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Propulsion Research and Academic Programs at the University of Alabama in Huntsville -

PRC Laboratory Capabilities - 2018

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The UAH Propulsion Research Center (PRC) is in its 27th year at the University of Alabama in Huntsville (UAH). 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 summarizes recent metrics from academic and research programs. The emphasis this year is on describing the fifteen different laboratories associated with the UAH Propulsion Research Center. Laboratory highlights in 2018 include a significant upgrade of our Rocket Test Stand capabilities, which includes a 2-pound-per-second cryogenic feed system, a 2,000 pound capacity thrust test stand, and a new high-speed data acquisition and control system. In the 2017 fiscal year, total research expenditures from fifteen different agencies rose to $1.884 million (a 20% increase). Two Ph.D., eight master's students, and numerous undergraduate students obtained degrees in conjunction with the center. The PRC continues to be a resource to perform both fundamental and applied research. It is also a significant contributor to workforce development in the propulsion and energy field.

I. Introduction

THE Propulsion Research Center (PRC) marked its 27th year as a University of Alabama in Huntsville (UAH) research organization in 2018. This paper is part of a series of periodic updates[1,2,3] about PRC activities and capabilities. In 2005, Drs. Hawk and Frederick wrote a summary of the research activities of the first thirteen years of the UAH Propulsion Research Center. A 25th-anniversary summary paper[2] provided insights into the formation and overall progress of the PRC at that anniversary. Last year, the PRC paper detailed seven technical research areas active in center operations.[3] This paper details fifteen laboratories operated by or associated with the UAH Propulsion Research Center and summarizes recent metrics from academic and research programs. The introduction describes the PRC mission and strategy, overall metrics, current research sponsorship. The following sections describe academic infrastructure, laboratory capabilities (the focus of this paper), team development, and plans.

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A. PRC Mission and Strategy

The mission of the PRC 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. Individuals and groups within the university collaborate to achieve the PRC's research goals. Researchers from government laboratories, other universities, and the aerospace industry also collaborate with the PRC. This environment produces leading-edge research results and scholarly activity leading to new discoveries and significant workforce development.

Figure 1 shows the current PRC Organization Chart. The Propulsion Research Center is an assembly of staff, faculty, and students that work together under the PRC business unit. Research centers are business units within UAH that focus on specific technical areas. Each box represents a functional area in the organization. Currently, there are over one hundred faculty, staff, and students associated with PRC research activities. The PRC Center Director

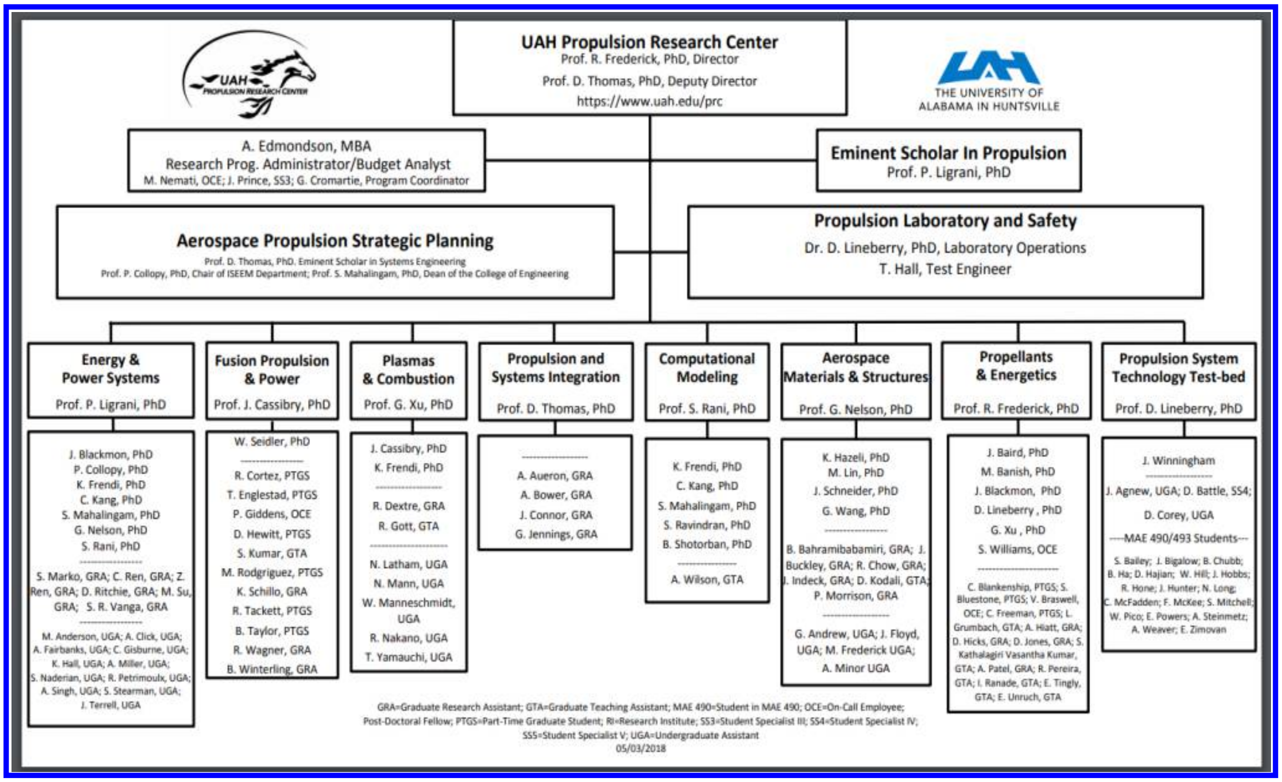

Figure 1. The PRC Organization Chart

oversees staff that include a Deputy Director that advises in strategic and technical matters, Program Coordinators who manage administrative/fiscal items, a Senior Researcher who oversees Safety and Test Operations, and a Test Engineer who oversees laboratory operations at the Johnson Research Center. The organization chart also shows eight Topic Areas from Energy and Power Systems to Propulsion Systems Technology Test-bed. Propulsion and Systems Integration is a new Topic Area added this year focusing on propulsion system reliability and nuclear thermal propulsion systems. Each of these eight areas has a lead person identified as contact. The names beneath these boxes show participating faculty, staff, graduates students, and undergraduate students who are active in each area.

B. Overall Metrics

Figure 2 shows the cumulative production of advanced degrees for students associated with the Propulsion Research Center from its inception in 1991 to 2018. The total master's degree production has now surpassed 210 and the total Ph.D. production is approaching 40. During the 2017 academic year (fall 2017 through summer 2018), eight master's students and two Ph.D. students completed advanced degrees while working on PRC research. Most of the students who receive advanced degrees are in the UAH School of Mechanical & Aerospace Engineering (MAE).

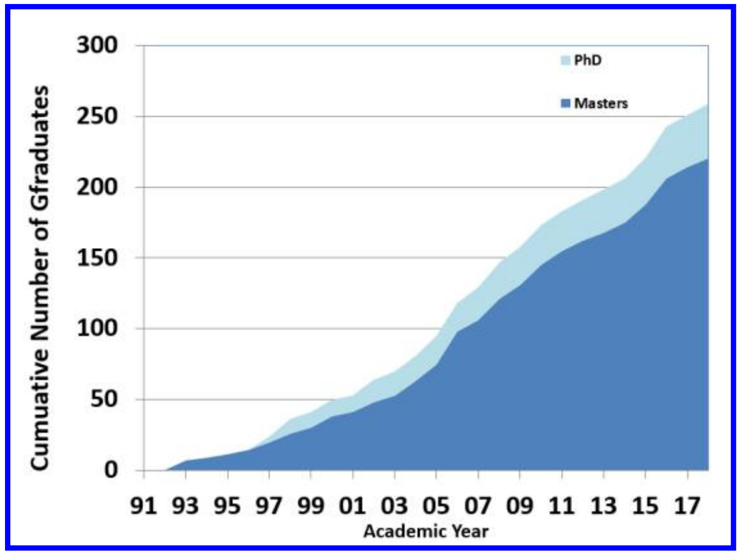

Figure 2. Cumulative Production of Advanced Degrees Associated with the PRC.

Vijay Rani's dissertation[4] described a new analytic model for thermoacoustic instabilities in a premixed combustor. Andrew Hiatt's dissertation explored the electrolytic properties and combustion characteristics of electric solid propellants.[5] Students also completed master's theses involving: experimentation on electric thrusters,[6,7] jet array heat transfer, [8,9] rocket test stand optimization,[10] and Nuclear Thermal Rockets.[11]

Figure 3 shows the annual research expenditures from external sources for the Propulsion Research Center since its inception in FY 1991 through a projection of FY 2018. The average annual expenditure level of the entire period is $1.5 million dollars per year. The periodic "surges" in funding generally represent the growth and completion of significant research programs with a particular sponsor.

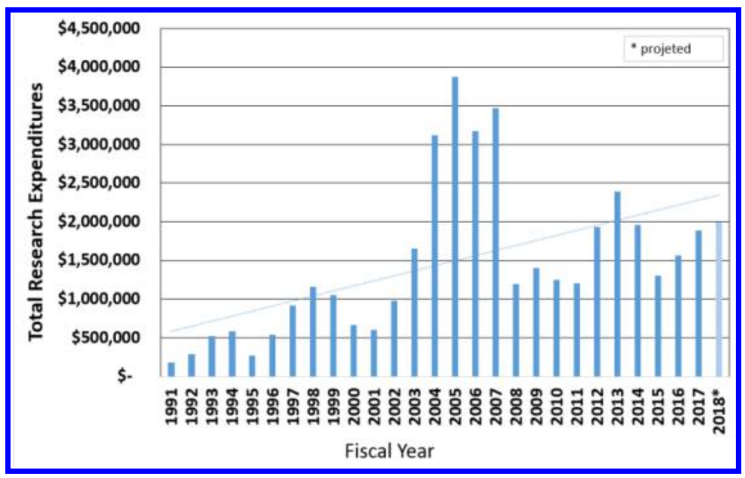

Figure 3. Annual PRC Research Expenditures by FY.

Research expenditures increased about 20% per year in both FY 16 and FY 17. Total expenditures rose from $1.308 million (FY15) to $1.563 million (FY16), to $1,884 million (FY17). The research expenditure numbers do not include cost shares, internal university research funds, or UAH Foundation investments into the PRC.

C. Current Research Sponsors

This section highlights the sponsors and funding distributions in FY17 and FY18 (October 2017 through May 2018). Figure 4 shows the percentage of total research expenditures categorized by income sources for the two periods. The "Business" category includes funding from small business (mostly SBIR) and corporate sponsorship. The main shift between FY17 and FY18 is the realignment of effort from DoD to NASA funding percentages. Two factors drive this change. The first is a short-term funding gap in one of the PRC's large DoD programs that reduced DoD expenditures this year. The second is the addition of several NASA research contracts related to Space Grant activities. The "Other" category has single DoD, DARPA, and State of Alabama Funds grouped in it.

Since the beginning of FY17, the PRC has received funding from 19 different agencies. The PRC FY17 sponsors included Aerojet Rocketdyne, Barber-Nichols, Inc., Boeing, C3 Propulsion, Combustion Research & Flow Tech., Inc., The Missile Defense Agency (MDA), Gloyer-Taylor Laboratories (GTL), Hyper V Technologies, NASA Goddard Spaceflight Center, NASA Marshall Spaceflight Center (MSFC), State of Alabama, and Varian Medical Systems, Incorporated. The PRC FY18 Sponsors add the following organizations: IHI Corporation, Jacobs, Manufacturing Technical Solutions (MTS), McConnell Jones Lanier & Murphy LLP, NASA Headquarters, Solar Turbines, Inc., and Vector (formally known as Garvey Spacecraft Corp).

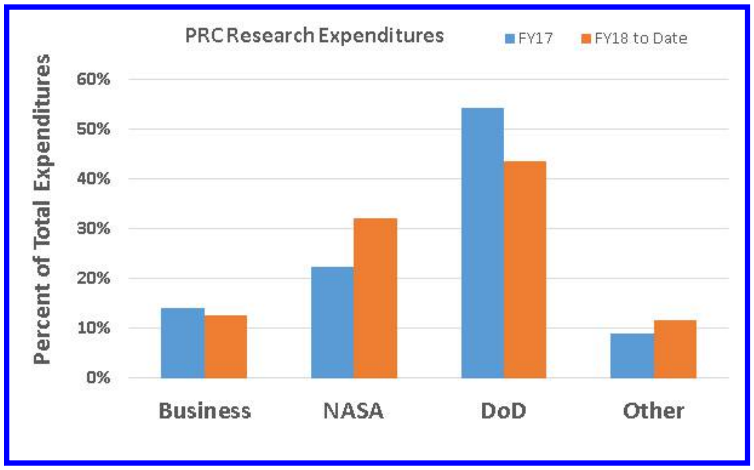

Figure 4. Research Expenditures Distribution by Sponsor Category for FY17, and FY18 to date.

II. Academic Infrastructure

A. Mechanical & Aerospace Engineering

The PRC draws a majority of academic participants from The UAH Department of Mechanical & Aerospace Engineering (MAE). This also fulfills our strategic priority to support academic achievements. The MAE Department offers Bachelors of Science Programs in both Aerospace Engineering and Mechanical Engineering accredited by the Accreditation Board for Engineering and Technology, Inc. (ABET). At the graduate level, the MAE Department offers Master's and Ph.D. Programs in Aerospace Systems Engineering and Mechanical Engineering.

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

Dual-Level Undergrad/Graduate	AY 15-16	AY 16-17	AY17-18
MAE 420/520 – Compressible Aero	49		
MAE 343 – Compressible Aerodynamics		97	104
MAE 440/540 – Rocket Propulsion I;	55	34	67
MAE 441/541 – Airbreathing Propulsion	17	38	33
MAE 444/544 – Intro. To Electric Prop.	22		20
MAE 468/568 – Eleme. of Spacecraft Des.	56	62	87
MAE 493/593 – Rocket Design I and II	56	38	40
MAE 495/595 – Intro. To Nuclear Prop		22	
TOTAL	255	291	351
MAE Graduate-Level	**AY 15-16**	**AY 16-17**	**AY17-18**
MAE 620 – Compressible Flow	21	11	30
MAE 640 – Rocket Propulsion II		21	0
MAE 644 – Adv. Solid Rocket Propulsion	22		15
MAE 645 – Combustion I	6		19
MAE 681 – Missile Trajectory Analysis			19
MAE 745 – Combustion II	0	0	0
MAE 795 – ST: Intro to Fusion Propulsion;	11		16
MAE 695/795 – ST Adv. Readings in Prop.	7	3	2
MAE 695 – Comb. Instability in Solid Rockets	15		
MAE 695 – Liquid Rocket Engineering	20		
MAE 754 – Hypersonic Flow	0	11	
TOTAL	102	46	101

The undergraduate MAE program had a remarkable growth rate last year, expanding from 1,068 undergraduates in academic year (AY) 16-17 to 1,238 in AY 17-18. The undergraduate Aerospace Engineering program component has concurrently grown from about one-third to just below one-half of the undergraduate population. The Aerospace Engineering enrollment may surpass that of the Mechanical Engineering program in fall, 2018. Enrollment in the graduate program increased slightly last year from 152 students in AY 16-17 to 158 students in AY 17-18.

The MAE Department added two new tenure-track faculty in AY 17-18, bringing the total to twenty-one tenured and tenure-track faculty. The new faculty members specialize in the areas of aerodynamics of unmanned vehicles and in computational materials science. The MAE Department also maintains five full-time lecturer positions to assist with the growing undergraduate population. Several part-time instructors also help carry the teaching load for the department.

B. Propulsion-Related Courses

Table 1 shows several propulsion-related classes offered at UAH in Mechanical and Aerospace Engineering. The dual-level courses allow undergraduate and graduate students to learn together. Qualified undergraduates can participate in a Joint Undergraduate Master's Program (JUMP) in which they can simultaneously earn undergraduate and graduate credit for taking up to nine hours of approved graduate-level classes. The increasing totals in the dual-level classes of Table 1 show how the student growth is increasing class production. The MAE Department has slated MAE 754, Hypersonic Flow, for the fall of 2018. It covers theories for treating the laminar and turbulent boundary layers of reacting fluids, mixtures, related chemical, thermodynamic, and physical phenomena in hypersonic flows, leading edge bluntness, shock wave interactions, and vorticity effects.

UAH also has a College of Professional and Continuing Studies (CPCS). The CPCS offers a certificate in propulsion by combing three of the following courses: Rocket Propulsion Fundamentals, Advanced Solid Rocket Propulsion, Combustion Instability in Solid Rockets, and Liquid Rocket Engineering. These courses assist professionals who might be transitioning into new technical areas and want to receive advanced material for professional development credit. CPCS offers these courses periodically in person or with on-demand, online learning.

III. PRC Laboratory Capabilities

Last year, the PRC review paper presented summaries of activities in each of the seven (now eight) technical topic areas shown in Figure 1. This year, the following sections present *specific laboratories* and their capabilities that the PRC uses to perform research. **Error! Reference source not found.**The Propulsion Research Center utilizes the sixteen laboratories shown in Table 2. The PRC manages operations at the Propulsion Test Facility and Johnson Research Center, the High-Pressure Solid Propellant Laboratory, and the Solar Thermal Laboratory. Other business or academic units at UAH manage the "Other" laboratories in which PRC Principal Investigators conduct in their research. The following sections present short capabilities write-ups for the laboratories listed in Sections A through M. Each section also contains a figure or diagram and cites publications relevant to each laboratory.

Figure 5 shows the Johnson Research Center. This floor plan illustrates the JRC laboratories shown in Table 2. The JRC is a 15,000 square foot facility that houses offices and laboratory spaces. PRC Staff and Students have office space in the south end of the building. The PRC Research Engineer and Test Engineer also have offices in the JRC. They oversee research operations and mentor our students. There is a classroom space suitable for holding classes, hosting a seminar for up to ninety people, and other group functions. Card access is required to gain access to the working laboratories. Aerojet Rocketdyne has autonomous office and laboratory space of their own in this facility as well. This paper presents overviews of each of the individual JRC laboratory spaces in subsequent sections.

The Propulsion Test Facility (PTF) is located behind the Johnson Research Center. The PTF has a bay that houses the Supersonic Wind Tunnel and a bay for the Rocket Test Stand. Between these two bays, an Instrumentation Room provides a climate-controlled, protected area for instrumentation, data acquisiton computers, and optical equipment. The Rocket Test Stand is operated remotely from the JRC. The JRC and the PRC have access limted by a security fence and a warning light system that shows when tests are in operation.

Table 2. Table PRC and Associated Laboratories*

Sec.	Propulsion Test Facility (PTF)	Location
A	Rocket Test Cell	UAH Johnson Research Center
B	Supersonic Wind Tunnel Laboratory (SWTL)	UAH Johnson Research Center
	Johnson Research Center	**Location**
C	Charger Rocket Works (Sounding Rockets)	UAH Johnson Research Center
D	Injector Spray Facility	UAH Johnson Research Center
E	Plasma and Electrodynamics Research Lab (PERL)	UAH Johnson Research Center
F	Thermal Fluids Sciences Lab	UAH Johnson Research Center
G	Vacuum Chamber Test Lab	UAH Johnson Research Center
	Other PRC	**Location**
H	High-Pressure Solid Propellant Lab	UAH Materials Science Building
I	Solar Thermal Lab	UAH Werner von Braun Research Hall
	Other UAH	**Location**
J	Adaptive Structures Lab	UAH Technology Hall
K	Advanced Materials and Processing Laboratory (AMPL)	Aerophysics Research Center at Redstone Arsenal
L	Charger 1	Aerophysics Research Center at Redstone Arsenal
M	Complex System Integration Lab (CSIL)	UAH Werner von Braun Research Hall
N	Mechanics of Materials Under Extreme Environments	UAH Optics Building
O	Transport, Reaction, and Energy Conversion Lab	UAH Shelby Center

* https://www.uah.edu/prc/facilities

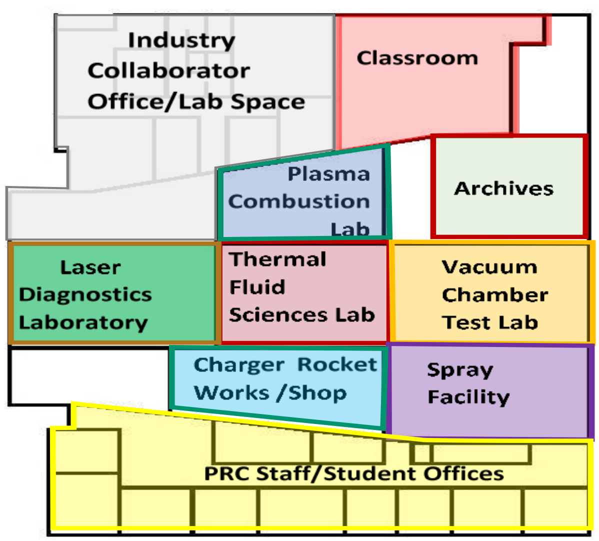

Figure 5. The PRC Johnson Research Center

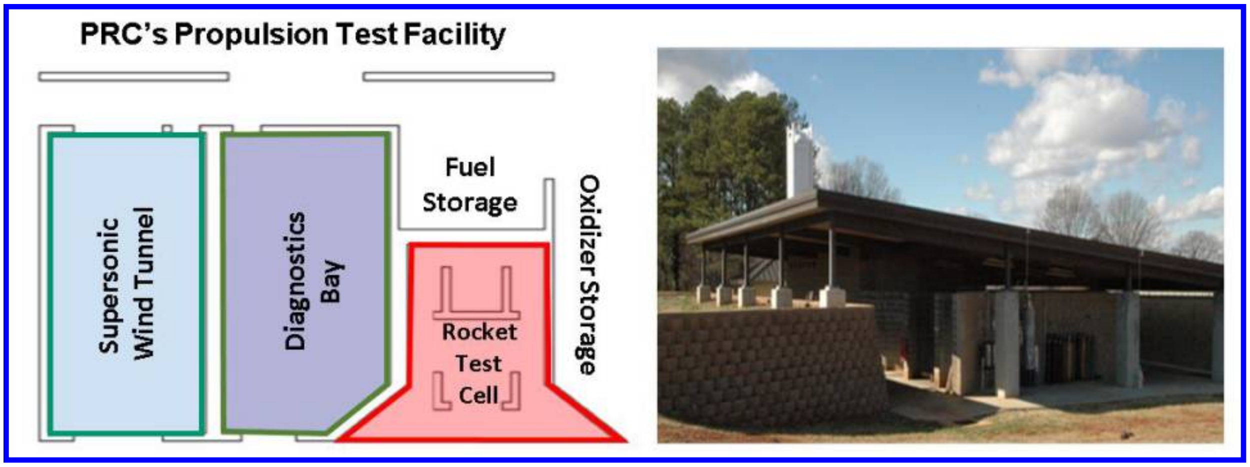

Figure 7. The Propulsion Test Facility

The PRC implemented improved safety infrastructure and practices in the past year highlighted in PRC 2017 Safety Plan.[12] The PRC staff completed the 2017 Safety Plan to consolidate safety practices that pertain to general and hazardous activities that are in the domain of the Johnson Research Center and PRC. The Safety Plan documents many of the practices already in place including emergency communication plans, Johnson Research Center safety information, testing guidelines, and JRC certification/inspections. All participants on PRC Red Teams (persons operating hazardous procedures) must now pass an online Quiz based on material from the PRC 2017 Safety Plan. The PRC also completed a formal Test Facility Site Plan in January of 2018. The plan describes test operations areas, proper handling and storage of energetic materials, and other pertinent matters.

The Safety Plan and Site Plan passed an external review by the Defense Contract Management Agency in conjunction with a new DoD-based contract award to UAH. The PRC hosted a course in Process Hazards Analysis for Energetic Materials and Hazardous Chemicals as well as a national meeting of the Rocket Test Group on our campus. These activities train our students, staff, and faculty in up-to-date and practical aspects of working in the propulsion test business safely.

Figure 6. Process Hazards Analysis for Energetic Materials and Hazardous Chemicals Course

A. Propulsion Test Facility (PTF) –Rocket Test Cell

The Propulsion Test Facility provides the PRC with capabilities to test propulsion systems and components. Propellant capabilities include gaseous oxygen, methane, hydrogen, and nitrogen. The facility can also provide controlled flows of liquid fuels such as RP-2, cryogenic oxygen, and cryogenic nitrogen. The PRC recently upgraded[13] the test stand, cryogenic flow, and instrumentation capabilities in the Rocket Test Cell. The Thrust Stand, shown in **Error! Reference source not found.**, has thrust load capabilities from 500 *lbf* to 2,000 *lbf*. Operators can also configure the test stand for either horizontal firing or inclined firing (up to 45 degrees) for cryogenic liquid engines. A new data acquisition chassis was installed on the PRC test stand and has sixteen high-frequency measurement

Figure 8. New UAH Vertical Rocket Test Stand (With LOX Liquid Rocket Engine)

Figure 9. New UAH Rocket Test Stand (With Solid Rocket Motor)[13]

channels, forty eight pressure channels, thirty two thermocouple channels, eight strain gauge channels, forty-eight digital input/output channels, integrated test camera support, analog and digital control cards, and enables remote monitoring of valve states and system pressures. The PRC pressure system was upgraded to support supply pressures of 3,000 psi, and two bulk nitrogen tanks for system pressure were acquired and added to the system. The new tanks provide 110 ft^3 of storage volume with pressure limits up to 3,000 psi. A new high-flow oxidizer leg was added to the test cell in 2018. The new leg has 1-inch feed lines that allow up to four times the mass flow rates of the existing PRC system and with the increased supply pressure, it can offer significantly longer test durations. Initial demonstration tests in 2018 consisted of a 1,600-lbf thrust solid rocket motor horizontal test firing that acquired chamber pressure and thrust. The new cryogenic flow system also demonstrated a 2.7 *lb./s* LN2 flow for over 30 seconds. Both systems used the new data acquisition system for measurements during testing.

The PRC also demonstrated a new vertical test stand in 2018 for small liquid rocket engines. Recent papers describe capabilities[13] and results of testing[14,,15,16.]at the Rocket Test Stand.

B. Propulsion Test Facility – Supersonic Wind Tunnel Laboratory (SWTL)

Laboratory capabilities include measurements of phenomena related to turbomachines, as well as aerospace engine components with test section inlet Mach numbers from 0.2 up to 3.0. Three parallel test sections provide means to investigate transonic and supersonic flow phenomena, either with or without heat transfer. The high-speed flows are provided using an elaborate air pressure tank supply system with specially provisioned flow and pressure control regulating valves. One currently employed research test section, shown in the foreground of Figure 10, is designed to operate at an inlet Mach number of 1.54. This facility provides excellent flow characteristics at supersonic velocities, including uniform inlet flow with low turbulence intensity, and minimal flow disturbances. Unique apparatus are employed to control shock wave structure, orientation, and unsteadiness, including a shock wave holding plate and a downstream choking flap. A photograph of a resulting normal shock wave, along with the associated lambda foot, obtained using shadowgraph visualization, is shown in Figure 11. [17,18] Unique capabilities include apparatus to investigate SWBLI – Shock Wave Boundary Layer Interactions, shock waves and surface heat transfer on and near gas turbine blade tips, and other aerodynamics and turbomachinery phenomena (as applied either to aero-propulsion, aerodynamic, aerospace, or turbomachinery components) with high-speed, compressible flows at transonic and supersonic Mach numbers. A new transonic test section, containing a linear turbine blade cascade, is under development, which will allow investigation of innovative blade tip configurations, both with and without advanced film cooling arrangements.[19,20] Also available is a test section for teaching laboratory demonstrations of oblique shock waves generated by wedge flows, which is shown within the left-hand side of Figure 9. 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 Schlieren and shadowgraph systems for visualization of shock wave phenomena. Note that components of these visualization systems are also evident within Figure 11.

Figure 10. Supersonic Wind Tunnel research test section, teaching demonstration test section, Schlieren and shadowgraph visualization apparatus, and associated components.

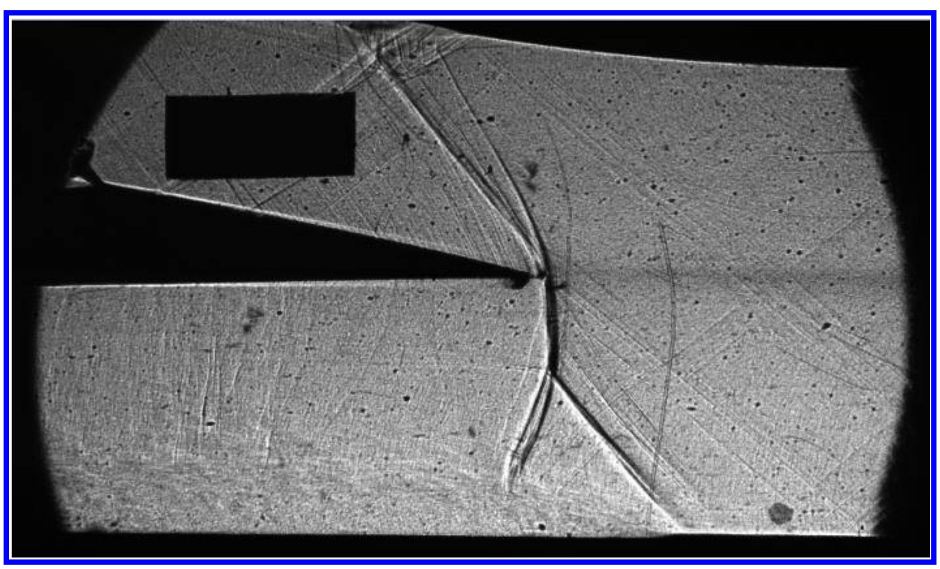

Figure 11. Shadowgraph visualization image from testing on 04-05-2018 of normal shock wave, lambda foot, and resulting separated boundary layer. Flow direction is from right to left, with shock wave holding plate on left side of image, and with rectangular distance reference marker.

C. JRC – Charger Rocket Works

Mechanical & Aerospace Engineering majors who participate in the NASA Student Launch Initiative (SLI) program through a two-semester senior design course, MAE 490/493 Rocket Design work on the Charger Rocket Works (CRW) space at the JRC. By participating in the SLI program, students gain hands-on experience in rocket design, fabrication, and testing and receive academic credit for MAE 490/493 Rocket Design. The CRW workshop has tools, works areas, equipment to fabricate small parts. It has capabilities to test mechanical, electrical, and computer components. There are areas to assemble the inert sounding rocket components. The area is equipped with a drill press, standard machine tools, an electronics bench, worktables, and racks for parts and materials. A recent addition to the laboratory is an ROBO R2 3D FDM Printer. This printer will facilitate rapid turnaround of both prototype and flightworthy components such as fins, electronics housing, nosecones, and other custom parts. Another recent addition is an X-winder® 4-Axis Model 4X-23 filament winder that enables fabricating of composite airframe components such as bodytubes, couplers, and nosecones.

Figure 12. Staff and Student at Charger Rocket Works

The following paper[21] describes recent activities supported by the Charger Rocket Works area.

D. JRC – Injector Spray Facility

The Injector Spray Facility, shown in
Figure ***13***, provides the ability to cold flow liquid and gaseous rocket injectors (with inert fluids), and rapid prototyped flow components, for the measurement of flow performance, observation of spray patterns, and measurement of droplets. The facility has an atmospheric spray bench dedicated to the observation of sprays at ambient pressures. There is also a high-pressure chamber to observe injection at pressures up to 500 psig and flow rates of up to 2 lb/sec. K-bottle packs or the wind tunnel tank farm supplies the pressure to run the system.

Instrumentation at the facility includes pressure, temperature, and flow rate sensors. There are also high-speed video cameras, a 2-D Phase Doppler Particle Analyzer (PDPA), and a 2-D Particle Image Velocimetry (PIV) system, all for the collection of atomization and velocity profile characteristics in flows and sprays.

Figure 13. The PRC Spray Facility

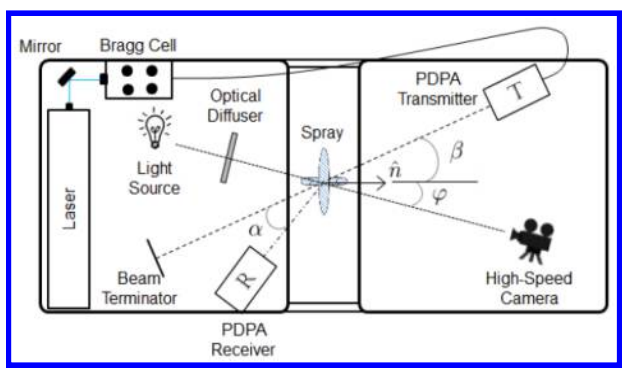

Figure 14. 2-D Phase Doppler Particle Analyzer.

Past work at the facility has included research on impinging[22] and the self-pulsation of swirl coaxial[23,24,25] bipropellant injectors. Current work includes developmental testing of shear coaxial injectors, impinging injectors, and fundamental research focused on the effects of surface roughness resulting from additive manufacturing in cavitating venturis.

E. JRC – Plasma and Electrodynamics Research Lab (PEARL)

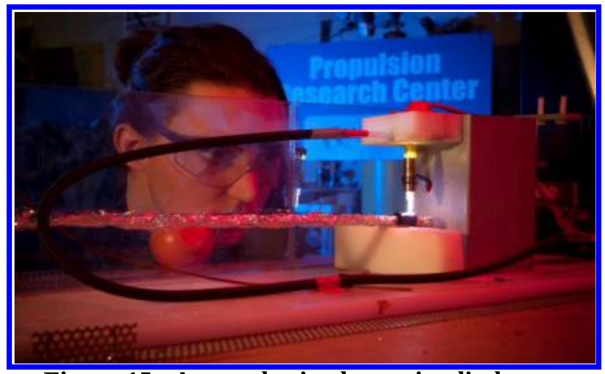

Figure 15. Atmospheric plasma jet discharge.

The Plasma Electrodynamics Research Lab conducts experimental research in areas of low-temperature plasmas and their engineering applications. Projects have included satellite electric propulsion, plasma-assisted combustion, nanomaterial synthesis, atmospheric plasma jets, and soft and biomaterial treatment with plasmas. The lab has a small vacuum chamber capable of 1E-6 Torr base pressure for space environment simulation. Laboratory power systems provide dc, pulsed high voltage dc, ac, rf, and microwave power to generate various plasmas. The available diagnostics include a tunable dye laser, nanosecond gated intensified CCD camera, nanosecond gated spectrometer, scanning monochromator, and various temperature, pressure, and other physical probes. Recent papers[26, 27, 28, 29, 30] detail results published by the research team.

F. JRC – Thermal Fluids Sciences Lab

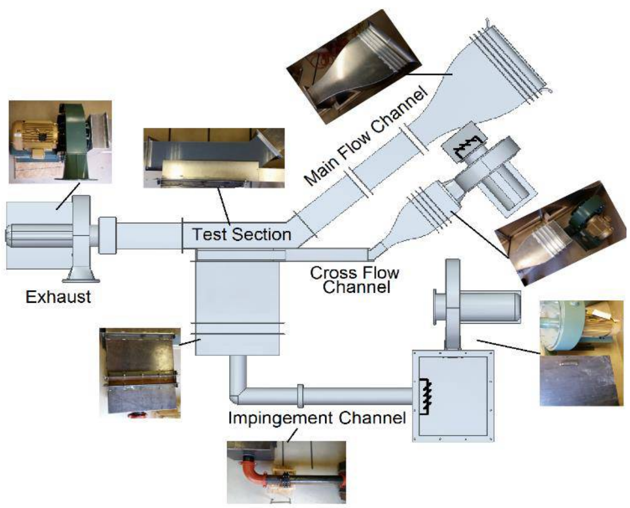

Figure 16. Double wall cooling experimental facility with heated main flow, cross channel coolant flow, and impingement coolant flow components.

The Thermal Fluid Sciences Laboratory (TFSL) capabilities include investigation of <u>impingement cooling</u> 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. Of particular interest are effects of special surface roughness textures, and shaped impingement-hole configurations [71-78]. Another facility is employed for <u>double wall cooling investigations</u> 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 [79-87]. 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, provides simultaneous spatially-resolved distributions of surface heat transfer coefficients and surface adiabatic temperature (from which, distributions of adiabatic film cooling effectiveness are determined) [84-86] Figure 3 shows a diagram of the double wall cooling test facility, including photographs of individual components [79-80]. The laboratory also has capabilities for investigations of <u>micro-fluidic and millimeter-scale-fluidic phenomena</u>, 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. Recent elastic turbulence investigations involve measurements within Viscous Disk Pumps and Rotating Couette Flow environments [88-95], where the heat transfer apparatus associated with the latter environment is shown in Figure 18 [95]. Also of interest is experimental and numerical investigation of <u>unsteady impingement cooling within a blade leading edge passage</u> [96], as well as <u>unsteady structure and development of both laminar and turbulent impingement jets, including Kelvin-Helmholtz vortex development</u> [97-101]. Other recent studies consider determination of <u>entropy production from the flow field around a turbine guide vane</u> [102-103], and the numerical simulation of this flow field by means of Computational Fluid Dynamics (CFD) [102]. Also considered is <u>impingement cooling of electronic chips</u>, which are equipped with different cylindrical pedestal fin arrangements [104-105]. More recently, confined, milliscale unsteady laminar impinging slot jets are investigated as they influence surface Nusselt numbers with constant surface heat flux and constant surface temperature thermal boundary conditions 106-[110]. Other investigations employ spiral inertial microfluidic devices for continuous blood cell separations [111], as well as microfluidic inertial, continuous SPLITT, and field-flow fractionation technologies for separations of whole blood components [112]. More recently, secondary Dean vortices [113-114] in spiral microchannels are investigated [115], and used to advantage for cell separations [115-116]. 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, liquid crystal thermography, and infrared thermography. Also available are a variety of flow visualization technologies and apparatus, including smoke wires, fog generators for gas flow visualizations, and dye injection in liquids.

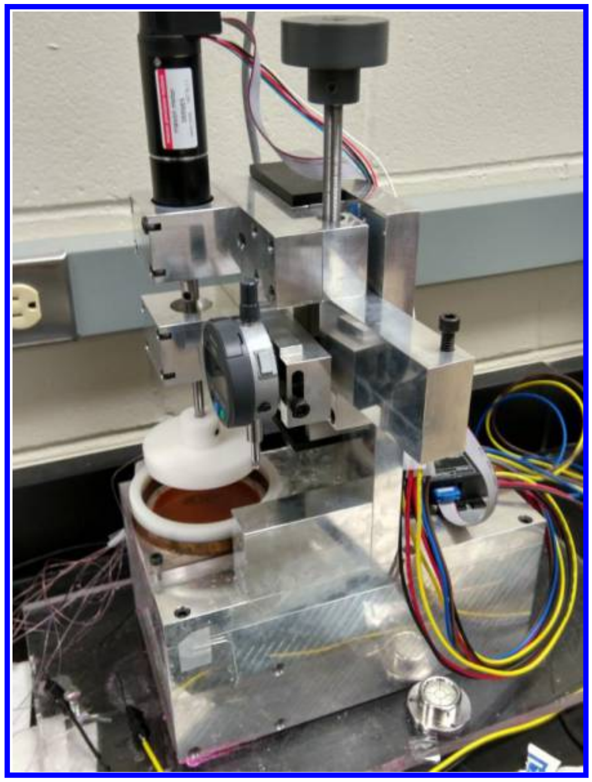

Figure 18. Photograph of experimental apparatus employed for heat transfer measurements and analysis of elastic turbulence phenomena within a Rotating Couette Flow configuration.

G. JRC – Vacuum Chamber Test Lab

The PRC Large Vacuum Test Facility is a 13-ft long by 6-ft diameter cylindrical stainless clad chamber. It has the capability of reaching base pressures down to 10^{-6} Torr or around 90 miles above sea level. It uses a combination of roughing pump and a diffusion pump to remove air from the chamber. It is configured with four convection gauges, one ionization gauge, and pressure transducers for measurement. The chamber wall features a series of high voltage/current, sensor and propellant feed ports. The test facility offers a relevant environment for low cost testing to evaluate: 1) high altitude atmospheric conditions for UAVs and flapping wing dynamics, 2) Low Earth orbit space conditions for small-scale air-breathing, chemical, and electric propulsion devices.

Figure 19. The PRC Vacuum Chamber

Past experimentation has included; gas-gas reaction control thruster at low earth conditions, Vicon motion capture of camera butterfly testing[31] at elevated altitudes, and a MagLev micro-thruster demonstration at reduced pressure environments.[32, 33]

H. Other PRC–High-Pressure Solid Propellant Laboratory

The PRC High Pressure Laboratory (HPL) is a state-of-the-art lab for performing experimentation on solid energetics. The PRC HPL allows researchers to test solid propellants under high-pressure conditions in order to evaluate burn rate at varying levels of chamber pressure up to 5000 psi. In the lab, there are two test cells with 1-foot thick steel reinforced concrete walls, a fume hood for chemical cleanup, and a grounded work area for handling energetics. One test cell utilizes a stainless steel combustion chamber with an ultrasonic sensor to take burn rate at high pressures. The other test cell has an x-ray system capable of doing live x-ray videography of burning samples through combustion chambers under high-pressure conditions. The x-ray system also performs computed tomography of samples configurations. The PRC established the HPL in 1991.

Recent research includes: fundamental studies of electric solid propellants with laboratory demonstrations of flame sensitivity and electrochemical dependency,[34] burn rate determination of solid propellant samples using ultrasonic pulse-echo techniques,[35,36] burn rate determination of electric solid propellants with live x-ray videography,[37] and non-destructive examination of porous hybrid grains using x-ray computed tomography.[38] A recent paper also details safety practices and technology control methods that are used in the HPL.[39]

Figure 20. Solid Propellant Sample Preparation in HPL

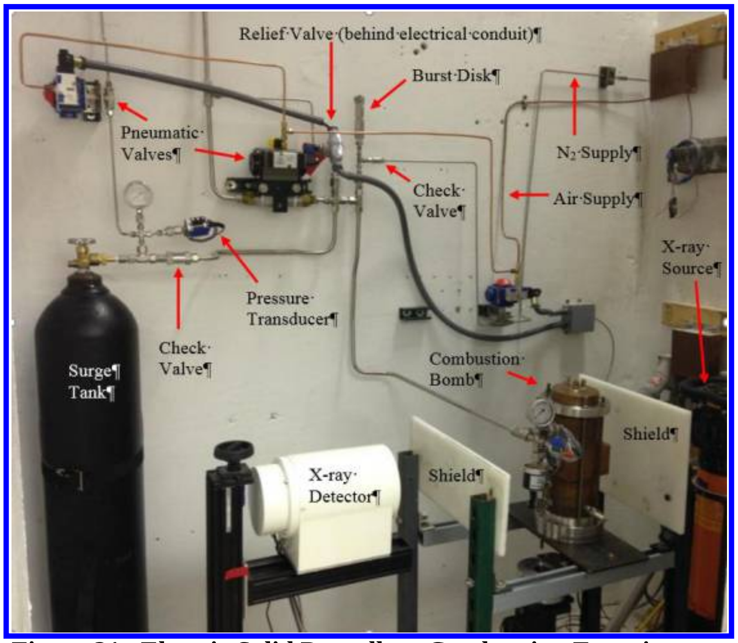

Figure 21. Electric Solid Propellant Combustion Experiment Showing Local Combustion at Electrode Inteface[34]

I. Other PRC– Solar Thermal Laboratory

The Solar Energy Test Facility (SETF) was originally developed in the 1990's for testing various flat plate solar thermal collectors. Its capabilities were extended to include a ~10-ft diameter parabolic concentrator for "solar furnace" and solar thermal rocket test. With the addition of a vacuum chamber and quartz windows, it was used to test optical properties of high temperature materials, including shield materials for a near-sun orbit satellite. Tests have also been conducted on a novel chain drive heliostat drive unit (patent pending) that incorporates special low-cost damping mechanisms to avoid the high impact loads from wind gusts exerted on conventional heliostats. The novel load configuration provides a constant static load with superimposed gust loads to more fully

Figure 22. The PRC Solar Laboratory

simulate actual wind load and gust conditions. That drive unit was subjected to thousands of cycles over several weeks to simulate the fatigue equivalent life of over 150 years, compared to the usual 30-year life, and it is still operational. The area has also been used to test Army remote power systems based on solar photovoltaic collectors coupled in a hybrid mode for use with conventional mobile/remote power generation.

The solar thermal laboratory was decommissioned in 2011. The heliostat and other mirror systems remain intact for future research programs. Past prgrams are document in the fillowng papers.[40, 41,42,43,44,]

J. Other UAH– Adaptive Structures Laboratory

The Adaptive Structures Laboratory conducts experimental research in areas of piezoelectricity for applications in structural health monitoring and energy harvesting. Current projects include the development of piezoelectric sensors from in-house poled fibers. The Adaptive Structures laboratory is created by the PI and offers a set of unique equipment to conduct both fundamental and applied research when these smart materials are integrated with aerospace structures. Laboratory equipment includes high-efficiency high bandwidth power amplifier, NI USB multifunction DAQ, Modal Shaker Table (1-3000Hz), Oscilloscope and Function Generators, Fast sampling Laser sensor.

Recent publications illustrate the capability of UAH Adaptive Structures Laboratory.[45, 46,47]

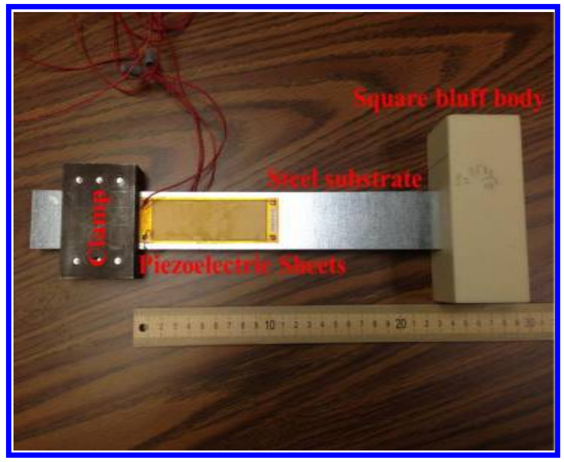

Figure 23. A Galloping Piezoelectric Energy Harvester (GPEH).

K. Other UAH – Advanced Materials and Processing Laboratory (AMPL)

Advanced manufacturing is a topic that draws upon many engineering disciplines and is vital to the new industrial revolution in the USA. Involvement in these advanced manufacturing processes relies on a fundamental understanding of material behavior and response to the conditions imposed by the manufacturing technique. Unique microstructures, and hence properties, can be obtained if the underlying principles are understood and used to control the process. Key to effective utilization of advanced manufacturing techniques is the link between structural performance and material properties.

In addition to designing and controlling the material microstructure and properties, for structural applications, many of these processes are automated and fully instrumented. Thus, the ability to design and control the robotics is also needed. Linking the robotic systems with the data generated during the processing provides the potential for both feedback control schemes and in-situ part qualification.

Equipment in the Advanced Materials and Processing Laboratory at UAH includes the friction stir weld equipment in (a) and the direct deposition, wire fed, additive manufacturing equipment in (b). Additional equipment is available for microstructural characterization and mechanical property measurement.

Figure 24. NovaTech G10K/ Large Panel Gantry FSW/TSW equipped with high torque motor and auxiliary induction heating

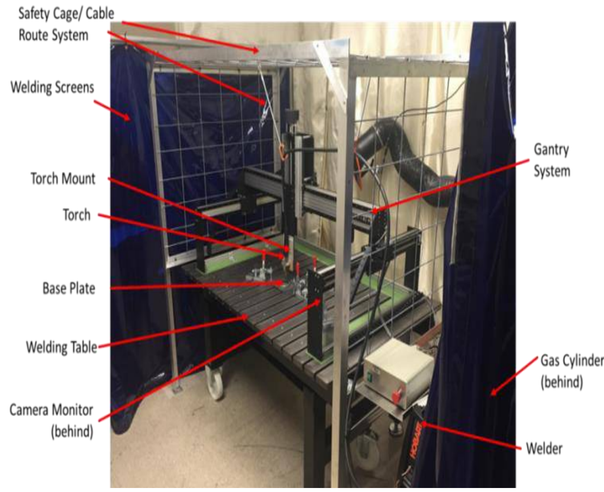

Figure 25. Direct Metal Deposition (DMD), wire fed, additive manufacturing platform.

Current research at UAH in areas of advanced manufacturing is focused on solid state joining (friction stir welding) and additive manufacturing. Current research topics are related to physics based process modeling, transient temperature mapping, design optimization of mechanical properties, feedback control schemes, in-situ process qualification. Results of UAH research are documented in recent publications.[48,49,50,51,52,53,54,55,]

L. Other UAH – Charger 1

The objectives of University of Alabama in Huntsville (UAH) Fusion Propulsion Research Facility (FPRF) are to study phenomena enabled by high power pulsed z-pinch technologies to develop fusion propulsion for human flight to the planets. Spacecraft concepts developed in collaboration with the NASA MSFC Advanced Concept Office could perform both 1-month and 3-month one-way trips to Mars were shown to be possible. UAH is focused on magneto-inertial fusion driven, specifically z-pinch. A Z-pinch is an electrical discharge created by pulsed power electrical sources. This effort initiated with the receipt of the 3 terawatt (TW), DECADE Module 2 from the Defense Threat Reduction Agency in May of 2012 which we have renamed Charger 1. The machine is the last existing prototype developed as part of a $65M program to develop the next generation of pulsed power for reaching high-energy states. The FPRF team has reassembled Charger 1 and is repurposing it for pulsed z-pinch research at the UAH Aerophysics Research Laboratory (ARC).

Figure 26. The 3 Terrawatt, DECADE Module 2 Pulse Power Machine

UAH Propulsion Research Center (PRC) and ARC are working with NASA MSFC, The Boeing Company, L3 Communications, Oak Ridge National Laboratories, and Y-12 National Security Complex in this effort. Recent publications[56, 57, 58,59 ,60, 61,] describe the ongoing work in Charger 1.

M. Other UAH - Complex Systems Integration Laboratory (CSIL)

The Complex Systems Integration Laboratory (CSIL) is a state-of-the-art facility for advanced systems engineering with a focus on Model Based Systems Engineering research. The CSIL has the capability to develop holistic system models supporting full product lifecycle from requirements development through manufacturing and long-term sustainment – end-to-end modeling and virtual prototyping. The laboratory includes desks and computer workstations for five Graduate Research Assistants. The CSIL also includes servers and large graphic displays for the development and communication of system models, which can be developed on hosted platforms including Cameo Enterprise Architecture (MagicDraw), using either System Modeling Language (SysML), or the Architecture Analysis and Design Language (AADL). System models can incorporate parametric models developed using Satellite Toolkit and MatLab/SimuLink, also hosted on the CSIL servers. Models developed within the CSIL are typically executable system models, and LabView is frequently employed to display key performance parameters and technical performance measures during life cycle or mission simulations.

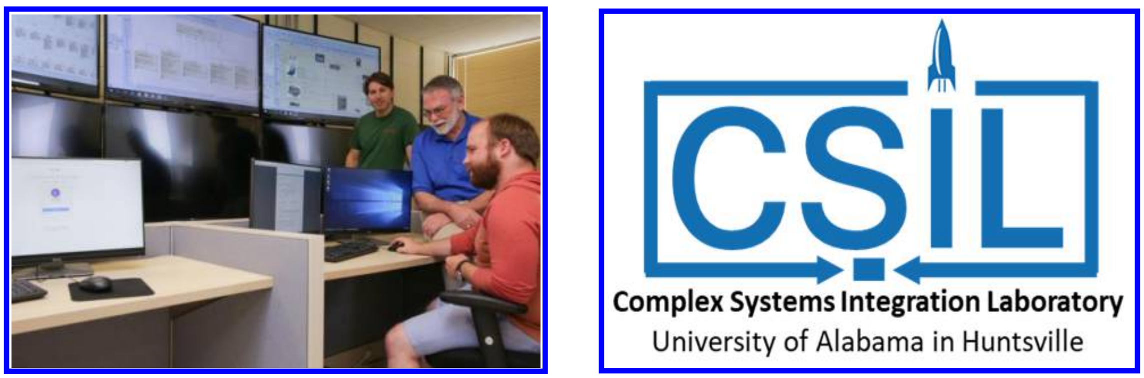

Figure 27. The Complex Systems Engineering Laboratory

Current NASA projects include development of executable integrated systems models for the Nuclear Thermal Propulsion Program, and integrated systems models for the Lynx X-ray Observatory Project and the Space Launch System Core Stage Engine (RS-25) Project. A variety of other DoD and commercial projects are underway within the laboratory.[62, 63,64,65,66,67,68,69,70]

N. Other UAH – Mechanics of Materials under Extreme Environments

The Mechanics of Materials Under Extreme Environments Laboratory has capabilities to perform mechanical loading over the following strain rates (quasi-static tension and compression:10^{-4} s^{-1}, dynamic tension: 10^{-3} s^{-1}, and dynamic compression: 10^{4} s^{-1}). The laboratory is also capable of performing low and high cycle fatigue tests. A dynamic tension and compression testing machine, such as a Kolsky bar (split Hopkinson pressure bar), is used to test the high strain rate material properties of varying materials. The versatile bar is used to impose a dynamic load on a material specimen akin to that which the material will experience in dynamic situations like vehicle crashes or other high-energy events. Test materials temperatures up to 800 ºC are possible. Mechanical loading capabilities in in vacuum are up to 10^{-4} torr. Mechanical loading in vacuum can be also perfumed at elevated temperature up to 500℃. We have a wide range of cameras from 75 frames per second to 1 million frames per second, which are coupled to the load cells for measuring full-field strain map (DIC) and failure analysis. We are also capable of performing tension test in vacuum for sub-size specimens. Expected outcomes include: (i) the relationship between stress-strain at different strain rates and temperature, (ii) failure analysis as a function of strain rates and temperature using ultra-high speed imaging in conjunction with digital image correlation technique, and (iii) identification and quantification of underlying deformation mechanisms that govern macroscopic response at different strain rates and temperature, by coupling high-speed imaging and post-mortem microscopic investigations.

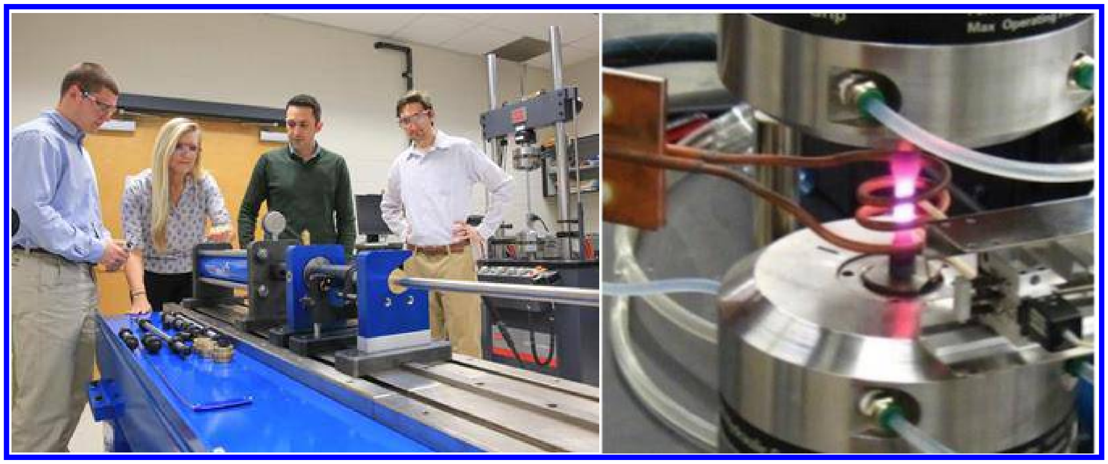

Figure 28. High Strain Rate Testing with Kolsky Bar and Servo Hydraulic Machine

O. Other UAH – Transport, Reaction, and Energy Conversion Lab

The Transport, Reaction, and Energy Conversion (TREC) Lab at UAH is a 1,500 ft^2 laboratory in the Shelby Center for Science and Technology that 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 equipment includes a controlled atmosphere glove box and a fume hood for materials handling, two furnaces (1000 °C and 1200 °C), a vacuum oven for materials processing, film coating equipment, and an Arradiance GEMStar-6 atomic layer deposition system with ozone generator. Catalyst testing is supported by two gas chromatographs for gas composition analysis and a furnace for environmental control. A multichannel potentiostat/galvanostat (Bio-Logic) with 5 A boosters is used for electrochemical testing. The TREC lab also houses a 600 W Rigaku Miniflex X-ray Diffraction (XRD) system and a Woollam Alpha-SE ellipsometer for characterization of powder and thin film materials. The potentiostat/galvanostat, XRD system, and ellipsometer were purchased with support from the UAH Research Infrastructure Fund.

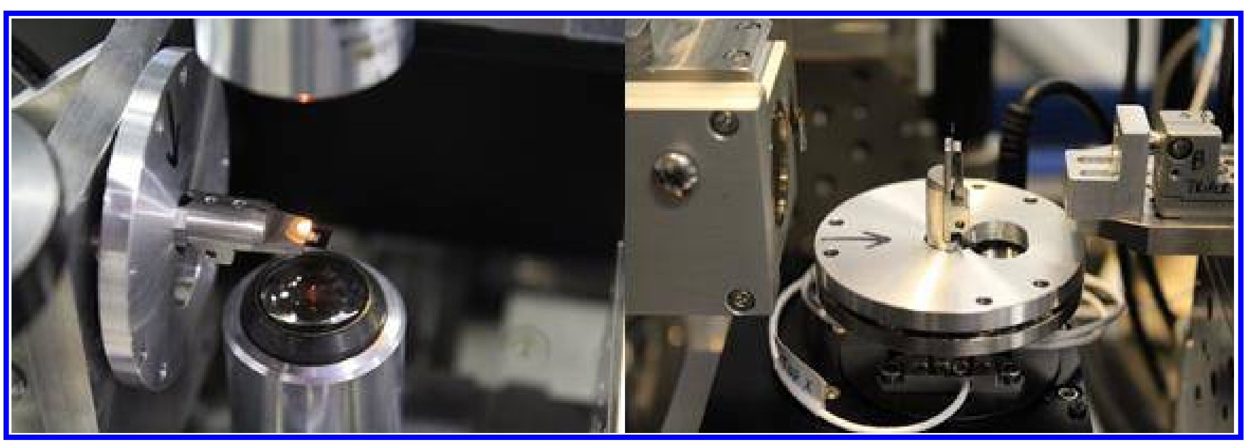

Figure 29. Work performed in the TREC lab is complemented by experiments at Department of Energy National User Facilities. Here battery samples are inspected (left) then imaged using a transmission x-ray

With respect to computational modeling and microstructural analysis, Prof. Nelson's research group has desktop workstations that are available for finite element simulations in COMSOL Multiphysics, image processing, and materials characterization. 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), and a T1700 (Quad Core Intel XEON, 3.1 GHz, 8 GB RAM). These workstations employ Nvidia GPUs with CUDA capabilities.

IV. People Make the Difference

During the past year, we continued to intentionally maintain and build our relationships with each other and our community. The PRC hosted monthly student mentoring cookout lunches at the lab that included guest speakers and tours of the facilities for guests. Luncheon topics included:

- "Hydrogen Peroxide Kerosene Engine for a Small Launch Vehicle Liquid Upper Stage," Steven Mustaikis, Dynetics
- "Lessons Learned in Rocket Propulsion Testing," Christina Blankenship, AMRDEC
- "PRC Recognition of Spring 2017 Graduates," Shankar Mahalingham, Dean, UAH College of Engineering
- "Turborocket Turborocket Technology," John Bossard
- "Aerojet Propulsion Student Scholar Recognition and Report from AIAA National Student Paper Competition." Dr. Robert Frederick
- "Gluten-Free Rocket Science," Dr. Ashley Ramirez, Co-Owner of Mason Dixon Bakery and Bistro, Huntsville, Alabama
- "UAH Student Launch Rocket Project: Roll Control of a Sounding Rocket Trough Aerodynamic Surfaces." Vivian Braswell, UAH Graduate Student
- "Blue Origin and My Experiences as an Intern," Dalton Hicks
- "Explorer 1, 60th Anniversary Celebration," Anna Frederick, Robert Naumann, Harry Reid, and William Snoddy
- "Behind the World's Largest Solid Rocket Motor, Julia Khodabandeh, NASA MSFC

Luncheon talks are usually kept short (about 20 minutes) to ensure that we have time to meet new people and interact with each other. We often have participants from our supporting organizations such as security, purchasing, sponsored programs, and accounting. We keep a light atmosphere, celebrate birthdays, and recognize achievements.

Our PRC Student Association (PRCSA) continued to support outreach events such as Girls Science and Engineering Day, the regional Science Olympiad, and NASA in the Park, a Huntsville tradition. Each year we hold two celebrations honoring our upcoming graduates and all the departments around campus that provide the support that makes our efforts successful. We also have periodic buffet lunches at a local BBQ restaurant where students and faculty perform on their musical instruments. Figure 23 shows the PRC team at our December 2017 Graduate Recognition gathering.

Figure 23. Propulsion Research Center faculty, staff, students, colleagues, and friends at the fall 2017 Recognition of Graduates Reception. "*Keep relationships more important than tasks or problems*" – Dr. Robert A. Frederick, Jr., Director, UAH Propulsion Research Center.

V. Strategies for the Future

Current growth areas that we are pursuing include upgrading our Propulsion Test Capability scramjet fuel studies, adding a new facility for heat transfer research, and the continued growth of additive manufacturing research for propulsion applications.

VII. Acknowledgments

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