Project 065(B) Fuel Testing Approaches for Rapid Jet Fuel Prescreening

University of Illinois Urbana-Champaign

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- PIs: Tonghun Lee, Professor
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- Period of Performance: June 5, 2020 to June 4, 2021
- Tasks:
    1. General characterization of the M1 combustor.
    2. Measurements for comparison with referee combustor (NJFCP).

Project Funding Level
FAA funding level: $150,000
Cost share: 100% match provided by software license support from Converge, Inc.

Investigation Team
- Tonghun Lee, Professor, University of Illinois at Urbana-Champaign (UIUC): Overall research supervision.
- Eric Wood, Jeongan Choi (Graduate Students, UIUC): Experimental efforts characterizing the M1 combustor including laser and optical diagnostics.

Project Overview
This study (Prescreening 65b) will aim to introduce a new compact test rig (M1 combustor), developed with OEM support within the National Jet Fuel Combustion Program (NJFCP), which can screen fundamental combustor behavior with much reduced fuel volume (~gallons) prior to Tier 3 and 4 tests in the ASTM D4054 evaluation. In the NJFCP, the referee rig at the Air Force Research Laboratory (AFRL) was utilized as a foundational test rig for this goal. The M1 may have the potential to carry out these tasks at reduced fuel volumes (~gallons versus ~hundreds of gallons) in a simplified and open architecture that can be readily shared and operated at different locations at a fraction of the cost. Both Army Research Laboratory (ARL) and Argonne National Laboratory (ANL) will be partners in the effort to fully characterize the M1 facility. If successful, it would allow both fuel providers and OEMs to conduct basic combustor tests using identical testing architecture and the same test conditions at multiple test locations. Through the NJFCP program, the referee rig at AFRL has shown the ability for a combustor rig to produce results that can lead to reduced uncertainty in Tier 3 and 4 ASTM testing. The M1 combustor may potentially provide similar capabilities with less fuel consumption, and ease of access compared to the referee rig, which is housed in a secure government facility (AFRL). Tests in smaller test rigs can provide a platform for each supplier to independently test their new fuels and make predictions without resorting to the use of one single combustor facility. Over

time as test data is massed, the potential for test rigs such as the M1 to predict actual Tier 3 and 4 performance will increase and may even reduce the burden of relying on capital intensive ASTM rig and engine tests.

Background of M1 Combustor

During the FAA-funded NJFCP program in 2016, the Referee Rig combustor at AFRL was being used to determine the sensitivity of combustor performance parameters such as lean blow-out (LBO) and ignition on the chemical composition of novel fuels. The results from this investigation were instrumental in establishing a relationship between fuel chemistry and its impact on combustor performance. Professor Tonghun Lee's research group carried out a significant portion of the laser and optical diagnostics in the referee rig as part of the NJFCP, including quantitative phase doppler particle analyzer (PDPA) measurements during full combusting conditions which will be leveraged here.

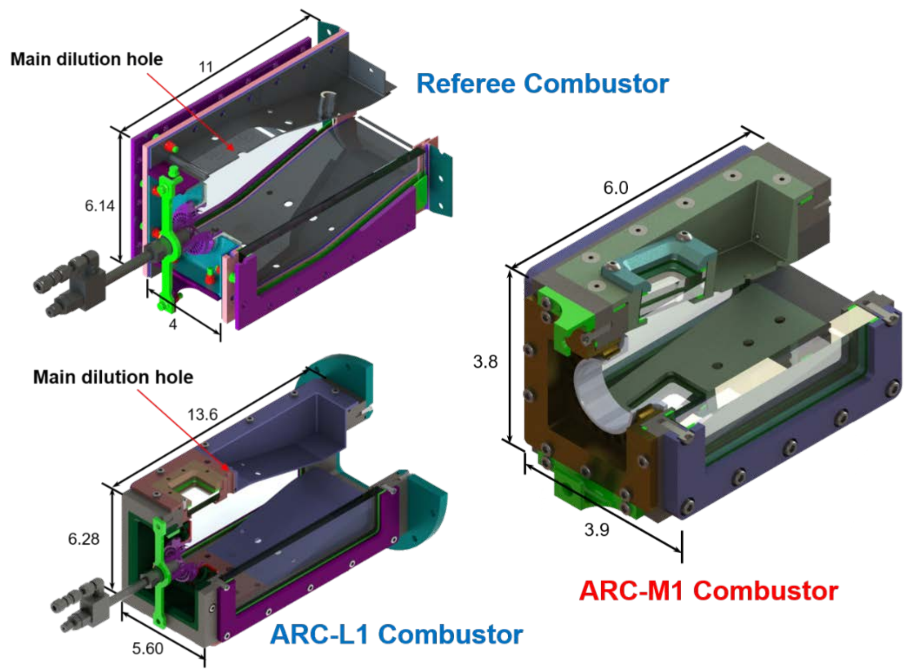

Figure 1. The referee combustor at AFRL), the ARC L1 combustor, and the M1 combustor.

Simultaneously, ARL was working with the NJFCP researchers to compliment the referee combustor work by carrying out high altitude relight tests at the ARL Aberdeen Proving Grounds, where a new altitude test chamber had just been commissioned. During the planning phase, ARL decided to build two new combustors for this purpose to address a couple of shortcomings of the referee combustor, namely optical access and flow split uncertainty. The first combustor would have the exact same dimensions as the referee combustor but with enhanced optical access and a less complicated liner for air cooling. Lack of vertical optical access had made velocity field measurements in the referee combustor virtually impossible, and the complicated liner had made accurate prediction of air flux into the combustor difficult. This new combustor would be code named ARC-L1 (Army Research Combustor-L1). Additionally, an effort was made to build a smaller combustor for more flexible testing with less fuel and air requirements. This smaller version would be code named the ARC-M1 and is the main architecture that is proposed in this study. Both combustors were designed through a subcommittee composed of NJFCP researchers and OEM representatives. The construction of both combustors was originally carried out in the research group of the PI (Tonghun Lee) at UIUC.

The referee combustor, L1, and M1 are shown in Figure 1. Continuing the heritage, ARL will be a key partner in the analysis of this combustor in terms of both numerical simulation efforts as well as x-ray imaging of spray break-up to be carried out at the Advanced Photon Source of ANL. In addition to the laser and optical measurements available at UIUC, the goal is to characterize the operating characteristics of the M1 in an unprecedented way so that it can be widely adopted in the academic/industrial community as a test platform for new fuel blends.

Task 1 – General Characterization of the M1 Combustor

University of Illinois at Urbana-Champaign

Objectives

The goal of this task is to perform a series of tests and diagnostics on the M1 combustor in order to quantify its operating characteristics in a manner which can allow it to be useful as a standard test platform for novel alternative fuels and for investigation of specific phenomena necessary for development of future combustion systems. This process includes developing the M1 combustion infrastructure to ensure repeatable and well-characterized operating conditions. The goal of the investigation is to characterize the M1 using x-ray diagnostics, laser and optical diagnostic techniques, as well as testing at LBO and high-altitude conditions to evaluate extremes of the operational envelope. This will allow the development of well-characterized numerical simulations for further study of complex combusting phenomena. Such information can be helpful for others who may choose to utilize the M1 architecture for future studies. The specific objectives in Task 1 are as follows:

- Setup and shakedown of the M1 combustor for testing.
- Selection of standard configuration and range of operating conditions.
- X-ray based spray imaging (ANL) and high-altitude testing at ARL.
- Laser and optical diagnostics in the laboratory at UIUC.

Research Approach

The ARC-M1 combustor is a single-swirl cup gas turbine combustor that has been designed to allow application of an array of diagnostic techniques. The combustor has full optical access on four sides to allow application of many different types of laser and optical diagnostic techniques. In addition to the combustor itself, the infrastructure surrounding it has been built up to allow careful control of combustor operating parameters including inlet air system, combustor pressure, and fuel injection flow rate. This infrastructure includes mass flow controllers on the air and fuel inlets and a high-temperature control valve on the combustor outlet. The inlet air preheat temperature is also carefully controlled with independent temperature and power controllers on the main and dilution airflow. Figure 2 shows an image of the combustor installed for laser diagnostics measurements at UIUC and an image of A-2 fuel (conventional Jet-A) burning in the M1 combustor, showing the swirl-stabilized shape of the flame through a side window.

It is critical for a standard combustor to be carefully characterized at standard operating conditions and Table 1 shows the range of operating conditions at which the M1 combustor is designed to operate. These span a wide range of air flow rates and fuel flow rates, allowing investigation of many varying combusting conditions. The M1 has the capability of operating at higher pressures, but we are limiting it to three bars in the preliminary characterization, which can be easily accommodated in the future at separate locations.

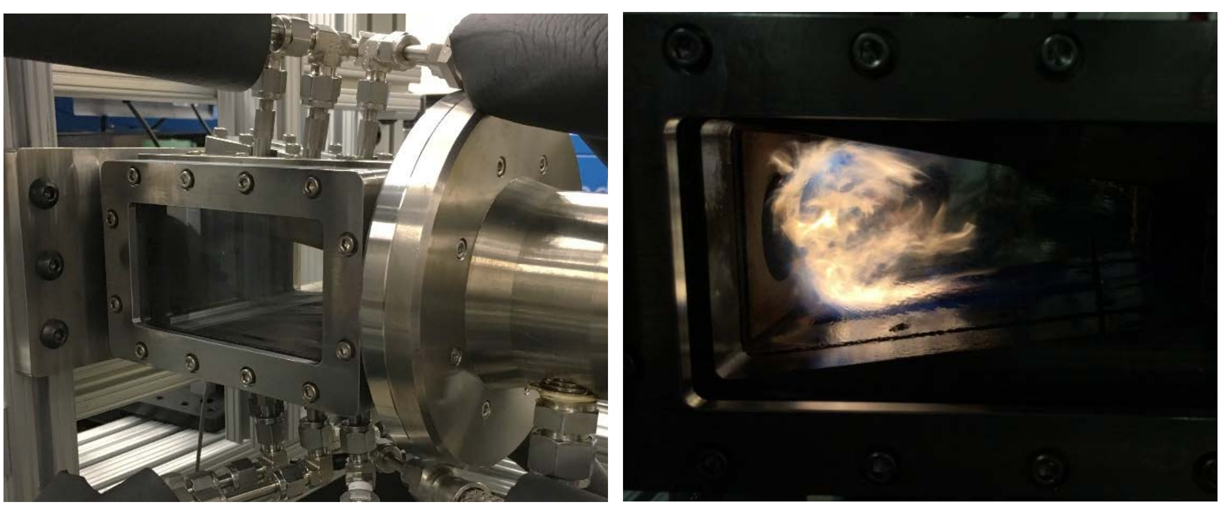

Figure 2. The ARC-M1 combustor installed at UIUC (left); the M1 combustor operating with A-2 jet fuel (right

Table 1: M1 Combustor Operating Conditions

Input Variable	Conditions
Combustor Pressure	1-3 bar
Air Inlet Temperature	300-423 K
Pressure Drop	3% - 5%
Air Flow Rate at 3% dP/P*	28-60 g/s
Fuel Flow Rates**	15-65 g/min
Global Equivalence Ratio	0.08-0.35

*With flow split of ~80% main, 20% dilution
**Fuel flow rates at each condition bounded by LBO and max combustor temperature

High-Speed Multiphase Liquid Spray Imaging (Advanced Photon Source, Argonne National Laboratory)
One of the unique capabilities afforded by the M1 is the ability to easily transport the combustor and supporting infrastructure to external facilities to perform specialized diagnostic measurements for characterization. One type of unique diagnostic capability that will be applied to the M1 combustor is high-speed phase contrast imaging using the Advanced Photon Source (APS) at ANL, one of the most powerful synchrotron light sources in the world for x-ray generation. The high brightness and spectral breadth of this source allows for a wide range of advanced diagnostics to be performed, most of which are difficult to perform on smaller, laboratory-scale sources with limited photon flux. The 7-BM beamline is utilized for imaging of the M1 at the APS and can support several time-resolved x-ray diagnostics. Specifically, phase contrast imaging is used to image the liquid spray breakup from the pressure-swirl atomizer inside the combustor. An overview of this approach is shown in Figure 3.

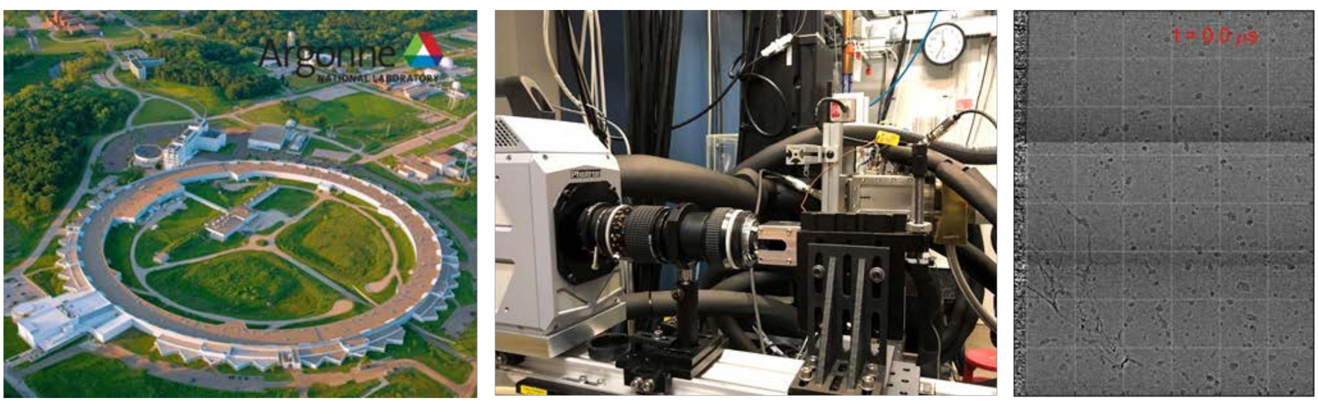

Figure 3. The Advanced Photon Source (APS) at Argonne National Laboratory (left); the ARC-M1 combustor installed at the 7-BM beamline at the APS (center); phase contrast image of fuel spray in the combusting ARC-M1 (right).

This technique utilizes the unfocused, raw emission from the bending magnet x-ray source (white beam) with beam power of approximately 600 mW/mm^2, as measured at the scintillator crystal, which is used to convert the x-rays into visible light. This imaging technique relies on differences in the indices of refraction between the fuel and the surrounding heated air. While the primary interaction between the x-ray beam and the fuel is absorption, gradients in the indices of refraction, which primarily occur at the boundaries between the two fluids, causing phase shifts in the x-ray beam, resulting in a Fresnel diffraction pattern. Diffraction at the boundaries between liquid fuel and air results in enhanced contrast in the collected images. Using this technique, the fuel spray passing through the beam can be tracked in high-speed (90,517 Hz) images as it undergoes breakup. The imaging itself is conducted using a Photron SA-Z, which images a YAG:Ce scintillator crystal using a reversed Nikkor 50mm f/1.2 lens and a forward Nikkor 105mm f/1.4 lens. The field of view is approximately 5.95 mm x 2.60 mm, with a resolution of 9.30 μm/pixel. To allow the x-ray beam to pass into the combustor, the quartz windows typically used for other diagnostic techniques are replaced with Kapton windows. These windows are 0.127 mm thick with overall dimensions of 21.0 x 3.18 mm. Kapton is chosen for these windows because of its high x-ray transmissivity, ensuring the x-ray is minimally attenuated before or after passing through the fuel spray. This type of phase contrast imaging is only possible on the M1 combustor due to its unique ability for it and its entire control system to be easily transported to ANL to allow these experiments to be conducted. The information that is gained through this diagnostic technique is extremely unique and allows characterization of these liquid sprays in a combusting environment with unprecedented accuracy. This data will be the foundation of initial conditions that will be supplied to high-fidelity numerical simulations.

High-Speed Diagnostic Techniques

In addition to the x-ray measurements at APS, high-speed laser and optical diagnostic techniques allow investigation into high-speed transient combustion phenomena that are critical for characterization of combustion performance but elusive to fully capture. These high-speed techniques have undergone tremendous development in the past decade, with new equipment allowing application at higher framerates than ever possible previously (routinely in the 10s of kHz and up to 1 MHz). The application of these techniques, including high-speed chemiluminescence, high-speed planar laser-induced fluorescence (PLIF), high-speed particle image velocimetry (PIV), and PDPA to the ARC-M1 combustion environment allow an extremely detailed understanding of the combustion environment and combustor boundary conditions. The design of the M1 has been specifically tailored to application of these diagnostic techniques with its large windows and multi-sided optical access. Figure 4 shows a sample image of high speed OH* chemiluminescence at reference conditions, which will be retaken using PLIF at UIUC.

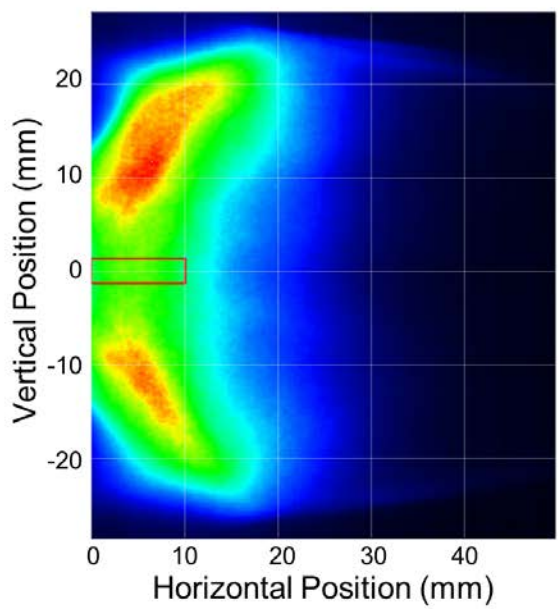

Figure 4. Average OH* chemiluminescence image in the M1 combustor operating at reference conditions.

In addition to the combustion dynamics, we will systematically characterize the relevant flow fields which will be of critical importance for numerical simulation validation. Figure 5 shows initial PIV data that has been collected on the ARC M1. This serves as an example of the advanced diagnostic techniques which will be applied to the combustors as part of this project. Future efforts will focus on simultaneous application of PIV and other diagnostics including PLIF at high frame rates (>10 kHz). Using these diagnostics, we plan to investigate the specific flow velocities and combustion radicals present within an operating gas turbine combustor environment; this information allows study of the behavior leading to both combustor ignition and LBO in extreme environments. By gaining a deeper understanding of the flow behaviors leading to these events, future engine technologies can be optimized to reduce the likelihood of unexpected flame-out events and improve the reliability of relighting an engine in extreme high-altitude conditions. Additionally, the suitability of new alternative fuels with these engines can also be ascertained. These boundary conditions also allow for well-characterized high-fidelity numerical simulations to be performed on this combustion environment, which can investigate combustion phenomena in ways that cannot be studied in experiments alone.

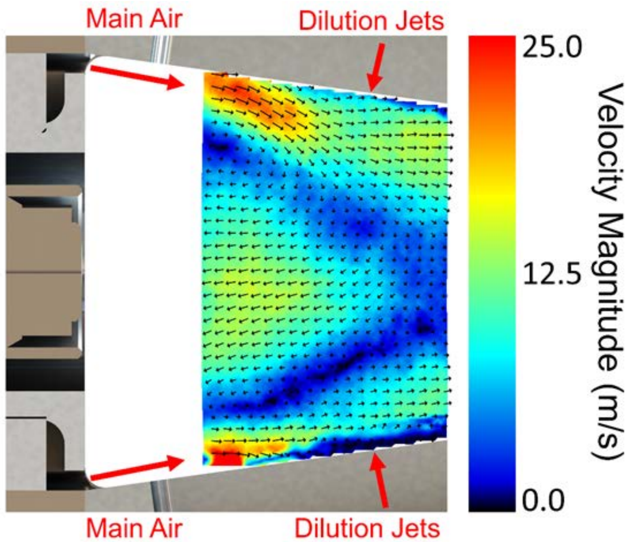

Figure 5. Average velocity from PIV in the M1 combustor operating at reference conditions.

The measurements proposed here ensure that M1 does not just become another combustor where fuels tests are reported. We will ensure that the M1 is the most extensively characterized combustor available so that the community can embrace its performance based on a firm scientific foundation and adapt further tests according to their needs.

Milestones

3 months: M1 combustor and control system setup and testing at UIUC.
6 months: Selection and testing of standardized testing conditions (basic LBO tests).
9 months: High altitude relight experiments at ARL.
12 months: APS x-ray measurements (depending on ANL reopening) and preliminary diagnostics measurements at UIUC.

Major Accomplishments

We are in the fifth month of the project. We have successfully operated the combustor and selected the test conditions. We have also been able to conduct some of the preliminary LBO measurements which will be shown in Task 2. At the outset of the project, we reassembled and received blessing of the original OEM, federal, and university team who participated in the M1 (we will keep them informed in the project).

Publications

N/A

Outreach Efforts

All test data will be made accessible through https://altjetfuels.illinois.edu/

Awards

None

Student Involvement

This project will be primarily conducted by two graduate students: Eric Wood (Ph.D.) and Jeongan Choi (Ph.D.).

Plans for Next Period

We are at the very beginning of this project and the next task is to set up the diagnostics equipment at UIUC as well as conducting the high-altitude measurements at ARL and the x-ray imaging measurements at ANL.

Task 2 – Measurements for Comparison with the Referee Combustor (NJFCP)

University of Illinois at Urbana-Champaign

Objective

The objective here is the carry out baseline LBO and ignition measurements that were carried out in the referee combustor for comparison. This is to test how this smaller standard combustor compares to the referee rig at similar test conditions. We will also carry out high altitude measurements to ensure that the test results compare well with the trends we have observed in the referee combustor.

Research Approach

Throughout the NJFCP, the referee combustor and several other combustors were carefully characterized in a variety of relevant operating regimes, including blowout and ignition. These studies were conducted at a variety of standard operating conditions which are relevant to gas turbine operational regimes that are likely to expose differences between fuels of varying properties. While these experiments in the referee combustor have provided valuable data about fuel effects near LBO, operating the referee rig comes with some disadvantages. The scale of the referee combustor brings large air and fuel flow rate requirements, which can make setup and operation expensive, especially when working with new alternatively derived fuels, which may be difficult to manufacture. As such, it would be beneficial if similar results could be obtained from a smaller combustor with reduced fuel and air requirements. By contrast, the ARC-M1 combustor uses significantly less air and fuel, reducing overall instrumentation expense and complexity, as well as reducing the volume of fuel needed to conduct tests over a range of conditions. This opens up the possibility that the M1 combustor could be used to evaluate performance of new fuels with much less fuel being used to conduct testing, reducing the supply requirements for a potential new fuel supplier. In order for this to happen, we need to ensure that the trends we see in a smaller combustor can convey the physics we saw in the referee combustor.

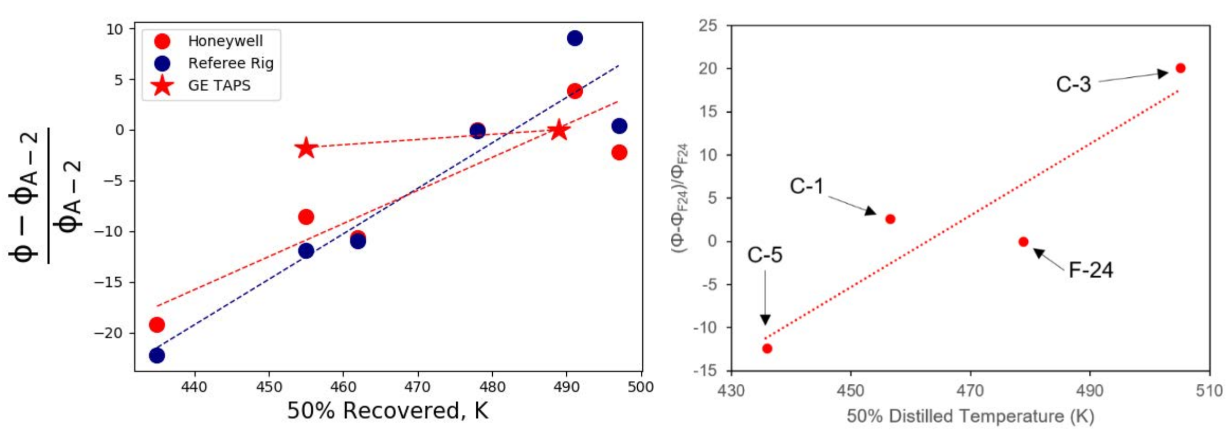

Figure 6. LBO data from several NJFCP rigs (left) and averaged data from the M1 combustor (right). Data from the M1 combustor was normalized using the F-24 data, as A-2 was not tested.

Testing of the ARC-M1 combustor will be conducted at near-LBO conditions to evaluate combustor performance and to facilitate comparisons to the referee combustor data that has been published as part of the NJFCP. These comparisons can give insight into how performance in the smaller combustion environment of the ARC-M1 compares to the larger referee rig. These comparisons will involve testing of the M1 combustor at identical conditions and evaluating how the performance across different fuels and different combustor operating conditions compares between the M1 and the referee rig data. Figure 6 shows some initial comparison data between the M1 and the referee rig. More in-depth comparisons will be performed in the future to allow scientific performance evaluation of the effects of fuel properties and how these effects vary between the M1 combustor and the referee combustor.

Milestone(s)
6 months: M1 combustor setup and shakedown and selection of test conditions.
9 months: Preliminary comparison measurements in the ARL high altitude chamber.
12 months: Comparison measurements of LBO for select NJFCP fuels in the M1 combustor for comparison with the referee combustor data.

Major Accomplishments
Currently, we have only preliminary measurements shown in Figure 6. We had planned and executed a high altitude relight campaign in August 2020 but due to an unexpected fire at ARL's Aberdeen Proving Grounds, we had to cancel the campaign during the first week. We are set to go back to carry out the measurements in the first two weeks of November.

Publications
N/A

Outreach Efforts
All test data will be made accessible through https://altjetfuels.illinois.edu/

Awards
None

Student Involvement
This project will be primarily conducted by two graduate students: Eric Wood (Ph.D.) and Jeongan Choi (Ph.D.).

Plans for Next Period
The very next task for execution is the high altitude relight campaign where two students will be traveling to the SmEARF high altitude facility at ARL with the M1 combustor. We anticipate that this campaign will take about three weeks followed by the analysis. After that, we will carry out the LBO measurements at UIUC along with a campaign at ARL's APS to investigate droplet behavior in near-LBO and ignition scenarios. Currently the APS is shut down for external researchers due to COVID-19, though we anticipate that this campaign will take place in the April-to-May 2021timeframe.