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Turbochargers to small turbojet engines for uninhabited aerial vehicles

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THESIS

TURBOCHARGERS TO SMALL TURBOJET ENGINES FOR UNINHABITED AERIAL VEHICLES

by

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June 1998

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Three test programs were conducted to provide the preliminary groundwork for the design of a small turbojet engine from turbocharger rotor components for possible Uninhabited Aerial Vehicle applications. The first program involved the performance mapping of the Garrett T2 turbocharger centrifugal compressor. The second program involved the bench testing of a small turbojet engine, the Sophia J450, at 115000 RPM, and comparing the results to another small turbojet, the JPX-240, from previously documented research. The compressor radii of the two engines were identical but greater than that of the Garrett compressor. The two engines, despite their physical similarities, had different fuel requirements. The J450 used heavy fuel (fuel pump required) while the JPX used liquid propane (pressurized fuel tank required). The third program involved the performance prediction of the J450 using GASTURB cycle analysis software. The compressor map generated from the Garrett T2 test was imported into GASTURB and used to predict the J450 performance at 94000, 105000, 115000, and 123000 RPM. The performance predictions agreed reasonably well with actual J450 performance.

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TURBOCHARGERS TO SMALL TURBOJET ENGINES FOR UNINHABITED AERIAL VEHICLES

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ABSTRACT

Three test programs were conducted to provide the preliminary groundwork for the design of a small turbojet engine from turbocharger rotor components for possible Uninhabited Aerial Vehicle applications. The first program involved the performance mapping of the Garrett T2 turbocharger centrifugal compressor. The second program involved the bench testing of a small turbojet engine, the Sophia J450, at 115000 RPM, and comparing the results to another small turbojet, the JPX-240, from previously documented research. The compressor radii of the two engines were identical but greater than that of the Garrett compressor. The two engines, despite their physical similarities, had different fuel requirements. The J450 used heavy fuel (fuel pump required) while the JPX used liquid propane (pressurized fuel tank required). The third program involved the performance prediction of the J450 using GASTURB cycle analysis software. The compressor map generated from the Garrett T2 test was imported into GASTURB and used to predict the J450 performance at 94000, 105000, 115000, and 123000 RPM. The performance predictions agreed reasonably well with actual J450 performance.

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I. INTRODUCTION

The Wright brothers, in 1903, changed the face of transportation with the world's first successful heavier-than-air powered flight. Their simple bi-plane design set off an evolutionary chain reaction that saw the creation of the aviation/aerospace industry. Soon, aerodynamic performance and structural engineering advances allowed higher flight speeds requiring more from the conventional propeller propulsion plants of that era.

Not more than a quarter-century later, Frank Whittle, a British Royal Air Force cadet, reasoned that aircraft would have to fly faster and higher to improve efficiency. He also recognized the limitations of the propeller engine and that the rocket was not the convenient solution. Instead, he concluded that a high-speed jet stream produced by a ducted fan driven by a turbine might be the answer to the propulsion dilemma. After several years of research and development, Whittle realized his vision when on May 15, 1941, the first British jet aircraft, the Gloster Meteor, powered by the Whittle engine, flew from Cranwell in Lincolnshire, England.

Since the introduction of the first operational jet engine, these engines have primarily grown larger in order to meet the increasing demands of thrust, fuel efficiency, and specific thrust. In more recent times, however, the popularity of remote control airplanes has created a new marketplace for scaled-down operational aircraft and jet engines. Additionally, the Department of Defense (DoD) has realized the potential of the Uninhabited Aerial Vehicle (UAV) in reconnaissance as well as strike roles [Ref. 1]. The DoD requires a low-cost, lightweight, low-maintenance, high-reliability engine that will propel the UAV to meet close and short-range mission requirements. A small expendable turbojet engine may also provide the necessary gas generator core for ramjet engines, which could be used to power supersonic UAVs.

The centrifugal compressor and radial inflow turbine meet the size and lightweight requirements for such an engine. Not only is the centrifugal compressor and pump probably the most predominant type of turbomachine application known to man (vacuum cleaner, washing machine, piston engine turbocharger, etc.), but its evolutionary development over the past four decades has produced a finely honed turbomachinery accessory that satisfies thermodynamic and economic constraints. [Ref. 2]

The present study lays the initial groundwork for the eventual design and construction of a small turbojet engine. The design would take advantage of readily made rotor systems available commercially through the automobile turbocharger market. The high strength and temperature resistant construction of these rotors provide a low-cost compressor and turbine system from which to build the engine around.

This study was comprised of three areas of investigation. The first test program consisted of the compressor performance mapping of a commercially available rotor system, the Garrett T2 turbocharger. The second test program consisted of the bench testing of a commercially available small turbojet engine, the Sophia J450 and comparing its results to previously documented tests conducted on another small turbojet engine, the JPX-240 [Ref. 3]. The third area of investigation consisted of the on and off-design performance prediction of the Sophia J450 turbojet engine using the GASTURB cycle analysis software program with the Garrett T2 compressor map and results of the design bench testing as inputs. The performance predictions of the third program were then compared to actual off-design bench tests of the Sophia J450.

II. GARRETT T2 TURBOCHARGER TEST PROGRAM

A. EXPERIMENTAL SETUP

1. Overview

The experiment was conducted in the Model Test and Calibration Cell of Building 215 at the Naval Postgraduate School. The purpose of the experiment was to map the performance characteristics of the Garrett T2 Turbocharger centrifugal compressor. The T2, purchased specifically for its physical dimensions, had a compressor radius (0.95 in.) close to that of the JPX-240 turbojet engine compressor (1.22 in.) researched by Lobik [Ref. 3]. The main components of this experiment consisted of the T2, the turbocharger test rig, the Allis-Chalmers axial compressor and air supply system, as shown in Figure 1, and a personal computer (PC) driven data acquisition system running Hewlett-Packard Visual Engineering Environment (HPVEE) software.

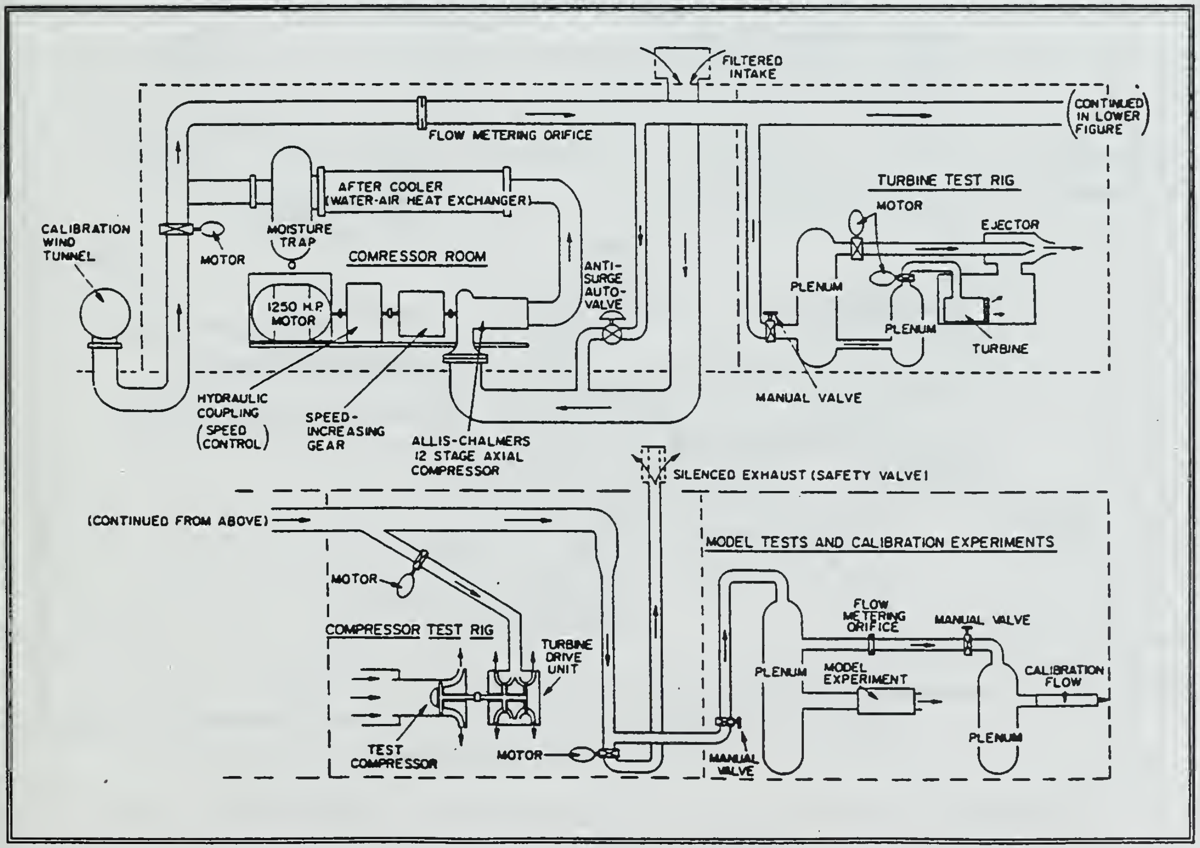


Figure 1. Building 215 Air Supply System.

2. Turbocharger Test Rig

The T2 was attached to the pre-existing turbocharger test rig, Figure 2, which was slightly modified to meet the smaller turbocharger requirements. Such modifications included reduced-area orifice plates (turbine and compressor inlet pipe orifice diameters of 1.90 and 1.25 in., respectively), a compressor exit throttle valve as well as compressor and turbine inlet adapters.

The test rig instrumentation included one temperature probe, four combination stagnation temperature-pressure probes, two pressure differential transducers (one ±2.5 psig, ahead of the compressor, and one ±1.0 psig, upstream of the turbine), and one magnetic speed pickup.

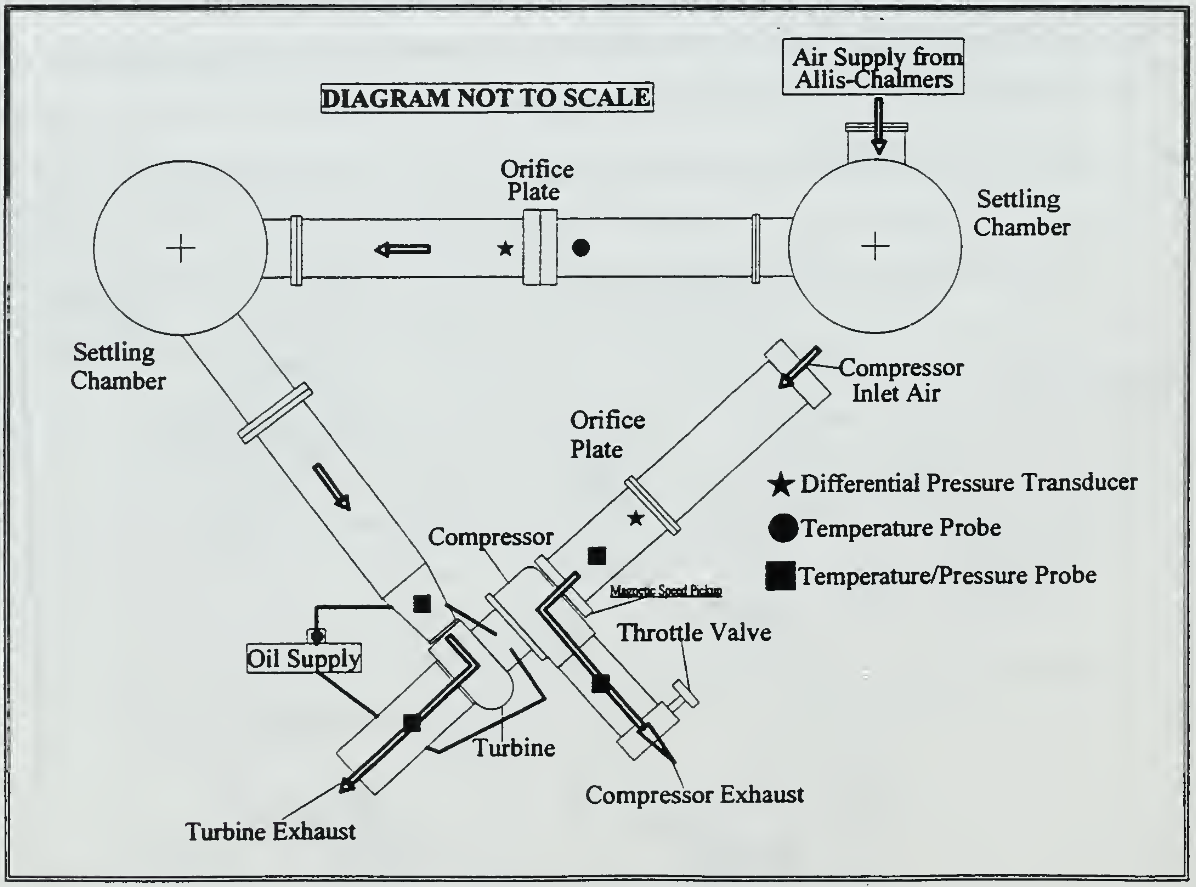


Figure 2. Turbocharger Test Rig Layout.

B. DATA ACQUISITION AND REDUCTION

1. Overview

The computerized data acquisition system consisted of a Hewlett-Packard HP75000 Series B VXI-Bus Mainframe controlled by HPVEE software running on a PC, a scanner, universal counter, signal conditioner, and an external digital voltmeter (DVM). The mainframe itself contained an internal DVM, along with two scanning multiplexers, a switchbox multiplexer, and a Quad 8-bit Digital I/O Module. The system, shown in Figure 3, provided near real-time data to the PC monitor and also provided the option to export the acquired data to Microsoft Excel spreadsheet format.

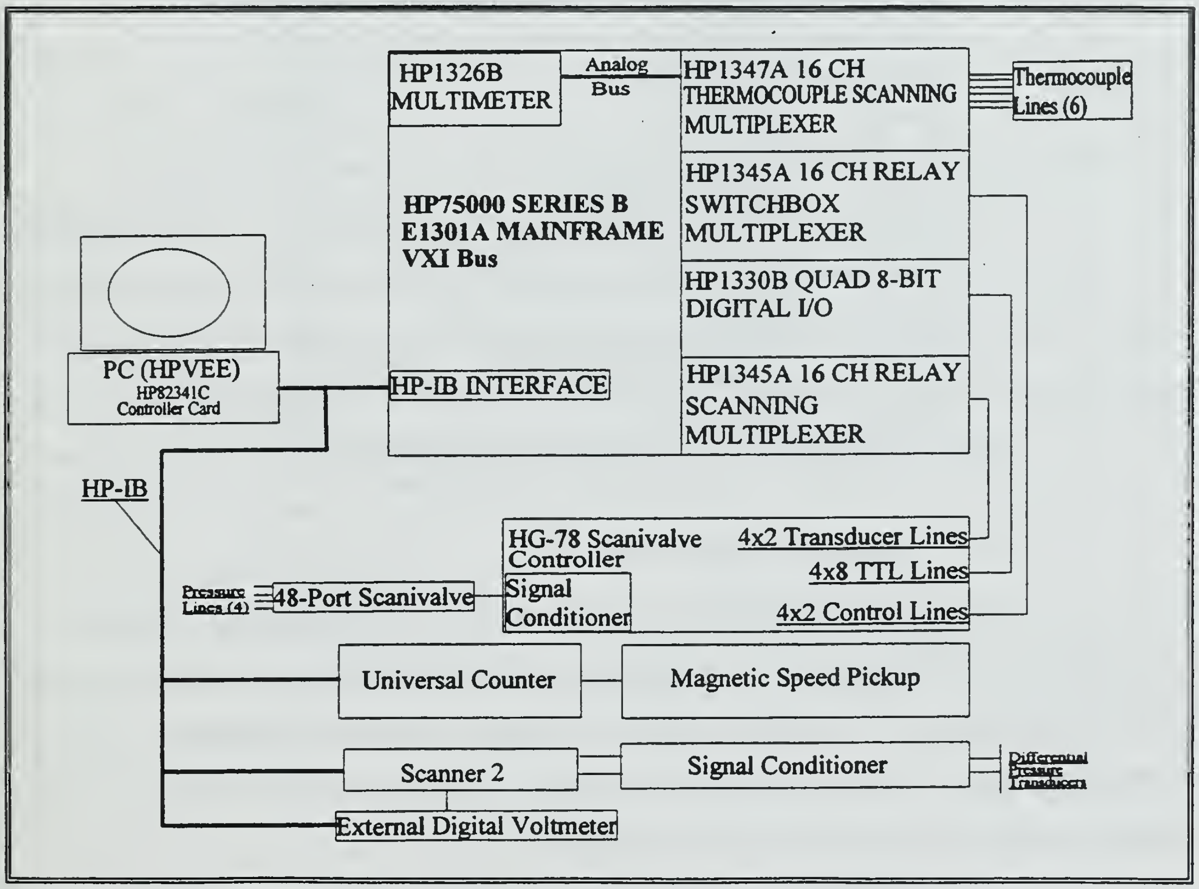


Figure 3. Turbocharger Data Acquisition Schematic.

2. Instrumentation and Control

The Hewlett Packard HP75000 Mainframe was used to control and directly address a variety of instruments grouped together. Communication between the PC (with a HP 823141C Controller Card installed) and the mainframe was via a HP-IB (IEEE-488) interface cable.

a. *Scanivalve Control*

Scanivalve control involved stepping and homing the 48-port pneumatic scanning valve (pressure port assignments summarized in Table 1) with the HG-78 Scanivalve controller and ensuring that the correct port was selected and measured. Grossman [Ref. 4] provided a detailed configuration and logic sequence description for the control of the Scanivalve.

Port #	Scanivalve Pressure Assignment
1	Tare, P1
2	Calibration, P2
3	Not Used
4	Not Used
5	Turbine Inlet, P5
6	Turbine Exit, P6
7	Not Used
8	Not Used
9	Compressor Inlet, P9
10	Compressor Exit, P10
11 - 48	Not Used

Table 1. Scanivalve Port Assignments.

b. *Scanning Digital Voltmeter*

A 16-channel multiplexer was connected to the HP75000 DVM allowing it to operate as a thermocouple relay multiplexer module (HP1347A). The module (channel assignments summarized in Table 2) was used to measure five stagnation temperatures as well as the lubrication oil temperature. Again, Ref. [4] provided a detailed configuration and logic sequence description.

c. *Scanner 2*

The two differential pressure transducers were used to measure the pressure differences across each of the two orifice plates. The turbine and compressor pressure differentials were connected to the signal conditioner and were assigned to

Scanner 2 (HP3495A) channels 27 and 28, respectively. The scanner switched each transducer's voltage to the external DVM, which was in turn read by the computer via the HP-IB bus.

Multiplexer Channel	Channel Assignment
100	Turbine Inlet Temperature, T1
101	Turbine Exit Temperature, T2
102	Compressor Inlet Temperature, T3
10[illegible]	Compressor Exit Temperature, T4
104	Turbine Orifice, T5
105	Oil Temperature, T6
106 – 115	Not Used

Table 2. Scanning Multiplexer Channel Assignments.

3. Software

The HPVEE software program "GARRETT_DELTA_P" used to control the instrumentation served three purposes. First, it initialized the instruments by programming each one to match the settings defined by the driver code. Second, the driver served as a virtual control panel for interactively controlling the instrument. Third, HPVEE performed immediate reduction of measured values to engineering units allowing timely feedback of data to the operator, which proved useful during the initial troubleshooting process.

4. Data Reduction

The measured data was reduced using HPVEE by assuming a fixed value for the flow coefficient within the mass flow calculation. Such an assumption was used to provide preliminary results to the operator in a timely manner. The measured data was also exported to a Microsoft Excel spreadsheet in which the final calculations were executed. The data reduction routine was performed for both the compressor and turbine sections of the turbocharger. The results, provided as Tables A1, A2, and A3 in Appendix A, were calculated using the following methods.

a. *Mass Flow Rate*

The mass flow rate (in lbm/sec) through the compressor and turbine orifice plates, in accordance with the American Society of Mechanical Engineers Power Test Codes, Chapter 4, Flow Measurement – Instruments and Apparatus, PTC 19.5 (ASME PTC) Publication [Ref. 5], were given by

$$\dot{m}\left(\frac{lbm}{\sec}\right) = 0.3117 \cdot K \cdot F_A \cdot Y \cdot \sqrt{\frac{h_w P}{T}} \tag{1}$$

where K, the flow coefficient, was a tabulated value in ASME PTC that depended upon the area ratio of the orifice to pipe and the pipe Reynolds Number, RD. The thermal expansion factor, F_A, was given by

$$F_A = 1 + 0.00204 \cdot \left(\frac{T - 528}{100}\right) \tag{2}$$

where T was, T3, the compressor inlet temperature (deg. R) for the compressor calculation and T1, the turbine inlet temperature (deg. R) for the turbine calculation. The net expansion factor for square-edged orifices, Y, was given by

$$Y = 1 - \left(0.41 + 0.35\beta^4\right)\left(\frac{1}{\gamma}\right)\left(\frac{h_w}{P(13.956)}\right) \tag{3}$$

where β, the ratio of orifice to pipe diameter, was 0.3075 for the compressor, and 0.3133 for the turbine; γ, the ratio of specific heats for air, was 1.4; h_w, the pressure drop across the orifice, ΔP_{comp}, (in. H_20); and P (in. H_20_{abs}) was P9, the compressor inlet pressure, for the compressor calculation and P5, the turbine inlet pressure, for the turbine calculation.

b. *Pipe Reynolds Number*

The pipe Reynolds Number, given by

$$RD = \frac{4\dot{m}}{\pi \frac{D}{12} \mu} \tag{4}$$

where D, the pipe diameter, was 4.065 in. for the compressor and 6.065 in. for the turbine; and μ, viscosity of air, was 0.000012024 lbm/ft-sec, provided the second of two entering arguments necessary to determine the flow coefficient, K, from the appropriate tables in ASME PTC which was graphically represented as Figure B1 for the compressor and Figure B2 for the turbine in Appendix B.

c. *Total-to-Total Pressure Ratio*

The total-to-total pressure ratios were given by

$$\Pi_C = \frac{P10}{P9} \quad \text{and} \quad \Pi_T = \frac{P6}{P5} \tag{5}$$

where P10 and P6 were the exit pressures (in. H_20_{abs}) for the compressor and turbine, respectively.

d. *Stagnation Temperature Change*

The stagnation temperature changes were given by

$$\Delta T_{comp} = T4 - T3 \quad \text{and} \quad \Delta T_{turb} = T1 - T2 \tag{6}$$

where T4 and T2 were the compressor and turbine exit temperatures, respectively.

e. *Total-to-Total Isentropic Efficiency*

The total-to-total isentropic efficiency was calculated as

$$\eta_c = \frac{T3\left(\Pi_C^{\frac{\gamma-1}{\gamma}} - 1\right)}{\Delta T_{comp}} \quad \text{and} \quad \eta_t = \frac{\Delta T_{turb}}{T1\left(1 - \Pi_T^{\frac{\gamma-1}{\gamma}}\right)} . \tag{7}$$

f. *Power*

The power absorbed by the compressor and produced by the turbine were obtained from the respective mass flows through the compressor and turbine as

$$HP = 0.33958 \cdot \dot{m} \cdot \Delta T \tag{8}$$

where ΔT, the total temperature difference, was ΔT_{comp} for the compressor and ΔT_{turb} for the turbine calculations.

g. *Referred Quantities*

The compressor and turbine performances were described in terms of referred quantities that retain their original units:

$$\dot{m}_{ref} = \dot{m}\frac{\sqrt{\Theta}}{\delta}; \; RPM_{ref} = \frac{RPM}{\sqrt{\Theta}}; \text{ and } HP_{ref} = \frac{HP}{\delta\sqrt{\Theta}} . \tag{9}$$

where $\Theta = \frac{T_{t\inf}}{T_{ref}}$; $\delta = \frac{P_{t\inf}}{P_{ref}}$; $T_{ref} = 518.7$ deg. R; $P_{ref} = 407.2112$ in. H_20; $T_{t\inf}$ was T3 and T1 for the compressor and turbine calculations, respectively; and $P_{t\inf}$ was P9 and P5 for the compressor and turbine calculations, respectively.

5. Experimental Procedure

Prior to the initial data acquisition, the ±2.5 psig and ±1.0 psig differential pressure transducers were both calibrated to 5 in. Hg and 2 in. Hg, respectively. Additionally, the calibration pressure for the Scanivalve was set at 10 in. Hg.

The rotational speed of the magnetic pickup, displayed by a frequency counter, was verified prior to testing by using a calibrated strobe light. One of the impeller blades on the exposed face of the T2 compressor was marked with paint which allowed the rotating compressor, when strobed at a known frequency, to appear non-rotational with the paint marking in a fixed position. Though the strobe frequency was limited to 25000 RPM, the compressor speed was verified up to 50000 RPM by viewing the strobed compressor face in the manner described and realizing that doubling the speed produced a similar result. The exception was that the strobe illuminated the painted blade every second revolution.

Once the Allis-Chalmers compressor was stabilized, the air supply valve system was set such that the desired T2 turbocharger compressor speed measured by the magnetic speed pickup was obtained.

The HPVEE program “GARRETT_DELTA_P”, once executed, led the user through a series of required inputs which included ambient pressure as well as the number of temperature and pressure samples desired. The first data point was collected with the T2 compressor exhaust throttle valve fully open, subsequent data points were obtained while throttling the valve in full, half, or quarter-turn increments until the throttle was closed. It should be noted that the air supply valve system was manipulated after each throttle adjustment in order to maintain the same T2 turbocharger compressor speed.

Data was collected for the Garrett T2 turbocharger at compressor speeds of 50000, 75000, 100000, and 125000 RPM. Multiple experiments were conducted in an effort to verify the repeatability of the results.

C. RESULTS OF THE GARRETT T2 TURBOCHARGER TEST PROGRAM

1. Performance Maps

The total-to-total pressure ratio, efficiency, and referred power were plotted against the referred mass flow rate for each constant speed test. The plots show the data collected for each speed line for two data runs. Additionally, the pressure ratio and efficiency plots were generated for the turbine and are provided as Figures A1 and A2, respectively, in Appendix A.

The total-to-total pressure ratio versus referred mass flow rate, Figure 4, indicated a slight increase in pressure ratio and decrease in mass flow rate as the compressor was throttled. The sudden increase in mass flow rate indicated compressor surge. This

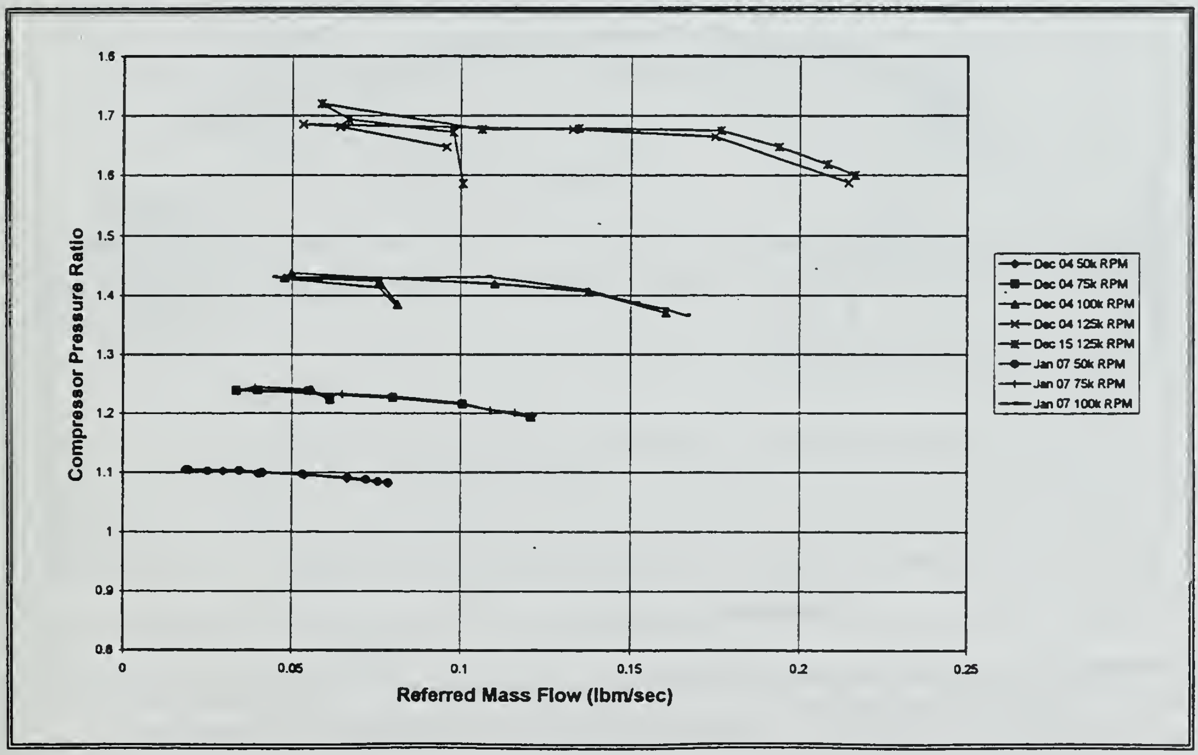


Figure 4. Garrett T2 Turbocharger Compressor Total-to-Total Pressure Ratio vs Referred Mass Flow Rate.

behavior was not typical of centrifugal compressors. The only explanation could be that the T2 compressor splitter blades caused the compressor to have two characteristics. At stall the compressor may have jumped to its second characteristic. Nonetheless, the overall peak pressure ratio noted was 1.72 for the 125000 RPM speed line. An example of a centrifugal compressor with splitter blades is provided in Appendix A as Figure A3.

The total-to-total isentropic efficiency versus referred mass flow rate, Figure 5, indicated an increase in efficiency up to a peak followed by a reduction as the mass flow rate was throttled. Again, the sudden increase in mass flow rate, which was accompanied by a dramatic decrease in efficiency, indicated compressor surge. The overall peak efficiency noted was 0.75 on the 100000 RPM speed line. This observation lead to the conclusion that the design speed for the compressor was between 100000 and 125000 RPM.

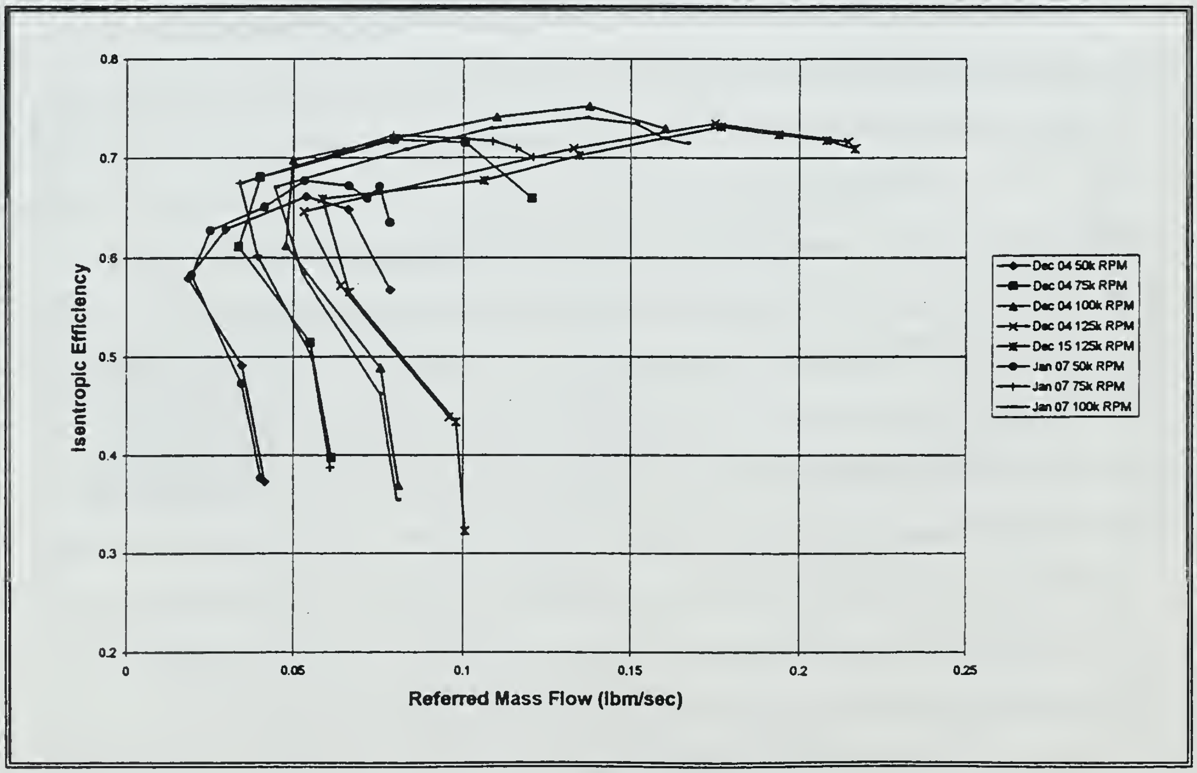


Figure 5. Garret T2 Turbocharger Compressor Total-to-Total Efficiency vs Referred Mass Flow Rate.

The referred power versus referred mass flow rate, Figure 6, indicated a near-linear relationship between power and mass flow. As expected, the peak referred power noted, 7.72 HP, corresponded to the highest speed line with the maximum mass flow throttle condition. Again, the sudden increase in mass flow rate accompanied by a dramatic increase in power indicated compressor surge.

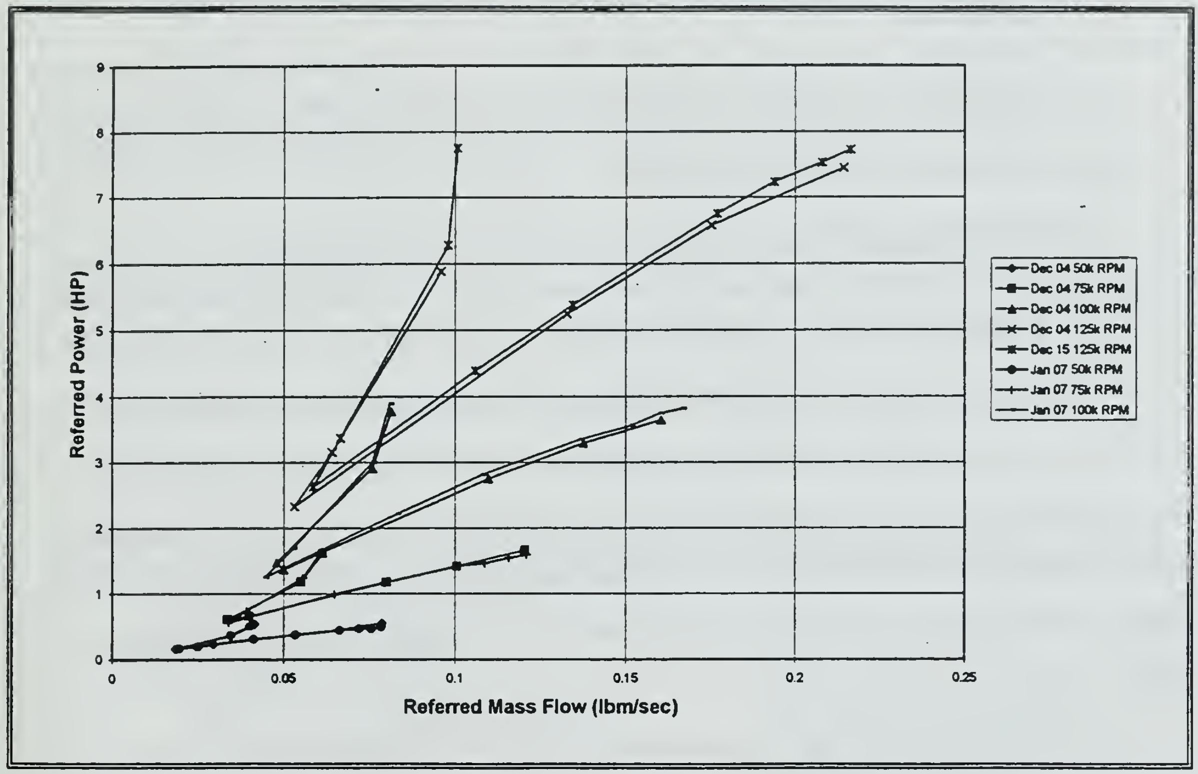


Figure 6. Garrett T2 Turbocharger Compressor Referred Power vs Referred Mass Flow Rate.

2. Summary

The compressor performance map of the Garrett T2 Turbocharger provided insight into the unique characteristics of small centrifugal compressors. Documented research into such studies has been few and far between. Despite the success in mapping the performance of the compressor, the attempt to test the performance of small rotating turbomachinery proved to be a difficult task. The primary difficulty involved the size of the turbocharger and the placement of the instrumentation. As a result, the following items represent the most evident limitations to the test program:

- The compressor size allowed high rotational speeds. Unfortunately, the rotational speed could only be confirmed up to 50000 RPM.

- The mass flow rate required by the compressor was so low that the pressure differential recorded across the orifice plate may not be accurate.

- The combination probes used to measure the stagnation temperature and pressure may have been relatively large enough to disturb the flow into the compressor.

- The combination probe used to measure the compressor exit conditions was placed in the exhaust pipe rather than inside the compressor diffuser casing, allowing additional friction losses.

- The differential pressure transducer response to fluid inertia effects may have made these measurements questionable at these low mass flow rates due to the physical pressure line distance between the orifice plates and the transducers.

It should be noted that the turbine performance maps provided in Appendix A were not considered to be accurate representations of the Garrett turbine in an actual turbojet application. The instrumentation and experimental procedures of the Garrett test program were specifically designed to measure the performance of the compressor. As a result, the turbine data reflected cold mass flow conditions, which are not typical of actual turbine operating conditions.

Additional research into compressor slip factor considerations and power factor calculations is provided in Appendix F.

III. SOPHIA J450 ENGINE TEST PROGRAM

A. EXPERIMENTAL SETUP

1. Overview

The Japanese-built Sophia J450 Turbojet is a small jet engine manufactured primarily for use in the remote-control model airplane industry. The Sophia J450 was purchased because of its physical similarities to the JPX-240 engine researched by Lobik [Ref. 3]. The only difference between the two engines was the fuel requirement and associated fuel delivery lines to the engine. The Sophia used heavy fuels (either jet fuel or a kerosene/Coleman lantern fuel mixture) while the JPX-240 used liquid propane supplied by a pressurized tank, which was fed to the combustion chamber after preheating in the exhaust nozzle. The J450 required an electric fuel pump which delivered 85 psi maximum pressure and was powered by a variable-current 12V supply. Table 3 provides a side-by-side comparison of the technical specifications for each engine.

Engine Specifications	JPX-240 from Ref. [6]	Sophia J450 from Ref. [7]
Length (in.)	13.18	13.19
Diameter (in.)	4.56	4.72
Weight (lbf)	3.75	4.00
Fuel	Liquid propane	Jet fuel for aircraft (JP-4) or Coleman fuel & Kerosene
Starting System	Compressed air	Compressed air
Ignition System	Spark plug and igniter	Spark plug and igniter
Lubrication	Self-feeding oil lubrication	Self-feeding oil lubrication
Fuel Feed System	Pressurized fuel tank	12V turbine type fuel pump
Compressor	Single stage centrifugal	Single stage centrifugal
Thrust	8.83 lbf at 120000 RPM	11 lbf at 123000 RPM
Fuel Consumption	15.95 lbm/hr	19.98 lbm/hr

Table 3. JPX-240 and Sophia J450 Specifications After Refs. [6] and [7].

2. Engine Test Rig

The engine test rig used for the Sophia J450, shown in Figure 7, was located in the Gas Dynamics Laboratory (Building 216) at the Naval Postgraduate School. It was the same apparatus that was designed and used by Lobik [Ref. 3] for the JPX-240 test program. The Sophia J450 was mounted in the test rig with several minor modifications required. The modifications included the placement of the fuel tank external to the building, the addition of the fuel pump, and the addition of a fuel pressure gage. Detailed engineering drawings of the test rig components may be found in Ref. [3].

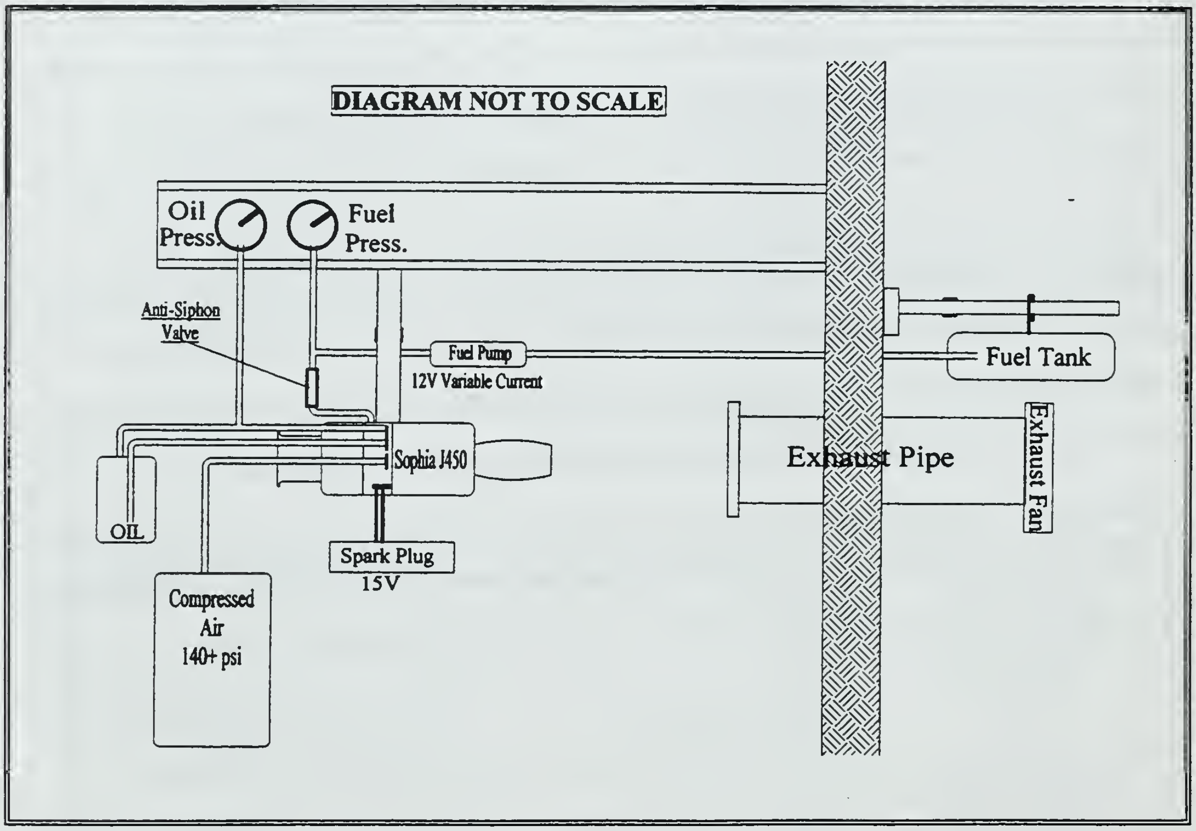


Figure 7. Building 216 Engine Test Rig.

Two pressure gages were mounted on the test rig I-beam. Sophia provided the fuel pressure gage, range 0 – 85 psig (0 – 6 kg/cm^2), which was connected to the fuel supply line by flexible tubing and provided a pressure reading of the fuel supply to the engine. The oil pressure gage, range 0 – 23.5 psig (0 – 1.6 bars), provided by JPX, and reused from the previous research (Lobik, Ref. [3]), was connected to the engine compressor pressure port by flexible tubing. The oil pressure gage sensed the pressure between the compressor impeller and diffuser, which was used to provide the pressure necessary to pump the oil from the reservoir to the engine bearings.

B. DATA ACQUISITION AND REDUCTION

1. Overview

A HP9000 Series 300 workstation was used to control the data acquisition system as well as store and process the data. The primary instruments used for data acquisition were strain gages and pressure lines. The strain readings were cued using a HP397A Data Acquisition Control Unit (DACU) in conjunction with a HP digital voltmeter (DVM) which received signals through a signal conditioner. The pressures were sensed using the Scanivalve Zero-Operate-Calibrate (ZOC-14) system in conjunction with the CALSYS 2000 calibration standard. The ZOC-14 and CALSYS systems were controlled by the workstation using the HP6944A Multiprogrammer. The DACU, DVM, CALSYS, and multiprogrammer were connected to the workstation via a HP-IB (IEEE-488) bus. The test rig data acquisition schematic is shown in Figure 8.

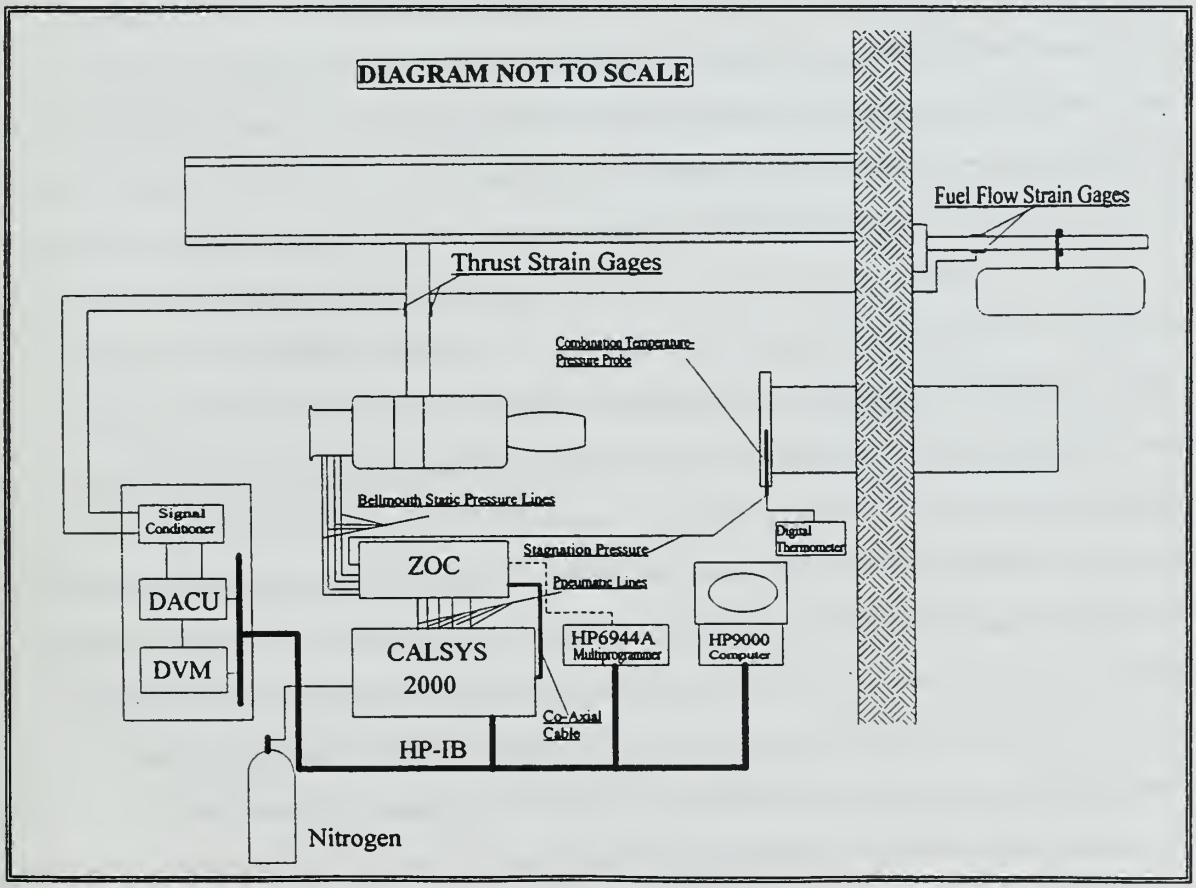


Figure 8. Engine Test Rig Data Acquisition Schematic.

2. Instrumentation and Control

a. *Thrust Measurement*

The engine thrust was determined by using the beam from which the engine was suspended as a thrust-measuring device. The beam contained four strain-gages (two on each side). The strain-gages were configured in a full Wheatstone bridge with the leads providing an output through a signal conditioner to the data acquisition system. The arrangement is shown in Lobik [Ref. 3]. Prior to engine testing, the beam was calibrated with known weights using HP Basic program "MICROJET_CAL". The calibration results are provided in Appendix C as Figure C1.

b. *Fuel Flow Rate Measurement*

The fuel flow rate was determined by using a cantilevered beam as a weighing device to calculate the change in fuel weight over given periods of time. The beam used two strain-gages configured in a half Wheatstone bridge to provide an output through a signal conditioner to the data acquisition system. Prior to engine testing, the beam was calibrated with known weights, again using "MICROJET_CAL". The calibration results are provided in Appendix C as Figure C2.

c. *Mass Flow Rate Measurement*

The flow rate into the compressor was measured using a bellmouth assembly. Lobik [Ref. 3] designed the bellmouth for the JPX-240 engine in accordance with ASME PTC [Ref. 5] specifications. The compressor inlet area for the Sophia J450 matched that of the JPX-240 allowing the bellmouth to be used on the Sophia engine without modification. The bellmouth had a diameter of 2.19 in. at the compressor entrance and a design flow coefficient, K, of 0.995. Complete engineering diagrams for the bellmouth are found in Ref. [3]. Inside the bellmouth were four static pressure ports, spaced 90 degrees apart, which sensed the static pressures using the Scanivalve ZOC-14 system with the CALSYS 2000 providing the nitrogen-pressurized calibration standard. Wendland [Ref. 8] provided a comprehensive guide to the system. The ambient air temperature and pressure were also independently recorded.

3. Software

a. *MICROJET*

The data acquisition program "MICROJET" was a modification to the Wendland [Ref. 8] program "SCAN_ZOC_08". The modification allowed the code to additionally read, calibrate, and display the strain beam results for thrust and fuel flow. The modification, made by Lobik is included in Ref. [3] as "SCAN_ZOC_08A".

b. *MICROJET_CAL*

The strain gage beams were calibrated using "MICROJET_CAL", written by Lobik [Ref. 3] as "THRUST". This program allowed the user to read the voltage sensed by the both strain beams and displayed the results on the computer screen. Applying known weights and employment of this program allowed calibration of the strain beams.

c. *READ_MJ_ZOC*

The pressure data stored by "MICROJET", once reduced, was stored on the HP9000 hard drive. The reduced data was then read and output to screen and/or printer using the program "READ_MJ_ZOC". Additionally, this program read the exhaust stagnation pressure, also measured with the ZOC system, and provided an initial calculation of the mass flow rate.

4. Data Reduction

The mass flow calculation was given by equation 1 and simplified to

$$\dot{m}\left(\frac{lbm}{\sec}\right) = 2.8857\sqrt{\frac{P_{amb}(psia)\cdot \Delta P(in.Hg)}{T_{amb}(\deg.R)}} \qquad (10)$$

where P_{amb} and T_{amb} were the ambient pressure and temperature, and ΔP was the pressure difference sensed by the ZOC pressure transducers. The mass flow rate was then corrected using the referred technique in equation 9.

5. Experimental Procedure

Once all necessary components of the engine test rig and data acquisition system were properly in place and energized, the fuel supply, which was placed outside of the building for safety reasons, was primed by placing the tank on a stand at a height higher than the engine. By placing the tank as such, the fuel pump, once engaged, was gravity-assisted in pumping the fuel into the building which freed the fuel supply line of any air bubbles. The fuel flow strain beam was calibrated to indicate zero strain under the given conditions. Once calibrated, the fuel tank was placed within the holding carriage of the fuel flow strain beam.

Inside the building, the thrust beam was calibrated at zero load. The data acquisition system was then setup using the program "MICROJET" to collect five data points at 1000 Hz using ZOC #1 and CALMOD 1 for pressure readings, of which there were ten samples per port, and ten seconds between data points.

With the air supply connected, the engine was started and fuel flow throttled using the variable-current 12V power supply connected to the fuel pump until the engine was operating in a stabilized manner. The fuel flow was then adjusted until the oil pressure gage read 1.15 bar. This oil pressure reading matched that of the highest data collection point used by Lobik during his JPX tests [Ref. 3]. The computerized data acquisition system was then initiated which provided screen-only outputs of the engine thrust and fuel flow rate while storing the pressure data to the computer hard drive. The engine thrust and fuel flow rate were manually recorded as well as the ambient pressure, temperature, and exhaust gas temperature. The entire data collection sequence had about a one-minute time duration. An engine startup checklist is provided in Appendix D.

The employment of the magnetic pickup used in the Garrett T2 Turbocharger experiment was attempted during this test program without success. As an alternate plan, the assumption was made that the Sophia and JPX engines had identical compressors. This assumption allowed the JPX manufacturer-provided engine operation guide, Table 4, to be used for the Sophia J450. The engine operation guide relates the pressure sensed by the oil pressure gage to compressor speed. The tests conducted for this program were for a compressor pressure reading of 1.15 bar, which represented the selected design speed of 115000 RPM.

Pressure (bar)	RPM
0.15	49,000
0.20	57,000
0.40	79,000
0.90	83,000
0.60	92,000
0.40	95,000
0.80	102,000
0.90	105,000
1.00	110,000
1.10	112,000
1.15	115,000

Table 4. JPX Engine Operation Guide From Ref. [6].

C. RESULTS OF SOPHIA J450 ENGINE TEST PROGRAM

1. Sophia J450 Test Results

Four design speed runs were conducted on the Sophia J450 engine. Each data run was performed at a compressor oil pressure reading of 1.15 bars (approximately 115000 RPM). The data, provided in Appendix C as Tables C1 and C2, were averaged for each run. The results are summarized in Table 5.

Data Run Date	**1 24-Mar-98**	**2 24-Mar-98**	**3 26-Mar-98**	**4 26-Mar-98**
Thrust (lbf)	9.55	9.83	9.89	9.91
$\dot{m}_{ref}$ (lbm/sec)	0.255	0.257	0.281	0.272
SFC (lb/lbf/hr)	1.315	1.310	**3.353**	**-0.532**
$\frac{F}{\dot{m}_{ref}}\left(\frac{lbf}{lbm/\sec}\right)$	37.45	38.25	38.48	39.17
EGT (deg. F)	698	699	814	808

Table 5. Sophia J450 Test Program Results.

The mass flow rate was referred in the same manner as described in Chapter II.B.4.g. The specific fuel consumption (SFC) was given by

$$SFC\left(\frac{lbm}{lbf \cdot \sec}\right) = 3600 \cdot \frac{\dot{m}_{fuel}(lbm/\sec)}{Thrust(lbf)} \tag{11}$$

where $\dot{m}_{fuel}$ was the fuel flow rate as measured by the fuel flow strain beam.

The specific thrust, $F/\dot{m}_{ref}$, was given by

$$\frac{F}{\dot{m}_{ref}}\left(\frac{lbf}{lbm/\sec}\right) = \frac{Thrust(lbf)}{\dot{m}_{ref}(lbm/\sec)} \ . \tag{12}$$

Of note, the SFC calculations for data runs 3 and 4 were deemed unreliable as a result of an oscillating fuel flow strain beam caused by gusty winds during testing on 26-Mar-98. Additionally, the exhaust gas temperature (EGT) readings may be questionable as the temperature probe used to measure the EGT had to be replaced twice as the result of damage while exposed to short duration peak temperatures above 1300 deg. F.

2. Sophia J450 vs JPX-240 Comparison

The results of the four J450 data runs were averaged and compared to Lobik's [Ref. 3] results of the JPX-240 engine at the same compressor speed (115000 RPM). Of note, the SFC averaged for the J450 only considered data runs 1 and 2 for the reasons mentioned in the preceding paragraph. The side-by-side comparison of the two engines (Table 6) indicated that the Sophia J450 produced greater thrust and lower specific fuel consumption than the JPX-240. However, one problem noted was excessive oil consumption, which was the primary limiting factor in the short engine run times.

	JPX-240 from Ref. [3]	**Sophia J450**
Thrust (lbf)	9.04	9.80
$\dot{m}_{ref}$ (lbm/sec)	0.300	0.256
SFC (lb/lbf/hr)	1.620	1.313
$\frac{F}{\dot{m}_{ref}}\left(\frac{lbf}{lbm/\sec}\right)$	30.13	38.28
EGT (deg. F)	1070	755

Table 6. Sophia J450 vs JPX-240 115000 RPM Test Comparison.

3. Summary

The Sophia J450 Test Program was intended to duplicate the tests conducted by Lobik on the JPX-240 engine operating at 115000 RPM [Ref 3]. The assumption that the two engines had identical compressors allowed a side-by-side comparison of the effect of the heavy fuel requirement for the Sophia versus the liquid propane requirement for the JPX. The results indicated that the Sophia J450 delivered improved performance, within the scope of this test. Additionally, the non-pressurized fuel tank requirement for the Sophia provided a safer work environment than the JPX.

IV. PERFORMANCE PREDICTION PROGRAM

A. OVERVIEW

The purpose of the Performance Prediction Program was to take the performance characteristic data of the centrifugal compressor obtained during the Garrett T2 turbocharger test program, import it into the GASTURB [Ref. 9] cycle analysis software program and use it to predict the Sophia J450 engine performance at various spool speeds. In doing so, the compressor performance data needed to be formatted using the SMOOTHC [Ref. 10] software program to reproduce the T2 compressor map in a GASTURB-recognizable format.

B. COMPRESSOR MAP GENERATION

1. Data Manipulation

The data sets from the Garrett T2 turbocharger test program for both the pressure ratio and efficiency plots (Figures 4 and 5, respectively) were merged, then trimmed to not include the surge condition data points. Once trimmed, a third-order least-squares polynomial curve was chosen as the best fit to the data in both plots for each speed line (Figures E1 and E2 in Appendix E). The polynomials were then used to generate smooth curve data for each plot, which were used as inputs into SMOOTHC.

2. Software Description

The SMOOTHC computer program was specifically designed as a tool to produce high-quality compressor characteristic maps from measured data. The Turbo Pascal-based program allowed the user to manually input the mass flow, pressure, and efficiency data and then determined the parabolic shapes that represent the input data on a single plot. The user could then manipulate the shapes of the parabolas to refine the presentation. [Ref. 10]

3. Results

Figure 9 represents the compressor performance map of the Garrett T2 Turbocharger test program as plotted using the SMOOTHC software. The 115000 RPM speed line was interpolated by SMOOTHC and represented the assumed design speed of the compressor.

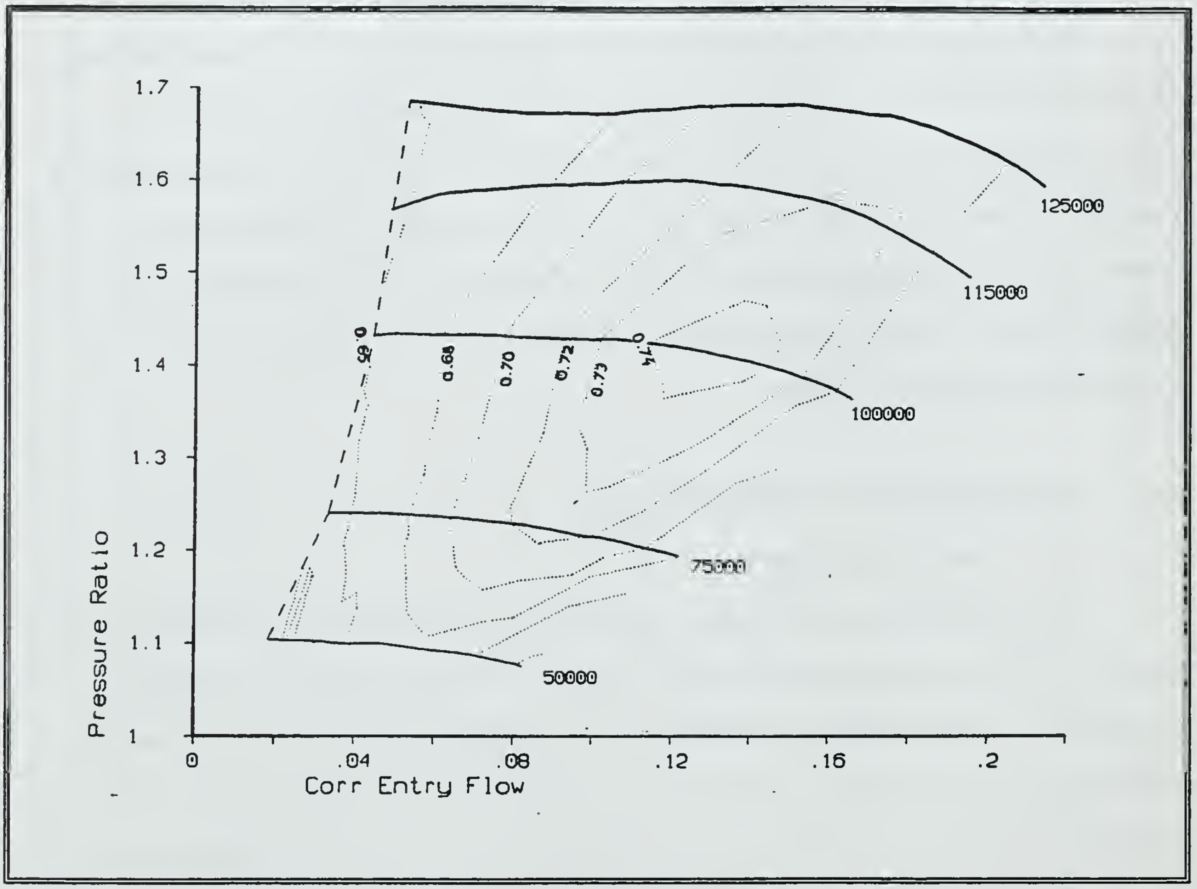


Figure 9. Garrett T2 Turbocharger Compressor SMOOTHC Performance Map.

C. ENGINE PERFORMANCE PREDICTION

1. Software Description and Interface

GASTURB is a software program used to calculate the design and off-design performance of gas turbine engines. In performing its cycle analysis, the program allowed the user to select from a number of available compressor maps for the engine. It also allowed the import of any experimentally derived maps provided that the format is recognizable by GASTURB. The SMOOTHC performance map met the GASTURB format requirement.

2. Cycle Analysis Procedure

The single spool turbojet design point analysis was selected once the GASTURB program was executed. The basic data design condition inputs (chosen to be the 115000 RPM Sophia J450 test program results) were:

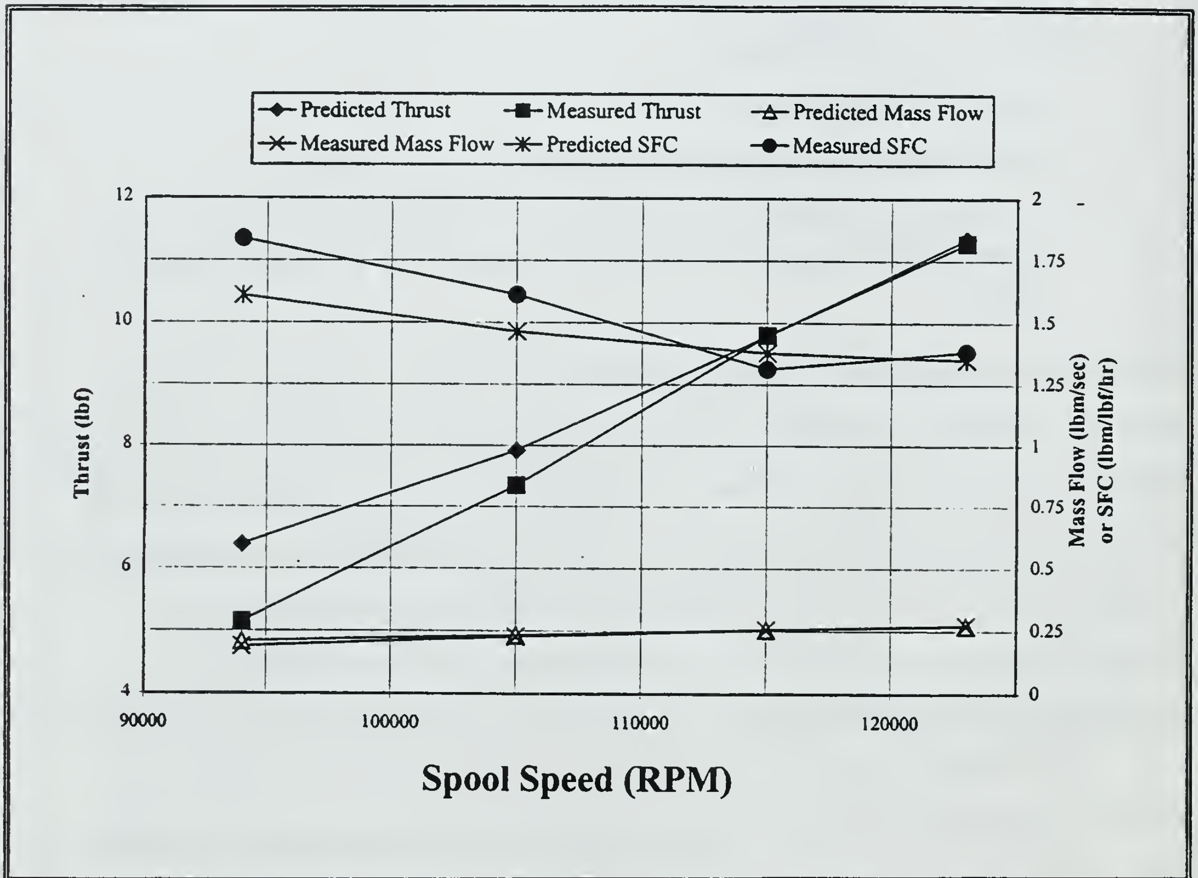
- Inlet corrected mass flow rate, 0.256 lbm/sec.
- The operator-controlled compressor pressure ratio, 2.15.
- Standard sea level conditions.
- Turbine isentropic efficiency, 0.77.
- Fuel heating value assumed, 18500 BTU/lbm, typical for jet fuels.
- The compressor isentropic efficiency, 0.73, determined from SMOOTHC-generated T2 compressor map (Figure 9) as the peak efficiency at the design speed.

The burner exit temperature was determined to be 1715 deg. R by using the iteration option of the software. Selecting the burner exit temperature as the iteration variable, and setting the net thrust determined from the J450 test program, 9.80 lbf, as the value to achieve, allowed the iteration algorithm of GASTURB to determine the necessary burner exit temperature. The GASTURB printout of the design point input conditions is provided in Appendix E as Table E1. The design point calculated results are also provided in Appendix E as Table E2.

The off-design performance prediction involved the evaluation of the J450 at different spool speeds. The first step was to select the off-design option of GASTURB, then select the special maps option. The SMOOTHC compressor map formatted and scaled for the GASTURB Sophia J450 prediction was then read into the program. The turbine performance was predicted using the default turbine map and is provided as Figure E3 in Appendix E. The limiter spool speed option was then turned on and set to the desired speed, as a percentage of the design spool speed, 115000 RPM. The off-design GASTURB performance prediction process was repeated three times for spool speeds of 94000 (81.7%), 105000 (91.3%), and 123000 (107%) RPM; and results are provided in Appendix E as Tables E3, E4, and E5, respectively.

3. Results

The performance predictions were summarized and compared to the actual J450 performance data at the 115000 RPM design condition of the Sophia J450 test program. The SFC was predicted to be within 5% of the design value. Additionally, the three off-design speeds were compared to actual J450 performance. Figure 10 represents the



Spool Speed (RPM)	Thrust (lbf)	$\dot{m}_{ref}$ (lbm/sec)	SFC (lbm/lbf/hr)
115000 Actual	9.80	0.256	1.313
115000 Predicted	9.79	0.256	1.378
94000 Actual	5.15	0.189	1.838
94000 Predicted	6.39	0.209	1.610
105000 Actual	7.35	0.228	1.613
105000 Predicted	7.92	0.233	1.464
123000 Actual	11.28	0.273	1.384
123000 Predicted	11.35	0.271	1.351

Figure 10. GASTURB Prediction vs Actual Sophia J450 Performance.

summarized comparison between the predicted and actual performance of the J450. The off-design data, included in Appendix E as Table E6, were collected in the same manner described in the Sophia J450 test program. It should be noted that steady fuel flow was difficult to maintain during the 94000 RPM run. At this speed the worst match was achieved in that the predicted thrust was off by 24% and the SFC was off by 12%.

The Garrett compressor map used in the GASTURB analysis is shown in Figure 11. The speed lines were represented as fractions of the design speed 115000 RPM. Additionally, the figure has the predicted operating line of the compressor displayed as squares while the circle on the 0.999 speed line denoted the compressor design point.

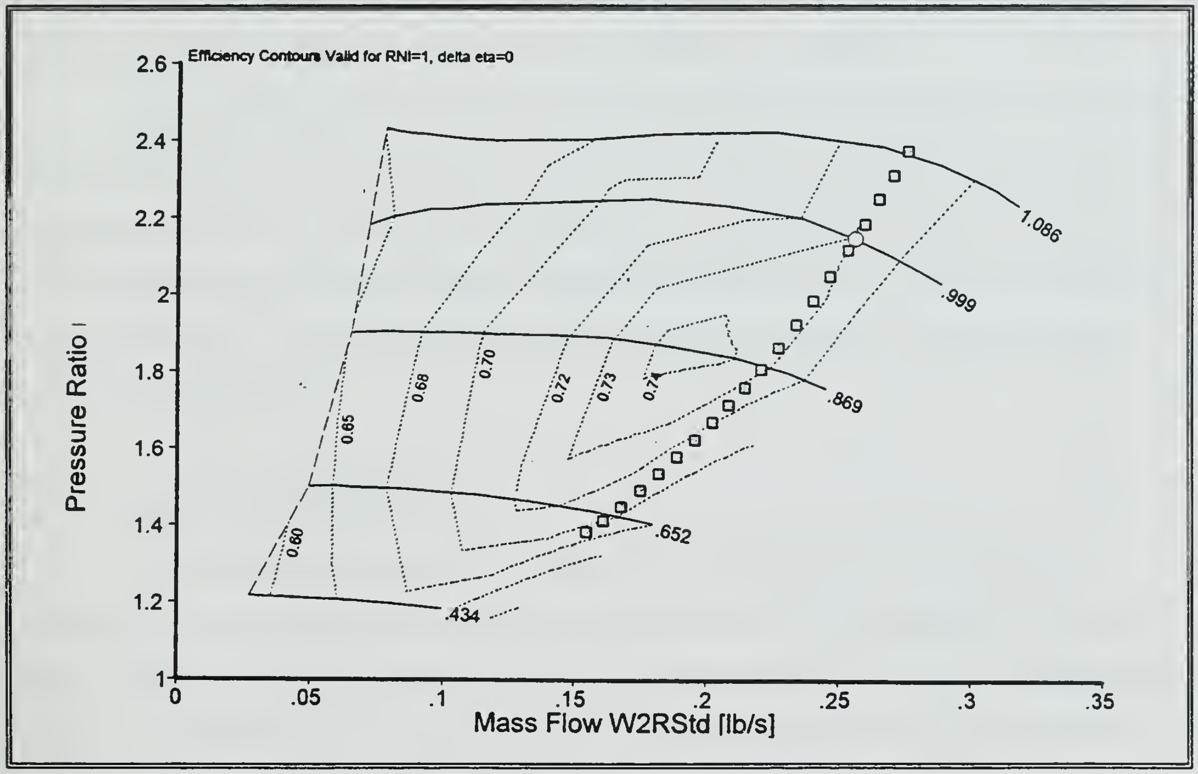


Figure 11. GASTURB-Predicted Sophia J450 Compressor Operating Line.

4. Summary

The results of the performance prediction program indicated that the Garrett T2 compressor map, once formatted for GASTURB recognition, proved to be a suitable model for the performance prediction of the Sophia J450 turbojet. With the exception of the 94000 RPM data, the GASTURB predictions fell within 10% of the actual engine performance data.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The preliminary groundwork for the eventual design and construction of a small turbojet engine was established during this study. In doing so, insight into the performance characteristics of small centrifugal compressors was gained.

The bench testing of a small turbojet engine at a selected design speed allowed the side-by-side comparison between two engines of different fuel requirements. Such testing indicated an improved performance for the heavy-fueled J450 turbojet over the propane-fueled JPX-240 turbojet. It provided quantitative data of the mass flow, thrust, and specific fuel consumption requirements of small-scale turbojets.

Taking advantage of the experimentally determined compressor performance map and actual small turbojet bench test results, a gas turbine cycle analysis software program was successfully used to predict the performance of a small turbojet engine. The results of the performance prediction program were then compared to actual engine test data with reasonable results. The compressor performance map can be used in future small gas turbine design studies.

B. RECOMMENDATIONS

The difficulty in mapping the compressor performance of the turbocharger primarily involved the size of the instrumentation relative to the compressor. To obtain more certain results, smaller, less intrusive instrumentation should be used. Additionally, the rotor speed should be measured using more reliable means at such high rotational speeds. Future studies should also include the performance testing of the turbine section in order to produce a more precise turbine map.

The mass flow coefficient of the engine test program assumed a value close to unity. Calibration of the bellmouth with respect to an orifice plate would help verify the ASME design.

The exhaust temperature readings were deemed unreliable as a result of the extreme short-duration temperature environment that the probe was exposed to during engine start up. A more robust combination probe would provide more reliable temperature readings as well as allowing the exhaust stagnation pressure to be recorded.

The fuel flow reading was subject to unsteady environmental conditions such as wind as well as uneven heating and cooling effects of sun exposure on the strain beam. The employment of a flow meter capable of meeting the small flow requirements of the turbojet may provide the best alternative to replace the strain beam.

The fuel used during the present study involved a mixture of Coleman gas and kerosene. This choice provided and inexpensive readily available safe fuel. Future studies should involve the employment of other jet fuels such as JP-4, Jet-A, etc.

APPENDIX A. GARRETT T2 TURBOCHARGER TEST RESULTS

GARRETT T2 TURBOCHARGER MEASURED DATA

Date: 4-Dec-97
Patm: 29.68 "Hg
Speed: 50000 RPM

PRESSURES (IN H20 GAUGE)							SPEED	TEMPERATURES (DEG R)				
CALIB.	TURBINE			COMPRESSOR			RPM	TURBINE			COMPRESSOR	
	ORIFICE ΔP	*INLET*	*OUTLET*	*ORIFICE ΔP*	*INLET*	*OUTLET*		*ORIFICE*	*INLET*	*OUTLET*	*INLET*	*OUTLET*
135.719	2.64465	83.3819	2.49998	8.7427	-10.308	21.9978	50035.7	537.705	533.752	513.207	521.134	542.071
135.737	2.50188	81.2534	2.36512	6.25495	-8.2424	27.3661	49960.1	538.141	534.269	514.497	521.159	541.205
135.761	2.26536	79.5596	2.21483	4.130225	-6.4475	31.837	50079.2	538.333	534.267	515.991	521.455	542.453
135.68	2.058865	75.7758	2.08739	1.260075	-3.8804	37.2363	50329.3	537.87	533.916	516.418	521.737	545.267
135.675	2.04524	72.0737	1.97457	0.48693	-2.3248	39.9233	50277.2	537.581	533.639	516.791	521.783	547.894
135.669	1.79139	68.5071	1.70426	1.744	-1.1632	40.8869	50227.4	537.333	533.419	517.413	522.073	552.641
135.666	1.61662	64.4086	1.45057	2.51514	-0.4382	39.7906	50245.8	537.246	533.478	518.548	522.736	561.28

GARRETT T2 TURBOCHARGER CALCULATED DATA

COMPRESSOR

K	FLOW (lbm/sec)	RD	Πc	ΔT (Deg R)	ηc	HP	FLOW(REF) (lbm/sec)	RPM(REF)	HP(REF)
0.6026	0.0763	23860	1.0821	20.937	0.5673	0.5427	0.0791	49918	0.5601
0.6032	0.0646	20206	1.0900	20.046	0.6480	0.4400	0.0667	49842	0.4517
0.6039	0.0526	16436	1.0963	20.998	0.6611	0.3749	0.0540	49946	0.3831
0.6066	0.0292	9119	1.1028	23.530	0.6285	0.2331	0.0298	50182	0.2366
0.6092	0.0182	5693	1.1052	26.111	0.5793	0.1615	0.0185	50128	0.1632
0.606	0.0343	10715	1.1044	30.568	0.4915	0.3558	0.0348	50064	0.3585
0.605	0.0411	12838	1.0997	38.544	0.3733	0.5375	0.0416	50051	0.5404

TURBINE

K	FLOW (lbm/sec)	RD	Πt	ΔT (Deg R)	ηt	HP	FLOW(REF) (lbm/sec)	RPM(REF)	HP(REF)
0.6032	0.1053	22068	0.8340	20.545	0.7617	0.7348	0.0893	49325	0.6053
0.6032	0.1022	21406	0.8374	19.772	0.7486	0.6860	0.0870	49226	0.5673
0.6036	0.0971	20337	0.8400	18.276	0.7041	0.6024	0.0830	49344	0.4999
0.6038	0.0923	19329	0.8464	17.498	0.7043	0.5482	0.0795	49606	0.4586
0.6038	0.0916	19194	0.8527	16.848	0.7096	0.5241	0.0795	49568	0.4421
0.604	0.0855	17908	0.8586	16.006	0.7040	0.4646	0.0747	49529	0.3949
0.6042	0.0809	16940	0.8656	14.930	0.6926	0.4099	3984.2269	49544	0.3514

Table A1(a). Garrett T2 Turbocharger Measured and Calculated Data for 50000 RPM for Tests Conducted on December 4, 1997.

GARRETT T2 TURBOCHARGER MEASURED DATA

Date: 4-Dec-97
Patm: 29.68 "Hg
Speed: 75000 RPM

PRESSURES (IN H20 GAUGE)							SPEED	TEMPERATURES (DEG R)				
CALIB.	TURBINE			COMPRESSOR			RPM	TURBINE			COMPRESSOR	
	ORIFICE ΔP	*INLET*	*OUTLET*	*ORIFICE ΔP*	*INLET*	*OUTLET*		*ORIFICE*	*INLET*	*OUTLET*	*INLET*	*OUTLET*
135.786	4.48781	172.574	4.33869	19.5477	-23.243	50.1761	75204.4	537.824	535.772	504.867	521.321	562.194
135.826	4.12101	167.766	4.70158	13.83745	-18.418	64.5383	75088.9	539.782	535.954	505.539	521.064	562.776
135.741	3.75795	160.834	4.82542	8.8546	-14.115	74.1288	74920.4	539.569	535.476	505.94	521.022	564.577
135.733	2.99907	150.567	3.6632	2.23527	-8.3449	86.4121	75229.6	538.874	534.837	506.719	520.632	569.029
135.73	2.64552	141	2.52562	1.60941	-4.8168	90.4608	75106.7	538.806	534.59	507.127	520.809	574.571
135.73	2.32177	133.249	1.77178	4.406085	-2.2074	93.4405	75099.8	538.777	534.453	508.017	520.979	584.756
135.733	2.07119	124.949	0.588524	5.53455	-1.0604	89.0593	75212.6	538.567	534.354	509.046	522.155	600.184

GARRETT T2 TURBOCHARGER CALCULATED DATA

COMPRESSOR

K	FLOW (lbm/sec)	RD	Πc	ΔT (Deg R)	ηc	HP	FLOW(REF) (lbm/sec)	RPM(REF)	HP(REF)
0.6016	0.1124	35121	1.1929	40.873	0.6591	1.5594	0.1205	75014	1.6638
0.602	0.0950	29703	1.2152	41.712	0.7153	1.3459	0.1006	74918	1.4184
0.6026	0.0764	23874	1.2264	43.555	0.7182	1.1296	0.0800	74753	1.1773
0.6054	0.0388	12114	1.2395	48.397	0.6807	0.6369	0.0400	75089	0.6544
0.606	0.0329	10294	1.2387	53.762	0.6110	0.6012	0.0337	74954	0.6121
0.6038	0.0542	16935	1.2381	63.777	0.5140	1.1733	0.0550	74935	1.1867
0.6035	0.0606	18936	1.2237	78.029	0.3973	1.6051	0.0614	74963	1.6170

TURBINE

K	FLOW (lbm/sec)	RD	Πt	ΔT (Deg R)	ηt	HP	FLOW(REF) (lbm/sec)	RPM(REF)	HP(REF)
0.6022	0.1491	31248	0.7082	30.905	0.6144	1.5652	0.1071	73996	1.0878
0.6023	0.1420	29756	0.7148	30.415	0.6203	1.4669	0.1028	73870	1.0278
0.6026	0.1350	28274	0.7238	29.536	0.6252	1.3535	0.0989	73737	0.9605
0.6028	0.1196	25052	0.7351	28.118	0.6245	1.1417	0.0892	74085	0.8257
0.6031	0.1114	23330	0.7459	27.463	0.6393	1.0385	0.0845	73981	0.7644
0.6034	0.1036	21712	0.7553	26.436	0.6418	0.9303	0.0797	73984	0.6947
0.6036	0.0971	20353	0.7649	25.308	0.6424	0.8349	4439.9354	74102	0.6333

Table A1(b). Garrett T2 Turbocharger Measured and Calculated Data for 75000 RPM for Tests Conducted on December 4, 1997.

GARRETT T2 TURBOCHARGER MEASURED DATA

Date: 4-Dec-97
Patm: 29.68 "Hg
Speed: 100000 RPM

PRESSURES (IN H20 GAUGE)							SPEED	TEMPERATURES (DEG R)				
CALIB.	TURBINE			COMPRESSOR			RPM	TURBINE			COMPRESSOR	
	ORIFICE ΔP	*INLET*	*OUTLET*	*ORIFICE ΔP*	*INLET*	*OUTLET*		*ORIFICE*	*INLET*	*OUTLET*	*INLET*	*OUTLET*
135.88	6.71295	324.489	8.98857	32.45465	-39.265	95.89	100289	538.204	539.03	497.109	521.43	588.799
135.826	6.36445	317.103	7.75922	24.43	-32.798	118.03	100275	548.644	542.9	497.923	521.621	592.594
135.865	5.57665	303.424	6.69499	15.9939	-25.4	133.658	99874.9	536.738	537.333	499.393	521.353	595.546
135.795	4.322325	281.26	7.0148	3.385135	-14.437	156.016	100298	549.458	543.715	501.548	521.958	603.684
135.791	3 577835	261.64	4.92721	3.206125	-8.2488	161.76	99905.5	531.822	536.4	502.829	521.492	613.056
135.786	3.00915	243.883	2.90755	8.39605	-3.5528	166.583	100210	539.933	539.752	504.22	522.015	635.761
135.772	2.6513	224.615	-0.21942	9.72525	-1.7796	153.062	99838.7	535.845	535.208	504.606	523.112	661.324

GARRETT T2 TURBOCHARGER CALCULATED DATA

COMPRESSOR

K	FLOW (lbm/sec)	RD	Πc	ΔT (Deg R)	ηc	HP	FLOW(REF) (lbm/sec)	RPM(REF)	HP(REF)
0.6009	0.1432	44757	1.3706	67.369	0.7295	3.2755	0.1603	100025	3.6479
0.6012	0.1250	39078	1.4064	70.973	0.7522	3.0129	0.1375	99993	3.2964
0.6018	0.1019	31859	1.4202	74.193	0.7408	2.5677	0.1099	99619	2.7551
0.6044	0.0475	14850	1.4376	81.726	0.6979	1.3184	0.0498	99984	1.3740
0.6044	0.0463	14463	1.4296	91.564	0.6124	1.4386	0.0477	99637	1.4765
0.6028	0.0744	23248	1.4249	113.746	0.4886	2.8727	0.0759	99890	2.9123
0.6024	0.0798	24957	1.3850	138.212	0.3691	3.7471	0.0812	99416	3.7780

TURBINE

K	FLOW (lbm/sec)	RD	Πt	ΔT (Deg R)	ηt	HP	FLOW(REF) (lbm/sec)	RPM(REF)	HP(REF)
0.6012	0.2047	42892	0.5669	41.921	0.5195	2.9143	0.1167	98379	1.5981
0.6012	0.1965	41161	0.5710	44.977	0.5599	3.0005	0.1135	98014	1.6563
0.6016	0.1843	38619	0.5805	37.940	0.4906	2.3748	0.1080	98127	1.3432
0.6020	0.1580	33099	0.5998	42.167	0.5707	2.2621	0.0961	97963	1.3131
0.6023	0.1440	30168	0.6143	33.571	0.4816	1.6415	0.0896	98242	0.9876
0.6025	0.1293	27099	0.6280	35.532	0.5290	1.5606	0.0829	98235	0.9617
0.6028	0.1201	25155	0.6423	30.602	0.4812	1.2477	4110.8226	98286	0.7957

Table A1(c). Garrett T2 Turbocharger Measured and Calculated Data for 100000 RPM for Tests Conducted on December 4, 1997.

GARRETT T2 TURBOCHARGER MEASURED DATA

Date: 4-Dec-97
Patm: 29.68 "Hg
Speed: 125000 RPM

PRESSURES (IN H20 GAUGE)							SPEED	TEMPERATURES (DEG R)				
CALIB.	TURBINE			COMPRESSOR			RPM	TURBINE			COMPRESSOR	
	ORIFICE ΔP	*INLET*	*OUTLET*	*ORIFICE ΔP*	*INLET*	*OUTLET*		*ORIFICE*	*INLET*	*OUTLET*	*INLET*	*OUTLET*
136.07	9.76005	591.994	6.94547	52.696	-62.249	138.523	124768	546.938	540.857	487.953	525.368	628.912
136.042	8.3532	576.069	-12.7239	36.74685	-49.641	185.863	125701	546.847	540.451	487.875	524.487	636.421
136.057	7.1475	538.203	-13.5319	22.18035	-36.916	211.557	124850	545.248	538.737	489.018	525.524	643.404
136.076	5.57735	483.331	-9.97846	3.735135	-20.724	242.195	124903	544.717	537.758	491.015	524.761	655.536
135.983	4.67553	449.803	-7.26648	5.70325	-12.256	254.869	125178	544.496	538.955	491.606	524.263	671.102
135.975	3.971055	401.459	8.11049	13.4303	-4.8302	253.426	125380	544.043	537.447	495.838	524.625	707.646

GARRETT T2 TURBOCHARGER CALCULATED DATA

COMPRESSOR

K	FLOW (lbm/sec)	RD	Πc	ΔT (Deg R)	ηc	HP	FLOW(REF) (lbm/sec)	RPM(REF)	HP(REF)
0.6004	0.1788	55902	1.5876	103.544	0.7163	6.2880	0.2145	123972	7.4459
0.6008	0.1514	47320	1.6647	111.934	0.7345	5.7539	0.1750	125004	6.5765
0.6014	0.1189	37170	1.6770	117.880	0.7096	4.7598	0.1328	124036	5.2464
0.6036	0.0497	15531	1.6861	130.775	0.6459	2.2064	0.0531	124178	2.3309
0.6034	0.0613	19171	1.6820	146.839	0.5718	3.0581	0.0641	124511	3.1624
0.602	0.0934	29186	1.6471	183.021	0.4392	5.8028	0.0958	124669	5.8869

TURBINE

K	FLOW (lbm/sec)	RD	Πt	ΔT (Deg R)	ηt	HP	FLOW(REF) (lbm/sec)	RPM(REF)	HP(REF)
0.6005	0.2905	60866	0.4126	52.904	0.4376	5.2191	0.1213	122184	2.0898
0.6007	0.2669	55918	0.3992	52.576	0.4215	4.7651	0.1132	123144	1.9397
0.6009	0.2424	50780	0.4144	49.719	0.4147	4.0921	0.1068	122505	1.7354
0.6013	0.2078	43547	0.4440	46.743	0.4199	3.2991	0.0971	122669	1.4870
0.6015	0.1865	39083	0.4646	47.349	0.4467	2.9993	0.0907	122802	1.4034
0.6018	0.1665	34882	0.5116	41.609	0.4443	2.3524	0.0857	123173	1.1685

Table A1(d). Garrett T2 Turbocharger Measured and Calculated Data for 125000 RPM for Tests Conducted on December 4, 1997.

GARRETT T2 TURBOCHARGER MEASURED DATA

Date: 15-Dec-97
Patm: 30.18 "Hg
Speed: 125000 RPM

PRESSURES (IN H20 GAUGE)							SPEED	TEMPERATURES (DEG R)				
CALIB.	TURBINE			COMPRESSOR			RPM	TURBINE			COMPRESSOR	
	ORIFICE ΔP	*INLET*	*OUTLET*	*ORIFICE ΔP*	*INLET*	*OUTLET*		*ORIFICE*	*INLET*	*OUTLET*	*INLET*	*OUTLET*
136.108	11.1503	674.009	-21.3306	54.0075	-65.3194	141.94	124823	537.071	528.423	477.288	512.52	616.395
136.013	10.9994	683.996	-21.5531	50.465	-62.4503	153.018	124260	538.796	529.965	479.724	512.588	617.926
135.993	10.74495	696.563	-23.0209	44.57415	-57.7214	171.04	125003	540.082	531.277	482.013	512.325	620.931
135.971	10.2456	690.773	-19.9995	37.83325	-52.0006	190.271	124946	539.597	531.14	482.425	512.801	624.148
135.948	8.8301	655.722	-24.7673	23.0046	-38.8539	213.623	124664	538.886	530.877	482.991	514.262	631.098
135.928	8.2581	653.932	-25.0357	14.70305	-31.1138	225.915	124473	541.383	532.231	486.031	513.058	633.683
135.917	7.03055	619.517	-14.3342	4.64141	-21.2239	259.394	124989	539.014	530.968	487.134	513.311	644.017
135.913	4.82343	481.117	-14.679	6.25245	-12.7405	263.673	125523	537.703	529.987	1.78E+38	515.013	663.286
135.951	3.757595	428.606	-14.0034	14.24095	-5.2277	267.311	125875	539.207	530.36	1.78E+38	514.119	701.394
135.881	3.350185	380.099	-13.8509	15.2897	-2.55351	236.911	125966	536.755	529.344	1.78E+38	516.57	742.389

GARRETT T2 TURBOCHARGER CALCULATED DATA

COMPRESSOR

K	FLOW (lbm/sec)	RD	Πc	ΔT (Deg R)	ηc	HP	LOW(REF (lbm/sec)	RPM(REF)	HP(REF)
0.6002	0.1790	55942	1.6186	105.338	0.7178	6.4015	0.2080	124997	7.5287
0.6006	0.1691	52856	1.6480	108.606	0.7237	6.2360	0.1938	125777	7.2377
0.6008	0.1565	48935	1.6753	111.347	0.7316	5.9191	0.1767	125661	6.7572
0.6012	0.1233	38551	1.6789	116.836	0.7023	4.8929	0.1345	125200	5.3806
0.6020	0.0994	31086	1.6770	120.625	0.6771	4.0734	0.1061	125154	4.3932
0.6038	0.0564	17643	1.7204	130.706	0.6585	2.5052	0.0587	125642	2.6326
0.6032	0.0653	20406	1.6945	148.273	0.5649	3.2868	0.0666	125970	3.3747
0.6020	0.0979	30595	1.6721	187.275	0.4343	6.2243	0.0978	126433	6.2779
0.6020	0.1011	31608	1.5866	225.819	0.3225	7.7538	0.1007	126224	7.7510

TURBINE

K	FLOW (lbm/sec)	RD	Πt	ΔT (Deg R)	ηt	HP	LOW(REF (lbm/sec)	RPM(REF)	HP(REF)
0.6002	0.3271	68540	0.3590	51.135	0.3813	5.6805	0.1240	123668	2.1127
0.6002	0.3267	68447	0.3555	50.241	0.3706	5.5737	0.1228	122931	2.0511
0.6002	0.3244	67966	0.3502	49.264	0.3579	5.4269	0.1207	123513	1.9719
0.6003	0.3165	66321	0.3547	48.715	0.3579	5.2365	0.1184	123473	1.9130
0.6005	0.2893	60603	0.3619	47.886	0.3579	4.7036	0.1117	123225	1.7753
0.6006	0.2790	58456	0.3623	46.200	0.3447	4.3772	0.1081	122879	1.6527
0.6008	0.2539	53205	0.3848	43.834	0.3457	3.7800	0.1016	123535	1.4767
0.6014	0.1954	40939	0.4441	############	#######	#########	0.0902	124178	########
0.6018	0.1670	34988	0.4727	############	#######	#########	0.0819	124482	########
0.6021	0.1530	32053	0.5019	############	#######	#########	0.0796	124692	########

Table A2. Garrett T2 Turbocharger Measured and Calculated Data for 125000 RPM for Tests Conducted on December 15, 1997.

GARRETT T2 TURBOCHARGER MEASURED DATA

Date: 7-Jan-98
Patm: 30.05 "Hg
Speed: 50000 RPM

PRESSURES (IN H20 GAUGE)							SPEED	TEMPERATURES (DEG R)				
CALIB.	TURBINE			COMPRESSOR			RPM	TURBINE			COMPRESSOR	
	ORIFICE ΔP	*INLET*	*OUTLET*	*ORIFICE ΔP*	*INLET*	*OUTLET*		*ORIFICE*	*INLET*	*OUTLET*	*INLET*	*OUTLET*
136.074	2.6949	86.0061	2.46338	8.79933	-10.4904	22.3177	49938	535.551	528.166	510.762	516.734	535.335
136.076	2.7828	85.802	2.45137	8.17667	-9.96816	23.9002	49963.3	537.067	528.49	510.883	516.855	534.997
136.071	2.48137	85.814	2.44017	7.43867	-9.34846	25.963	50272.4	537.872	528.812	511.085	517.096	536.309
136.079	2.77627	84.4805	2.40655	6.34	-8.39601	28.4266	50172.2	538.507	528.976	511.249	516.788	536.372
136.039	2.2136	82.5782	2.33411	4.09633	-6.45288	32.8743	50345.8	539.296	529.097	511.456	517.261	537.887
136.035	2.22837	79.4135	2.25308	2.45567	-4.98798	35.5522	50190.4	539.438	529.252	511.757	517.212	539.243
136.023	1.8588	76.6556	2.17124	0.912	-3.59952	38.2076	48724.5	539.845	529.267	511.877	518.014	541.498
136.028	1.82057	74.1376	2.10501	0.552333	-2.24947	40.3075	50098.7	540.353	529.657	512.318	518.167	543.797
136.017	2.2606	70.687	2.05758	1.76	-1.08812	41.0958	49842.9	540.503	529.611	512.793	518.213	549.458
136.004	1.59677	66.4822	1.77205	2.385	-0.48163	39.6325	47995	540.436	529.842	513.563	518.875	556.221

GARRETT T2 TURBOCHARGER CALCULATED DATA

COMPRESSOR

K	FLOW (lbm/sec)	RD	Πc	ΔT (Deg R)	ηc	HP	LOW(REF (lbm/sec)	RPM(REF)	HP(REF)
0.6028	0.0742	23198	1.0849	18.142	0.6709	0.4572	0.0756	50052	0.4674
0.6028	0.0708	22133	1.0884	19.213	0.6590	0.4620	0.0720	50350	0.4714
0.6032	0.0655	20470	1.0919	19.584	0.6714	0.4355	0.0664	50264	0.4435
0.6038	0.0528	16490	1.0977	20.626	0.6769	0.3695	0.0533	50415	0.3743
0.605	0.0410	12809	1.1003	22.031	0.6503	0.3065	0.0412	50262	0.3094
0.6076	0.0251	7842	1.1031	23.484	0.6273	0.2001	0.0252	48756	0.2011
0.6092	0.0196	6120	1.1046	25.630	0.5831	0.1704	0.0196	50124	0.1707
0.6058	0.0347	10855	1.1034	31.245	0.4730	0.3684	0.0347	49866	0.3680
0.6054	0.0404	12614	1.0982	37.346	0.3769	0.5118	0.0402	47986	0.5101

TURBINE

K	FLOW (lbm/sec)	RD	Πt	ΔT (Deg R)	ηt	HP	LOW(REF (lbm/sec)	RPM(REF)	HP(REF)
0.6032	0.1073	22486	0.8312	17.404	0.6405	0.6343	0.0891	49488	0.5171
0.6032	0.1089	22821	0.8315	17.607	0.6489	0.6513	0.0905	49498	0.5310
0.6032	0.1028	21535	0.8315	17.727	0.6527	0.6187	0.0854	49789	0.5043
0.6032	0.1084	22718	0.8337	17.727	0.6617	0.6527	0.0904	49682	0.5334
0.6036	0.0967	20260	0.8368	17.641	0.6716	0.5793	0.0809	49848	0.4751
0.6036	0.0967	20257	0.8420	17.495	0.6895	0.5744	0.0814	49687	0.4741
0.604	0.0881	18453	0.8466	17.390	0.7073	0.5201	0.0746	48235	0.4317
0.604	0.0869	18207	0.8509	17.339	0.7261	0.5117	0.0740	49577	0.4268
0.6036	0.0963	20186	0.8569	16.818	0.7358	0.5502	0.0826	49326	0.4623
0.6045	0.0808	16921	0.8639	16.279	0.7505	0.4465	0.0699	47487	0.3783

Table A3(a). Garrett T2 Turbocharger Measured and Calculated Data for 50000 RPM for Tests Conducted on January 7, 1998.

GARRETT T2 TURBOCHARGER MEASURED DATA

Date: 7-Jan-98
Patm: 30.05 "Hg
Speed: 75000 RPM

PRESSURES (IN H20 GAUGE)							SPEED	TEMPERATURES (DEG R)				
CALIB.	TURBINE			COMPRESSOR			RPM	TURBINE			COMPRESSOR	
	ORIFICE ΔP	*INLET*	*OUTLET*	*ORIFICE ΔP*	*INLET*	*OUTLET*		*ORIFICE*	*INLET*	*OUTLET*	*INLET*	*OUTLET*
136.111	4.73453	181.331	5.36472	19.889	-23.946	51.6836	75502.3	532.974	528.249	502.58	515.34	553.981
136.12	4.67327	179.346	5.31671	18.3663	-22.6251	55.2955	75141.2	532.562	527.908	502.54	515.328	554.44
136.113	4.48793	175.47	5.1475	16.2983	-20.764	59.0531	74719.8	532.429	527.737	502.749	515.477	554.927
136.046	4.3276	174.597	5.1131	14.0147	-18.8743	65.8265	75143.3	532.715	528.132	503.035	516.148	557.573
136.035	3.76423	167.528	5.0235	8.86967	-14.4454	75.8191	75006.8	532.079	527.533	503.416	515.888	559.136
136.018	3.54377	162.836	4.89109	5.95	-11.8001	80.7505	74948.5	532.017	527.611	503.823	515.94	560.939
136.018	2.92443	153.491	4.04324	1.64667	-7.89026	87.8428	74598	531.684	527.441	504.512	516.014	564.235
136.017	2.6437	147.305	3.4384	2.223	-4.43606	94.4968	75446.4	531.925	527.555	505.018	516.152	571.437
136.032	2.34803	138.906	2.46314	4.54833	-2.20653	95.5972	75400.8	531.416	527.163	505.8	516.471	581.995
135.973	1.98707	130.038	0.195011	5.54633	-1.07846	89.9197	75210.9	531.309	526.982	506.513	517.406	596.401

GARRETT T2 TURBOCHARGER CALCULATED DATA

COMPRESSOR

K	FLOW (lbm/sec)	RD	Πc	ΔT (Deg R)	ηc	HP	LOW(REF (lbm/sec)	RPM(REF)	HP(REF)
0.6018	0.1104	34508	1.2015	39.112	0.7096	1.4662	0.1159	75386	1.5493
0.6018	0.1041	32552	1.2055	39.450	0.7166	1.3950	0.1088	74952	1.4668
0.602	0.0967	30227	1.2170	41.425	0.7190	1.3602	0.1006	75328	1.4224
0.6026	0.0773	24168	1.2286	43.248	0.7228	1.1354	0.0795	75210	1.1743
0.6032	0.0635	19856	1.2329	44.999	0.7067	0.9706	0.0649	75148	0.9971
0.606	0.0337	10527	1.2385	48.221	0.6744	0.5514	0.0341	74791	0.5609
0.6054	0.0391	12213	1.2444	55.285	0.6018	0.7335	0.0392	75632	0.7397
0.6036	0.0556	17386	1.2403	65.524	0.5002	1.2375	0.0555	75563	1.2407
0.6032	0.0613	19157	1.2229	78.995	0.3877	1.6439	0.0611	75304	1.6420

TURBINE

K	FLOW (lbm/sec)	RD	Πt	ΔT (Deg R)	ηt	HP	LOW(REF (lbm/sec)	RPM(REF)	HP(REF)
0.5984	0.1547	32402	0.7020	25.669	0.5055	1.3481	0.1076	74816	0.9211
0.5984	0.1535	32157	0.7043	25.368	0.5043	1.3222	0.1071	74482	0.9067
0.5984	0.1499	31413	0.7087	24.988	0.5054	1.2722	0.1053	74077	0.8784
0.5984	0.1471	30814	0.7097	25.097	0.5092	1.2534	0.1035	74469	0.8664
0.5986	0.1365	28594	0.7183	24.117	0.5067	1.1177	0.0972	74375	0.7825
0.5986	0.1318	27624	0.7239	23.788	0.5113	1.0650	0.0947	74312	0.7517
0.5987	0.1189	24912	0.7344	22.929	0.5150	0.9258	0.0868	73977	0.6643
0.5987	0.1124	23546	0.7415	22.537	0.5216	0.8601	0.0829	74810	0.6240
0.5989	0.1052	22037	0.7511	21.363	0.5161	0.7630	0.0788	74792	0.5623
0.5990	0.0960	20111	0.7592	20.469	0.5132	0.6672	0.0731	74617	0.4998

Table A3(b). Garrett T2 Turbocharger Measured and Calculated Data for 75000 RPM for Tests Conducted on January 7, 1998.

GARRETT T2 TURBOCHARGER MEASURED DATA

Date: 7-Jan-98
Patm: 30.06 "Hg
Speed: 100000 RPM

PRESSURES (IN H20 GAUGE)							SPEED	TEMPERATURES (DEG R)				
CALIB.	TURBINE			COMPRESSOR			RPM	TURBINE			COMPRESSOR	
	ORIFICE ΔP	*INLET*	*OUTLET*	*ORIFICE ΔP*	*INLET*	*OUTLET*		*ORIFICE*	*INLET*	*OUTLET*	*INLET*	*OUTLET*
136.077	7.45247	352.342	9.02931	35.0627	-42.1253	92.1899	100008	533.866	526.824	489.553	513.433	580.382
136.057	7.41837	353.227	0.435237	32.689	-40.2031	98.8029	100262	534.131	527.464	490.2	513.782	582.064
136.029	6.96913	343.004	-1.88703	29.5457	-37.4021	106.716	99952.1	533.738	527.065	490.263	514.755	583.531
136.021	6.1749	335.305	-2.28084	24.352	-33.2033	120.892	100011	533.916	527.381	490.73	513.751	585.301
136.023	5.9131	323.007	-3.42726	15.6087	-25.6912	139.812	100317	533.853	527.541	491.311	513.834	589.862
136.015	5.01177	304.662	9.90398	9.358	-20.0287	146.975	99845.8	531.775	526.89	492.408	513.692	591.645
135.959	4.32593	287.094	8.20186	2.72033	-13.9316	156.423	99201.5	524.872	526.544	504.742	512.674	595.157
135.82	3.48707	265.094	6.04209	3.981	-7.67557	163.316	96646.7	532.058	529.122	500.892	514.29	608.296
135.819	3.05353	244.529	3.29339	8.50333	-3.35442	164.511	98690.8	531.675	528.611	501.691	515.03	630.834
135.82	2.6724	230.214	-1.07098	9.74733	-1.78397	153.803	99564.2	531.929	527.672	501.118	516.65	657.932

GARRETT T2 TURBOCHARGER CALCULATED DATA

COMPRESSOR

K	FLOW (lbm/sec)	RD	Πc	ΔT (Deg R)	ηc	HP	LOW(REF (lbm/sec)	RPM(REF)	HP(REF)
0.6008	0.1456	45527	1.3768	68.282	0.7198	3.3770	0.1600	100740	3.7454
0.6008	0.1387	43344	1.3877	68.776	0.7345	3.2384	0.1513	100333	3.5612
0.6012	0.1266	39567	1.4099	71.550	0.7405	3.0754	0.1365	100491	3.3474
0.6018	0.1021	31911	1.4316	76.028	0.7296	2.6356	0.1079	100790	2.8123
0.6026	0.0795	24859	1.4292	77.953	0.7079	2.1051	0.0828	100330	2.2139
0.605	0.0433	13536	1.4311	82.483	0.6702	1.2128	0.0444	99782	1.2571
0.604	0.0522	16311	1.4259	94.006	0.5837	1.6657	0.0527	97059	1.6968
0.6026	0.0758	23694	1.4137	115.804	0.4624	2.9807	0.0758	99041	3.0020
0.6024	0.0809	25300	1.3820	141.282	0.3541	3.8830	0.0808	99761	3.8895

TURBINE

K	FLOW (lbm/sec)	RD	Πt	ΔT (Deg R)	ηt	HP	LOW(REF (lbm/sec)	RPM(REF)	HP(REF)
0.6011	0.2212	46351	0.5491	37.271	0.4495	2.8000	0.1192	99233	1.4858
0.6011	0.2208	46265	0.5372	37.264	0.4343	2.7943	0.1189	99425	1.4801
0.6012	0.2127	44572	0.5414	36.802	0.4343	2.6586	0.1161	99155	1.4279
0.6014	0.1993	41761	0.5465	36.651	0.4383	2.4808	0.1099	99184	1.3458
0.6014	0.1934	40526	0.5541	36.230	0.4425	2.3797	0.1085	99472	1.3125
0.6017	0.1764	36952	0.5870	34.482	0.4636	2.0652	0.1014	99066	1.1690
0.6020	0.1629	34122	0.5994	21.802	0.3044	1.2058	0.0960	98459	0.7000
0.6023	0.1430	29955	0.6158	28.230	0.4124	1.3706	0.0872	95689	0.8196
0.6025	0.1318	27616	0.6309	26.920	0.4130	1.2050	0.0829	97760	0.7436
0.6028	0.1220	25553	0.6382	26.554	0.4179	1.0998	0.0784	98713	0.6945

Table A3(c). Garrett T2 Turbocharger Measured and Calculated Data for 100000 RPM for Tests Conducted on January 7, 1998.

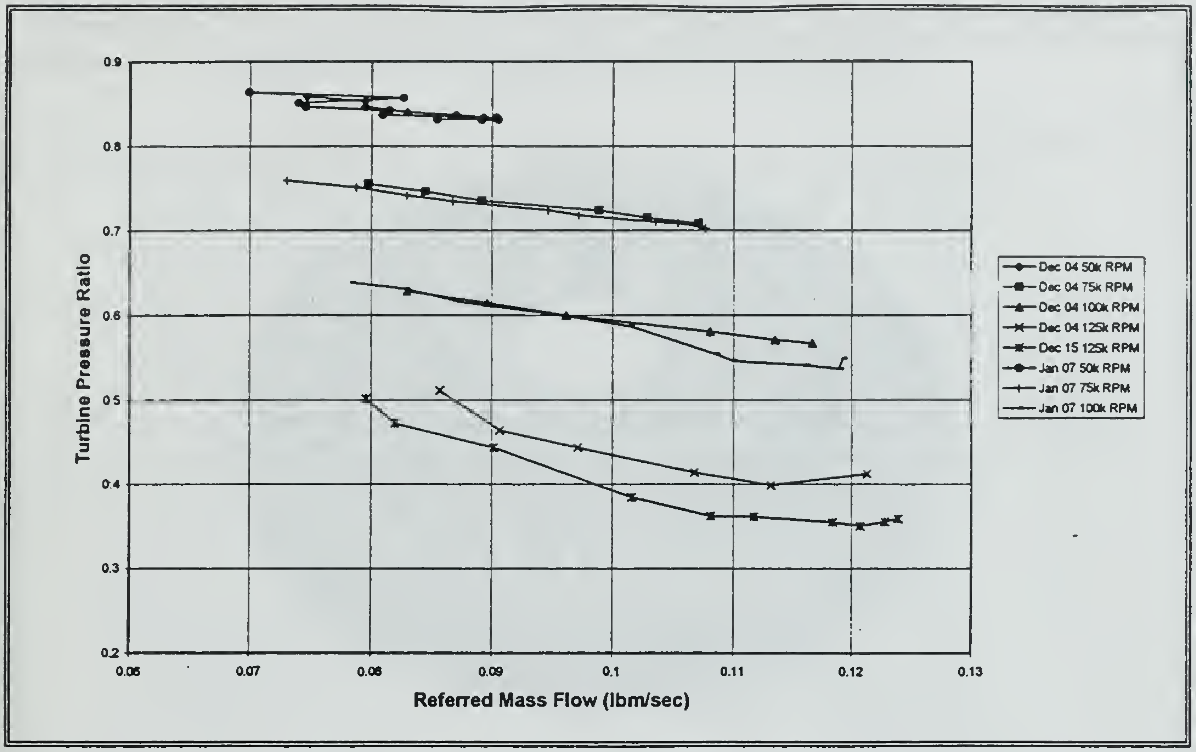


Figure A1. Garrett T2 Turbocharger Turbine Total-to-Total Pressure Ratio vs Referred Mass Flow Rate.

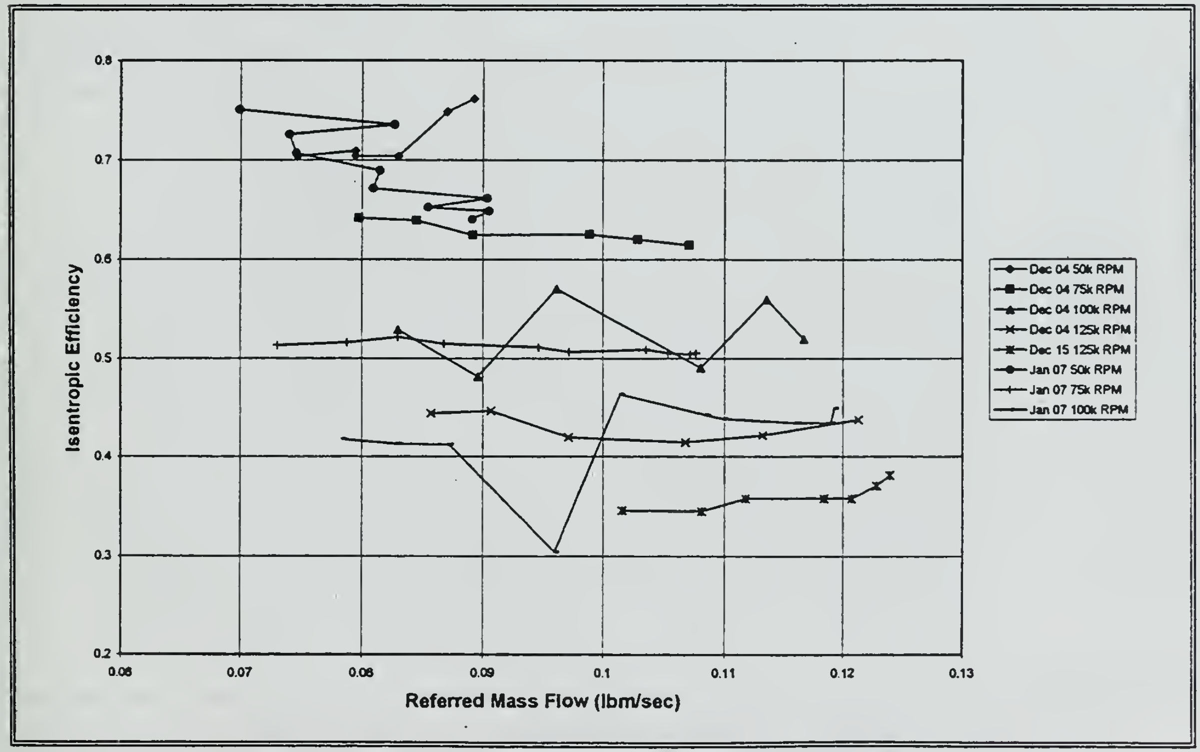


Figure A2. Garrett T2 Turbocharger Turbine Total-to-Total Efficiency vs Referred Mass Flow Rate.

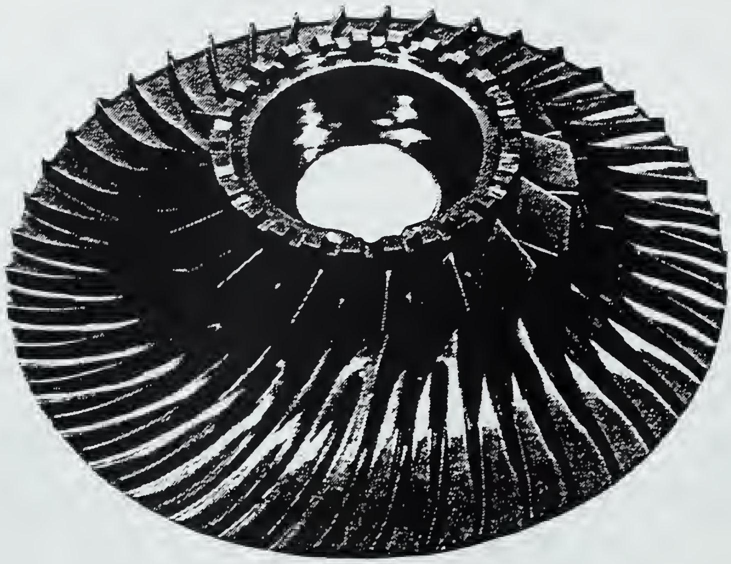


Figure A3. Centrifugal Compressor Impeller with Splitter Blades.

APPENDIX B. PLOTS OF FLOW COEFFICIENT AS A FUNCTION OF PIPE REYNOLDS NUMBER AND DIAMETER RATIO

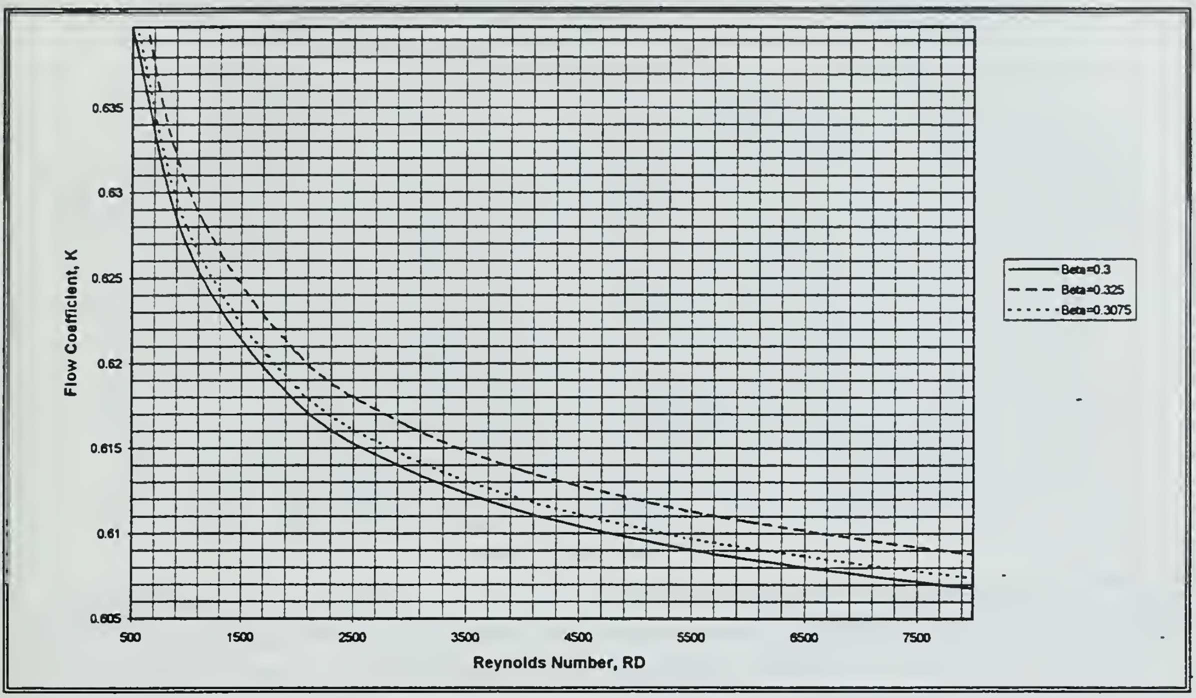


Figure B1(a). Flow Coefficient, K, as a Function of Pipe Reynolds Number and Diameter Ratio, Beta, for 4.026 in. Diameter Pipe, After Ref. [5].

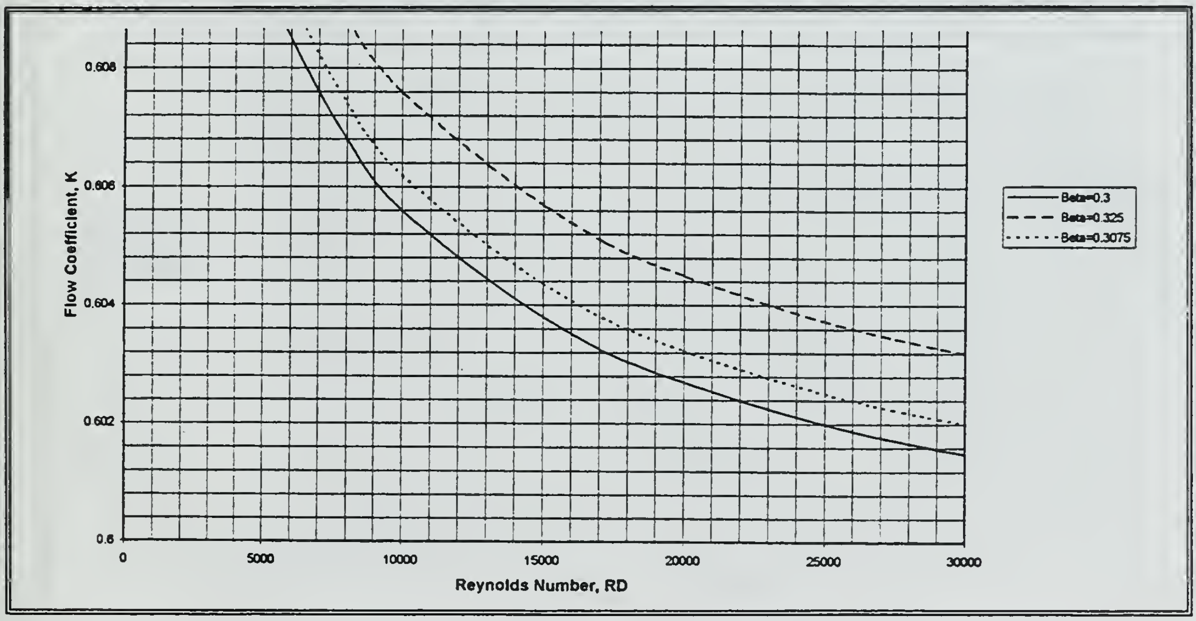


Figure B1(b). Flow Coefficient, K, as a Function of Pipe Reynolds Number and Diameter Ratio, Beta, for 4.026 in. Diameter Pipe, After Ref. [5].

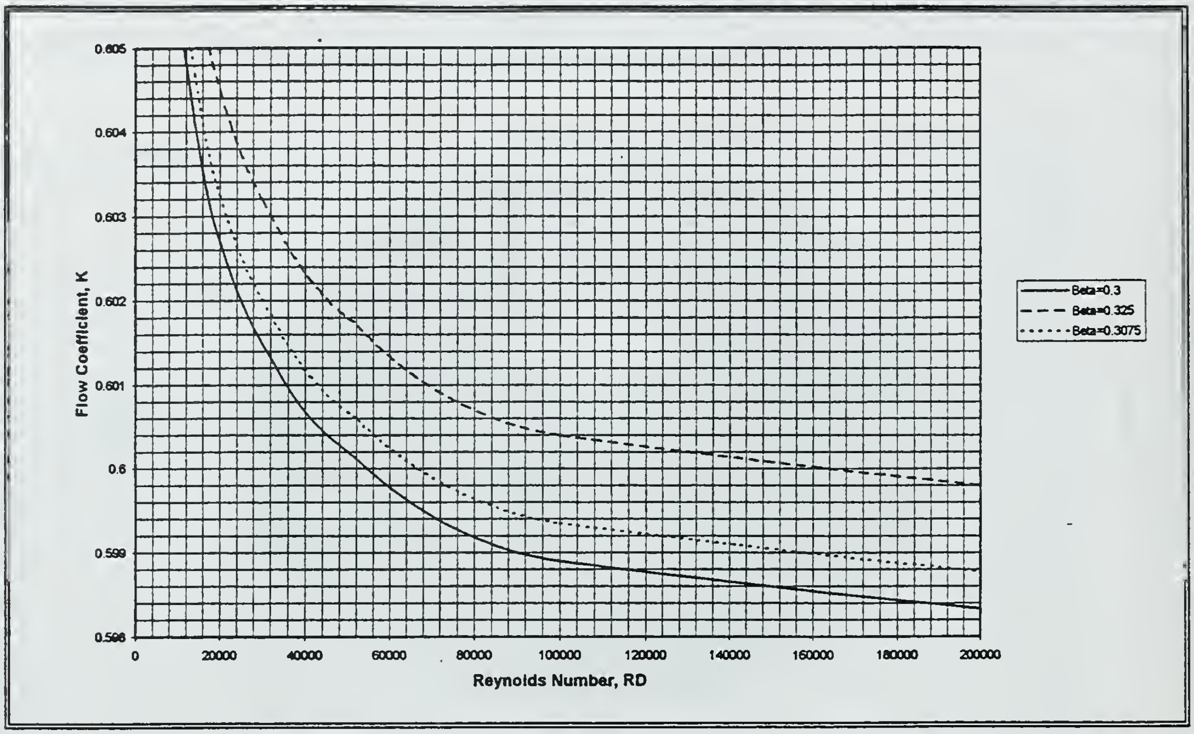


Figure B1(c). Flow Coefficient, K, as a Function of Pipe Reynolds Number and Diameter Ratio, Beta, for 4.026 in. Diameter Pipe, After Ref. [5].

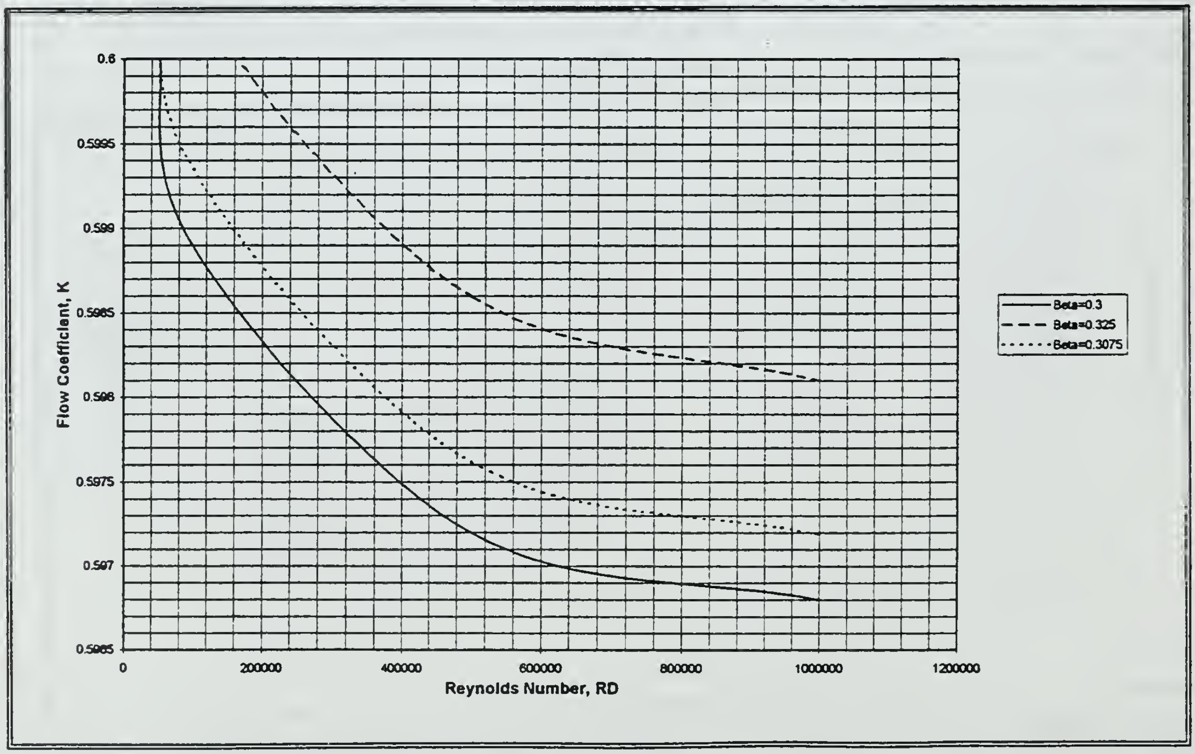


Figure B1(d). Flow Coefficient, K, as a Function of Pipe Reynolds Number and Diameter Ratio, Beta, for 4.026 in. Diameter Pipe, After Ref. [5].

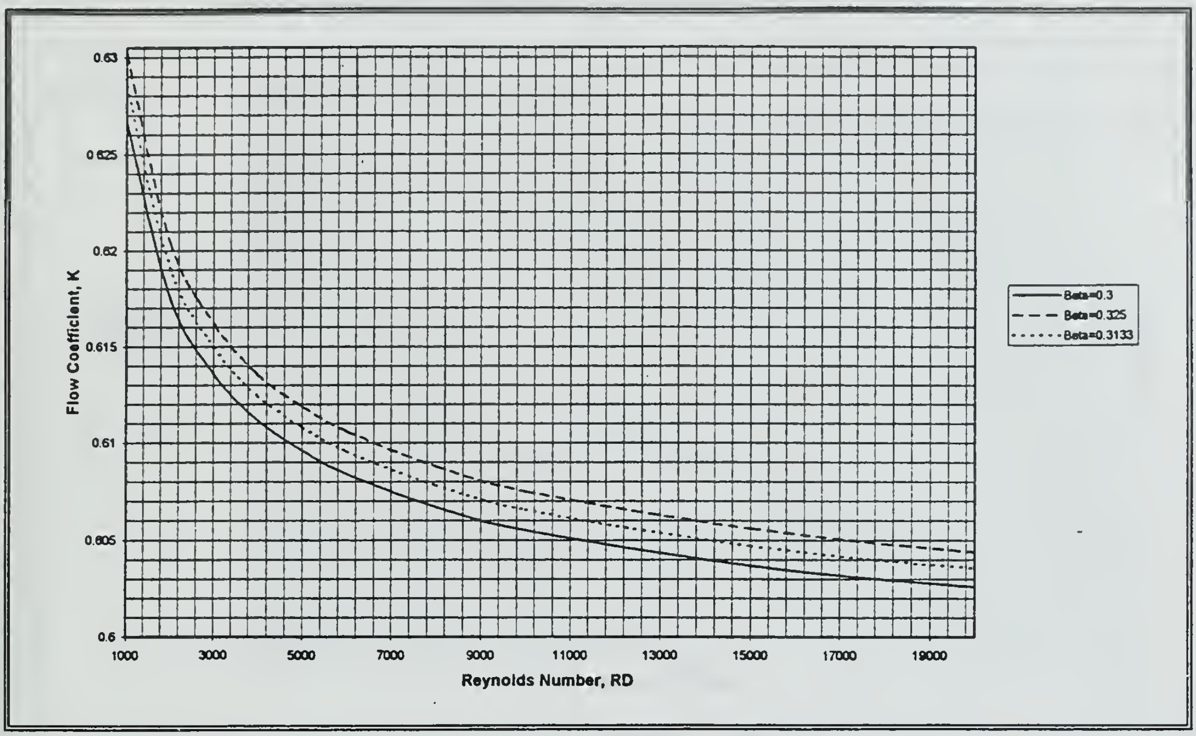


Figure B2(a). Flow Coefficient, K, as a Function of Pipe Reynolds Number and Diameter Ratio, Beta, for 6.065 in. Diameter Pipe, After Ref. [5].

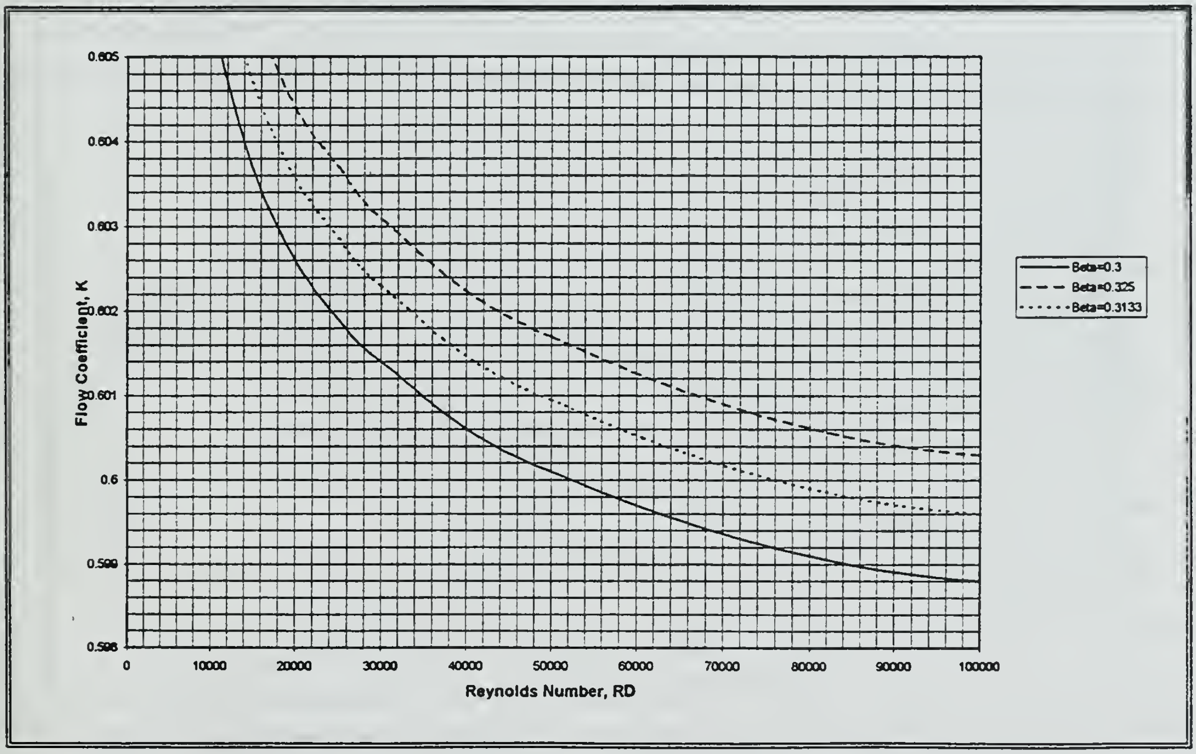


Figure B2(b). Flow Coefficient, K, as a Function of Pipe Reynolds Number and Diameter Ratio, Beta, for 6.065 in. Diameter Pipe, After Ref. [5].

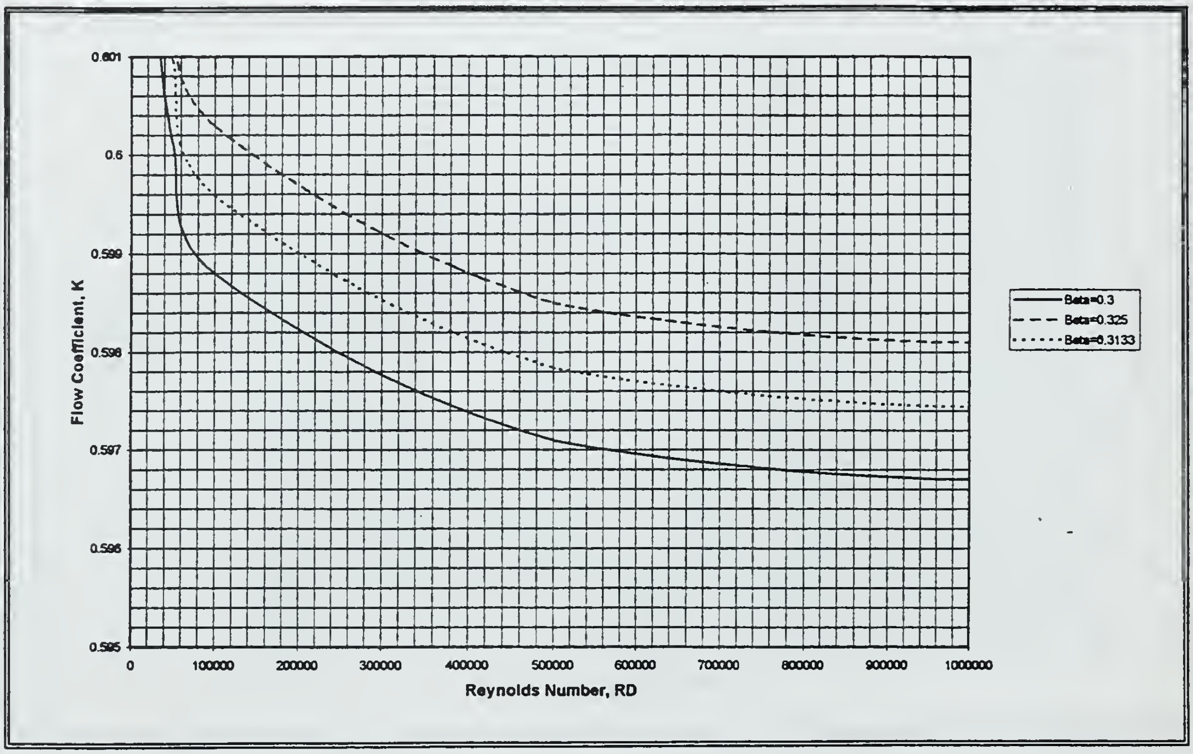


Figure B2(c). Flow Coefficient, K, as a Function of Pipe Reynolds Number and Diameter Ratio, Beta, for 6.065 in. Diameter Pipe, After Ref. [5].

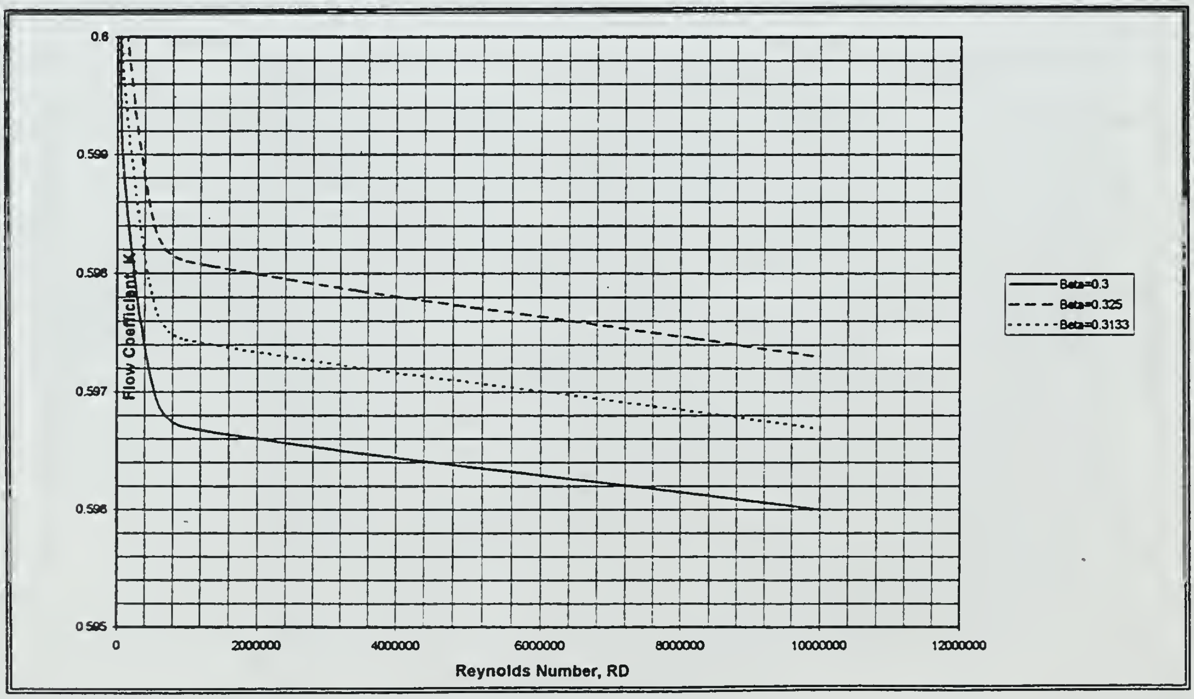


Figure B2(d). Flow Coefficient, K, as a Function of Pipe Reynolds Number and Diameter Ratio, Beta, for 6.065 in. Diameter Pipe, After Ref. [5].

APPENDIX C. SOPHIA J450 ENGINE TEST RESULTS

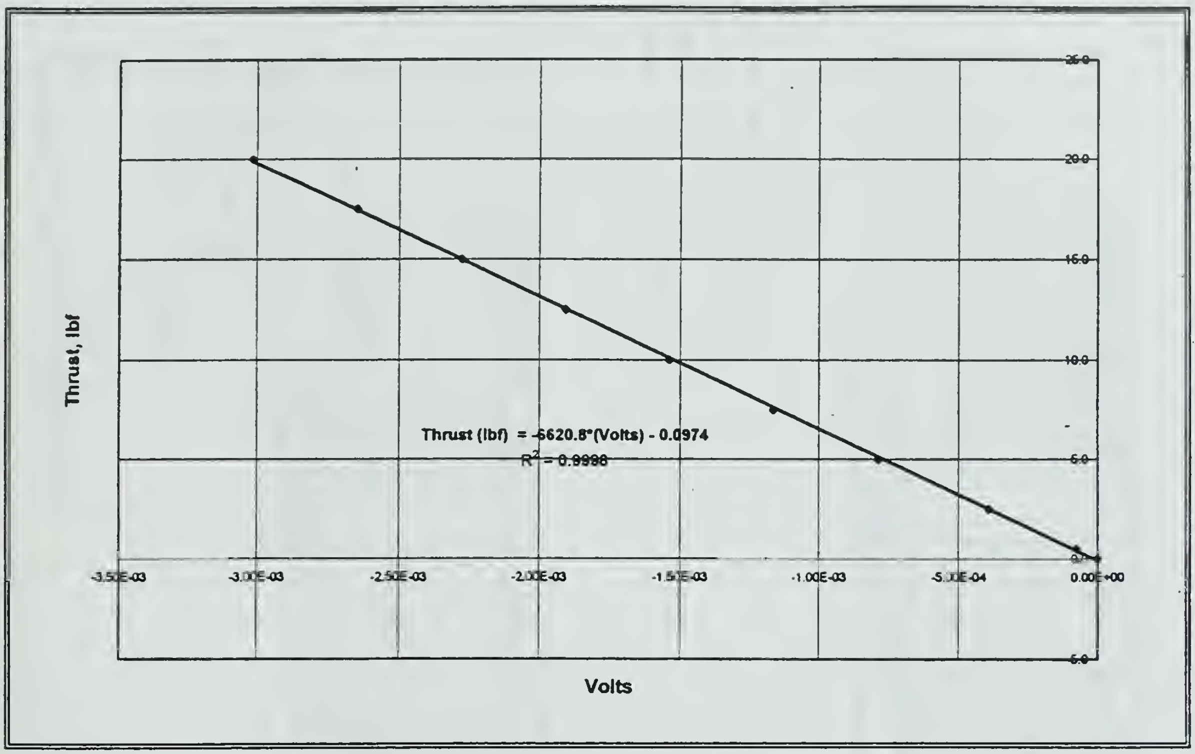


Figure C1. Sophia J450 Test Program Thrust Beam Calibration Curve.

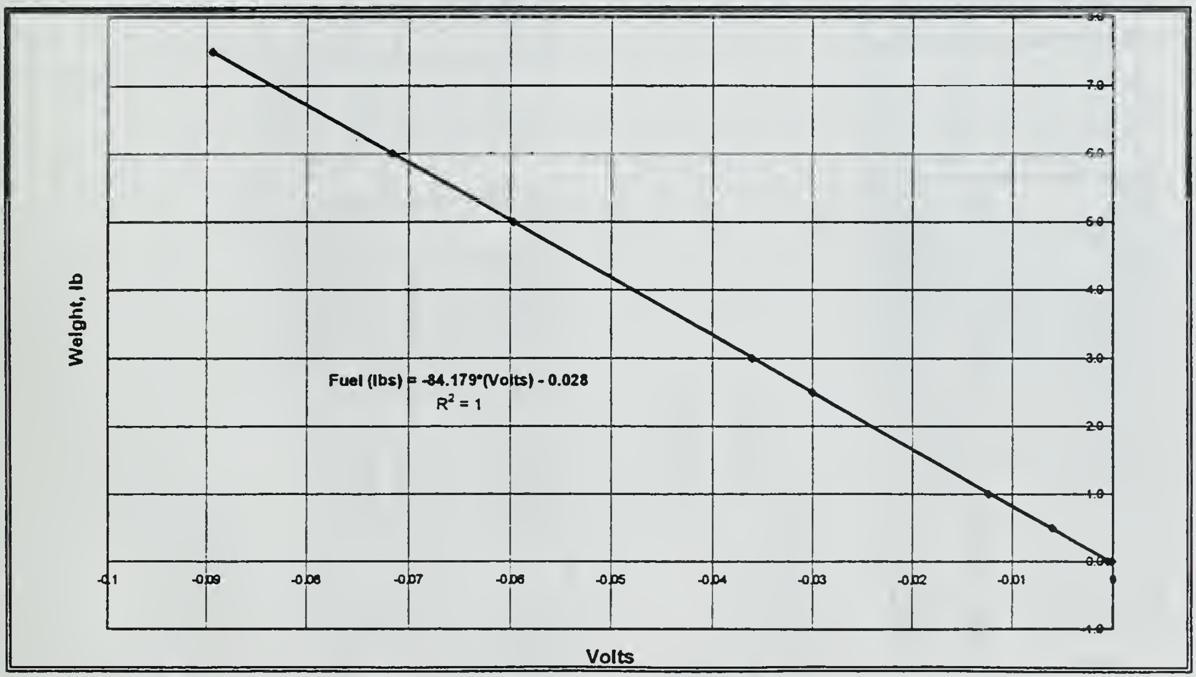


Figure C2. Sophia J450 Test Program Fuel Flow Strain Beam Calibration Curve.

SOPHIA J450 TEST PROGRAM

Date: 24-Mar-98
Run: 1
Pamb (psia): 14.65738
Tamb (Deg. F): 66
EGT (Deg. F): 698

	Mass Flow Rate Calculation		
	Pamb-Port	Mass Flow	Mass Flow (Ref.)
Data Point	(In. Hg)	(lbm/sec)	(lbm/sec)
1	0.281426756	0.255546048	0.257910708
2	0.271737846	0.251108574	0.253432172
3	0.273010592	0.251695949	0.254024982
4	0.27427344	0.252277404	0.254611818
Average	0.275	0.253	0.255

Thrust and Fuel Flow Rate Calculations			
Data Point	Thrust (lbf)	Fuel Flow (lbm/sec)	SFC (lbm/lbf/hr)
1	9.5354	-----	-----
2	9.5917567	0.0034714	1.302890012
3	9.51882	0.0034861	1.318421401
4	9.5639097	0.003514	1.322707595
Average	9.55	0.0035	1.315

Date: 24-Mar-98
Run: 2
Pamb (psia): 14.642882
Tamb (Deg. F): 66
EGT (Deg. F): 699

	Mass Flow Rate Calculation		
	Pamb-Port	Mass Flow	Mass Flow (Ref.)
Data Point	(In. Hg)	(lbm/sec)	(lbm/sec)
1	0.279016762	0.254323641	0.256931126
2	0.276760578	0.253293299	0.25589022
3	0.271545526	0.250895523	0.25346786
4	0.285967021	0.257471736	0.260111497
5	0.280201001	0.254862786	0.257475798
Average	0.279	0.254	0.257

Thrust and Fuel Flow Rate Calculations			
Data Point	Thrust (lbf)	Fuel Flow (lbm/sec)	SFC (lbm/lbf/hr)
1	9.75369	-----	-----
2	9.840646	0.0035201	1.287756922
3	9.83209	0.0035669	1.306013269
4	9.884409	0.0037324	1.359377177
5	9.86285	0.0034962	1.27614148
Average	9.83	0.0036	1.310

Table C1. Sophia J450 Test Program Results for Runs 1 and 2 on March 24, 1998.

SOPHIA J450 TEST PROGRAM

Date: 26-Mar-98
Run: 1
Pamb (psia): 14.773363
Tamb (Deg. F): 64
EGT (Deg. F): 814

	Mass Flow Rate Calculation		
Data Point	Pamb-Port (In. Hg)	Mass Flow (lbm/sec)	Mass Flow (Ref.) (lbm/sec)
1	0.277727056	0.25534909	0.255202111
2	0.280453374	0.256599351	0.256451652
3	0.280705403	0.256714622	0.256566857
4	0.283438789	0.257961481	0.257812998
5	0.282471491	0.257520929	0.2573727
Average	0.281	0.257	0.257

Thrust and Fuel Flow Rate Calculations			
Data Point	Thrust (lbf)	Fuel Flow (lbm/sec)	SFC (lbm/lbf/hr)
1	9.820995	-----	-----
2	9.88956	-0.002421	-0.88111099
3	9.8715386	-0.02257	-8.2309646
4	9.9518621	0.0554155	20.04608828
5	9.9291528	0.0064351	2.333165836
Average	9.89	0.0092	3.353

Date: 26-Mar-98
Run: 2
Pamb (psia): 14.787861
Tamb (Deg. F): 69
EGT (Deg. F): 808

	Mass Flow Rate Calculation		
Data Point	Pamb-Port (In. Hg)	Mass Flow (lbm/sec)	Mass Flow (Ref.) (lbm/sec)
1	0.284217691	0.257218129	0.258040412
2	0.275940227	0.253444884	0.254255105
3	0.287169769	0.258550499	0.259377042
4	0.274355404	0.252716024	0.253523915
5	0.240553793	0.236636714	0.237393202
Average	0.272	0.252	0.253

Thrust and Fuel Flow Rate Calculations			
Data Point	Thrust (lbf)	Fuel Flow (lbm/sec)	SFC (lbm/lbf/hr)
1	9.867182	-----	-----
2	9.9032522	-0.01103	-4.00954176
3	9.9352969	0.0199047	7.212342888
4	9.9394547	-0.00099	-0.35853238
5	9.9132231	-0.013742	-4.9902654
Average	9.91	-0.0015	-0.532

Table C2. Sophia J450 Test Program Results for Runs 1 and 2 on March 26, 1998.

APPENDIX D. SOPHIA J450 TEST PROGRAM CHECKLISTS

SYSTEM CONFIGURATION CHECKLIST

1. Ensure that the test rig is configured in accordance with Figures 7 and 8 and that all devices are properly energized.

2. The fuel pump power supply should be ON with the timer on ZERO and the control knob turned fully CCW.

3. The fuel pump should be primed and the fuel supply hose should be clamped just ahead of the fuel pump.

4. Zero the thrust beam by connecting the CHANNEL 5 output of the signal conditioner to the DVM front panel. Once properly connected, adjust the ZERO KNOB accordingly until the DVM reads 0 mV. Once zeroed, restore the signal conditioner and DVM to their initial configuration.

5. Calibrate the fuel flow beam in the following manner:

    5.1. Connect the strain gages (1 and 2) in a half Wheatstone bridge configuration as shown on the P-3500 cover panel.

    5.2. Set the bridge push button to proper, ½, position.

    5.3. Depress AMP ZERO and adjust thumbwheel control to read ±0000.

    5.4. Depress GAGE FACTOR and set range to 1.7-2.5.

    5.4. Adjust GAGE FACTOR knob to 2.08 and lock the knob.

    5.5. Depress RUN and set the BALANCE Control for a reading of ±0000. Lock the knob.

    5.6. With a DVM connected to the P-3500 output, adjust the OUTPUT thumbwheel until the DVM reads 0 mV.

6. Open the Nitrogen bottle valve and adjust the pressure reducer at the bottle so that it reads 110 psi and adjust the pressure reducer at the rear of the CALSYS 2000 so that it reads 90 psi.

7. Set the CALSYS 2000 pressure range on the front panel so that the high, middle, and low ranges on CALMOD 1 are at 20, 10 and 0 in. Hg (or close to it), respectively.

DATA ACQUISITION SETUP CHECKLIST

1. Turn on the power for the HP9000 computer system.
2. The first screen is the HP9000 Series 300 Computer Data Acquisition/Reduction System introduction.
3. Select F7, set the current time and date. The format is HH:MM:SS for the time and 23 Jan 1992 for the date.
4. Select F3, Old HP6944A Directory.
5. Select F1, ZOC-14 Module Menu.
6. Select F4, Read CALSYS 2000 Calibration Pressures.
7. Select CALMOD 1 for scan.
8. Select 0, for CRT display.
9. If the high, middle, and low pressures displayed are correct, then select F2 to continue. If the calibration pressures are not correct, then select F2 to continue and repeat steps 6-8, until the correct pressures are displayed.
10. Select F1, Scan 1-3 ZOC-14 Modules (32 ports each). The system will now load the default program "SCAN_ZOC-08".
11. Once "SCAN_ZOC-08" introduction screen is displayed, select the "STOP" key.
12. Select F5, LOAD and type "MICROJET".
13. Once "MICROJET" is loaded, select F3, RUN.
14. Once "MICROJET" introduction screen is displayed, select F3 for system setup.
15. Select 0 for hard drive ":,700" storage.
16. Select 1000 Hz for sampling rate.
17. Select 10 for samples per port.
18. Select 1 ZOC connected to Multi-programmer.
19. Select 5 for the number of desired runs.

20. Select 10 for the time interval (in seconds) between data runs.

21. Select 1, for CALMOD set for ZOC #1.

22. Select F4 to begin data acquisition.

ENGINE STARTUP AND OPERATION CHECKLIST

1. Connect the air-trigger to the J450. Ensure that the air compressor will provide at least 140 psi.

2. Ensure that the spark plug is wired correctly. The thick cable should be connected to the spark plug and the thin grounding cable should be connected to any bright metallic object on the engine.

3. The engine should now be ready to start.

4. Unclamp the fuel line.

5. Grasp the air supply handgrip valve firmly, the sound of rotation gradually becomes higher as the rotor rapidly increases in speed.

6. The rotation sound level should reach a very high pitch. If the sound level is not high or if you hear an abnormal sound, stop the engine.

7. Once the rotor sound level has peaked, push the red button on the igniter.

8. Turn on the timer to the fuel pump power supply and open the clamp on fuel supply line ahead of the pump.

9. Adjust the fuel pressure to 1.0 kg/cm^2 (14 psi).

10. After combustion starts, continue the air supply from the compressor until the engine compressor pressure is over 0.3 bar (4.2 psi) on the compressor pressure gage, then release the red button of the igniter, and stop supplying the starting air. Now adjust the throttle/fuel pump pressure to 0.4 kg/cm^2 (5.5 psi). The engine compressor pressure should be about 0.3 bar (4.2 psi).

NOTE: If engine does not start within 10 seconds, turn off fuel pump and cease air and spark. Allow sufficient time for the oil and fuel to drain from the engine through the combustor drain located at the bottom of the engine.

NOTE: If hot start occurs (Tail Pipe Glows Red-Hot) cut the power to fuel pump immediately but continue to apply ignition to spark plug and starting air. After 5 seconds, while continuing spark and starting air, reduce transmitter throttle setting slightly and start fuel pump again.

11. Confirm the flow of lubrication oil is normal while operating.

12. For maximum output, increase the fuel pressure by adjusting the control knob on the fuel pump power supply to 2.8kg/cm^2 (40 psi) and compressor pressure to about 1.3 bar (18 psi). The rotor speed at this state is about 123,000 RPM and the thrust is over 11 lbs. **NEVER EXCEED 1.3 bar compressor pressure**. This is regulated by the supply of fuel to the engine. Decrease the fuel pressure to decrease the compressor pressure.

13. To stop the engine operation, cut power to the fuel pump and clamp the fuel supply line.

14. The engine remains hot for about 1 hour after stopping.

DATA ACQUISITION CHECKLIST

1. Once the engine is operating at the desired speed and in a stable manner, select F5 to start the data acquisition sequence.

2. Manually record the Thrust and Fuel Flow rate for each of the 5 data runs as displayed on the screen.

3. Once the data collection is completed, select F6 to reduce the data.

4. Once the data reduction is complete, select F8 to exit.

5. To display the reduced data, select the STOP key.

6. Select F5, LOAD and type "READ_MJ_ZOC".

7. Once loaded, select F3 to RUN.

8. Enter 1, date (YMMDD), Run #. Example: for Run 1 on April 20, 1998, type: **1,80420,1** .

9. Select 1, Printer output.

10. Select 0, Exit.

NOTE: Selecting Exit does not actually exit the program but rather displays the average of the 10 port readings for the selected data run.

11. To exit the program, select the STOP key.

12. Repeat steps 7-11 for the remaining data runs.

DATA FILE PURGE CHECKLIST

1. The raw data files are stored on the HP9000 ":,700" hard drive as ZW1804201 (example for April 20, data run 1) through ZW1804205 (for data run 5).

2. The reduced data files are stored on the same drive under similar file names with ZR replacing ZW in the name.

3. The calibration pressure data is stored as ZC1804201 (for the present example).

4. Experience has shown that it is wise to purge the data files once the information has been downloaded to hard copy.

5. Select F5, LOAD type "ZOC_MENU".

6. Select F3, Run.

7. Select F8, EXIT MENU.

8. Type **MSI ":,700"** .

9. Type **PURGE "FILENAME"**. Example PURGE "ZW1804201" for each file created.

10. To ensure complete deletion of files, type CAT.

11. There should no longer be any files listed for that date.

12. Cycle the power switch on the lower left face of the HP9000 CPU to reset the computer.

APPENDIX E. PERFORMANCE PREDICTION

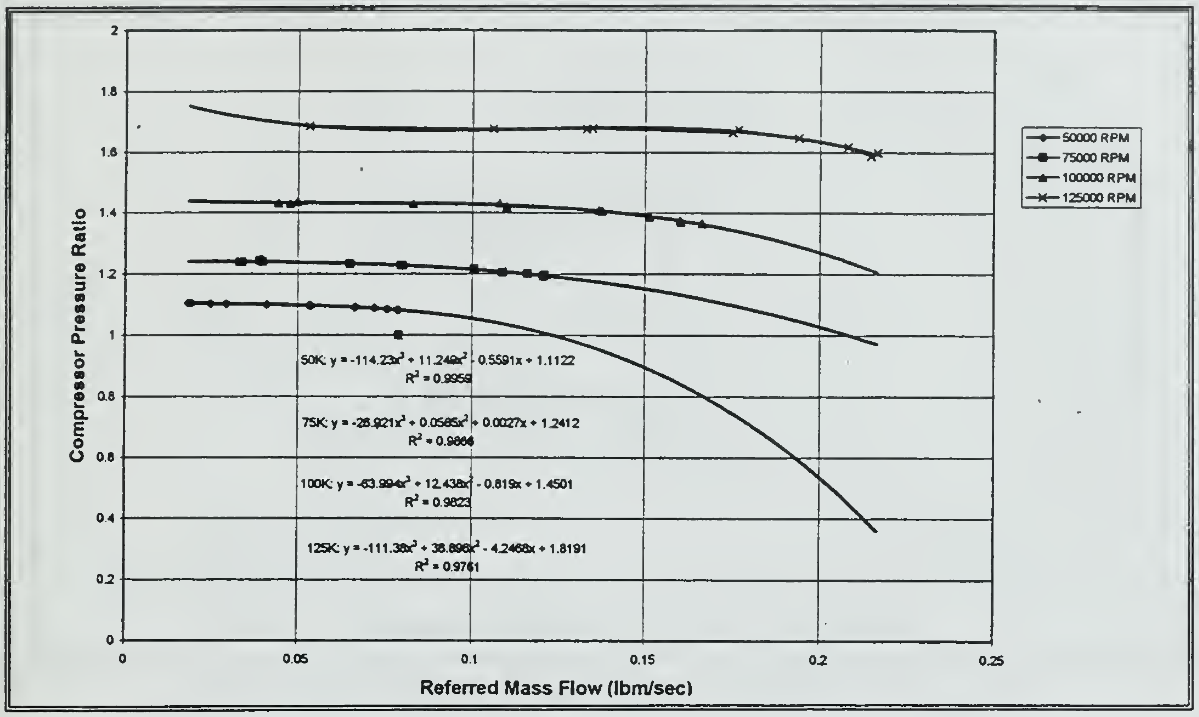


Figure E1. Garrett T2 Compressor Pressure Ratio Map (Trimmed and Fitted).

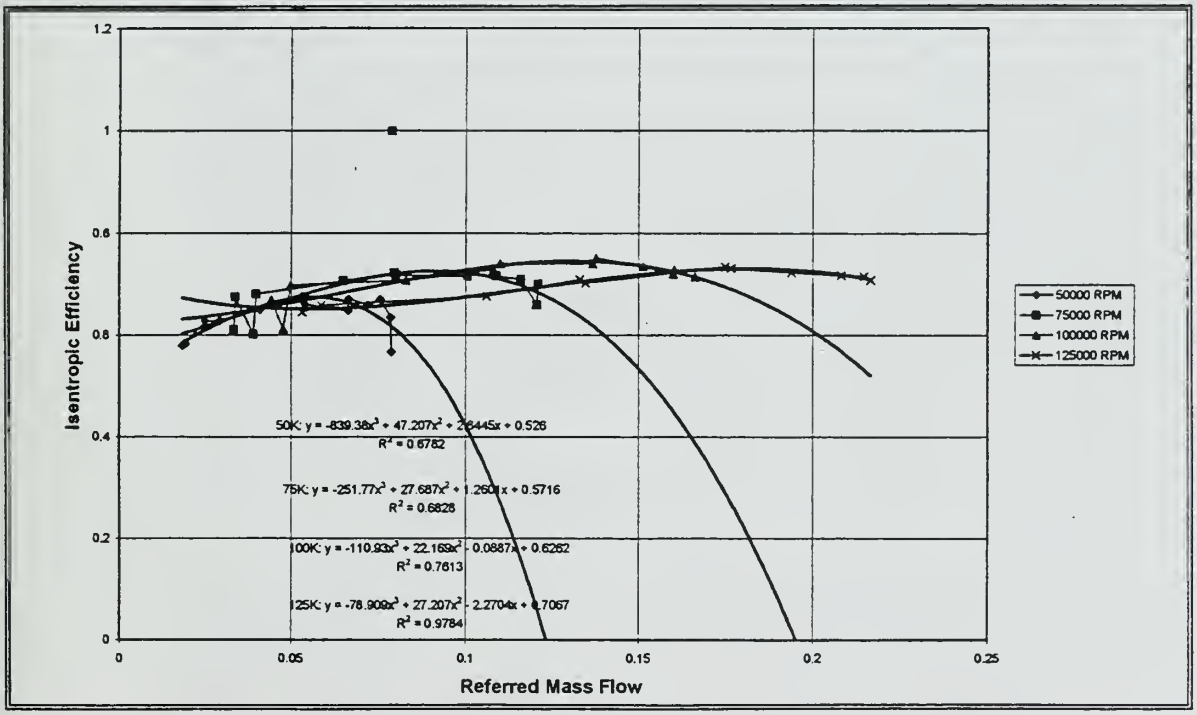


Figure E2. Garrett T2 Compressor Efficiency Map (Trimmed and Fitted).

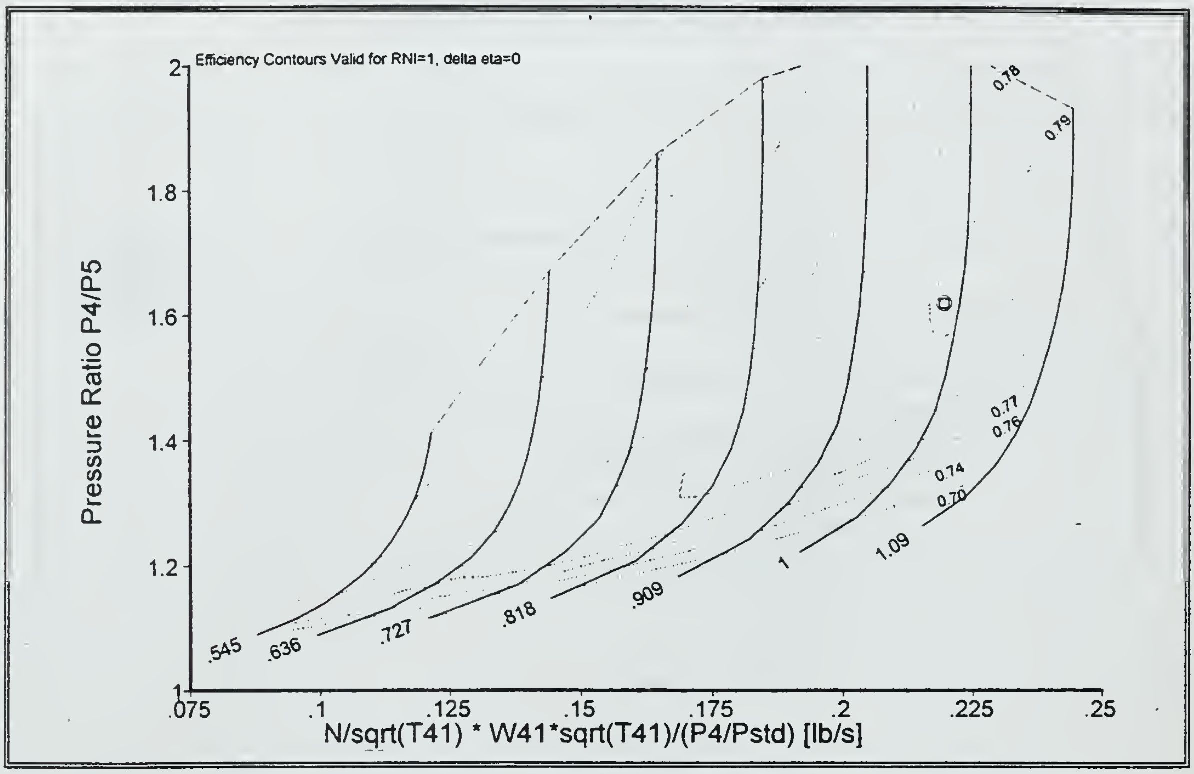
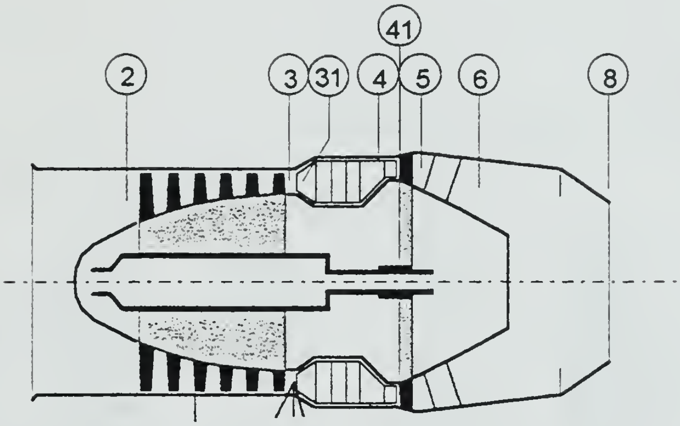


Figure E3. GASTURB Default Turbine Performance Map.



```
 File: A:\SOPHIA.CYJ
 Date: Apr1598
 Time: 11:41

 Turbojet SL static, ISA

SOPHIA J450 Design Calculations (115000 RPM)

Basic Data
Altitude                           ft            0
Delta T from ISA                   R             0
Mach Number                                      0
Inlet Corr. Flow W2Rstd            lb/s          0.256
Intake Pressure Ratio                            1
Pressure Ratio                                   2.15
Burner Exit Temperature            R             1715
Burner Efficiency                                1
Fuel Heating Value                 BTU/lb        18.5
Rel. Handling Bleed                              0
Overboard Bleed                    lb/s          0
Rel. Overboard Bleed W_Bld/W2                    0
Rel. Enthalpy of Overb. Bleed                    0
Turbine Cooling Air W_Cl/W2                      0
NGV Cooling Air W_Cl_NGV/W2                      0
Power Offtake                      hp            0
Mechanical Efficiency                            1
Burner Pressure Ratio                            1
Turbine Exit Duct Press Ratio                    1
Nozzle Thrust Coefficient                        1

Comp Efficiency
Isentr.Compr.Efficiency                          0.73

Turb Efficiency
Isentr.Turbine Efficiency                        0.77
```

Table E1. GASTURB Design (115000 RPM) Input Parameters.

```
 File: A:\SOPHIA.CYJ
 Date: Apr1598
 Time: 11:41

 Turbojet SL static, ISA

SOPHIA J450 Design Calculations (115000 RPM)


   Station   W          T          P         WRstd        FN          =       9.79
    amb                518.67    14.696                   TSFC        =     1.3783
     2      0.256      518.67    14.696     0.256         FN/W2       =    1230.97
     3      0.256      692.21    31.596     0.138         Prop Eff    =     0.0000
     4      0.260     1715.00    31.596     0.220         Core Eff    =     0.1101
    41      0.260     1715.00               0.220         WF          =     0.0038
     5      0.260     1565.32    19.520     0.340         WFRH        =     0.0000
     6      0.260     1565.32    19.520                   A8          =     1.1322
     8      0.260     1565.32    19.520                   P8/Pamb     =     1.3282
   P2/P1 = 1.0000   P4/P3 = 1.0000   P6/P5 = 1.0000       PWX         =          0
   Efficiencies:    isentr  polytr   RNI      P/P         W_NGV/W2    =    0.00000
    Compressor      0.7300  0.7572   1.00    2.150        WCl/W2      =    0.00000
    Turbine         0.7700  0.7555   0.29    1.619        WBld/W2     =    0.00000
    Spool mech      1.0000
```

Table E2. GASTURB Design (115000 RPM) Performance Prediction.

```
 File: A:\SOPHIA.CYJ
 Date: Apr1598
 Time: 11:43

 Turbojet SL static, ISA

SOPHIA J450 Off-Design Prediction at 94000 RPM


   Station   W          T          P         WRstd        FN          =       6.39
    amb                518.67    14.696                   TSFC        =     1.6095
     2      0.209      518.67    14.696     0.209         FN/W2       =     985.12
     3      0.209      638.61    25.276     0.135         Prop Eff    =     0.0000
     4      0.212     1607.00    25.276     0.217         Core Eff    =     0.0755
    41      0.212     1607.00               0.217         WF          =     0.0029
     5      0.212     1502.44    17.727     0.299         WFRH        =     0.0000
     6      0.212     1502.44    17.727                   A8          =     1.1322
     8      0.212     1502.44    17.727                   P8/Pamb     =     1.2062
   P2/P1 = 1.0000   P4/P3 = 1.0000   P6/P5 = 1.0000       PWX         =          0
   Efficiencies:    isentr  polytr   RNI      P/P         W_NGV/W2    =    0.00000
    Compressor      0.7251  0.7452   1.00    1.720        WCl/W2      =    0.00000
    Turbine         0.7591  0.7479   0.26    1.426        WBld/W2     =    0.00000
    Spool mech      1.0000
```

Table E3. GASTURB Off-Design (94000 RPM) Performance Prediction.

```
File: A:\SOPHIA.CYJ
Date: Apr1598
Time: 11:44

Turbojet SL static, ISA

SOPHIA J450 Off-Design Prediction at 105000 RPM


   Station   W          T          P          WRstd        FN          =      7.92
    amb               518.67     14.696                    TSFC        =    1.4642
     2      0.233     518.67     14.696      0.233         FN/W2       =   1094.49
     3      0.233     663.81     28.228      0.137         Prop Eff    =    0.0000
     4      0.236    1638.39     28.228      0.219         Core Eff    =    0.0922
    41      0.236    1638.39                 0.219         WF          =    0.0032
     5      0.236    1512.13     18.518      0.320         WFRH        =    0.0000
     6      0.236    1512.13     18.518                    A8          =    1.1322
     8      0.236    1512.13     18.518                    P8/Pamb     =    1.2601
   P2/P1 = 1.0000   P4/P3 = 1.0000   P6/P5 = 1.0000        PWX         =         0
   Efficiencies:    isentr  polytr   RNI       P/P         W_NGV/W2    =   0.00000
    Compressor      0.7326  0.7558   1.00      1.921       WCl/W2      =   0.00000
    Turbine         0.7648  0.7518   0.28      1.524       WBld/W2     =   0.00000
    Spool mech      1.0000
```

Table E4. GASTURB Off-Design (105000 RPM) Performance Prediction.

```
File: A:\SOPHIA.CYJ
Date: Apr1598
Time: 11:45

Turbojet SL static, ISA

SOPHIA J450 Off-Design Prediction at 123000 RPM


   Station   W          T          P          WRstd        FN          =     11.35
    amb               518.67     14.696                    TSFC        =    1.3514
     2      0.271     518.67     14.696      0.271         FN/W2       =   1349.53
     3      0.271     713.68     34.200      0.136         Prop Eff    =    0.0000
     4      0.275    1802.63     34.200      0.220         Core Eff    =    0.1230
    41      0.275    1802.63                 0.220         WF          =    0.0043
     5      0.275    1636.22     20.387      0.352         WFRH        =    0.0000
     6      0.275    1636.22     20.387                    A8          =    1.1322
     8      0.275    1636.22     20.387                    P8/Pamb     =    1.3873
   P2/P1 = 1.0000   P4/P3 = 1.0000   P6/P5 = 1.0000        PWX         =         0
   Efficiencies:    isentr  polytr   RNI       P/P         W_NGV/W2    =   0.00000
    Compressor      0.7248  0.7551   1.00      2.327       WCl/W2      =   0.00000
    Turbine         0.7689  0.7533   0.29      1.678       WBld/W2     =   0.00000
    Spool mech      1.0000
```

Table E5. GASTURB Off-Design (123000 RPM) Performance Prediction.

SOPHIA J450 OFF-DESIGN PERFORMANCE PREDICTION

Date: 14-Apr-98
Pcomp: 1.9 (105000 RPM)
Pamb (psia): 14.787861
Tamb (Deg. F): 59
EGT (Deg. F): 760

	Mass Flow Rate Calculation		
Data Point	Pamb-Port (In. Hg)	Mass Flow (lbm/sec)	Mass Flow (Ref.) (lbm/sec)
1	0.222858626	0.229950788	0.228495103
2	0.226413045	0.231777301	0.230310054
3	0.209950388	0.223191946	0.221779048
4	0.233617458	0.235435975	0.233945567
5	0.216918904	0.22686572	0.225429566
Average	0.222	0.229	0.228

Thrust and Fuel Flow Rate Calculations			
Data Point	Thrust (lbf)	Fuel Flow (lbm/sec)	SFC (lbm/lbf/hr)
1	7.315618	-----	-----
2	7.320624	0.0031075	1.528135339
3	7.3950018	0.0035759	1.740778481
4	7.396286	0.002913	1.417861343
5	7.3106396	0.0035708	1.758379664
Average	7.35	0.0033	1.613

Date: 14-Apr-98
Pcomp: 1.66 (94000 RPM)
Pamb (psia): 14.787861
Tamb (Deg. F): 60
EGT (Deg. F): 730

	Mass Flow Rate Calculation		
Data Point	Pamb-Port (In. Hg)	Mass Flow (lbm/sec)	Mass Flow (Ref.) (lbm/sec)
1	0.157233768	0.192963468	0.191926562
2	0.151487332	0.189404522	0.188386741
3	0.148124743	0.187290604	0.186284182
4	0.157396204	0.193063116	0.192025675
5	0.151031792	0.189119527	0.188103277
Average	0.153	0.190	0.189

Thrust and Fuel Flow Rate Calculations			
Data Point	Thrust (lbf)	Fuel Flow (lbm/sec)	SFC (lbm/lbf/hr)
1	5.189706	-----	-----
2	5.1274176	0.0034675	2.434559572
3	5.1486571	0.001723	1.204763634
4	5.1295639	0.002537	1.780530317
5	5.1604156	0.0027937	1.948936039
Average	5.15	0.0026	1.838

Table E6(a). Sophia J450 Off-Design Performance for 105000 and 94000 RPM Tests Conducted on April 14, 1998.

Date: 14-Apr-98
Pcomp: 2.3 (123000 RPM)
Pamb (psia): 14.787861
Tamb (Deg. F): 60
EGT (Deg. F): 853

	Mass Flow Rate Calculation		
Data Point	**Pamb-Port (In. Hg)**	**Mass Flow (lbm/sec)**	**Mass Flow (Ref.) (lbm/sec)**
1	0.325215948	0.277516048	0.276024792
2	0.322004641	0.276142499	0.274658624
3	0.317424523	0.274171573	0.272698288
4	0.316974907	0.273977328	0.272505088
5	0.311473926	0.271589536	0.270130126
Average	**0.319**	**0.275**	**0.273**

Thrust and Fuel Flow Rate Calculations			
Data Point	**Thrust (lbf)**	**Fuel Flow (lbm/sec)**	**SFC (lbm/lbf/hr)**
1	11.448666	-----	-----
2	11.34048	0.0043983	1.396210742
3	11.214766	0.0042583	1.3669519
4	11.221361	0.0040596	1.302377551
5	11.196083	0.0046394	1.491744819
Average	**11.28**	**0.0043**	**1.384**

Table E6(b). Sophia J450 Off-Design Performance for 123000 RPM Test Conducted on April 14, 1998.

APPENDIX F. GARRETT T2 COMPRESSOR SLIP FACTOR CONSIDERATIONS AND POWER FACTOR CALCULATIONS

COMPRESSOR SLIP FACTOR

A calculation of the Garrett T2 turbocharger compressor impeller slip factor, σ, was calculated using the following method adopted from Wiesner [Ref. 11].

The slip factor,

$$\sigma = 1 - \frac{\sqrt{\sin\beta_2}}{Z^{0.70}} \tag{F1}$$

is valid up to the blade solidity limit given by,

$$\ln\left(\frac{r_2}{r_1}\right)_{\max} = \frac{8.16 \cdot \sin\beta_2}{Z} \tag{F2}$$

where r_2, the impeller meridional radius at discharge, was 0.7185 in. (18.25 mm),
r_1, the impeller meridional radius at inlet, was 0.5020 in. (12.75 mm),
β_2, the impeller discharge angle, was 36 deg, and
Z, the number of blades, was 12.

The result of equation (F2) was 1.4914 while the actual radius ratio was 1.4313 which indicated that the slip factor equation (F1) was valid for the T2 impeller.

The resulting slip factor was determined to be $\boxed{\sigma = 0.8654}$.

POWER FACTOR CONSIDERATIONS

An investigation into the relative temperature rise by the backward-leaning impeller using the experimental data (Appendix A) collected from the Garrett test program was conducted. A work coefficient was defined as [Ref. 12, page 431]

$$\frac{T_{02} - T_{01}}{(\gamma - 1)\left(\frac{U_2}{a_{01}}\right)^2 T_{01}} \tag{F3}$$

where T_{01} was the compressor inlet stagnation temperature,
T_{02} was the compressor exit stagnation temperature,
γ, the ratio of specific heats for air, was 1.4,
a_{01} was the sonic velocity based on compressor inlet stagnation temperature,
U_2 was the impeller tip speed based on impeller radius of 0.9449 in. (24 mm) as well as the rotor speed.

A flow coefficient was defined as [Ref. 12, page 431]

$$\frac{w_{r2}}{U_2} = \frac{\dot{m}}{2\pi r_2 b \rho_2 U_2} \tag{F4}$$

where $\dot{m}$ was the measured mass flow rate,
r_2 was the impeller exit radius 0.9449 in. (24 mm),
b was the impeller blade height at exit 0.1969 in. (5 mm),
ρ_2 was the density of air at the compressor exit.

The density of air was calculated used the perfect gas relationship by assuming that the flow velocity at the compressor exit was the same as the tip velocity. This assumption allowed the determination of the static temperature and pressure at the compressor exit using the isentropic relationships

$$P_2 = P_{02}\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma-1}{\gamma}} \tag{F5}$$

$$T_2 = T_{02}\left(1+\frac{\gamma-1}{2}M^2\right)^{-1} \tag{F6}$$

$$\rho_2 = \frac{P_2}{RT_2} \tag{F7}$$

where P_{02} was the measured compressor exit stagnation pressure,
T_{02} was the measured compressor exit stagnation temperature,
M was the impeller tip Mach number, and
R was the gas constant for air, 53.3 ft lbf/lbm deg. R.

Figure F1 illustrates the results of the equations F3 and F4 as they were applied to the experimental data collected. As shown, an increase in mass flow caused a decrease in work coefficient. These results were consistent with the Figure 9.6 [Ref. 12, page 431] for backward-leaning impeller blades.

The compressor pressure ratio can be predicted using equation F8 [Ref. 12, page 432] and equation F9 [Ref. 13, page 93].

$$\Pi_C = \left[1+\eta_c(\gamma-1)\left(\frac{U_2}{a_{01}}\right)^2\left(1-\frac{w_{r2}}{U_2}\tan\beta_2\right)\right]^{\frac{\gamma}{\gamma-1}} \tag{F8}$$

$$\Pi_C = \left[1+\eta_c\Psi\frac{\sigma U_2^2}{C_p T_{01}}\right]^{\frac{\gamma}{\gamma-1}} \tag{F9}$$

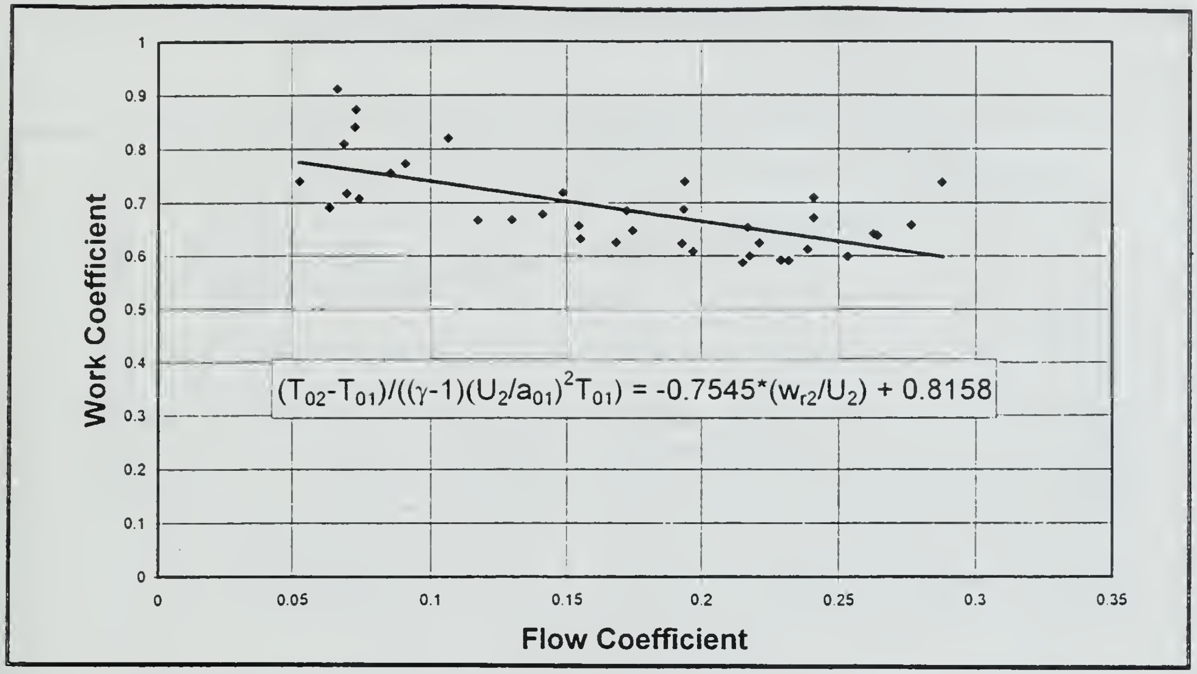


Figure F1. Work Coefficient Characteristic of the Garrett T2 Compressor.

where η_c was the measured compressor efficiency,
Ψ was the power factor, and
C_p was the specific heat of air (constant pressure).

Equating equations F8 and F9 and using the relationships

$C_p = C_v + R$, where C_v was the specific heat of air (constant specific volume)

and

$\gamma=C_p/C_v$

resulted in the following equation

$$\Psi\sigma = 1-\frac{w_{r2}}{U_2}\tan\beta_2 . \qquad \text{(F10)}$$

Since the slip factor and blade angle were constant, equation F10 permitted the calculation of the power factor as a function of the flow coefficient.

The results of this relationship, Figure F2, indicated a linear relationship between the power factor and flow coefficient. Again, the negative slope, was indicative of backward-leaning impeller blades.

Equations F8 and F9 were then used to determine a theoretical compressor pressure ratio based on all known parameters derived from the T2 test program data. The results, Figures F3, F4, F5, F6, illustrate the experimental compressor pressure ratio plotted with the theoretical compressor pressure ratios calculated using equation F8 from Ref. [12], equation F9 from Ref. [13].

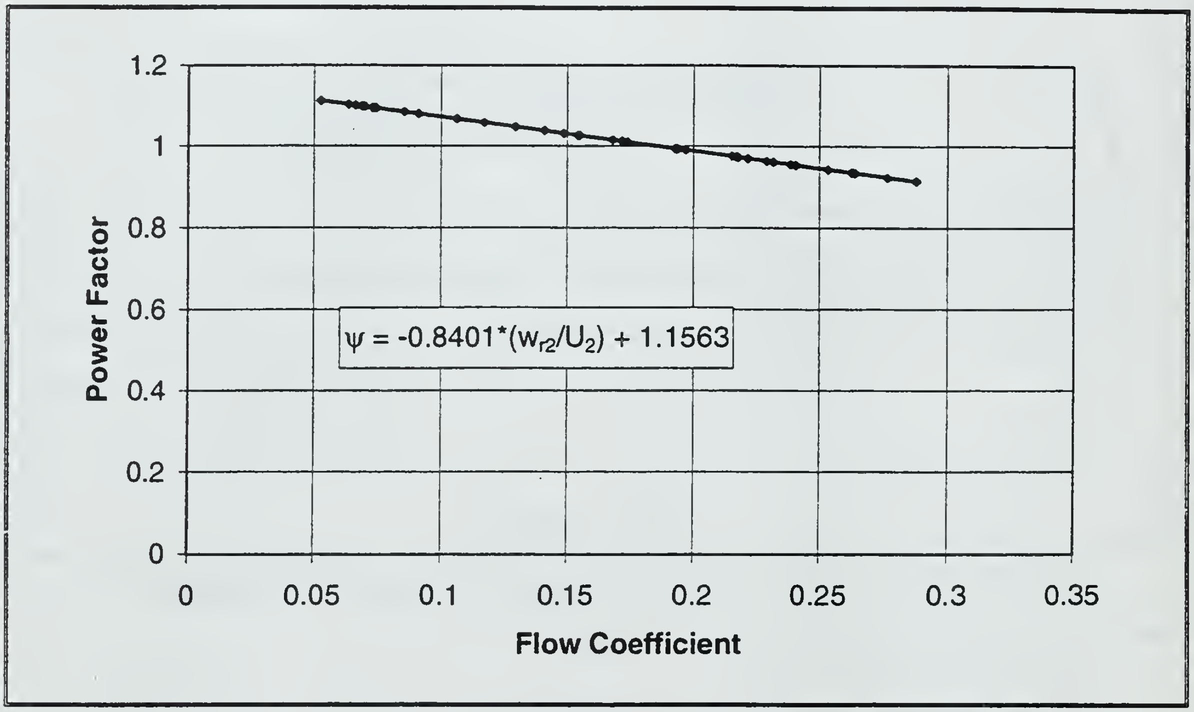


Figure F2. Garrett T2 Turbocharger Power Factor Plot.

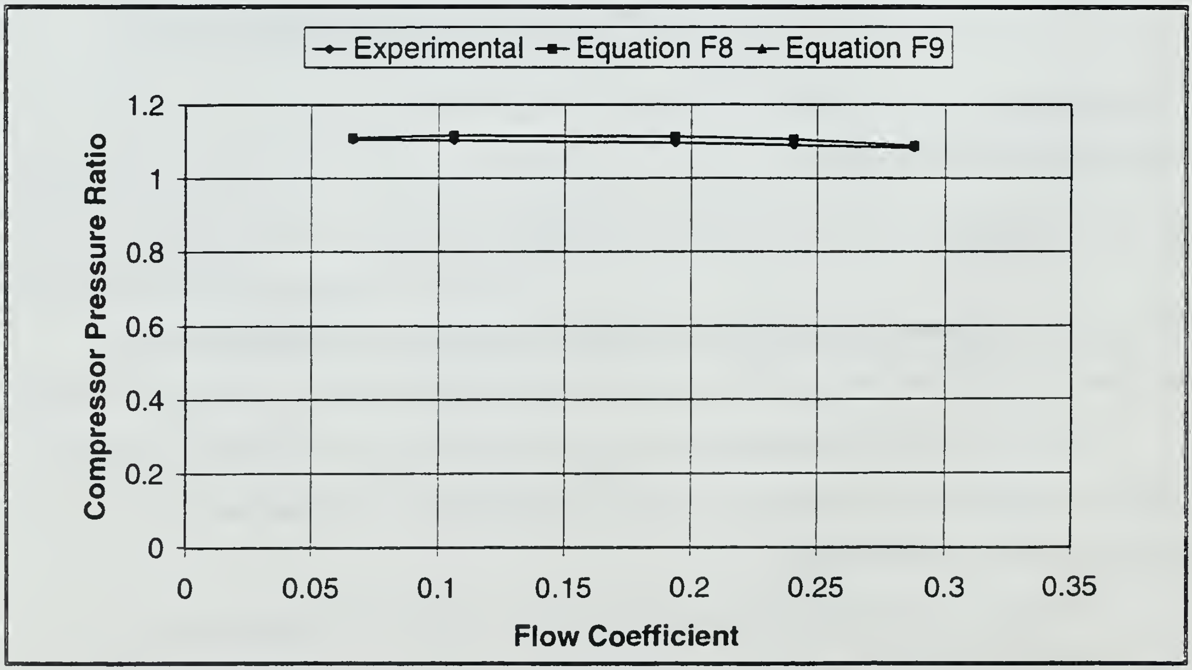


Figure F3. Garrett T2 Turbocharger Compressor Pressure Ratio (50,000 RPM).

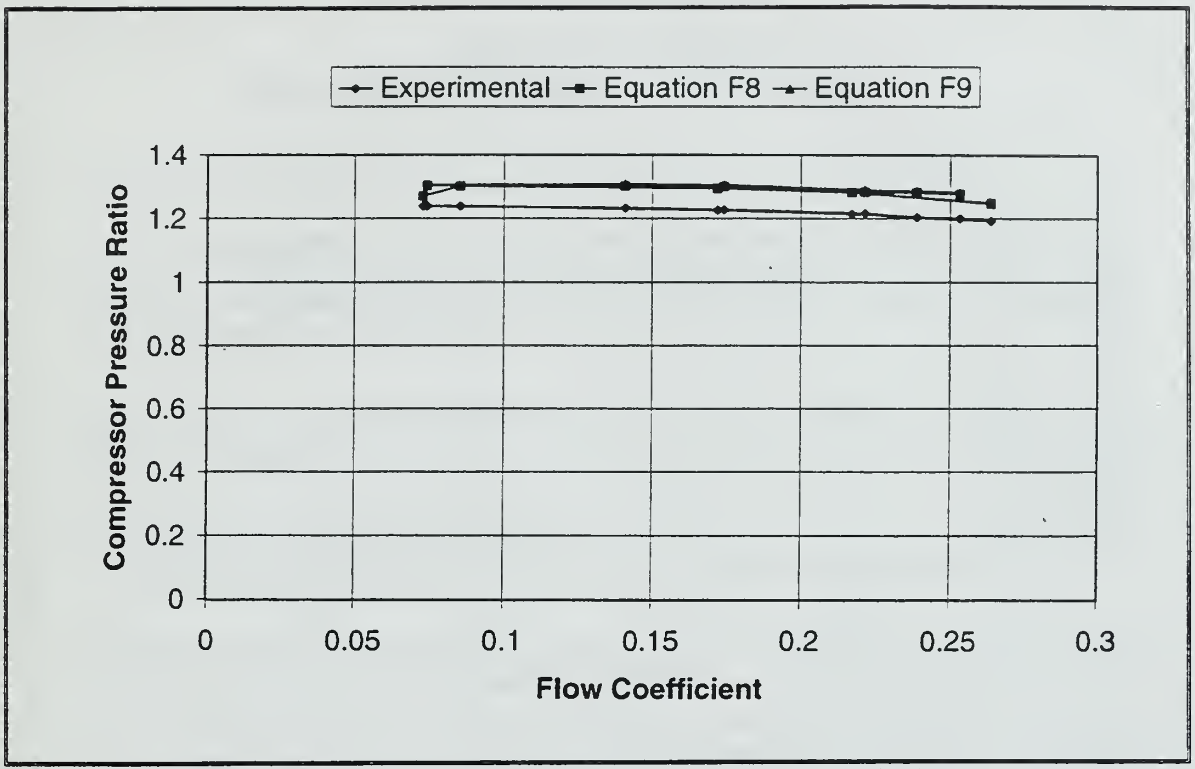


Figure F4. Garrett T2 Turbocharger Compressor Pressure Ratio (75,000 RPM).

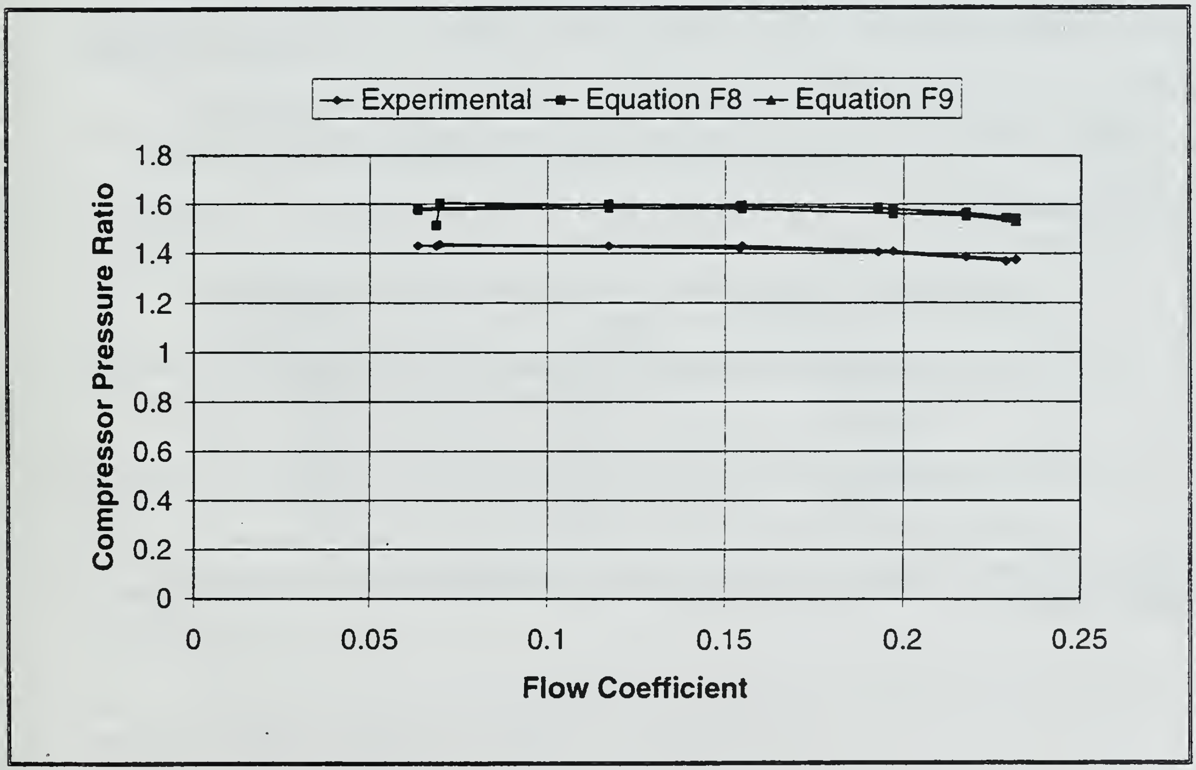


Figure F5. Garrett T2 Turbocharger Compressor Pressure Ratio (100,000 RPM).

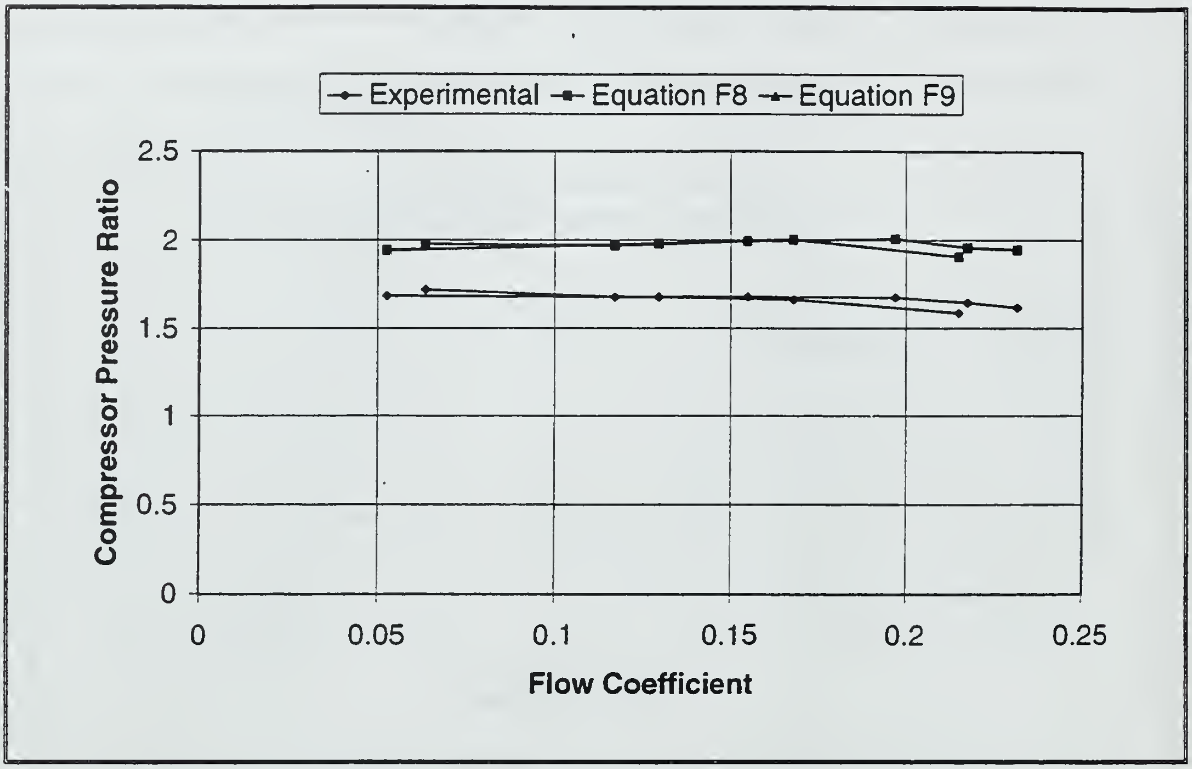


Figure F6. Garrett T2 Turbocharger Compressor Pressure Ratio (125,000 RPM).

Figures F3, F4, F5, and F6 indicated that the equations, F8 and F9, predicted similar compressor pressure ratios. The figures also illustrate that the accuracy of such predictions declined as the rotor speed increased. The difference, reflected as a percentage, between the experimental and theoretical compressor pressure ratios is summarized in Table F1.

ROTOR SPEED (RPM)	EQUATION F8 after Ref. [12]	EQUATION F9 after Ref. [13]
50000	1.79	1.78
75000	6.33	6.79
100000	12.92	12.82
125000	20.43	20.34

Table F1. Percent Difference Between Theoretical and Experimental Compressor Pressure Ratios.

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