NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

DEVELOPMENT AND QUALIFICATION OF A SPECIALIZED GAS TURBINE TEST STAND TO RESEARCH THE POTENTIAL BENEFITS OF NANOCATALYST FUEL ADDITIVES

by

Nathan A Kraemer

December 2007

Thesis Advisor: Jose O. Sinibaldi
Second Reader: Christopher M. Brophy

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** December 2007	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE: Development and Qualification of a Specialized Gas Turbine Test Stand to Research the Potential Benefits of Nanocatalyst Fuel Additives	**5. FUNDING NUMBERS**
6. AUTHOR(S) Nathan A Kraemer	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER** N/A

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

Due to the wide use of gas turbine engines, any performance improvements would yield significant impacts to many military and civilian programs. While hardware upgrades require costly replacements to existing equipment, fuel performance enhancement could provide a near term cost effective solution.

This thesis research focused on the development and qualification of a suitable test stand system to provide bench testing of nanocatalyst additives for jet fuels on a full-scale tactical gas turbine engine.

A Williams International F-121 fanjet engine was acquired and set up as the centerpiece component for the desired test stand. The required auxiliary systems and sensor equipment were designed and constructed. Initial baseline performance of the test stand and F-121 engine were demonstrated. These included the ability to determine lean ignition limits, capability to perform on-the-fly switching of fuel supply during engine operation, and capability of dynamically performing lean flame-out tests.

14. SUBJECT TERMS Nanocatalyst, F-121 Fanjet, Fuel Additives, Gas Turbine, Test Stand	**15. NUMBER OF PAGES** 87
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

DEVELOPMENT AND QUALIFICATION OF A SPECIALIZED GAS TURBINE TEST STAND TO RESEARCH THE POTENTIAL BENEFITS OF NANOCATALYST FUEL ADDITIVES

Nathan A Kraemer
Lieutenant, United States Navy
B.S. Mechanical Eng., Louisiana State University, 2000

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ASTRONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 2007

Author: Nathan A Kraemer

Approved by: Jose O. Sinibaldi
Thesis Advisor

Christopher M. Brophy
Second Reader

Anthony J. Healey
Chairman, Department of Mechanical & Astronautical Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Due to the wide use of gas turbine engines, any performance improvements would yield significant impacts to many military and civilian programs. While hardware upgrades require costly replacements to existing equipment, fuel performance enhancement could provide a near term cost effective solution.

This thesis research focused on the development and qualification of a suitable test stand system to provide bench testing of nanocatalyst additives for jet fuels on a full-scale tactical gas turbine engine.

A Williams International F-121 fanjet engine was acquired and set up as the centerpiece component for the desired test stand. The required auxiliary systems and sensor equipment were designed and constructed. Initial baseline performance of the test stand and F-121 engine were demonstrated. These included the ability to determine lean ignition limits, capability to perform on-the-fly switching of fuel supply during engine operation, and capability of dynamically performing lean flame-out tests.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

The author would like to thank Professors Jose Sinibaldi and Chris Brophy for their invaluable assistance and support. This thesis development experience proved to be one of the most educational experiences at NPS. The author would also like to thank Mr. George Hageman, who patiently contributed many hours of his time and effort at the lab to ensure my efforts were successful. The efforts and support of Mr. John Moore of the Naval Air Warfare Center, Weapons Division in China Lake as well as our research sponsors at the Office of Naval Research (ONR) are truly appreciated.

Last but certainly not least, much appreciation goes to my wife and kids who have allowed me to spend the required time away from home to pursue this thesis research. Their excitement for my progress was a key motivator during times of frustration.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. MOTIVATION

This research effort has its roots in the expressed desire by the Office of Naval Research (ONR) to explore potential technologies to increase performance and/or increase propulsive efficiency in existing and future generation propulsion systems. This thesis investigates the potential benefits from the use of nanoparticles that are soluble in energetic fuels. These nanoparticles act as catalysts which drastically reduce the temperatures required to carry-out the complex chemical branching reactions needed to combust fuel-air mixtures. In this manner, much lower fuel concentration levels are required to combust the mixtures, hence yielding potential for substantial increases in propulsion efficiency. The nanoparticles are composed of either fullerenes such as C_{60} or C_{70} nanoparticles or Palladium acetylacetonate (ACAC). However these nanocatalysts are not typically soluble in the fuels of interest. Therefore using a proprietary industrial process, their surfaces have been functionalized so that long chain paraffinic ligands are attached to the nanoparticle's surface. These ligands in turn allow the nanoparticles to become fully soluble in the fuels of interest at concentrations on the order of 10s to 100s ppm. The intent of this research was to apply these nanocatalysts to energetic fuels and perform tests to measure propulsion metrics in full-scale tactical gas turbine engines.

Although the initial intend of use and motivation for this research was to apply the nanocatalyst technology to military weapons and platforms (cruise missile engines, air and marine propulsion devices), there are many other important applications in the modern world. Examples of these include commercial and private aircraft, power generation both at the boilers in steam power plants and to the gas turbine engines in co-generation stations, commercial marine power from small personal use craft to large oil tankers, etc… This technology has the potential to make a substantial impact up to 10% reduction on the oil consumption worldwide. Other interesting applications include the use of nanocatalyst technology into a solid propellant formulation for a rocket booster and also into the liquid propellant of a two stage to orbit rocket launch vehicle. Whatever the specific application may be, the desire to increase performance on these engines has and will always exist. Redesigning existing gas turbines would be an extremely costly prospect when examining the trade space on improving performance on gas turbines. A natural conclusion would be trying to increase the efficiency and performance at a lower overall cost by modifying the properties of the fuels used in gas turbines.

1. Military Requirements for Extended Range

If a fuel that increases gas turbine engine performance could be found, several benefits to the military could be realized. Jets requiring a specified design range could achieve that range with less fuel therefore enable either a lighter plane or larger payload. Ships would be able to achieve a longer range of operations between high risk at sea refueling evolutions. Launches to space with a two stage to orbit vehicle would become more practical. Increased payload mass or increased range of operation with a first stage air breathing engine due to wider achievable ignition limits could be realized. Missiles would be able to achieve longer ranges or higher payloads. Any application that utilizes gas turbine engines could benefit from more efficient fuels.

B. THE PROBLEM

Leaning out fuel mixtures can result in decreased fuel consumption by gas turbine engines. However, this also results in unstable combustion and even can induce flame-out conditions in addition to the decreased performance in the amount of power provided. Overall increased performance can not be realized by simply altering existing performance optimized fuel ratios. Another means of increasing fuel performance must be explored. In order to validate theoretical gains, a suitable qualified test stand must be developed.

C. THE ANSWER

To realize increases in fuel performance, current fuels must be altered on a molecular level in order to achieve higher catalytic energies or increase operating ranges. The use of nanocatalysts as a means of improving catalytic activity in current fuels could provide an answer to the problem of increasing gas turbine engine performance. The design of an appropriate test stand utilizing actual hardware is the first step down the road towards solving the issue of increased gas turbine engine performance.

D. BACKGROUND

1. Jet Fuels

a. Civil and Military Jet Fuels

Fuels used for powering jet and turbo-prop engine aircraft are called Aviation turbine fuels. These fuels should not be confused with Avgas. Domestically, two main grades of turbine fuel are currently in use in civil commercial aviation. Each grade is a kerosene type fuel, Jet A-1 and Jet A. Jet B, a wide cut kerosene blend of gasoline and kerosene is used only in cold climates.

> Jet A-1 is a kerosene grade of fuel suitable for most turbine engined aircraft. It is produced to a stringent internationally agreed standard, has a flash point above 38°C (100°F) and a freeze point maximum of -47°C. Jet A is a similar kerosene type of fuel, produced to an ASTM specification and normally only available in the U.S.A. It has the same flash point as Jet A-1 but a higher freeze point maximum (-40°C). Jet B is a distillate covering the naphtha and kerosene fractions. It can be used as an alternative to Jet A-1 but because it is more difficult to handle (higher flammability), there is only significant demand in very cold climates where its better cold weather performance is important. [1]

The military fuel most resembling the characteristics and blend of Jet B is JP-4. JP-4 contains additives to Jet B that act as a corrosion inhibitor and anti-icing agent. JP-5 is another military fuel which is simply high flash point kerosene. The military equivalent of Jet A-1 is JP-8 which also contains additives that act as a corrosion inhibitor and anti-icing agent.

2. Jet Fuel Additives

Many jet fuel additives already exist and provide various benefits. These compounds are added in very small quantities, typically on the order of parts per million, to provide specific improvements. Some commonly used additives are:

1. Anti-knock additives used to reduce the tendency of gasoline to detonate. The only approved aviation fuel anti-knock additive is Tetra-ethyl lead (TEL).

2. Anti-oxidant additives prevent the formation of gum deposits on fuel system components. These deposits are caused by oxidation of stored fuel. Anti-oxidants can also act to inhibit the formation of peroxide compounds.

3. Static dissipater additives reduce the effects of static electricity generated in high flow-rate fuel transfer systems.

4. Corrosion inhibitors provide protection for ferrous metals in fuel handling systems from corrosion.

5. Anti-icing additives are used to reduce the freezing point of water precipitated from jet fuels. This allows for the prevention of ice crystal formation due to cooling at high altitudes which can restrict the flow of fuel to the engine. Protection against microbiological growth in jet fuel can also be achieved by the use of anti-icing additives.

6. Metal de-activators suppress the catalytic effect of certain metals on fuel oxidation.

7. Biocide additives can be used to suppress microbiological growths in jet fuel.

8. Thermal Stability Improver additives are typically used in military JP-8 fuel to produce a grade referred to as JP-8+100. These additives inhibit deposit formation in high temperature areas of the fuel system. [1]

3. Power Boosting Fluids

Large piston engines sometimes require special fluids to increase take-off power. These fluid injection systems can also be incorporated into certain turbo-jet and turbo-prop engines. Power increase is achieved by raising air density and thus increasing the weight of combustion air. This is accomplished by cooling the air consumed. Cooling can be obtained by using only water. However, typically a mixture of methanol and water to is used. Water or methanol/water mixtures can be used in gas turbine engines. These mixtures are used primarily to restore the take-off power that can be lost when operating under low air density conditions. [1]

4. Nanocatalyst

A potential means to improve the performance of baseline fuels is the addition of soluble nanocatalysts. If these fuel additives can achieve a performance boost in the form of allowing combustion at lower fuel to air ratios and wider ignition limits, then the specific fuel consumption (SFC) can be lowered. This performance boost could be realized in the forms, among others, of increased range of air based platforms; more fuel efficient land and sea based turbine systems or increased operating range on a two stage to orbit launch vehicle. Near term potential applications are their use in advanced propulsion systems which exhibit the characteristic of high combustor air velocities resulting in short residence times. These short resident times force the need for even shorter ignition delay times in order to produce stable, efficient combustion. Performance improvement can be realized if the combustion catalyst is able to reduce the activation energy. The impact of activation energy or minimum energy for a molecule to react on residence time with a fixed temperature rise parameter is shown in Figure 1. High θ, activation energy parameter, values result in high temperatures from the reactions. This condition can support the reactions with lower residence times than auto ignition residence times. W_τ is the degree of reaction parameter and τ_r multiplied times Q, the lumped constant, is the residence time. [14] As theta increases proportional to activation energy, lower and upper residence times increase. The relationship for activation energy is developed in equations 1-3. [2]

$$E_a = -RT\ln\left(\frac{k}{A}\right) \quad \text{eq 1}$$

$$\theta = \ln\left(\frac{k}{A}\right) \quad \text{eq 2}$$

$$\theta = \frac{E_a}{RT} \quad \text{eq 3}$$

Where: E_a=Activation Energy R=Universal Gas Constant

T=temperature in Kelvin A=frequency factor

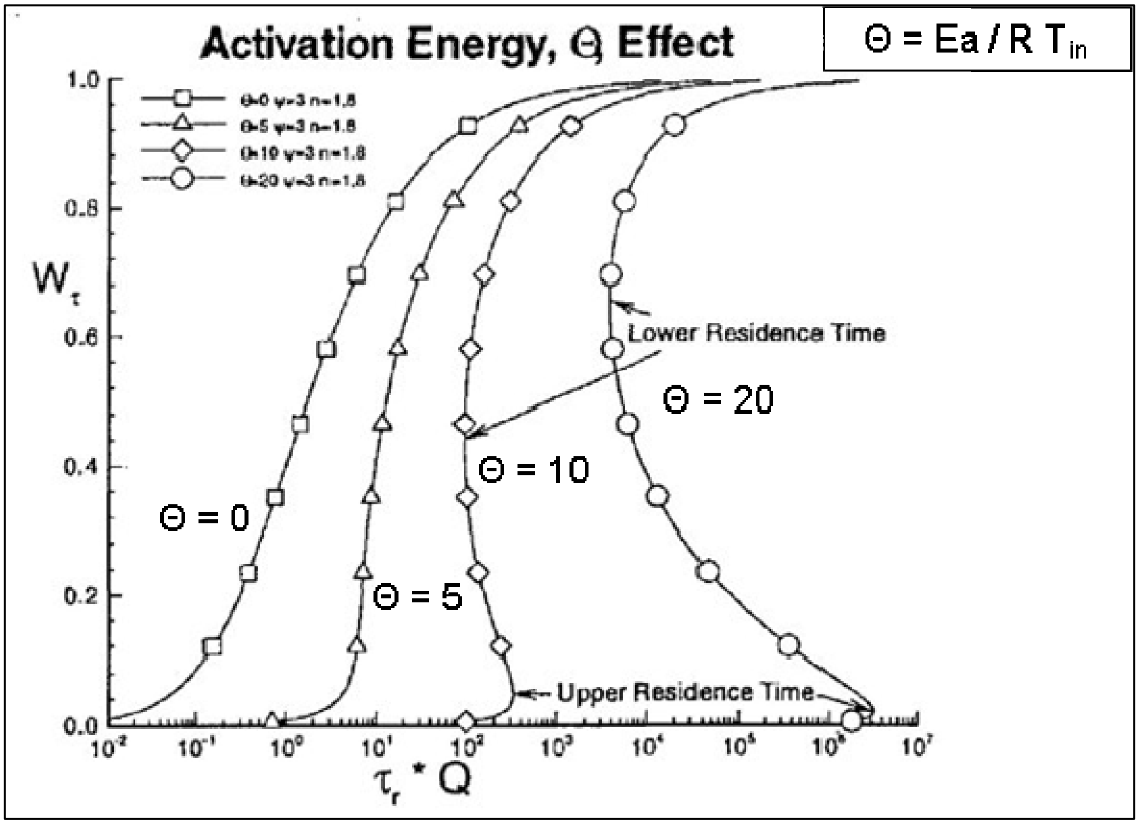


Figure 1. Activation Energy Affect on Residence Time (from Davis and Bowersox, AIAA-97-3274)

A proprietary process to manufacture nanocatalysts soluble in hydrocarbon compounds, that comprise jet fuel, has been developed by TDA Research Inc. The process entails attaching long chain paraffinic ligands to nanoscale boehmite (AlOOH) particles or other nanoparticles such as fullerenes and palladium ACAC. The resultant particles do not agglomerate so average particle sizes are less than 200nm. Many different catalytically active metals can be added to the boehmite matrix utilizing a proprietary exchange procedure in order to achieve a wide variety of catalytic activity. Laboratory scale test have shown that the nanocatalysts are effective in lowering fuel temperatures and yielding leaner combustion limits. With increased catalysts concentrations, lower fluid temperatures for a given carbon dioxide concentration were realized as shown in Figure 2. Leaner combustion levels were also achieved in laboratory test. Lower required equivalence ratios for combustion were achieved for given air preheat temperatures as illustrated in Figure 3. Longer residence times and leaner operating limits in laboratory settings lead to the promise of better fuel performance in gas turbine engines.

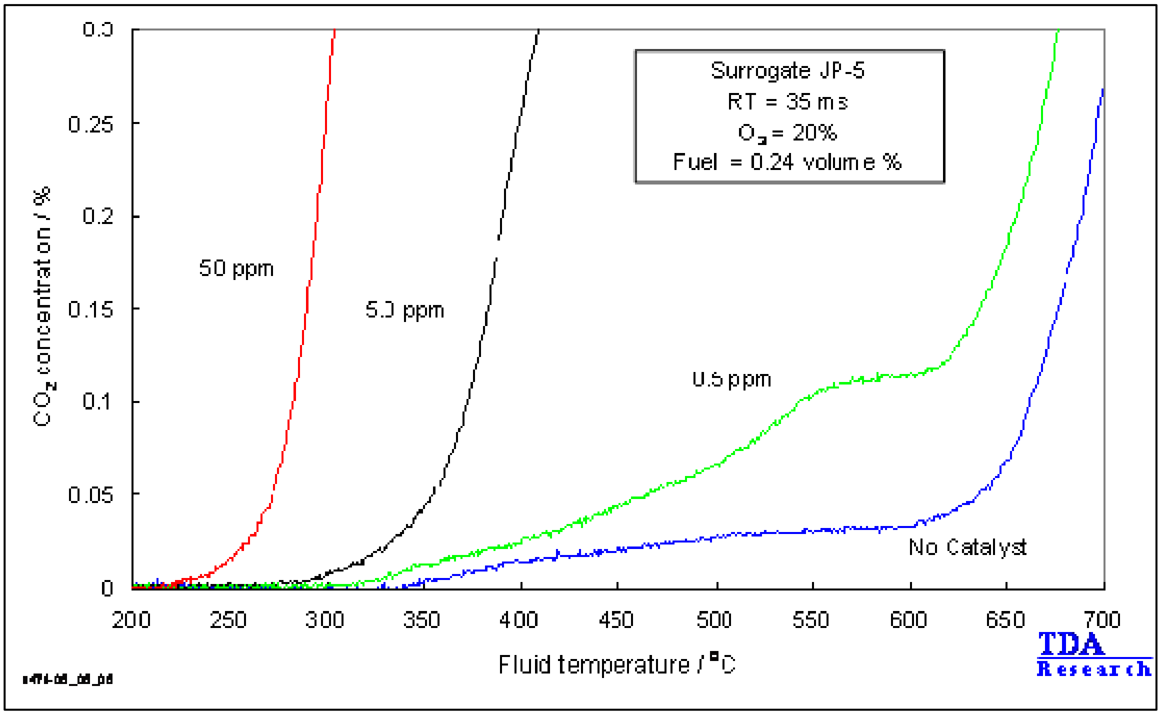


Figure 2. Nanocatalyst Effect on Fluid temperatures during Laboratory Scale Tests (from TDA Research Inc.)

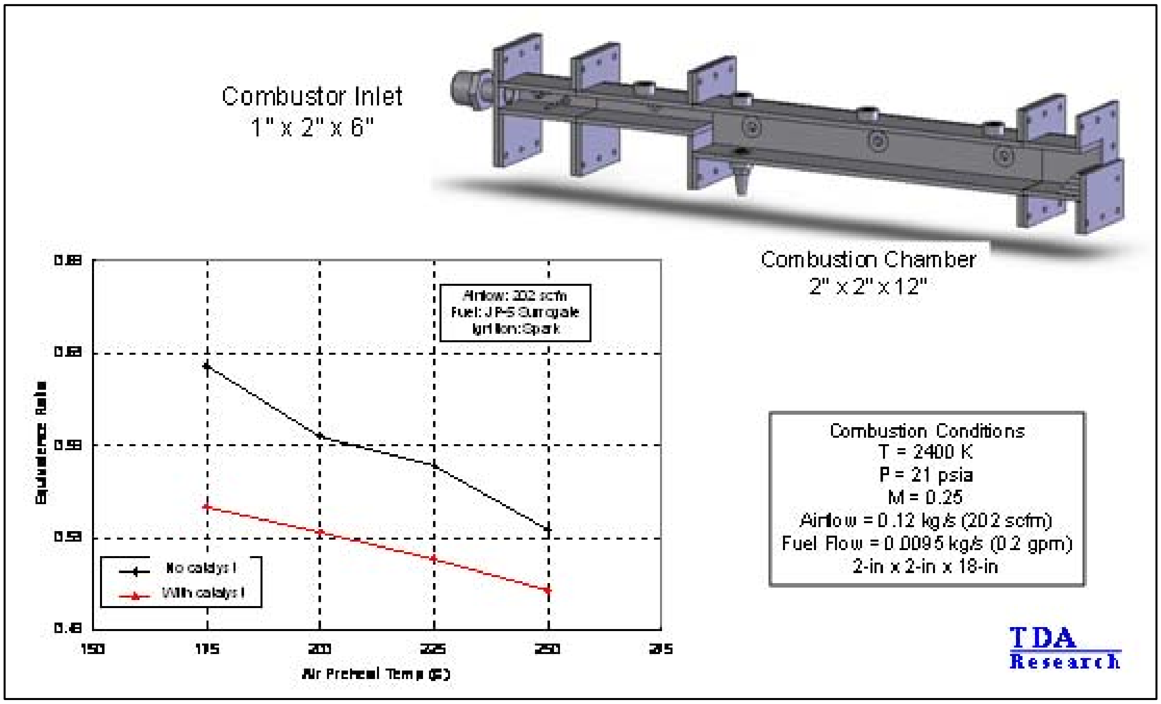


Figure 3. Lean Combustion Limit in Pilot Scale Tests (from TDA Research Inc.)

Palladium acetylacetonate (Pd(acac)- Pd($CH_3COCHCOCH_3$)$_2$) has shown best performance in small scale testing.

> Palladium Acetylacetonate is a Palladium source that is soluble in organic solvents. The acetylacetonate anion complexes by bonding each oxygen atom to the metallic cation in order to form a chelate ring. Because of this property, Palladium Acetylacetonate is commonly used in various catalysts and catalytic reagents for organic synthesis. [3]

The most effective chemistry results were found when used with Norpar 12 or Norpar 13 fuels.

> Norpar Fluids are normal paraffins that have been extracted from complex hydrocarbon streams and fractionated into desired volatility ranges. Heavier Norpar Fluids (Norpar 12 Fluid and above) are high-purity hydrocarbon fluids with low odors and low orders of toxicity. When compared to mixed hydrocarbon fluids in the same volatility range, they have the lowest viscosity, density, surface tension, solvency and photochemical reactivity, along with the fastest biodegradation rate and the greatest penetration ability. Norpar Fluids contain more than 97% in weight of normal paraffins. The grade number indicates the most abundant

normal paraffin in the product; e.g., n-tetradecane is the main component of Norpar 14 Fluid. Other significant components are normal paraffins with slightly lower and slightly higher carbon numbers. Total aromatics concentrations for Norpar 12, 13, and 14 Fluids are all less than 0.03 weight percent. [4]

At this time, very little if any improvements were observed in JP-10 ($C_{10}H_{16}$). Without further research the current hypothesis proposed by TDA Research scientists is with regards to the hydrogen release during the second catalysis of JP-10. The hydrogen substantially increases the rate of reactions and thus the catalytic nanoparticles cannot surpass or enhance H_2's effects. However it is still unknown why these nanocatalysts do not help during the first catalysis JP-10 undergoes. This is an area of active research.

5. Jet Engine Performance

Jet engine performance can be measured several different ways. The engine selected for fuel performance testing was the Williams International F-121 fanjet. Turbofans typically provide for more economical operation than turbojets. By accelerating a larger mass of air to a lower velocity, turbofans operate at a higher propulsive efficiency. [5] In order to provide baseline evaluation of the F-121, overall engine efficiency was the chosen metric to evaluate performance. Overall efficiency (η_o) is simple the product of propulsive and thermal efficiencies [6] as shown in equation 4.

$$\eta_o = \eta_{th} * \eta_p \qquad \text{eq 4}$$

Thermal efficiency is the ratio of kinetic energy rate addition to the propellant to the total energy consumption rate as shown in equation 5.

$$\eta_{th} = \frac{\dot{m}_a \left[(1+f)\left(\upsilon_e^2 / 2 \right) - \upsilon^2 / 2 \right]}{\dot{m}_f Q_R} \qquad \text{eq 5}$$

Where: $\dot{m}_f$ = mass flow rate of the fuel υ_e = exit velocity

$\dot{m}_a$ = mass flow rate of the air υ = inlet velocity

$f = \dot{m}_f / \dot{m}_a$ = fuel to air ratio   n= number of moles

$$Q_R = H_{prod} - H_{react} = \sum_j \left(n_j Q_{fj}\right)_{prod} - \sum_i \left(n_i Q_{fi}\right)_{react}$$

The equation for thermal efficiency then reduces to the one shown in equation 6.

$$\eta_{th} = \left(\frac{1}{fQ_R}\right)\left[(1+f)\left(\upsilon_e^2 / 2\right) - \upsilon^2 / 2\right] \qquad \text{eq 6}$$

The propulsive efficiency is the ratio of thrust power to the rate of production of propellant kinetic energy as shown in equation 7.

$$\eta_p = \frac{F_T \upsilon}{\dot{m}_a\left[(1+f)\left(\upsilon_e^2 / 2\right) - \upsilon^2 / 2\right]} \qquad \text{eq 7}$$

The thrust force is represented by F_T and can be found using equation 8.

$$F_T = \dot{m}_a\left[(1+f)\upsilon_e - \upsilon\right] + \left(p_e - p_a\right)A_e \qquad \text{eq 8}$$

Where: p_e = exit pressure A_e = exit cross sectional area

p_a = ambient pressure

For most air breathing engines, such as gas turbines, the overall fuel to air ratio (f) as well as the pressure term in the thrust equation are very small and can be neglected. Thus the overall equation for thermal efficiency reduces to a relationship dependent on velocity ratio and thermal efficiency, which is also dependent on velocity ratio, as shown in equations 9-11.

$$F_T \approx \dot{m}_a\left(\upsilon_e - \upsilon\right) \qquad \text{eq 9}$$

$$\eta_p \approx \frac{\left(\upsilon_e - \upsilon\right)\upsilon}{\upsilon_e^2 / 2 - \upsilon^2 / 2} \approx \frac{2\upsilon / \upsilon_e}{\left(1 + \upsilon / \upsilon_e\right)} \qquad \text{eq 10}$$

$$\eta_o = \eta_p \eta_{th} \approx \frac{F_T \upsilon}{\dot{m}_f Q_R} \approx 2\eta_{th}\left(\frac{\upsilon / \upsilon_e}{1 + \upsilon / \upsilon_e}\right) \qquad \text{eq 11}$$

Another key parameter which can help demonstrate performance gain and "is widely used as an experimental indicator of engine quality"[6] is thrust specific fuel consumption, TFSC. TFSC is inversely proportional to the range of an aircraft as shown in equation 12.

$$TSFC = \frac{\dot{m}_f}{F_T} \qquad \text{eq 12}$$

In turbojets and turbofans the exit pressure and ambient pressure are effectively equal, so equation 13 is valid.

$$TSFC = \frac{\dot{m}_f}{\dot{m}_a\left[(1+f)\upsilon_e - \upsilon\right]} \qquad \text{eq 13}$$

Typical values for TFSC in turbofan engines range from 0.3-0.5 $lb / lb_f \cdot hr$.[6] Based on the above relationships, in order to properly characterize gas engine performance, $\dot{m}_f$, $\dot{m}_a$, υ_e, υ, p_a and Q_R need to be measured directly or derived indirectly with a high degree of accuracy.

E. PROGRAM GOALS

The overall goals for this program were to characterize suitable nanocatalysts and their potential for increased gas turbine engine performance. Laboratory test have demonstrated the possibility for better performance. In order to validate the theories and test results, full scale testing on an actual gas turbine engine is desired.

F. RESEARCH OBJECTIVES

The objectives for this thesis were fairly straightforward. The studies performed on a chemistry laboratory level needed to be validated on a hardware level. The most logical hardware choice was an actual gas turbine engine. A suitable gas turbine had to be found and acquired. A test stand needed to be developed with the capabilities of measuring performance of a gas turbine engine and the capability of switching fuels on the fly. Then the site and required connections for operation had to be researched and constructed. A standard operating procedure for the safe and proper operation of the selected engine then had to be developed. The next objective was to operate the engine under self-sustaining conditions. In addition, determination of the range of operating conditions and capabilities for the engine had to be performed. The baseline performance of the engine operating without the nanocatalysts fuels was required for comparison analysis and test stand qualification. This thesis research should provide a working test stand suitable for nanocatalysts testing and to determine its effectiveness in enhancing gas turbine engine performance.

II. JET ENGINE TEST STAND DEVELOPMENT

A. ENGINE SELECTION/ACQUISITION

The engine selected for fuel performance testing was the Williams International F-121 fanjet. First flown in 1984, the F-121 fanjet was originally designed to propel the AGM-136A Tacit Rainbow unmanned aircraft. This engine was designed as a one way engine with a long shelf life and short operational life expectancy. Several of these engines were being used as fuel performance test engines at the Naval Air Warfare Center, Weapons Division (NAWCWPNS) in China Lake, California. The Naval Postgraduate School (NPS) acquired four engines from NAWCWPNS for the purposes of conducting test on the fuel performance benefits resulting from the addition of soluble nanocatalysts. There were several alternative engines that could have also performed as a test engine. However, due to low cost and availability of the engines as well as the history of fuel testing already having been performed on the F-121, it was the best choice. Another benefit from using the F-121 was that all of the prior operating procedures and test stand setup data from NAWCWPNS were made available to NPS. This saved valuable time and effort when initially building the new test stand. An illustration of the F-121 [7] engine is shown in Figure 4.

Figure 4. Illustration of Williams International F-121 Fanjet

The primary concern with utilizing the F-121 is the age of the engines. Even though the engines were designed for a long shelf life, the use of grease packed bearings in a 20 year old engine introduces an uncertainty into the continued operation of the engines. Another concern was the lack of original manufacturing technical data available on these engines. The AGM-136A Tacit Rainbow unmanned aircraft started as a classified program. This meant that all technical manuals and data was handed over to the government and controlled at the time of hardware delivery. In order to learn how to properly operate these engines, several experimental operations were necessary. These tests were performed with knowledge of NAWCWPNS operating procedures and test results.

1. F-121 Fanjet Specifications

The F-121 engine is a single shaft turbofan gas turbine propulsion engine. It has a single-stage axial fan and a six-stage axial compressor driven by a two-stage axial turbine. This engine falls into the 5 lb/sec airflow size class. Fuel in this engine is delivered to a Turboméca Piméné type combustor [8], shown in Figure 5, by using 3 slinger type nozzles installed inside the turbine shaft. Grease-packed bearings support all the rotating components on a single shaft.

Figure 5. Illustration of the Turboméca Piméné type combustor inside the F-121 fanjet engine.

The published technical data for the F-121 fanjet is shown in Table 1. [7] Additional important limits were noted for maximum exhaust temperature of 1350ºF and maximum bearing temperature of 200ºF. Existing k-type thermocouples connections for measuring these limiting parameters were already installed on the test engines provided to NPS. Pressure sensing ports and leads for rpm indications were also already installed on the test engines.

TABLE 1. WILLIAMS INTERNATIONAL F-121 FANJET TECHNICAL DATA.

MODEL	F-121
LENGTH	40 in
DIAMETER	5 ½ in
COMPRESSOR	multi-stage axial
TURBINE	2-stage axial
THRUST	~70 lbs at 45,000 rpm
WEIGHT	49 lbs
BYPASS AIR RATIO	1.7:1

B. TEST SITE SELECTION

The engine and test stand were located in a test shed separate from the main facility in order to provide a dedicated test area as well as prevent exhaust gases from entering closed spaces. The exhaust from the test shed is directed straight outside into the open atmosphere. The test shed location was placed in the vicinity of test cell #1 due to the proximity to main gas lines. These gas lines would supply the needed connections to the test stand. This location also was desirable due to the location of a solid wall which could be used to isolate pressurized gas tanks and personnel from the operating engine for safety purposes.

Figure 6. Illustration of Test Shed

C. THRUST STAND

The thrust stand used was provided by NAWCWPNS along with the engines. The stand provided rigid support to the engine and was mounted directly to the concrete floor of the test shed. While the thrust stand was capable of accommodating a thrust measurement cell, for nanocatalysts fuel testing it was not utilized. An illustration of the test stand is included in Figure 7.

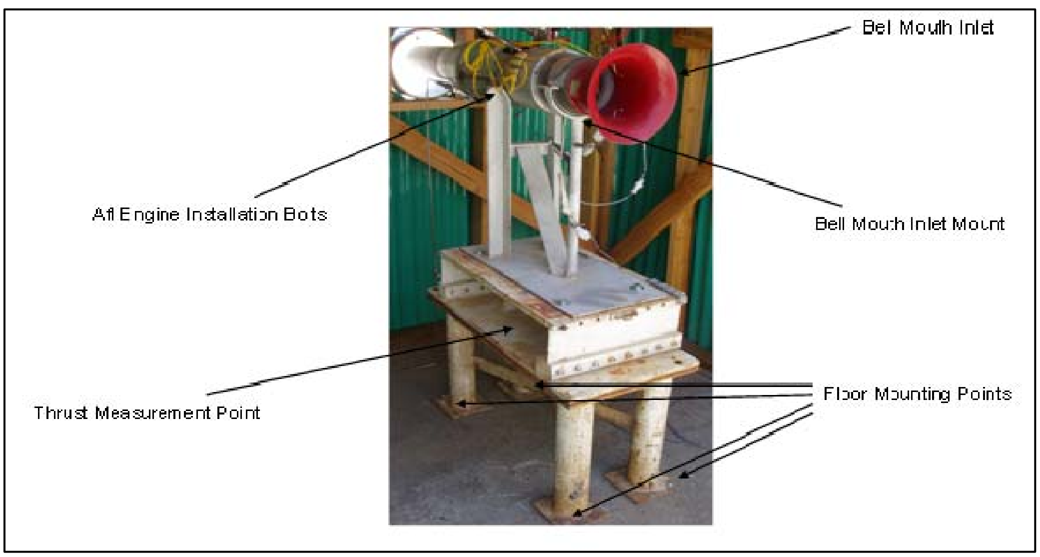


Figure 7. Illustration of Engine and Test Stand

1. Mechanical

One of the main efforts associated with readying the test stand was the design and completion of all the mechanical systems needed to support the operation of the F-121. The first step was to identify all the required support gases and plumb the required tubing and fittings out to the test shed. Once deciding on the required gases, a control panel for gases was built and mounted on the inside wall isolated from the test cell as shown in Figure 8. This board also provided a central location for manual control and isolation of all gases as well as remote pressure indications. Manual control and isolation was achieved by the use of air operated ball valves as illustrated in Figure 10. Also for safety purposes a gas line color coding system was decided upon and the lines were marked with the appropriate colored tape at all visual inspection points along each line. The color codes use are shown in Figure 9.

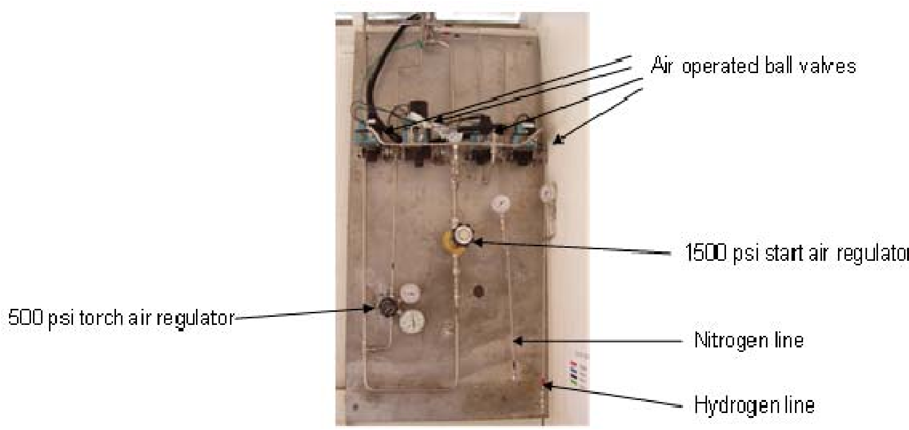


Figure 8. Illustration of Gas Control Board

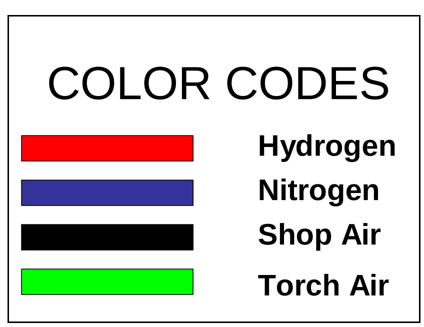


Figure 9. Gas Line Color Codes

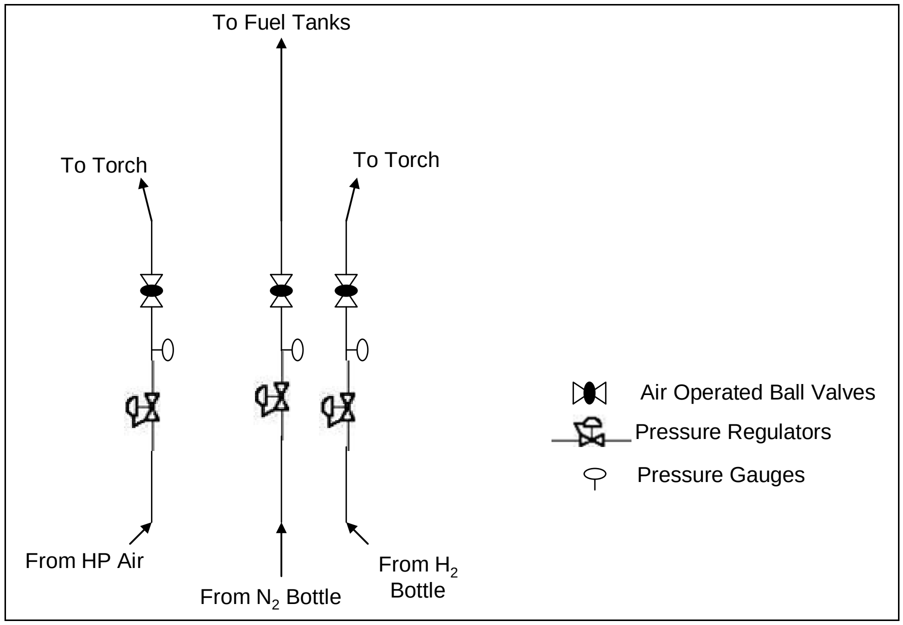


Figure 10. Schematic of Gas Control Board

The next logical step was to take the identified gases and build the required engine's auxiliary systems. The ignition system was one of the critical systems identified. The original design called for a solid fueled canister used to generate high temperature products that were rapidly introduced into the combustor. During standard operational conditions this was a very good choice to make sure ignition was achieved. However in the laboratory, more than one ignition event was required. Therefore a hydrogen-air torch was implemented. The torch design chosen to achieve engine light off was a hydrogen-air mixture system utilizing a spark plug. A stand alone hydrogen supply bottle was used in conjunction with a 500 psi regulator to achieve the desired hydrogen pressure to the torch system. High pressure air supplied through a separate 500 psi regulator was used to achieve the desired air pressure the torch system. The torch gases' supply system was designed to provide pressurized gases up to remotely operated ball valves that served as the system's supply valves. Once these were opened, the gas supply lines would pressurize up to a set of solenoid control valves. Downstream of the solenoid valves, both air and hydrogen mass flow rates were metered through the use of choked orifices. Prior to entering the engine, check valves were put in line to prevent flashback of the combustion products. The design called for the gases to then enter the torch body, where they mixed and were ignited using a conventional spark system. The spark was produced by a DC transformer which was turn on for a few seconds at a time. Without the spark the torch gases would not remain lit in order to provide fail-safe operational characteristics. The system was designed so that the solenoid valves and the igniter operated simultaneously in order to ensure proper firing timing. Illustrations of the torch system and igniter transformer board are shown in Figures 11 and 12. A schematic of the overall torch system is shown in Figure 13.

Figure 11. Ignition System Illustration

Figure 12. Igniter Transformer Illustration

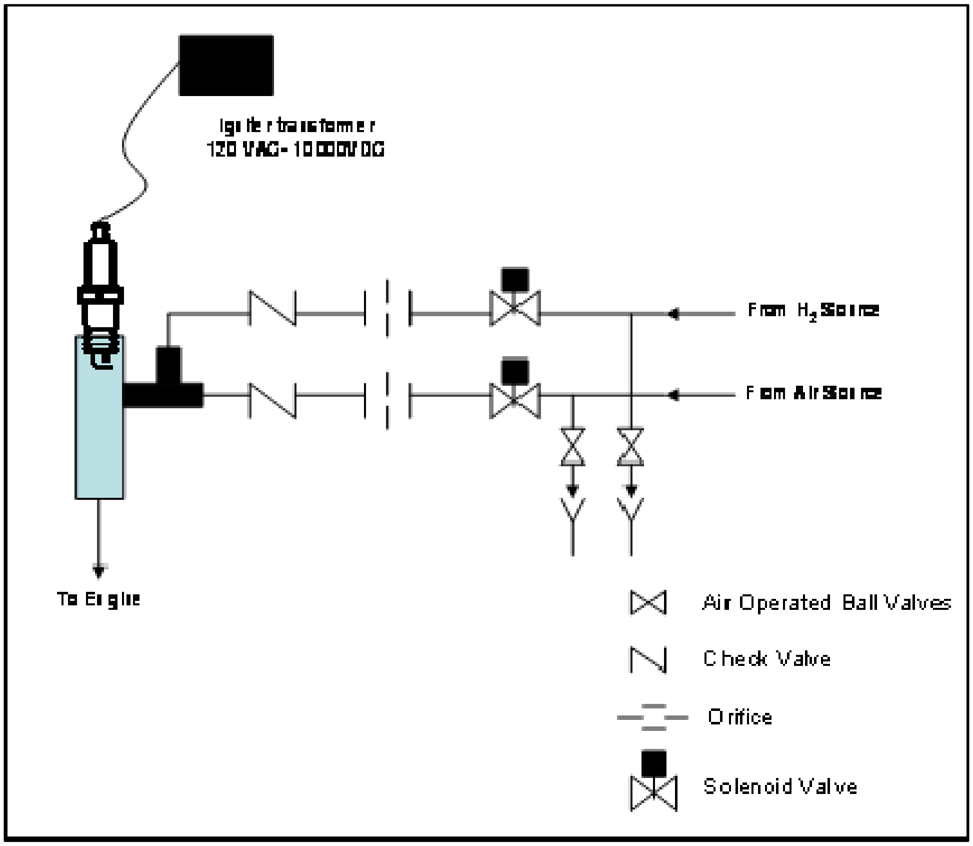


Figure 13. Ignition System Schematic

The torch system calibrated chokes were sized to achieve an adequate fuel-air equivalence ratio (φ). An φ = 2.0 was chosen to ensure proper torch capacity and temperature based on the chemical equation and mathematical relationships shown equations 14-17. Equation 14, shows the stoichiometric chemical balance and assumes complete combustion without any dissociation. In order to obtain an equivalence ratio of 2.0, two moles of hydrogen are required instead of one shown in equation 14. [9]

$$H_2 + \frac{1}{2}\left(O_2 + 3.76N_2\right) \rightarrow H_2O + \frac{3.76}{2}N_2 \qquad \text{eq 14}$$

$$\varphi = \left(\frac{\frac{f}{a}_{ACT}}{\frac{f}{a}_{stoich}} \right) \qquad \text{eq 15}$$

$$\frac{f}{a}_{stoich} = \frac{2}{\frac{1}{2}\left(32+3.76*28\right)} = \frac{1}{34.32} = 0.029 \qquad \text{eq 16}$$

$$\frac{f}{a}_{ACT} = \frac{2}{34.32} = 0.058 \qquad \text{eq 17}$$

Choke sizes of 0.020 inches in diameter for hydrogen and 0.0425 inches in diameter for air yielded the desired mass flow rates and allowed us to set identical supply pressures to the air and hydrogen gas supply systems and obtain a $\varphi = 2$. All gas lines utilized in the torch system were made of 1/4″ stainless steel tubing with Swagelok connections. The vent valves in the torch system were used to bleed pressure off the system as a safety procedure whenever work on the engine was required between tests and when shutting down and securing the test stand. The hydrogen vent valve was directed outside of the test shed to prevent any explosive hazards from hydrogen buildup. Of the four engines acquired, two separate variants of the engine were received. One of the minor differences between the two variants was the use of a different torch fitting. Three torch bodies were manufactured for the two different variant engines.

The engine's main fuel system also required gas delivery mechanism. A nitrogen pressurized fuel tank was selected to supply and deliver main fuel to the engine. Inert nitrogen gas (N_2) was selected to provide the required head pressures to the fuel tanks for safety purposes. The decided design included a stand alone pressurized nitrogen bottle connected through a 500 psi regulator. Initially a hand regulator seemed sufficient, however future designs may benefit from a computer controlled PID regulator in order to match fuel delivery to engine operation. The required nitrogen pressure was delivered to the fuel tanks via an air operated ball valve and 1/4″ stainless steel tubing with Swagelok connections.

Shop-air was also utilized as an auxiliary gas system. Electro-pneumatically operated ball valves were used at both the remote gas control board as well as locally inside the test shed. In order to provide the actuating medium for each remotely controlled air operated ball valve, control lines were connected from the buildings main low pressure (80 psi) shop air lines. Tapping off the buildings main shop air lines with 1/4in stainless steel tubing and Swagelok connections along with a manually operated ball valve provided a means of isolation for the entire shop-air system when not in use.

2. Electrical

The electrical system requirements called for the use of 110VAC and 28VDC. The 110VAC power connections were used for control power to electro-pneumatically operated ball valves, power to the igniter transformer, input power to the 28VDC power supply and power for the data acquisition system. The 28VDC power was used for control power for the torch solenoids and as the excitation source for all pressure transducers. Two main control boards were used for the wiring of all the electrical components. A terminal strip was located in a remote electrical box to provide ease of interface between the 110VAC supplied from the main building and the co-located data acquisition system. The second terminal strip was placed locally inside the test shed to provide 28VDC excitation source connections for the locally located pressure transducers. This strip was mounted on grounded metal board along with the 28VDC power supply.

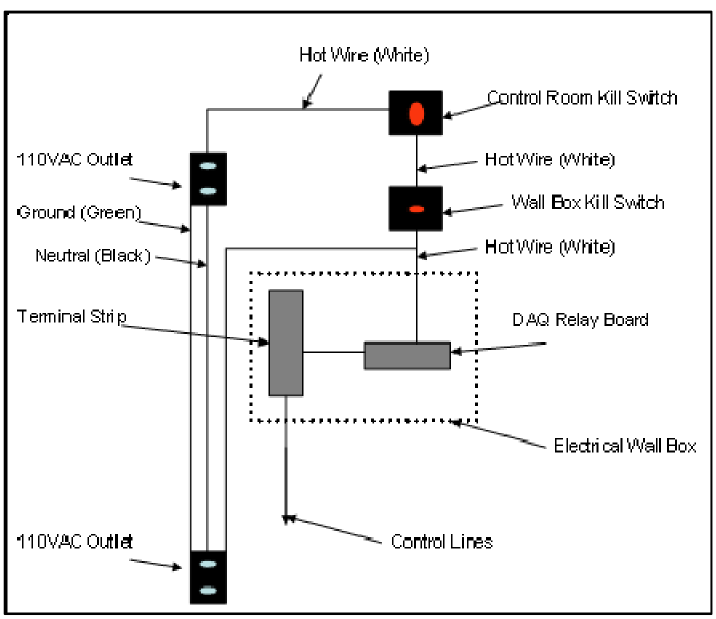


Figure 14. Remote electrical board schematic

The electrical wiring for 110VAC was designed to support the myriad of auxiliary systems; however throughout the design process regards to personnel safety was the primary driver. Two kill switches which would completely shut down the engine were placed in the 110 VAC lines. The switches were located in the main building where all test were controlled from and remotely at the electrical terminal box for outside isolation access. Either kill switch independently could disable the entire 110VAC circuitry. The 110 VAC wiring design also included the use of two outlets to ensure positive control over the electrical state of the system. When testing was not being conducted a 110 VAC outlet was unplugged in the main building to de-energize the entire system. When partial testing was being performed, an outlet in the test shed was utilized to allow partial de-energizing of the system.

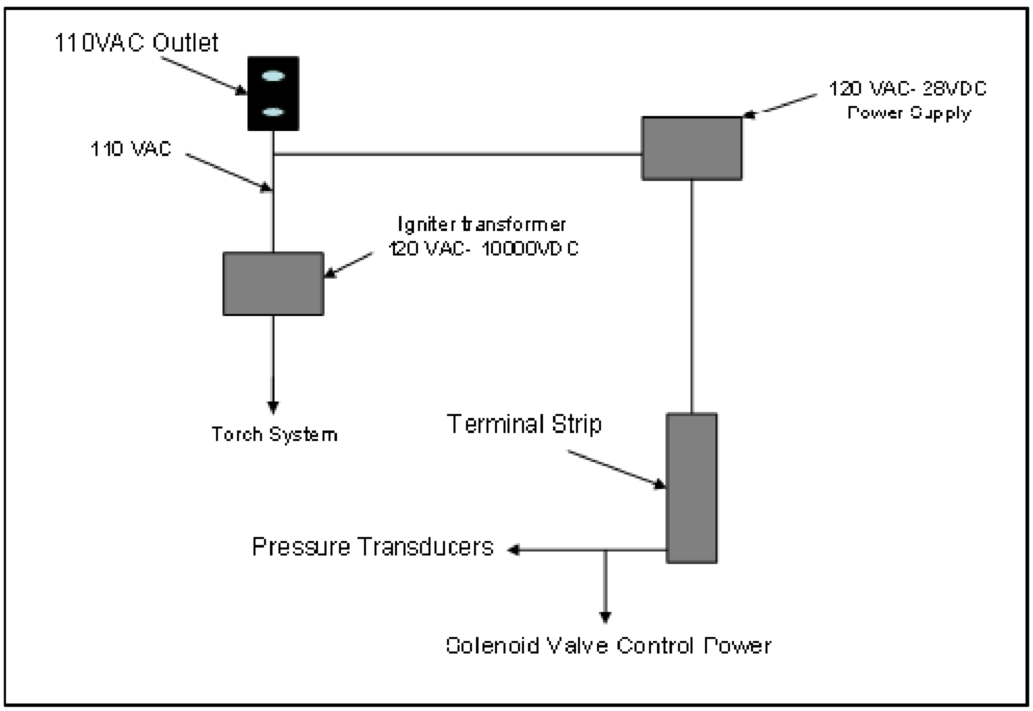


Figure 15. Local Electrical Board Schematic

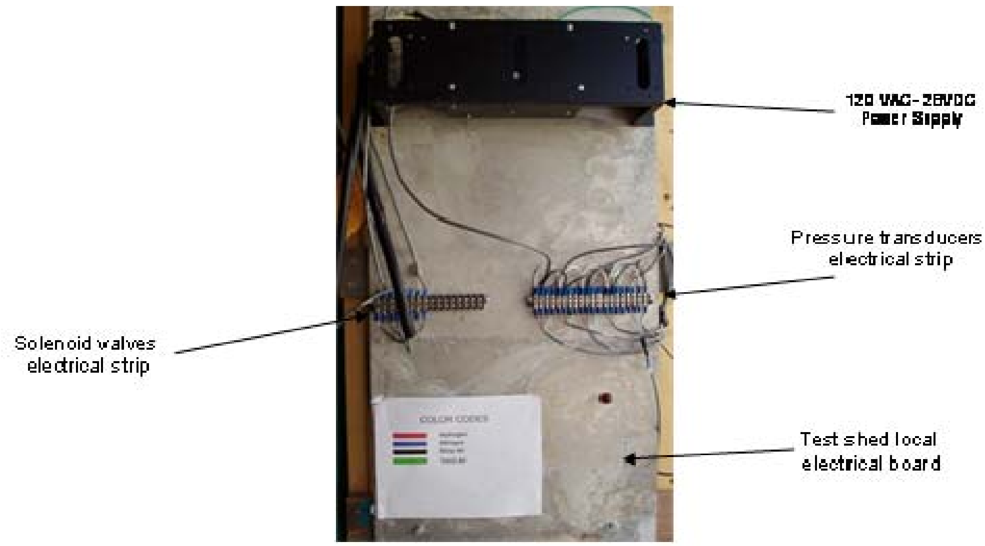


Figure 16. Local Electrical Board Illustration

D. FUEL SYSTEM

The fuel system was designed to operate as a pressurized head system. By applying a head pressure to the fuel tanks along with the use of a flow venturi on the tank outlet, the desired flow rates were achieved. The use of two separate fuel tanks with the capability to shift between tanks during operation was required in order to gather accurate comparison data between the base fuel and the fuel with the soluble nanocatalysts. The two high pressure tanks chosen had a capacity of three gallons and one gallon respectively with a maximum operating pressure of 1800psi and hydrostatic test pressure of 3000psi for each. Nitrogen was selected as the pressurizing gas in order to prevent any flammable gas mixture inside the tank. In addition, 7μm filters were placed in each line to ensure no particulates entered the fuel delivery stream to the engine. A simplified schematic of the fuel system is shown in Figure 17.

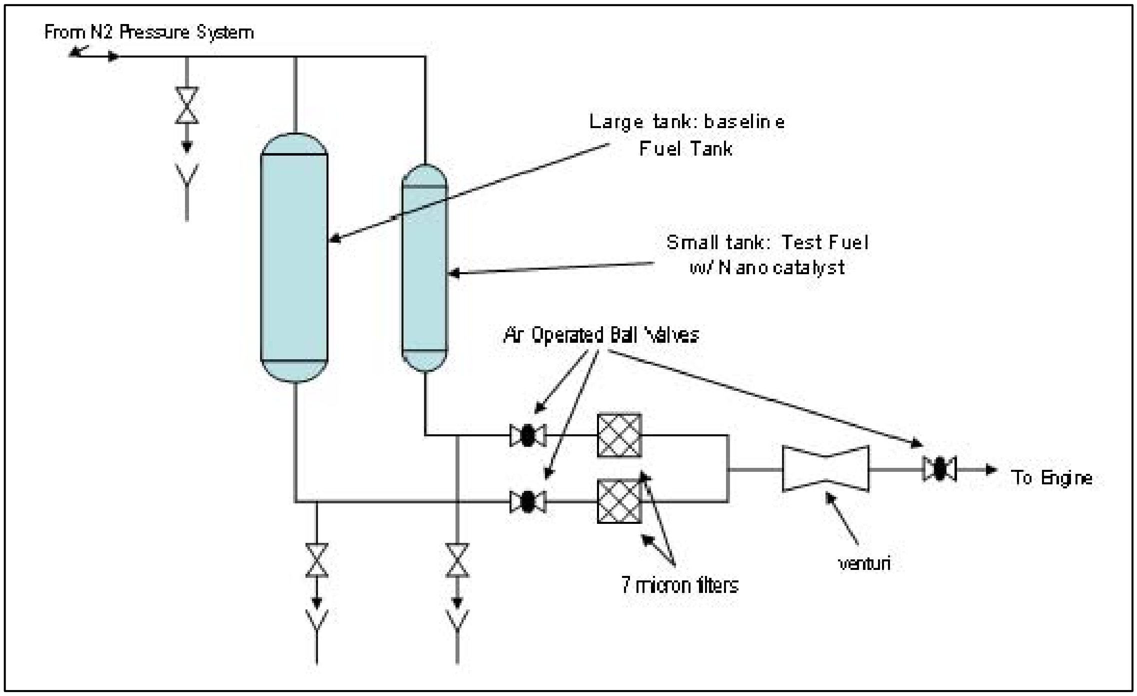


Figure 17. Fuel System Schematic

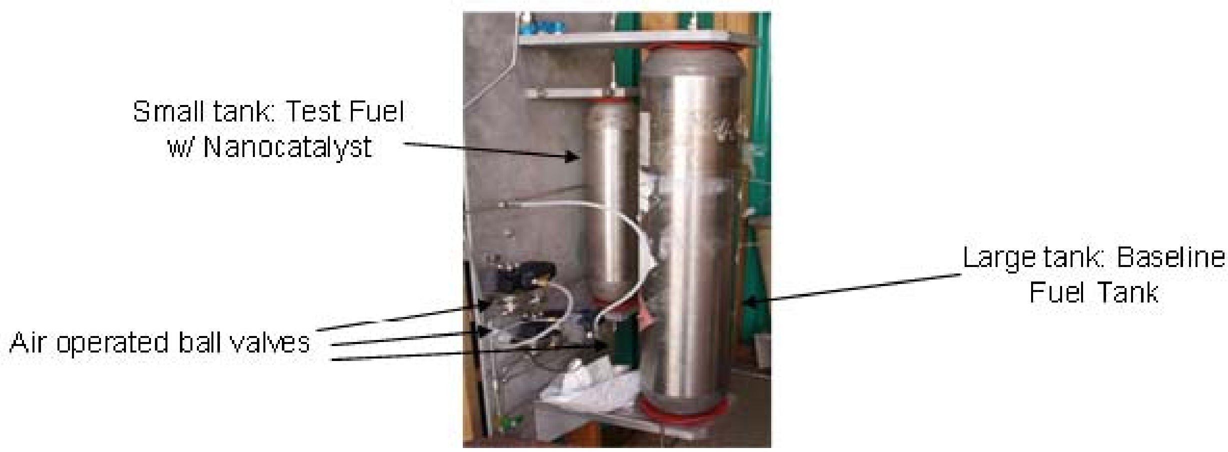


Figure 18. Fuel System Illustration

The flow venturi used for initial engine light off testing had a 0.012in diameter throat. The calibration curves for Kerosene flow rates and corresponding head pressures is shown in Figure 18. Eight separate data points were found and a linear fit was utilized to find an approximate flow rate curve. According to NAWCWPNS data, the F-121 engine required fuel flow rates of approximately 3 g/s for engine light off speeds of less than 16,000 rpms.

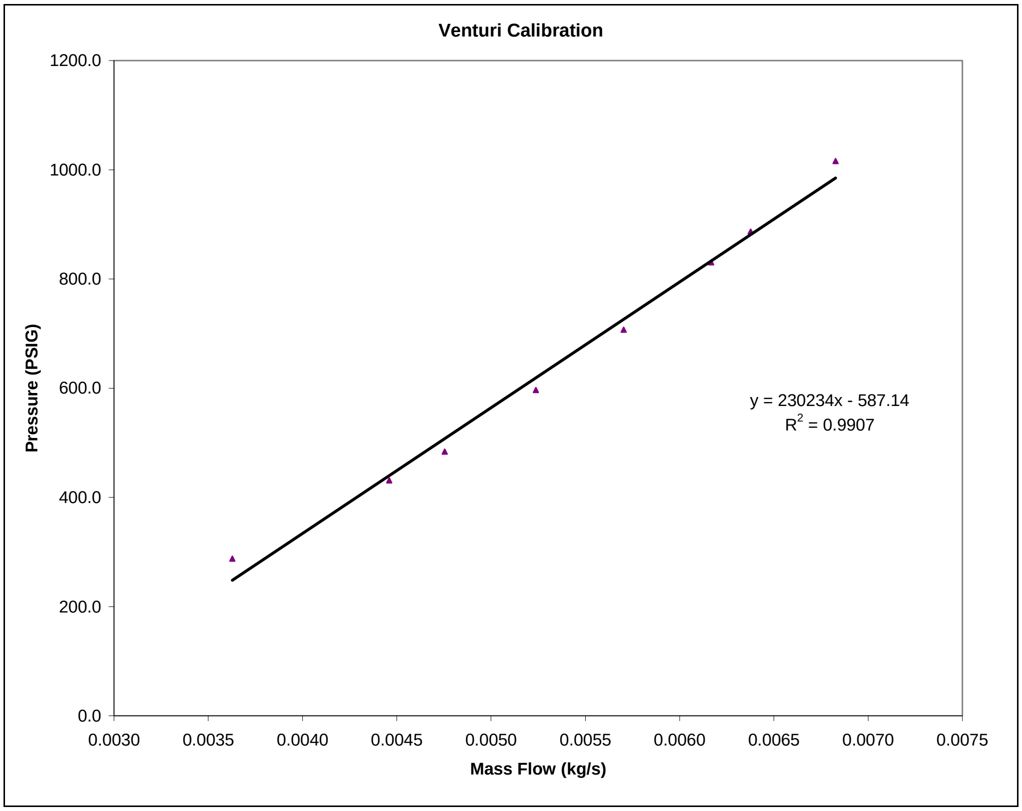


Figure 19. Venturi Calibration Curve for Kerosene

E. AIR SYSTEM

The F-121 was originally designed as an air launched gas turbine engine. [10] In order to achieve the required fuel to air ratios for engine light off, air delivery systems were required. The F-121 test engines received from NAWCWPNS had a connection line leading into the turbine blades in the aft part of the engine at a 90º angle. This connection was for start air on the engine used to achieve the desired shaft revolutions per minute (rpms) for engine light off. The high-pressure air jet impinges onto the turbine blades, thus transferring its kinetic energy to the turbine.

The start air system was constructed by tapping off of the buildings main high pressure (HP) air supply. Two manually operated ball valves provided isolation from the HP system when the system was not in use. When the test stand was in use, HP air was delivered to the engine through a 1500 psi hand regulator and air operated ball valve on the gas control board via 1/2in stainless steel tubing and Swagelok connections. The start air was designed to be able to deliver a range of pressures based on the desired rpms of the engine. Figure 20 shows the relationship engine rpms as a function of start air pressure for F-121 engine number 206-1A.

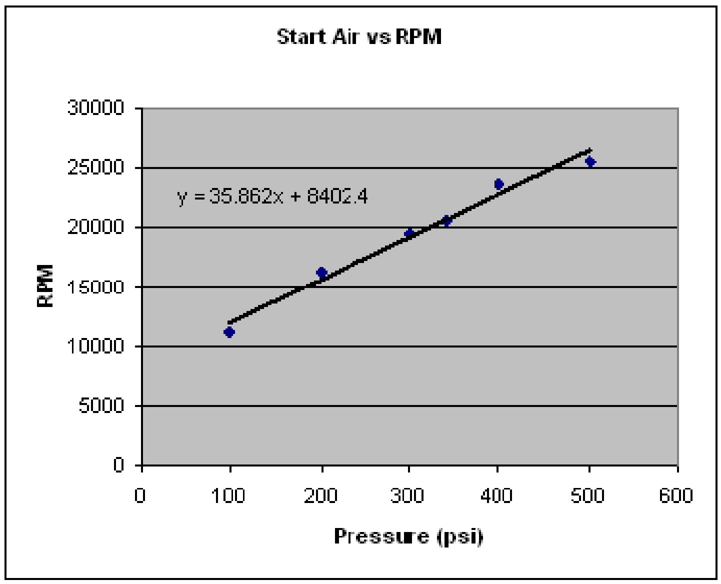


Figure 20. Start Air pressure vs Engine Speed

An additional air system was set-up in order to ensure proper air ingestion through the core of the engine and combustor to sustain engine light off and operation. This secondary system was used to provide a ram air effect at the entrance of the engine - at the bell mouth inlet.

The ram air system for the 5 lb/sec airflow class F-121 engine was designed to deliver the desired air to achieve engine light off. The ram air system was constructed by also tapping off of the buildings main high pressure (HP) air supply. The supply of ram air had a solenoid operated regulating valve in line to provide a remotely controlled means of throttling system pressure to the ram air piping. This desired pressure along with the use of a calibrated 1/2in diameter choked orifice allowed for the fine control of air flow rates to the engine. The ram air piping consisted of 2in schedule 80 stainless steel piping leading up to 2.5 feet from the engine's bell mouth inlet as illustrated in Figure 24. The design included the use of a coupling in the piping to allow for ease of fine air direction adjustments. Figure 21 illustrates the relationship between resultant ram air flow rates (in lbm/sec) as a function of HP air supply pressure (in psi).

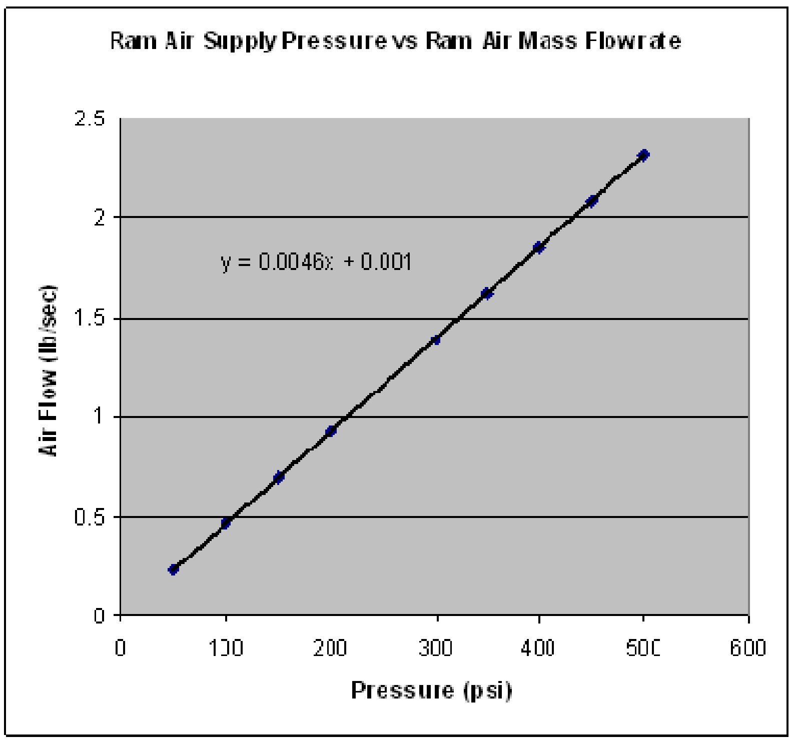


Figure 21. Ram Air Supply Pressure vs Mass Flow Rate Utilizing a 1/2″ In-Line Orifice

Figure 22 shows the relationship experimentally found between ram air flow rates and engine rpms for F-121 engine number 206-1A.

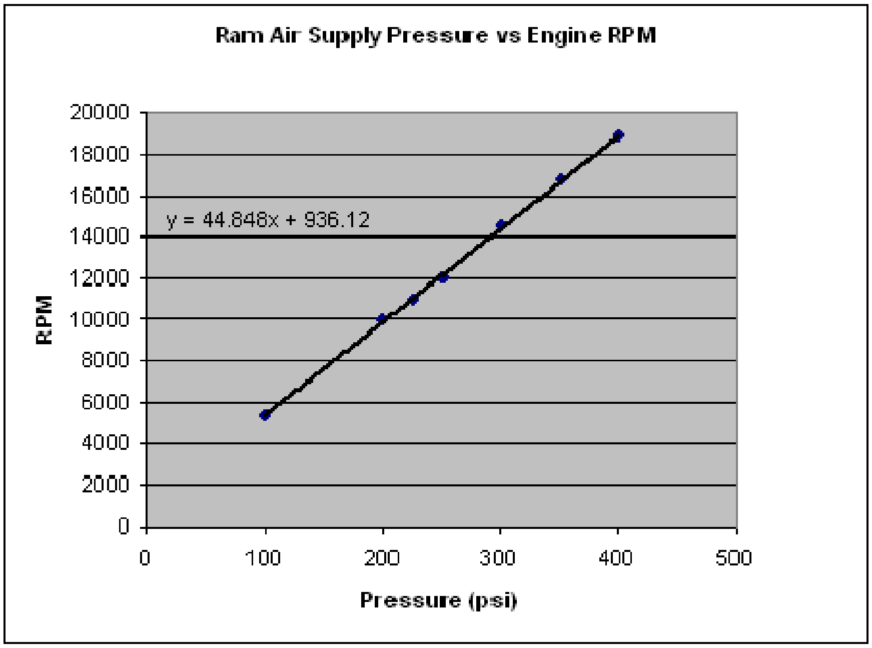


Figure 22. Engine RPM versus Ram Air Supply Pressure

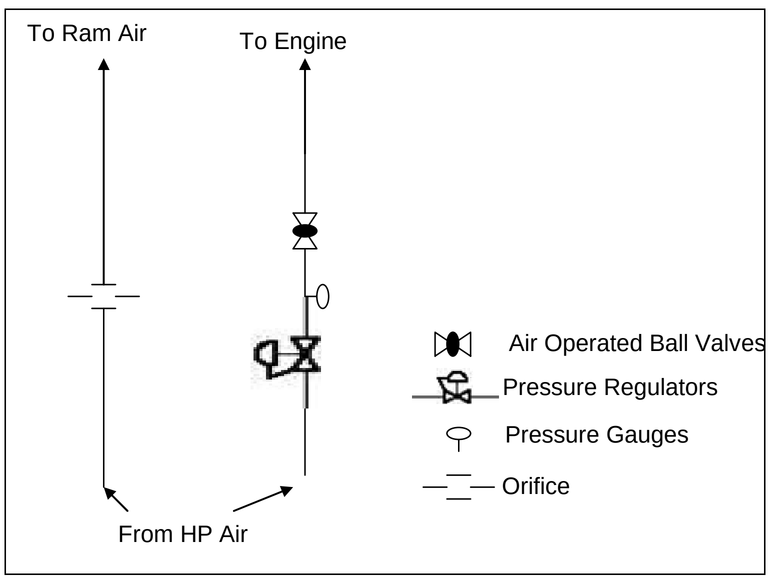


Figure 23. Air System Schematic

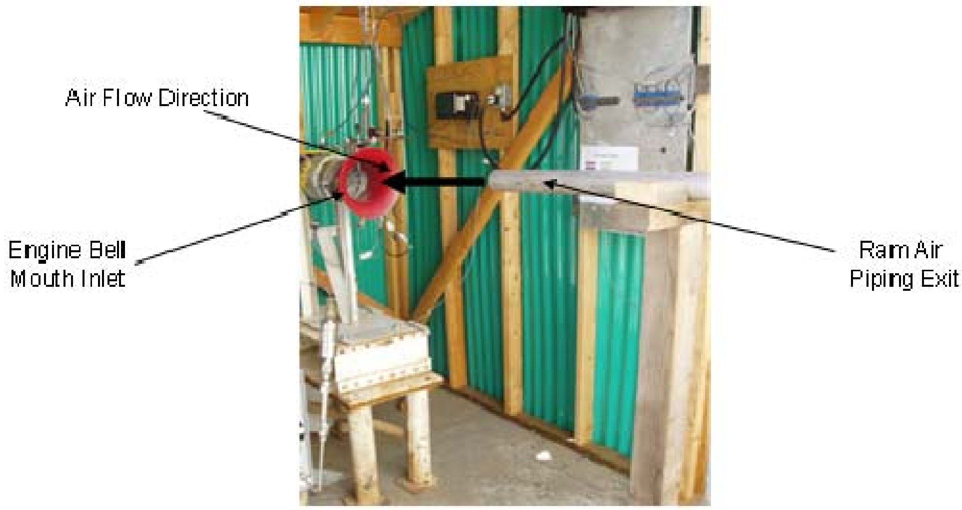


Figure 24. Ram Air Inlet to Bell Mouth Illustration

F. DATA ACQUISITION AND CONTROL

The first step in designing the Data Acquisition and Control (DAQ) system was to determine what measurements and controls were required. Based on the selected metrics for jet engine performance measurements, $\dot{m}_f$, $\dot{m}_a$, υ_e, υ, p_a and Q_R were determined as parameters which needed to be measured directly or derived indirectly with a high degree of accuracy. In order to measure $\dot{m}_f$, the fuel tank head pressure along with a calibrated venturi was required for accurate measurement. To achieve required $\dot{m}_a$ measurements, differential pressure (ΔP) between total pressure (p_t) and static pressure (p) was required. This ΔP is proportional to the velocity of the air squared $(\upsilon)^2$. [11] In turn, the velocity of the air along with air temperature and flow area cross section were required to determine $\dot{m}_a$. The exit velocity was indirectly determined by knowing exhaust gas temperature and air mass flow rate.

The required engine sensors to accurately characterize engine performance and monitor engine operation included bearing temperatures, exhaust gas temperatures, ambient temperature, total pressure, static pressure, ambient pressure and fuel tank head pressure. Auxiliary sensors (not-on-engine) used to ensure proper engine operation included start air supply pressure, ram air supply pressure and torch gas supply pressures. Control signals were required for the actuation of air operated ball valves, torch solenoid valves and the ignition transformer. To achieve the required signals and controls interface a National Instruments Compact DAQ Chassis [12] was acquired.

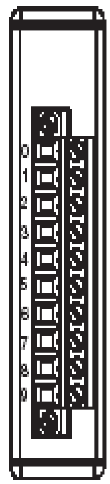
Chassis	Module Slots	Connection to PC	Channels per Chassis	Analog Resolution	Analog Sampling Rate	Analog Throughput
cDAQ-9172	8	Hi-Speed USB	Up to 256 analog input, or 32 analog output, or 64 digital I/O	Up to 24 bits	Up to 400 kS/s per module	3.2 MS/s total throughput

Figure 25. NI cDAQ-9172 chassis and data

The chassis was mounted to the outside wall in an electrical box for weather protection and safety. Five modules were utilized to enable the required system interfaces. An illustration of the electrical box internals is shown in Figure 26. Two NI-9211 modules were used to provide the means of required temperature measurements

Figure 26. Electrical box internals

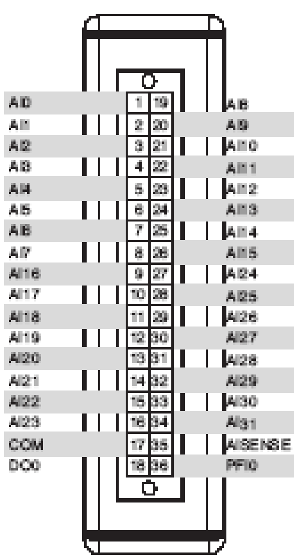
The temperature sensor interface configuration with the DAQ module is shown in Figure 27.

Module	Terminal	Signal
	0	TC0+
	1	TC0–
	2	TC1+
	3	TC1–
	4	TC2+
	5	TC2–
	6	TC3+
	7	TC3–
	8	No connection
	9	Common (COM)

DAQ NI 9211 (QTY 2)

Figure 27. DAQ Temperature Module Setup

One NI-9205 module was used to provide the interface for pressure signals. The pressure sensor interface configuration with the DAQ module is shown in Figure 28.

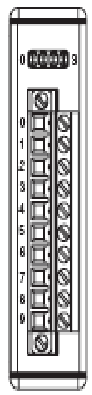


Channel	Signal+	Signal–	Channel	Signal+	Signal–
0	AI0	AI8	16	AI16	AI24
1	AI1	AI9	17	AI17	AI25
2	AI2	AI10	18	AI18	AI26
3	AI3	AI11	19	AI19	AI27
4	AI4	AI12	20	AI20	AI28
5	AI5	AI13	21	AI21	AI29
6	AI6	AI14	22	AI22	AI30
7	AI7	AI15	23	AI23	AI31

DAQ NI 9205

Figure 28. DAQ Pressure Module Setup

Two NI-9481 modules were used to provide control signals to the required equipment. The control interface configuration with the DAQ module is shown in Figure 29.



Module	Terminal	Signal
	0	CH0a
	1	CH0b
	2	CH1a
	3	CH1b
	4	CH2a
	5	CH2b
	6	CH3a
	7	CH3b
	8	No connection
	9	No connection

DAQ NI 9481 (QTY 2)

Figure 29. DAQ Control Signal Module Setup

1. Instrumentation

The required temperature interfaces with the DAQ module are shown in Table 2. K type thermocouples were used to measure each temperature parameter. At the start of each test session temperature signals were compared to known atmospheric temperature to ensure proper readings.

TABLE 2. DAQ NI 9211 parameter wiring

Upper Module		
TC0+/-	Bearing 1A Temp	Wire T1
TC1+/-	Bearing 1B Temp	Wire T2
TC2+/-	Bearing 1C Temp	Wire T3
TC3+/-	Exhaust Gas Temp1	Wire T4
Lower Module		
TC0+/-	Exhaust Gas Temp2	Wire T5
TC1+/-	Exhaust Gas Temp3	Wire T6
TC2+/-	Spare	Wire T7
TC3+/-	Spare	Wire T8

DAQ NI 9211 (QTY 2)

Required control signals to remotely operated valves and for the ignition system with the corresponding wiring interfaces to the DAQ module are shown in Table 3. Each component was cycled and observed for desired operation to ensure proper wiring.

TABLE 3. DAQ NI 9481 parameter wiring

Upper Module		
Channel 0	Torch Air Ball Vlv	Wire 2C-5
Channel 1	HP Air Ball Vlv	Wire 2C-6
Channel 2	N2 Ball Vlv	Wire 2C-7
Channel 3	H2 Ball Vlv	Wire 2C-8
Lower Module		
Channel 0	Fuel Tank Ball Vlv	Wire 2C-1
Channel 1	Torch Solenoids	Wire 2C-2
Channel 2	Ignition Box	Wire 2C-3
Channel 3	Spare	Wire 2C-4

DAQ NI 9481 (QTY 2)

The required interfaces for the pressure measurements and rpm signal with the DAQ module are shown in Table 4.

TABLE 4. DAQ NI 9205 parameter wiring

Channel 0	Stagnation Press	Wire P1(r,bk)
Channel 1	Dynamic Press	Wire P1(g,w)
Channel 2	Chamber Press	Wire P2(r,bk)
Channel 3	Fuel Head Press	Wire P2(g,w)
Channel 4	RPMs	Wire P3(r,bk)

DAQ NI 9205

Each pressure transducer was calibrated with the use of a highly accurate HEISE gauge.

2. Software

The NI DAQ modules interfaced with National Instruments LabVIEW 8.0 software. LabVIEW provided a means for software interface to control test hardware. LabVIEW also provided the interface for sensor detection and measurement as well as data recording and storage. A program VI was designed in LabVIEW 8.0 to control the test stand. A graphical user interface (GUI) provided controls for all test hardware as well as real time parameter measurement readings.

The LabVIEW program was designed to take the input signals to the DAQ chassis and provide appropriate outputs. Each temperature and pressure signal was input and controlled through a DAQ assistant block. This block provided for selection of data acquisition rates and control of where each input signal was sent inside the program. The temperature and pressure signals were demuxed and individually manipulated. The individual signals were calibrated and sent to selected output graphs or numerical indicators. The design also provided desired control output signals for remotely operated valves. Switches were designed for control signals using logic inputs in the LabVIEW program. Illustrations of the LabVIEW design program and GUI are included in Appendix A. All data was taken at 1kHz rate, and then every 100 data points were averaged which produced data recorded at 10Hz rate.

THIS PAGE INTENTIONALLY LEFT BLANK

III. RESULTS

A. LIGHTING OFF TEST

Due to the lack of manufacturer technical documentation, several iterations of experimental configurations were required prior to successful engine light off and self sustaining operation. The first difficulty encountered was the proper connection points for fuels and air. Engine number 206-1A, which had undergone previous testing, was dismantled after some basic operational data was found to provide a better understanding of the engine internals specific to this model. The basic data acquired was typical engine rpm for various supply pressures of ram air and start air. The information gathered from inspection of the engine internals was invaluable. The specific type of combustor used was identified. Visual analysis of the combustor resulted in confirmation of air and fuel flow paths and connections. Connection points for sensors and supply gases were also confirmed.

The first configuration tried was an attempt to replicate the test set up used by NAWCWPNS. This configuration included using start air feeding into the turbine and ram air into the bell mouth to achieve approximately 12,000-14,000 rpm. Fuel supply of 3 g/s at engine speeds of up to 16,000rpm was recommended by the NAWCWPNS test documentation. To provide a scenario more conducive for light off, Coleman Fuel was used. After light off and self sustaining operation was noted at NAWCWPNS, the compressor bleed valve was closed and start air was secured. Attempts to replicate this test proved unsuccessful. While light off was achieved with Coleman fuel, it was found that run temperatures were too high and start air temperatures were too low. The start air supply used at the NPS rocket lab undergoes a significant pressure drop from 2500 psi to supply pressure. The corresponding temperature drop caused the casing around the turbine to contract. The high temperatures seen by the core of the turbine blades caused expansion that resulted in excessive casing rubbing. These high temperatures were also an indication that the selected fuel flow rates were causing a fuel rich condition. A three to one mixture of Kerosene and Coleman Fuel was then tried in an effort to lower exhaust gas temperatures (EGTs). EGTs remained higher than expected and still resulted in an undesirable thermal gradient across the turbine section.

The next configuration tried was based on the knowledge of the original engine design application. As a designed air launched engine, ram air alone was provided to attempt to achieve design air flow rates and target engine speed of approximately 15,000 rpm. Very low fuel flow rates of Kerosene were initially used with the idea of increasing fuel flow rates incrementally until engine light off was achieved. This was done to ensure that lean fuel conditions and subsequent lower exhaust gas temperatures were achieved during light off. The compressor bleed port was shut off for this configuration. At lower than expected fuel flow rates, engine light off and steady state self sustaining operations were achieved with acceptable EGTs. The first successful light off was achieved with a kerosene fuel head pressure of 60 psi and ram air supply pressure of 300 psi. This resulted in a steady state EGT of approximately 1,000°F and a maximum of 29,800 rpms as shown in Figure 30. At the end of the test, ram air was secured to test the engines ability to ingest air. The resulting temperature spike before fuel supply was isolated confirmed the need for sustained supply of ram air for proper engine operation. The data acquisition system was set up to take data at 1 kHz and averages every 100 data points, thus resulting in an effective data rate of 10 data points per second (10 Hz). In this manner, each data point represents 0.1 sec.

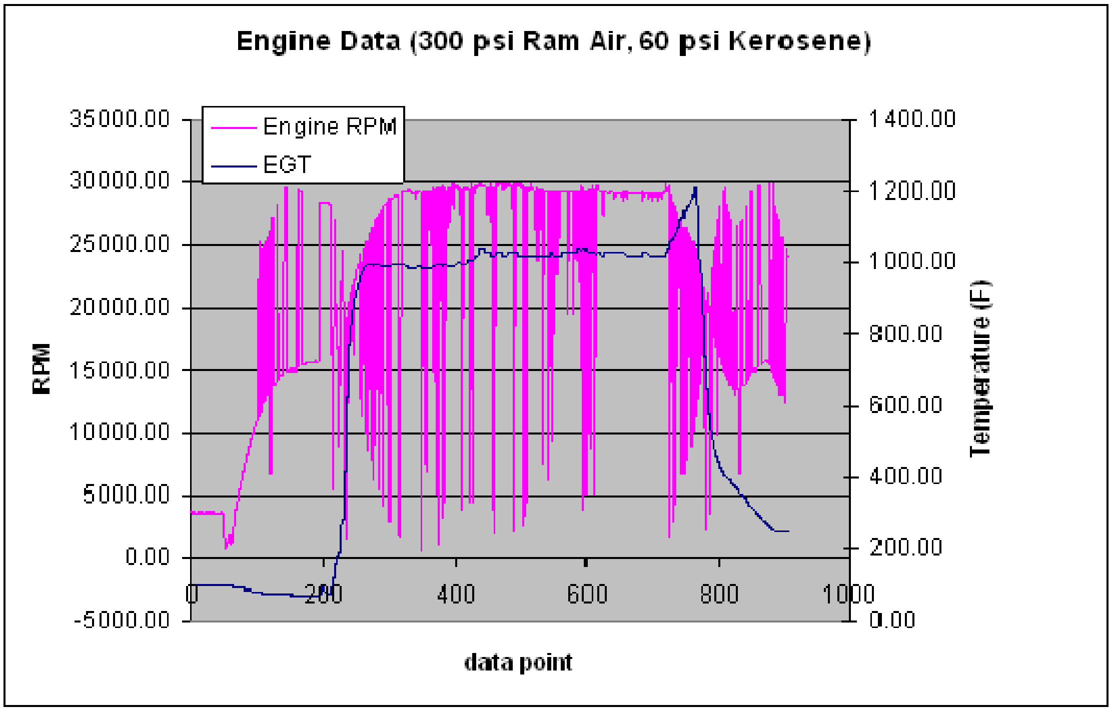


Figure 30. Engine run data for initial steady state light off

With lower fuel pressures required for engine light off than previously expected, new calibration data for low fuel head pressures was required. These fuel flow rate calibration curves for Kerosene and Biodiesel at lower pressures are included in Figure 31.

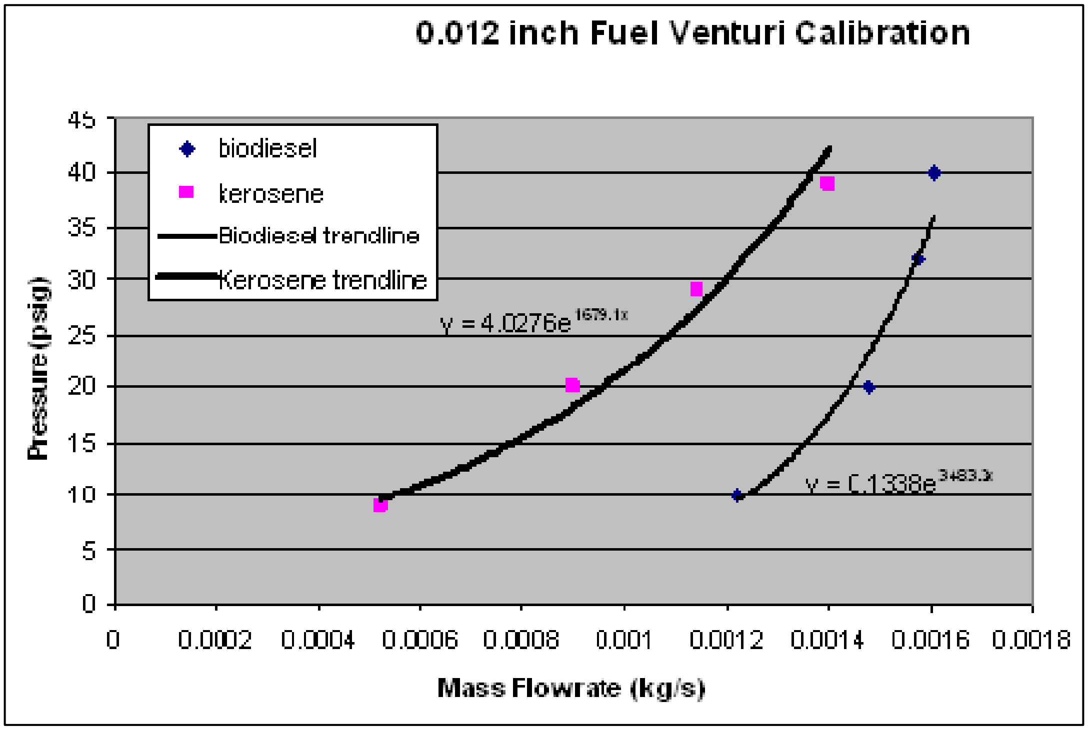


Figure 31. Fuel venturi calibration curves for 0.012" venturi at low head pressures

B. BASELINE TEST

1. Kerosene

After the first successful light off, fuel pressures were incrementally lowered to find the bottom limit for fuel supply flow rates for engine operation. In essence the flame-out conditions for the engine were determined in this form. Fuel tank pressures were decreased in 10 psi increments until light off could not be attained. Once fuel pressures were found where light off could no longer be achieved, a second Kerosene test sequence with 400 psi ram air and decreasing fuel supply pressures was performed. This test sequence was performed to verify flame-out conditions would occur earlier (higher fuel flow rates) due to the larger ram air flow rates. Despite the ignition and self sustaining conditions thumb rule of 3.0 g/s provided by NAWCWPNS, successful engine operation was achieved with Kerosene at mass flow rates of 1.6g/s (60 psi fuel tank head pressure) all the way down to 0.95 g/s (20 psi fuel tank head pressure) with 300 psi ram air supply pressure. The corresponding maximum engine steady state rpm and EGTs are shown in Figure 32. Below 20 psi supply head pressure, engine light off was unattainable.

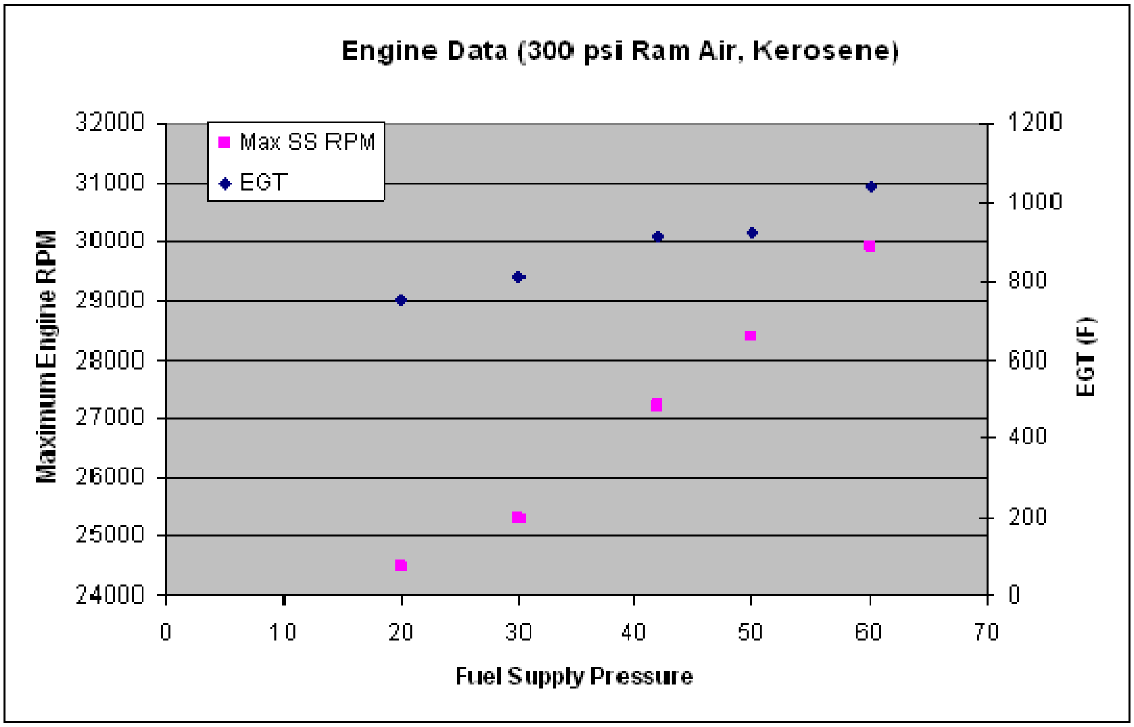


Figure 32. Engine data for 300 psi ram air and Kerosene fuel test sequence

The next test sequence with Kerosene and 400 psi ram air supply pressure yielded higher air flow rates, and a subsequently higher required minimum fuel flow rates (or fuel tank head pressures) were observed during flame-out. Similarly, light-off fuel flow rates were required, engine light off was unattainable below 40 psi Kerosene supply pressure. The corresponding maximum engine steady state rpm and EGTs for the second Kerosene test sequence are shown in Figure 33.

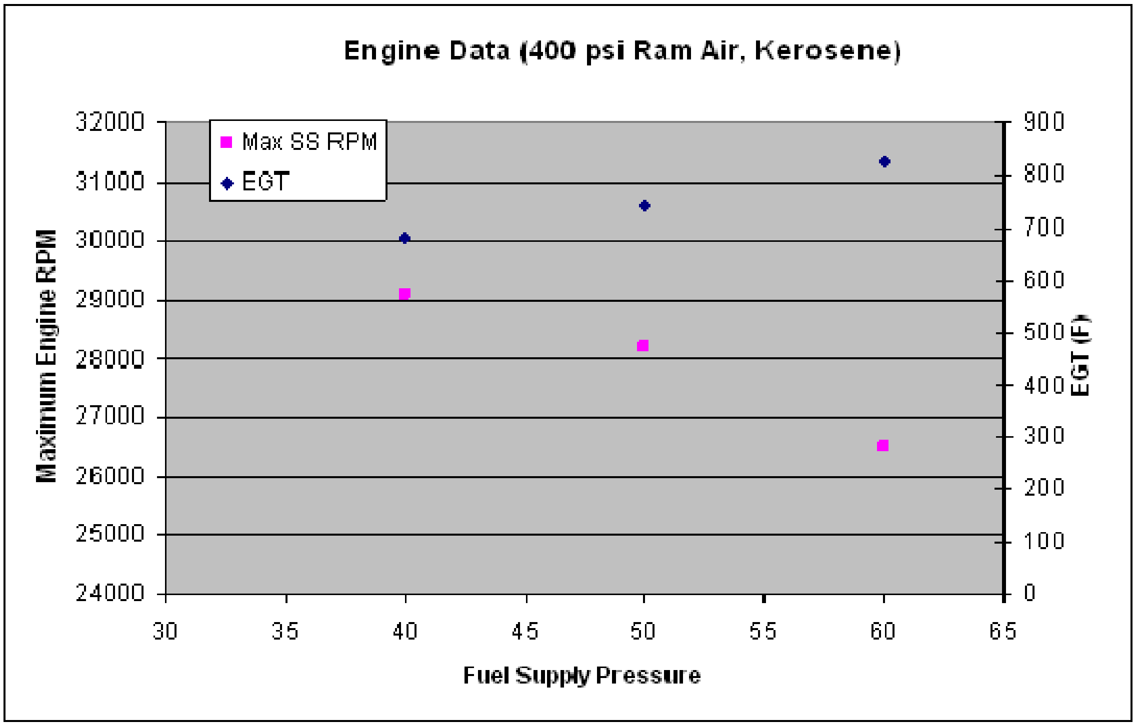


Figure 33. Engine data for 400 psi ram air and Kerosene fuel test sequence

The test results showed a condition of decreasing engine rpms as fuel mass flow rate was increased with a given ram air supply pressure. This is believed to be caused by a mixture yielding poor combustion. It was hypothesized that the large ram-air flow rates forced on the engine produced a highly uneven mixture in the combustor. However, without proper exhaust gas instrumentation to measure combustion efficiency by monitoring unburned hydrocarbon concentrations and CO2 and NOx production we cannot conclude anything at this point.

2. Biodiesel

The desire to achieve light off using a different fuel arose by the requirement to illustrate the feasibility to perform tests of different fuels and switching between them on the fly. Biodiesel was selected because of the significant variance in composition when compared to Kerosene. The initial test was run with 300 psi ram air supply pressure and 1.7 g/s (60 psi head pressure) biodiesel mass flow rate. This test resulted in the inability to achieve engine light off. Due to the limited run life of these engines, the continuous testing to find proper ignition conditions for Biodiesel was not performed.

3. Fuel Switching During Engine Operation

While testing for light off conditions for Biodiesel was undesirable, the demonstrated ability to switch fuels during operation was important. The ability to see different parameters with sustained operations would result in fewer engine starts and stops and concise comparison data when testing fuels with and without nanocatalyst. A test sequence which entailed lighting the engine off with 300 psi ram air and 60 psi Kerosene and then switching to 60 psi Biodiesel was performed to demonstrate fuel switching capability during operation. The results, included in Figure 34, showed a change in performance with sustained operation halfway through the test around data point 700. Engine speeds decreased from 29,500rpm to 27,500rpm and EGTs decreased from approximately 1,020°F to 980°F.

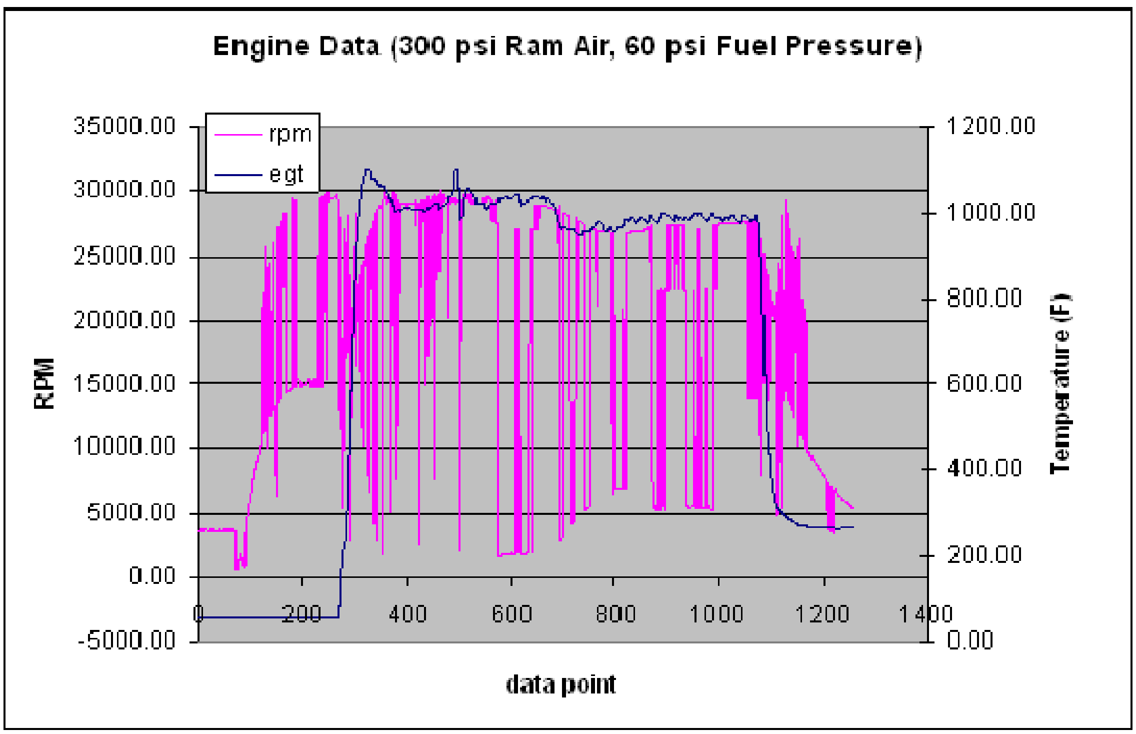


Figure 34. Engine data for 300 psi ram air and 60 psi fuel switching test sequence

The fuel switching test was also performed at 50 psi fuel pressure and switched from Kerosene during light off to Biodiesel then back to Kerosene with similar results. A side benefit is the proven ability to run fuels at conditions where light off is otherwise unattainable. Biodiesel provided a capable fuel for combustion in a hot combustor under the same air pressures and fuel rates tried unsuccessfully during light off tests.

4. Testing for Flameout Conditions

The final series of tests demonstrate the capabilities of the test stand to perform flameout tests. Flameouts in engines occur with the removal of one of three required factors for combustion. The absence of heat, fuel or oxygen results in the loss of flame inside the combustor. This was an effort to capture data concerning the fuel flow rates where an operating engine no longer sustains combustion. This first test consisted of 300psi ram air and 1.1 g/s (27 psi head pressure) Kerosene mass flow rate. The engine was started and fuel supply pressure was lowered from 27 psi until engine combustion stopped as evidenced by noticeable decrease in EGT. Engine combustion was sustained down to 5 psi fuel pressure as shown in Figure 35.

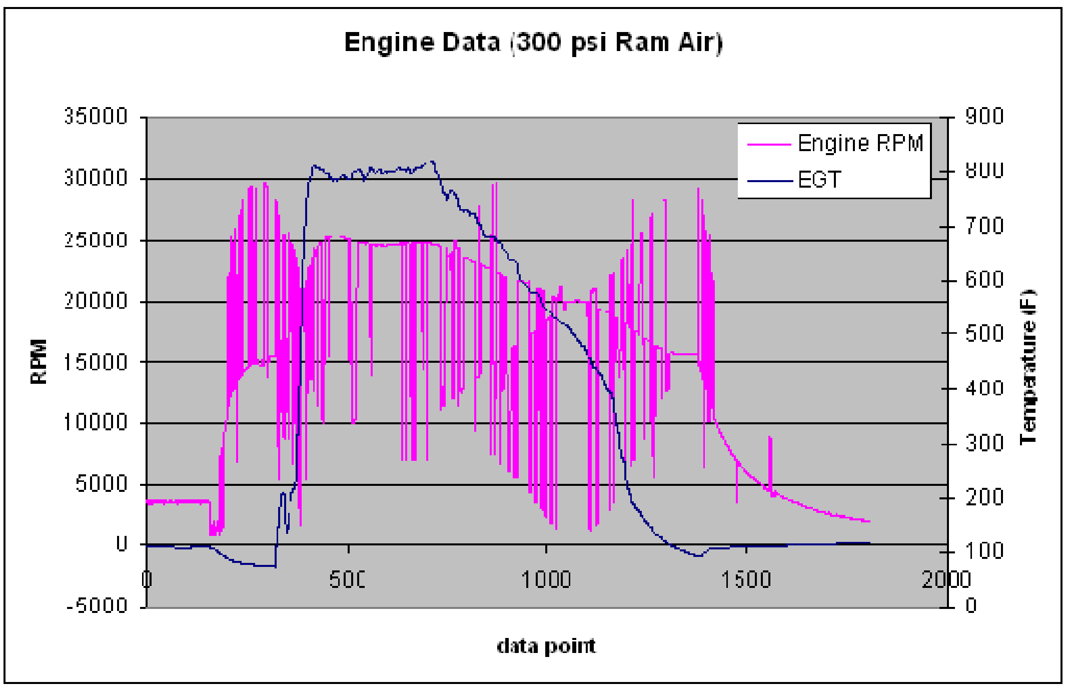


Figure 35. Engine data for 300 psi ram air and Kerosene flameout test

The second flameout test was performed with 400 psi ram air and a start mass flow rate of 1.4 g/s (20 psi head pressure) Kerosene. This time engine combustion was sustained down to 12 psi fuel pressure as shown in Figure 36.

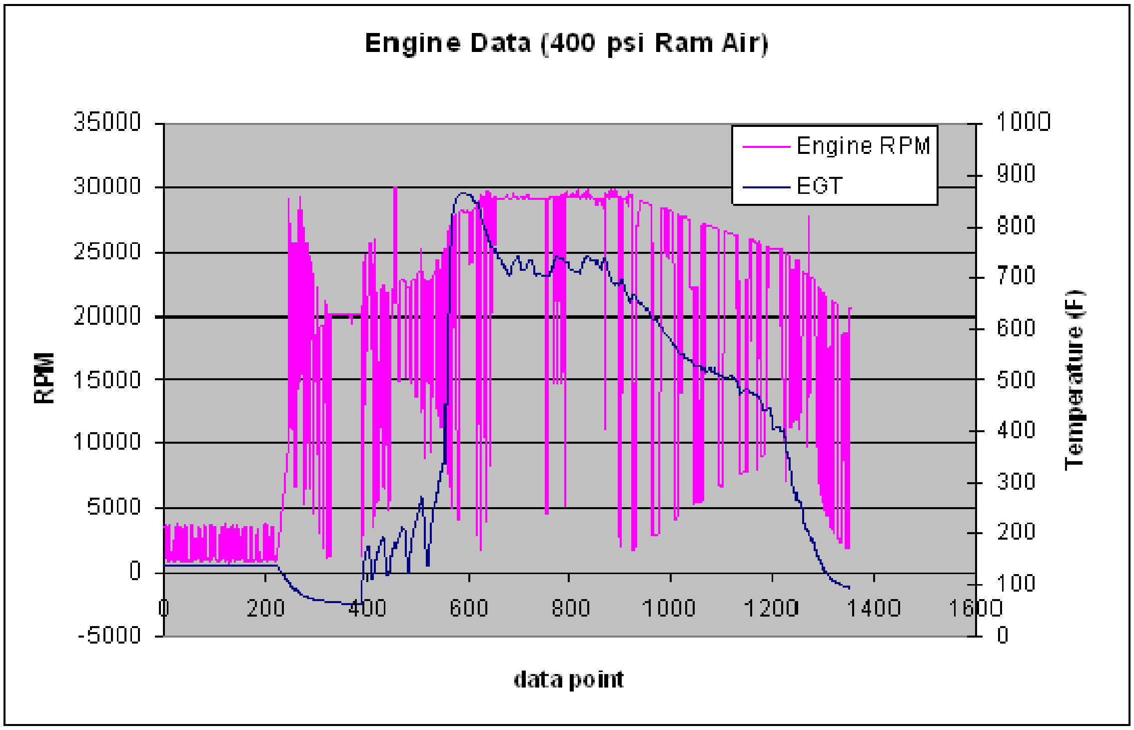


Figure 36. Engine data for 400 psi ram air and Kerosene flameout test

The flameout point was observed by utilizing a remote broadcasting video camera feed focused on the fuel tank analog pressure gauge. The digital remote pressure transducer failed to transmit proper pressure readings during engine operation. Therefore it was only used to properly set the fuel tank pressures and discarded during engine operation.

The flameout point for each run is illustrated on Figures 35 and 36 by a clear change in decreasing slope on both the EGT and RPM parameters. The change in flameout fuel pressure from 5psi to 12 psi with a leaner mixture from increased air was consistent with expected results.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. DISCUSSIONS

A. TEST STAND DEVELOPMENT

The process of building a functional test stand for a specified purpose with minimal funding and simply using available equipment not being used at the rocket lab was quite a challenge. After a candidate engine was selected and acquired the real design work started. Finding background on an engine designed over 20 years ago as part of a classified program provided additional obstacles. Armed with knowledge of overall program goals, a desired performance evaluation set was established for the test engine. The required parameters to be monitored were then derived from selected performance evaluation set. The next step was to ensure that enough installed instrumentation existed on the test engine to provide adequate evaluation. The required instrumentation connections on this engine already existed in part due to the prior history the F-121 turbofan engine had as a test engine platform. The engine then had to be adequately mounted in a suitable site. The primary criteria for choosing this site was to provide proper interface for required gases, electrical and piping connections with the existing laboratory facility. All of the required auxiliary systems were constructed and tested for proper operation. The first engine connected was tested for basic cold operational data and then dismantled to provide more detailed knowledge of the engine design. After tedious design, setup and construction processes were complete the real challenge of operating the engine began. All valve operations were controlled remotely via the LabVIEW 8.0 interface and gas pressures were manually set locally between each run.

B. TEST STAND QUALIFICATION

Extensive effort was put into gathering information on the existing engine specifications. With the operational test data provided by NAWCWPNS and continual adjustments for the existing differences in test setup, a standard operating procedure for the safe and proper operation of the selected engine was developed. Several iterations of light off conditions were tried until proper conditions were found for self sustaining engine operation. After achieving sustained engine operations, the engine was tested for suitability to achieve the program goals. To clearly illustrate any performance enhancement with the use of nanocatalyst additives, the engine had to demonstrate proper operation in the range where the desired benefits would be realized. The nanocatalyst had shown potential in providing for leaner combustion limits and lower operating temperatures. The test engine showed the ability to sustain operation under very low fuel flow rates. Another desired system function was the ability to switch between fuel supply sources without securing and restarting the engine. This capability was confirmed and measurements illustrated the change in fuels. To provide additional information or potential benefits of any test fuel, flameout test were performed. Flameout tests reinforced the conclusion that very lean engine operations are within the test stand capability. These tests also provided an additional capability of testing flameout limits in gas turbine engines. This phenomenon is of particular interest to aircraft.

V. CONCLUSIONS

A. TEST SYSTEM CONCLUSIONS

A specialized test stand was designed and developed to perform novel nanocatalyst fuel studies on full-scale tactical gas turbine engines. The test stand developed demonstrated the following capabilities:

- Was able to remotely light-off and sustain F-121 turbofan engine operation using kerosene fuel-air mixtures and test for lean ignition limits.
- Was able to operate the F-121 engine and perform on-the-fly fuel switching from kerosene to biodiesel and back to kerosene fuels. Performance changes were observed using the DAQ system developed for this test stand.
- Was able to operate the F-121 engine at normal operating conditions and then dynamically bring the engine to lean flameout conditions.

Therefore, ignition lean limits for the F-121 engine using kerosene-air mixtures were partially determined. Performance differences between kerosene and biodiesel fuels were observed. Flame-out conditions of the F-121 engine running on kerosene fuel were determined.

The test stand has demonstrated its suitability to perform nanocatalyst fuel additive performance measurements on tactical gas turbine engines.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. FUTURE WORK

Test stand improvements could be achieved by providing cleaner signals. The location of the test shed resulted in long runs of electrical wire. Long wire runs in conjunction with the use of unshielded connectors has led to some noise in the remotely read signals. Electro-Magnetic Interference (EMI) noise from the engine also influences the amount of signal noise present. A mechanism to provide filtering of signals would provide cleaner data.

Another benefit could be realized with greater remote operability. During test system qualification, fuel pressure was manually adjusted locally between runs. A remotely operated fuel control valve has been acquired. The proper inlet and outlet adapters, allowing for connection into the present fuel lines, has been designed and constructed. The engineering drawings for these adapters are shown in Figures 41 and 42 in Appendix D.

An installed differential pressure (ΔP) transducer for total and dynamic pressure reading at the inlet to indirectly determine thrust needs to be calibrated. Direct thrust measurement by use of a strain gauge system is also desired.

Additional engine baseline performance characterization with norpar-12 is required. After baseline testing is complete the engine will be ready to perform testing on norpar-12 and nanocatalyst.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A: LABVIEW DIAGRAMS

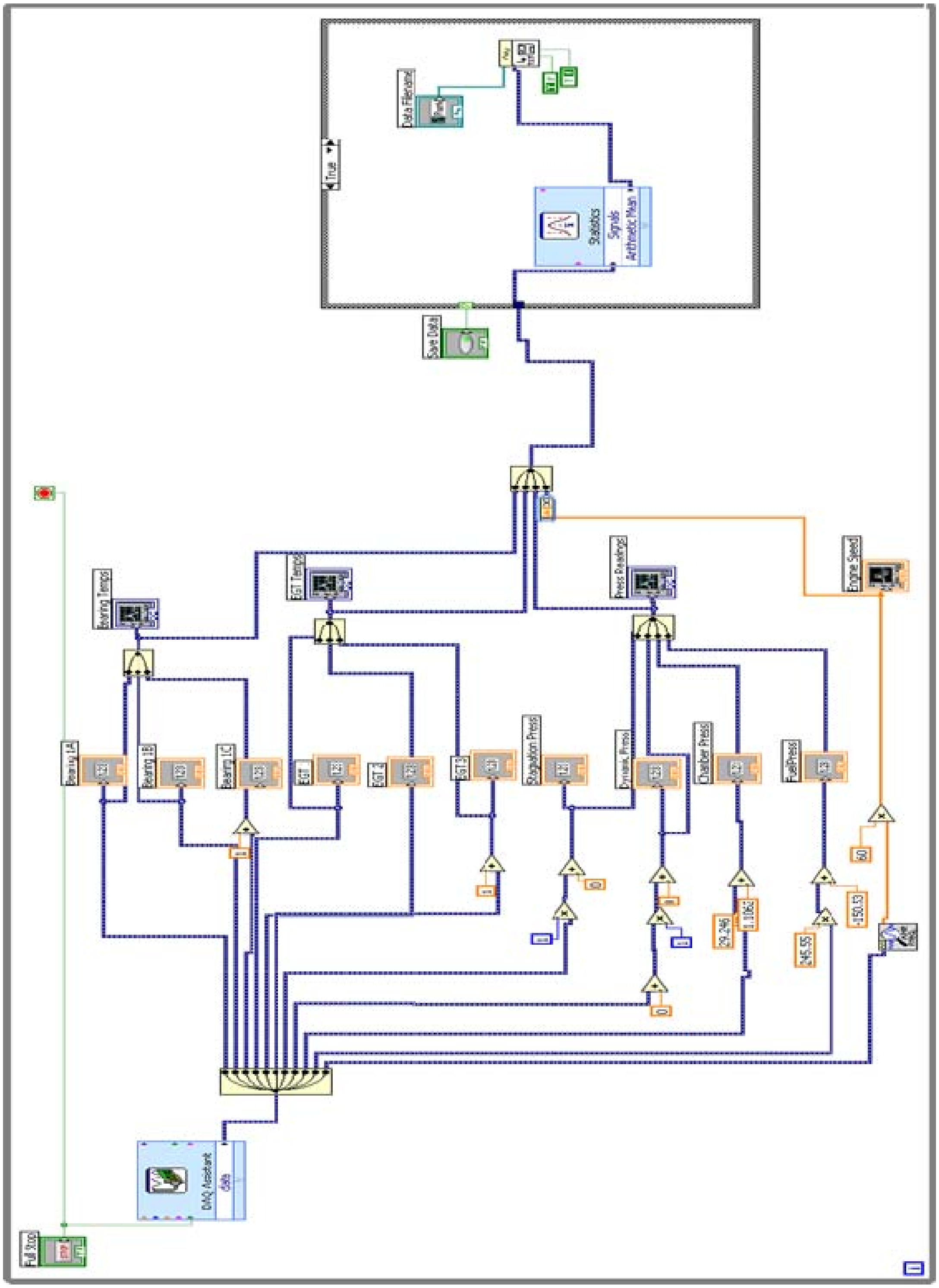


Figure 37. Lab VIEW VI part 1

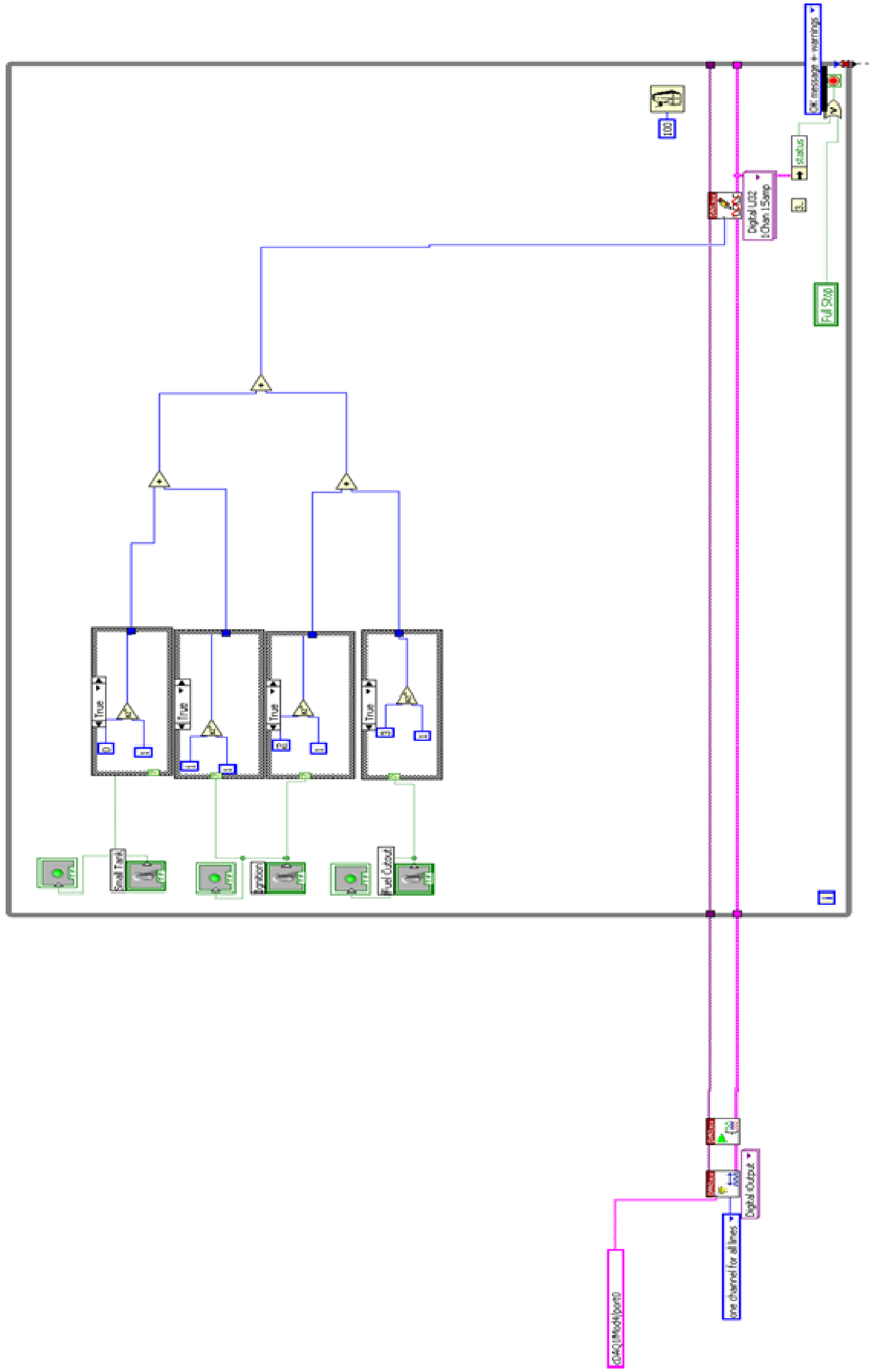


Figure 38. LabVIEW VI part 2

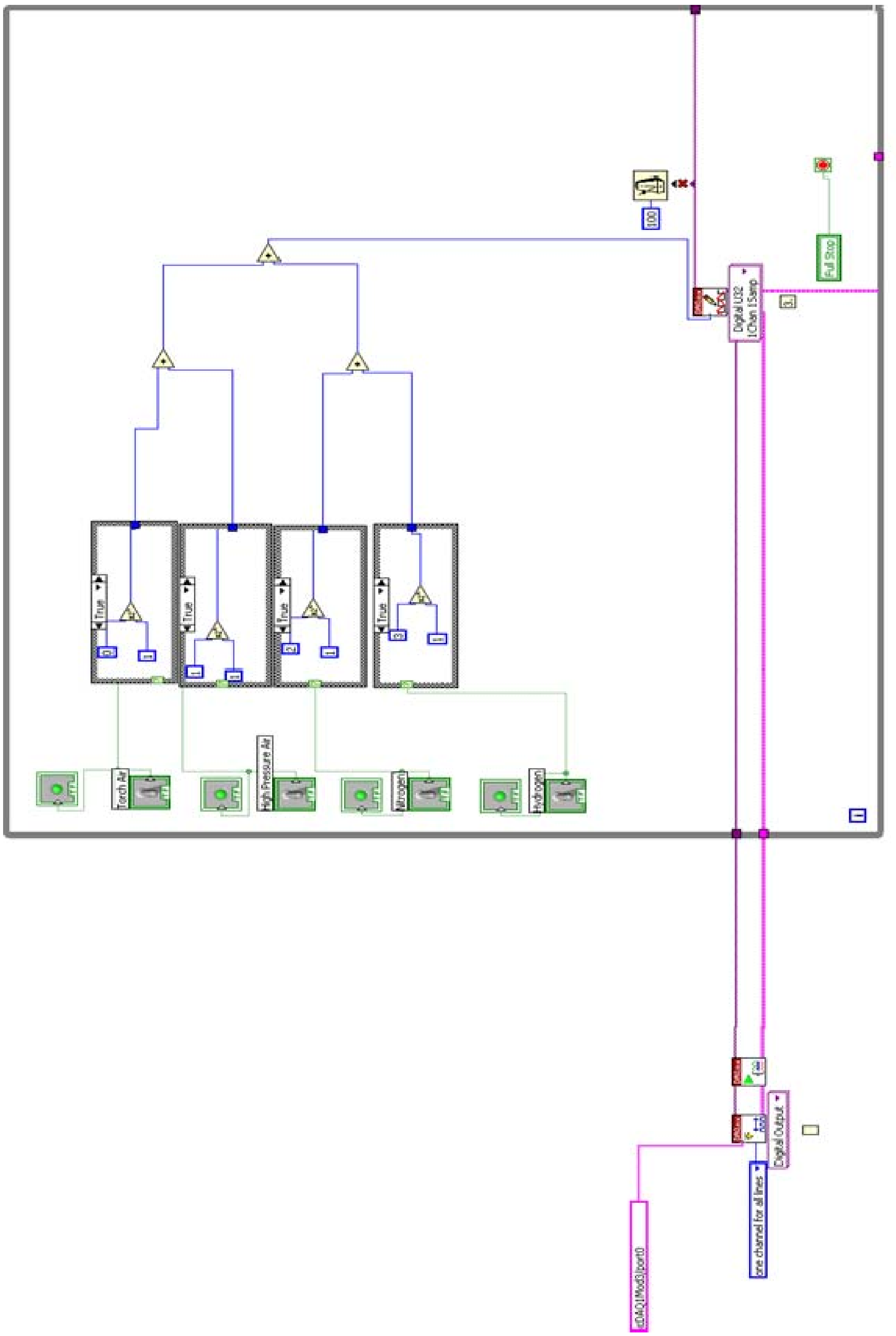


Figure 39. LabVIEW VI part 3

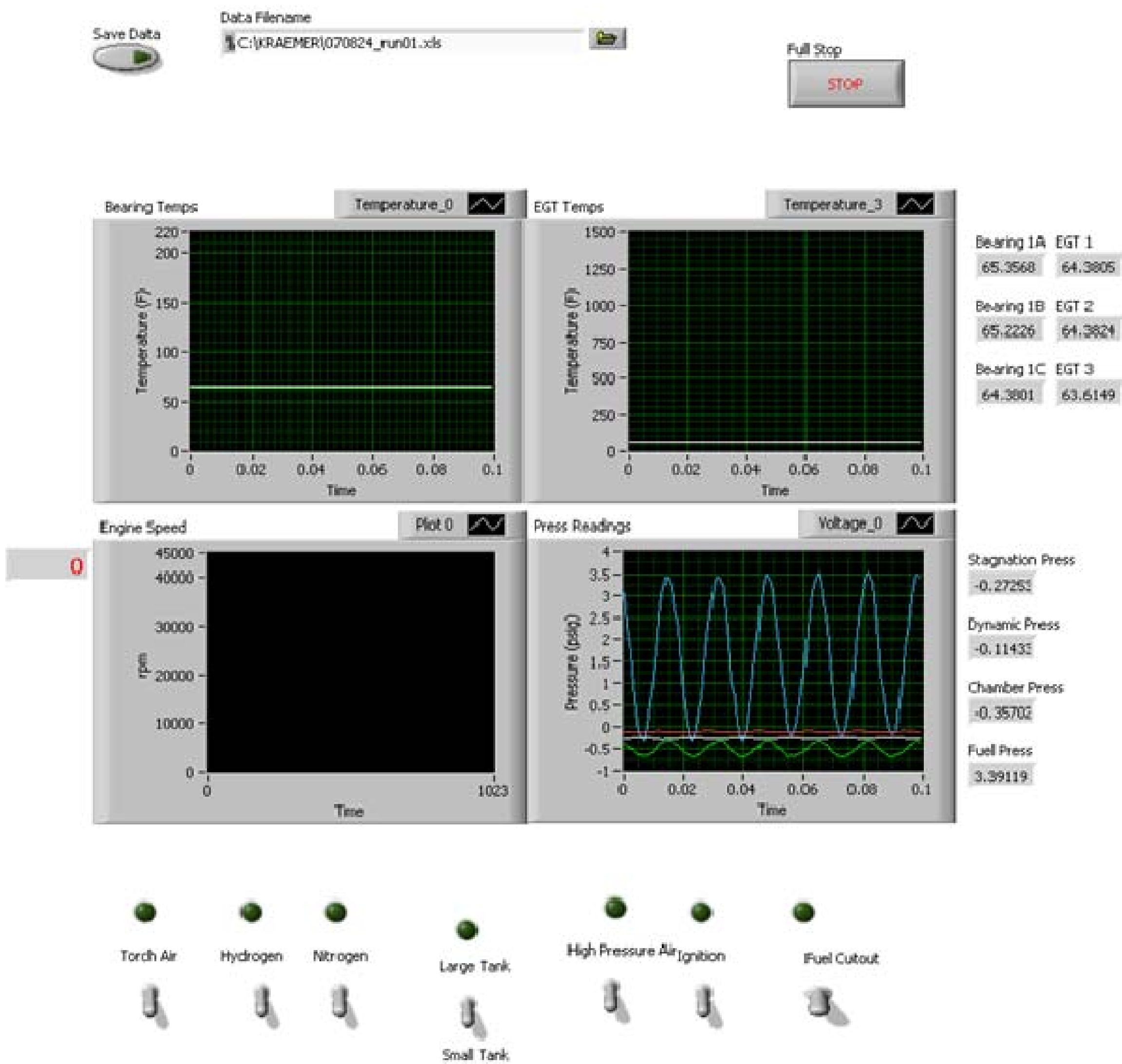


Figure 40. LabVIEW VI control interface

APPENDIX B: TEST CELL SOP

Test Shed Standard Operating Procedure

****Warning: Ensure Oxygen tanks are removed from the vicinity of the test shed***

Initializing:
1. Notify all personnel that HP air will be in use and energize outside warning light
2. Verify system is in a shutdown lineup
3. Verify desired fuel level in fuel tank
4. Open applicable LABVIEW VI on computer RPL01
5. Ensure power cords for 110 VAC and DAQ are plugged in inside test cell 0
6. Turn DAQ switch to ON and verify power
7. Position both emergency stops to allow power
8. Ensure power cord for power supply is plugged in inside test shed
9. Remove turbine outlet cover
10. Open shop air supply valve
11. Turn on Tescom power in test cell 2 (TCH2)
12. Ensure Node 4 air is isolated from test cells 1-4 by shutting cutout valve in test cell 1
13. Open HP air cutout valve from Node 4 Tanks
14. Open HP air branch valve to air control board
15. Open two jamesbury valves in test cell 1 to align ram air
16. Align ram air piping to bell mouth inlet
17. Throttle torch air tescom to desired pressure
18. Throttle HP air tescom to desired pressure
19. Slowly open Nitrogen bottle cutout valve
20. Throttle Nitrogen tescom to desired pressure
21. Slowly open Hydrogen bottle cutout valve
22. Throttle Hydrogen tescom to desired pressure
23. Set torch throttle control valves to desired position

****Following procedural steps will result in engine running***

Running: 1. Run automatic sequenced VI or per steps 2 –
2. Throttle ram air pressure set point on main control board computer
2. Open HP air ball valve to admit spinning air to engine
3. Open Nitrogen ball valve to apply head pressure to fuel tank
4. Open Torch air and Hydrogen ball valves
5. Open fuel supply valve to admit fuel to engine
6. After 5 seconds open torch solenoids
7. Apply ignition voltage for required time

Securing:
1. Secure torch solenoids and ram air
2. Shut torch air and hydrogen ball valves
3. Shut fuel supply and nitrogen ball valves
4. Shut HP air ball valve after desired temperatures are reached
5. Shut torch air, HP air, Nitrogen and hydrogen tescoms
6. Shut Nitrogen and hydrogen bottle cutout valves
7. Shut HP air branch valve and air cutout valve
8. Secure shop air
9. Bled off head pressure on fuel tank, torch air and hydrogen to 0#
10. Ensure pressure in all gas lines is bled down to 0#
11. Unplug power supply power cord and 110 VAC
12. Turn both emergency power switches to break circuit
13. Secure DAQ module and LABVIEW
14. Replace turbine outlet cover and ensure vent valves are closed

Emergency Op:
1. Turn emergency power switches to disengage
2. Secure all air sources

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX C: ENGINEERING DRAWINGS

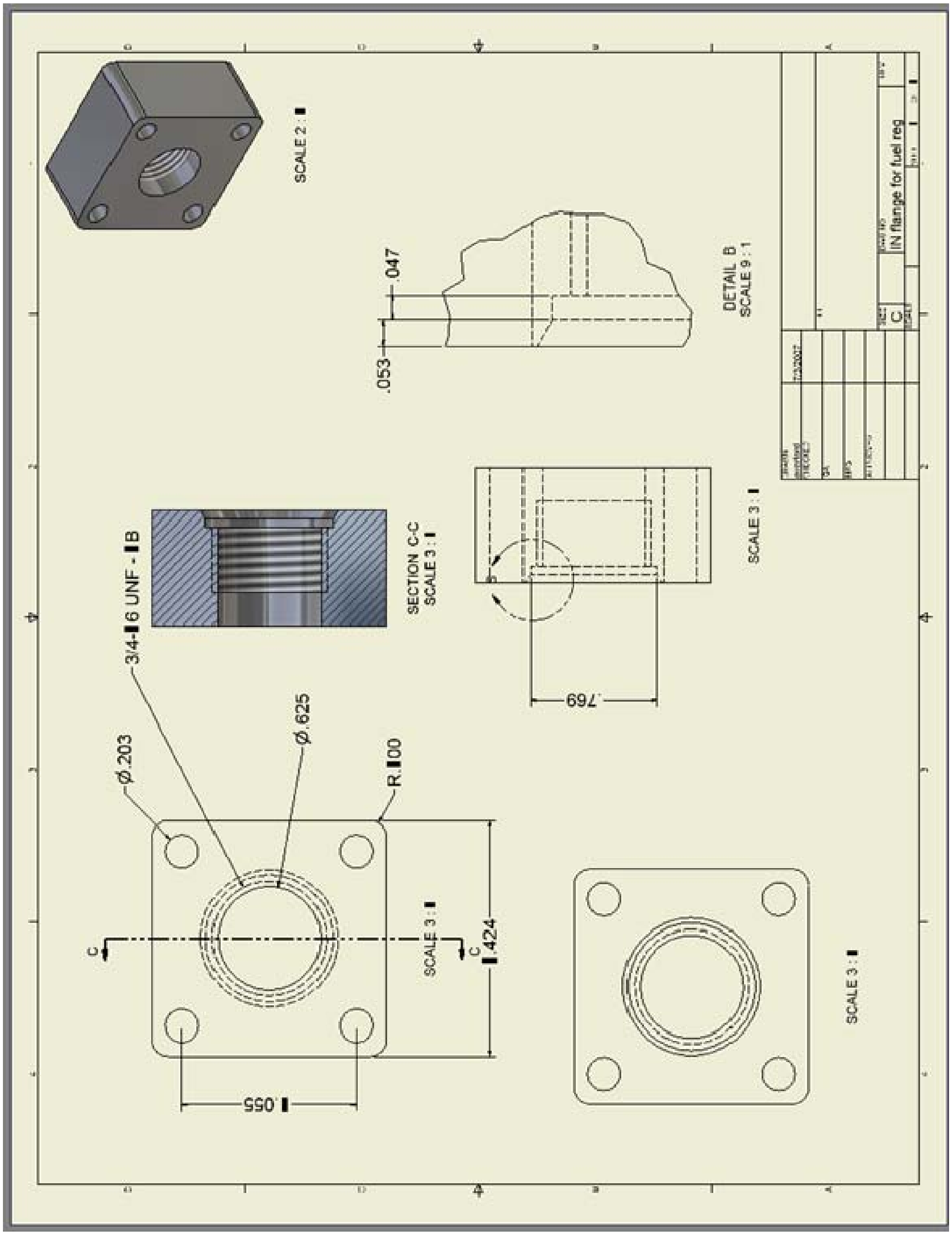


Figure 41. Fuel regulating valve inlet flange adapter engineering drawing

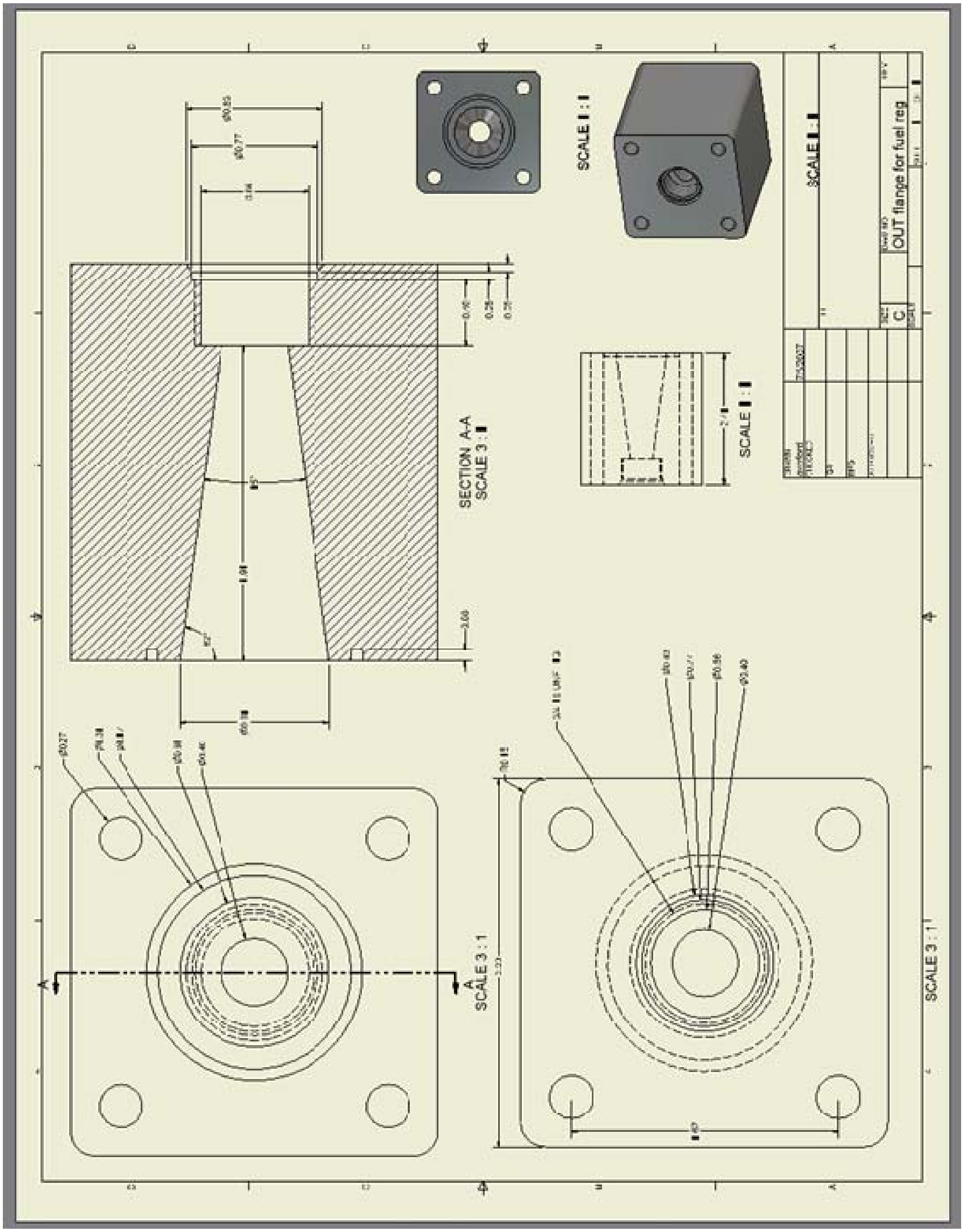


Figure 42. Fuel regulating valve outlet flange adapter engineering drawing

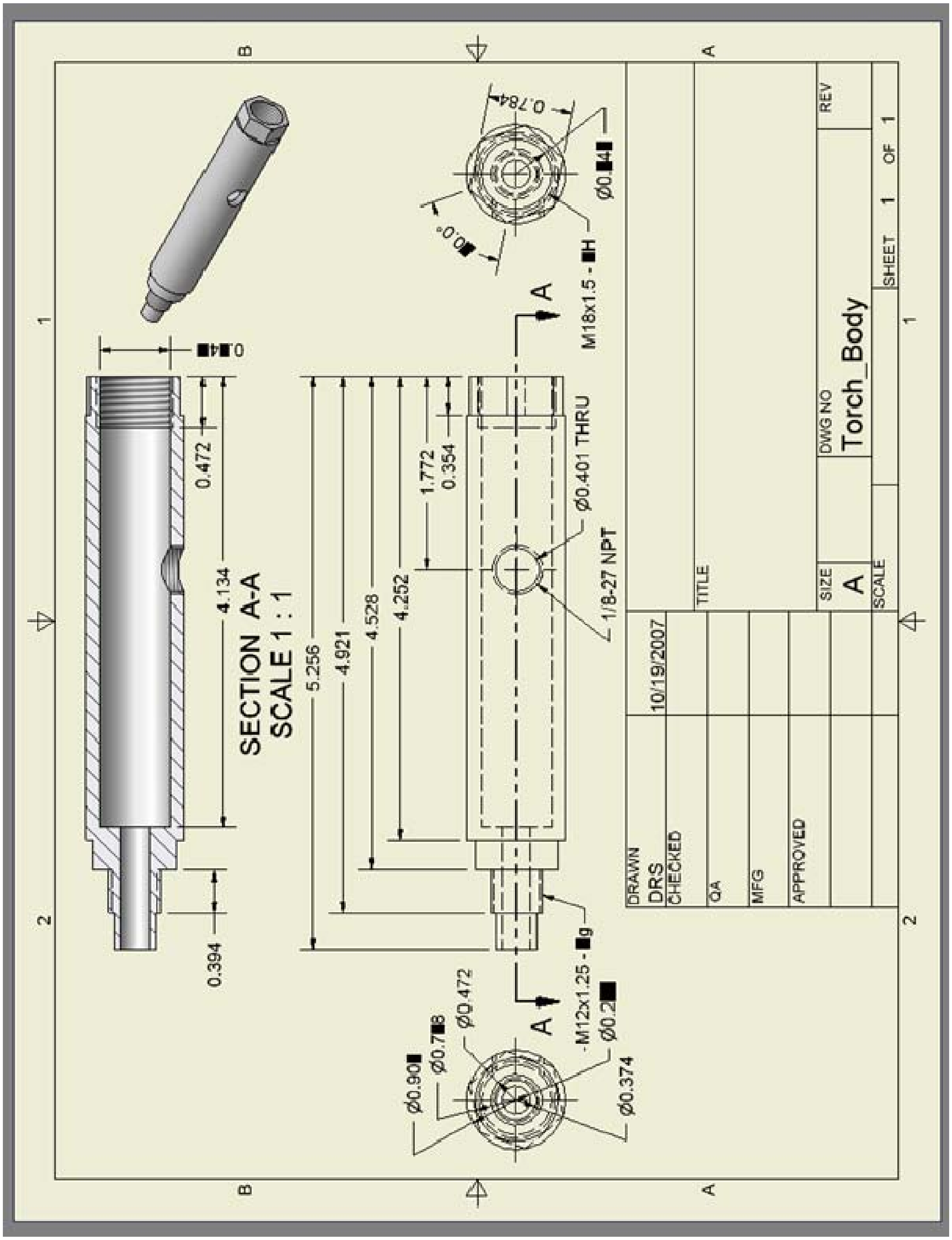


Figure 43. Engineering drawing for second engine variant torch body

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX D: DATA RUNS

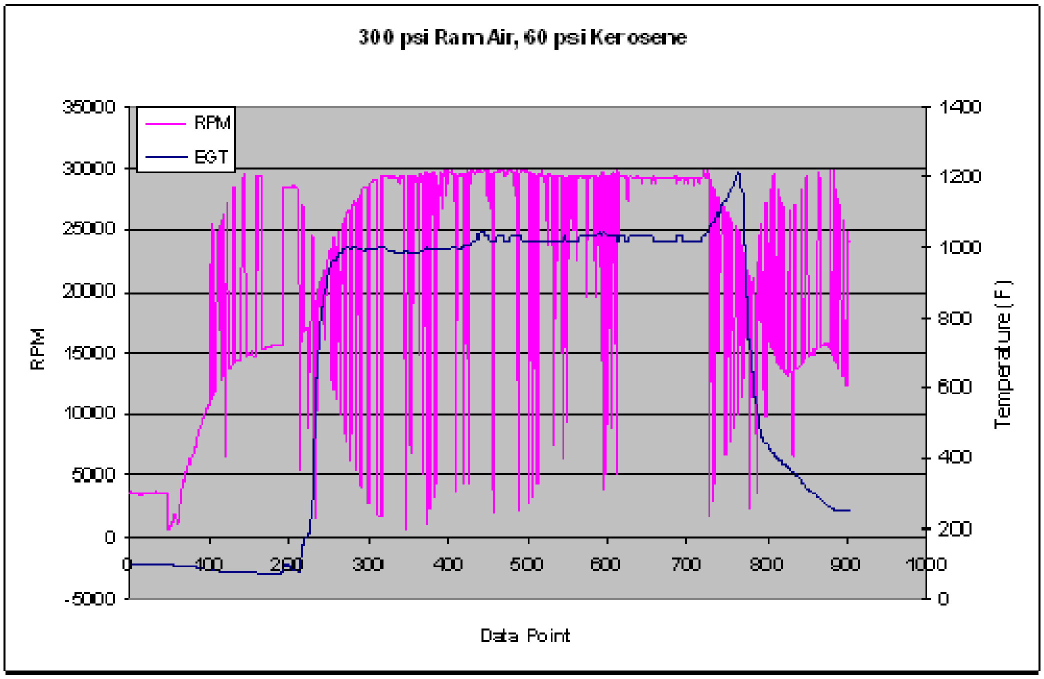


Figure 44. Engine baseline run 300 psi ram air and 60 psi Kerosene

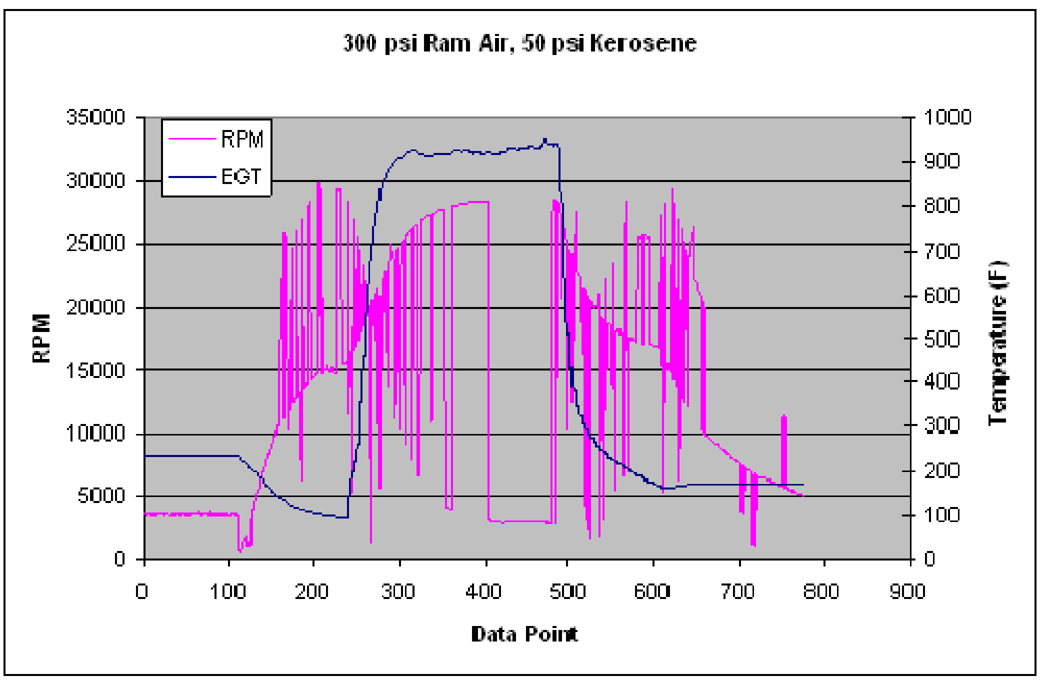


Figure 45. Engine baseline run 300 psi ram air and 50 psi Kerosene

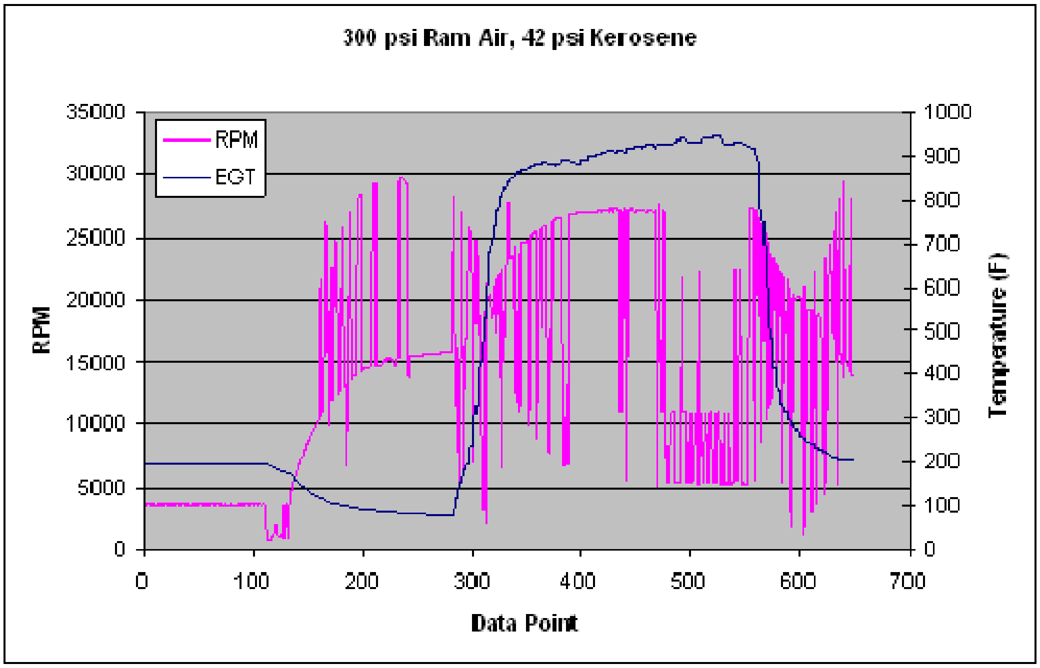


Figure 46. Engine baseline run 300 psi ram air and 42 psi Kerosene

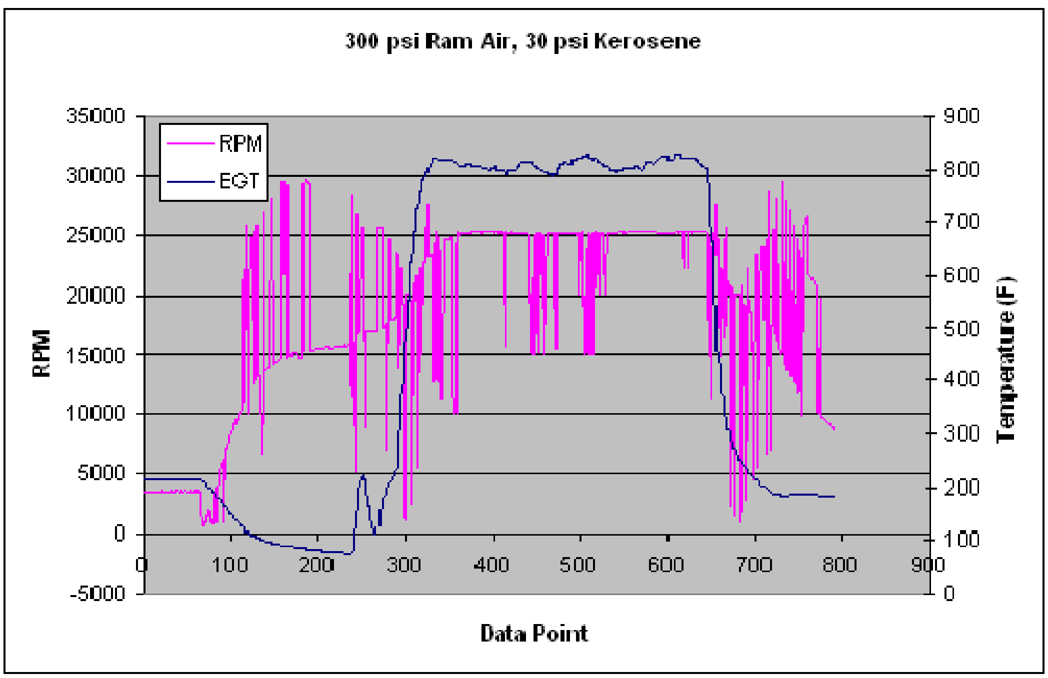


Figure 47. Engine baseline run 300 psi ram air and 30 psi Kerosene

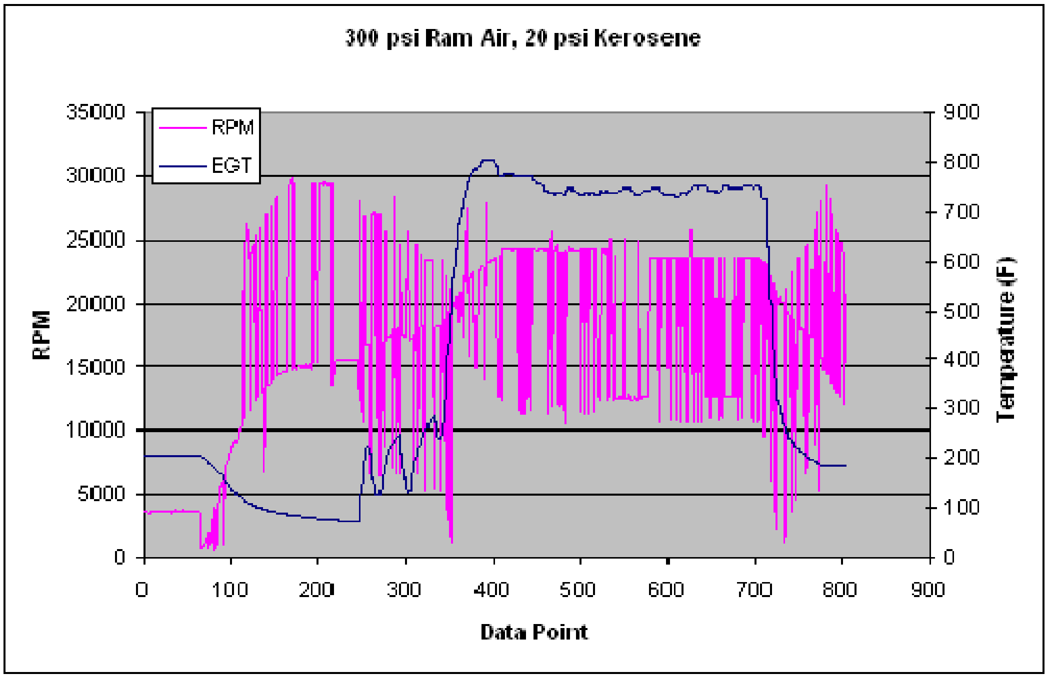


Figure 48. Engine baseline run 300 psi ram air and 20 psi Kerosene

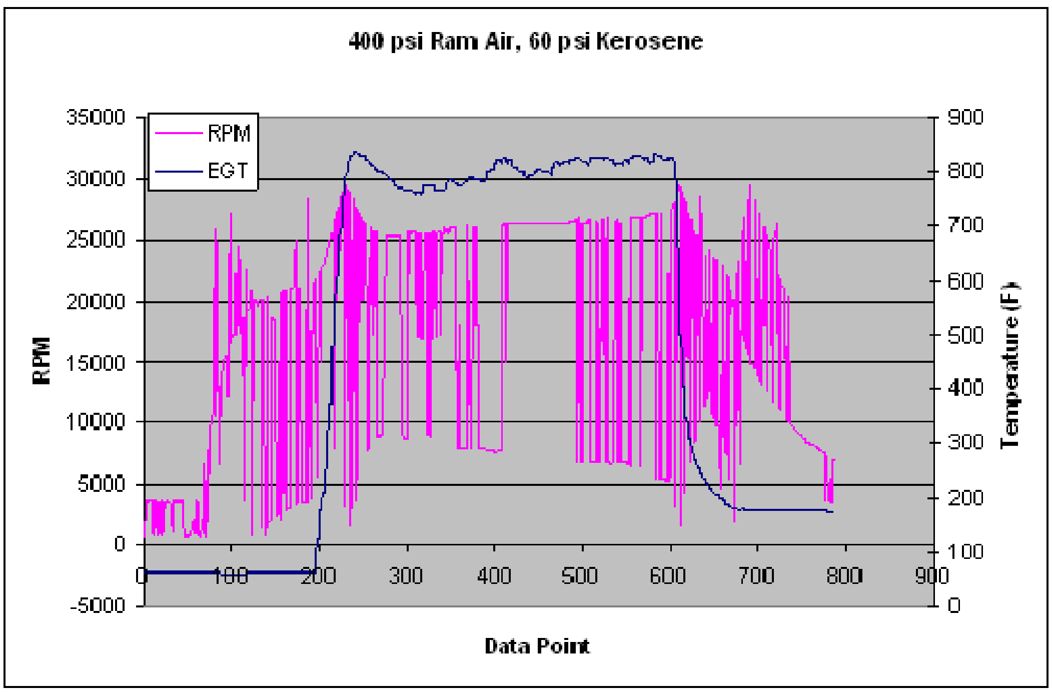


Figure 49. Engine baseline run 400 psi ram air and 60 psi Kerosene

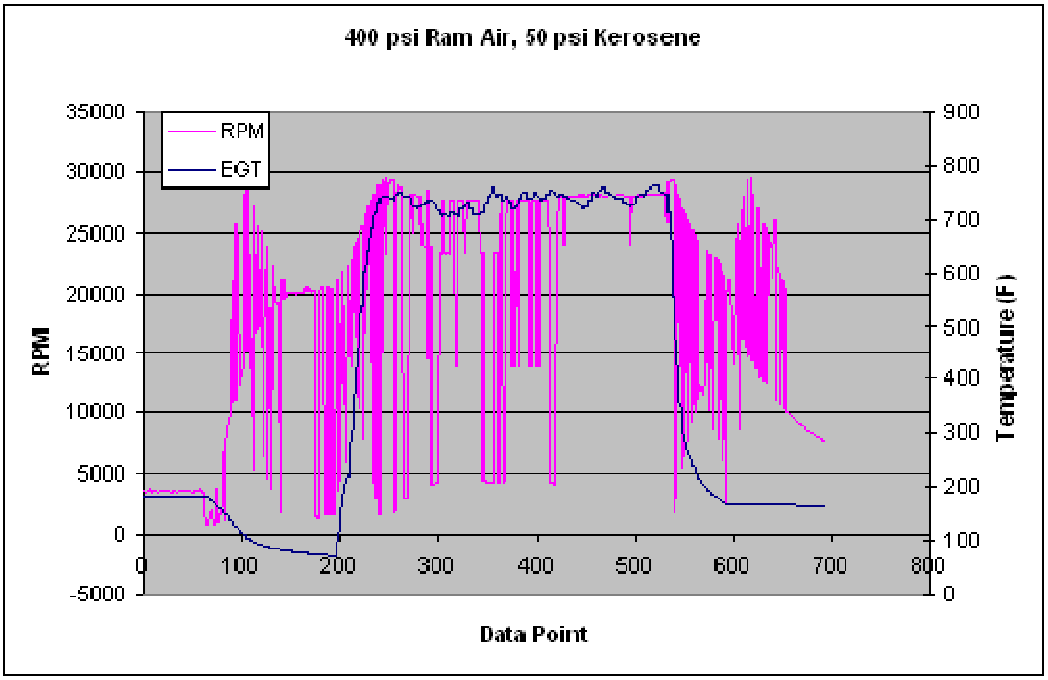


Figure 50. Engine baseline run 400 psi ram air and 50 psi Kerosene

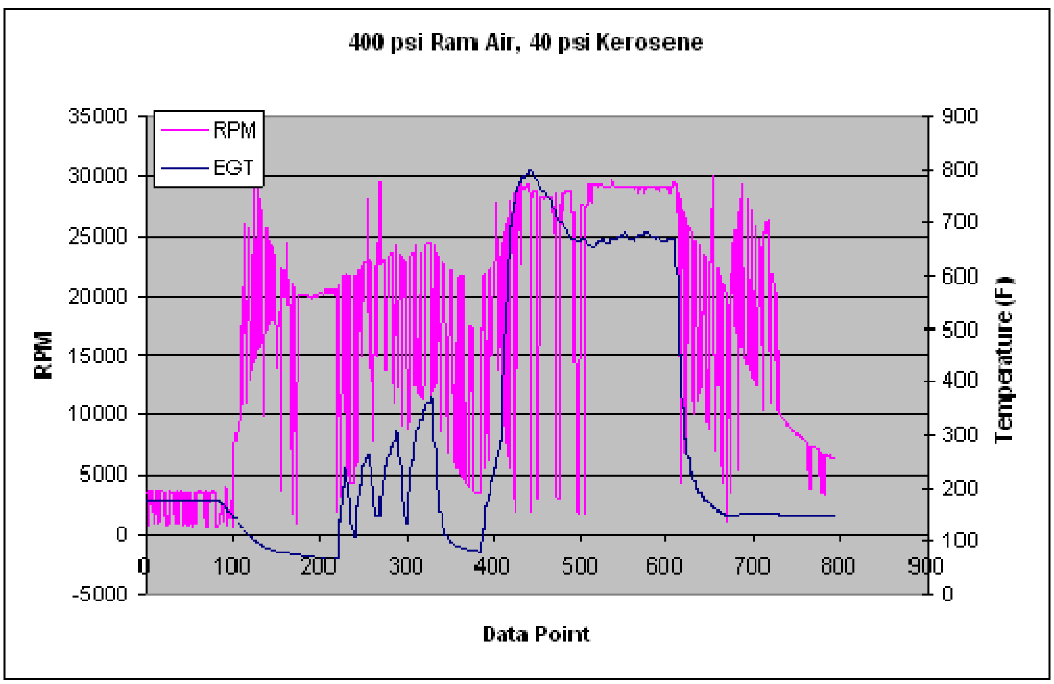


Figure 51. Engine baseline run 400 psi ram air and 40 psi Kerosene

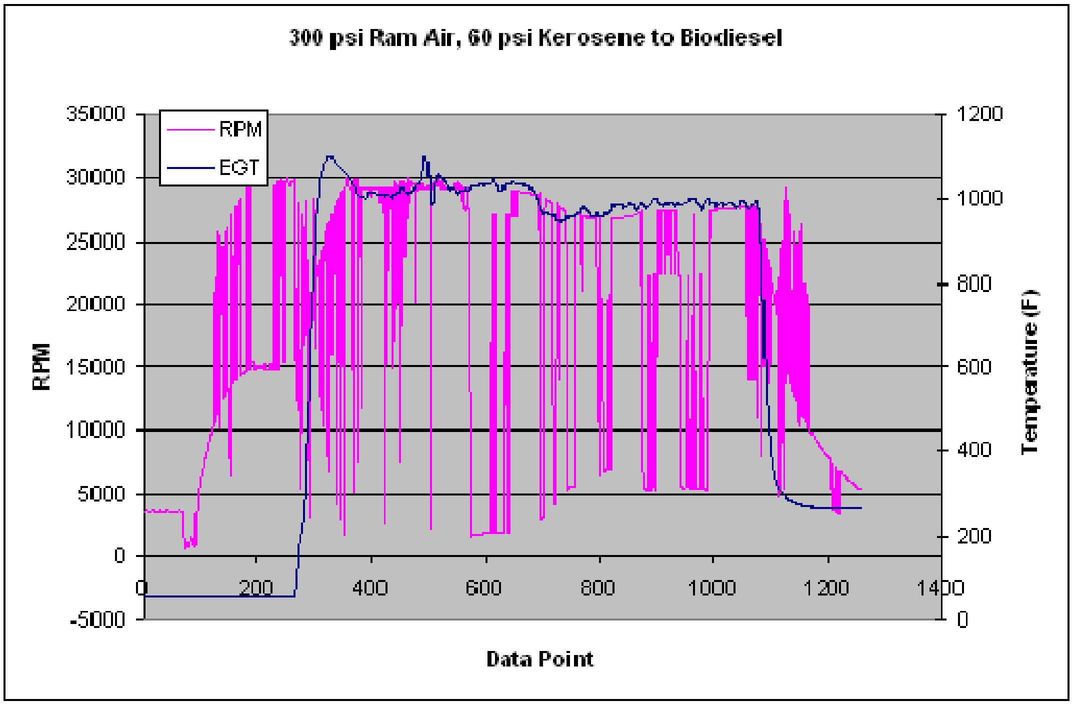


Figure 52. Engine fuel switch run 300 psi ram air and 60 psi fuel

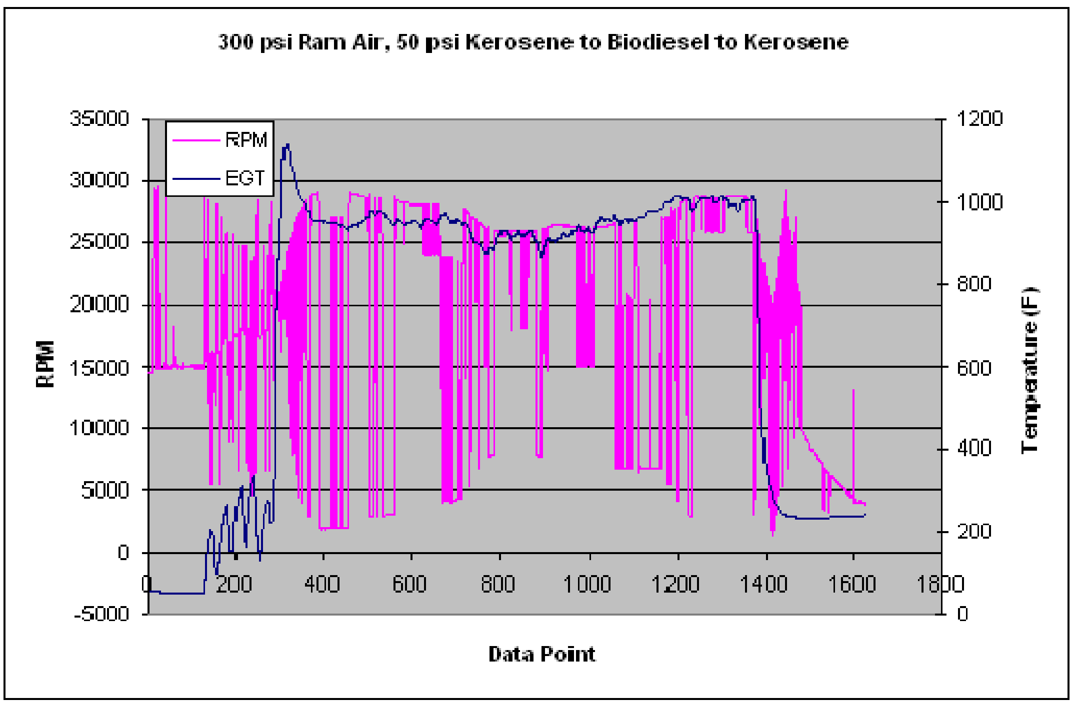


Figure 53. Engine fuel switch run 300 psi ram air and 50 psi fuel

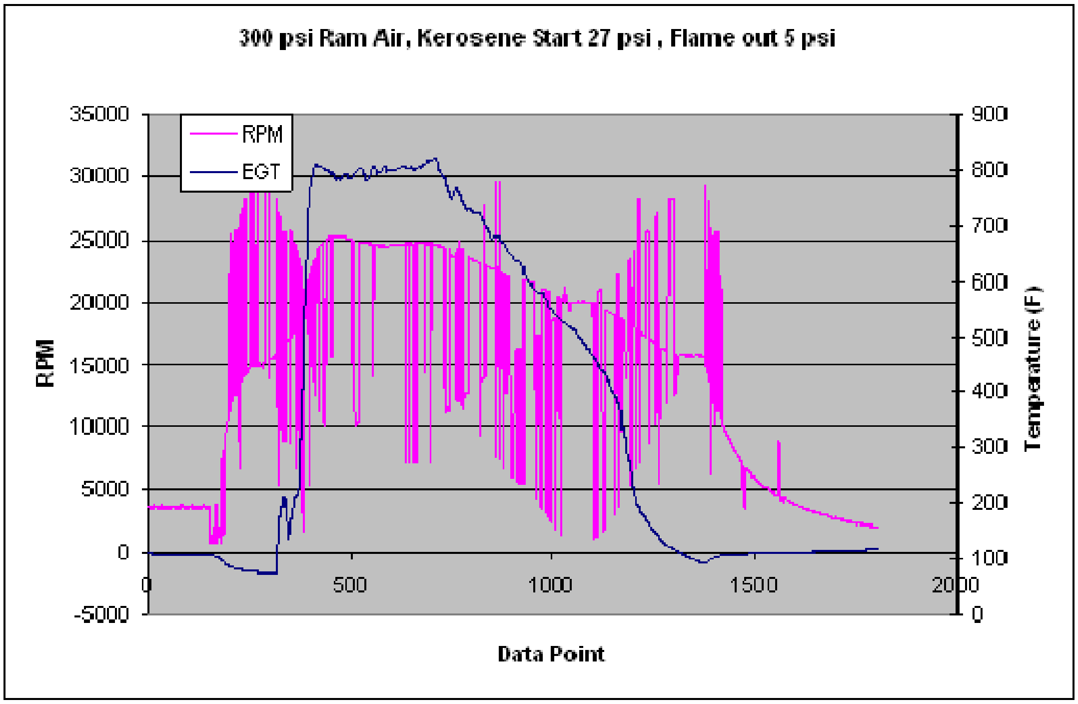


Figure 54. Engine flameout run 300 psi ram air and 27 psi fuel

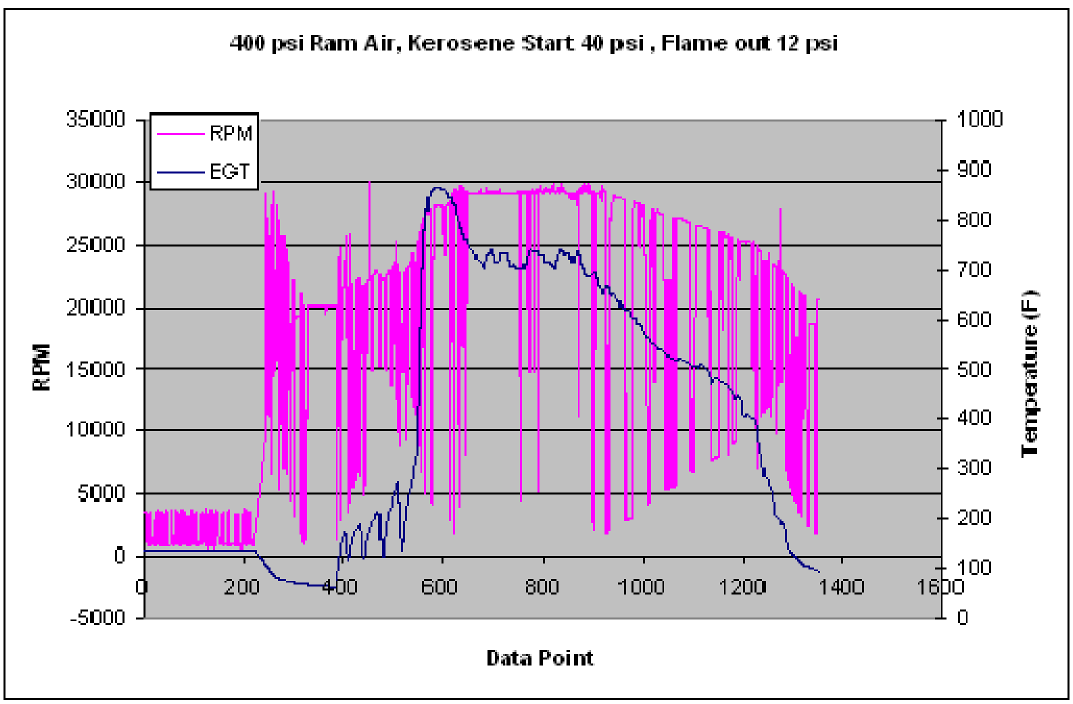


Figure 55. Engine flameout run 340 psi ram air and 40 psi fuel

LIST OF REFERENCES

[1] *Aviation Jet Fuel Information* Version 3.3.2 2007, CSG, Computer Support Group, Inc. and CSGNetwork.Com, viewed 20 October 2007, <http://www.csgnetwork.com/jetfuel.html>.

[2] A.J Mee., *Physical Chemistry,* Heinemann Educational Books Ltd., 1968.

[3] *Palladium Acetylacetonate* 2007, American Elements, viewed 10 November 2007, <http://www.americanelements.com/pdacac.html>.

[4] *Aliphatics FAQs* 2002, Exxon Mobil Corporation, viewed 10 November 2007, <http://www.exxonmobilchemical.com/Public_Products/Fluids/Aliphatics/Worldwide/FAQs/Fluids_Aliphatics_FAQ_Norpar.asp>.

[5] Jack D Mattingly, *Elements of Gas Turbine Propulsion,* McGraw-Hill Inc., 1996.

[6] Philip Hill and Carl Peterson, *Mechanics and Thermodynamics of Propulsion,* Second Edition, Addison-Wesley, 1992.

[7] *Williams International F-121 Fanjet,* National Museum of the USAF, viewed 13 April 2007, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=887>.

[8] W.R. Hawthorne and W.T. Olson, *Design and Performance of Gas Turbine Power Plants,* Princeton University Press, 1960.

[9] K.K. Kuo, *Principles of Combustion,* Second Edition, John Wiley and Sons, 2005.

[10] J. Moore and J. Loundagin of Airframe, Ordance and Propulsion Division and j. Kincheloe of Comarco, Inc., *Turbofan Testing with High Energy Fuels*, NAWCWPNS TM 7793, January 1995.

[11] Robert P Benedict, *Fundamentals of Temperature, Pressure, and Flow Measurements,* John Wiley and Sons, 1984.

[12] *Products and Services* 2007, National Instruments Corporation, viewed 22 May 2007, <http://NI.com>.

[13] Dr. David T. Wickham, Jeffrey Engel, Marcus Jones, and Jim Nabity, *Soluble Nano-Catalysts for High Performance Fuels*, SBIR Phase II Project July 2005 - July 2007 Powerpoint, TDA Research Inc.

[14] D.L. Davis and R.D.W. Bowersox, *Stirred Reactor Analysis of Cavity Flame Holders for Scramjets*, AIAA-97-3274, Presented at the 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 1997.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, VA

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, CA

3. Dr. Gabriel Roy
   Office of Naval Research
   Arlington, VA

4. Professor Jose Sinibaldi
   Department of Mechanical and Astronautical Engineering
   Naval Postgraduate School
   Monterey, CA

5. Professor Christopher Brophy
   Department of Mechanical and Astronautical Engineering
   Naval Postgraduate School
   Monterey, CA

6. Professor Knox Millsaps
   Department of Mechanical and Astronautical Engineering
   Naval Postgraduate School
   Monterey, CA

7. LT Nathan Kraemer
   Naval Postgraduate School
   Monterey, CA

8. Mr John Moore
   NAWCWPNS
   China Lake, CA

9. Mr Jim Nabity
   TDA Research Inc.
   Wheat Ridge, CO