Project 027A National Jet Fuels Combustion Program – Area #3: Advanced Combustion Tests

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*this report covers portion of University of Illinois

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- P.I.(s): Tonghun Lee, Associate Professor
- FAA Award Number: 13-C-AJFE-UI-004
- Period of Performance: 12/1/2014 to 12/31/2017
- Task(s):
    1. Optimize and apply laser diagnostics for application in the advanced combustion tests at GA Tech.
    2. Optimize and apply laser diagnostics for application in the Referee Combustor.
    3. Optimize and apply laser diagnostics for ignition experiments at Georgia Tech.
    4. Conduct high altitude relight ignition probability measurements in the modified sector rig at ARL.
    5. Conduct ignition delay measurements of the targeted cetane number fuels in the RCM at UIUC.

Project Funding Level

FAA Funding Level: $360,000
Cost Share: In-kind academic time of the PI, Lab Renovation Cost by Department for Diagnostics Work, cost share provided by software support from Convergent Sciences, Inc.

Investigation Team

- Eric Mayhew (Graduate Student, University of Illinois at Urbana-Champaign): Execution of laser and optical diagnostics at ARL.
- Kyungwook Min (Graduate Student, University of Illinois at Urbana-Champaign): Rapid Compression Machine testing of fuels.
- Brendan McGann (Graduate Student, University of Illinois at Urbana-Champaign): Execution of laser and optical diagnostics at ARL.
- Constandinos Mitsingas (Graduate Student, University of Illinois at Urbana-Champaign): Execution of laser and optical diagnostics at ARL.
- Stephen Hammack (Graduate Student, University of Illinois at Urbana-Champaign): Execution of laser and optical diagnostics at GATech.

Project Overview

The goal of this study is to develop, conduct, and analyze advanced laser and optical measurements in the experimental combustors developed under ASCENT National Fuel Combustion Program to measure sensitivity to fuel properties. We conducted advanced spatially resolved high-speed planar imaging, high-speed Schlieren imaging, high-speed OH* chemiluminescence imaging, 2D phase Doppler anemometry, and other advanced diagnostics to provide insight into the physicochemical response of the combustion process for various alternative fuels. Moreover, the results provided data for development of new predictive combustion models in ASCENT. Once fully characterized, the standard referee combustor rig can streamline and simplify fuel certification procedures outlined in the ASTM D4054 (Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives) through minimization of full-scale engine testing.

Task 1 – Optimize and Apply Laser and Optical Diagnostics for Application in the Referee Combustor

University of Illinois at Urbana-Champaign

Objective(s)

The main objectives of the work in this proposal are to work with UDRI and AFRL in carrying out diagnostics measurements for the referee combustor. The following tasks will guide this collaboration:

- Identify the operating conditions and key parameters for detection in the referee combustor
- Evaluate and modify the referee combustor at AFRL for laser and optical diagnostics
- Design laser and optical diagnostics setup and assist in the fuel screening process
- Analyze data and pass on data to modeling groups in combustion program.

Research Approach

The main effort in year 1 was the assembly of the laser system around the test rig at GATech and completion of simultaneous stereo PIV and two camera PLIF. A picture of the experimental setup, with the four high-speed cameras positioned around test rig, is shown in Figure 1.

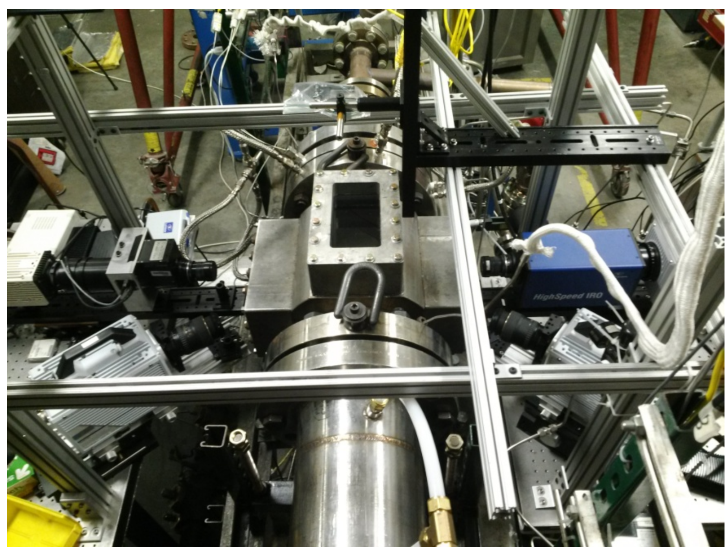
Figure 1. Diagnostics Setup at GATech with Stereo PIV and 2 Camera PLIF (4 high speed cameras + 2 lasers)

The laser system, which is composed of a high speed Nd:YAG pumping a tunable high-speed dye laser is situated in the adjacent room and the beam is routed to the experimental setup. Prior to reaching the test rig, the beam is expanded into a sheet using a custom set of optics and is routed into the test rig from the top. The beam is about 4 inches in width and about 100μm in thickness. The combustor itself is fully accessible through the top port and two side windows on either side. Prior to the measurements, the Illinois calibration burner is inserted into the chamber and imaging is done with the exact same setup to ensure wavelength position of the laser as well as the intensity of the OH LIF signal, which can later be fully quantified using a spectroscopic model. The laser is tuned to the A-X (1,0) transition of OH at 283nm. For the shakedown of the rig, an air pressure atomizer was used while for the actual tests in August, an air blast atomizer was mainly utilized.

The two cameras on either side at the top are the PLIF detection cameras, which are both intensified. The bottom two cameras at a slight angle are the PIF cameras which are mounted in a scheimpflug setup so as to ensure clear focus across the entire imaging plane. The entire system is synchronized at 5 kHz, which is an adequate repetition rate considering the turbulent intensity of the required flow conditions. The setup was installed and tested in May 2015 and the actual full-scale measurements of A2, C5 fuels were conducted in August.

In addition to the quantification issue of the LIF signal, it became obvious during the May campaign that fuel PLIF was a major interference source in our measurements. In order to resolve this issue and to isolate the OH PLIF signal, a two camera PLIF setup was utilized with two differing spectral bandpass filters. The difference in the optical bandpass allows the ratio of OH and fuel PLIF to be varied and the strategy is to use one set of images to correct for the fuel PLIF in the other image. An example of this is shown in Figure *2*.

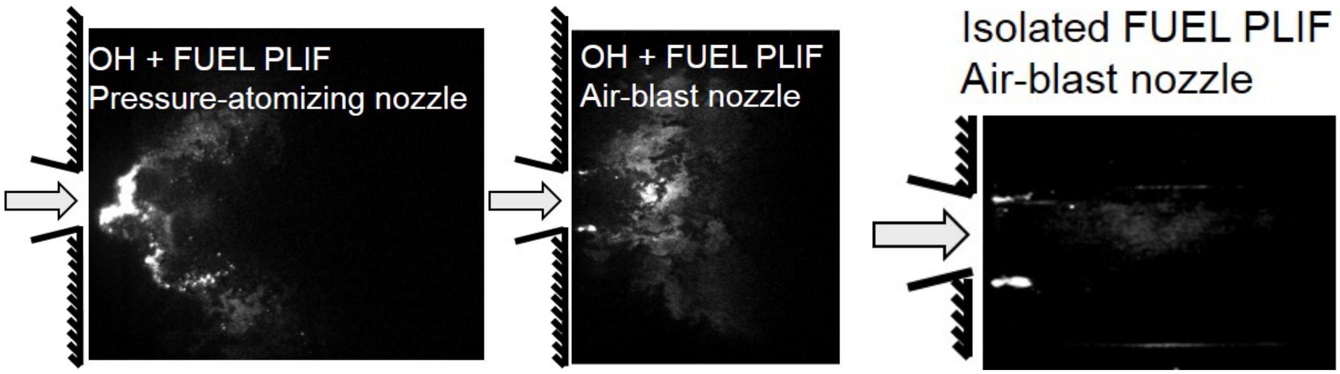

Figure 2. Two camera OH PLIF setup for isolation of fuel PLIF from the images. The image on the right shows the isolation of the fuel PLIF using the added camera with a wide band-pass filter and suppression of OH PLIF

Task 2 – Optimize and Apply Laser and Optical Diagnostics to Characterize Fuel Spray in Advanced Combustor Tests at the Referee Combustor

University of Illinois at Urbana-Champaign

Objective(s)

The objectives in this proposal are to work with AFRL in their referee rig experiments and achieve the following goals:

- Design and set up laser diagnostic and optical diagnostics for referee rig measurements.
- Implement phase Doppler anemometry to determine fuel spray characteristics, including droplet diameters and velocities.

Diagnostics Optimization and Setup

A 2D PDPA system was used to characterize the fuel droplets during combustion, measuring diameter and two components of velocity. The 2D PDPA (Dantec 112mm fiber PDPA) measures the frequency of the Doppler burst signal to determine velocity (one component from each pair of beam wavelengths) and the phase difference between two Doppler bursts to calculate the droplet diameter. An argon-ion laser (Ion Laser Technology), which produces a continuous laser beam with wavelengths ranging from 457 nm to 514.5 nm, is directed into a transmitter where the beam is split up by wavelength and coupled into optical fibers. Four beams, two at 488 nm and two at 514.5 nm (about 4 mW of power per beam), are focused by a 500mm focal length lens on the PDPA transmitter head and directed into the combustion chamber. The transmitter head and receiver head, with an 800mm focal length lens, are mounted on traverses placed on either side of the combustor. The traverses, fitted with encoders, are linked and controlled via a LabVIEW code. Data is collected using BSA Flow Software, and the data is written to text files.

Fuel Droplet Characterization

Droplet axial and radial velocity distributions, SMD distributions, and data collection rates for the fuels studied are presented. For A-2 at ϕ = 0.096, data collection rate is shown in Figure 1 as a function of y-position at various axial locations. The origin is taken to be the intersection of the centerline of the injector and the downstream face of the heat shield. Positive z-position is taken to be positive downstream (flowing out of the combustor) and y-position is taken to be positive up (towards the top of the combustor). The axes and basic referee rig geometry is shown in Figure 4 for reference. The data rate is a good indicator of where the spray is located and can be used to calculate and report spray angles. The low data collection rate near the centerline verifies that the fuel injection is a hollow cone.

It is unsurprising that the width of each side of the spray increases with increasing distance downstream, and the overall width of the spray increases until it spans nearly the full height of the combustor (109 mm) by 35 mm downstream. At 35 mm downstream, the data collection rates are greatly diminished, which can be explained by further spread of the spray as well as evaporation due to combustion.

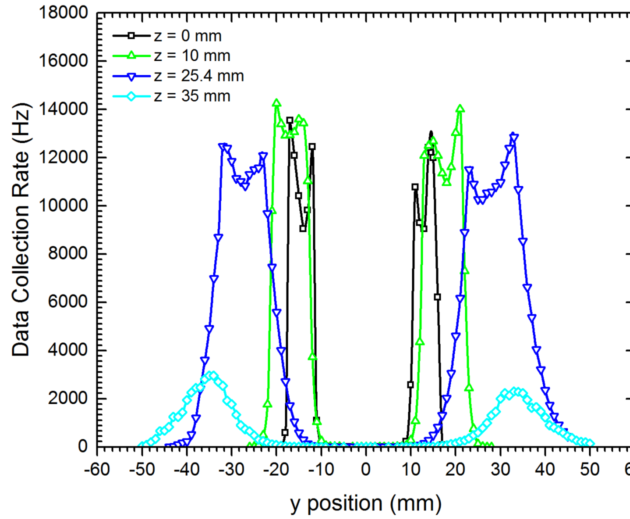

Figure 3. A-2 data collection rate. Data collection rate versus y-position at various axial locations for A-2 at ϕ=0.096

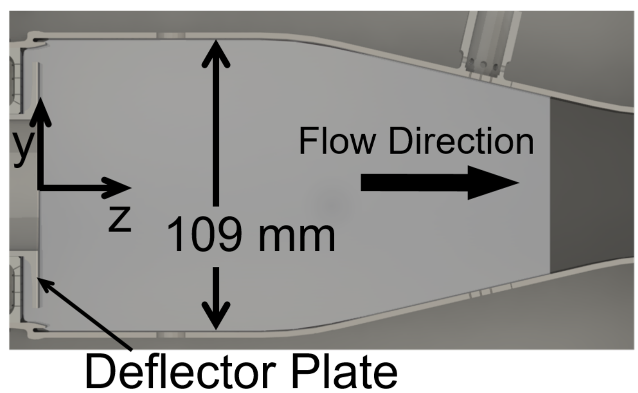

Figure 4. Cutaway of the single cup referee combustor. The origin is taken to be at the intersection of centerline of the combustor with the front plane of the deflector plate as marked.

A. Comparison of Fuel Droplet Diameters

SMD is calculated at each position where diameter data is collected, and Figure 5a shows the SMD versus y-position 0 mm, 5 mm, and 10 mm downstream of the deflector plate for each fuel tested. SMDs are only reported at locations where more than 1000 droplets were measured. Figure 5b, 5c, and 5d show normalized histograms of the droplet diameters 10 mm, 15 mm, and 20 mm above the centerline at each axial location shown. The differences in SMD between the fuels are seen in the diameter histograms as a larger fraction of large droplets. As seen in Figure 5a, just downstream of the deflector plate (z = 0 mm), C-1 has a higher SMD than either A-2 or C-5, between 10 and 35 microns greater at y positions more than 12 mm above the centerline. This can be seen in Figure 5b, as C-1 has relatively few droplets with a diameter less than 20 microns compared with A-2 and C-5 at the same y positions. This seems to indicate that C-1 is either still undergoing fuel droplet breakup or that C-1 experiences less upstream evaporation compared to A-2 and C-5. At 5 mm downstream of the deflector plate, the A-2 and C-5 fuels have very similar SMDs at all measurement points where enough droplets were collected. The maximum difference between the SMDs for those two fuels is about 8 microns, occurring at y = 15 mm. The histograms in Figure 5c and 5d explain this difference; about 65 percent of the A-2 fuel droplets have diameters smaller than 20 microns while less than 50 percent of C-5 fuel droplets have diameters smaller than 20 microns. A-2 also has fewer than 4 percent of droplets with diameters larger than 40 microns while C-5 has about 10 percent of droplets with diameters larger than 40 microns. The C-1 fuel droplets have similar SMDs to A-2 and C-5 at y positions greater than 12 mm above the centerline, but below 12 mm, the SMDs of C-1 are 10 to 15 microns smaller than those of A-2 or C-5. It is also notable that the maximum C-1 SMD has dropped by about 25 microns, bringing it in line with the SMDs of A-2 and C-5.

At 10 mm downstream of the deflector plate, C-1 and A-2 have similar SMD profiles, with a maximum difference of about 11 microns from y = 10 mm up to 22 mm. The profiles diverge at y positions above 22 mm, with the A-2 SMDs increasing slightly, while the C-1 SMDs slowly decrease with increasing y position until it hits a minimum of 20 microns at 27 mm above

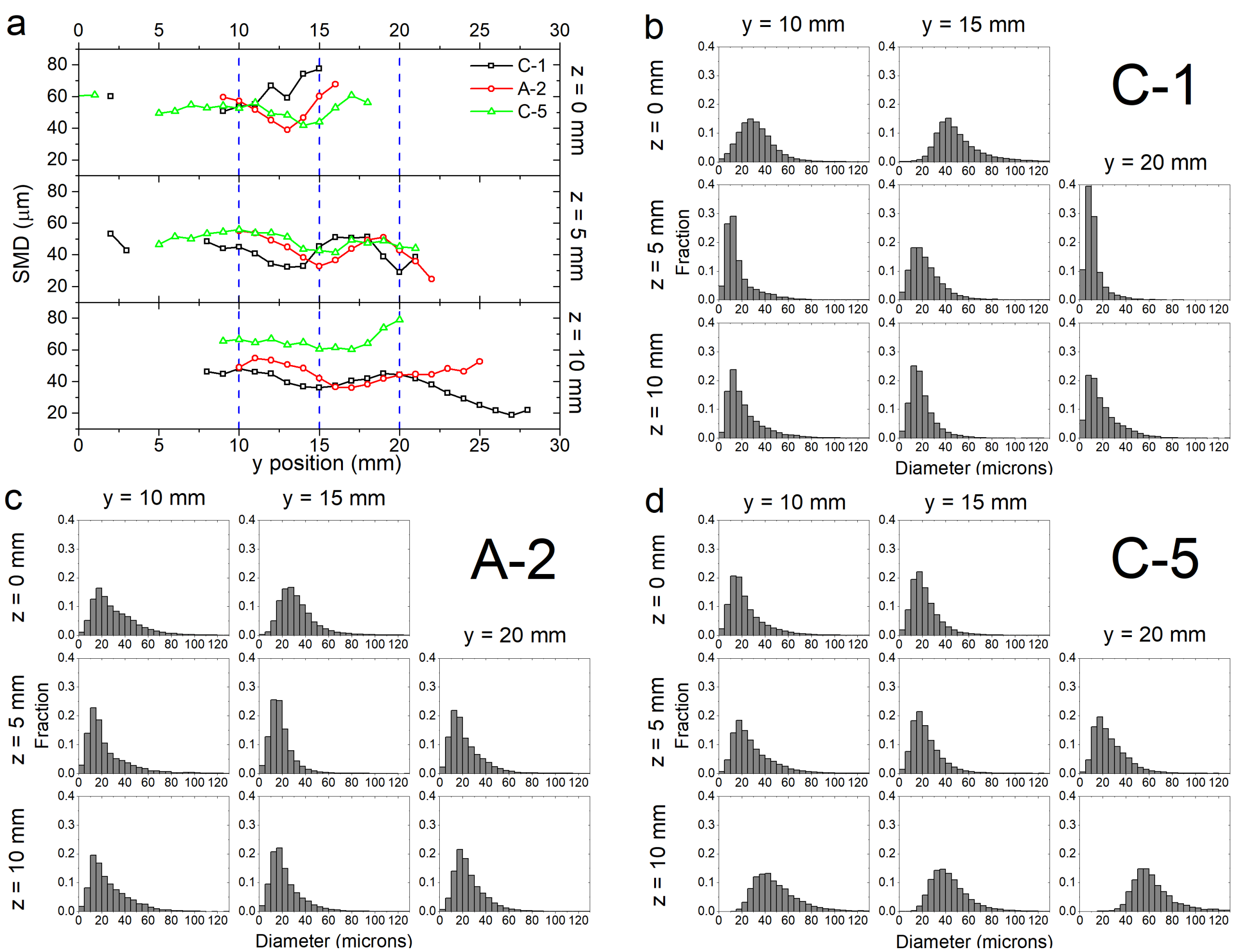

Figure 5. Sauter mean diameter and representative diameter histograms a) Sauter mean diameter plotted versus y position for each fuel 0 mm, 5 mm, and 10 mm downstream of the deflector plate for comparison with b) C-1 diameter histograms, c) A-2 diameter histograms, and d) C-5 diameter histograms

the combustor centerline. The C-5 fuel droplets at 10 mm downstream of the deflector plate show a marked decrease in the fraction of droplets smaller than 20 microns in diameter as seen in the last row of Figure 5b. Less than 3 percent of C-5 fuel droplets measured 10 mm downstream of the deflector plate (at y = 5, 10, 15 mm) have diameter smaller than 20 microns. At those same locations, at least 40 percent of A-2 and at least 57 percent of C-1 fuel droplets are smaller than 20 microns in diameter. The result of this absence of small C-5 fuel droplets is an SMD that is 12 to 37 microns greater than the corresponding C-1 or A-2 SMD. This indicates that small C-5 fuel droplets have almost completely evaporated between 5 mm and 10 mm downstream of the deflector plate. The small droplets are expected to evaporate first because they have a larger surface area to volume ratio than larger droplets. The evaporation of the small C-5 droplets before those of C-1 and A-2 is consistent with C-5's flat boiling curve (0 to 95 percent distillation between 155˚C and 165˚C). The C-1 (0 to 95 percent distillation between 175˚C and 246˚C) and A-2 (0 to 95 percent distillation between 160˚C and 255˚C) fuels boil over a much wider range of temperatures.

B. Droplet Velocities

Figure 6 shows the A-2 fuel droplet mean axial and radial velocity distributions versus y-position at various axial locations. Both the axial and radial velocity distributions are symmetric about the centerline, and the distributions broaden with increasing downstream location. One interesting feature present in both the axial and radial velocity distributions is the near zero or slightly negative velocities along the centerline. This indicates the presence of an inner recirculation zone, but very few droplets are present in the center as indicated by the low data collection rates near the centerline. As seen in Figure 6, the mean radial velocity profiles at 0 mm, 5 mm, and 10 mm downstream of the deflector plate are very similar to each other. At 25 mm and 35 mm downstream of the deflector plate, the radial velocity profiles broaden and the maximum droplet velocities decrease. The axial velocity profiles at 5 mm and 10 mm for A-2 exhibit a sharp peak that roughly corresponds with the center of the spray as marked by the data collection rate. As with the radial velocity, the axial velocity profiles broaden and have a lower maximum value further downstream (25 mm and 35 mm).

A comparison of fuel droplet radial velocity for the different fuels is shown on the left in Figure 7 at 0 mm, 5 mm, and 10 mm downstream of the deflector plate, and a comparison of fuel droplet axial velocity at 5mm is shown on the right in Figure 7. The radial velocity profiles for each fuel have a great deal of similarity across the fuels at each downstream position shown. Figure 7 also shows the axial velocity profile 5 mm downstream of the deflector plate. The C-1 axial velocity profile is slightly different from C-5 and A-2, reaching its peak about 2 mm inside of the peaks for C-5 and A-2.

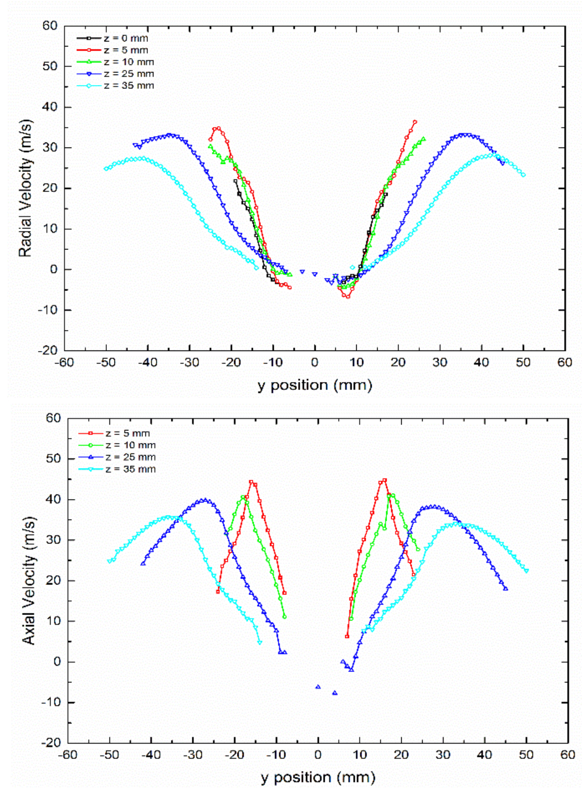

Figure 6. A-2 fuel droplet mean radial and axial velocity. Mean radial velocity plotted against y position (top) and mean axial velocity plotted against y position (bottom) at various distances

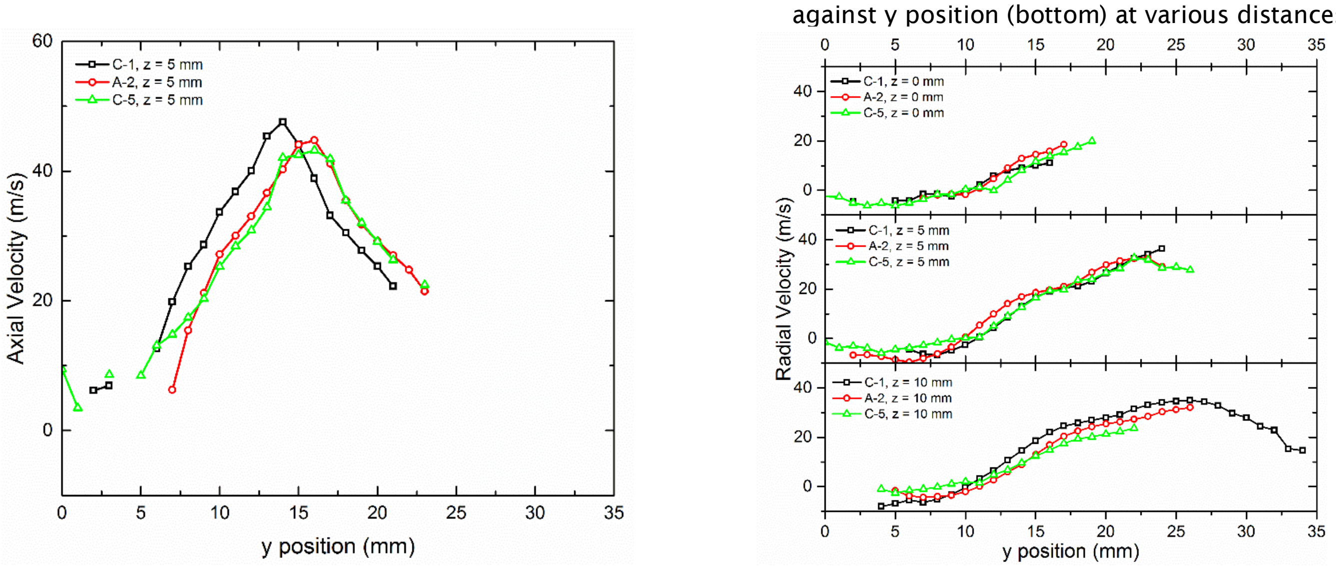

Figure 7. Axial and radial velocity profiles. a) Axial velocity plotted versus y position for each fuel 5 mm downstream of the deflector plate and b) radial velocity plotted as a function of y position at 0 mm, 5 mm, and 10 mm downstream of the deflector plate for each of the tested fuels.

Comparison to OH* Chemiluminescence

The imaging of OH* chemiluminescence is conducted using a LaVision High-Speed IRO and Photron FASTCAM SA-Z with a Semrock Brightline 320/40 bandpass filter in front of a Cerco, 100 mm, f/2.8 UV lens. Images are taken at 20 kHz with a 1000 ns gate and 60 percent gain. The spatial resolution for the imaging is approximately 0.29 mm per pixel, and a total of 3000 images are used for each average image. Excited OH* is a good indicator of heat release rate from the flame zone, which makes it useful for visualizing flame structure. The OH* chemiluminescence signal is normalized by the maximum possible intensity to yield the reported image.

Average OH* chemiluminescence images show significant differences in the flame structures of the different fuels as seen in Figure 8. The averaged chemiluminescence images are normalized by the maximum intensity in each averaged image. The C-1 flame has straight top and bottom edges, suggesting that the flame is stabilized on the spray edges, while the A-2 and C-5 flame have more rounded top and bottom edges. The flames for all three fuels demonstrate some amount of asymmetry; gravitational effects likely play some role in this asymmetry. However, the A-2 flame has significantly more OH* emission in the lower half of the combustor than in the top half. A proposed explanation for C-1's lower deviation from axisymmetry is that, because of its lower cetane number, the flame anchors more closely to the spray zone where equivalence ratio will be highest, resulting in flame emission that largely follows the spray cone. A proposed explanation for C-5's reduced deviation from axisymmetry is that low-temperature vaporization results in the fuel droplets rapidly evaporating, creating a fuel vapor cloud that is negligibly affected by gravity. A-2 has neither of these fuels' extreme properties, allowing gravitational effects on the A-2 fuel droplets to play a larger role, resulting in more lower half OH* emission.

Figure 8 shows the SMD distribution superimposed on the average OH* image with marker size corresponding to the SMD. The C-1 droplet SMD profile at 10 mm downstream (the closest SMD profile to the start of the C-1 flame) shows a decrease in SMD at y-positions greater than 19 mm, corresponding to an absence of OH* emission at these locations. This indicates that outside of the main body of the flame, the smallest droplets do not evaporate as rapidly. A comparison of the SMD profile and diameter histograms for C-5 at 10 mm downstream of the deflector plate show that the smallest droplets have already evaporated before reaching the body of the flame, which starts at about 15 mm downstream. The local minimum in the SMD distribution at z = 10 mm, corresponding to a y position of 17 mm for A-2 and C-5 and 15 mm for C-1 spatially correlates with outer edge of flame structure, indicating that the flame is stabilizing on the interior of the spray cone. The observable differences in flame structure, as marked by the averaged OH* emission, combined with the SMD distributions provides valuable insight into the complex spray combustion processes near LBO.

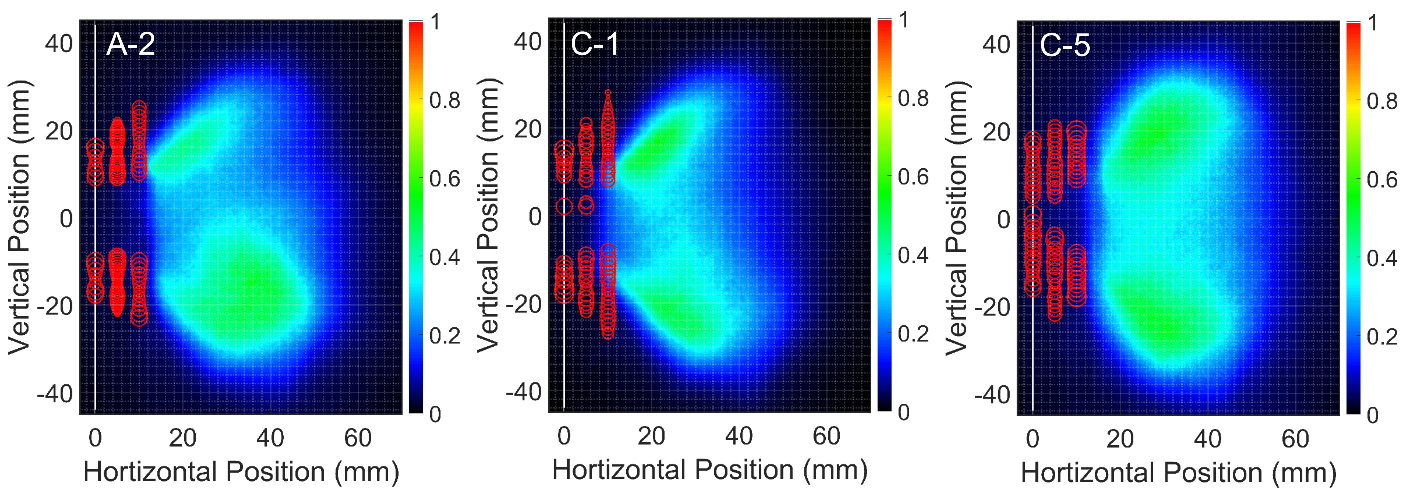

Figure 8. Average OH* chemiluminescence images. SMD distributions are superimposed on the average normalized OH* image with the marker size corresponding to the SMD calculated at each point.

Task 3 – Optimize and Apply Laser and Optical Diagnostics for Application in the Advanced Ignition Tests at Georgia Institute of Technology and Army Research Laboratory

University of Illinois at Urbana-Champaign

Objective(s)

The objectives in this proposal are to work with Georgia Tech in their advanced ignition experiments and achieve the following two goals:

- Evaluate the experimental ignition testing setup and operating conditions for laser and optical diagnostics
- Design and set up laser and optical diagnostics for use in ignition experiments at Georgia Institute of Technology

Research Approach

Diagnostics Optimization and Setup on Georgia Tech Atmospheric Ignition Rig

The main goal is the development of 2D diagnostics using Planar Laser Induced Fluorescence (PLIF), Schlieren, and OH* chemiluminescence to understand the ignition development at the boundaries and flame dynamics in the GATech atmospheric ignition rig. The goal is to apply simultaneous measurements from high speed PLIF, Schlieren, and chemiluminescence. For each of the imaging sets, we will look to obtain spatially resolved data. We will configure and set up the laser and optical diagnostics equipment around the ignition rig at GATech. For the high speed PLIF measurements, we pumped a high speed dye laser (Credo, Sirah) with a high speed diode pumped Nd:YAG (Edgewave) for generation of the UV light. The PLIF, Schlieren, and chemiluminescence imaging will be 10 kHz. Energy per laser pulse at these conditions may be small (200 µJ/pulse) and light collection from the PLIF will be enhanced using a f/2.8 UV lens.

Georgia Tech Ignition Experiments

The primary effort on the ignition experiments was transporting the Edgewave Nd:YAG high repetition rate laser to Georgia Tech. The laser was coupled to the Sirah Credo Dye Laser, as shown in Figure 9 (left), and both lasers were tuned to optimize laser power and beam profile. Optics to form and steer the laser sheet in through the top of the combustor, as shown in Figure 9 (right). The primary ignition testing campaign was carried out by Georgia Tech personnel.

Figure 9. Edgewave pump laser (left) and dye laser with sheet forming optics, and the ignition rig

Task 4 – Measure Ignition Probability for Various Fuels at High Altitude Conditions and Implement High-Speed Imaging to Visualize Ignition Process

University of Illinois at Urbana-Champaign

Objective(s)

The objectives in this proposal are to work with ARL in the design, setup, and implementation of ignition experiments in the high-altitude chamber at Army Research Laboratory at Aberdeen Proving Ground:

- Design and set up sector rig in high altitude chamber at Army Research Laboratory at Aberdeen Proving Ground.
- Conduct measurements of ignition probability at high altitude conditions (low temperature, low pressure).
- Implement high-repetition rate broadband and OH* imaging to visualize ignition kernel and flame kernel propagation.

Research Approach

The process of developing and approving new jet fuels derived from alternative feedstocks requires certifying that those fuels, whether neat or blended with conventional fuels, can be used in current engines without hardware modification. Understanding how these new fuels perform in extreme combustion regimes is important to ensuring that the fuels can be used as drop-in replacements. One regime in which it is essential that new fuels perform as well as conventional fuels is in a scenario where an engine needs to be relit at high altitude. The lower temperatures and pressures seen at high altitudes result in a lower probability of spark kernel ignition and flame stabilization when compared to sea level conditions. A few of the causes of this reduced probability include slower chemistry, poorer atomization due to the higher fuel viscosity, slower evaporation due to the reduced vapor pressure of the fuel, and shorter spark kernel lifetime due to the entrainment of the lower temperature air. To study the effects of fuel differences in this high altitude relight scenario, a gas turbine combustor sector rig was designed and built. The sector rig is operated inside of a high-altitude chamber with the chamber conditions varying as shown in Table 1, with 30,000 ft being the highest altitude that the chamber is capable of simulating.

Table 1. Chamber air temperature and pressure as a function of altitude

Altitude (ft)	T_{air} (K)	P_{air} (kPa)
0	288	101.3
10,000	268	69.6
20,000	249	46.6
25,000	239	37.7
30,000	229	30.2

Ignition probabilities for alternative and conventional jet fuels are measured in a gas turbine sector rig inside of a high-altitude chamber as shown in Figure 10. Experiments are designed to simulate combustor relight at high altitude conditions. Initial relight experiments were conducted at conditions representative of ambient air at 10,000 feet with an air mass flow rate of 0.3lbm/s. This air flow mass flow rate resulted in a pressure drop across the swirler of 3.87%. The fuel is chilled by placing the fuel holding vessel in the inlet air flow path, resulting in an average fuel injection temperature of -15˚C. The equivalence ratio is varied by changing the inlet fuel pressure, and fuel flow rates could be varied to achieve equivalence ratios from 0.6 and 1.0. This range of equivalence ratios was sufficient to span from no ignition to always igniting.

A single test begins with the opening of a solenoid valve just upstream of the nozzle, allowing fuel flow at the desired equivalence ratio. After two seconds in which the fuel flow rate is allowed to stabilize, a 24 VDC voltage is supplied to an ignition exciter (Champion CH305050), which supplies high voltage to an igniter from a General Electric T700 at a frequency of 3.7 Hz. The igniter is allowed to spark for 10 seconds, after which the voltage and fuel supply are stopped. The sparks and flame are monitored with a photo diode as well as a high-speed camera (Photron SA-Z) coupled to a high-speed intensifier (LaVision IRO), fitted with a bandpass filter centered at 320 nm, with a full-width, half-max of 20 nm. A sample photodiode trace is shown in Figure 12. The spark emission events are shown as the sharp peaks, and the flame is observed as the slight increase in photodiode signal above the baseline between the sharp peaks.

A total of 5 fuels were tested, all from the National Jet Fuel Combustion Program. Three conventional fuels, designated A-1 (JP-8), A-2 (Jet A), and A-3 (JP-5), represent current petroleum-derived fuels that are used in modern aircraft engines. Two category C fuels were tested as well, designated C-1 and C-3. The C-1 fuel is Gevo alcohol-to-jet; its notable properties are a low derived cetane number (~16) and a relatively low temperature boiling curve. C-3 is notable for its high viscosity, a parameter that is particularly important for atomization at these low temperatures.

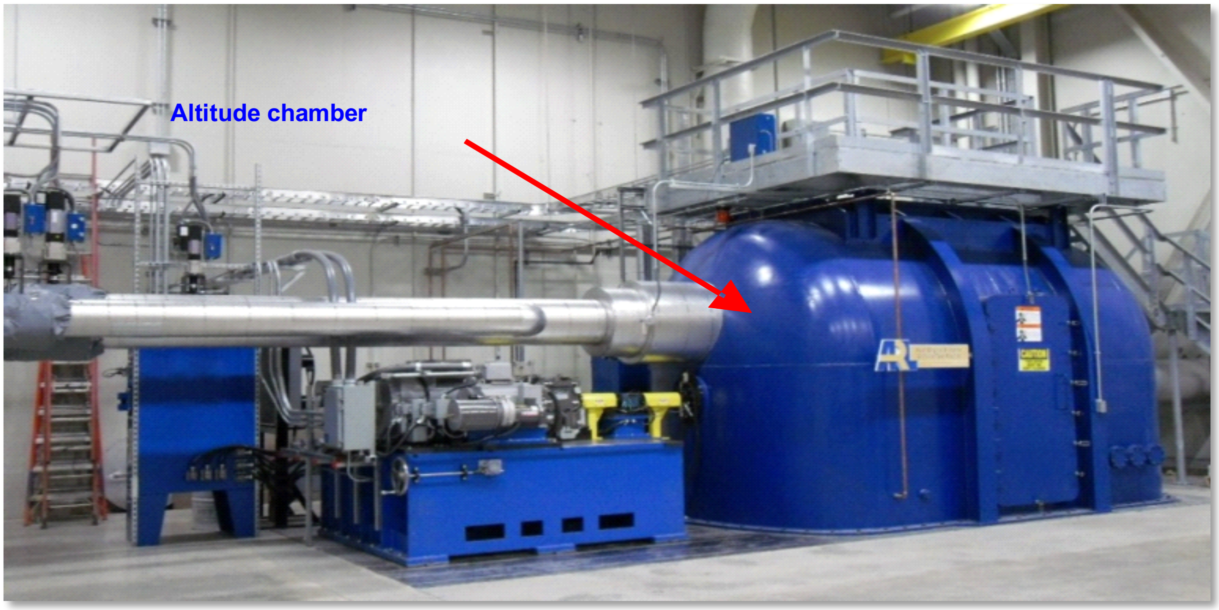

Figure 10. High altitude chamber at the Army Research Laboratory at Aberdeen Proving Ground

For each test, a photo diode trace is obtained, like the one shown in Figure 12 (Task 5). A flame is considered to have stabilized when the ratio of the absolute value of the integrated negative signal to the integrated positive signal is less than 1% for two consecutive periods between sparks. The number of sparks that do not result in a stable flame are counted along with the one spark that resulted in the stable flame. The ignition probability for a single equivalence ratio for a single fuel is the number of successful sparks divided by the total number of sparks. The ignition probability for all of the fuels and equivalence ratios tested are shown in Figure 10 as well as the binomial regression fits calculated from the ignition probabilities. Defining the 'best' fuel case as the fuel that has the highest ignition probability for each equivalence ratio, the preliminary analysis yielded a fuel ordering, from best to worst of: A-1, C-1, A-2 and A-3 about equal, and then C-3. More complete analysis of the images and ignition probabilities is ongoing; however, the parameters that appear to be most important in determining ignition probability are viscosity and vapor pressure at the temperatures measured in the rig. Further analysis of the video will provide a better qualitative understanding of the process in which a spark kernel leads to a flame kernel, eventually resulting in stabilization of the flame in the combustor. Further testing is required and planned to obtain lower uncertainties in the probability curves as well as to obtain data for more fuels and at more altitudes.

Task 5 – Measure Ignition Delay at Low Temperature Conditions for Fuels with Targeted Cetane Numbers

University of Illinois at Urbana-Champaign

Objective(s)

The objectives in this proposal are to make measurements of ignition delay of targeted cetane number fuels developed by ARL cetane number has shown a strong correlation to lean blow out equivalence ratio.

Varied Cetane Number Army Research Fuels

Six different fuels have been tested to measure the ignition delay time in the RCM. These fuels are blended to match a targeted cetane number between 30 and 55. CN 50 appears to be the base fuel used prior to the inclusion of cetane inhibitors /improvers. Isododecane (pentamethylheptane) is used as the cetane inhibitor, as well as naphthalene in the CN 30. Inclusion of higher n-alkanes (C14 - C16) is used as the cetane improver for CN 55. Navy Fuel Composition and Screening Tool (FCAST) have been used to classify detailed chemical group composition of the fuels as in Table 2. Contents of isoalkanes and aromatics are higher for low cetane number fuels, whereas higher cetane number fuels tend to contain more normal alkanes.

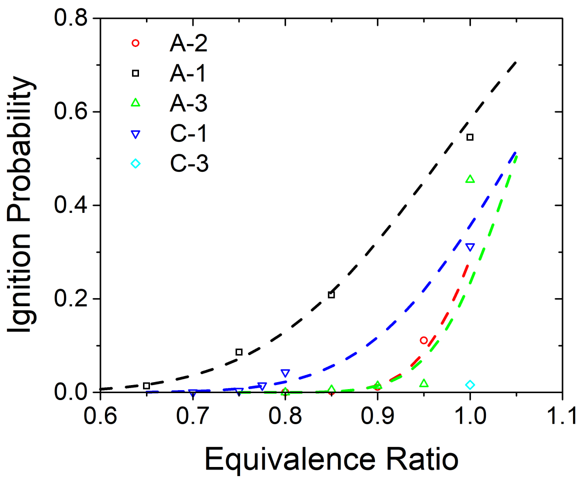

Figure 11. Ignition Probability versus equivalence ratio for the 3 category A fuels and 2 category C fuels at 10,000 ft.

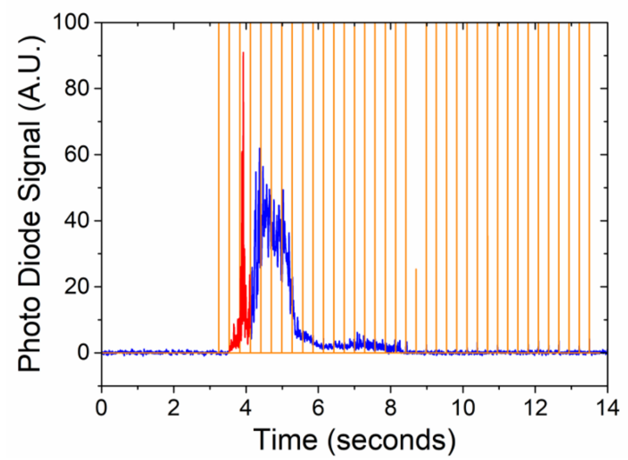

Figure 12. Example photodiode trace of sparks and a successful ignition

Table 2. Composition of the Army research fuels tested

mass %	Jet A-30CN	Jet A-35CN	Jet A-40CN	Jet A-45CN	Jet A-50CN	Jet A-55CN
Normal Alkanes	16.02	16.48	21.83	19.54	36.50	54.10
Isoalkanes	54.80	58.22	41.41	48.14	34.14	28.33
Cyclocalkanes	3.85	1.21	3.22	10.94	12.18	6.08
Aromatics	25.32	24.08	33.53	21.41	17.18	11.46

Ignition Delay of Varied Cetane Number Fuels

Ignition delay time measurements have been conducted for compressed pressures of P_c=20 bar, at equivalence ratios (φ) of 1.0, 0.5, and 0.25. Compressed temperature T_c varies by compression ratio: 615K to 725K. Figure 14 shows measured ignition delay time at P_c=20 bar.

As expected, fuel with lower cetane number results in longer ignition delay, and the tendency is more prominent at leaner conditions. In the φ=1 case, some of the ignition delay time results do not exactly follow the cetane number ordering. No negative temperature coefficient (NTC) behavior is observed in these tests. Further analysis of the φ=0.25 case is illustrated in Figure 13, where dotted lines are separated first stage ignition delay time. The difference in first stage ignition delay time by fuels are much less than difference in overall ignition delay time. In other words, the second stage ignition delay constitutes nearly all of the differences in the overall delay time. Additional ignition delay time measurements will be conducted at lower compressed pressure, P_c=10 bar. Further analysis on multistage ignition will be investigated using CHEMKIN, chemical kinetics simulation results.

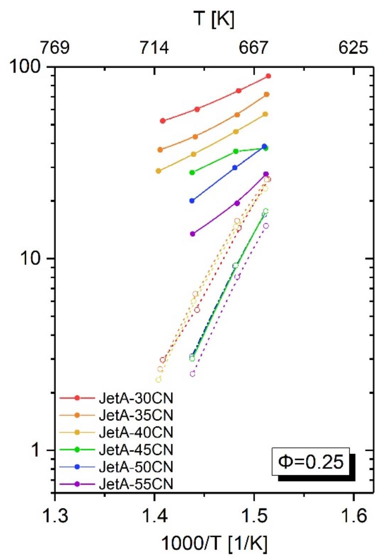

Figure 14. First and overall ignition delay time results at φ=0.25

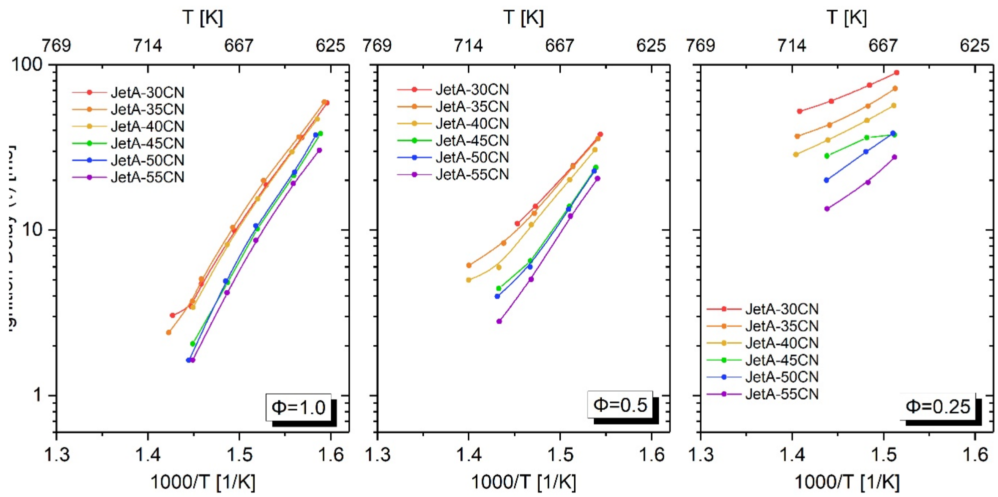

Figure 13. Ignition delay times of Jet A fuels with varied cetane numbers at Pc=20 bar, varied temperatures, and equivalence ratios

Milestone(s)

Milestones from each period

Year I

Proposed (3 Month): At the 3-month mark, we will conclude the analysis of the experimental setup and should be close to finishing the design of the laser and diagnostics setup.
Achieved: Design of the laser setup complete and fabrication of calibration torch started.

Proposed (6 Month): At the 6-month mark, we should be finalizing the experimental setup and getting ready to deploy measurements described in Task 1 of the proposal. Fuel screening will be conducted during this phase.
Achieved: Most of experimental setup was completed. Calibration torch completed and initial quantification of radicals complete.

Proposed (9 Month): At the 9-month mark, we should be almost complete with the initial shakedown of the tests in Task 1 and making changes to optimize the experimental setup. Send preliminary test guidelines and results of the fuel screening studies (sensitivity to fuel characteristics) to the modeling groups.
Achieved: First test run at GATech for simultaneous PLIF and PIV successfully completed and results analyzed. Laser and optical setup successfully implemented and tested. Identified key problems such as fuel PLIF. Main measurement campaign set for last quarter.

Proposed (12 Month): At the 12-month mark, we should have completed an initial set of data for tasks outlined in the proposal. We should be planning for additional measurements in the next phase of the combustion program.
Achieved: Major three-week campaign completed at GATech for two of the test fuels. Experiments included two camera PLIF and stereo PLIF over a wide range of test conditions. Data analysis started. Fuel PLIF isolated using two camera PLIF setup with differing detection bandwidth.

Year II

Proposed (3 Month): At the 3-month mark, we will have identified the key features that are important in the design of the rig. Preliminary designs will have been shared with the OEMs for feedback.
Achieved: Two rounds of preliminary designs have been completed and key features have been identified.

Proposed (6 Month): At the 6-month mark, we should be have finalized the design and sent the drawings to the machine

shop for construction.
Achieved: The designs have been finalized and drawings sent to the machine shop. Materials for the rig have been ordered.

Proposed (9 Month): At the 9-month mark, we should have the main body of the high altitude relight rig constructed and windows for the rig purchased.
Achieved: The main body of the rig has been machined and assembled.

Proposed (12 Month): At the-12 month mark, we should have obtained the swirler and injector and made any modifications to the rig to ensure that they fit into the main body.
Achieved: The swirler and injector have been retrieved from Wright-Patterson Air Force Base. Preparations have been made to transport the rig to ARL.

Year III
Proposed (3 Month): At the 3-month mark, we should have shipped the sector rig to ARL to begin setting it up in the high altitude chamber.
Achieved: Army Research Combustor-L1 shipped to ARL, and preparations for high altitude relight campaign have begun.

Proposed (6 Month): At the 6-month mark, we should have purchased peripheral components for the high altitude relight campaign, and a test matrix should have been decided.
Achieved: The designs have been finalized and drawings sent to the machine shop. Materials for the rig have been ordered.

Proposed (9 Month): At the 9-month mark, we should have completed the high altitude ignition probability test matrix set out in the previous period. The ignition delay measurements in the RCM should have been completed.
Achieved: High altitude relight measurements at 10,000 ft, and hardware upgrades for future campaigns have been planned. Ignition delay measurements have been completed.

Proposed (12 Month): At the 12-month mark, we should have finished analyzing the ignition probability data and RCM ignition delay data.
Achieved: Preliminary analysis of the ignition probability data and RCM data has been completed.

Major Accomplishments

High-Speed OH PLIF and Stereo-PIV imaging in the Georgia Tech Gas Turbine Rig
Laser and camera systems for the high-speed OH PLIF and stereo-PIV were set up and implemented at Georgia Tech on the advanced gas turbine rig. One observed issue was the presence of significant fuel PLIF, which was mitigated using a two camera PLIF setup with two differing spectral bandpass filters. The difference in the optical bandpass allows the ratio of OH and fuel PLIF to be varied; one set of images is used to correct for the fuel PLIF in the other image set. Quantification of the OH PLIF signal was also conducted using a flat-flame calibration burner developed at UIUC.

Fuel Spray and Flame Characterization in the Referee Combustor
A 2D PDA system is used to make measurements of fuel droplet diameters and velocities for Jet-A and two alternative jet fuels under the ASCENT's NJFCP. Average OH* chemiluminescence images are used to determine flame structure to correlate spray characteristics with flame location. The axial and radial velocity profiles show great similarity between the fuels with near identical radial velocity profiles and only small differences in the axial velocity profiles. The OH* emission reveals some distinct differences in the flame structure for each of the fuels. The observed differences in SMD profiles and mean velocity distributions do not seem sufficient to explain the differences in LBO equivalence ratio.

Georgia Tech Atmospheric Ignition Experiments
We transported and setup the laser system around the ignition rig at GATech for the execution of simultaneous PLIF, Schlieren, and OH chemiluminescence imaging. Imaging and measurements of ignition probability in a stratified flow of pre-vaporized fuel and air were conducted.

High Altitude Relight Combustor
Design and fabrication of a high altitude relight rig, replicating the key geometry and flow features of the referee rig has been completed. The sector rig was set up in the high-altitude chamber, and modifications to the chamber and fuel delivery system were made. Measurements of ignition probability for 5 fuels across a range of equivalence ratios at

ambient pressure and temperature conditions that correspond to 10,000 ft. Further data is needed at higher altitudes to gain a better understanding of the fuel properties that drive ignition behavior at these conditions.

Target Cetane Number Ignition Delays

Ignition delay measurements for targeted cetane number fuels, with cetane numbers varying from 30 to 55, were made in a rapid compression machine at the University of Illinois at Urbana-Champaign. Higher cetane number correlated strongly with shorter ignition delay at low temperature. The results warrant further investigation into the targeted cetane number fuels in the NTC region to gain a better understanding of how the cetane number drives autoignition delay time in this regime.

Publications

Chterev II, Rock NN, Ek HH, et al. Reacting Pressurized Spray Combustor Dynamics: Part 2 — High Speed Planar Measurements. ASME. Turbo Expo: Power for Land, Sea, and Air, Volume 4A: Combustion, Fuels and Emissions ():V04AT04A020. doi:10.1115/GT2016-56345.

E. Mayhew, C. Mitsingas, B. McGann, T. Lee, T. Hendershott, S. Stouffer, P. Wrzesinski, A. Caswell, Spray Characteristics and Flame Structure of Jet A and Alternative Jet Fuels, AIAA SciTech, AIAA-2017-0148, 2017

I. Chterev, N. Rock, H. Ek, B. Emerson, J. Seitzman, T. Lieuwen, D. Noble, E. Mayhew, T. Lee, Simultaneous High Speed (5 kHz) Fuel-PLIE, OH-PLIF and Stereo PIV Imaging of Pressurized Swirl-Stabilized Flames using Liquid Fuels, AIAA SciTech, AIAA-2017-0152, 2017

Outreach Efforts

None

Awards

I. Chterev, N. Rock, H. Ek, B. Emerson, J. Seitzman, T. Lieuwen, D. Noble, E. Mayhew, T. Lee, Simultaneous High Speed (5 kHz) Fuel-PLIE, OH-PLIF and Stereo PIV Imaging of Pressurized Swirl-Stabilized Flames using Liquid Fuels, AIAA SciTech, AIAA-2017-0152, 2017
(winner of the ***The Walter R. Lempert Student Paper Award in Diagnostics for Fluid Mechanics, Plasma Physics, and Energy Transfer***)

Student Involvement

Five graduate students (listed above) have participated in this project on a rotational basis to address various aspects of the project. Rajavasanth designed and fabricated the calibration burner used at GATech, and conducted experiments to determine the actual concentration of radical concentrations in the flame. Two other students (Stephen Hammack and Eric Mayhew) made trips to GATech to make test measurements in the high shear combustor. This included assisting in the setup of the laser and optics as well as participating in the actual measurements. The calibration torch as well as other optical and imaging equipment was taken down to GATech for testing.

Two students (Brendan McGann and Eric Mayhew) set up and executed the PDPA measurements outlined in Task 1and they (Brendan McGann and Eric Mayhew) traveled to GATech to transport and couple the Edgewave Nd:YAG pump laser to the dye laser for use in the PLIF imaging. In addition, they assisted in the setup of the optics and participated in the initial phase of the measurements. The Edgewave and other optical and imaging equipment was taken down to GATech for testing. Rajavasanth designed and fabricated the high altitude relight chamber.

Brendan McGann and Eric Mayhew also made trips to ARL to deliver and set up the Army Research Combustor-L1 in preparation for the high altitude experiments. Three students (Brendan McGann, Constandinos Mitsingas, and Eric Mayhew) set up and executed the high altitude relight experiments outlined in Task 1. Kyungwook Min conducted the ignition delay measurements in RCM at UIUC.

Plans for Next Period

As of this report, all tasks have been completed but if required we will continue to participate in the NJFCP program to gather more high altitude data at the Army Research Laboratory.