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LDRD PROJECT NUMBER: **176311**

LDRD PROJECT TITLE: **Rocket Engine Test System for Development of Novel Propulsion Technologies**

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ABSTRACT:

A 150 lb_f thrust class, modular, bi-propellant, rocket engine/gas-generator and supporting test infrastructure has been developed in a cooperative effort between Sandia National Laboratories and the New Mexico Institute of Mining and Technology's (NMIMT's) Energetic Materials Research and Testing Center (EMRTC). This modular test engine design consists of a head end fuel-oxidizer injector, a spark ignition gaseous H_2/O_2 torch igniter, combustion chamber and nozzle module. This robust design allows for rapid configuration changes as well as economical repair should hardware become damaged in testing. The engine interfaces with a permanently installed pressurizing system capable of delivering liquid nitrous oxide and a variety of liquid fuels for both rocket engine development and propellant performance evaluation. The regulated high pressure systems allow for delivery of liquefied gases above their saturation pressure as well as allowing for high pressure rocket engine/gas-generator operation. The facility test cell houses a 1 ton thrust capacity test stand leaving room for larger scale engine development.

Initial testing of the modular bi-propellant rocket engine involved evaluation of nitrous oxide and ethanol as potential "green" rocket propellants. Thrust and pressure measurements along with high-speed digital imaging of the rocket engine exhaust plume were conducted. Prompt starting without pressure oscillation or instability was demonstrated. Nitrous oxide and ethanol were shown to perform well as rocket propellants, with specific impulses experimentally measured in the range of 250 to 265 lb_f-sec/lb_m at ground level operating conditions. This report will discuss the design, development and fabrication of the test facility and the modular bi-propellant rocket engine/gas-generator as well as potential applications. Future testing plans will be discussed.

INTRODUCTION:

The advancements in space exploration have expanded the need for methods to improve current and develop new propulsion technologies. For liquid fueled rocket engines, this includes the development of propellants and rocket engine designs. To develop new propulsion technologies (especially rocket propellants) significant testing is necessary to establish the viability of concepts and develop reliable system designs. Small scale laboratory testing is vital as large scale testing is expensive and challenging with new or unproven propulsion technologies. Small scale laboratory testing is best supported by dedicated test facilities with hardened infrastructure to safely and economically explore the performance ranges of new propulsion technologies, including those with probabilities of failure.

New test facility development - especially at universities - is important to respond to changing needs for propulsion systems and to train the next generation of propulsion engineers. By leveraging the Campus Executive LDRD process at Sandia, a cooperative effort between Sandia National Laboratories and the New Mexico Institute of Mining and Technology (NMIMT) resulted. The intent of the effort was to create a hardened test facility to support testing of novel liquid propellant combinations and rocket engine designs at the Energetic Materials Research and Testing Center (EMRTC). The facility was designed to allow quick changes to support testing and provide data collection for a variety of propellants and rocket engine designs, while being simple enough to allow direct usage by undergraduate and graduate engineering students for coursework and research. The facility has an operational nitrous oxide and ethanol bi-propellant rocket engine developed in house that is the basis for operational envelope testing.

Research efforts have focused on the use of nitrous oxide and ethanol as rocket engine propellants from both a performance and safety standpoint [1,2]. Ethanol is a clean burning and renewable fuel with high potential as a next generation fuel [2]. Nitrous oxide has potential as an oxidizer for use in both hybrid and liquid bi-propellant rocket engines [3, 4], and can be simpler to handle than cryogenic liquid oxygen. Research at Stanford University has successfully implemented nitrous oxide with hybrid rocket engines [4]. In Japan, a bi-propellant rocket engine using ethanol and nitrous oxide was successfully demonstrated by Tokudome et al. with a thrust of 2kN (225lbs) and a vacuum specific impulse of 294 seconds [5]. Clearly, nitrous oxide has potential as a rocket propellant oxidizer.

Development of new testing facilities can be difficult from a safety and environmental standpoint, but research papers have described laboratory-scale facilities supported by both corporate and government interests. Peretz et al. [6] from Israel has built a hybrid rocket motor testing facility, and academic groups from Purdue [7] and Stanford University [8] operate laboratory scale test facilities for a range of rocket engine testing applications. The High Pressure Laboratory at the Maurice Zucrow Laboratories at Purdue University is one of the most active academic-scale rocket engine test facilities in the USA. The facility was designed for testing new and novel technologies with a hardened infrastructure [7], and serves as a model for the facility developed at NMIMT.

DETAILED DESCRIPTION OF EXPERIMENT/METHOD:

The current test facility, referred to as the Rocket Engine Facility (REF), was developed through collaboration between Sandia National Laboratories and NMIMT which commenced in October 2013. The facility was constructed within the EMRTC field laboratory in a former explosive manufacturing facility. EMRTC is a research division of NMIMT located in Socorro, NM, and is adjacent to the main campus. The structure comprising the REF was originally designed for explosive operations up to 498kgs (1100lbs) of TNT equivalence. With an estimated TNT equivalence of all propellants on-site of 66.2kgs (146lbs) of TNT, a significant safety margin is provided with room for future expansion to larger rocket engine testing [9].

The floor plan of the facility permits isolation of the propellant feed system from the test engine; this eliminates a cascading failure case from destroying the entire test apparatus. This is ideal for testing novel engine designs and propellant combinations where failure may be a common occurrence. The installed rocket engine mounting hardware is capable of supporting test firing of rocket engines of up to 8896N (2000lbf) thrust. Figure 1 shows the layout of the REF, including the separation of the propellant supply system from the rocket engine test cell.

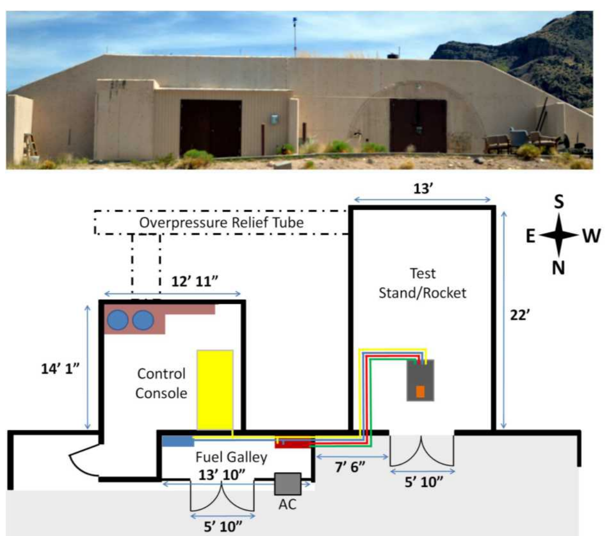

Figure 1: Rocket Engine Facility Layout

The fuel galley consists of three reinforced concrete walls on the West, East, and South sides. The North side is a blowout wall designed to fail under over-pressure conditions. This allows any energetic event that may occur inside of the fuel galley to be directed away from the facility, thereby limiting damage to personal and hardware. The fuel galley is temperature conditioned to allow year round operations.

The rocket engine is housed in a test cell originally utilized for explosive manufacturing operations. The test cell is also constructed with a blowout wall at the North end for over-pressure relief. The test cell can be sealed to protect all equipment and instrumentation from weather and allows precision optical instruments to be fielded for tests performed over long periods of time. During test firing of the rocket engine the North wall is opened. The current engine nozzle exit plane is recessed inside the test allowing for optical diagnostics of the exhaust plume that subsequently exists to the outlying area.

The operators and control systems are housed in the facility's control room. The close proximity of the control room to the test cell permits rapid changes to be made in the fuel galley as well as modification to the rocket engine configuration. Data acquisition and control lines are routed from the control room directly to the fuel galley and test cell through dedicated passages in the reinforced concrete walls.

Rocket Engine Design

Three design principles were adhered to during the development of the rocket engine housed at REF:

1. *Robustness* for increased safety and survivability of the engine.
2. *Modularity of design* to provide increased versatility and ease for future modifications and repairs.
3. *Simplicity* to decrease operational down time by using commercial off the shelf, easily replaceable parts where possible and simple machining methods for custom manufactured parts.

The intended use of the rocket engine was to experimentally evaluate the performance of nitrous oxide and ethanol as liquid propellants across a range of operating conditions while providing an academic opportunity for training undergraduate and graduate students in rocket propulsion experimental techniques and analysis. The rocket engine was also designed to allow development of optical diagnostics techniques to be developed for exhaust plume research.

The rocket engine was designed for a nominal chamber pressure of 6.89MPa (1000psi) and approximate thrust of 667N (150lbf)[9]. A conical 15 degree half angle exhaust nozzle design was chosen for simplicity in fabrication and designed for optimal expansion (Mach 3 flow condition). The rocket engine has a characteristic length, L*, of 7.33m (288.6 inches)[9]. The rocket engine was designed to be passively heat sink cooled via the mass of the rocket engine and allows for 10 second run times. The combustion chamber and nozzle were fabricated from oxygen-free, high conductivity (OFHC) copper. Sealing between sections was accomplished by fluorocarbon elastomer O-rings which have demonstrated multi-fire use without degradation or loss of sealing ability [9]. Typical post fire equilibrium temperature of the engine is 533K (500 °F). Figure 2 is a cross-sectional view of the assembled engine, and shows the dual O-rings seals at the flange interface, the igniter-engine interface port, the force transducer mounting assembly, and the injector plate and injector assembly.

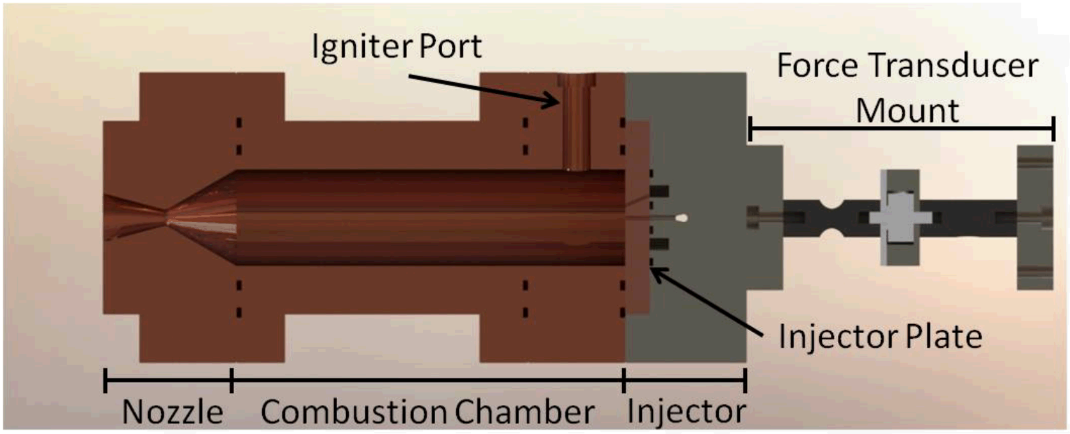

Figure 2: CAD cutaway of assembled rocket engine. Main components are labeled.

Propellant flow rates are controlled by cavitating venturis; this allows the propellant flow rates to be only a function of the upstream nitrogen supply pressure [10]; this decouples the propellant feed system from combustion chamber pressure fluctuations. The propellants flow into the engine through a simple impinging jet injector plate as discussed by Sutton[12]. Three fuel ports surround a single central oxidizer port, each with a 24° relative angle to the oxidizer port. The interchangeable injector plates permit different injector configurations to be interchanged as needed. Ignition of the propellants is accomplished by a gaseous hydrogen-oxygen torch based on a design by Repas[11]. Figure 3 shows the assembled rocket engine.

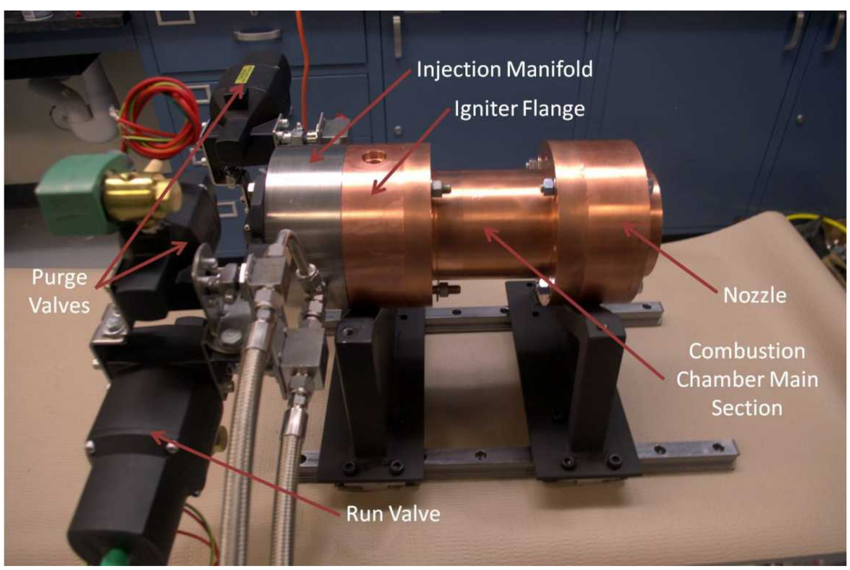

Figure 3: Assembled rocket engine prior to installation in test facility

Propellant Supply System

A constant pressure system is used for supplying propellants to the rocket engine. This system uses nitrogen gas to push propellant from storage tanks through feed lines to the rocket engine. Liquid propellants are supplied to the engine from bottom tank outlets while maintaining the tank pressures above the saturation pressure of the propellant. Figure 4 is a simplified schematic of the propellant supply system. The system is designed to isolate the fuel and oxidizer, with each system having its own nitrogen supply and purge system. In the schematic, green represents the oxidizer, red represents the fuel, and blue represents the nitrogen push and purge gases.

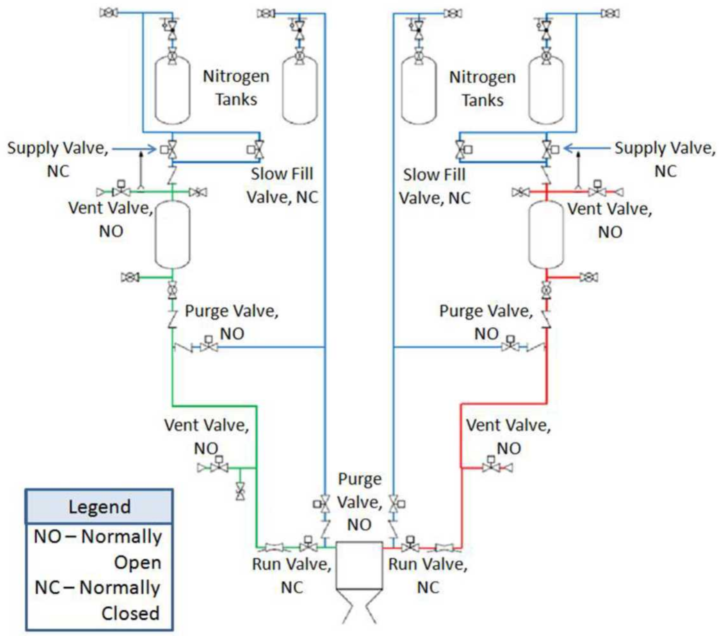

Figure 4: Simplified schematic of propellant supply system detailing valve function and operation

Pneumatically actuated valves are used to control propellant flow. The valve's unpowered state (normally closed/normally open) operation was selected so the system vents all propellants and pressure automatically from the system during emergency shut down situations or power loss. In the event of an emergency such as full-system power loss, the system is purged and placed in a safe state simply by removing power to the valves.

The system is constructed using Swagelok stainless steel fittings and 304 stainless steel tubing in order to allow a variety of propellants to be implemented without concern for corrosion or material incompatibility. The use of Swagelok components also permits reconfiguration and modifications to the system with off-the-shelf components. The oxidizer side of the system is oxygen cleaned in accordance with Compressed Gas Association (CGA) requirements. The system is limited to a maximum allowable working pressure (MAWP) of 12.4MPa (1800psi), which is established by the stainless steel sample cylinders used as propellant tanks. For safety, pressure relief valves are incorporated on both sides of the supply system in addition to burst disks rated for 12.4Mpa (1800psi) +/-0.69MPa (100psi).

The propellant supply system is divided into three main sections: the nitrogen supply panel, the propellant run tank panel, and the rocket engine connection hardware. Figure 5 shows the installed nitrogen supply panel.

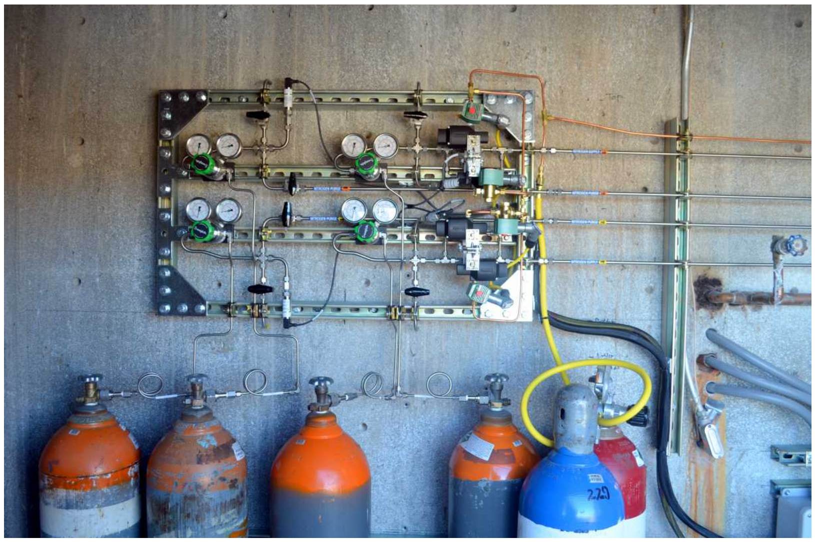

Figure 5: Installed nitrogen supply panel

The nitrogen supply panel consists of four regulators which allow supply and purge pressures to be individually set for the fuel and oxidizer sides of the system. The panel is designed to be supplied by four 41.4MPa (6000psi) high pressure nitrogen gas cylinders, and the regulators are rated to provide up to 20.7MPa (3000psi) although the system is limited to 12.4MPa (1800psi) at this time. A slow pressurization system is incorporated on both the fuel and oxidizer supply sides to prevent rapid adiabatic compression of the propellants in the supply tanks.

Figure 6 shows the installed run tank panel. The propellant run tank panel consists of two 3.78L (1 gal) double-ended sample cylinders manufactured by Swagelok. Each run tank is instrumented for tank pressure and temperature and is equipped with a burst disk and a pressure relief valve located at the top of the cylinder. Pressure and temperature monitoring is vital during the filling operations with nitrous oxide to ensure that the nitrous oxide does not reach a temperature that could lead to decomposition [9]. These temperature and pressure measurements are used to determine the flow rate of each propellant through the cavitating venturis.

Figure 6: Installed propellant run tank panel

Filling of the system with propellants is handled remotely to minimize operator exposure. Remotely operated pumps are used to transfer the ethanol and nitrous oxide into their respective tanks. The nitrous oxide is stored in a bulk nitrous oxide cylinder that is inverted to allow the liquid nitrous oxide to be drawn from the cylinder. The nitrous oxide source cylinder and ethanol supply tank are mounted on load cells allowing the mass loaded into the run tanks to be determined remotely. Figure 7 shows a view of the final connections made to the rocket engine. The exhaust nozzle is on the left side of the image, with two lenses from the schlieren optical diagnostic system visible in front of and behind the engine. The igniter is located on the top head end of the rocket engine. The fuel and oxidizer are injected into the propellant manifold section from the front and back sides of the engine in the image, respectively.

Figure 7: Side view of installed rocket engine and rocket engine connections

Control System

A National Instruments (NI) based system is used as a control system and for data acquisition. The NI hardware interfaces to the computer command console uses NI's LabVIEW software. A NI cDAQ-9188 permits interfacing with up to eight data processing and control modules. System pressure is monitored through an eight channel NI9203 current sensing analog measurement module capable of up to 200,000 samples per second for a single channel. Transducers Direct 20ma current pressure transducers are connected to this module for all system pressures. Temperature measurements are made using Type-K thermocouples connected to a sixteen channel NI 9213 thermocouple analog sensing module capable of 75 samples per second per channel. Engine thrust is measured using an Interface Force WMC-500 load cell paired with a four channel NI 9237 full bridge transducer module capable of 50,000 samples per second per channel.

The LabVIEW displays system pressures and temperatures and permits variable and automated timed valve actuation for rocket engine operation as well as manual override control of individual valves while providing real-time data acquisition. Figure 8 shows the control console utilized for operations at REF.

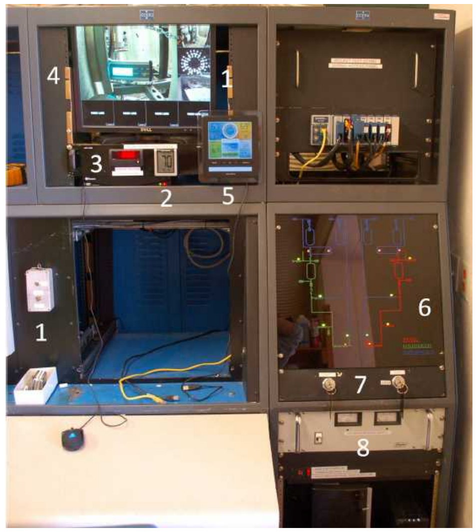

Figure 8: Console for operations and site monitoring. Visible are: Deadman'sswitch (1); Fuel galley temperature monitoring (2); Igniter supply voltage (3); Video observation system (4); Weather station (5); Valve status indicator panel (6); Propellant loading controls (7); and system power (8).

RESULTS:

The first successful test firing of the rocket engine at REF took place on March 25, 2015. Figure 9 shows the steady state operation of the rocket engine during a test.

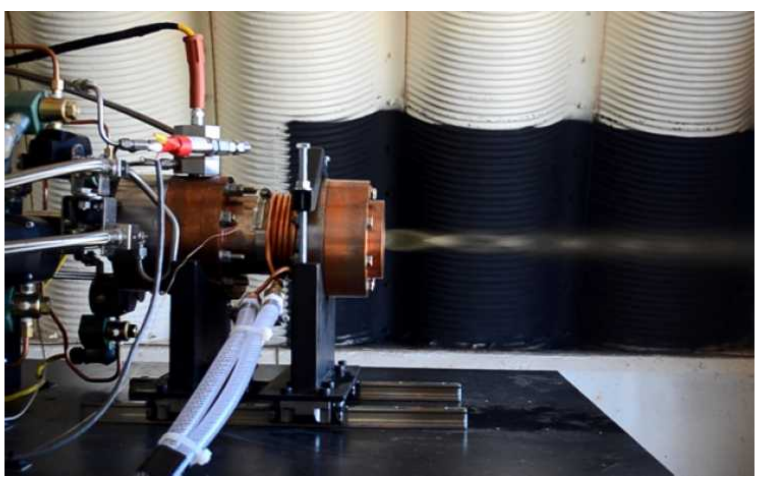

Figure 9: Steady-state rocket engine operation during Test 5/29/2015
External cooling loop visible for rapid engine cool down between tests.

Figures 10 and 11 show the plotted engine performance for Tests 5/29 and 6/2 respectively, with the measured performance for Tests 5/29 and 6/2 summarized in Table 1. The minor overshoot in chamber pressure is an artifact of the pressure transducer port measuring igniter pressure until the igniter is shut down.

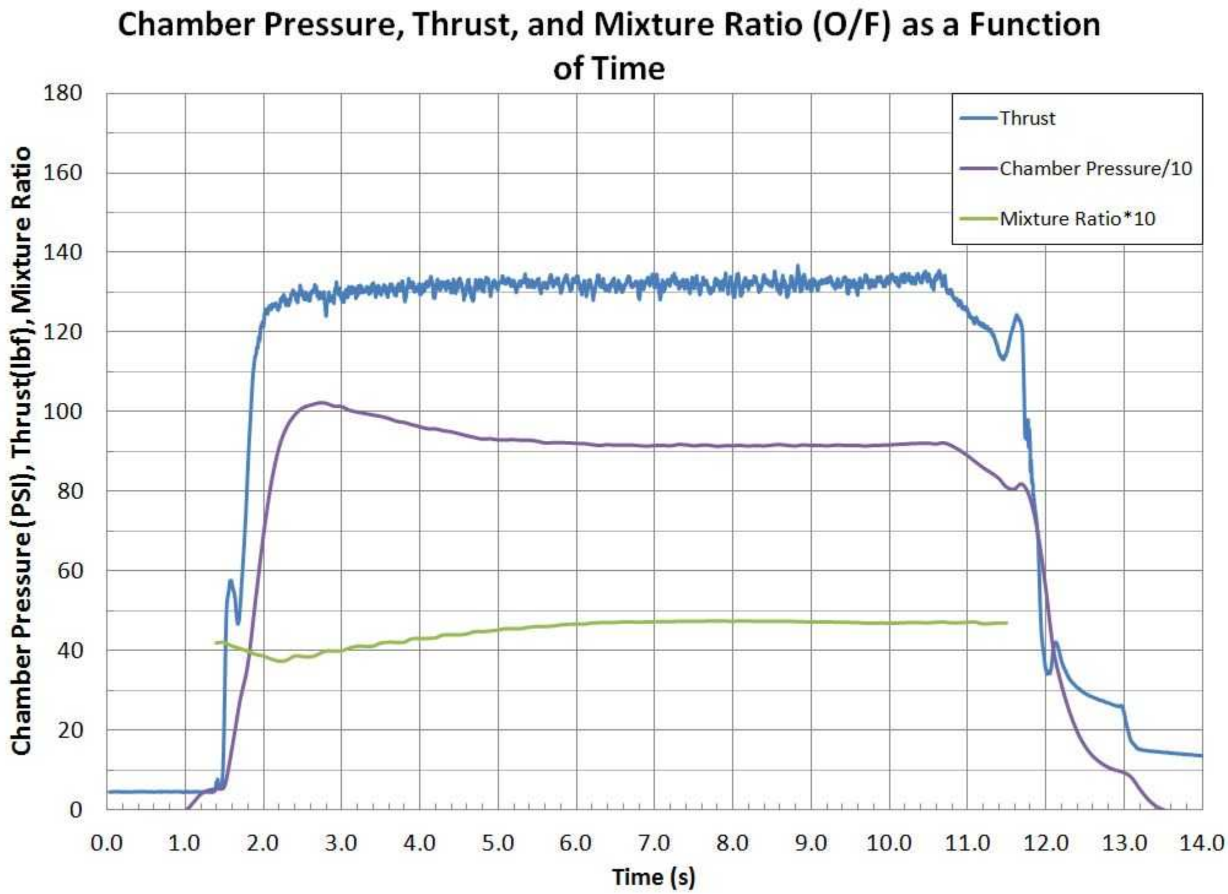

Figure 10: Rocket engine performance for Test 5/29. Chamber pressure, thrust, and mixture ratio are p as a function of time. The average steady-state flow rates were 0.190kg/s (0.419lbm/s) of nitrous oxide and 0.040kg/s (0.089lbm/s) of ethanol. The average mixture ratio was 4.71.

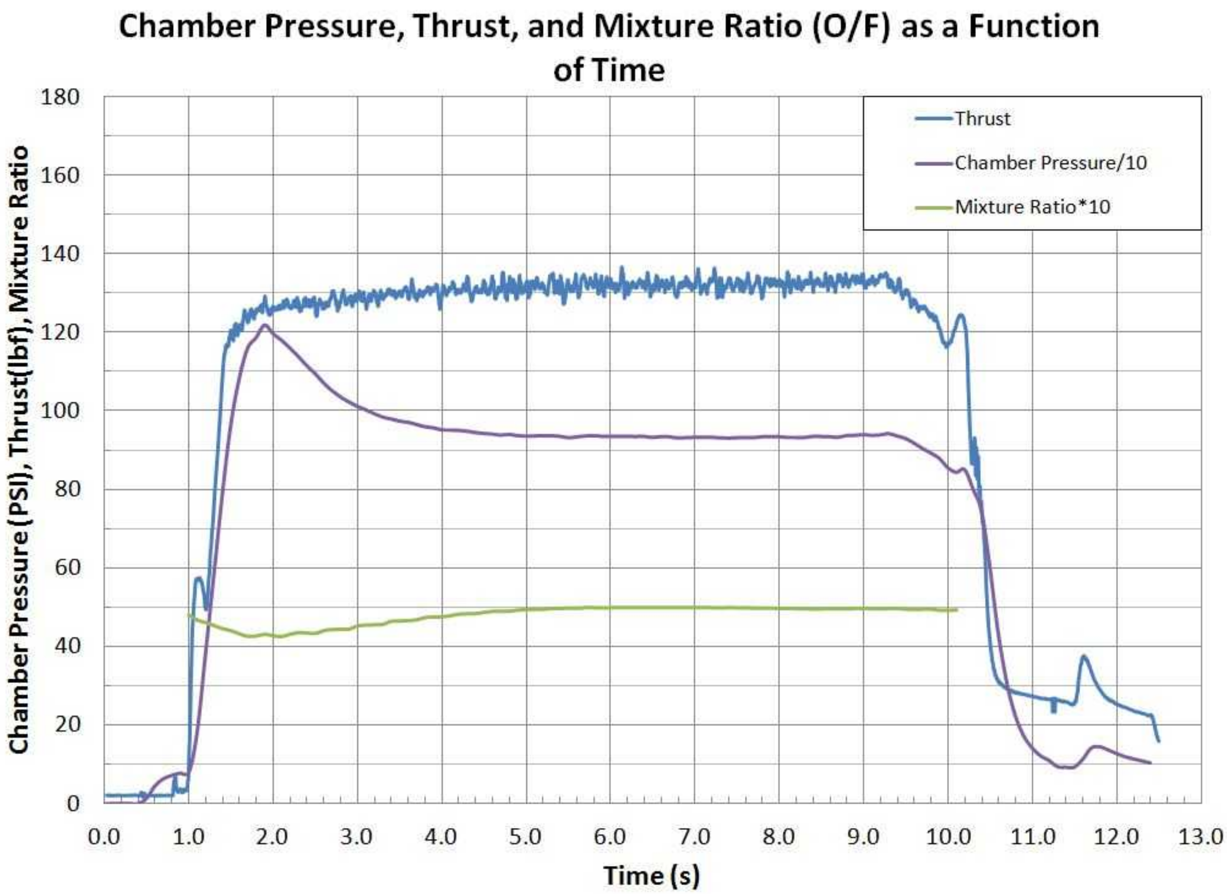

Figure 11: Plotted rocket engine performance for Test 6/2. Chamber pressure, thrust, and mixture ratio are plotted as a function of time. The average steady-state flow rates were 0.200kg/s (0.442lbm/s) of nitrous oxide and 0.040kg/s (0.089lbm/s) of ethanol. The average mixture ratio was 4.97.

Table 1: Experimental engine performance result summary for Test 5/29 and Test 6/2

Test	Calculated Flow Rate	MR	Chamber Pressure	Thrust	Isp
Units	kg/s (lbm/s)		Mpa (psi)	Nt (lbf)	Nt·s/kg (lbf-s/lbm)
Uncertainty	±0.004 (±0.008)	±0.2	±0.06 (±8)	±4 (±0.8)	±49 (±5)
5/29	0.230 (0.508)	4.71	6.32 (917)	592 (133.2)	2569 (262)
6/2	0.241 (0.532)	4.97	6.44 (935)	590 (132.6)	2461 (251)

The calculated specific impulses for Tests 5/29 and 6/2 were close to the theoretical values calculated by the NASA CEA code of 2599 Nt·s/kg (265 lbf-s/ lbm) for both run conditions. These two tests demonstrated successful operation of the REF and generated initial performance data for nitrous oxide and ethanol.

High-speed schlieren imaging was conducted during these tests to image the engine exhaust plume. The schlieren imaging demonstrated that the flow was approximately perfectly expanded through the nozzle, indicating the test was performing near design conditions. In the future these schlieren images will be combined with a seedless schlieren image velocimetry technique [14] to measure velocities in the nozzle flow field. Figure 12 shows an image of a high-speed schlieren image series of exhaust flow exiting the nozzle.

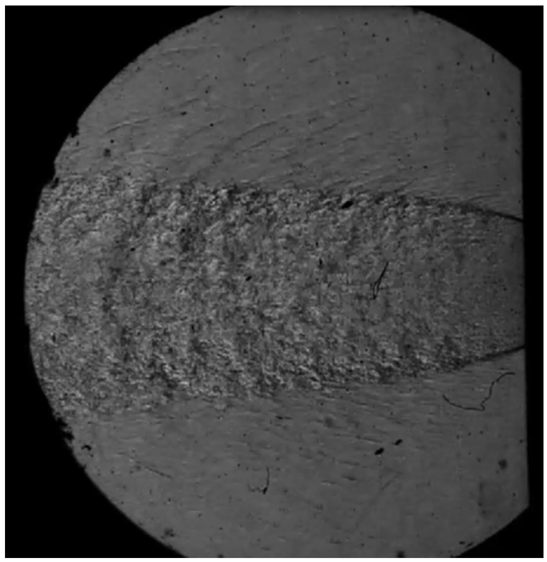

Figure 12: High-speed schlieren imaging of nozzle exhaust flow during steady state operation

The completion of the LDRD will be focusing on data acquisition and system control software improvement. The original system used a single LabVIEW instance to run both data acquisition and system control from the same computer. Because the entire system ran through one physical NI chassis computer, issues with insufficient computer processing power and memory resulted.

The NMT team split the data acquisition portion of the system from the system control part such that they run on separate computers and separate physical chassis. The data acquisition portion of the system runs on the desktop at REF and the system control runs on a laptop. The reduced strain on the computers has eliminated the past issues with processing power and memory while improving data sampling rates. The current system is able to record pressure and thrust data at 10 kHz where the old system was limited to 1kHz. The system being split also ensures that any potential issues in the data acquisition cannot interfere with the system control.

The rocket engine has been fired multiple times in the final months of the LDRD effort with the August 18 test concluding the pressure sweep of the system. The test was intended to run at a steady state chamber pressure of 800 psi. The actual chamber pressure was approximately 790 psi during steady state. The experimental ISP was found to be 234.

The team has used high speed schlieren imaging on all recent tests of the rocket engine. The video and images from this technique provide valuable information on the startup of the rocket engine and allow for verification of the expansion ratio of the engine.

The LDRD is concluding with a new phase of testing to gather experimental evidence of the relationship between specific impulse and chamber temperature when the ethanol fuel is diluted with water. A computational study of this phenomenon has been performed and shown significant drops in chamber temperature relative to the loss in ISP when the fuel is diluted. A new cavitating venturi has been received and installed for the testing of the fuel dilution. This new venturi will allow for testing of approximately 20% total mass fraction H2O in the propellants. The computational results indicate a drop of around 8% in ISP and 18% in chamber temperature at 20% water dilution when compared to 0% dilution.

DISCUSSION:

The REF continues to evolve in several areas. Enhanced imaging techniques are being integrated into the system along with improved data acquisition techniques for measuring system pressures, thrust, and other critical parameters.

Future research at REF will include the expansion of rocket engine performance evaluation tools as well as continued testing of nitrous oxide and ethanol as potential rocket engine and gas generator propellants. Future performance evaluation tools will include the expansion of the data acquisition system at the facility to provide additional engine instrumentation capabilities. This will include the addition of capabilities for exhaust temperature measurements as well as temperature measurements along the engine to measure heat flux from the chamber and nozzle in order to determine thermal losses and develop a fuel based regenerative cooling system. High speed optical analysis of the exhaust plume will also be further developed. This will include integration of seedless schlieren image velocimetry and focusing schlieren [14] to permit interior analysis of the exhaust plume and optical velocity measurement.

Future propellant evaluation of nitrous oxide and ethanol will include testing of neat ethanol and nitrous oxide as propellants over a range of chamber pressures and mixture ratios and ethanol-water mixtures to determine ignitability limits of diluted ethanol as a fuel. As a result of previous academic work [15] anhydrous ammonia will be evaluated as a potential clean burning gas generator fuel with nitrous oxide.

ANTICIPATED IMPACT:

The LDRD effort has had numerous past and anticipated impacts. The effort has resulted in a substantial body of undergraduate and graduate research. Several undergraduate students benefited by participating in the mechanical design and construction of the system, while graduate students are successfully utilizing the system to test and defend novel propellant theses. In this regard the capability will produce skilled propulsion engineers which will benefit Sandia's DS&A mission and similar missions of other entities.

With the system now being fully operational and some baseline propellant combinations being established, propellant initiatives to improve the safety and reliability of future propulsion systems will result.

The existence of this facility and Sandia's access to it could benefit work Sandia performs for DS&A customers. To the degree that those customers value national lab/university collaborations, the existence of this facility could attract missions to Sandia it does not presently have. As well Sandia will work with New Mexico Tech to incorporate this facility/capability into the Campus Executive Engagement Plan that will guide Sandia interactions with key faculty at Tech and that will form the basis for future Campus Executive LDRD projects.

CONCLUSION:

The work was successfully executed through a collaborative effort between Sandia National Laboratories and NMIMT. NMIMT developed a test facility with capabilities to support bi-propellant rocket engine development and testing. Nitrous oxide and ethanol was successfully test fired in a bi-propellant rocket engine that delivered a specific impulse in the range of 2452 to 2550 N·s/kg (250 to 260 lb_f-sec/lb_m). These preliminary results of nitrous oxide and ethanol testing support further investigation of the propellant combination to evaluate the operational envelope and suitability as a green propellant combination for both engine and gas generator use.

The establishment of the REF at EMRTC provides for future research capabilities in engine and propellant development and the development of diagnostic techniques including flow visualization and plume analysis. As well the REF provides a teaching tool for both graduate and undergraduate propulsion engineers at NMIMT.