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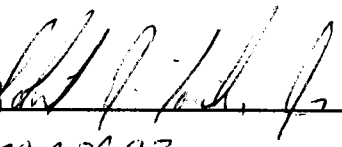
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A Statistical Model for Determining Firevalve Controller Settings to Regulate Gaseous Rocket Propellant Mass Flow

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Robert J. Torick, Jr.

May 1993

DEDICATION

This thesis is dedicated to my wife, Dana, who I love with all my heart, my Mom, Peggy Torick, who always been there when I needed her, and finally to my Dad, Robert Torick, for if he were here today, I know he would be proud.

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ABSTRACT

Testing throttleable rocket engines at simulated altitude requires controllable firevalves to adjust propellant mass flows for desired O/F's and chamber pressures (P_c's). Obtaining accurate mass flows is essential for determining the operational O/F's and chamber pressures for the engine during test. The ability to predict mass flows, when the O/F and chamber pressure changes, is crucial. How so? Because, if the predictions aren't accurate, the engine operating parameters do not match the desired engine performance during a test. This results in another test run. Another test run increases costs, shortens the engine's life, and possibly results in not meeting all of the test objectives. Also, because the engine run times are so short, the firevalves must be set prior to the test run. The controller settings must accurately reflect the proper mass flow rates for the desired O/F and P_c. If throttling is involved, the initial set point for the controller needs to be accurate.

Obviously, the best solution is to provide a feedback mechanism between the valve and the controller to automatically adjust the mass flow. However, during my tour at NASA Lewis Research Center (1986-1988), the computers weren't fast enough to maintain a constant O/F and P_c. It was estimated that a sampling rate of 50 Hz was required. Also, digital technology wasn't cost effective at that time. Today, there is a strong interest in implementing a feedback, controller system, but none has been installed.

Another possible method to vary propellant mass flow rate would be to change the propellant supply pressures during a run. Unfortunately, it makes throttling the engine very difficult and could possibly lead to undesirable rocket engine and propellant feed line dynamics. If throttling is not part of the test matrix, and the

regulated pressures are preset prior to engine test firing, then this method will work. However, it complicates the process the test engineer uses to determine correct controller settings.

Therefore, in a research environment with declining budgets, the need to accurately predict firevalve plug positions during test firings, without controller to valve feedback systems, demands a simple and inexpensive methodology for doing so. The purpose of this thesis is to design a technique for predicting firevalve controller settings to regulate propellant mass flow based on rocket engine P_c and O/F.

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NOMENCLATURE*

A_d^*	Area of the rocket engine throat, desired
A_m^*	Area of the rocket engine throat, measured
b	The y intercept of a line; used for linear regression
BLIMP-J	Boundary Layer Integral Matrix Procedure, version J
C^*	Characteristic exhaust velocity
C_d^*	Characteristic exhaust velocity, desired
C_m^*	Characteristic exhaust velocity, measured
C_v	Firevalve flow coefficient
GH_2	Gaseous hydrogen
GOX, GO_2	Gaseous oxygen
JANNAF	Joint Army, NASA, Navy, Air Force
m	The slope of a line; used for linear regression (least squares method)
$\dot{m}_f$	Fuel mass flow
$\dot{m}_{f_d}$	Fuel mass flow, desired
$\dot{m}_{f_m}$	Fuel mass flow, measured
$\dot{m}_{f_n}$	Fuel mass flow, new (for the next test firing)
$\dot{m}_o$	Oxidizer mass flow
$\dot{m}_{o_d}$	Oxidizer mass flow, desired
$\dot{m}_{o_n}$	Oxidizer mass flow, new (for the next test firing)

* These symbols and acronyms are not part of the POTPRED program. See Appendix C for POTPRED variable definitions.

$\dot{m}_{tot}$	Mass flow, total
$\dot{m}_{tot_d}$	Total propellant mass flow, desired
$\dot{m}_{tot_m}$	Total propellant mass flow, measured
n	Total number of coordinates
NASA LeRC	NASA Lewis Research Center
$\frac{O}{F}$	Oxidizer to fuel mass flow ratio
$\left(\frac{O}{F}\right)_d$	Oxidizer to fuel mass flow ratio, desired
P_c	Rocket engine chamber pressure
P_{c_d}	Rocket engine chamber pressure, desired
P_{c_m}	Rocket engine chamber pressure, measured
POTPRED	POTentiometer PREDiction program
RCAL	Reference Calibration
RETF	Rocket Engine Test Facility
ROB	Rocket Operations Building
TRADAR	Transient Research Data Reduction
x_i	The i^{th} value of the x-axis quantity being measured (mass flow)
y_i	The i^{th} value of the y-axis quantity being measured (controller potentiometer setting)
η_{C^*}	Characteristic exhaust velocity efficiency

CHAPTER I

INTRODUCTION AND PURPOSE

Testing throttleable rocket engines at simulated altitude requires controllable firevalves to provide gaseous oxidizer and fuel mass flows to match desired O/F mixtures and chamber pressures (P_c) in the engine. This can be accomplished by two methods: adjusting the propellant supply pressures* or using a feedback control system. Because of the very short engine run times (3-4 seconds), adjusting the supply pressures is slow, and therefore, doesn't lend itself to throttling the engine. Setting the supply pressure prior to the test firing provides some capability, but it complicates the prediction process. Changing the supply pressure changes the slope of the linear lines on the controller settings versus propellant mass flows graph. This graph is the primary tool the test engineer uses to predict controller settings for the next test run. These slope changes are due to the changes in supply pressures changing the density of the propellants and requiring a different firevalve flow area. Large changes in regulated pressures may result in guess work by the test engineer on which curve to use. The test engineer doesn't know for sure how accurate his predictions are until the test firing is completed and actual data is available. Finally, adjustments for the regulated pressures are typically course and are hard to repeat. Several iterations may be required to "hit" the desired regulated pressure, wasting time and consumables.

Feedback control systems weren't fast enough to sample the O/F and P_c for valve adjustment (during my tour, 1986-1988). Today, computers are much faster and

---

* Oxidizer and fuel supply pressures or regulated pressures (down stream of the pressure regulator).

can perform the sampling and calculations fast enough, however, there has been no move to implement this solution.

The system that is used attempts to preset the controller valves to positions that will give the correct propellant mass flow rates. To improve this process, the historical operational database for the operation of the facility and engine must be analyzed to determine the nominal valve settings. This thesis is focused on providing a numerical method, based on linear regression, for analyzing the database of valve settings with their respective propellant mass flows, and predicting the needed valve setting (controller potentiometer setting*) for each new, or test specific engine operational point.

After an engine firing, the data system reports numerous data points to the test team. However, the test engineer is typically concerned about the performance of the test facility and the rocket engine, and not so concerned with the research data. The data acquisition computer determines the rocket engine's O/F and reports its P_c. At that point, a test engineer manually plots oxidizer and fuel mass flows versus their respective controller potentiometer settings on individual graphs (oxidizer and fuel). After a series of engine firings, enough points are gathered to make a line or a curve, depending on the valve flow coefficient (C_v). In this case, a linear valve plug is defined as one that produces a linear line on the controller setting versus mass flow graph.

Curve fitting is required to predict new potentiometer settings for changes in chamber pressure and O/F ratio. In order to remain on the line, the regulated pressure

---

* Controller potentiometer settings and controller settings are used interchangeably.

must remain constant for each run. By changing the regulated pressure, the slope of the line being plotted changes, and a new curve fit is required.

The purpose of this thesis is to design and develop a computer program to perform the calculations and linear regression analysis required by test engineers at NASA Lewis Research Center's (NASA LeRC) Rocket Engine Test Facility (RETF). This computer program, given the acronym POTPRED, takes input from the user (P_c, O/F, regulated pressure, firevalve C_v, C^* measured, desired O/F for the next run, and the desired P_c for the next run), performs linear regression of the controller potentiometer settings versus mass flows, plots controller potentiometer settings versus mass flows graph, and based on the desired O/F and P_c for the next run, predicts the firevalve controller settings to use for that run. This research provided in this document is a practical solution to a real world situation.

Chapter II provides an overview of the Rocket Engine Test Facility (RETF) at NASA Lewis Research Center. A brief description, the types of programs tested, and the test facility systems are provided. The final section of this chapter details elements of the B Stand: the thrust stand, the test capsule, and the facility operations. This helps the reader understand the facility where data was taken and used by POTPRED.

Chapter III discusses the propellant system and the various equipment that is used to tailor this system to match the rocket engine performance conditions. The majority of the data input to POTPRED is related to mass flow, firevalve plug position, supply pressures, and firevalve flow coefficients. An understanding of this system provides insight into the relationship between POTPRED and the propellant system.

Chapter IV discusses the data systems. The data systems at the RETF include signal conditioners, controllers, computers, and sequence timers. Knowing how the

data systems are configured tells the test engineer what type of data he will be receiving, and how it should be handled.

A discussion on the rocket engine is contained in Chapter V. A brief description of the test objectives and conditions as well as a description of the 1030:1 area ratio rocket engine are provided. Further details on the injector, the throat section, and the exit diffuser or nozzle are contained in Section 5.3 of this chapter. Engine combustion parameters* and operating conditions provide critical inputs to POTPRED for predicting the new firevalve controller potentiometer settings for the next run. If a different engine is used, then the historical data must be loaded into data files for POTPRED to perform calculations and controller setting predictions.

The focus of this thesis is contained in CHAPTER VI, where the computer program POTPRED is described. The structure of the program, the subroutines, and data files are all discussed. Critical equations used for linear regression and predicting new controller potentiometer settings are derived and explained.

The final chapter, Chapter VII, provides a discussion of the program, including results, further improvements to the program, and the conclusion of the study.

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* Combustion parameters are O/F and P_c. These terms are used throughout this document.

CHAPTER II

THE ROCKET ENGINE TEST FACILITY (RETF)

2.1 Introduction

The following information on the NASA Lewis Research Center (NASA LeRC) Rocket Engine Test Facility (RETF) came from a briefing describing NASA LeRC's rocket capabilities [1]. Although the description is general in nature, it is provided for background information only. A more detailed description of the simulated altitude test stand* will provide further insight on how the test stand was configured for the rocket firings. This discussion can be found in Section 2.4.

The Rocket Engine Test Facility (RETF) Complex is an integrated stand-alone test facility dedicated to the testing of full scale rocket thrust chambers. The complex is locate in Cleveland, Ohio, and occupies approximately ten acres of land as can be seen in figure A.1. The complex includes two major buildings and extensive on-site support services. The RETF is used for sea level testing of vertically mounted rocket thrust chambers and space simulation testing of horizontally mounted rocket engines. The data used by POTPRED was taken from a rocket engine fired from the latter test stand. The Rocket Operations Building (ROB) is located one-quarter mile north of RETF and contains the facility remote control room.

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* Often referred to as B Stand.

2.2 Programs

The RETF is used for experimental investigations of rocket enabling technologies (cryogenic and earth storable propellants) with emphasis on reusability, high performance, advanced thrust chamber cooling techniques, low thrust-high performance engines, and engine operational stability. This work is directed toward specific propulsion needs envisioned for future NASA missions.

The RETF B Stand is used to test rocket engine performance in a space environment and also to evaluate advanced cooling systems for the orbital transfer vehicle program. General research and technology programs include testing stowable nozzles and advanced nozzles for space rocket propulsion applications. Data is accumulated on rocket engine ignition, life and durability of the engine walls, heat transfer information, nozzle boundary layer conditions, and engine efficiency at space simulation conditions. Prototype auxiliary propulsion engines for the Space Station Freedom have been tested for performance and life.

2.3 RETF Systems

RETF (figure A.2) is comprised of 1,325 square foot test building containing two test stands, A Stand (vertical orientation, sea level) and B Stand (horizontal orientation, simulated altitude). Pressurized propellant run tanks, propellant flow line systems, and a rocket exhaust gas treatment scrubber/muffler* are also a part of this facility.

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* Often referred to as the scrubber, spray chamber, or spray cooler. Theses terms are used interchangeably throughout this document.

The scrubber system consists of a 100 foot long by 25 foot diameter, horizontal tank containing six water spray banks connected to a vertical stack 20 feet in diameter (which necks down to a 6 foot diameter), reaching a height of 118 feet. During a test firing, water from the reservoir tank flows to the exhaust scrubber at a rate of 50,000 gallons per minute. The rocket exhaust gases passing through the test cell diffuser enter the scrubber/muffler system. There, the scrubber water cools and condenses the exhaust particles. The condensible particles are piped to a detention tank for treatment, if necessary. The non-condensible exhaust particles pass through the scrubber stack and are released to the atmosphere.

Located at the top of the scrubber stack, a flare stack provides the capability for open air burn-off of excess hydrogen that does not get condensed in the scrubber.

2.4 B Stand [1]

In 1984, B Stand was built providing space simulation test capability for the study of extremely large area ratio nozzles (about 1000:1) on small, low thrust rocket engines. This test stand includes a large 8 foot diameter by 11 foot long vacuum tank which houses the rocket engine, a long, water cooled pumping diffuser into which engine exhaust is funnelled, a spray cooler for cooling and quieting the exhaust gases, and two gaseous nitrogen ejectors and one air ejector to provide the pumping necessary to maintain the low vacuum environment during testing.

B Stand is capable of testing rocket chambers with GOX* (gaseous oxygen) and GH_2 (gaseous hydrogen) with chamber pressures ranging from 300 to 1,000 psia at thrust levels from 10 to 1,500 lbs.

---

* RETF personnel often refer to GO_2 as GOX.

Figure A.3 shows the Rocket Engine Test Facility (RETF) with cutaway views of the test capsule and spray cooler for the simulated altitude test stand.

2.4.1 Thrust Stand

As explained by Smith [2], B Stand contains a horizontal thrust stand (figure A.4) that is capable of measuring thrusts to 3,000 lb. full scale. The thrust structure [3] passes through the test capsule bulkhead by isolation ports that are sealed by metal bellows. This thrust structure is attached to a foundation outside the test capsule that is separate from the bulkhead. The thrust stand is designed to have a 2σ (standard deviation) variation of less than ± 0.1 percent of full scale [2]. The thrust stand can be calibrated remotely while at altitude, against an additional load cell. This load cell has a 2σ variation of less than ± 0.05 percent full scale and a calibration traceable to the NIST (National Institute of Science and Technology) [3].

To improve the accuracy of the thrust stand, a special propellant system was designed to minimize the impact of the thrust and vibration of the propellants on the thrust measurement system. This unique propellant system is called the "bird cage". As depicted above and in front of the rocket engine (figure A.5), the "bird cage" directs the propellant flow in a vertical axis while providing flexibility in the horizontal direction, therefore, minimizing the effects of the propellant flow and pressure on the thrust measuring system.

Because of the unique capabilities of this thrust stand, small changes in engine performance can be measured. Trying to increase engine efficiencies of 97 - 98% by nozzle design improvements requires a very accurate and sensitive thrust stand. As a secondary purpose, the codes that develop these nozzle design improvements need to be verified.

2.4.2 Test Capsule [3]

The test capsule is constructed in two parts. One part, the fixed end, is where the rocket engine is mounted. The other part is the movable can, which can be rolled back to provide access to the engine. Figure A.4 also shows B Stand with the test capsule rolled back. The engine with a 1030:1 area ratio nozzle can be seen installed on the fixed end of the capsule.

2.4.3 Facility Operations for B Stand

A typical altitude firing starts with the air ejector pumping the test capsule and spray chamber to approximately 0.5 psia. This ejector is used to hold a "nominal" altitude between test firings. Next, gaseous nitrogen ejectors evacuate the test capsule and spray cooler to a pressure between 0.3 psia and 0.6 psia. Refer to figure A.6 for the remainder of the discussion in this section. Gaseous hydrogen and oxygen at ambient temperatures are supplied from high-pressure storage bottles and used as propellants for the rocket engine. The propellant firevalves open to allow the desired amount of mass flow enter the engine for the selected combustion parameters (P_c and O/F). The igniter ignites, and the engine begins firing. A typical engine runs for a approximately 3 to 4 seconds.

The exhaust gases flow into the pumping diffuser where the kinetic energy of the exhaust is used to accomplish a portion of the altitude pumping [2]. This pumping action further reduces the test capsule's pressure to between 0.03 to 0.05 psia. A steady-state pressure condition would be achieved at approximately 2.5 seconds, allowing about 0.5 second of steady state data to be obtained before shutdown [3]. The exhaust gases are moved from the diffuser into the spray cooler. These gases are

removed by two means [4]. Approximately half of the exhaust gases (product of hydrogen/oxygen combustion) are condensed to water in the spray cooler. This water, along with the cooling spray water, exit the spray cooler though a vertical drain line into the detention tank. This vertical drain line functions as a barometric leg, allowing water to exit while preventing atmospheric air from entering the spray cooler. The remaining exhaust gases (the noncondensibles) are pumped by the gaseous nitrogen driven ejectors shown mounted on top to the spray cooler (Figure A.3 or A.6). Four ejectors, connected in a series-parallel arrangement, provided two trains of two stages each. The exhaust from these ejectors is directed up though two short stacks and vented to the atmosphere. The nitrogen ejectors could by themselves maintain an altitude for about 60 seconds.

At rocket engine shutdown, the exhaust flow through the diffuser stops, and a pressure pulse backflows from the spray cooler into the test capsule, raising the test capsule pressure back to the original 0.3 to 0.6 psia. Experience has shown that the pressure pulse has not damaged the rocket engine nozzle.

At this time, two isolation valves between the ejectors and the spray cooler close, and the gaseous nitrogen to the ejectors is turned off. The air ejector maintains the test capsule at about 0.5 psia. The process would repeat itself for more firings. If testing for the day is complete, the pressure in the test capsule is slowly raised to atmospheric pressure by bleeding air through a small valve.

CHAPTER III

THE PROPELLANT SYSTEM

3.1 Introduction

Gaseous oxygen and hydrogen are the propellants for the high area ratio 1030:1 rocket engine tested in B Stand. Supply pressures ranging from 1,500 to 6,000 psig are connected to the test stand with stainless steel pipelines and tubing. These systems provide the capability to test engines without the need for high pressure rocket turbomachinery and pumps. Hydraulic, variable position firevalves control the propellant gas flow to the rocket engine.

This chapter will go into greater detail about the propellant system used for these tests. Figure A.7 shows the propellant system from the tanks to the engine, while figure A.8 shows a closer view of the propellant system near the rocket engine and its instrumentation.

3.2 Description

For the following description, refer to figure A.7. The fuel propellant system utilizes a GH_2 trailer and is supplemented by a 4,000 psig tank. If higher fuel pressures are needed, a 6,000 psig tank can be connected to the system. Theses systems feed the engine injector, and will be referred to as the injector lines. The system uses pneumatic open/close valves to isolate the tanks from the engine. Pressure regulators are used to set the appropriate pressure in the trailer and 4K psig fuel line. The pressure regulator set point is a function of the chamber pressure plus line losses. For instance, if the engine P_c is 350 psia, the pressure regulator may be set at two

times 350 psia, or 700 psia. Branching off the 4K psig injector line, is the supply to the engine ignitor. This ignitor line also contains a shut off valve and a calibrated orifice sized for the ignitor. Both the 4K psig injector line and the trailer injector line connect and enter a calibrated venturi. This venturi is used to measure the flow rate of the propellant. Upon exiting from the venturi, the fuel injector line is connected to the firevalve. This is a hydraulically operated valve that is controlled by the controller in the ROB, and is used to set the mass flow for the desired combustion parameters. See Chapter IV, Section 4.5 for more information on the controllers. The firevalve plugs used during this test series were linear. In other words, on a percent flow versus percent opening chart, the graph would be a straight line. Once passing through the firevalve, the fuel ignitor line is attached the engine ignitor.

The oxidizer (GO_2) propellant system is very similar to the fuel system. However, the oxidizer uses a tank farm and its pressure can vary depending on the test conditions. Other than the calibrated and sized items in the oxidizer line, the two propellant systems are the same.

CHAPTER IV

CONTROL AND DATA SYSTEMS

4.1 Introduction [1]

The RETF test stands are remotely controlled from the control room in the Rocket Operations Building (ROB). Manual, automatically timed, and computers control the facility instrumentation, data acquisition, hydraulic servo systems, valve operations, and the rocket engine operation. A combination of solid state, programmable and manual sequence timers provide propellant flow control, sequence timing, and cut-off control for the rocket engine during a test firing.

Data are processed through a 200 channel high speed (31K Hz) digitizer/multiplexer data acquisition system, and are fed by a digital data link to the Lewis Research Center central data system (VAX Cluster). This system provides millivolt to engineering units conversion and on-line data reduction capabilities to the control room.

4.2 Sequence Timers

The discrete (open or closed, no analog inputs or outputs) sequence timers provide the timed sequence of events from shutting off engine purges, flowing propellant, to providing the shutdown sequence. They also ramp the ejectors up and down during startup and shutdown procedures. RETF uses two types of timers: a Gould Modicon model 384 Programmable Timer and a in-house built, discrete hardware timer. Figure A.9 is a picture of the in-house built, discrete hardware timers. This seems to be a dichotomy of technology, however there is a good reason for it, as the following paragraphs will describe.

The actual testing of the rocket engine is divided into four time or sequence of operation zones: zones 1-4. Zone 1 shuts off the purges and pre-chills, starts the water flows (engine cooling and scrubber water), and turns on the instrumentation with sensors on the engine and around B Stand. Basically, Zone 1 times all of the events that lead up to the actual firing of the engine. Zone 2 times the propellant valves, ignitor, etc. It also is responsible for shutting the engine down. Zone 3 provides the timing sequence for shutdown of the facility, i.e., purges start up, ejectors ramp down, etc. Zone 4 handles the sequence of events for an abort of an engine firing.

Why are these operational zones important? The Modicon is responsible for zones 1, 3, and 4 while the discrete hardware timers handle zone 2. The reason for this configuration is quite simple: the Modicon scan rate cannot operate fast enough to coordinate all of the events that take place in a 3-4 second rocket engine firing. The discrete hardware timers can, and therefore, are assigned the responsibility of sequencing the actual engine firing. Table B.1 is a summary of sequential timer's zone of responsibility and the activity that takes place in that zone.

4.3 Data Computers

The RETF uses a TRADAR* system for data gathering. The TRADAR is composed of a NEFF** front end and a DEC PDP 1123 computer. Both the NEFF front end and the DEC PDP 1123 are located in the ROB. The NEFF front end is simply an amplifier buffer that gathers the raw data from the rocket engine and the test facility instrumentation. The PDP 1123 serves as the "brains" for the TRADAR

---

* Transient Research Data Reduction

** NEFF is the name of the computer company that built the front end.

system. It basically controls the data flow, initializes the disks, sets the number of samples to take, where to store the data, etc. After the TRADAR system is finished doing its tasks, it sends the data to the VAX Cluster for data analysis. The VAX Cluster is located at the central computing facility and used for millivolt to engineering units conversion and post test data analysis.

The following discussion describes the data flow from the instrumentation to post test analysis. The TRADAR (NEFF front end, in particular) is triggered by the Modicon in zone 1 to begin taking data from the rocket engine and test facility. The TRADAR will run an internal program that will automatically shut itself off at a desired point in time. The data is taken throughout the test firing, sequentially (approximately 500 blocks) or continuously, depending on the test format. Data is taken at 200,000 samples a second. In zone 3, the front end stops taking data.

Next, the NEFF front end digitizes the data and sends it to the PDP 1123. The PDP 1123 determines where the data is to be sent and stored. From the PDP 1123, the data now travels to the VAX Cluster. There, the digitized millivolt data is converted to engineering units and post test analysis begins. When this segment is completed, the data is printed out and stored at the ROB for use by research and test engineers

4.4 Signal Conditioners

Signal output from pressure transducers, venturi flow meters, turbine flow meters, thermocouples, etc., all require the use of signal conditioners. These types of instrumentation are calibrated at an on-site calibration laboratory to a reference calibration (RCAL) that is traceable to NIST* . During the pre-test set-up, a

* National Institute of Science and Technology.

technician will use the RCALs to set the signal conditioners. Therefore, there is a match between the instrumentation and signal conditioner.

Each morning during a test day the "zeroes" are checked in order to find any drift that might have occurred between test days. If there is a zero-shift, then the TRADAR signals an error. That error could be due to a bad transducer, signal conditioner, or electrical resistance drift. Also, an electronic calibration of 20 mv (full scale) is done before and after each engine test firing* to insure that the instrumentation is reading accurately. The VAX Cluster uses the calibrations for conversions from millivolts to engineering units.

4.5 Controllers

The controllers used to adjust the oxidizer and fuel propellant valves for desired mass flows are BAFCO Model 884 Servo Controllers. Built in the 1970's, they are two stage controllers comprising a first stage that is a proportional/integration/ differential controller (or parameter controller) and a second stage that is a proportional controller (position controller). Since valve position is being measured and adjusted, only the second stage is used.

These controllers are electronically tied to MOOG hydraulic servo valves. The MOOG, in turn, controls the firevalve. The servo valve provides a resistor potentiometer feedback that measures valve stroke position and sends the measurement back to the controller. The controller compares the MOOG feedback to the desired input set by the test engineer. If the desired input and the feedback don't match, then

* An engine firing is sometimes referred to as a run.

the error between the two is sent to the MOOG to adjust the valve position. The cycle continues until the error becomes zero.

CHAPTER V

THE ROCKET ENGINE

5.1 Introduction

This section of the thesis will describe the rocket engine that was tested at NASA Lewis's Rocket Test Facility, B Stand. It is useful to understand the type of rocket engine tested because it's operating parameters (O/F and P_c) provide specific input to POTPRED.

5.2 Test Objectives and Conditions

The majority of information in this section and the discussions on the construction, throat section, and the nozzle of the rocket engine were taken from Smith [3], NASA Lewis Research Center, unless otherwise noted. Her discussions of the rocket engine were very detailed and provided good insight into the design, operation, and test of the rocket engine.

The primary purpose of the rocket engine tests were to determine the rocket engine chamber pressure at which the boundary layer flow in the NASA Lewis 1030:1 nozzle is laminar, and at which pressure it will be turbulent, at a simulated altitude of about 200,000 feet. This information is needed in interpreting the measured thrust performance of the nozzle and to accurately predict its performance for specific test conditions. In 1986, the performance of a 1030:1 rocket nozzle at a chamber pressure of 350 psia was measured at the NASA Lewis Research Center. A subsequent study determined that the flow within the nozzle was laminar. There is a need to determine the chamber pressure of the engine which will produce fully developed turbulent

boundary layer flow in the nozzle since turbulent flow produces more viscous drag than laminar flow and occurs in most high Reynolds number nozzle flows. Therefore, the zones of laminar, transitional, and turbulent boundary layer flow need to be defined for this nozzle as a function of Reynolds number or chamber pressure.

Tests were performed at chamber pressures (P_c's) from 350 to 1,000 psia, and at a simulated altitude of about 200,000 feet. The propellants used were gaseous oxygen and gaseous hydrogen. Thrust measurements and nozzle outer wall temperature measurements were taken during the 3 second test runs. The 3 second run times provided enough time for the engine to reach steady state thrust and nozzle pressure and temperature conditions. See sections 5.3.1 through 5.3.3 for further details on the rocket engine hardware.

5.3 Construction

The NASA Lewis 1030:1 rocket engine hardware consists of four components: the injector, the combustion chamber, throat section, and the nozzle skirt (exit nozzle). Figure A.10 is a drawing (not to scale) of the engine. As shown, the combustion chamber was 6.0 in. long and had an internal diameter of 2.055 in. This combustor was made of copper with 1.0 in. thick walls and was uncooled (heat sink) hardware. The following three sections provide further detail on the injector, throat section, nozzle.

5.3.1 Injector [3]

Typically, a coaxial, concentric tube injector element (oxygen in the center tube with hydrogen flowing around the oxygen tube) is used in the rocket engine. However, it was discovered that there was uneven heat flux with this type of injector. This heat

flux is important because uneven burning of the propellants in the combustor can produce "hot spots" that may result in burn throughs. Therefore, a new injector was needed. Designed at NASA Lewis Research Center, a rigimesh injector was built. This injector was used in the 1030:1 test program, and comprised of a thirty six tube, gaseous oxygen showerhead with gaseous hydrogen co-flowing through a porous faceplate (or rigimesh). See figure A.11 for details. This injector proved to mix the propellants better than the concentric tube injector, creating a uniform distribution of propellant exhaust gas composition across the exhaust flow. Also, because of this design, the injector face plate was cooled by the fuel flow through the rigimesh, allowing for a longer injector life.

5.3.2 Throat

The throat section had a half angle of convergence of 25° and a contraction ratio of 4.223. The radius of curvature upstream was 1.0 in. and downstream was 0.2 in. The throat section converged to a 1.00 in. throat and then diverged to an area ratio of 29.9. For the 350 psia chamber pressure tests, the throat section was made of nickel with ceramic coating on the inner wall and a water jacket around the throat that extended to an area ratio of approximately five. For all other tests, the throat section was made of copper with water coolant channels along the entire length of the section.

5.3.3 Nozzle

The tested hardware was an optimally designed bell nozzle. The nozzle skirt section extended form an area ratio of 29.9 to 1030. The axial length was approximately 4 ft and the exit plane diameter was 32 in. This section was made of

0.25 in. thick carbon steel and was uncooled (heat sink) hardware. Figure A.12 shows the engine with a 1030:1 area ratio nozzle under test.

The nozzle contour past the throat was designed using the Rao Nozzle Contour Program and the Boundary Layer Integral Matrix Procedure (BLIMP-J) Program.

At this point, a little history is needed to shed some light on Rao's method for optimal nozzle design. Rao [5], worked out the theory for the optimization of a gas dynamic nozzle contour. Rao noted that the German scientists Guderley and Hantsch attempted an approach where they assumed that within the nozzle, a surface could be defined as a control surface for momentum, mass flow, and the given nozzle length. They assumed that the control surface was a characteristic surface. This is a surface on which the flow variables would be constant, but across which the variable could change discontinuously. Rao attempted a similar approach, but did not specify the nature of the control surface. It is important to note that another constraint of the problem is that the optimal contour be obtained by a process that conserves mass flow, momentum and total energy of the exhaust flow. Rao's method is based on a conservation of mass flow constraint. The method does result in the other fluxes being conserved. The result is a minimum length nozzle, for a desired exit Mach number, that provides optimum thrust.

The BLIMP-J program, by Evans [6], describes a JANNAF (Joint Army, Navy, NASA, Air Force) standardized procedure for predicting boundary layer development in liquid rocket engine nozzles. A computer program, designated as Version J of the Boundary Layer Integral Matrix Procedure, hence, BLIMP-J, computes the nonsimilar chemically reacting laminar or turbulent boundary layer for ablating, transpiration cooled or nonablating internal flow configurations. The program uses a novel numerical solution procedure, termed an integral matrix approach, which is equivalent

to a higher order finite difference approach (using spline fits). Thus, the code is capable, within practical limits, of obtaining very accurate and economical solutions to the governing differential equations (momentum, energy, and species) for viscous boundary layer flow.

Smith [2] states that the Rao program calculated the inviscid optimal nozzle contour with GH_2/GO_2 propellants, a 1 in. throat, a 1,000 psia chamber pressure, and a nozzle length appropriate for a 1030:1 area ratio nozzle. Using the Rao nozzle contour outputs, the BLIMP-J program was run with GH_2/GO_2 propellants, a chamber pressure of 1,000 psia, mixture ratio of six, and an estimated inner wall axial temperature distribution [3] to calculate the boundary layer displacement thickness and other characteristics along the nozzle. The BLIMP-J program then added this thickness to the original Rao contour at all stations along the flow axis. Thus, a new contour was produced that had an estimated "inviscid" core in the center with the boundary layer thickness added to the outside. In other words, the BLIMP-J boundary thickness was added to the Rao Contour core to produce the nozzle coordinates that were used to manufacture the hardware. As seen in figures A.4 an A.12 show the end result of the Rao/BLIMP-J nozzle design.

CHAPTER VI

POTPRED DESCRIPTION

6.1 Introduction

The previous chapters described the test facility and the rocket engine which constituted the test program from which data was obtained in order to develop this code. These chapters are important because they set the stage by describing the type of rocket engine, the specific test configuration, what type of data, and how the data is taken. That information is used in POTPRED to help the test engineer set the firevalve controller potentiometers that set the desired performance of the rocket engine.

How does data from the test run interact with POTPRED? The measured rocket chamber pressure, the measured propellant mass flows and their respective controller potentiometer settings, the supply pressures, firevalve C_v's, the measured C^*, and the desired O/F and chamber pressures are entered into the POTPRED program. The desired O/F and chamber pressures are the values the test engineer wants the engine to operate at for the next test firing. Based on that entered data, POTPRED performs several calculations and a curve fit. When those operations are complete, POTPRED outputs the new controller settings and their respective mass flows. The test engineer then sets the firevalve controllers to POTPRED's predictions in preparation for the next test firing. As this process continues, the data files are updated, and the prediction ability of POTPRED becomes more accurate. For the purposes of this thesis, POTPRED was configured for the 1030:1 area ratio rocket engine using gaseous oxygen and hydrogen.

POTPRED can be used for other rocket engines with little reprogramming, however, new data files need to be built that represent a particular rocket engine and test conditions. These data files would contain controller settings, mass flows, and the slopes of their lines for each of the types of engines tested.

6.2 POTPRED Structure

POTPRED is a FORTRAN program containing a main control program that carries out the coordination of the subroutines, interacts with the data files, and provides for over all management of the program. Subroutines are set up functionally to perform particular activities necessary for determining the new potentiometer settings, while the data files contain data representative of a particular rocket engine and test conditions. Figure A.13 is a simple flow diagram of the program.

6.3 Subroutines

Subroutines are the modules that perform specific functions, i.e., curve fitting, interacting with the user to initialize the program, saving data, etc. The following subsections will describe each of the subroutines, discuss their major equations, and describe the general "flow" of data through them.

6.3.1 NDATA

The NDATA subroutine calculates the slope and y-intercept of the entered data and predicts the controller settings based on the propellant mass flow data provided by the CALCS subroutine. Interacting with the user, basic information including the run date, firevalve C_v's, propellant supply pressures, run number, the oxidizer and propellant controller potentiometer settings, and the corresponding propellant mass

flows are entered into POTPRED. In addition to interacting with the user, the subroutine calls gaseous oxygen and gaseous hydrogen data files. These files contain supply pressures, valve C_v's, and slopes for the curve fits. By using this data and the data entered by the user, this subroutine calculates a new slope and y-intercept based on the curve fit of all the data for a particular tank pressure. The first time through this routine during a run day, the code searches the data files for a matching tank pressure. If it finds a match, then there is historical data for the slope and firevalve C_v. The subroutine uses this data to calculate the slope and y-intercept of the oxidizer and fuel. However, if there is no match, the subroutine prompts the user for the closest match and uses that data to continue with the calculations. A problem arises when, during the test day the test engineer changes the tank pressure because of a required change in the test program. Changing the tank pressure changes the slope of the curve. An increase in tank pressure inversely affects the slope, as can be seen in figure A.14. Therefore, propellant supply pressures become another set of variables for the problem. Incorrect tank pressure would cause the program to calculate incorrect slopes in the regression analysis, and result in poor controller setting predictions.

Subroutine NDATA transfers the predicted inputted oxygen and fuel mass flows to subroutine CALCS. CALCS predicts new oxidizer and fuel mass flows for the next run based on the desired next run chamber pressure, next run desired O/F, current, actual chamber pressure and actual flows. When CALCS is finished calculating the next run predicted propellant mass flows, it transmits them back to NDATA. NDATA then transposes the actual input oxygen and fuel data (propellant mass flows, controller potentiometer settings, and supply pressures) with specific variables into generic variables. The reason for this is to reduce the size of the code by not having to use separate slope and y-intercept calculations for the oxidizer and fuel. Instead, by using

generic parameters, the slope and y-intercept equations can accommodate both the fuel and oxidizer information.

Next this subroutine code performs a least squares linear regression on the data. Calculating the slope from the equation:

$$m = \frac{\sum x_i \sum y_i - n\sum x_i y_i}{\left(\sum x_i\right)^2 - n\sum x_i^2} \qquad \text{[7, pg. 535]} \quad (6.0)$$

where m is the slope of data points, x_i is each individual x coordinates for the data set, y_i is each individual y coordinates for the data set, and n is the total number of data points in that data set.

In terms of the equation used in the POTPRED slope equation above can be written as:

$$\text{m=(((TFLO*TPOT)-(TS*FLOPOT))/((TFLO**2)-(TS*SFLO)))} \qquad (6.1)$$

where TFLO is the summation of the mass flow data points (equivalent to $\sum x_i$), TPOT is the summation of the controller settings (equivalent to $\sum y_i$), FLOPOT is the summation of the product of the mass flow and controller settings (equivalent to $\sum x_i y_i$), SFLO is the summation of the square of the mass flows (equivalent to $\sum x_i^2$), and TS is the number of data sets with the same supply pressures and firevalve C_v's. POTPRED groups data by supply pressures and firevalve C_v's, and only uses data (controller settings, oxidizer mass flows, and fuel mass flows) within that criteria for the slope calculations (equation 6.1). When a new run tank pressure is used, POTPRED searches the appropriate data files for matching supply pressures and

firevalve C_v's and uses that data for calculating the slope. Following the slope calculation, the y-intercept is determined using:

$$b = \frac{\sum y_i - m\sum x_i}{n} \qquad \text{[7, pg. 535]} \quad (6.2)$$

or as used in the program:

$$B = ((TPOT-(M*TFLO))/TS). \qquad (6.3)$$

where B is the y-intercept, TPOT is the summation of the controller settings (equivalent to $\sum y_i$), M is the slope calculated by equation 6.1, TFLO is the summation of the mass flows (equivalent to $\sum x_i$), and TS is the number of data sets with the same tank and valve C_v's. The new potentiometer settings are calculated using

$$NPOT = (M)(NFLO)+B, \qquad (6.4)$$

for both the oxidizer and fuel. NPOT and NFLO are generic variables used for either the oxidizer calculations or the fuel calculations. NFLO is the new flow (either oxidizer or fuel) calculated by the CALCS subroutine, M is the slope from equation 6.0, and B is the y-intercept found by equation 6.3. For the next test run, the test engineer would set the firevalve controllers to NPOT calculated by this equation.

Before leaving this subroutine, the SAVE subroutine is called to save the current slopes for the oxidizer and fuel in their respective data files.

6.3.2 SAVE

As this subroutines name implies, it is used to store the updated slopes. If the firevalve C_v is not in the data file, then the supply pressures, firevalve C_v's, and the newly calculated slopes are saved. However, if the only change is the tank pressure, then that is all that is updated in the data file.

6.3.3 CALCS

This subroutine calculates the new propellant mass flows for the next run based on desired chamber pressure, actual chamber pressure*, desired O/F, measured C^*, measured oxidizer flow, and measured fuel flow.

The subroutine interacts with the user by asking for the desired and actual chamber pressures, the desired O/F, and the measured C^*. Using this data and the data transferred from the NDATA subroutine, the new propellant flows for the next test run are calculated.

Using the characteristic velocity efficiency equation [4],

$$\eta_{C^*} = \frac{C_m^*}{C^*} \tag{6.5}$$

where C_m^* is the measured characteristic exhaust velocity, and C^* is the desired (ideal) characteristic exhaust velocity or $C^* = C^*_{desired} = C_d^*$. Realizing $C^* = \frac{P_c A^*}{\dot{m}_{tot}}$, and substituting into equation (6.5),

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* The actual chamber pressure is sometimes referred to the measured chamber pressure in this document.

$$\eta_{C^*} = \frac{C_m^*}{C_d^*} = \frac{P_{c_m} A_m^* / \dot{m}_{tot_m}}{P_{c_d} A_d^* / \dot{m}_{tot_d}} \tag{6.6}$$

Solving (6.6) for $\dot{m}_{tot_d}$:

$$\dot{m}_{tot_d} = \dot{m}_{tot\,m}\left(\frac{C_m^*}{C_d^*}\right)\left(\frac{P_{c_d}}{P_{c_m}}\right). \tag{6.7}$$

To find the fuel mass flow, use:

$$\dot{m}_f = \frac{\dot{m}_{tot}}{\left(1+\frac{O}{F}\right)}. \qquad [4] \tag{6.8}$$

Since the desired fuel mass flow is based on a desired O/F and a desired total mass flow, substitute $\dot{m}_{f_d}$ for $\dot{m}_f$, $\dot{m}_{tot_d}$ for $\dot{m}_{tot}$, and $\left(\frac{O}{F}\right)_d$ for $\frac{O}{F}$ in equation (6.8) yields,

$$\dot{m}_{f_d} = \frac{\dot{m}_{tot_d}}{\left[1+\left(\frac{O}{F}\right)_d\right]} \tag{6.9}$$

Solving (6.9) for $\dot{m}_{tot_d}$:

$$\dot{m}_{tot_d} = \dot{m}_{f_d}\left[1+\left(\frac{O}{F}\right)_d\right] \tag{6.10}$$

Substituting (6.10) into (6.7)and solving for $\dot{m}_{f_d}$, get

$$\dot{m}_{f_d} = \frac{\dot{m}_{tot_m}\left(\frac{C^*_m}{C^*_d}\right)\left(\frac{P_{c_d}}{P_{c_m}}\right)}{\left[1+\left(\frac{O}{F}\right)_d\right]} \tag{6.11}$$

where $\dot{m}_{f_d}$ is the desired fuel mass flow. The desired fuel mass flow as described in (6.11) is actually the new fuel mass flow based on the measured total flow, the measured C^* (user input), the desired C^* (calculated by POTPRED), the desired P_c (user input), the measured P_c (user input), and the desired O/F ratio (user input). The desired C^* is calculated by interpolating the curves in the graph located in figure A.15. Figure A.16 is a similar curve, and is for informational purposes only. Reflecting this, the new fuel mass flow can be rewritten as

$$\dot{m}_{f_n} = \frac{\dot{m}_{tot_m}\left(\frac{C^*_m}{C^*_d}\right)\left(\frac{P_{c_d}}{P_{c_m}}\right)}{\left[1+\left(\frac{O}{F}\right)_d\right]} \tag{6.12}$$

where $\dot{m}_{f_n}$ is the new fuel mass flow based on the desired inputs for the next run. Rewriting equation (6.12) using variables in the POTPRED program for the desired gaseous hydrogen mass flow:

$$\text{NFLFLO} = \text{PERC}/\{\text{OF(n)}+1\} \tag{6.13}$$

where

$$\text{PERC} = \text{PROP}*\text{FLOT}*\text{PCSTAR}, \tag{6.14}$$

and

$$\text{OF(n)} = \text{the desired O/F} \tag{6.15}$$

PROP is the ratio of the desired P_c to the measured P_c, FLOT is the total mass flow based on the measured oxidizer and fuel flows, and PCSTAR is the ratio of the measured C^* to the desired C^*.

To find the gaseous oxidizer mass flow, with

$$\frac{O}{F} = \frac{\dot{m}_o}{\dot{m}_f} \tag{6.16}$$

where O/F is the desired O/F, the equation can be written as

$$\left(\frac{O}{F}\right)_d = \frac{\dot{m}_{o_d}}{\dot{m}_{f_d}} \tag{6.17}$$

Solving for $\dot{m}_{o_d}$ gives

$$\dot{m}_{o_d} = \left(\frac{O}{F}\right)_d \dot{m}_{f_d}. \tag{6.18}$$

Since the desired oxidizer mass flow is actually the new oxidizer mass flow and substituting the new fuel mass flow for the desired fuel mass flow ($\dot{m}_{o_d} = \dot{m}_{o_n}$ and $\dot{m}_{f_d} = \dot{m}_{f_n}$), rewriting (6.18), get

$$\dot{m}_{o_n} = \left(\frac{O}{F}\right)_d \dot{m}_{f_n} \tag{6.19}$$

where $\dot{m}_{o_n}$ is the new oxidizer mass flow for the next run. Since $\dot{m}_{f_n}$ was found in equation (6.12), the new oxidizer flow is easily calculated. Rewriting equation (6.19) in terms of POTPRED variables

$$\text{NOXFLO} = \text{OF(n)}*\text{NFLFLO.} \tag{6.20}$$

where NOXFLO is the new oxidizer flow, OF(n) is the desired O/F ratio, and NFLFLO is the new fuel flow.

Once these calculations are completed, they are transferred back to the NDATA subroutine to be used to calculate their respective controller potentiometer settings.

6.3.4 TANK

The TANK subroutine calls the various data files that contain actual data consisting of slopes, firevalve C_v's, and supply pressures. The tank pressure and firevalve C_v is sent from NDATA to TANK. First, the firevalve C_v that was entered by the user is compared to actual firevalve C_v's that exist at the test facility. This comparison is done directly in the TANK subroutine, not by using a data file. If there is no match, the user is prompted to enter a firevalve C_v that is closest to the existing

firevalve C_v's. The facility operator needs to update this part of the program if a new firevalve plug is used to configure the propellant system, and the new firevalve C_v isn't listed in this subroutine. If this is the first run with either a brand new firevalve C_v, or a tank pressure that doesn't exist in the data file, then two runs are for regression analysis slope. Typically, picking data that is close to the user's anticipated settings/configurations provides the first data point for the linear regression. The second test run will provide the second data point, and linear regression can begin.

6.3.5 PLOT

The PLOT program [8] (behaves like a subroutine) does what the name implies. It plots the actual propellant mass flows and their corresponding firevalve controller potentiometer settings along with the linear regression data. Therefore, at the end of a test firing series (or test day) POTPRED uses the PLOT program to plot two controller setting versus mass flow plots. One for the oxidizer and one for the fuel. Because of the linear firevalve plug, the data plotted gathers in a linear form. Figure A.14. is a generic controller potentiometer setting versus propellant (oxidizer or fuel) mass flow graph. Notice that the tank pressure is inversely related to the slope of the line, i.e., the steeper the line, the smaller the tank pressure.

The PLOT program is located in a batch file external of the POTPRED program. This means that after exiting POTPRED, the batch file calls the PLOT program to plot the day's data points.

These plots provide the test engineer with hard copy plots that he can use for the next test series to accurately configure the rocket engine's combustion parameters i.e., O/F and P_c.

6.3.6 VIEW

The VIEW subroutine takes the data entered into the test day identifier data file, performs a series of comparisons, reformats into a configuration that the PLOT program can recognize, and stores the data into data files used for plotting as discussed in section 6.4.1.

6.3.7 PRPLNT

The PRPLNT subroutine provides the user with options on the type of propellants used for rocket engine test program. For the 1030:1 area ratio nozzle engine program, only GH_2 and GO_2 were used as propellants, therefore, there are no choices. However, if the engine was tested with cryogenic propellants, then that would be an option.

This subroutine can be expanded to include the type of test stand, i.e., A Stand or B Stand. Based on the type of test stand inputted, POTPRED would use historical data pertinent to that particular stand.

Therefore, for this document, the PRPLNT subroutine only "opens" data files relating to gaseous oxygen and hydrogen and B Stand for POTPRED to use for its calculations and linear regression. There are no other options.

6.4 Data Files

POTPRED uses five primary data files. These include BGOX.DAT, BGH2.DAT, OPLOT.DAT, FPLOT.DAT and the test day identifier data file. It is intended that the names of these data files describe their use, and will be described in greater detail in the following two sections.

The first two data files contain information necessary for POTPRED to perform the linear regression calculations. The second two data files contain the information entered into the POTPRED program and the linear regression data calculated by POTPRED to use for plotting controller settings versus propellant mass flows for both the oxidizer and fuel. The test day identifier data file stores the data that a test engineer would keep for documentation purposes.

6.4.1 BGOX.DAT and BGH2.DAT data files

The data files used by POTPRED program are BGOX.DAT and BGH2.DAT. The "B" in the data file name references the test stand, and the "GOX" and "GH2" represent the types of propellant used by the large area ratio engine, i.e., gaseous oxygen and gaseous hydrogen, respectively. Appendices D and E list the data contained in each of these data files. These data files contains past and present firevalve C_v's (in the first column), supply pressures that large area ratio engine has been tested at (the second column), and the slopes calculated by linear regression. The number located at the upper right above the first column is the total number of entries in that data file used by POTPRED subroutines for storing and retrieving data.

POTPRED searches these data files for matching firevalve C_v's, and supply pressures that the test engineer would input for his test configuration. If there is a match for both of these variables, then POTPRED uses the assigned slope. If there is a match for one, but not the other, POTPRED prompts the user to either choose a chamber pressure or firevalve C_v that is closest to the test facility configuration, and the nearest slope is used. This procedure is done for the first test point in order to provide a second data point for linear regression to begin. As the test firings accumulate, the slope becomes increasingly more accurate.

With new information, POTPRED updates the C_v's , supply pressures and slopes as the test firings continue. Therefore, the data files are continually updated.

6.4.2 OPLOT.DAT and FPLOT.DAT data files

As the titles of these two data files infer, they are used to plot the actual controller potentiometer setting versus the corresponding mass flow along with the linear regression performed on those points for both the oxidizer and fuel. Appendices F and G list the data these two files contain for a typical test firing.

After the test day is complete, POTPRED enters all of the controller settings and propellant mass flows into their respective data files. The PLOT program [8] is then used to plot controller potentiometer settings versus mass flows. Therefore, at the completion of a test day, POTPRED provides the test engineer with two plots (oxidizer and fuel) of controller settings versus propellant mass flows as a permanent record.

6.4.3 Test Day Identifier data file

This data file contains information the test engineer may use for documentation purposes. It also serves as a historical reference for that run day.

The test day identifier is a series of letters and numbers describing which test cell is used, the propellants, and how many test days there were in this configuration. For example, a test day identifier might look like: BHO066. This is how one could interpret this particular identifier:

B - the test stand,

HO - the propellants, hydrogen and oxygen,

066 - the number of days tested for this rocket engine program.

The test day identifier data file would be named after the test day identifier without the extension, i.e., BHO103 not BHO103.XXX.

This data file contains information such as the test day identifier, the number of test firings that day, the date of the test firings, the run number, the firevalve C_v, the controller potentiometer settings, respective propellant mass flows, and the respective propellant supply pressures. The run number is a sequential numbering of the number of rocket engine test firings for a particular program. See table B.2 for an example of a run day identifier data file.

CHAPTER VII

DISCUSSION AND CONCLUSION

7.1 Discussion

For rocket test stand B, NASA Lewis Research Center, the process for determining firevalve controller settings that regulate gaseous rocket propellant mass flow, based on desired engine combustion parameters (O/F and P_c), was manually intensive requiring time to calculate, plot, and predict controller settings. This process lends itself to human errors. These errors can lead to incorrect engine performance resulting in extra rocket engine test firings. Extra test firings reduce the life of the research hardware, increase the cost of testing, and may result in a loss of test objectives and hardware.

Potential solutions to this problem were reviewed. One solution involves setting the propellant supply pressures for their respective mass flows prior to the engine firing. This solution can work, and has been proven in the past. However, there are limitations. By changing the supply pressure, the slope of the lines on the controller setting versus propellant mass flow graph change (see figure A.14), and the test engineer may not know what curve this new supply pressure will be on until the test run is completed . This change in slope is a result of new regulated pressures creating new propellant densities and new firevalve flow areas. This increases the difficulty of predicting mass flow. Also, adjustments to the regulated pressure are course. It is difficult to "hit" the same pressure from test run to test run, and may require several iterations to get the desired supply pressure. Finally, this method doesn't lend itself to

throttling. To throttle the engine by varying the propellant mass flows, during the engine operation, by adjusting the propellant supply pressures could achieve the desired results for relatively slow operations or long duration tests. However, for very short duration testing, this is not possible. Varying supply pressures is long and slow compared to the typical engine test.

Another solution is to provide a feedback mechanism between the firevalve and a mass flow metering sensor to set up a control system for automatically adjusting the mass flow. During the mid 1980's, computers weren't fast enough to sample the engine P_c and O/F, calculate new firevalve positions, and adjust the firevalves (adjust propellant mass flows) to reach the desired O/F and P_c during a 3-4 second test firing. It was estimated that a sampling rate of 50 Hz was required to perform this function. Also, digital technology wasn't cost effective. Today, the speed is available, and the digital technology is reasonably priced. However, despite the strong interest in applying this technology to the firevalve controller system, no action has been taken to install it.

The third solution, adopted by the NASA Lewis Research Center, was to develop a methodology for accurately predicting controller settings based on historically obtained test data to set firevalve plug positions (mass flows) for desired rocket engine O/F's and P_c's. The historical database is obtained from existing hardware. This thesis automated and computerized the process of analyzing the database for pre-test firevalve controller settings. Before this thesis, the task was done entirely by hand. The automation provided by this thesis is a solution to a real world problem!

POTPRED was written to reduce the number of errors the test engineer might make in calculating the slope and y-intercept of the data points, performing linear

regression on those data points, predicting the new controller settings based on O/F and desired P_c for the next test firing, and calculating the respective propellant mass flows for the controller settings.

Besides reducing errors, POTPRED reduces the time between test firings. Typically, the technicians, mechanics, and research engineers are ready to test relatively quickly after a rocket firing. While the test engineer is busy calculating and plotting, every one waits. This time between rocket engine firings increases the test costs because in order to maintain a nominal altitude consumables are being used. POTPRED reduces this time significantly. Once the data is entered, its a matter of seconds before the predicted controller settings are calculated.

7.2 Results and Conclusions

Table B.3 in Appendix B is a sample of actual test data used by POTPRED to predict controller settings. Also included in the table is the error between POTPRED's results and the actual data. POTPRED's predictions are located in the desired or predicted columns. Errors for the oxidizer flows based on POTPRED's controller setting predictions for runs 147 to 149 were between 1.43% and 0.402%. While runs 150 to 152 demonstrated errors between 2.65% and 0.100%. It is interesting to note that runs 148 and 151 had a smaller errors than last runs 149 and 152. Despite this anomoly, the errors were relatively small.

Errors for the fuel flows based on POTPRED's controller setting predictions were between 11.76% and 3.12%. For runs 150 to 152, the errors were between 4.73% and 0.059%. Errors were large for the first run and reduced as more data points were gathered. The larger error in the first run of each of these O/F groups depicts a small amount of historical data contained in the BGH2.DAT data file. As

demonstrated, POTPRED's predictions became more accurate as data points were gathered.

Looking at the O/F, errors ranged from 1.33% to 13.17%. The 13.17% error was due to the high error in the fuel controller setting prediction, since O/F is primarily a function of the fuel. For both sets of data (O/F's of 5.5 and 6), the error is reduced as the number of data points increases. Since the chamber pressure is constant for all of the data points in this series of tests, the data points are moving up and down the controller setting versus propellant mass flow graph. Depending on how many data points are at the 5.5 and 6.0 O/F areas of that graph, depends on how accurate the prediction is. Therefore, since the error diminishes, POTPRED's predicting ability improves.

Chamber pressure errors ranged from 0.850% to 5.51%. Since the oxidizer controller errors are relatively small (as compared to some of the fuel controller errors) and P_c is primarily a function of the oxidizer, small chamber pressure errors would be expected.

Therefore, it has been seen that POTPRED can do the manual calculations and linear regressions normally done by the test engineer. Also, the program has demonstrated that with large data sets, error is reduced. As demonstrated by this thesis, POTPRED is a simple, PC based, inexpensive tool to increase the efficiency of the test engineer and the test program while minimizing calculation errors.

7.3 Future Improvements

Improvements to the POTPRED program could include data files on other types of engines and test stands (altitude versus sea level). Also, the PLOT program could be linked into POTPRED, acting more like a subroutine, to print plots after each

engine test firing instead of at the end of the test day. This would allow the test engineer to see the progression of the linear regression during the test day versus one plot (per propellant) with all the data points at the end of the day.

Another possibility would be to calculate the correlation coefficient [7], r, of the data points on the controller setting versus propellant mass flow chart. The correlation coefficient is calculated by the following equation:

$$r = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - (x_i)^2 n\sum y_i^2 - (\sum y_i)^2} \qquad \text{[7, pg. 536]}$$

The correlation coefficient establishes the correlation (variation) between x and y. If the correlation coefficient is large (0.8 to 1.0), then most of the variation in the dependent variable y (or controller settings) would be accounted for in terms of the independent variable x (or propellant mass flows), and the linear regression relationship provided by $y = mx + b$ (ultimately results in equations 6.0, page 25, and 6.2, page 26) is good. However, if the correlation coefficient is small, $y = mx + b$ is not the correct equation to use for this regression analysis because the relationship between x and y (controller settings and propellant mass flows) is not linear or there are other independent variables that have not been accounted for and may be influencing y (controller settings). In other words, r, would establish the amount of variation between the propellant mass flows and the controller potentiometer settings. This would give the test engineer some insight as to how good the linear regression is, and in turn, allow the engineer to decide if POTPRED's controller prediction should be "tweaked".

A third improvement would include adding A Stand (sea level test stand) and the types of propellants used, and upgrading B Stand to include more propellants to the PRPLNT subroutine. PRPLNT would access more data files similar to BGOX.DAT and GH2.DAT for calculations and linear regression purposes.

Finally, POTPRED could be expanded to include other types of firevalve plugs such as a percentage plug or a semi throttle plug. It's not important to know specifics about these types of plugs, but it is important that they are curvilinear. Therefore, regression analysis would have to be done on curves rather than lines, and this increases the difficulty of programming.

These improvements would allow POTPRED to operate over a wide range of test stands, use many types of propellants, and predict controller potentiometer settings for non linear firevalve plugs. Improvements of this magnitude may make it attractive to other test organizations that use controllers and throttle their rocket engines.

As a result of my observations while stationed at NASA Lewis Research Center, and inputs from the engineers at the RETF today, there continues to be a strong desire to implement POTPRED. At the conclusion of this study, a copy of this document and the software will be provided to them for use in their rocket testing programs.

REFERENCES

REFERENCES

[1] Thomas, Wayne, NASA Lewis Research Center, Rocket Engine Test Facility, S-40, Test Facility Capabilities, Briefing.

[2] Smith, Tamara, A., Boundary Layer Development as a Function of Chamber Pressure in the NASA Lewis 1030:1 Area Ratio Nozzle, AIAA-88-3301.

[3] Pavli, Albert, J., Kacynski, Kenneth, J., and Smith, Tamara, A., Experimental Thrust Performance of a High-Area-Ratio Rocket Nozzle, NASA Technical Paper 2720, 1987.

[4] Schultz, Roy, J., "Lecture Notes in Rocket Propulsion", UTSI, ME581, Vol. I.

[5] Rao, G.V.R., "Exhaust Nozzle Contour for Optimum Thrust", Jet Propulsion, 1958.

[6] Evans, R., Michael, preparer, Boundary Layer Integral Matrix Procedure for JANNAF Rocket Engine Performance Evaluation Methodology, BLIMP-J User's Manual, Aerotherm UM-75-64, July 1975.

[7] Dally, James, D., Riley, William F., McConnell, Kenneth, G., Instrumentation for Engineering Measurements, John Wiley & Sons, Inc., New York, NY, 1984.

[8] Turner, Allen, PLOT, Campus Copy Shop, Clemson University, SC.

SUPPLEMENTAL REFERENCES

SUPPLEMENTAL REFERENCES

Engineering Division, Crane Co. 1957. Flow of Fluids Through Valves, Fittings, and Pipe. Chicago: Crane Co.

Kacynski, Kenneth, J., Pavli, Albert, J., and Smith, Tamara, A., 1987, Experimental Evaluation of Heat Transfer on a 1030:1 Area Ratio Rocket Nozzle, AIAA-87-2070.

Mattingly, Jack, D., editor, 1985, Elements of Propulsion, The Department of Aeronautics, United States Air Force Academy.

Schmidt, Stephen and Robert Launsby. 1989. Understanding Industrial Designed Experiments. Longmont: CQG Ltd Printing.

Scientific VAX Cluster User's Manual, NASA Lewis Research Center, Rev. 1.1, May 1990.

Smith, Tamara, Albert Pavli and Kenneth Kacynski. 1987. Comparison of Theoretical and Experimental Thrust Performance of a 1030:1 Area Ratio Rocket Nozzle at a Chamber Pressure of 2413 KN/m^2 (350 psia). AIAA-87-2069.

Sutton, George, P. 1992. Rocket Propulsion Elements, An Introduction to the Engineering of Rockets. New York: John Wiley & Sons, Inc.

Walzer, Carl, John Kobak and Henry Speier. Fluid System Calculations Manual, NASA Lewis Research Center, Space Station Directorate, Cleveland, OH.

APPENDICES

APPENDIX A

FIGURES

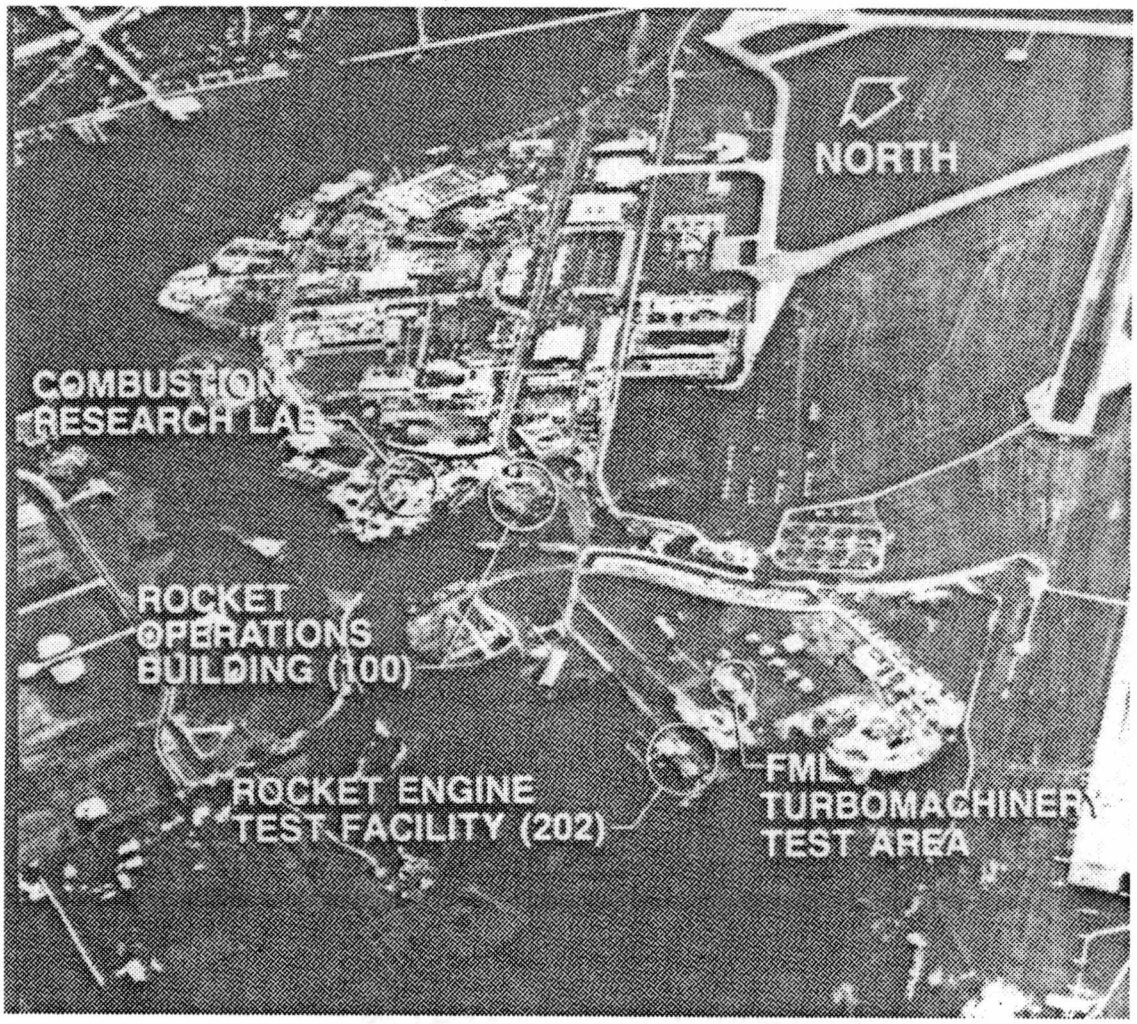


Figure A.1. - Aerial View of NASA Lewis Research Center

APPENDIX A



Figure A.2. - Aerial View of the Rocket Engine Test Facility (RETF).

APPENDIX A

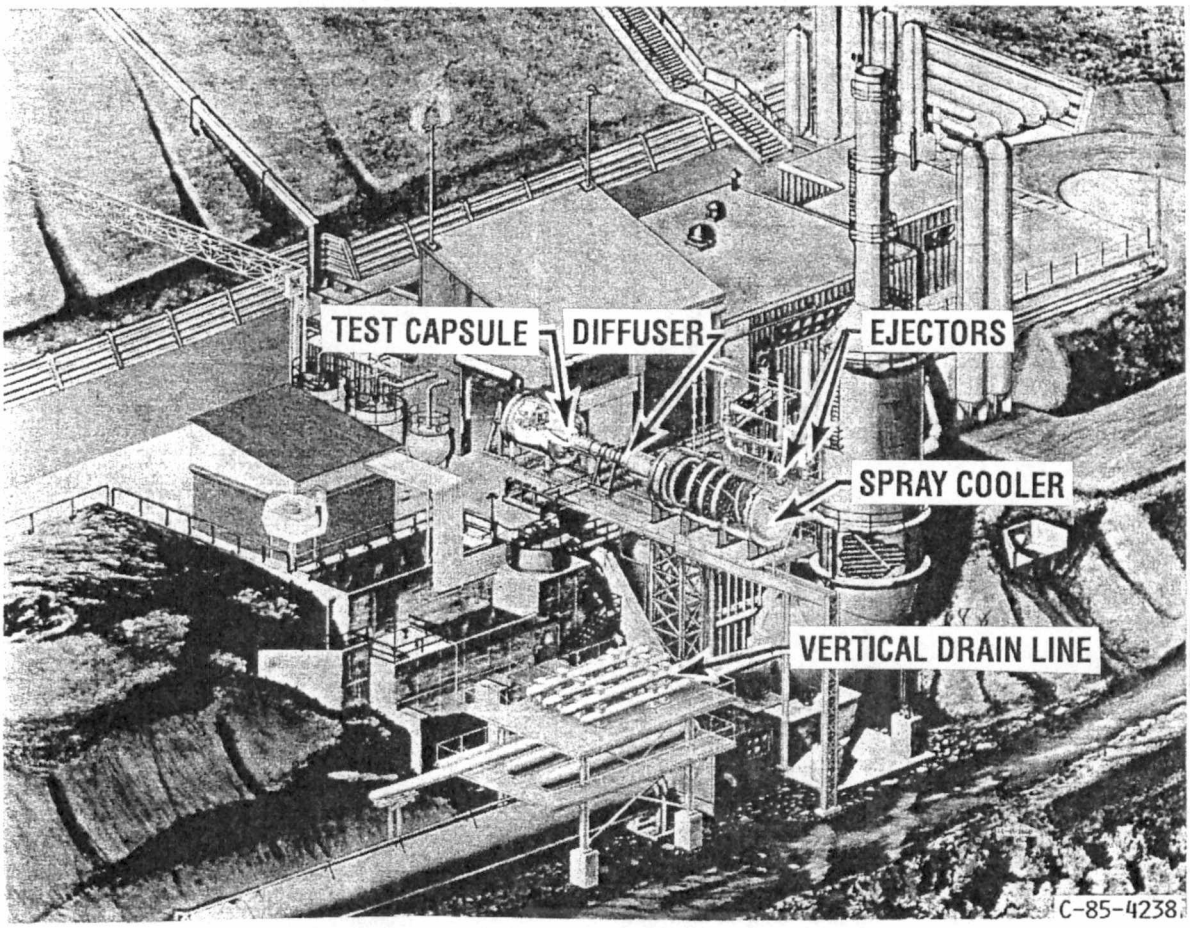


Figure A.3. - RETF with Cutaway Views of the Test Capsule and Spray Cooler.

APPENDIX A

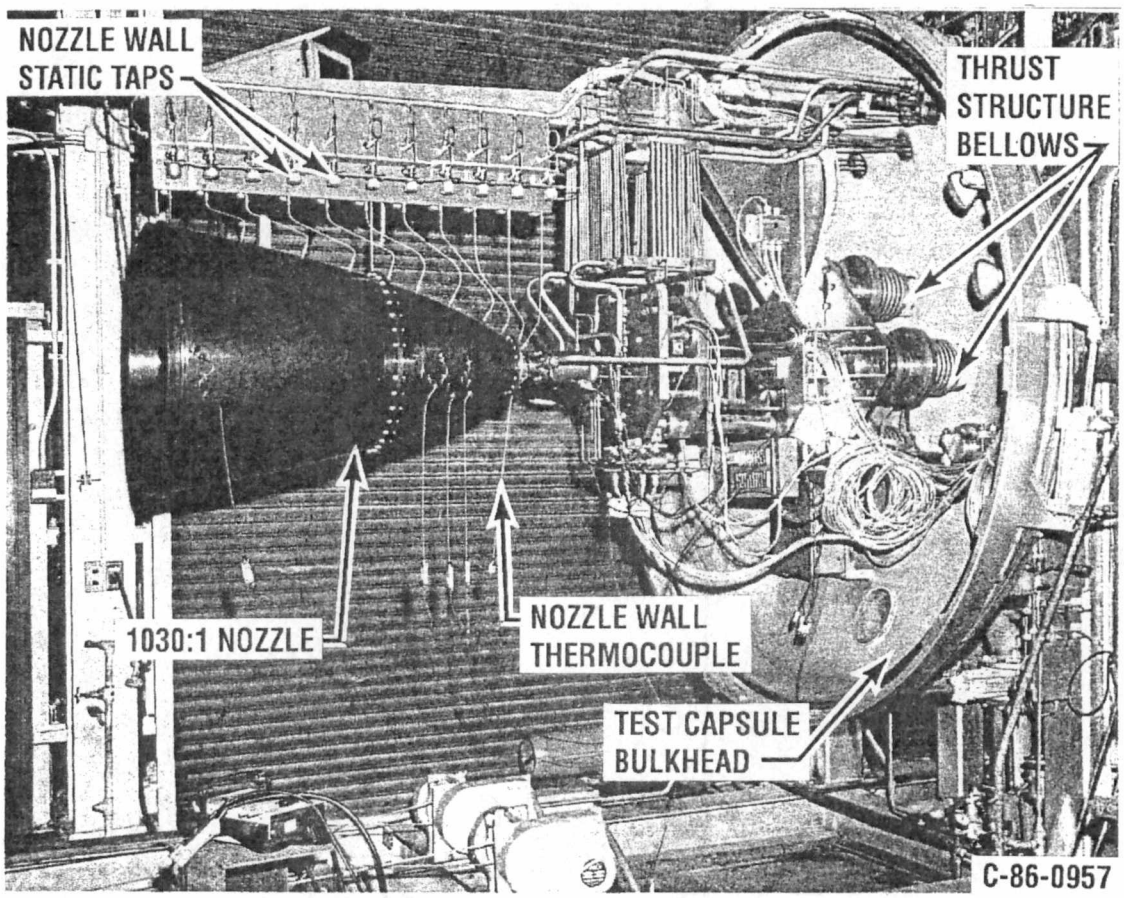


Figure A.4. - B Stand with the 1030:1 Area Ration Nozzle Installed in the Thrust Stand.

APPENDIX A

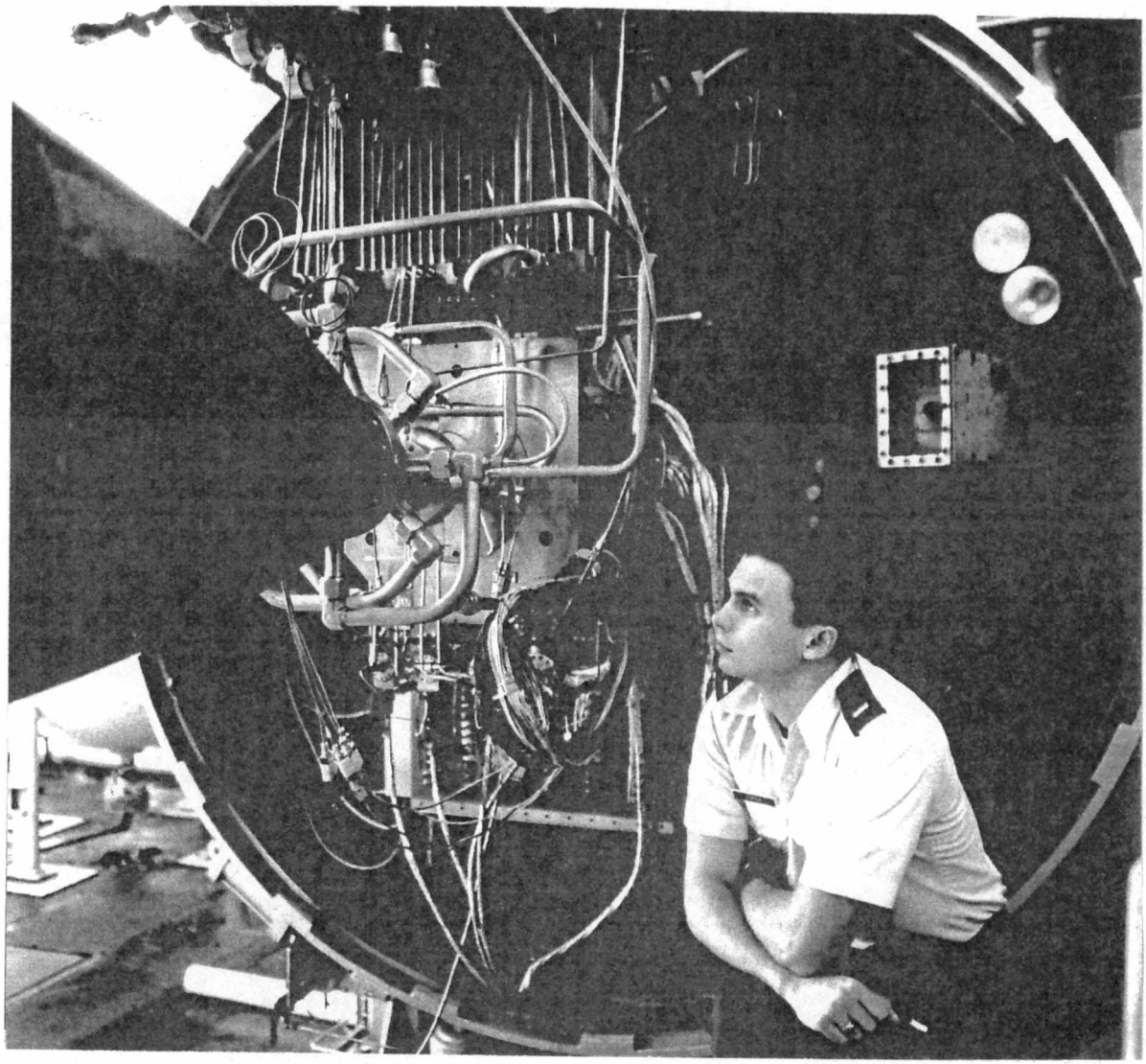


Figure A.5. - The "Bird Cage".

APPENDIX A

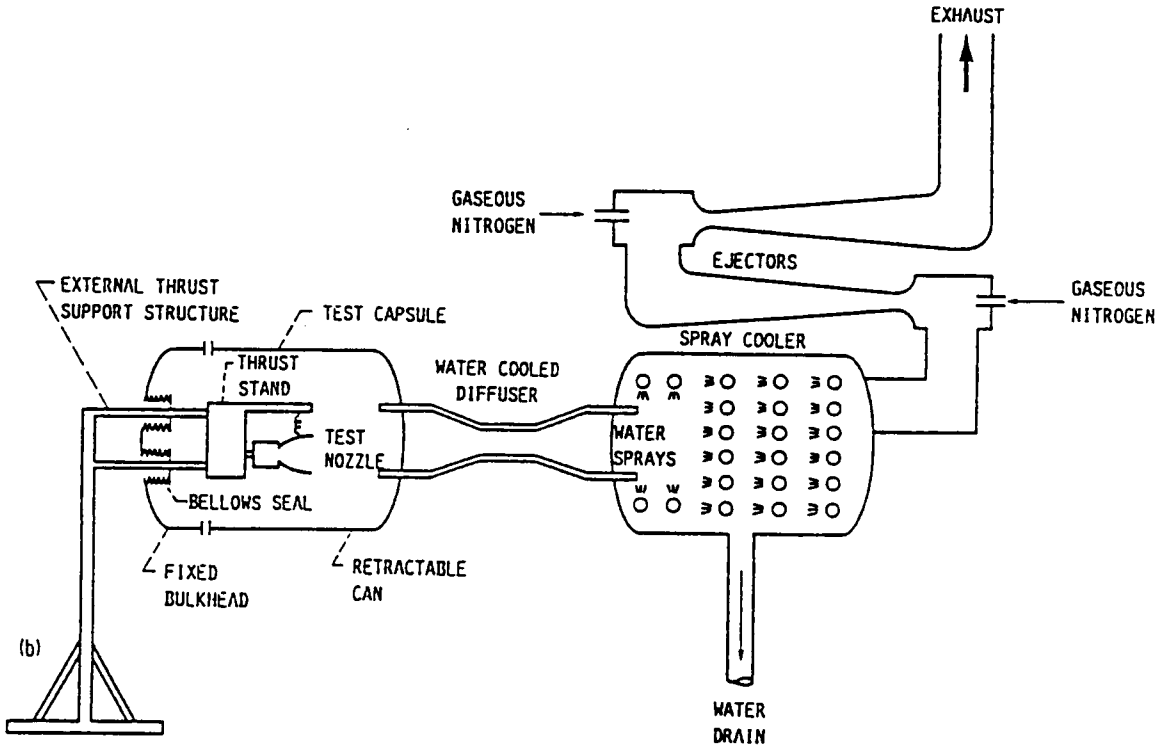


Figure A.6. - B Stand, Spray Coolers, and Ejectors.

APPENDIX A

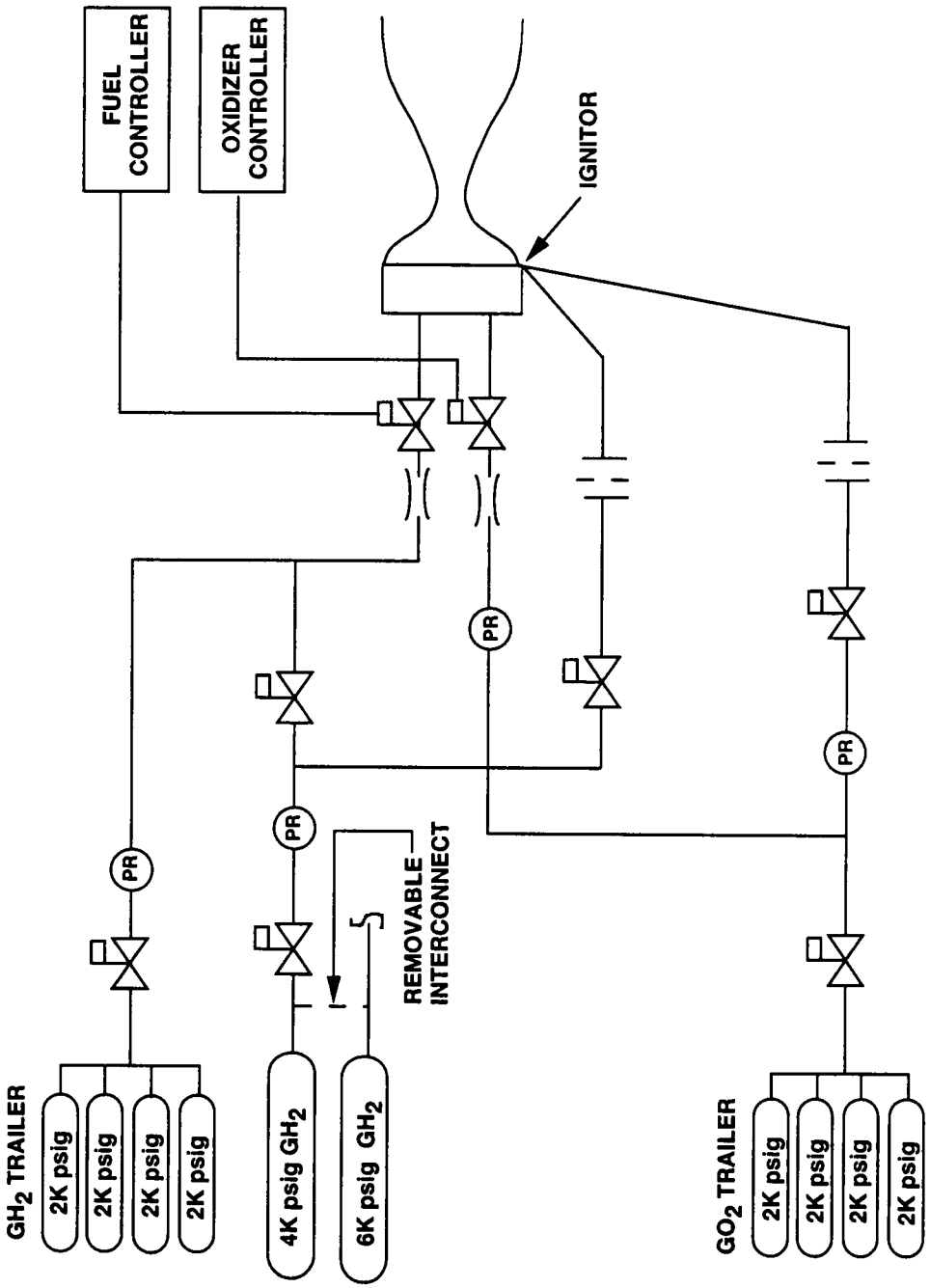
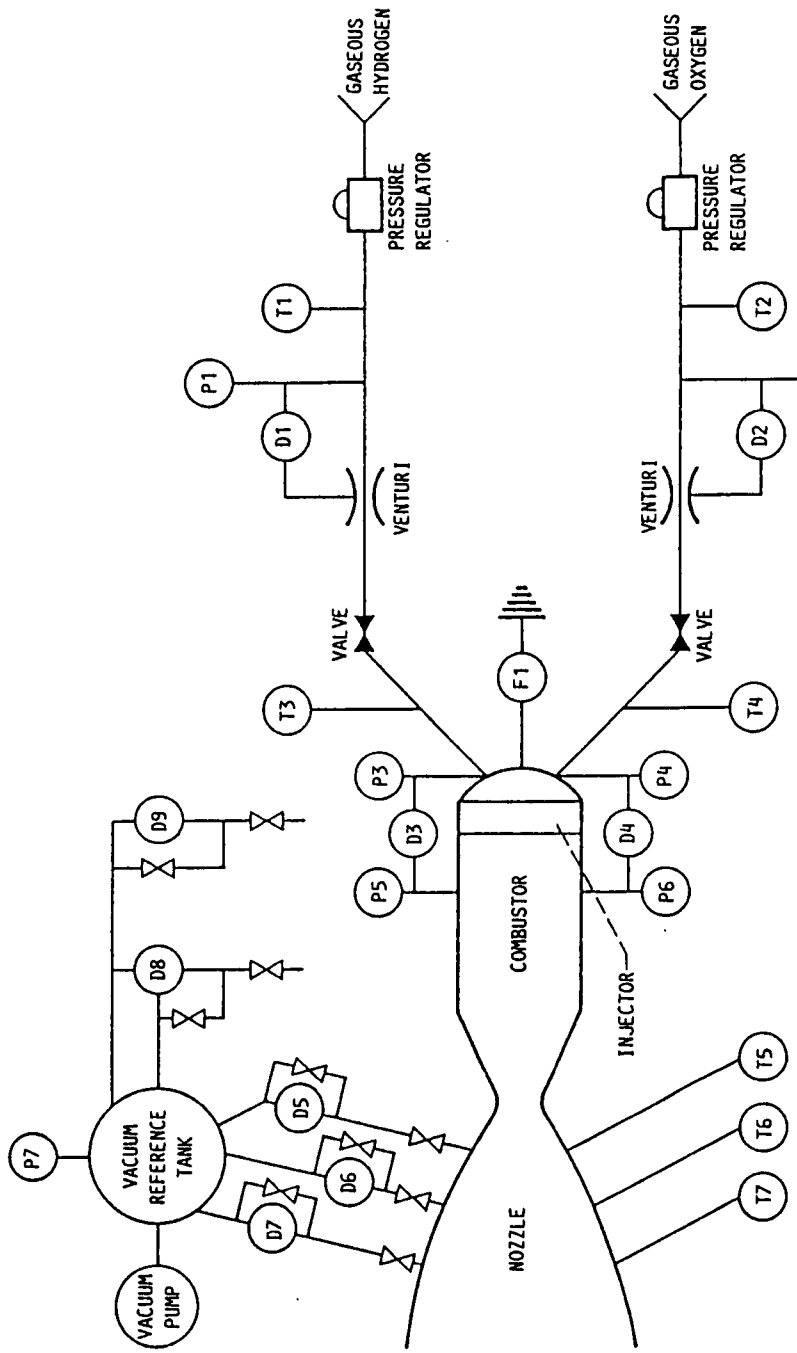


Figure A.7. - GO_2/GH_2 Propellant System Schematic (Tanks to Engine).

APPENDIX A



D1 FUEL VENTURI ΔP
D2 OXYGEN VENTURI ΔP
D3 FUEL INJECTION ΔP
D4 OXYGEN INJECTION ΔP
D5 NOZZLE WALL ΔP
D6 NOZZLE WALL ΔP
D7 NOZZLE WALL ΔP
D8 ALTITUDE ΔP
D9 ALTITUDE ΔP
F1 THRUST
P1 FUEL SUPPLY PRESSURE
P2 OXYGEN SUPPLY PRESSURE
P3 FUEL INJECTION PRESSURE
P4 OXYGEN INJECTION PRESSURE
P5 CHAMBER PRESSURE
P6 CHAMBER PRESSURE
P7 VACUUM REFERENCE PRESSURE
T1 FUEL SUPPLY TEMPERATURE
T2 OXYGEN SUPPLY TEMPERATURE
T3 FUEL INJECTION TEMPERATURE
T4 OXYGEN INJECTION TEMPERATURE
T5 NOZZLE WALL TEMPERATURE
T6 NOZZLE WALL TEMPERATURE
T7 NOZZLE WALL TEMPERATURE

Figure A.8. - GO2/GH2 Propellant with Instrumentation (Near Engine).

APPENDIX A

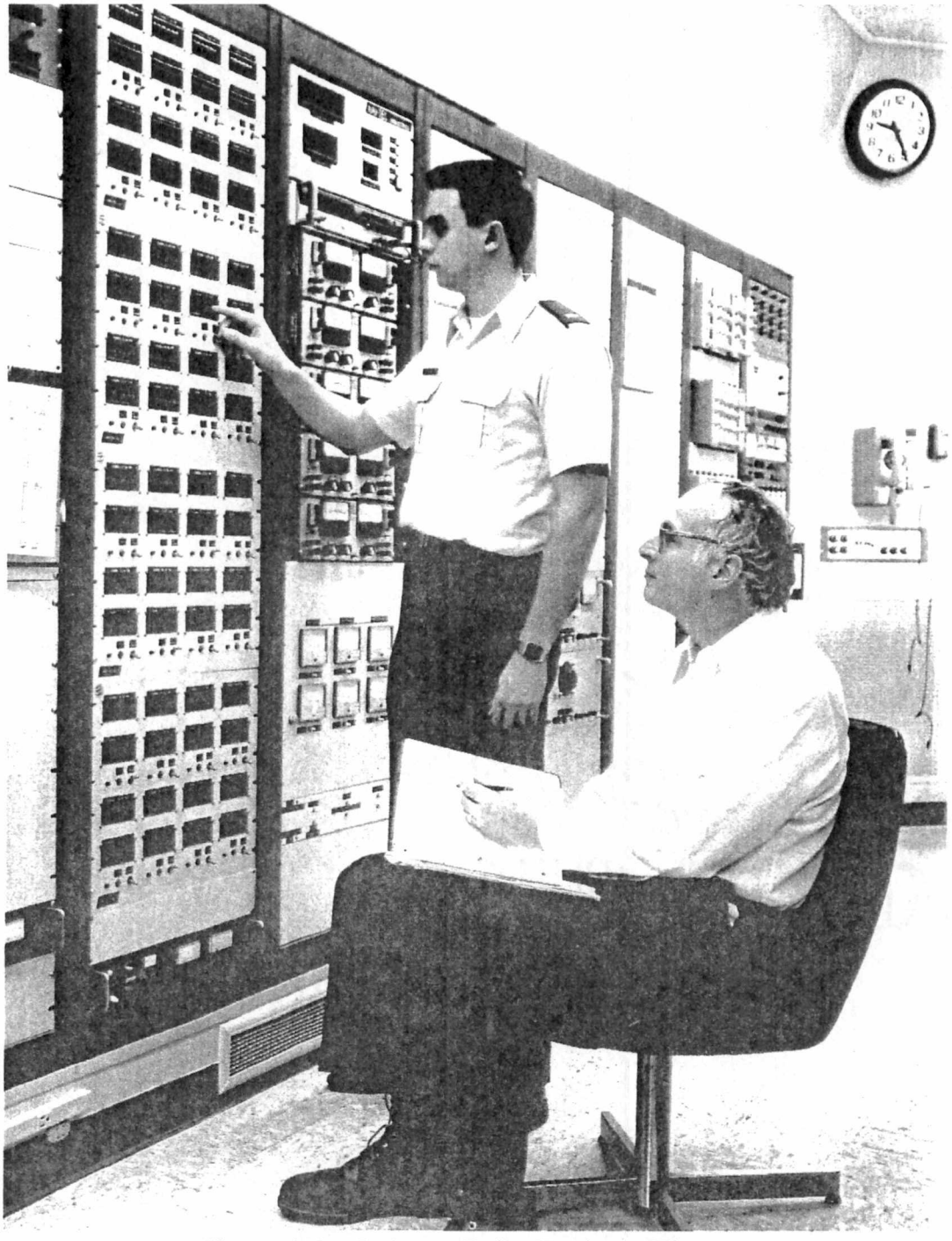


Figure A.9. - In-house Built, Hardware Timers.

APPENDIX A

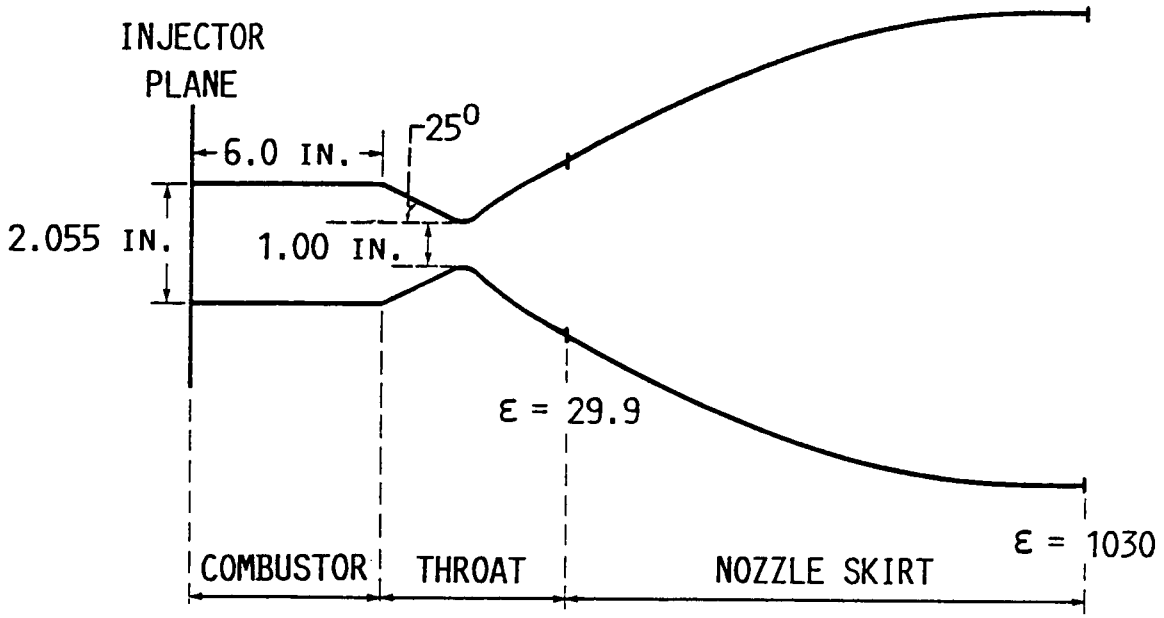


Figure A.10. - Dimensions of the 1030:1 Area Ratio Engine (Not to Scale).

APPENDIX A

	FUEL	OXYGEN
Number of holes	-----	36
Hole diameter, cm (in.)	-----	0.20 (0.078)
Nominal flow rate, *W*, kg/sec (lb/sec)	0.102 (0.224)	0.432 (0.953)
Nominal pressure drop, ΔP, kN/m^2 (psi)	514.3 (74.6)	366.8 (53.2)

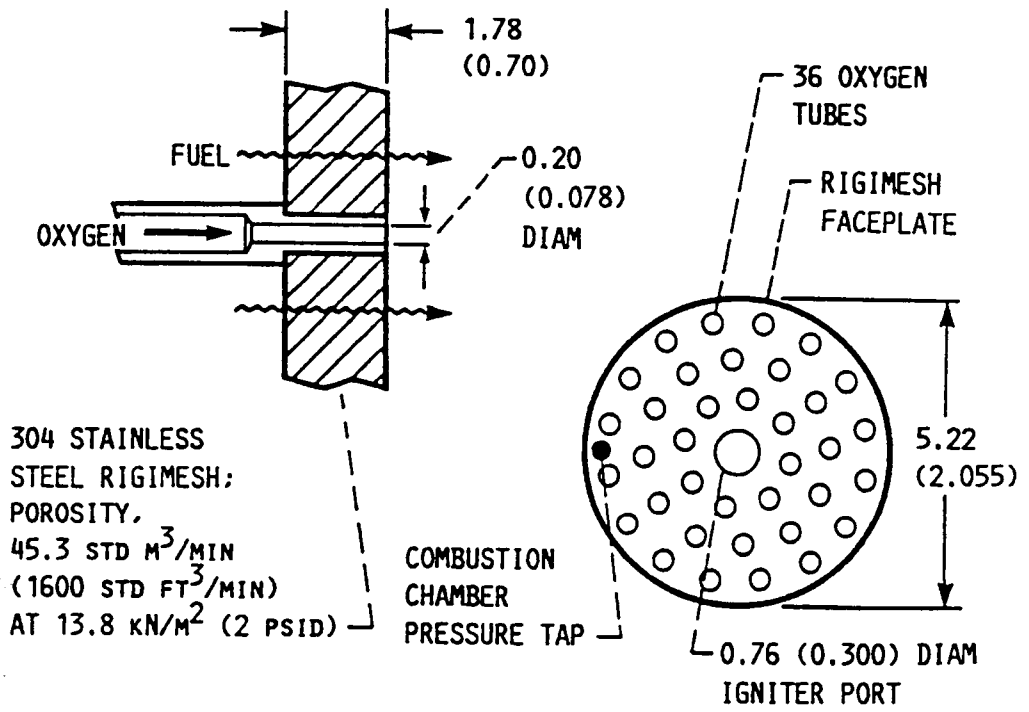


Figure A.11. - Rigimesh Injector Details (Dimensions are in Centimeters (Inches)).

APPENDIX A

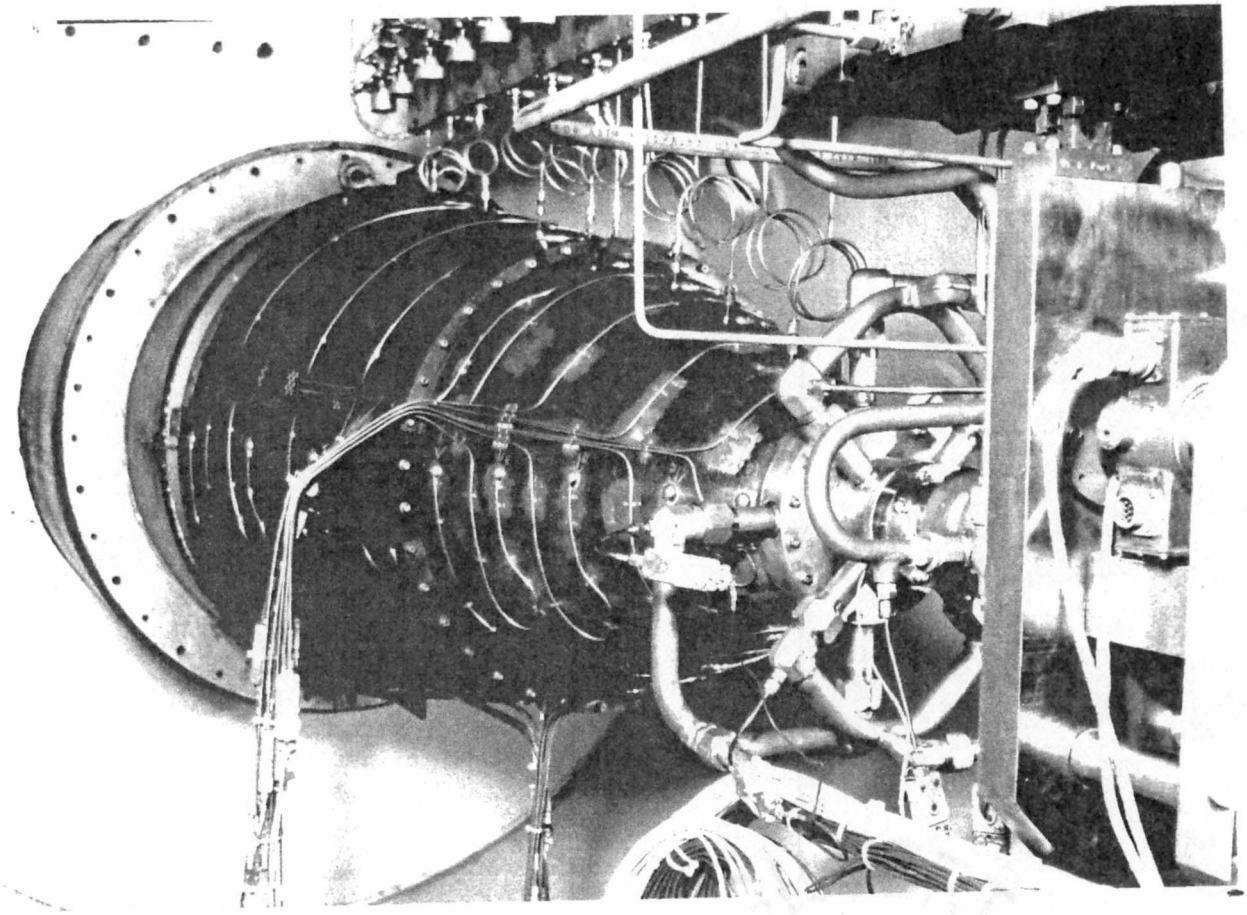


Figure A.12. - The 1030:1 Area Ratio Engine Under Test at Simulated Altitude.

APPENDIX A

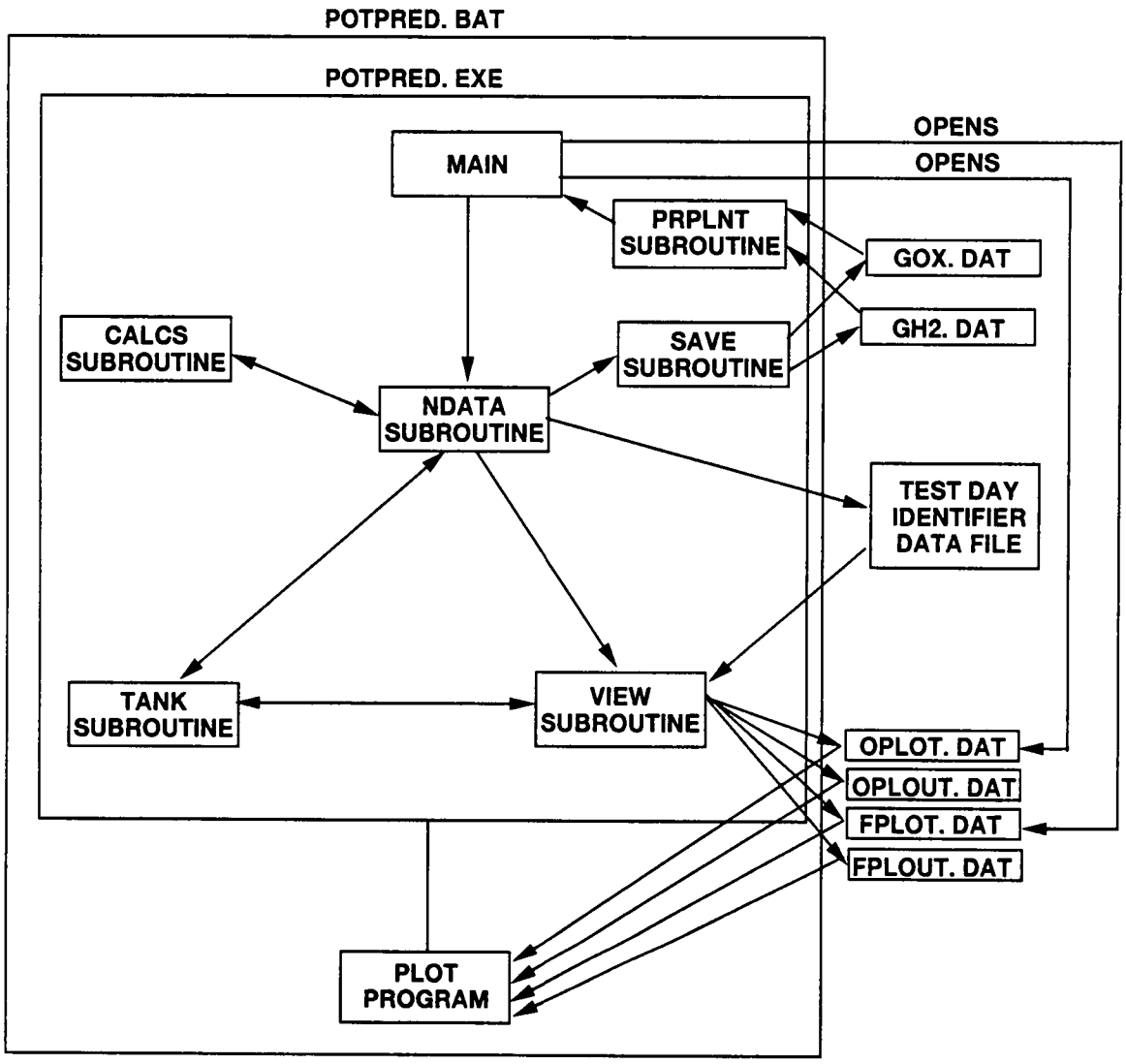


Figure A.13. - Simple POTPRED Flow Diagram

APPENDIX A

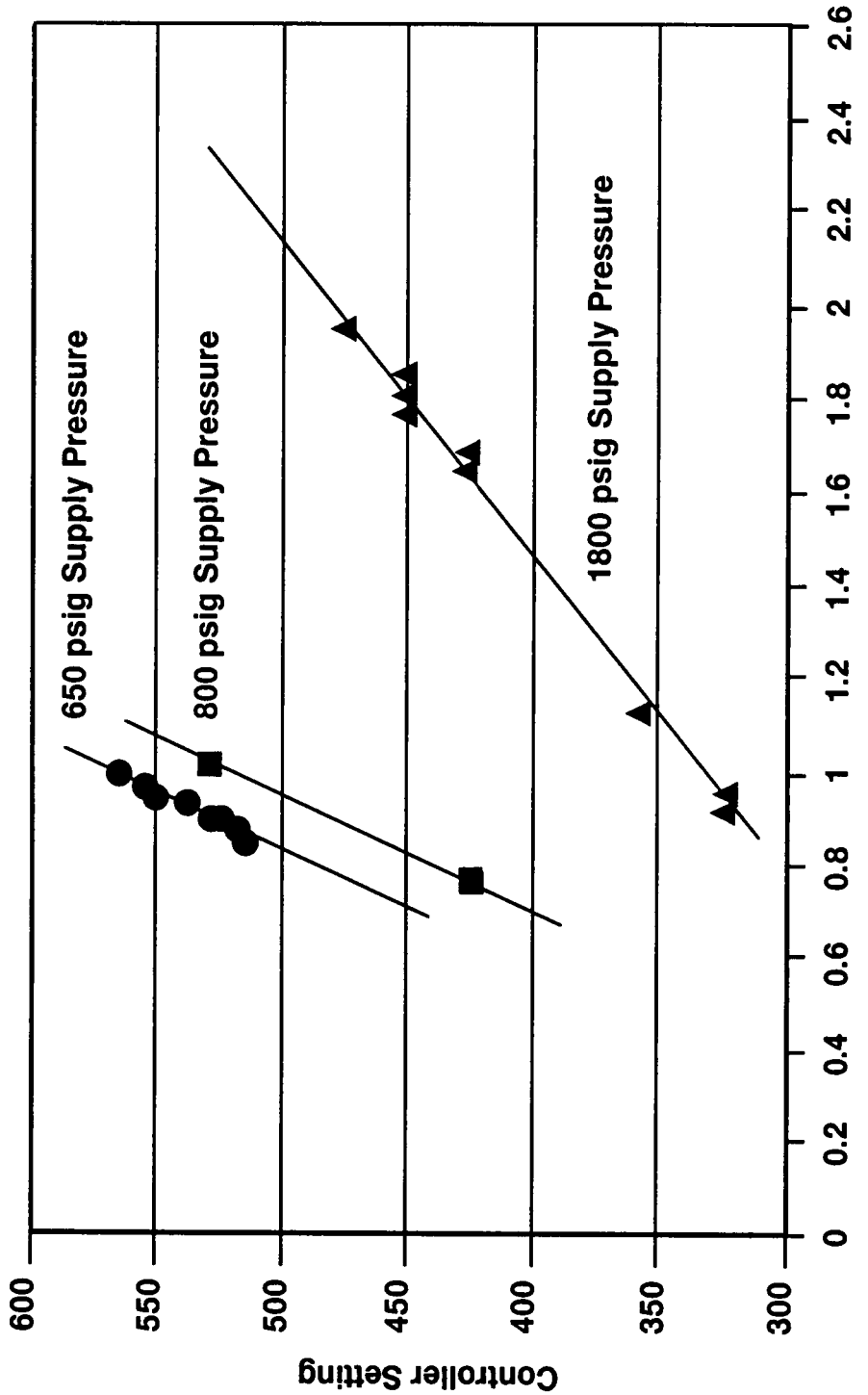


Figure A.14. - Controller Setting Versus Mass Flow

APPENDIX A

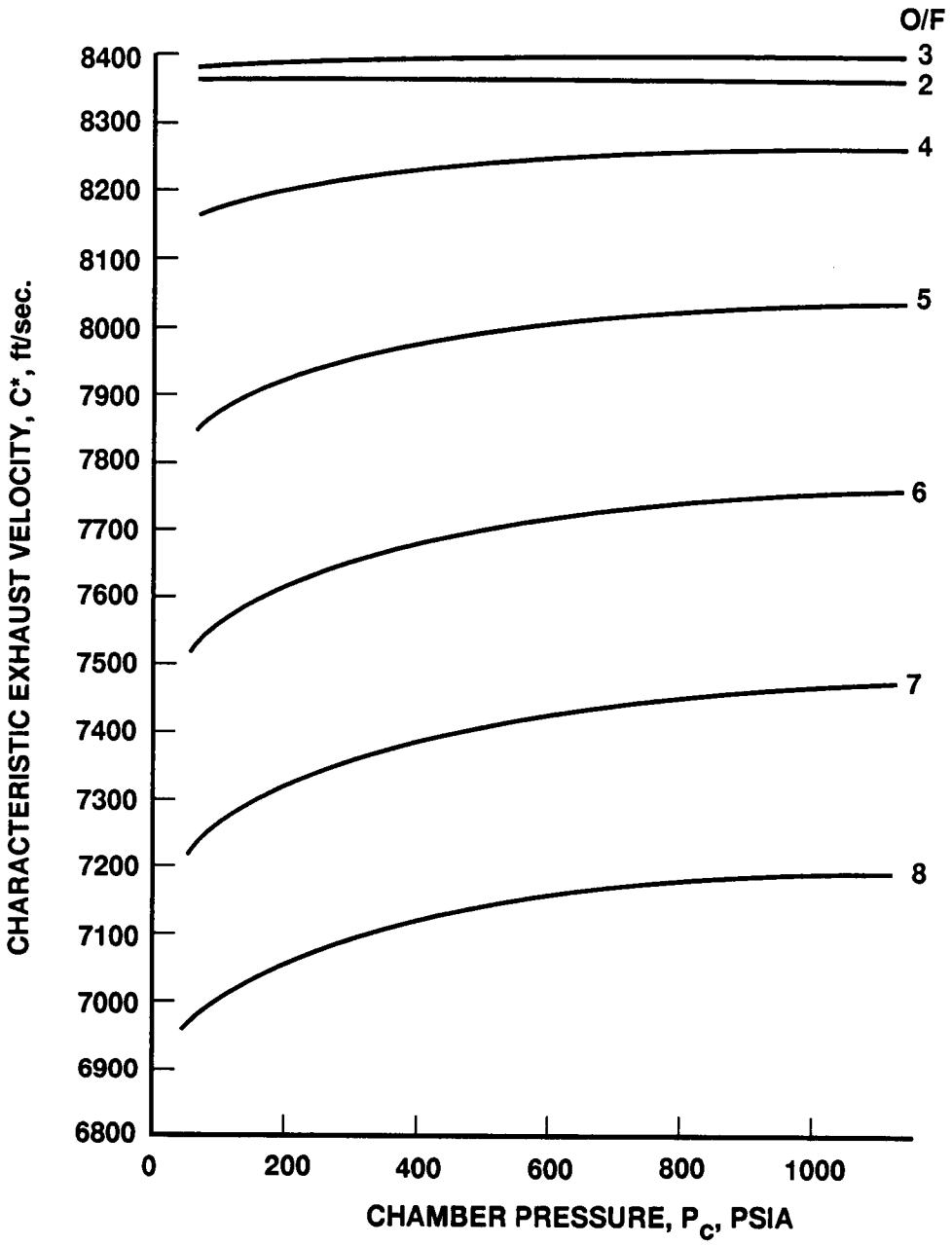


Figure A.15. - C* Versus P_c.

APPENDIX A

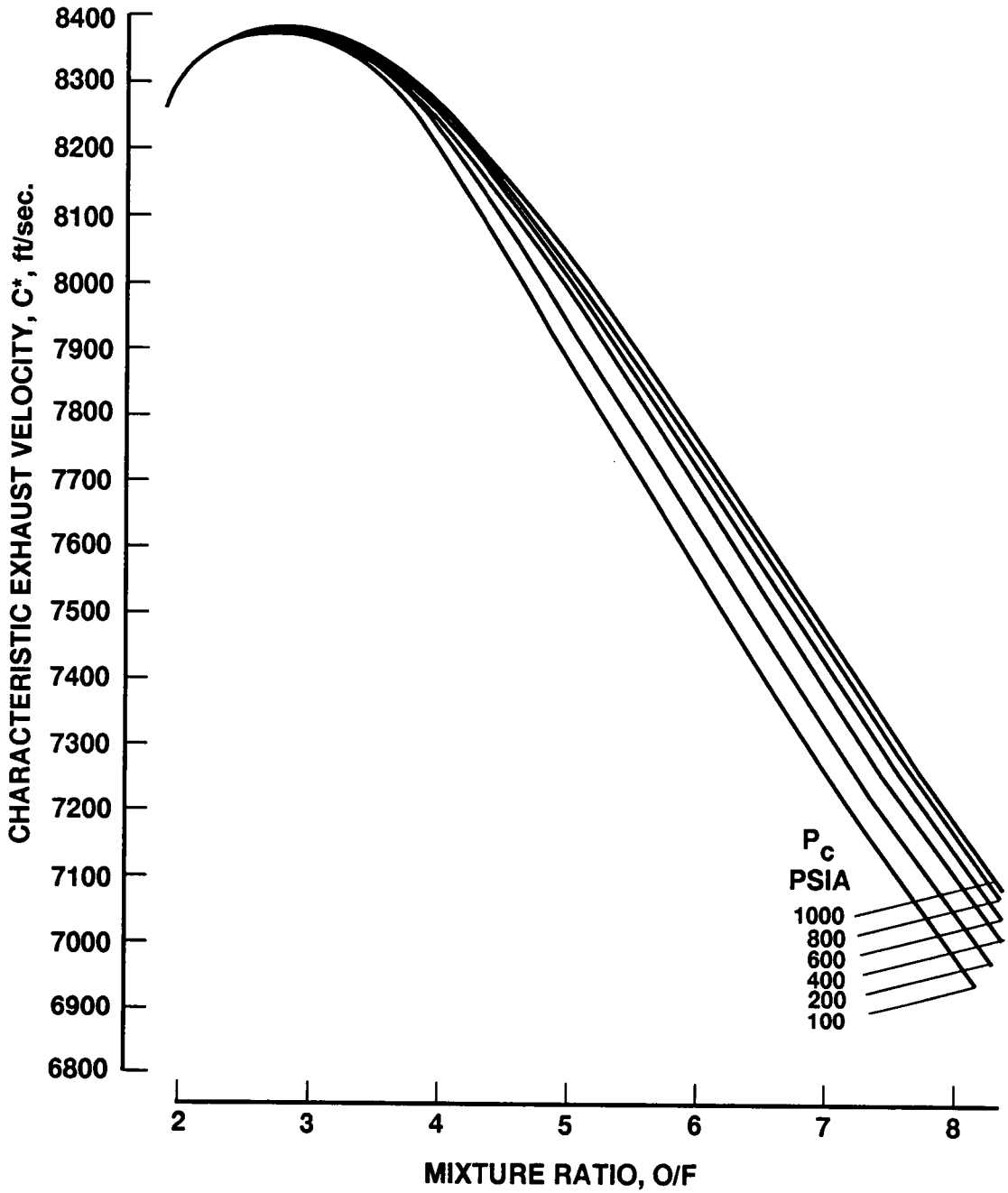


Figure A.16. - C* Versus O/F.

APPENDIX B

TABLES

Table B.1. - Summary of Sequential Timers' Zone of Responsibility

Zone	Timer	Activity
1	Modicon	Pre- fire Events
2	Discrete Hardware Timer	Rocket Firing
3	Modicon	Normal Shutdown
4	Modicon	Test Run Abort

APPENDIX B

Table B.2. - Sample Test Day Identifier Data File

RUN DAY I.D. #: BHO102 DATE: 13 JUN 88
NO. OF RUNS: 5

	OXIDIZER			FUEL		
	Firevalve Cv: 2.50			Firevalve Cv: 2.50		
RUN #	FLOW	POT. SET.	TANK PRESS.	FLOW	POT. SET.	TANK PRESS.
195	1.0760	530.00	850.00	.3110	603.00	850.00
196	1.0760	530.00	850.00	.3110	603.00	850.00
199	1.2320	530.00	965.00	.3530	603.00	965.00
200	1.3930	530.00	1080.00	.3680	603.00	1020.00
201	1.1001	535.00	850.00	.3210	605.00	850.00

Table B.3. - POTPRED Results

RUN NUMBER	OXIDIZER				FUEL				O/F			P_c		
	CONTROLLER SETTING	ACTUAL FLOW	PRED FLOW	ERROR (%)	CONTROLLER SETTING	ACTUAL FLOW	PRED FLOW	ERROR (%)	DESIRED	ACTUAL	ERROR (%)	DESIRED	ACTUAL	ERROR (%)
147	534	0.893	0.906	1.43	536	0.1870	0.165	11.76	5.5	4.78	13.17	350	330.7	5.51
148	566	0.986	0.967	1.93	531	0.1858	0.176	5.27	5.5	5.31	3.51	350	350.5	0.143
149	569	0.994	0.990	0.402	530	0.1858	0.180	3.12	5.5	5.35	2.73	350	353	0.850
150	550	0.944	0.919	2.65	520	0.1753	0.167	4.73	6.0	5.39	10.25	350	335.8	4.06
151	570	0.999	1.0	0.100	515	0.1743	0.167	4.18	6.0	5.73	4.48	350	346.2	1.09
152	572	1.007	1.017	0.983	510	0.1701	0.170	0.059	6.0	5.92	1.33	350	345.3	1.34

APPENDIX C

POTPRED VARIABLE DEFINITIONS

The definitions contained in this appendix are from the POTPRED Program.

ANS	A response to a question.
APC	Actual (measured) chamber pressure
B	The y-intercept of the line through the data points of the controller settings vs. propellant mass flow
B1	The y-intercept of the line through the data points of the controller settings vs. propellant mass flow. Used in the VIEW Subroutine.
C	Counter variable for transferring oxidizer and fuel variables to generic variables
CV	Generic firevalve flow coefficient variable
C1,2...,n	Do loop or counter variables
DATE	Test run date
DCSTAR	Desired or the next test firing's C^*
DCV( )	The firevalve flow coefficient stored in the GO_2/GH_2 data files
DF	Generic name variable for the oxidizer or fuel data file used in the SAVE subroutine
DPC	Desired or the next test firing's chamber pressure

APPENDIX C

DPM( )	The slope of the line through the data points of the controller settings vs. propellant mass flow graph that is stored in the GO_2/GH_2 data files
DTNKP	Propellant tank pressure stored in the GO_2/GH_2 data files
FCV	Fuel firevalve flow coefficient
FDF	The fuel data file identifier.
FFLO( )	Fuel mass flow array corresponding to its potentiometer setting
FLO( )	Generic array for propellant flow
FLOF	Fuel mass flow
FLOO	Oxidizer mass flow
FLOPOT	The generic summation of the product of the oxidizer or fuel mass flow with their respective controller potentiometer settings
FLOS	Generic variable for the summation of the squares of the propellant mass flows
FLPOT	The generic summation of the product of the oxidizer or fuel mass flow with their respective controller potentiometer settings
FLOT	Total propellant mass flow
FP	Fuel data file number. In this case: BGH2.DAT
FPLOT.DAT	The fuel data file that contains mass flows and controller settings necessary for plotting the controller setting vs. the fuel mass flow.
FPOT( )	Fuel controller potentiometer setting array
FTNKP( )	Fuel tank pressure array

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GTNKP	The delta between the propellant tank pressure entered into POTPRED and the propellant tank pressure in the data file
IDNUM	The run day ID number, i.e., BHO66 (user input). The run day ID number has meaning: B - B Stand (simulated altitude stand) HO - hydrogen and oxygen propellants 66 - the number of test days
IFLO	An intermediate flow variable when there is no historical data
K	A variable used in an array that contains information for records that have the same tank pressure
K1	A variable used in an array that contains information for records that have the same tank pressure
LC	The line in the GO_2/GH_2 data file that is to be updated
M	The slope of the line through the data points of the controller settings vs. propellant mass flow graph
MCSTAR	Measured C^*
N	Counter for the number of test firings
NFLFLO	Fuel mass flow for the next rocket engine test firing
NFLO	Generic propellant mass flow variable
NL	Variable for the first line of the GO2/GH2 data files that tells POTPRED how many line of information is contained within those data files.
NOXFLO	Oxidizer mass flow for the next rocket engine test firing

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NPOT, IPOT	Generic variable for the next rocket engine test firing controller potentiometer setting
NREC( )	The number of data entries (test runs) kept in an array
N	The number of data entries (test runs)
N1,N2	Intermediate number of data entries (test runs)
OCV	Oxidizer firevalve flow coefficient
ODF	The oxidizer data file identifier
OFLO( )	Oxidizer mass flow array corresponding to its potentiometer setting
OP	The oxidizer data file identifier
OPOT( )	Oxidizer controller potentiometer setting array
OPLOT.DAT	The oxidizer data file that contains oxidizer flows and their corresponding controller settings necessary for plotting the controller setting vs. the oxidizer mass flow
OTNKP( )	Oxidizer tank pressure array
P	Variable for the type of propellant (1=oxidizer, 2=fuel)
PCSTAR	Ratio of measured C^* to desired C^*
PDF	Generic name variable for the oxidizer or fuel data file
PERC	The product of PROP, FLOT, and PCSTAR
PM	The slope of the line through the data points of the controller settings vs. propellant mass flow graph stored in the GO_2/GH_2 data files.
POTT	Summation of the controller settings; used for linear regression

APPENDIX C

POT( )	Generic array for propellant controller potentiometer settings
PROP	Ratio of DPC to APC
RNUM( )	Run number (each test firing has a number assigned to it)
S	The value of a particular location in the TSREC( ) array
SAME	Counter for keeping track of controller settings at a propellant tank pressure
SAMREC( )	Array for grouping controller potentiometer settings at different propellant supply pressures
SFLO	Generic variable for the summation of the squares of the propellant mass flows
S1, S2	Counters
TD	Counter for propellant supply pressures that are different
TDREC( )	Array for propellant supply pressures that are different
TFLO	The generic variable for the summation variable of all of the oxidizer flows or fuel flows that have the same run tank pressure.
TNKP( )	Generic array for propellant tank pressure
TPOT	Generic variable for the summation of the controller potentiometer settings
TS	Counter for tracking data with the same supply pressures
TSREC( )	Array for grouping the test runs with the same propellant tank pressures together

APPENDIX D

BGOX.DAT DATA FILE LISTING

```
49
  2.50     630.00     034.3558
  0.16     650.00     000.0000
  0.25     650.00     000.0000
  0.40     650.00     000.0000
  0.60     650.00     000.0000
  1.00     650.00     000.0000
  1.50     650.00     000.0000
  2.50     650.00     354.1245
  4.00     650.00     000.0000
  4.60     650.00     000.0000
  5.00     650.00     000.0000
  5.60     650.00     000.0000
  6.00     650.00     000.0000
  8.00     650.00     000.0000
 12.00     650.00     000.0000
 13.00     650.00     000.0000
 24.00     650.00     000.0000
  0.16     800.00     000.0000
  0.25     800.00     000.0000
  0.40     800.00     000.0000
  0.60     800.00     000.0000
  1.00     800.00     000.0000
  1.50     800.00     000.0000
  2.50     800.00     289.2562
  4.00     800.00     000.0000
  4.60     800.00     000.0000
  5.00     800.00     000.0000
  5.60     800.00     000.0000
  6.00     800.00     000.0000
  8.00     800.00     000.0000
 12.00     800.00     000.0000
 13.00     800.00     000.0000
 24.00     800.00     000.0000
```

APPENDIX D

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0.25	1800.00	000.0000
0.40	1800.00	000.0000
0.60	1800.00	000.0000
1.00	1800.00	000.0000
1.50	1800.00	000.0000
2.50	1800.00	144.1398
4.00	1800.00	000.0000
4.60	1800.00	000.0000
5.00	1800.00	000.0000
5.60	1800.00	000.0000
6.00	1800.00	000.0000
8.00	1800.00	000.0000
12.00	1800.00	000.0000
13.00	1800.00	000.0000
24.00	1800.00	000.0000

APPENDIX E

GH2.DAT DATA FILE LISTING

```
49
  2.50     630.00     141.9355
  0.16     650.00     000.0000
  0.25     650.00     000.0000
  0.40     650.00     000.0000
  0.60     650.00     000.0000
  1.00     650.00     000.0000
  1.50     650.00     000.0000
  2.50     650.00     354.1245
  4.00     650.00     000.0000
  4.60     650.00     000.0000
  5.00     650.00     000.0000
  5.60     650.00     000.0000
  6.00     650.00     000.0000
  8.00     650.00     000.0000
 12.00     650.00     000.0000
 13.00     650.00     000.0000
 24.00     650.00     000.0000
  0.16     800.00     000.0000
  0.25     800.00     000.0000
  0.40     800.00     000.0000
  0.60     800.00     000.0000
  1.00     800.00     000.0000
  1.50     800.00     000.0000
  2.50     800.00     289.2562
  4.00     800.00     000.0000
  4.60     800.00     000.0000
  5.00     800.00     000.0000
  5.60     800.00     000.0000
  6.00     800.00     000.0000
  8.00     800.00     000.0000
 12.00     800.00     000.0000
 13.00     800.00     000.0000
 24.00     800.00     000.0000
  0.16    1800.00     000.0000
```

APPENDIX E

0.25	1800.00	000.0000
0.40	1800.00	000.0000
0.60	1800.00	000.0000
1.00	1800.00	000.0000
1.50	1800.00	000.0000
2.50	1800.00	144.1398
4.00	1800.00	000.0000
4.60	1800.00	000.0000
5.00	1800.00	000.0000
5.60	1800.00	000.0000
6.00	1800.00	000.0000
8.00	1800.00	000.0000
12.00	1800.00	000.0000
13.00	1800.00	000.0000
24.00	1800.00	000.0000

APPENDIX F

OPLOT.DAT DATA FILE LISTING

1.0760 530.00 530.00

1.0760 530.00 530.00

1.0010 535.00 535.00

1.0760 538.04 538.04

1.0760 538.04 538.04

APPENDIX G

FPLOT.DAT DATA FILE LISTING

.3110 603.00 603.00

.3110 603.00 603.00

.3210 605.00 605.00

.3110 599.46 599.46

.3110 599.46 599.46

VITA

Robert J. Torick, Jr. was born in Red Bank, New Jersey on November 18, 1963. He attended school in Freehold, New Jersey, and graduated from Freehold Borough High School in 1982. In August of that year, he entered Fairleigh Dickinson University, Teaneck, New Jersey. There, he received the degree of Bachelor of Science in Mechanical Engineering, Cum Laude, in 1986, and commissioned as a 2nd Lieutenant in the United States Air Force. Between 1986 and 1988, he worked at NASA Lewis Research Center, Cleveland, Ohio, as a Rocket Engine Test Engineer in the Rocket Engine Test Facility (RETF). In 1988, he was assigned to the Arnold Engineering Development Center, Propulsion Test Division, Rockets, Arnold Air Force Base, Tennessee as a Rocket Propulsion Test Manager. He entered The University of Tennessee Space Institute in 1988, graduating with a Master of Science in Mechanical Engineering in May, 1993.

Still on active duty, he is currently assigned to the Arnold Engineering Development Center, Directorate for Plans and Requirements, Arnold Air Force Base, Tennessee.