U.S. Department of Transportation
Federal Aviation Administration

FINAL PROJECT REPORT

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9/30/2013

PART I - PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. FAA Program	3. FAA Award Number
University of Dayton Research Institute	Environment and Energy	13-C-AJFE-UD-002
300 College Park Dayton, OH 45469	4. Award Period From 11/5/2014 To 11/30/201	5. Cumulative Award Amount $209,949.00

6. Project Title

Referee Swirl-Stabilized Combustor Evaluation/Support for National Jet Fuel Combustion Program

PART II - SUMMARY OF COMPLETED PROJECT (For Public Use)

See attachment

PART III - TECHNICAL INFORMATION (For Program Management Uses)

1. ITEM (Check appropriate blocks)	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM: Check (X)	TO BE FURNISHED SEPARATELY TO PROGRAM: Approx. Date
a. Abstracts of Theses	✘				
b. Publication Citations	✘				
c. Data on Scientific Collaborators	✘				
d. Information on Inventions	✘				
e. Technical Description of Project and Results		✘			
f. Other (specify)					

2. Principal Investigator/Project Director Name (Typed)	3. Principal Investigator / Project Director Signature	4. Date
Steven Zabarnick		7/13/2017

FAA Form 9550-5 (03-03) Supersedes Previous Edition

Project 030
National Jet Fuels Combustion Program – Area #6: Referee Swirl-Stabilized Combustor Evaluation and Support

Universities:
- University of Dayton
- University of Illinois

Industrial Partners:
- GE
- Williams International
- Honeywell
- Rolls-Royce
- Pratt & Whitney/United Technologies Research Center
- Parker Hannifin

Federal Agencies:
- Air Force research Laboratory
- Air Force Office of Scientific Research
- National Aeronautics and Space Administration
- Defense Logistics Agency - Energy
- NavAir
- Department of Energy
- Army Research Laboratory
- National Institute of Standards and Technology

International Partners
- National Research Council (Canada)
- DLR (Germany)
- University of Sheffield (UK)

ASCENT Committee Member
- CAAFI
- Boeing
- Shell

Project Lead Investigator
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University Participants

University of Dayton

- P.I.: Steve Zabarnick
- Division Head, Energy and Environmental Engineering
  University of Dayton Research Institute
- FAA Award Number: 13-C-AJFE-UD, Amendment 02
- Period of Performance: December 1, 2014 to November 30, 2015
- Task(s):
  1. Referee Swirl-Stabilized Combustor Evaluation and Support.

University of Illinois at Urbana-Champaign

- P.I.: Tonghun Lee
- Associate Professor
  Mechanical Science & Engineering
- FAA Award Number: 11757359
- Period of Performance: December 1, 2014 to November 30, 2015
- Task(s):
  1. Optimize and apply laser diagnostics for application in the Referee Combustor.

Project Funding Level

University of Dayton:
Funding Level: $209,949.00
Cost Share: NRC Canada

University of Illinois at Urbana-Champaign:
Funding Level: $140K
Cost Share: In-kind academic time of the PI, Lab renovation cost by department for diagnostics work

Investigation Team

University of Dayton

Dr. Steve Zabarnick- Team Leader
Dr. Scott Stouffer- Referee Combustor Lead Engineer
Dr. Matt Dewitt- Lead for Emissions
Tyler Hendershott- Referee Combustor Engineer
Jeff Monfort- Graduate Student- Thermo-Acoustics Research Engineer

University of Illinois at Urbana-Champaign

Eric Mayhew -Graduate Student-Execution of laser and optical diagnostics.
Rajavasanth Rajasegar -Graduate Student-Optimization of laser diagnostics strategy.
Stephen Hammack -Graduate Student-Execution of laser and optical diagnostics

Project Overview

This project will develop, conduct, and analyze combustion experiments for alternative jet fuels in the National Jet Fuel Combustion Program's referee combustor.

The effort involves rig testing of combustion parameters as well as implementation of advanced laser and optical measurements in the referee combustor to provide insight into details of the combustion process and provide data for new predictive combustion models under ASCENT Project 028. The goal of this research is to simplify alternative fuel certification procedures by reducing the need for full-scale engine testing. It is part of the National Jet Fuels Combustion Program and will satisfy Area #6, Referee Swirl-Stabilized Combustor Evaluation and Support.

Task 1: Referee Swirl-Stabilized Combustor Evaluation and Support

University of Dayton

Objective(s)

The main objective of this work is to work with AFRL, the OEM rig committee, and the other team areas of the NJFCP to obtain and interpret the combustor operability for alternative fuels. Specific operational characteristics examined include lean blowout (LBO), combustor stability, and ignition. One of the major purposes of this initial phase was to determine if the facility could be used to determine differences in the operational characteristics between different fuels. In addition to these overall measurements we will also acquire, in cooperation with University of Illinois at Urbana-Champaign, high quality optical diagnostic measurements, which will be passed on to the modeling groups within the NJFCP

Research Approach

<u>Initial Shakedown of the referee combustor rig</u>

The referee combustor is located at the Air Force Research Laboratory (AFRL). The referee combustor is shown in operation in Figure 1. The combustor incorporates many of the features of current state of the art combustor including a realistic swirler and two stage nozzle, dilution holes, and effusion cooling. At the start of the project the referee combustor had just become operational. We worked in collaboration with the OEM rig committee of the NJFCP to identify means for improving the combustor, combustor facility, and test methods for lean blowout tests. As a result of these collaborative efforts many improvements were made to the referee rig including:

1. Improvements in the air temperature, fuel temperature, and back pressure control.
2. Automatic control of fuel ramping rate during LBO experiments.
3. Improvements in light off and flameout detection.
4. Refinements to the dome cooling.

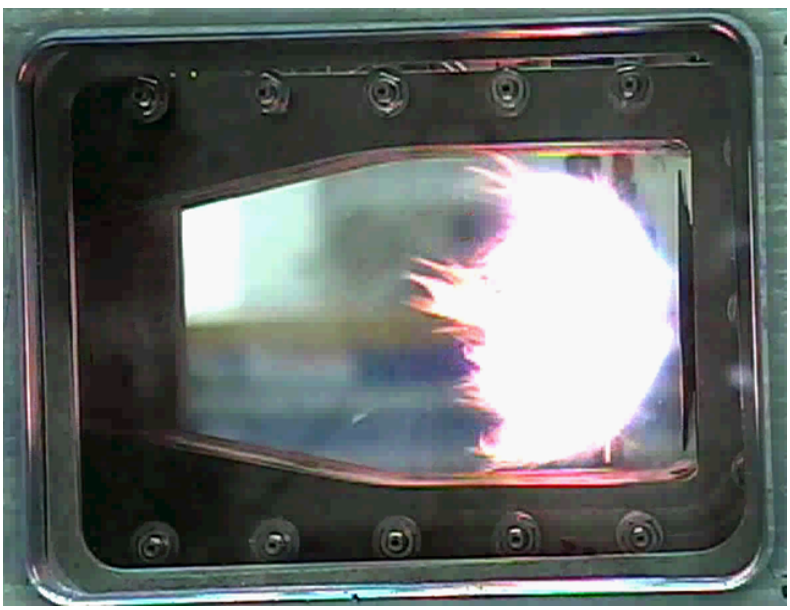

Figure1. Referee combustor during operation.

For the lean blowout experiments a method based on the use of syringe pumps was used to improve the fuel control. Figure 2 shows the fuel flow rate vs time for three successive tests. The close control of fuel flow rate was an essential element of the improvement of the LBO results.

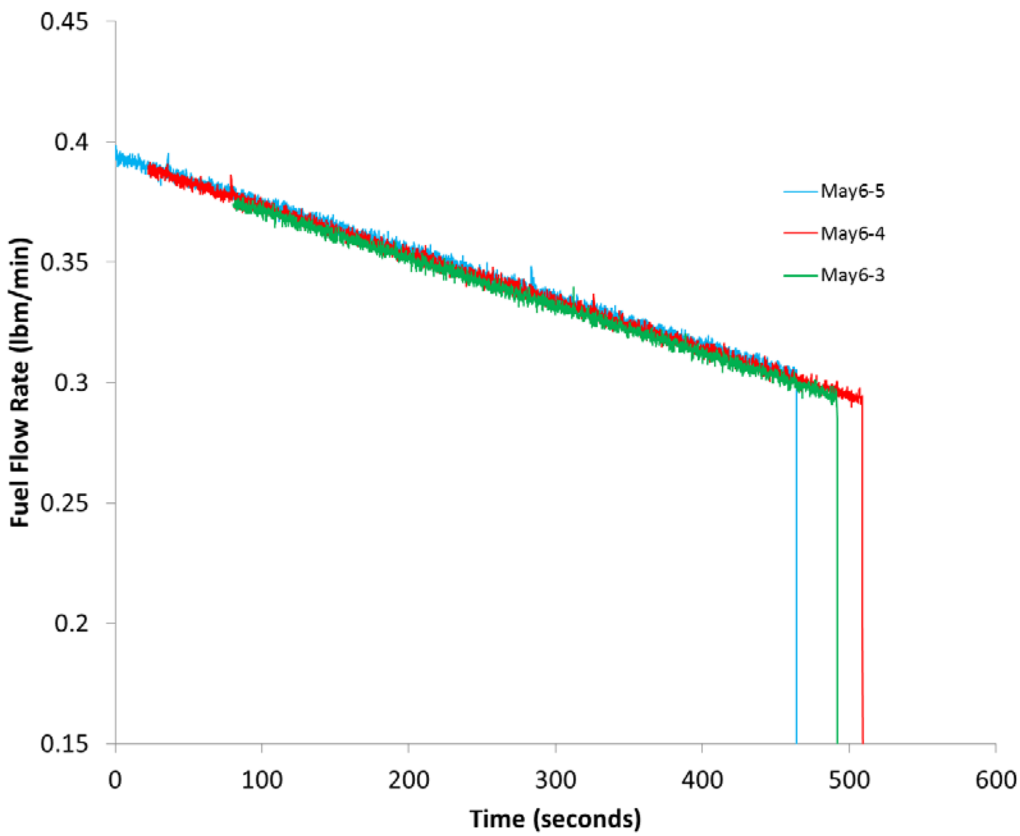

Figure 2. Fuel Ramping Employed during LBO Experiments

During this phase of the experiments we also characterized the acoustic response of the combustor and it was determined that acoustics coupling with the facility was not a factor near lean blowout.

An initial series of LBO experiments was conducted for the fuels. The experiments were showed significant differences in the ignition characteristics of some of the fuels. Differences in the LBO characteristics of the system were not seen during the initial experiments. Further refinements were made on the fuel system which resulted in greatly reduced scatter in the LBO measurements, allowing fuel effects to be seen in the LBO experiments.

We also conducted cold flow experiments of the measurements of the effective areas of the combustor parts (dilution jets, effusion cooling holes, swirler passages), and passed this data onto the modeling groups.

<u>LBO measurements and Optical Diagnostic measurements</u>

With the refinements in the fuel system completed we determined LBO data for the down selected fuels. We also worked with the University of Illinois and the AFRL team to obtain temperature measurements, high speed images, shadowgraph images, and chemiluminescence of the OH*, C_2* and CH*.

Milestone(s)

Proposed (3 months): During the first quarter we will transition geometry to the modeling teams.
Achieved: The combustor design information transferred to the modeling teams

Proposed (6 months): During the second quarter we will finish the shake-down and characterization experiments for the facility.
Achieved: Initial shakedown experiments were completed with the fuels.

Proposed (9 months): Conduct Lean blowout experiments and begin diagnostics experiments
Achieved: Lean Blowout experiments conducted and optical diagnostics experiments started

Proposed (12 months): Finish initial phase of optical diagnostics experiments
Achieved: In progress to transition all data to modelers.

Major Accomplishments

After refinement of the rig we conducted LBO experiments on the pilot nozzle circuit for the downselected fuels. The shakedown phase of this experiment resulted in improvements in test methods and reduction of data scatter. Figure 3 shows the overall equivalence ratio at lean blowout for the experiment at the experiment at 3%. The results clearly show differences in the lean blowout point between the C-1 and the other three fuels. The results show that the referee rig and combustor is sensitive enough to show fuel effects on LBO.

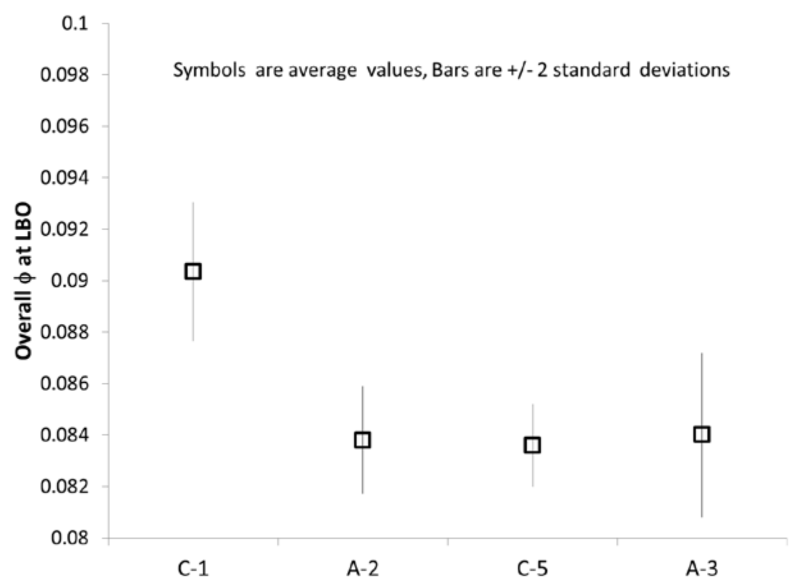

Figure 3. Lean Blowout Data measured at dome ΔP =3%, T_{air} = 250˚F, T_{fuel}= 120˚F

During the LBO measurement campaign we discovered differences in ignition characteristics of the fuels. A detailed ignition experiment was not attempted yet the differences in the ignition characteristics between the different fuels were evident, as shown in Figure 4. Note that the ignition data was acquired at elevated temperatures (Tair = 250˚F, Tfuel = 120˚F) yet even at these elevated temperatures we see the differences between the different fuels. It is expected that follow on experiments to be conducted at low fuel temperatures will show even more pronounced fuel effects on the ignition characteristics.

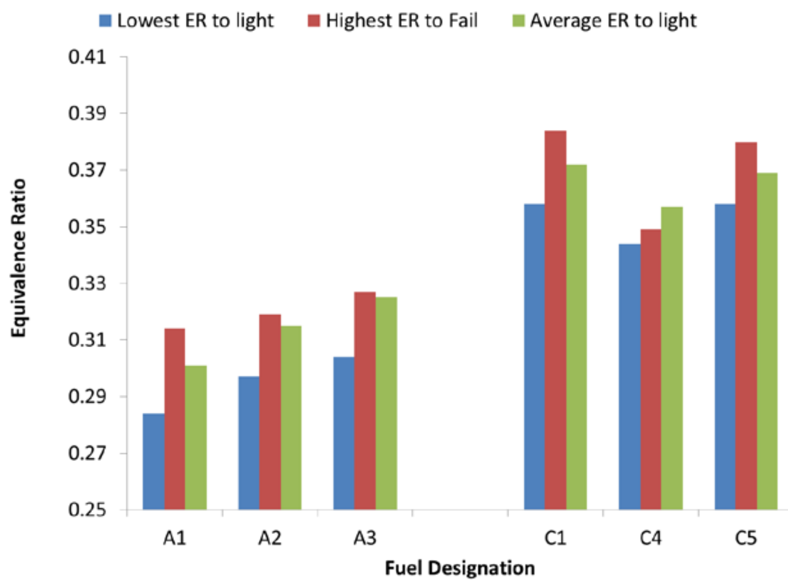

Figure 4. Ignition characteristics measured at T_{air}= 250 F, T_{fuel} = 120 F, P = 2 atm, Dome ΔP = 3%.

Optical experiments were also conducted in cooperation with University of Illinois at Urbana-Champaign, and AFRL. The results from these experiments will be discussed in the next task.

Accomplishments during the last month of the FY 15 money

Work proceeded on the cold fuel system for future cold air cold fuel experiments. We have installed the fuel heat exchanger and anticipate delivery of the fuel chiller in early 2016. We have also performed design work on the cold air capability and high altitude capability. The heat exchangers for the air system have been specified, ordered and received. We also performed preliminary air flow tests on the heat exchangers and have verified that the pressure drop through the air heat exchangers was low enough to accomplish future test objectives. We have also ordered the air chiller and the ejector.

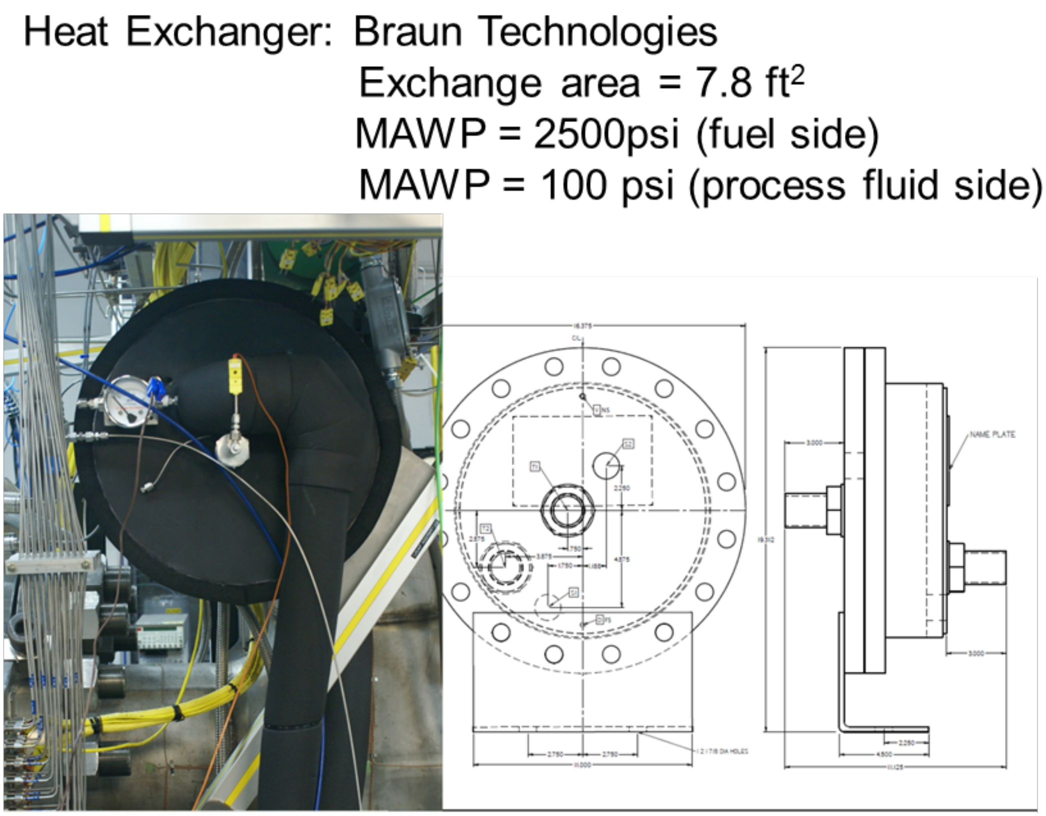

Figure 5. Details of the Fuel Heat Exchanger for Fuel Cooling

In parallel, related work we also started examining the LBO characteristics of other surrogate fuels in the same work and examined the acoustical characteristics of the fuels. Although it was not an objective of the program to explore the thermoacoustic characteristics of the various fuels, it was found that some of the fuels had higher acoustic interactions at lower equivalence ratios. In particular, the C-5 fuel was shown to have a higher acoustic pressure at lower equivalence ratios than A-1 or C-1, as shown in Figure 6.

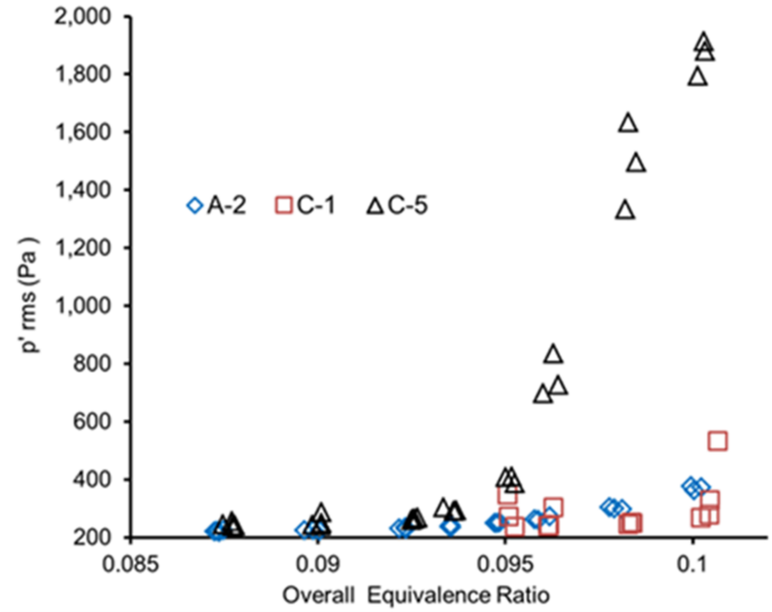

Figure 6. The Acoustic Pressure in the Referee Rig at inlet Conditions of T_{air} = 394 K, T_{fuel} =322 K, P_{comb} = 207kPa, ΔP_{dome} = 3%

Publications
None

Outreach Efforts

Poster Presentation

Edwin Corporan, Scott Stouffer, Tyler Hendershott, Chris Klingshirn, Matt Dewitt, Steve Zabarnick, Craig Neuroth, Dale Shouse, Jacob Diemer, "Initial Studies of Fuel Impacts on Combustor Operability and Emissions at the Air Force Research Laboratory", IASH 2015, the 14TH International Symposium on Stability, Handling, and Use of Liquid Fuels, Charleston, South Carolina USA, 4-8 October 2015

Awards
None

Student Involvement

Jeff Monfort – University of Dayton, Ph.D. Candidate
Research – Acoustic analysis of the Referee combustor
Graduated in Aug 2015 with Ph.D. in Mechanical Engineering
Currently employed by University of Dayton

Plans for Next Period

No further FAA funding was received for a second year, but AFRL has funded continued work in this area. Plans for the next year include more refined ignition experiments with cold fuel. We will also be developing the cold air and low pressure (altitude simulation) capability for future experiments. The LBO characteristics of the fuels will also be explored on the main circuit of the nozzle.

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

Diagnostics Optimization and Setup

The main goal here is the development of multi-phase high-speed diagnostics using 2D imaging to understand the combustion instabilities at the operational boundaries and flame dynamics. The goal will be to apply selected measurements from PLIF, PIV, and/or chemiluminescence (10 to 50 kHz). Additional high fidelity measurements from AFRL may be integrated with our efforts. In both PLIF and PIV, we will look to target OH and CH radicals in the flame. When required, we may employ high power low repetition PLIF measurements to look at various other flame properties such as nitric oxide generation (226 nm, Nd:YAG pumped dye laser) and/or formaldehyde (355 nm, Nd:YAG laser). For high speed chemiluminescence measurements, we plan to utilized a series of high-speed intensified cameras around the referee combustor. For the high PLIF measurements, we plan to first utilize a conventional 10 Hz PLIF laser system and ultimately move to a high speed dye laser (Sirah) pumped by a high speed diode pumped Nd:YAG (Edgewave). AFRL is in possession of a 200 W Edgewave system which may be deployed for the studies. Energy per laser pulse at these conditions maybe small (~30 μJ/pulse) and light collection from the PLIF will be enhanced using a f/1.8 UV lens from Cerco.

Quantification of the LIF Signal and Light Sheet Integration

To ensure that the signal is fully quantified, we set out to build and calibrate a small scale flat flame burner for use in the referee rig. The combustor will be fully calibrated at Illinois using a combination of laser absorption and multi-line nitric oxide LIF thermometry. By calibrating the intensity of the setup with the flat flame combustor, we can assess first order values for concentration of radical concentrations in the flame. One critical issue in the referee combustor is to insert a light sheet into the combustion chamber itself as there as only side windows for detection and no top view or bottom view window for propagation of the laser sheet.

Milestone(s)

Milestones from Each Period

Proposed (3 Month): At the 3 month mark, we will conclude the analysis of the experimental setup and start to modify the optical access of the referee combustor. Simultaneously, we will pursue development of the diagnostics with AFRL.
Achieved: Design of the laser setup complete and fabrication of calibration torch started. Construction on a mockup of the referee combustor begins at Illinois to test out the laser sheet feasibility.

Proposed (6 Month): At the 6 month mark, we should be well into building the experimental setup and modification of the referee combustor for optical access. We should also have made considerable progress in optimization of the CH PLIF strategy in the laboratory as well as commenced in the development of 50 kHz PLIF of OH for deployment in the referee combustor. Preliminary fuel screening measurements using high speed chemiluminescence will be carried out during this phase.
Achieved: CH PLIF is demonstrated at AFRL in a separate lab and is ready for deployment. 50 kHz OH PLIF is also ready for deployment. Measurement plans are pushed back slightly to accommodate for fuel screening in the referee combustor. Design of a multi-species chemiluminescence and shadowgraph setup commences.

Proposed (9 Month): At the 9 month mark, we should have completed the combustor optical access modifications and also conducted an initial shakedown of the tests. The diagnostics setup should also be completed and tested. We will start to share diagnostics data with other groups, notably 2, 4, and 6.
Achieved: Chemiluminescence measurements of C_2, OH and CH along with shadowgraph measurements of the fuel spray in

a cold flow are completed.

Proposed (12 Month): At the 12 month mark, we should have obtained an initial set of data for the 10 Hz OH PLIF. Depending on the progress we may also have some preliminary data set for 10 and/or 50 kHz OH PLIF. We should be fully prepared to implement high speed PLIF measurements for year 2.
Achieved: Data analysis of the chemiluminescence measurements to begin. Test of the light sheet insertion in the referee combustor to begin.

Major Accomplishments

During July 2015, 10 kHz shadowgraph was implemented on the Area 6 referee rig with the primary objective of obtaining the fuel spray cone angle. Shadowgraph images were taken of steady state combustion for each of the C-1, C-5, and A-2 fuels over a range of equivalence ratios. For the C-1 fuel, the equivalence ratios tested were: 0.1, 0.098, 0.096, and 0.095. For the C-5 and A-2 fuels, the equivalence ratios tested were: 0.1, 0.098, 0.096, 0.095, 0.0925, 0.09, and 0.0875. All of the data was taken with an air temperature of 250 ˚F, fuel temperature of 120 ˚F, combustor pressure of 30 psia, and a ΔP of 3%. Fuel spray tests were also conducted without combustion over the same range of equivalence ratios; a representative set of shadowgraph images of the fuel spray tests are shown in Figure 1. The images taken are currently being processed to obtain spray cone angle and RMS intensity along the centerline and at the edge of the spray.

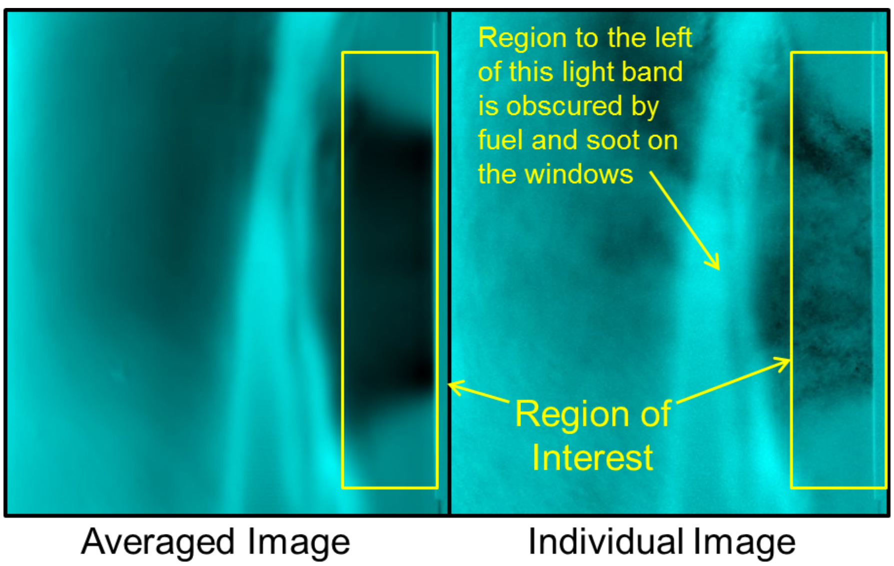

Figure 1 Sample shadowgraph images of an A-2 fuel spray test

During the same measurement campaign, 10 kHz OH*, CH*, and C_2* chemiluminescence images were taken at the same combustion conditions as the shadowgraph images described above. The chemiluminescence was captured using a Photron SA-5 intensified with a LaVision High Speed IRO with a Cerco f/2.8 UV lens. The OH* chemiluminescence was captured by using a Semrock Brightline 320/40 bandpass filter, the CH* chemiluminescence was captured using a Semrock Brightline 427/10 bandpass filter, and the C_2* chemiluminescence was captured using a Semrock Brightline 494/20 bandpass filter. The white vertical stripe shows sooting on the windows of the combustor during these runs, showing the difficulties of running in an actual combustor with real kerosene fuels.

Through discussions in the diagnostics subcommittee, several aspects of the data will be analyzed and transferred over to the modeling groups in the first pass. These include the angle of the spray as shown by the cold shadowgraph images as well as the OH* and CH* chemiluminescence signals. Additionally, we will provide contours of the OH generated in the flame as well as some relative intensities between the various chemiluminescence signals. This type of data will enable the modeling teams to anchor their models and in particular to ensure that the flow characteristics of their simulations are accurate. All the information will be placed on a grid system so that the PIs can ensure that their computations are to scale. Sample images of OH*, CH* and C_2* are shown in Figure 2.

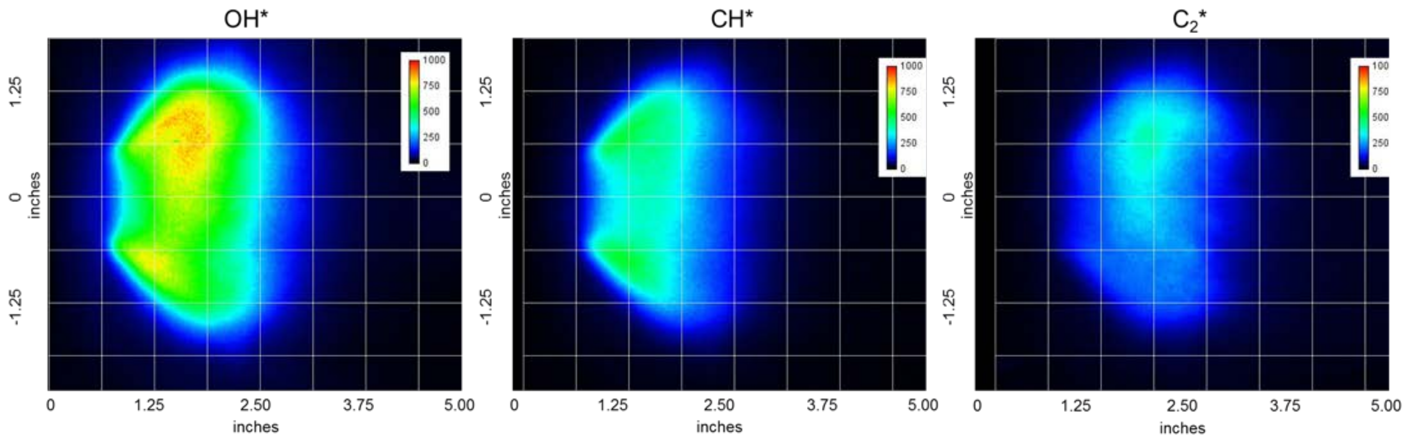

Figure 2 Representative averaged chemiluminescence images of OH*, CH*, and C_2* of the C-5 fuel at an equivalence ratio of 0.096

In addition to the analysis of the data, significant effort was made to develop a method of inserting a laser sheet into the referee combustor using optical engineering. As noted above, the referee combustor does not have top or bottom windows for inserting a laser beam and therefore require creative means for both pitching of the laser sheet into the combustor as well as detection. Several methods were proposed and two are shown in Figure 3. During this year, a mockup SLA of the referee combustor was constructed at Illinois and these light sheet integration methods were tested. They are expected to be integrated into the actual referee combustor in the following years.

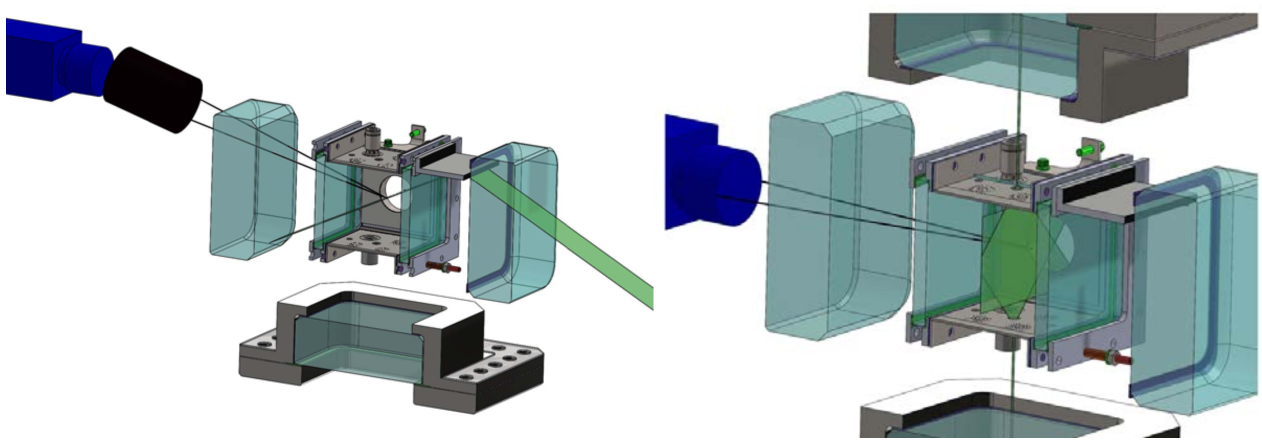

Figure 3 Methods of light sheet integration to the referee combustor. Left side shows a sheimpflug setup coupled with a reflected beam while the right shows the rapid expansion of a single beam.

Publications
None

Outreach Efforts
None

Awards
None

Student Involvement

Three 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 to be used in the referee combustor, and conducted experiments to determine the actual concentration of radical concentrations in the flame. Two other students (Stephen Hammack and Eric Mayhew) made multiple trips to AFRL 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.

Plans for Next Period

In year II of the NJFCP, an effort will be made to fully integrate the laser sheet in the referee combustor. We also expect to continue assisting in their effort to take images in the referee combustor and analyze the data. The high speed laser systems are already at AFRL and will be ready for deployment when we can find a window of run time in the referee combustor. Finally, we will assist with quantification of the referee combustor using the calibration torch built for this project at the University of Illinois.