and External Protuberance

J. Computational Modeling

The computational modeling area includes modeling and simulation of combustion stability, acoustics and turbulence using a variety of home grown codes as well as Loci Chem, FUN3D and OpenFoam. With so many laboratories in the PRC, there is an ongoing emphasis to collaborate with the experimenters to gain better modeling and simulation algorithms. Areas of application include launch vehicle acoustics, combustion stability, fluid-structure acoustic interactions, bio-inspired UAV design, low-order models for engineers, and numerical method development.

Example project include noise from a supersonic impinging jets, analysis of pressure fluctuations in a sensor port, fluid structure interactions in a rocket engine, and noise reduction using a wavy leading edge airfoil. Figure 12 shows the results from CFD calculations of supersonic flow past an external protuberance. Projects are being formulated to combine these analysis with data for the UAH supersonic wind tunnel.

K. Aerospace Materials and Structures

The primary materials lab is located in the UAH Shelby Center Room and houses equipment for materials processing and characterization, electrochemical testing, and catalyst testing. This facility supports research on electrochemical and catalytic material systems relevant to sustainable energy. Materials processing and handling equipment includes a controlled atmosphere glove box and a fume hood for materials handling, two furnaces (1000 °C and 1200 °C), and a vacuum oven for materials processing. A multichannel potentiostat/galvanostat with 5 A boosters is available for electrochemical testing. An X-ray diffraction system is available for characterization of powder and thin film materials. These facilities support the fabrication and testing of battery and fuel cell electrodes, and the preparation of samples for x-ray and neutron imaging experiments. X-ray and neutron imaging experiments focus on ex situ and in situ studies of battery electrodes and novel propellants. X-ray nanotomography and microtomography are performed using synchrotron facilities at the Argonne

National Laboratory Advanced Photon Source (Beamlines 2-BM- A/B and 32-ID- C) and the Stanford Synchrotron Radiation Lightsource (Beamline 6-2c). Neutron imaging is performed at the Oak Ridge National Laboratory High Flux Isotope Reactor (Beamline CG-1D). On campus x-ray imaging is performed using the PRC's x-ray facility located in the Materials Science Building (Room 401). Imaging studies are complemented with computational modeling and microstructural analysis. Several desktop workstations are available for finite element simulations in COMSOL Multiphysics, image processing, and microstructural analysis. These systems include four Dell Precision workstations: T7810 (Dual 8 Core Intel XEON, 2.4 GHz, 64 GB RAM), T5600 (Dual Six Core Intel XEON, 2.0 GHz, 64 GB RAM), a Dell Precision T7500 (Quad Core Intel XEON, 2.8 GHz, 24 GB RAM), T1700 (Quad Core Intel XEON, 3.1 GHz, 8 GB RAM). These workstations employ Nvidia GPUs with CUDA capabilities. Research is also underway in the application of rapid prototyping for applications to hot components in propulsion systems.

L. Propellants and Energetics

Propellants and energetics is the heritage area of the PRC. Figure 13 shows a cryogenic oxygen/gaseous methane rocket engine firing at the UAH Propulsion Test Facility. PRC expertise includes advanced controllable solids, hybrid rocket testing, liquid injector fluid dynamics, cryogenic propellants, hypergolic ignition measurement, and measurement of lateral thrust of misaligned nozzles.

The Hot Fire Test Cell contains a single-axis thrust stand capable of supporting rocket engine thrust levels of up to 500 lbs. Testing subjects have included hybrids, solids, liquids (storable and cryogenic), gels, and gaseous rocket fuel motors. The propellant feed system for the test stand is capable of gaseous propellants including Oxygen, Nitrous Oxide, Hydrogen, and Methane; as well as liquid propellants including Nitrous Oxide, RP, Propane, and Lox. The integrated test stand data acquisition system is capable of providing measurements with 16 bit resolution at speeds up to 1.25 Msamples/sec. Test stand operations are conducted remotely from a control room located in an adjacent building to ensure personnel and are monitored through security cameras located around the facility. Valve sequencing and ignition are controlled through a programmable logic controller which operates independently of the data acquisition system.

A variety of sponsors have used the facility including government, industry, and small businesses. A significant upgrade of the cryogenic and storable propellant flow rates in currently underway. A new test stand, upgraded data acquisition, higher pressure, and capabilities for low back pressures will also be included.

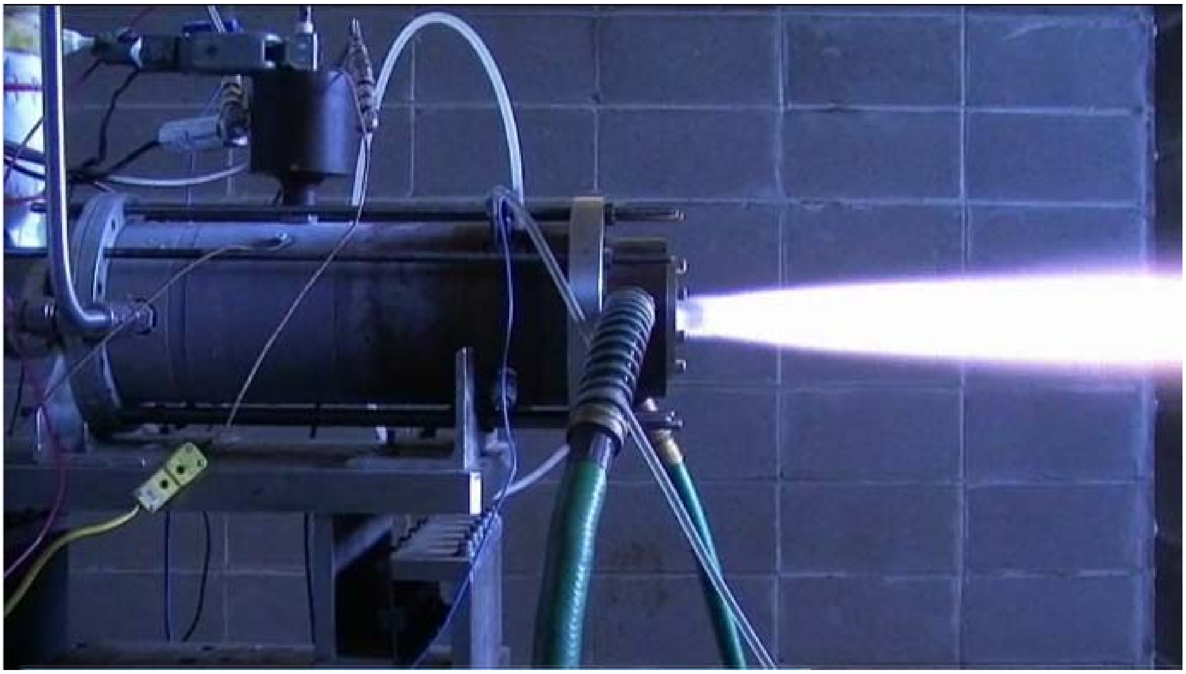

Figure 13. Cryogenic Oxygen Gaseous Methane Rocket Engine Firing at the UAH Propulsion Test Facility

Researchers at The UAH Propulsion Research Center investigate the physics and chemistry of combustion process and the performance of advanced high-temperature materials. The High Pressure Combustion Laboratory has an ultrasonic combustion bomb that is used to investigate the burning rates of new formulations over operational pressure and temperature ranges. A new real-time x-ray diagnostic capability has been commissioned at our High Pressure Combustion Laboratory. This system has been used to study the time-dependent deflagration of solid propellants[6], diagnosing propellant crack propagation[7], the erosion of nozzle materials, and the behavior of liquid injection systems. Additional capability in performing x-ray computed tomography of these materials is also being demonstrated. The capability will provide new insights into the complex, time-dependent behavior of combustion and erosion process.

M. Propulsion Systems Technology Testbed

Since 2001, the PRC has been supporting student sounding rocket projects (Fig. 14) at UAH. The PRC involvement in the program began in 2001 as a NASA MSFC pilot program to have student teams design, build, and fly a sounding rocket which would carry a student designed and built scientific payload to an altitude of 1 mile. The student team carried the project forward following the NASA design cycle template which included a proposal, preliminary and critical design reviews, a flight readiness review, and a post launch assessment report. Under the guidance of NASA MSFC, during the first year of the program UAH designed and fabricated the rocket in partnership Alabama A&M University developed the payload. After the first year of the program, the sounding rocket program evolved to include more teams from Alabama, and eventually into its current form, the NASA Student Launch Program (formerly Student Launch Initiative), which includes teams from universities across

Figure 14. UAH Student Launch Initiative Students with Sounding Rocket

the United States. Through the PRC, UAH teams have participated in the SLI program since its inception, including variations of the program which included a hybrid rocket (2008), a 2 mile altitude launch from NASA Wallops (2011), two stage boosted dart rockets (2012, and 2013), and a supersonic rocket (2014). Each rocket has carried unique payload developed by students for their rocket. These payloads have ranged from guided parafoils, to atmospheric sensing payloads, propellant management concepts, and an additively manufactured pitot probe nosecone tip. Rocket sizes have ranged from 10 lbs to 60 lbs and have used a variety of high powered motors ranging from J class to M class motors.

VII. A Purpose and Strategy for the Future

A. Challenges Ahead

As we look forward to the next 25 years, we consider what new challenges the PRC can be in position to address that are important to the propulsion community. Looking back, even just after our second year, external reviewers were remarking that we needed to consider how to sustain our operations "*in the face of serious downturns in the propulsion industry*." Many of the companies who were are supporters over the years are no longer in business or have been consolidated in to other organizations. With every challenge, however, comes an opportunity.

Figure 15 shows a graph, recently compiled by the National Institute of Rocket Propulsion Systems (NIRPS). The graph is based on survey of propulsion industries about the age distributions in their workforce. Looking at the graph, it is evident that there is a core group of people who are now approaching their 60s who will soon be reaching retirement age. It also seems as if the younger workforce has not been added in the current financial environment. This could indicate that there will be a significant need over the next 10 years to provide highly competent, experienced graduates to sustain and advance our propulsion workforce. Increased collaboration and bringing many of the experienced industry experts into the educational process has been a strategy the PRC has used effectively to address this need. The urgency also exists to get these graduates into the companies before the very experienced current workforce retires in in order for the current work force to effectively mentor industry newcomers.

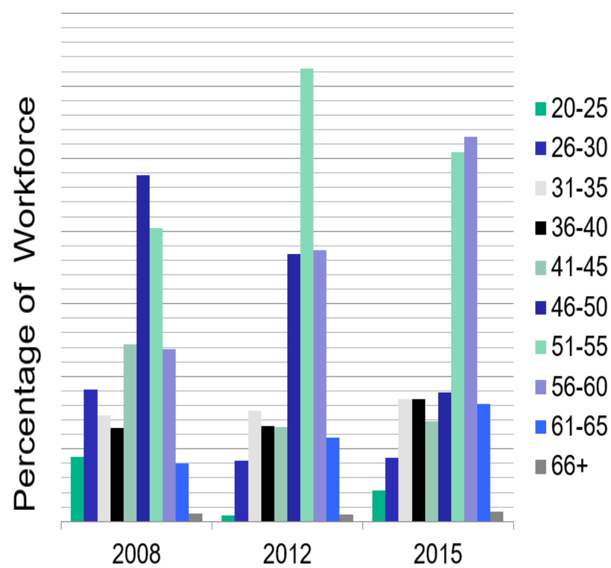

Figure 15. The Propulsion Workforce is Aging

The PRC has a demonstrated track record of producing excellent graduates and can address workforce development needs. UAH has led three national workshops involving key universities, government, and industry to help refine strategies for universities to effectively develop new technologies and produce high-quality graduates.[8]

For the near term we are also investing in upgrading our most important laboratories. The Propulsion Test Facility is undergoing a $500,000 upgrade to update data acquisition systems, augment propellant flow capabilities, and provide sub-atmospheric back pressures. Over $1,000,000 is being invested in establishing our new blow-down supersonic wind tunnel facility. This opens up new streams of research and diversifies our research portfolio. The wind tunnel is co-located in the Propulsion Test Facility, which also opens up the synergism of putting the rocket test together with the high pressure flow in a connect pipe configuration for scramjet combustion investigations.

The UAH Charger One, Fusion Propulsion Research, facility has been steadily progressing. In the next 10 years it should reach a critical point where foundational experiments can explore new ways to produce propulsion for inter-planetary travel. The reliable use of additive manufacturing for propulsion components will require serious research and the development of practical standards for ensuring consistency and quality of the material properties. We are positioned with excellent researchers and facilities to contribute to these challenges. Finally, with resources always seeming in short supply, the new work going on in Propulsion Systems Engineering Research will be valuable in identifying new technologies to enable new missions in a way that reduces risk and cost.

B. People Make the Difference

"*Relationships are more important than tasks or problems.*" Robert Frederick

After all of the planning, charts, proposals, reports, articles, and effort, it is becoming increasingly apparent that people make the difference. Healthy relationships and an environment that fosters respect and collaboration is a valuable commodity. Figure 16 shows our team at one of our monthly mentoring lunch sessions. Each month we have a cookout lunch followed by recognition of recent achievements, birthdays, and a short technical presentation. Past programs have featured talks by our new eminent scholars, presentations by past PRC graduates about their experiences in the workforce, and even a joint meeting with the department of music with lectures on "how music is like rocket science." Stakeholders and support staff from around the university from contracts, legal, safety, advancement, accounting, and others come and sometimes even bring a friend or family member. We also have several people from local industry come as well as local sponsors. These events have grown to about 100 people per month. These gatherings help us to encourage one another, discuss new ideas, and build our relationships.

Our students also recently formed a Propulsion Research Center Student Association (PRCSA). This student-led organization consisting of Propulsion Research Center affiliated students promotes multi-generational relationships and experiences for students interested in propulsion and energy. The PRCSA aims to further the education and professional development of the students, as well as promoting propulsion education and outreach activities to reach out to K-12 students. The student organization provides a platform to present papers at professional forums, conducted tours of PRC laboratories to prospective students and professionals from the community, and impacted hundreds of K-12 students through outreach. The PRCSA was recognized by the UAH College of Engineering in 2016 as its outstanding student organization and their advisor was recognized as faculty advisor of the year by the university.

Figure 16. The Current UAH Propulsion Research Center Team

Our founding director, the late Dr. Clark Hawk, developed the center around relationships that he had with his colleagues and friends. He recognized and clearly stated in his original annual report that "*the reputation of the center will in large part, be established by the students we produce*," and our mission is to "*to provide an environment that connects*," communities. After 25 years, we are very proud of the hundreds of students we have mentored, grateful for the faculty and staff who have invested their time and talents into their education, appreciative of the support provided by our many customers, and thankful that the University of Alabama in Huntsville established this organization.

"*Aerospace is not for the faint of heart*," Author unknown
"*I have an opportunity for you*, " The late Dr. Clark Hawk
"*Relationships are more important than tasks or problems*," Dr. Robert Frederick

Courage-Opportunity-People

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