**Miniature Gas Turbine Test Stand for
Laboratory Exercises**

Major Qualifying Project Report submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the Degree of Bachelor of Science of

AEROSPACE ENGINEERING

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Abstract

The goal of this project was to design and fabricate a test stand for a miniature gas turbine. The requirements for this design were to include a system of sensors able to obtain data to perform a turbine cycle analysis using reasonable operational assumptions, in addition to providing safety measures adequate for a lab environment. The location for the engine's operation was determined to be the Fire Science Laboratory in the basement of Higgins Laboratories. An uncertainty analysis was performed to determine the accuracy required for all sensors purchased for the stand. LabVIEW was utilized to provide an easy to use interface to record the data collected by the sensors. Engine control was addressed and solutions were developed to be implemented in the future to simplify the start-up and running process.

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1. Introduction

The Mechanical Engineering Department at Worcester Polytechnic Institute had a need for a laboratory for use in the course ME4710 'Gas Turbines for Propulsion and Power Generation'. The focus of this lab is to analyze the performance of a miniature turbojet. This project report details the establishment and design of this laboratory following its approval for funding from the Provost.

The creation of the laboratory presented many challenges as a complete engineering problem. These challenges range from aerospace engineering problems to safety and facilities issues. The most prominent challenges of the design included providing for the safety of those working in the laboratory and allowing for the accurate collection of all desired data from the engine.

Research revealed few other academic groups attempting similar laboratory designs. Those that have attempted a similar task all sought to do so with fewer engine parameters to be calculated [1, 2]. It was found that all-in-one units are available commercially for what the WPI laboratory is intended to achieve. These available technologies are however expensive and reach well beyond the budget of this project [3].

A properly designed test facility for a gas turbine engine consists of a test cell and a test stand. The test cell is normally a building or room that houses the test stand while the engine is running. In this instance the test cell will be the main Fire Science Laboratory here at WPI. The test stand is the actual piece of equipment that will hold the engine in place during operation. The test stand design is particularly important in this project as the test cell, allowing personnel to be close to the engine while it is running, will not provide the operators with primary protection

from failure of the engine. As such, the test stand will contain safety shields to protect the operators.

1.1 Objectives

In outlining our project there were several objectives that were outlined by the provided problem statement. After review with our adviser, we constructed the following list of objectives:

- To design and fabricate an engine test stand that will operate under the safety restrictions of the Fire Science Laboratory and the WPI Occupational and Environment Safety organization.

- To incorporate adequate sensors to be able to gather the measurements that are necessary to perform the cycle analysis for the Gas Turbines for Propulsion and Power Laboratory.

- To record the measurements taken from the sensors using a user interface that is easy for undergraduate students to manage.

- To be able to control the turbine to reach different levels of power, rotational speed and thrust; in order to perform the cycle analysis under different operating conditions.

2. Background

Before starting this project, the group researched and reviewed several articles on designing and constructing miniature gas turbine engine test stands. We used this information, in conjunction with requirements from the Department of Facilities at Worcester Polytechnic Institute, to design the test stand and test cell. Our primary design concerns focused on safety, accurate sensor measurements and data output, and an easy-to-operate user interface. Liou and Leong [1] and Léonard *et al* [2] discuss the construction of a miniature gas turbine test stand at their respective universities, and detail many of the considerations they put into their design.

Liou and Leong [1] discuss the construction of both a miniature gas turbine turbojet and turbo-prop at Western Michigan University. They selected the MW54 engine for their test-stands which was produced by Wren Turbines Ltd. This engine has since been discontinued and replaced by the Wren 70. The important considerations driving the engine choice of Liou and Leong [1] were ease of assembly and setup, low maintenance, and operational flexibility. One of the key differences between the two assemblies at Western Michigan University is that the design for the turbo-prop used an auto-start-up kit. This simplified the start-up process considerably compared to the turbojet. The turbojet design was much more difficult to start and required practice and training in order to start it on the first try. The Western Michigan University students designed a visual LabVIEW interface to control the engine during this process.

Liou and Leong emphasized safety considerations during their design process. Several power sources were implemented into the design to operate separate devices of the test-stand. An emergency shut-down was designed into the system in case of equipment failure, and was integrated with the separate power sources to deactivate the system immediately when initiated. A secondary safety control was designed for the engine which ensures the performance remains

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within the programmed specifications, in the event that an untrained operator does not initiate the start-up procedure properly.

Parameters measured by the University of Western Michigan students are listed in Table 1. Also included is a description of how the measurements were taken on the test stands.

Table 1. Parameters measured by the University of Western Michigan

Parameter Measured	How
Thrust	Using a modified potentiometer and servo. As the engine moves the cart, the servo arm is affected by an angular displacement which can apply and measure resistance based on that displacement. This resistance is measured and converted to a thrust measurement.
Case Pressure	A pressure gauge mounted so that is in visible to the operators.
Exhaust Gas Temperature	A thermocouple installed into the flow in the exhaust cone.
Shaft RPM	The compressor nut is fixed with a magnet. A Hall Effect Sensor picks up the flux created by the magnet and sends a pulse signal to the Data Acquisition System for the RPM readout.
Fuel Flow Rate	Using a fuel flow meter from DigiFlow Systems.

Léonard *et al* [2] discusses the construction of a test-stand for a Turbine Technology's SR-30 at the University of Liege, in Belgium. The students' primary criteria for selecting an engine were making sure the engine was small enough to operate safely in a lab environment on campus but large enough to house the necessary sensor instrumentation, and did not require too many safety measures. The original design did not include measurements necessary to calculate fuel consumption or air flow for the engine. The test stand did not directly measure thrust, but calculated it from the pressures measured in the engine.

Over the years, students at the University of Liege incorporated these measurements (thrust and fuel flow) into the engine. To measure thrust they used a load cell, and removed the stable legs and replaced them with a plate of aluminum. This plate is suspended on steel cables, making it free to react to the engines thrust. A variable-area nozzle was also designed into the test-stand to allow the engines operating line to be adjusted, therefore eliminating the need to

control the engine through varying the fuel flow rate. To measure fuel flow, a volumetric flow rate sensor, such as those used in diesel engines, was implemented. A flow meter was used to accurately determine the airflow in the engine by measuring the difference between static and ambient pressure.

Key lessons learned from this survey of the literature includes safety concerns that need to be taken into consideration, the needs behind obtaining certain measurements such as thrust, air and fuel flow, and sensor implementation and integration issues. These lessons are listed below:

- Catastrophic failure safety precautions

- Department approved fire protection and elimination procedures

- Adequate sensors to handle temperature and pressure ranges at each location and the space limitations

- The selected load cell must accurately measure thrust, be easy to install, and appropriately designed for this project's application.

- Implement an simple and user friendly user interface to eliminate confusion

- Integrate an emergency shutdown switch to be easily accessible and uncomplicated

These concepts were all taken into consideration when deciding what engine to purchase, and how to design our test stand.

3. Laboratory Experiment Design

3.1 Laboratory Experiment Requirements

The purpose of a laboratory experiment is to supplement the presented material from lectures with a physical representation of the concepts being taught. It is with this concept in mind that the design for the laboratory exercise has taken shape. The major goals of the laboratory exercise are as follows:

- Illustrate the operational characteristics of a gas turbine

- Provide a working example of lecture concepts

- Calculate the performance metrics associated with engine comparisons

- Gain an understanding of engine design elements in addition to operational parameters

Throughout the course material of the ME4710 course, the differences between ideal and real operating situations are noted. With the majority of the developed calculations coming from ideal assumptions, such as a calorically perfect gas or an ideal combustion chamber, the 'real' characteristics of an engine are accounted for with correction factors. The physicality of the laboratory exercise is meant to show that with a degree of accuracy these assumptions hold in the actual operation of a turbojet engine.

In order to generate a significant understanding of how the application of the theoretical equations melds with the operational limitations of the engine, we focused on four performance metrics. These metrics were specific thrust, specific fuel consumption, compressor efficiency, and turbine efficiency. These four characteristics are used to compare not only engines of similar size and functionality, but different sized engines as well.

3.2 Required Parameters

The parameters required to calculate the performance metrics for the laboratory experiment come from analysis performed with reference to each station through the gas turbine. Below is a representation of a turbojet with all of the stations labeled throughout the engine.
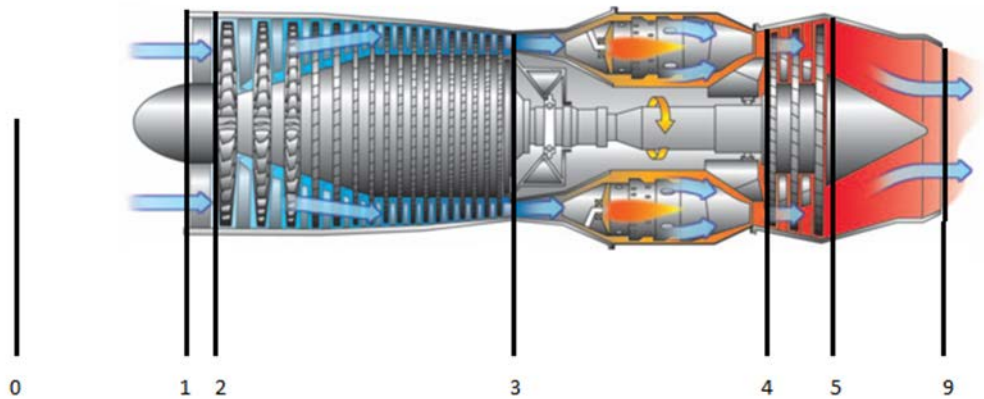
Figure 1 - Turbojet Engine with Station Numbers

3.2.1 Specific Thrust

The first of the required metrics, uninstalled specific thrust, is the ratio of the total uninstalled thrust and the mass flow rate of air through engine, as described in equation (1). The thrust (FA) is the non-ideal thrust and will be measured with a load cell designed into the test stand. By using the measured thrust, the subsequent calculations will be a more accurate representation of the real conditions of the engine. The mass flow term in this equation is the mass flow measured at the inlet to the gas turbine.

$$T_{S\,(uninstalled)} = \frac{F_A}{\dot{m}_0} \tag{1}$$

To solve for the mass flow at the inlet of the engine we used equation (2) with assumptions for the Gas Constant of air, R, and the specific heat at the compressor, Cpc and measured the inner diameter of the inlet nozzle to get A1. A detailed derivation of equation (2) is

included in Appendix A. We will be using sensors to measure the differential pressure at inlet, $\Delta P1$, the static pressure at inlet, P1, and the stagnation temperature at inlet, Tt1.

$$\dot{m}_1 = \sqrt{\frac{2A_1^2 \Delta P_1 \left(P_1 C_{p_c} + R \Delta P_1\right)}{R T_{t1} C_{p_c}}} \tag{2}$$

By substituting equation (2) into equation (1), we produced equation (3) for Specific Thrust. The second part of equation (3) has assumed values for Cpc and R substituted in.

$$T_s = F_A \left\{\frac{2A_1^2 \Delta P_1 \left(P_1 C_{pc} + R(\Delta P_1)\right)}{R T_{t1} C_{pc}}\right\}^{-\frac{1}{2}} = F_A \left\{(4.64151 * 10^{-9}) \frac{\Delta P_1 [2.59537 P_1 + \Delta P_1]}{T_{t1}}\right\}^{-\frac{1}{2}} \tag{3}$$

3.2.2 Specific Fuel Consumption

The second metric to be calculated is the specific fuel consumption of the engine. This is calculated by normalizing the mass flow rate of fuel into the engine with the thrust output of the engine, as shown in equation (4). Like specific thrust, this performance metric allows engines of different size to be compared.

$$S = \frac{\dot{m}_f}{F_A} \tag{4}$$

By using the uninstalled thrust measured from the test stand, the specific fuel consumption can be determined with a high degree of accuracy. The mass flow rate of the fuel is acquired through the fuel flow sensor supplied with the engine.

3.2.3 Fuel to Air Ratio

Calculating the Fuel to Air ratio of the engine is a simple calculation as shown in equation (5) and only relies on the mass flow of the fuel and mass flow of air at inlet.

$$f = \frac{\dot{m}_f}{\dot{m}_1} \tag{5}$$

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As shown in earlier sections finding mass flow at the engine inlet requires some calculations and makes the equation for fuel to air ratio more complex. Equation (6) is what the equation for fuel to air ratio becomes when only involving known values and measured variables. This process is described in more detail in Appendix A.

$$f = \dot{m}_f * \left\{ \frac{4A_1{}^2(\Delta P_1)\left(P_1 C_{pc} + R(\Delta P_1)\right)}{2RT_{t1}C_{pc}} \right\}^{-\frac{1}{2}} \tag{6}$$

3.2.4 Compressor Efficiency

Following the lines of a non-ideal cycle analysis, the laboratory will take into account the differing efficiencies of the various components of the turbojet. The first of these components is the compressor. When looking at the entire engine, the compressor efficiency is important because it dictates the efficiency with which the compressor delivers power from the turbine to the flow. Compressor efficiency is defined as the ratio of the ideal to actual work interaction for a given compressor pressure ratio, as shown in equation (7).

$$\eta_c = \frac{\text{ideal work interaction}}{\text{actual work interaction}} \tag{7}$$

Since the compressor is drawing power from the turbine, a higher efficiency means that the compressor used less power for a given overall pressure rise, resulting in a smaller turbine, and therefore leaving more power available in the flow for thrust or external power extraction. The work interaction across the compressor is defined as a change in stagnation enthalpy across the compressor. Assuming a calorically perfect gas and setting γc based on constant heat capacities upstream of the compressor, the equation for compressor efficiency becomes:

$$\eta_c = \frac{(\pi_c)^{\frac{\gamma_c - 1}{\gamma_c}} - 1}{(\tau_c - 1)} \tag{8}$$

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Equation (8) shows that the compressor efficiency can be determined from the stagnation pressure and temperature ratios across the compressor.

To find compressor efficiency using equation (8) we must solve for compressor pressure ratio, πc, and compressor temperature ratio, τc. To solve for these variables we used equations (9) and (10). Equation (9), solving for compressor pressure ratio, is shown in its original form, and then in a form that includes the equation for mass flow at the inlet to express the equation only in terms of known and measured parameters. A detailed derivation of equation (9) is included in Appendix A.

$$\pi_c = \frac{P_3}{(\Delta P_1 - P_1)} + \frac{\dot{m}_1{}^2}{2\rho_3 A_3{}^2(\Delta P_1 - P_1)} = \frac{A_3 P_3\left(C_{pc}+2R\right)-C_{pc}\sqrt{A_3{}^2 P_3{}^2-\left\{\frac{4RT_{t3}A_1{}^2(\Delta P_1)\left(P_1 C_{pc}+R(\Delta P_1)\right)}{T_{t1}\left(C_{pc}{}^2\right)}\right\}}}{2RA_3(\Delta P_1 + P_1)} \tag{9}$$

$$\tau_c = \frac{T_{t3}}{T_{t1}} \tag{10}$$

Once equations (9) and (10) are simplified to measurable variables they can then be substituted into equation (8) to solve for compressor efficiency in terms of the measured variables, as shown in equation (11).

$$\eta_c = \frac{\left\{\dfrac{A_3 P_3\left(C_{pc}+2R\right)-C_{pc}\sqrt{A_3{}^2 P_3{}^2-\left\{\dfrac{4RT_{t3}A_1{}^2(\Delta P_1)\left(P_1 C_{pc}+R(\Delta P_1)\right)}{T_{t1}\left(C_{pc}{}^2\right)}\right\}}}{2RA_3(\Delta P_1 + P_1)}\right\}^{\frac{\gamma_c-1}{\gamma_c}} - 1}{\left(T_{t3}/T_{t1}\right)-1} \tag{11}$$

Equation (12) shows the substitution of the utilized constants into equation (11). Equation (12) proves that we can solve for compressor efficiency by measuring static pressure after the compressor, P3, stagnation temperature after the compressor, Tt3, the differential pressure at inlet, ΔP1, static pressure at inlet, P1, and stagnation temperature at inlet, Tt1.

$$\eta_c = \dfrac{\left\{\dfrac{6.68177P_3 - 1004.15\sqrt{.000014P_3{}^2 - .0002063\dfrac{T_{t3}\Delta P_1(2.59537P_1+\Delta P_1)}{T_{t1}}}}{2.90804(\Delta P_1+P_1)}\right\}^{.285714} - 1}{\left(\dfrac{T_{t3}}{T_{t1}}\right) - 1} \qquad (12)$$

4. Component Selection

4.1 Engine Selection

An important part of the project was the selection of the gas turbine engine that would be tested in the lab. This engine selection drove many other aspects of the project, including the choice of parameters to be measured, and the exhaust requirements of the room. The selection was based upon many criteria and four engines from different companies were compared. The engines and respective companies being considered include the Wren 70 and Wren 75 from Wren Turbines Ltd, the Pegasus model from AMT, and the AT280 from US Microjet. This comparison considered not only factual data but also input and opinions from all group members, our advisor and others.

Table 2. Quality Function Deployment Matrix

	AMT Pegasus	Wren 70	Wren 75	US Microjet AT280	Category Value
Thrust	4	2	2	3	1
Footprint	3	3	3	3	3
Mass Flow Rate	2	3	3	2	1
Exhaust Temperature	3	3	3	3	3
Fuel Type	3	3	3	3	3
Fuel Consumption	1	4	4	2	3
Order Delay	1	2	3	4	2
Price	1	3	3	2	4
Safety	2	4	4	2	5
Noise	1	2	2	1	3
Instrumentation Included	3	2	2	2	4
Total	79	109	111	87	

To begin the selection, a list of criteria was created upon which to compare the engines. This list is shown on the left hand side of Table 2. Engine size was of small concern as all the engines we were looking into were designed for remote-controlled aircraft. The four engines did

not therefore vary in size enough to impact the engine choice decision. The engines did however vary in thrust. Although none of the engines produced enough thrust to constitute a safety concern, the thrust output of the engine was important to the design of the test stand itself. The weight of the engine was similar to the thrust, in that it gave important parameters to consider in the design of the test stand and varied between all engines. However these differences were not sufficient to greatly impact the design and so weight was not included as a decision criterion. The footprint of the stand required for each engine was an important parameter due to space limitation in the test cell. The difference in size of the engines is not however, large, and footprint, although important, did not therefore truly affect the selection process. The mass flow rate of each engine was a particularly important parameter that not only varied across the engines but also dictated the exhaust requirements of the test cell. The exhaust temperature, like the mass flow rate, determined some of the exhaust parameters and therefore extraction requirements. This parameter did not however vary greatly between the engines. The exhaust gas composition, as with the exhaust temperature, dictated exhaust requirements, an important part of the test cell, but did not vary between engine choices as they all required the same fuels. The fuel consumption of each engine increased significantly with the larger engines, which drove the fuel storage requirement for the test cell and was an important parameter considered for the selection process. Price varied greatly across the engines, typically going with thrust. All engines were, however, within the budget allocated, and so this criterion was not a major concern of the project. These known criteria accounted for a great deal of the reasoning for our eventual selection.

Amongst the list of criteria considered for the engine selection there were many unknown variables in various categories. The reason for these unknown parameters was the unavailability

of this information from the manufacturers. The main unknown parameter was the safety factor of the engine. We determined the factor of safety to be based almost solely on revolution speed of the turbine as the engine diameter did not vary widely between the models that were looked into. This safety factor was of great importance to the project and had to be estimated based on a number of other known parameters. The internal structure and design of the engine was also important: a more densely designed engine would limit the placement of our required sensors inside intricate engine parts. This criterion was, however, decided to be an issue of little to no difference between the engines as we had only a basic idea of what any of the internal structures looked like and, as their size did not vary greatly, we assumed that there would be no major advantage of one over another. The noise created by the engines was also an important parameter as it would determine the requirements for sound proofing the room and test stand. The decibel level for a running engine was only provided by one company from which similar qualities were assumed for the other engines. Although each engine manufacturer did provide a list of included instruments and parts, these lists were not sufficiently detailed to allow differences between the engines to be identified.

In order to evaluate the engines, a quality function deployment matrix (or decision matrix), which assigned weighted values to the identified criteria, was drawn up. The weighting on each criterion is a measure of the importance of that criterion to the application. Each engine was then scored under each criterion, higher scores going to the engines that performed better in that criterion. The engine scores and criterion weightings were then multiplied and added for all criteria to yield an overall score for each engine. This matrix was filled out by all group members, taking all opinions objectively and applying them to the four engines. This matrix

acted as an aid to clearly gather the weighted criteria in a single chart, allowing the engine decision to be made with all information available. This matrix is shown in Table 2.

Some of the differences noted between engines were small; however others were significant and had the potential to affect successful completion of some aspects of the project. The main difference between the engines was the thrust the engines were capable of producing. This difference was split into the two groups of engines: the Wren Turbines engines had a lower output thrust while the AMT and US Microjet engines were both around twice the output of their Wren counterparts. The prices of all four engines also varied according to this difference in performance. This difference in power drove other criteria. The thrust is directly related to the load that the test stand was required to support, as well as the concern for safety. The power of the engines was also directly related to their fuel consumption which then drove the fuel storage requirements of the test cell. High thrust therefore not only increased facility related challenges, but also reduced the safety factor of the lab. The power difference also raised the mass flow of the engine which would require increased exhaust extraction rates in addition to an increased exhaust temperature. The sole downside of the smaller Wren engines, from a technical stand point, was the questionable freedom inside the engine with which sensors could be placed.

The end result of the selection process was the Wren 70 engine due to many of the parameters listed above but also due to our correspondence with our contact at Wren Turbines. The reason the Wren 70 was selected over the 75 was that the package available for the 70 was a pre-built kit assembly that was built with greater tolerances. This kit model was recommended over the 75 by Wren Turbines Ltd associates based on the need to make modifications to the engine to accommodate sensors.

4.2 Sensor Selection

To be able to create a lab in which the students will be able to properly interact with the engine, sensors are required that will allow the students to accurately calculate the required measurements in addition to the assumed constants that are explained in the previous section. To know how the accuracy of the sensor would affect the equations used to find the engines abilities certain calculations needed to be completed.

To calculate how the accuracy percentages of each sensor would affect an equation that is dependent on the variable that the sensor is measuring, the equation must be simplified to only contain the variables that are being measured. The more variables the equation has the more complex the uncertainty analysis. Once the equation is simplified to only include variables that will be measured, the equation was manipulated using each variable to find the influence coefficient of that variable on that particular equation. If the coefficient is in terms of other variables then it is solved for by substituting in for the variables using the minimum value that the sensor will measure, in this case the values when the engine is at idle. We found the values for the engine at idle and max in order to calculate the ideal values for specific thrust, specific fuel consumption, fuel to air ratio, compressor pressure ratio, compressor temperature ratio, and compressor efficiency at max and ideal. Most of these values were given in the engine manual or were calculated by comparing the know values. These values are show in Table 3.

Table 3. Ideal Max and Idle Values of the Engine

	IDLE	Max	Units
RPM	750	2667	rev/s
Thrust	3	70	kg*m/s^2
Mass flow of Fuel	0.00053247	0.003277	kg/s
Tt1	288.15	288.15	K
P1	101321.28	101278	kg/(m*s^2)
ΔP1	3.7175	46.996	kg/(m*s^2)
Tt3	315.817	845.0499	K
P3	111325	297325	kg/(m*s^2)
m1	0.00396824	0.0141074	kg/s
Ts	756.001848	4961.9423	m/s
SFC	0.0001775	4.681E-05	s/m
f	0.1342	0.2323	*100=%
πc	1.1058	2.9625	*100=%
τc	1.096	2.9327	*100=%
ηc	0.30373585	0.1882531	*100=%

Once the influence coefficient was solved for, we used the max and idle values for a specific measurement and compared them to the sensor's accuracy and max which produces how accurate that sensor will be, in a percentage, at each of those values. That percentage is then multiplied by the corresponding influence coefficient, and then squared, added to the other sensors set of these, and is then square rooted to find the accuracy of the equation at max and idle. These percentages and influence coefficients are shown in table 4, with the two right columns representing the accuracy range of values of the variables in the left most column.

Sensor Location:	T	T_{t1}	P_1	ΔP_1	T_{t3}	P_3		
Sensor Full Scale (N, Pa, K):	98.1	311.15	206842.5	2490.89	750	344737.5		
Sensor accuracy (%):	0.15	0.47	0.25	0.08	0.75	0.25		
Max measurment needed:	70	288.15	101278	46.996	845.0499	297325		
Sensor accuracy @ max (%):	0.21021429	0.50751518	0.51058102	4.24017363	0.66564117	0.28986589		
Idle measurements:	3	288.15	101321.28	3.7175	315.817	111325		
Sensor accuracy @ Idle (%):	4.905	0.50751518	0.51036293	53.6035508	1.78109475	0.7741691		
Effects each sensor has on bellow values:	C_T	C_{Tt1}	C_{P1}	$C_{\Delta P1}$	C_{Tt3}	C_{P3}	MAX Total (%)	IDLE Total (%)
T_s	1	0.5	-0.5	-0.5			2.160676818	27.24928805
SFC	-1						0.210214286	4.905
f		0.5	-0.5	-0.5			2.150426532	26.80419136
π_c		-0.0008182	-0.9991	0.0007815	0.00081818	0.9984	0.586505731	0.926919789
τ_c		-1			1		0.837048279	1.851990864
η_c		11.4067	-10.074	0.0079	-11.4067	10.662	11.27708681	23.2597286

As Table 4 shows the accuracy of the variables is significantly higher at max than at idle because of the small values of the measured variables and the large range of the sensors in comparison. The accuracy of the sensor is measured in terms of the max value of the sensor's range. The accuracy of the Specific thrust, fuel to air ratio, and compressor efficiency at idle are higher than 23% uncertainty, which could make the calculations the students do challenging. The uncertainty of compressor efficiency at max is still higher than we would like, but the equation to find it involves all of the sensors so the uncertainty will always be around that range for such low values for a turbine engine.

The max and idle accuracy percentages for the equations change for each sensor, and decide which sensors are best based on what accuracy is acceptable for the measurement. After multiple different comparisons of sensors we finally found sensors that have a reasonable range compared to what was needed and a high enough accuracy that the calculations will not be unreasonable for their overall cost.

5. Test Stand Design

5.1 Facilities Restrictions

In order to satisfy the requirements from the Environmental and Occupational Safety Office (EOSO), the test stand was designed to include features that would provide the students and operators with a safe laboratory experience. The primary areas of concern were the isolation and removal of the high temperature exhaust gases, the storage of the fuels needed to start and run the engine, and the noise level the engine would produce. These concerns were individually researched to determine design solutions that would adequately meet the policies of the EOSO.

5.1.1 Exhaust (composition, mass flow, and temperature)

The two aspects considered for exhaust emissions were gas composition and temperature. The primary fuel for the gas turbine engine chosen is Kerosene, a hydrocarbon, which when put through combustion emits carbon-dioxide, water and hydrocarbons, as described in equation (13).

$$2C_{12}H_{26} + 37O_2 \rightarrow 12CO_2 + 13H_2O + Hydrocarbons \tag{13}$$
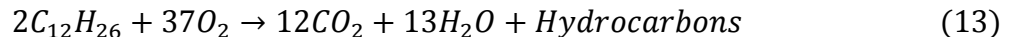
The carbon-dioxide and hydrocarbons present in the exhaust means that there must be an adequate ventilation unit to remove the exhaust from the building to the outside where the concentrations will not harm anyone. In order to determine the necessary volumetric flow rate of the ventilation unit we determined the mass flow rate of the exhaust through the engine from specifications given by Wren Turbines. Although not available for the Wren 70, the mass flow rate for the Wren 75 - an almost identical model that is only capable of 1 more pound-force of thrust - was quoted as 210 grams per second at the engine's maximum rpm [4]. This allowed us to determine the minimum requirement of the ventilation unit to cover all possible flow rates of the engine. Assuming an exhaust gas density of 1.2 kg/m3, this is equivalent to 370 ft3/min.

The other characteristic of the exhaust that needs consideration is the flow's high temperature as it exits the engine. Again, the Wren 75 was quoted as having an exhaust gas temperature of around 650°C at maximum rpm [4]. The constraints that accompany this temperature deal with the placement or layout of the test cell footprint. The exhaust of the engine must be traveling in the direction of the ventilation unit with no objects to interfere with its course. This is to ensure the proper removal of all exhaust gases.

5.1.2 Noise

The primary reasons for considering the noise levels that the engine is likely to produce are in order to establish the effect on nearby classrooms that may have lectures running, and for the health risks associated with being exposed to high decibel noise levels for extended periods of time. The Fire Science Laboratory location eliminates the possibility of classroom interference but there are offices nearby. As with the exhaust specifications, we were only able to obtain noise levels for the Wren 75 which we can assume are similar to the Wren 70. The noise level of the Wren 75 was quoted at approximately 112 decibels "outside with buildings in proximity" [4]. Because this measurement of sound was conducted outside it is fair to estimate that the noise levels of the engine when being operated inside will be higher. According to several articles [5,6] concerning hearing loss due to occupational hazards, long term exposure begins to become a health risk at around 85 decibels. NIOSH (National Institute for Occupational Safety and Health) sets the time limit for the range of exposure of 112-115 decibels at around 30 seconds to 2 minutes [7]. Dangerous Decibels®, a public health organization, recommends less than one minute [6]. If we assume there are no problems while conducting the lab, the necessary run time for the engine will be at least 5-10 minutes to procure necessary measurements at several different power levels, placing the exposure time to the noise above the damaging time limits.

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The chosen solution is to purchase enough noise reducing ear defenders to accommodate everyone that is present in the test cell area while conducting the laboratory experiment.

5.1.3 Fuel

The fuel used by the engine is Kerosene. The concerns associated with Kerosene include flammability and spill prevention. The primary issue therefore lies in the storage of a flammable liquid and the associated restrictions imposed by state law and general safety requirements. The engine fuel will comprise 95% Kerosene and 5% oil for lubrication. The properties of Kerosene can therefore be assumed for the fuel. Document 527 Code of Massachusetts Regulations (CMR) 14.00 [8] describes specifications for storing a flammable liquid. The document defines different classes of flammable liquids based on the flash point temperatures and the boiling point temperatures. The properties of Kerosene define the flash point of the liquid to be between 100°F and 162°F which under section 14.02 (definitions) of the CMR classifies Kerosene to be a Class II or Class IIIA Combustible liquid [8].

According to the National Fire Prevention Agency document 30, table 4-2.3 [9], the maximum container size allowable without obtaining a permit and receiving an inspection from the fire department for Class II and Class IIIA combustible liquids is 20 liters (5.3 gallons). Another invaluable resource for dealing with chemicals or other dangerous materials are MSDS sheets [10]. The recommendations from these documents are not required by law but provide an extra level of safety to ensure the most secure lab environment. Under the storage section of the MSDS sheet for Kerosene it is recommended that all sources of sparks or ignition be avoided. A recommended means of achieving this is by simply grounding the fuel tank to avoid any type of static charge buildup.

5.2 Design Decisions

As a result of these recommendations and research, the stand was designed to include an enclosure that prevents the engine operators from being able to place their hands in the exhaust stream at any point. This entails enclosing the area of the turbine stand that contains the actual engine with a transparent material that the students would still be able to view the engine through. The enclosure was designed so that the inlet and exhaust holes in the transparent material are sufficient in size and location to prevent interference with the air flow to keep measurements and assumptions accurate. Based on where the engine will be located during operation, an exhaust pipe was fashioned to more directly funnel the exhaust stream towards the ventilation unit.

In addition to the hearing protection purchased, it was determined that attachments for the inlet and exhaust could be designed to help reduce the noise level. The important design factor of these attachments would be the elimination of any line of sight to the rotating parts of the engine. Each attachment is discussed in further detail below.

The primary concerns for the safety requirements of the fuel tank design were the location on the test stand and elements of the container itself. To prevent the high temperature exhaust stream from influencing the fuel tank it was necessary to place the tank near the front end of the stand on the intake side of the engine. This is an easy requirement to accommodate as there are very few components of substantial size that will occupy space on the stand itself allowing for free placement of any parts that need to be considered. The more important design consideration that needed to be addressed to satisfy the facilities safety requirements was the design of the fuel tank itself. A secondary containment system was required that would act as a tray around the fuel tank to prevent any spills from spreading out of an easily contained area.

This design consideration was fulfilled by simply having the floor of the interior of the cart being a solid sheet of metal.

5.2.1 Silencer

The goal of the silencer and exhaust muffler system is to achieve a level of noise reduction that will reduce the negative impact on surrounding offices or classrooms for a reasonable price. The inlet and the exhaust pose their own separate requirements that influence the design of each component. The inlet requires a greater level of noise reduction than the exhaust, with the restriction that the flow entering the engine be as undisturbed as possible to achieve accurate sensor measurements. The exhaust requires that the noise reduction component be operational under extreme heat conditions, as the exhaust temperature can reach up to 600°C, and durable enough to last through many exposures to these conditions.

The silencer was required to serve both to silence the noise generated by the engine inlet and also to ensure the smooth flow of air into the engine. The original concept for the silencer was derived from the Turbine Technologies, LTD. HushKit™ that can be purchased as an add-on to the *MiniLab™ Gas Turbine Power System*. The design of this silencer consisted of a circular barrel that contained a series of parallel baffles stationed perpendicular to the flow. These baffles were created with holes to allow for air to flow through to the engine.

Research into sound attenuation was performed in order to understand the basic design elements to be satisfied by the system. The key to maximum sound attenuation is to eliminate any line of sight paths through the silencer to the engine's compressor [11]. Figure 2 shows a cut-away view of the silencer designed, showing the baffle system chosen. Figure 3 shows a front view of the same component. Figure 3 shows that there are no line of sight paths through the silencer.
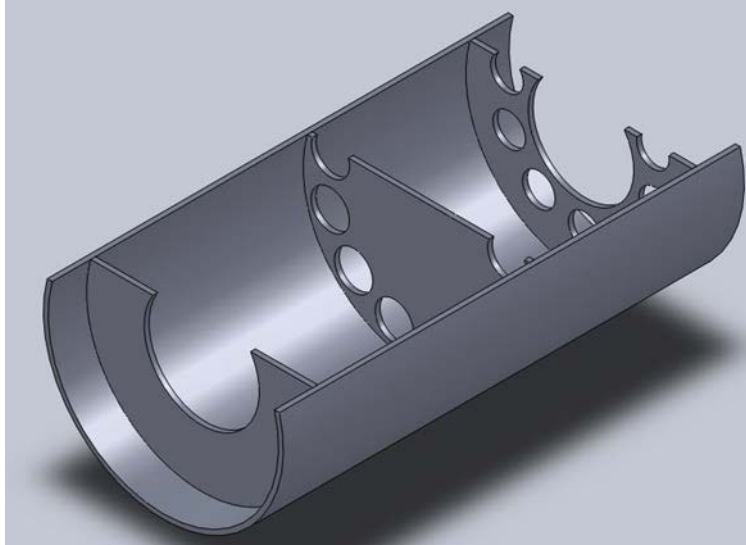
Figure 2 - Cross sectional view of silencer design
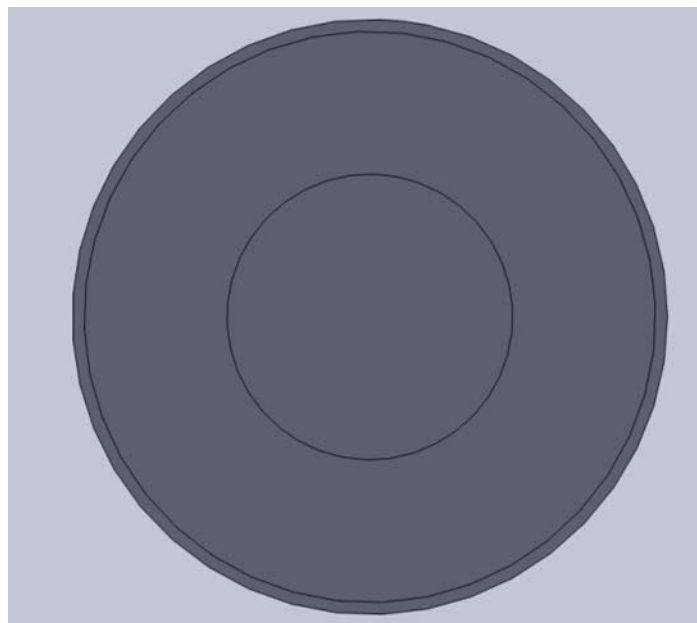
Figure 3 - Front view of Silence design

Following choice of a design the materials that would serve to attenuate the sound were chosen. Typical materials used in aerospace sound dampening trials and tests include fiberglass options and different types of foam [12]. In the interest of remaining within the budget, less expensive alternative materials were chosen. The outer pipe has no function other than to be the casing for the baffles, allowing for the selection of less expensive material such as PVC piping.

Following communication with B.E. Crowley, an industrial supplies distributer, we received a 4 foot off-cut section of 6 inch diameter PVC piping which provides enough length for 2 inlet silencers to be fabricated.

For the sound dampening baffles foam was chosen. Through correspondence with Polymer Technologies Inc. an Applications Engineer recommended suitable products and widths for each application of the foam inside the silencer. Donations of foam samples were received from Polymer Technologies Inc.: one sheet of ¼ inch thick Polydamp Acoustic Foam for the lining of the PVC pipe and one sheet of ½ inch thick Polydamp Acoustical Foam laminated onto 1 lb/sq.ft. Polydamp Acoustical Barrier for the vertical baffles.

5.2.2 Bell-mouth

Figure 4 shows the bell-mouth to be mounted on the front of the silencer. This is made of ½" thick circular pipe insulation fastened around the front edge of the PVC pipe. This bell-mouth is to ensure smooth air flow into the silencer and over the sensors in the flow downstream of the silencer.
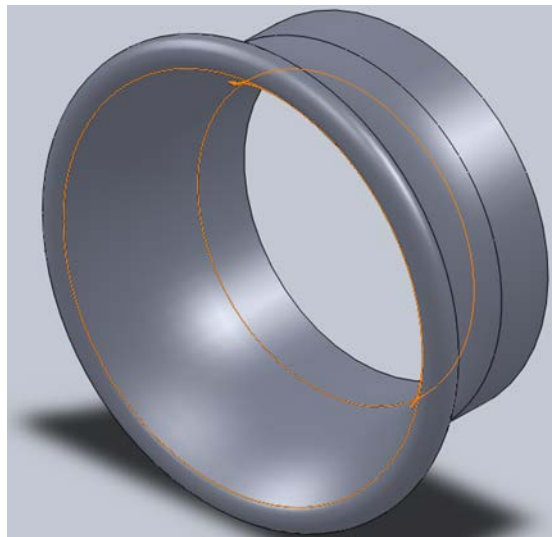
Figure 4 - Inlet bell-mouth

5.2.3 Silencer to Engine Interface

Figure 5 shows the part that will mount onto the front of the engine to help smoothly transfer the flow from the 6" PVC silencer pipe diameter to the 3.5" engine inlet diameter. The key element to the design is that the wider side of this part will be able to slide freely along the inside rim of the silencer. This motion will allow accurate measurements of thrust to be acquired by the load cell while not detracting from the silencers goal of reducing noise by allowing gaps to form when the engine moves. Fabrication of this part was avoided due to the complexity of trying to machine the reducing section in one piece. A generic PVC reducer that satisfied our requirements was purchased.
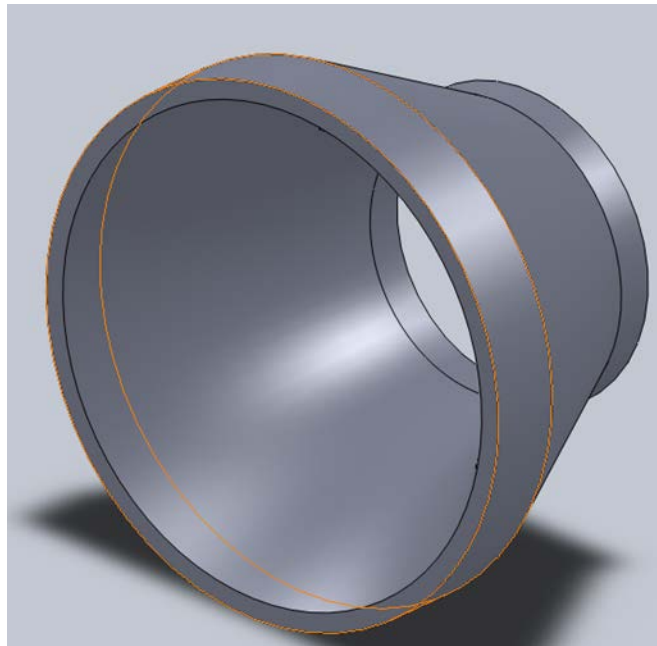
Figure 5 - Silencer to Engine Interface

5.2.4 Exhaust Muffler

The turbine emits exhaust gases at temperatures up to 600°C. This constraint meant that the material selection and design of the exhaust was significantly different to that of the inlet silencer. The exhaust also produces noise at a lower decibel level than the inlet, which allows for a simpler design. The concept for the exhaust attachment is based on the design of mufflers.

These have direct flow into a reservoir around the main pipe, which then exhausts into the flow of the ventilation system. Figure 6 shows a cut away of the design, and shows how the pipe is perforated on the end away from the engine, and how the chamber is attached over the perforated section. This design results in a disruption of the flow as well as the elimination of line of sight access to the source of the noise through the exhaust muffler attachment. The impact of the muffler on the sound from the outlet of the turbine has yet to be determined. Application of a muffler will be determined by the overall operational impact on both the performance of the test stand as well as the possible noise reduction.
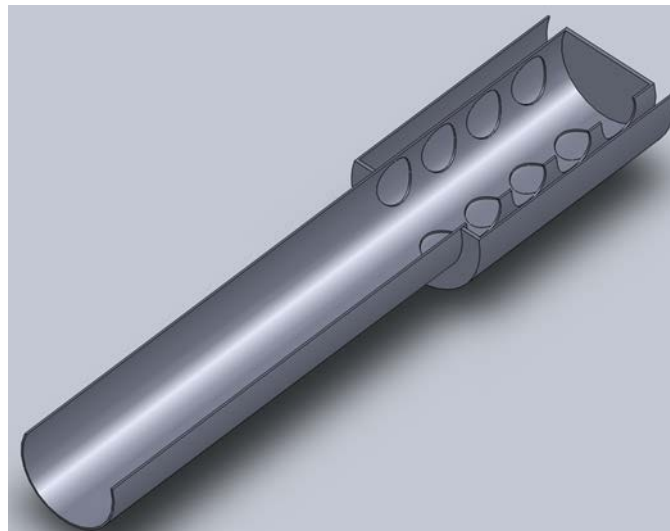
Figure 6 - Exhaust Tube and Muffler

Due to the temperature of the exhaust flow, the chosen exhaust material was steel. B.E. Crowley was able to supply a donation of 4 feet of carbon steel pipe that is a suitable diameter to handle the diameter of the engine exhaust nozzle. The exhaust chamber at the end of the exhaust pipe has a greater diameter than the steel pipe in order to encompass the perforated area, and keep the flow traveling towards the ventilation unit. This proposed design will be added onto the existing exhaust system after its value to the test stand has been determined. Due to a lack of time, this task was not completed and so the exhaust consists of a simple steel exhaust duct.

5.2.5 Test Stand Considerations

Initially the location for the storage and use of the test stand was undetermined. Creating a devoted test cell was considered, however due to the costs of converting a room into a test cell for the use of the engine, it was ultimately decided that the operation of the engine would take place in the Fire Science Laboratory. The necessity of operating the engine in the Fire Science Laboratory drove the requirement that the test stand be portable, as the engine will be stored in the Gas Turbines Research Laboratory, three flights up from the Fire Science Laboratory.

Containment is an important concern while operating the engine, insuring the safety of the students observing the test. Catastrophic failure of the rotation shaft, resulting in blade-out, provides the worst case scenario that should be contained by the test stand. This requires a substantial debris shield to take the sudden impact of a failed rotor. The possibility of failure also necessitated the integration of an emergency shutdown switch to kill the power and fuel supply.

5.3 Design Evolution and Model

The original design was a simplistic open body cart constructed out of square steel tubes with the main stage being at standard table height. In addition to this, the cart had an open top with a small shroud over the engine in the rare case of turbine blade failure. The next design iteration of the cart included a polycarbonate top with access for both the inlet and exhaust on either end of the turbine. The design of the lower region of the cart included side walls, a solid metal floor and doors to better contain the system. The next model update included a silencer in order to reduce inlet noise as well as a muffler on the exhaust side to reduce jet noise as well as to deal with the hot exhaust gases. Subsequent designs included the computer and monitor on the stand along with a keyboard tray to maximize the portability of the system. The final update

to the design simplified the eventual manufacturing of the stand by reducing all parts to be made of stock materials or purchased parts. This update also edited the design to reduce the quantity of materials required and to leave plenty of room for those parts not previously acquired.

5.3.1 Main Test Stand Frame

The main structure of the test stand, as shown in Figure 7, bellow, is made of hollow 1" square, 1/8" thick, steel tubing cut and welded into a rectangular 2' by 3' cart shape. The upper portion of the cart opens with hinges in the rear to allow access to the engine and other components on the main shelf. The main shelf support (that shown in Figure 7 with five beams running into the short dimension of the cart) of the stand was designed to support the engine and other parts that require close proximity or attachment, while providing ample open space. This open area allows sensors and fuel lines to run from their respective end points to the engine with ease. The secondary shelf support (below the main shelf, as seen in Figure 7, with three beams running into the shorter dimension of the cart) is meant to hold the main senor hardware with the exception of the data acquisition card and to provide a location for the keyboard tray. The attachment shown to the left of the stand in Figure 7 is the mounting location for the monitor arm as well as the engine control and emergency kill switch. These components were placed externally for ease of access and distanced from the operational components of the engine. The exact dimensions of this component are to be determined dependent on the development of the relevant systems being placed there.
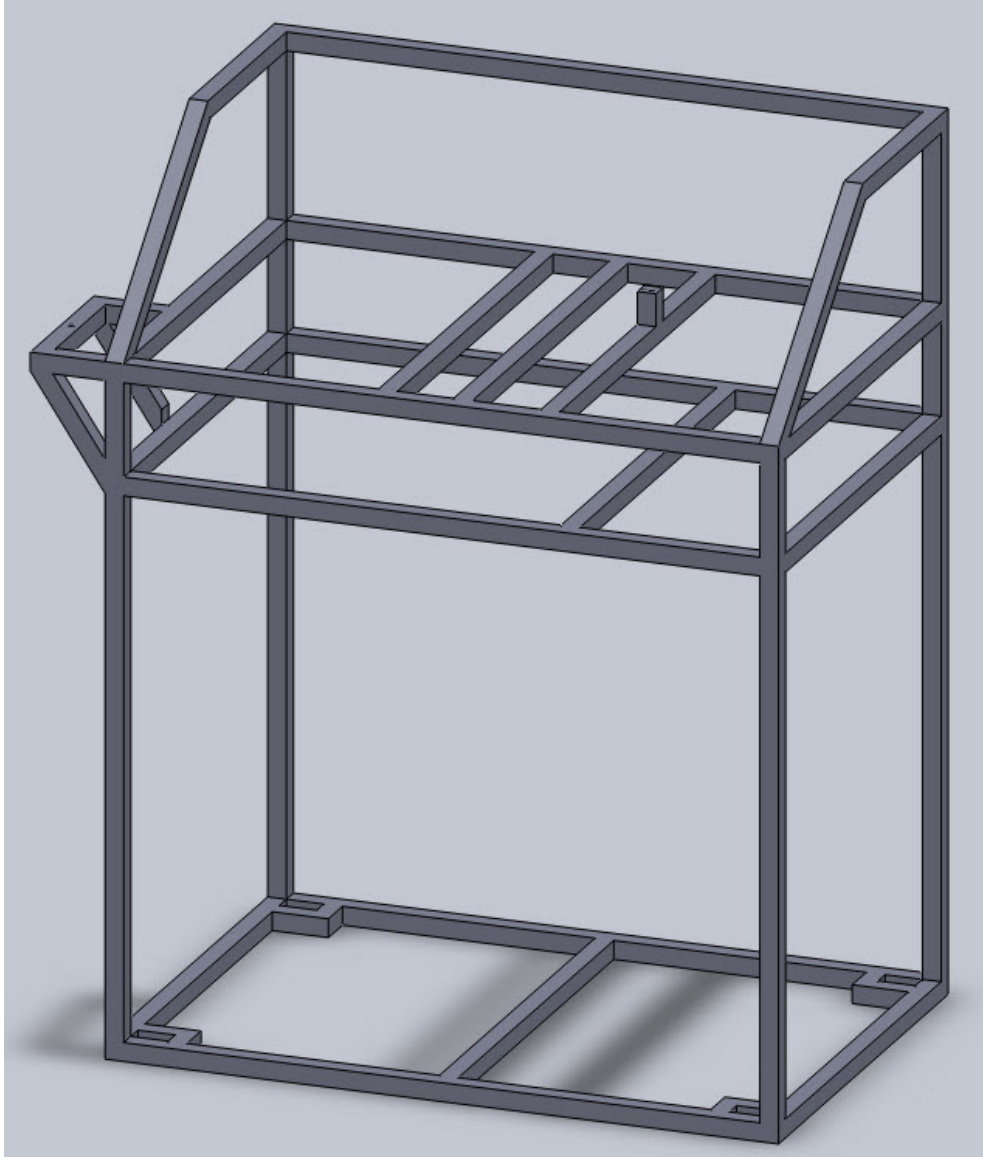
Figure 7 - Main Stand

The large amount of empty space shown below the second shelf support will contain the sensor and fuel lines as well as the fuel tank and the computer tower. This area is covered on the bottom by steel plate, all sides by paneling, and has doors on the front side for access. This area is also used to store the ear defenders and earplugs when they are not in use. The flooring of the stand is metal sheeting for additional support and the small rectangular sections in the corners will serve as the mounting locations for the rolling casters. The driving factors behind this design were ease of construction, functionality, as well as the restrictions mentioned previously.

Though an easier method of construction would have been to modify an existing computer cart, the cost of such an undertaking was determined to be greater than the materials needed for this finalized design.

5.3.2 Engine Mount

The engine holder assembly, as shown in Figure 8 below, has a number of components each serving a unique purpose. The green component in Figure 8 is the Wren 70 turbojet. The bands around the engine are those provided by the supplier in order to mount the engine. These are screwed into the sides of the main engine holder. The main engine holder is comprised of three pieces of quarter inch thick steel plate. This part has the holes for the mounting brackets as well as the bolt connecting to the load cell (the component shown to right of the engine in Figure 8). Attached to the bottom of the engine holder there are two rails which rest in tracks. These allow the engine mount to move, thus allowing the load cell to measure the thrust created. Under these rails are two pieces of quarter inch steel plate that are used to align the engine with the inlet and exhaust axially.
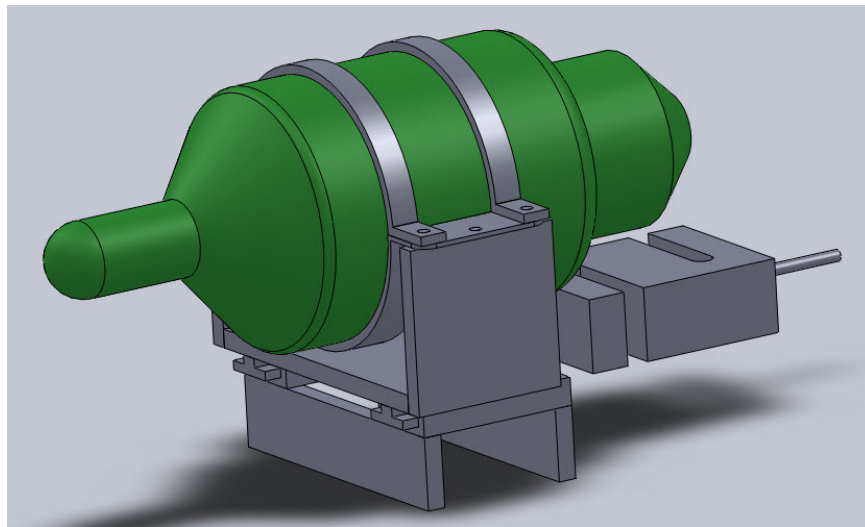
Figure 8 - Engine Mount

5.3.3 Turbine Failure Shield

Figure 9 shows the turbine failure shield designed to contain a catastrophic, turbine blade-out failure. It is comprised of quarter inch thick steel plate to take the impact of a lost blade and protect the operator and lab participants against debris. The base also serves as the mounting plate for the engine holder shown in Figure 8. This was determined to be an adequate level of protection from blade out by comparing the energy of a rotating blade to the energy of a bullet fired from a handgun. The energy of the blade was estimated at approximately two-thirds that of the handgun bullet and the quart inch steel was adequate protection against such a failure with the additional protection of the stainless steel engine casing that surrounds the turbine at just shy of one-tenth of an inch [4].
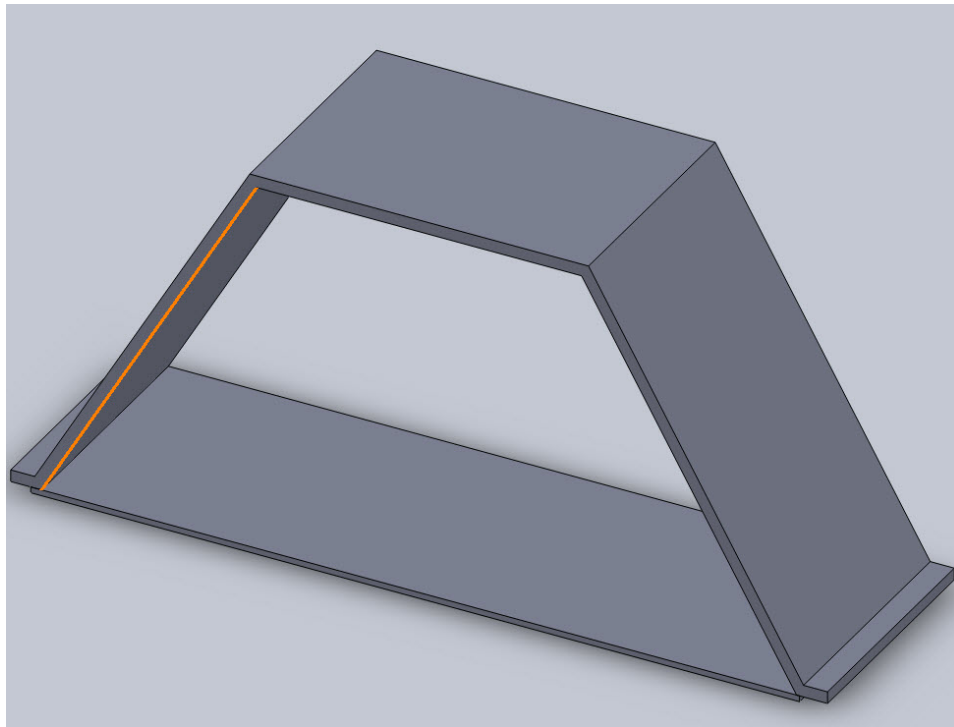
Figure 9 - Turbine Failure Shield

5.3.4 Polycarbonate Cover

The polycarbonate cover shown in Figure 10 is meant to prevent the occurrence of any accidental harm to students when dealing with the engine as well as protecting the engine from

any external interference. This shield is supported by the top section of the steel structure shown

in Figure 7 and is meant to be shatter resistant in the case of unforeseen engine problems.
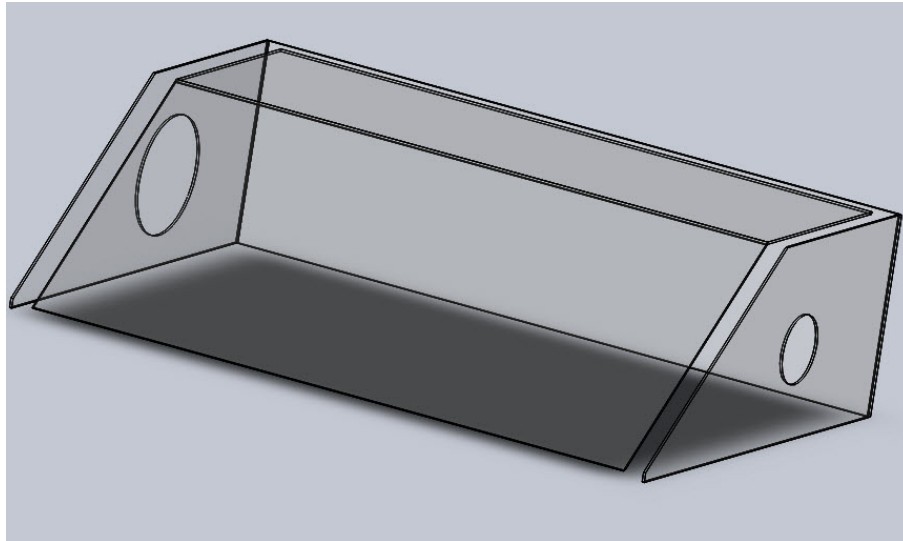
Figure 10 - Polycarbonate Cover

5.3.5 Full Test Stand Assembly

The full test stand assembly is shown in Figure 11 (sensors, wires and pressure lines not

shown). This design includes a computer monitor on an armature as seen on the left of Figure 11,

as well as the gas tank and computer tower, both in the enclosed lower level of the stand. The

keyboard and mouse for the computer are located on a tray which lies below the main shelf of

the main test stand structure. Other fixtures shown in the figure include handles on surfaces

functioning as the doors to the stand. The secondary shelf also has a platform for the sensors,

which is shown on the right of the second level of the main stand structure. The design of this

test stand is meant to meet all the safety requirements imposed, while minimizing the cost of the

project and providing optimal functionality as a learning tool to aid in the understanding of gas

turbines.
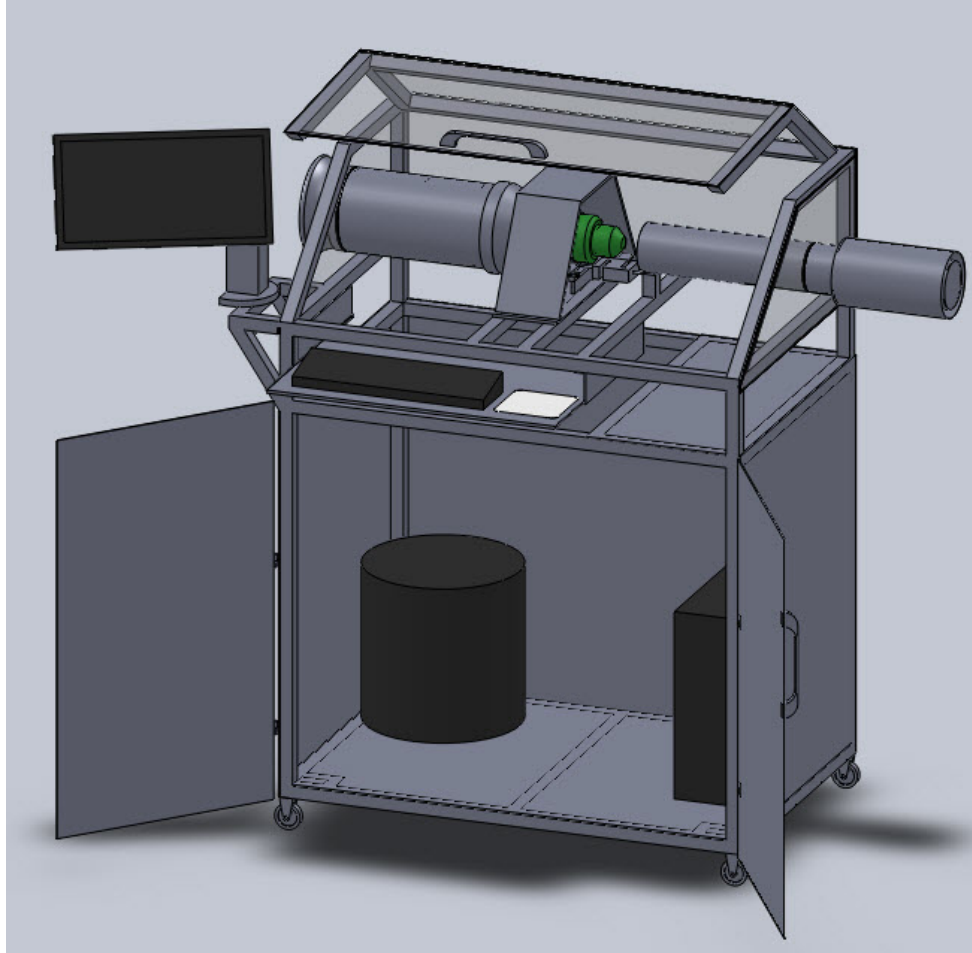
Figure 11 - Full Test Stand Assembly

5.4 Fabrication

5.4.1 Materials and Tools

The materials used were the least expensive and easiest to use for the purposes required by the project. The 1" square steel tubing with .12" wall thickness was used for all the beams and dependent structures of the stand itself. 120' of this steel tubing was purchased for use in the construction of the stand. Sheet steel was bought in one-ninth inch thickness in 2' by 3' sheets, three were purchased. Quarter inch thick steel plate was used from a 4' by 4' stock piece supplied by the Higgins Laboratories Machine Shop.

The tools and techniques used on the materials that comprise the stand were those suggested by the monitors of the machine shops in both Washburn and Higgins Machine shops.

The tool most significantly used was the MIG welder, used in most of the metal to metal connections (all except those which are removable). The plasma cutter was the second most used tool, utilized to cut all the sheet metal used on the stand from stock sizes. The chop saw was used to cut the steel tubes to lengths appropriate for use. The angle grinder, grind wheel, and pneumatic grinder were used to smooth over the flaws of the welds and cuts as well as prepare the materials for welding. The drill press was used to create all the holes of varying diameters in the stand except where constraints required a hand drill to be used. The metal tap was used solely on the engine mount to allow the engine to be firmly secured as instructed by Wren Turbines in the manual that came with the engine.

5.4.2 Differences between Fabricated and Designed Stand

The design of the stand has a number of differences from the fabricated version of the stand, each for certain reasons taken into account only after construction began. The lid has two strips of steel plate that run across the front of the stand to give structure and support for the handle on the front of the stand as well as the polycarbonate shield. The engine mount has changed to better deal with the geometry of the load cell which was confirmed after the actual unit was chosen. The main shelf was changed to a full sheet of steel with only an access port for sensor and fuel lines, in order to better separate the sensors and fuel tank from the heat of the engine. The exhaust no longer has the full muffler design in favor of just a straight tube of high carbon steel. The engine rail system was changed to simple drawer slides with the engine mount itself welded to the rails; this was decided the best simple way to minimize the friction affecting the load cell measurement. The rail system and the failure shield were also made fully removable via bolts and nuts that secure them down so the engine may be easily accessed. The

casters are a different type and size than those depicted in the design models and are mounted inside the box corners which can be seen in Figure 7.

Figure 12 - Fabricated Test Stand

5.4.3 Challenges

There were a number of challenges in the fabrication process starting with the stock materials which took far longer to arrive than expected. Learning to weld was a challenge, however this did not take very long to reach proficiency for what our project needed. Learning

to use the plasma cutter was simpler than using the welder however more dangerous and requiring unexpected skill to cut clean edges. The trouble with using the grinders was to create straight edges as the grinding surface was not perfectly suited for such a use. Creating the angled pieces on the front of the top part of the stand so that they would match up cleanly with both surfaces and each other proved rather difficult. Welding in some of the joints proved difficult as the angle required was very awkward and challenging. The attachment of the casters proved that the floor in the shop was not level and that the stand itself had to be leveled. The alignment of the engine with both the exhaust pipe and the silencer proved challenging as they needed to be aligned axially across the length of the test stand. The attachment of the keyboard proved challenging as drilling the holes for its bolts proved impossible as a last step so an additional bar had to be first attached.

6. Lab User Interface Design

National Instruments LabVIEW 2009 is an application used to collect information from a source and output the data on screen. Code for this program is setup visually, and remains hidden when run. A separate user interface has to be designed for students to use while gathering information.

Our goal for using this program was to allow all pressure inputs to be displayed and updated on screen. This display would also have a throttle control to see how fast the engine is operating. The idea behind the interface was to allow students to easily view the data being collected in order to get the most out of the lab. Below in figure 13 is a picture of the user interface. The interface was designed based upon the information students would be quizzed on in their labs. This ultimately drove our design process for what we wanted to collect, and how we would design it on screen.
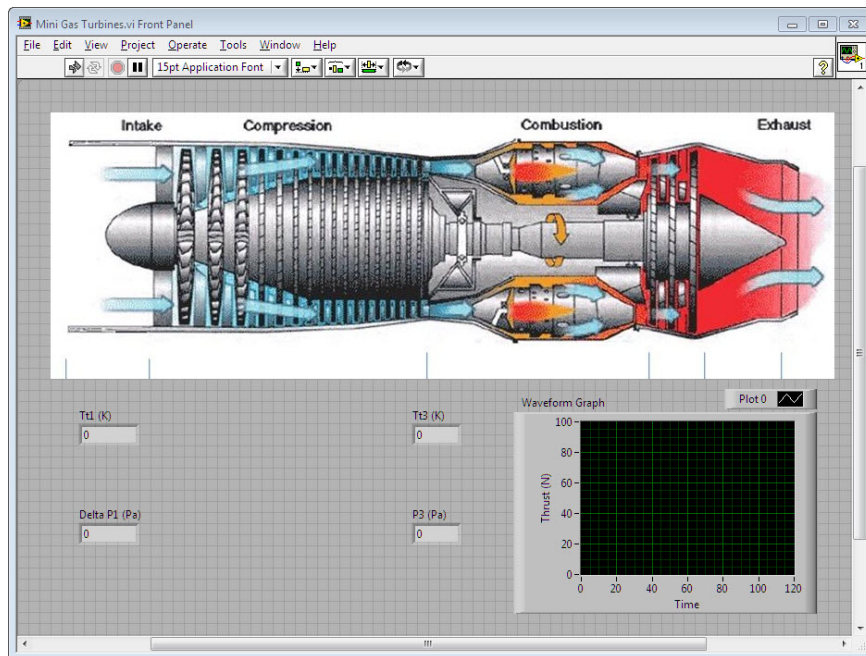
Figure 13 - LabVIEW Front Panel

Collecting information from the test stand required installing two DAQ cards with our selected sensors. After debugging the sensor inputs, we were able to set up the code so that

anyone who has to use it in the future can easily understand how it works. Below in figure 14 is a picture of the LabVIEW code setup used for our program. Originally, the code was setup for use by one DAQ card, but due to difficulties with sensor voltages we had to update the system to be used by two DAQ cards. The sensors were each installed on the DAQ individually and tested to figure out where their inputs were going. After this, the data being collected is put through filters to give us usable on-screen information and numbers. Finally, the information is sent to the visual user interface the students will be using during their labs.
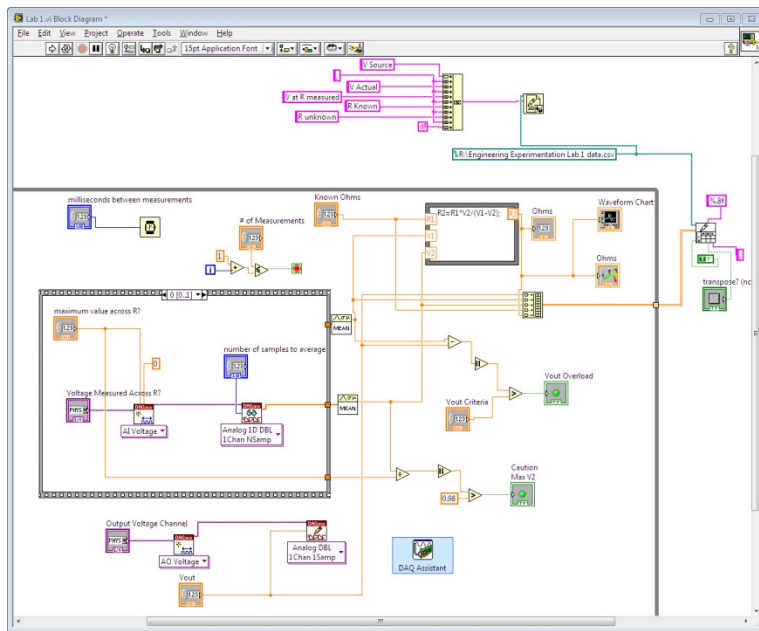
Figure 14 - LabVIEW Block Diagram

7. Sensor Integration

The sensors we chose had to not only work over the range we needed for data acquisition, but also interface correctly with our DAQ cards. This posed a serious challenge due to the age of the DAQ card we had to use for this project. The sensors had to be installed with the DAQ and tested to make sure they worked properly and were interacting with the DAQ. After interfacing the sensors with the DAQ, we were able to set up the sensors in a manner that worked well with LabVIEW.

The Data Acquisition Hardware that we used was two National Instrument's SCXI-1322, each connected to a National Instrument's SCXI-1122 that then connected to one National Instruments SCXI-1600, which transferred the analog signals into the computer using a USB to USB cable. This whole setup was housed and powered using a National Instrument's SCXI-1000. The SCXI-1322 DAQ boards have sixteen single signal channels that connected to the sensors using screw pins to grab the wires. The fact that the channels were single signal was a challenge because it meant that the power to the sensor and the signal that the DAQ has to read cannot be connected to the same channels, requiring each sensor to require two channels to work. The pressure sensors and the load cell put out a signal in voltage changes meaning they required one channel for voltage in and ground, and one channel for signal output. The temperature sensors, a thermistor and a thermocouple, were measured in resistance change which meant they required one channel for voltage in and ground, a constant current channel to allow a reference point for the current without resistance, and another channel for signal output. The different types of analog measurements, voltage and current, is what required two separate DAQ cards for LabVIEW to read and change into readings.

The setup of the sensors was rather intricate process requiring other equipment besides the sensors themselves. Both the absolute pressure transducer and the differential pressure

transducer required converters from the metric threading around the air inlet to hose and small hosing to connect the pressure transducer to the engine, one for the absolute and two for the differential. Each pressure transducer required one connection to the engine which would meet flush with the inner surface of the engine case and the silencer. The differential pressure transducer also required a small metal tube which was bent at a 90° angle to allow the intake to be facing the airflow instead of being along the airflow. The thermocouple required a specific channel of the DAQ card that measured very small changes in current and compared the measurements to a "cold junction" installed in the card and uses a Wheatstone bridge configuration to measure the surrounding temperature. The thermistor came with two pre-calibrated resistors that connected to the thermistor in two locations to measure the change in resistance of the thermistor. This setup is similar to a Wheatstone bridge, but uses the channel inputs in the DAQ card to connect.

After setting up the LabVIEW and the hardware of the sensors we tested the sensors using the specifications of the hardware, shown in Appendix C, and known pressures, temperatures, and weights to check the sensors and the LabVIEW set up and made sure that they interacted together correctly. This process was done before the sensors were installed in case there were any issues with the set or hardware that would need editing. Once the sensors were accurate they were installed in the engine test stand.

8. Engine Control

The final element for the project was to integrate the engine itself into the test stand. This process was broken down into a couple key stages. In order to ensure the functionality of the test stand, the operational requirements of the engine must be met. From these requirements we came up a control scheme for the engine and the user interface for the system. After creating the control layout, we addressed the challenges of the actual integration into the stand due to both time and skill limitations.

8.1 Control Requirements for Engine

The requirements for the operation of the engine were fairly straight forward. Upon receiving the Wren 70 we examined the included parts and documentation. The user manual laid out the operational schematic for the engine in both schematic and pictorial representations. Provided below is the pictorial representation of the required system in full. Both of these layouts can be found on pages 19 and 21 of the Wren 70 Operation Manual.
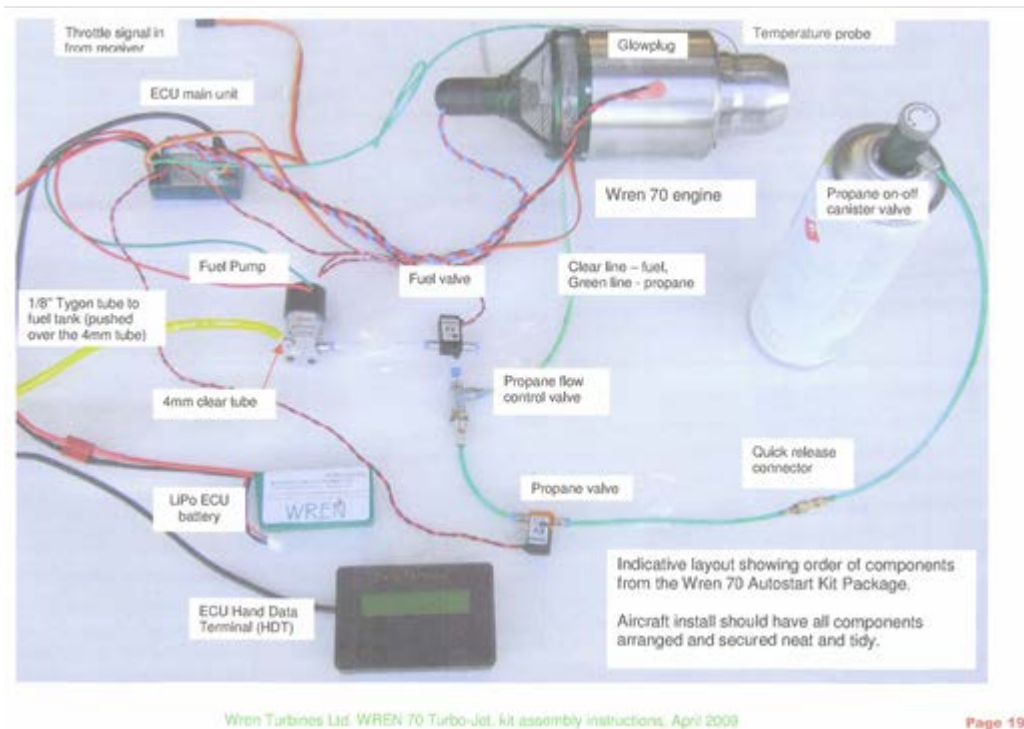
To clarify what is outlined in the image above, the entire system relies on the necessary requirements for the engine as well as the included engine control unit (ECU). Below is a compact table listing the requirements for each.

Operational Requirements	
Engine	**Engine Control Unit (ECU)**
Main Fuel	Battery Input
Starter Fuel	Fuel Servo Connections
ECU Input	*Throttle Input from Controller*

Upon arrival, the engine came with all of the necessary components for operation, including the battery and all necessary connecting cable, except the method of inputting a throttle signal. Due to its normal application in model aircraft, the included ECU was configured to receive standard pulse width modulated (PWM) signals from a remote control transmitter/receiver system.

In order to integrate the engine into the test stand, we would have to satisfy several key elements. These elements are, making sure the cart is capable of storing both starter and running fuel for the engine, supplying the required power to the control systems, and providing the means for engine control by the user. The fuel integration would not be complicated, we would just have to integrate two fuel containers for the respective fuels and make sure that the fuel lines were long enough. The throttle signal input would be slightly trickier to implement. In order to run the engine properly with the automatic start feature, the throttle signal must be able to maintain a steady state input as well as having trim control. Incorporating these elements into the test stand was the final stage in its creation. Due to the remaining time available in our project

period as well as the skill-set of our group, we put together a compilation of short term and long term plans for the implementation of these final stages of the project.

8.2 Short Term Recommendations

The initial goal for the test stand was to get the engine up and running as soon as possible. Considering the fact that we were unable to run the engine without first constructing the test stand, the functionality of the engine has yet to be reviewed. Before the installation of sensors in the engine, we thought it prudent to make sure that the engine worked up to its specifications before augmenting it in anyway. To this effect, we wanted the easiest method available to perform this evaluation.

Our recommendation for the short term time period of simply getting the engine running would be to treat the engine as if it was on the wing. To elaborate on this, the engine comes already equipped to accept the standard PWM signal from a remote control receiver. It would make sense that the first attempt at engine operation would be in the manner that the engine was designed for. The additional equipment required for this setup would require no augmentation and would be relatively easy to acquire.

In order to run the engine as if it was installed on a model aircraft, we would require a couple of additional pieces of equipment. The required additions to the cart would be a radio transmitter and companion receiver and a power system for the receiver. The transmitter and receiver would function as normal to provide the required input to the ECU. The receiver unit requires power, which for the short term would be provided by an additional model aircraft battery. These additions to the cart are not the best solutions, but are the quickest in the hopes of getting the engine up and running as soon as possible.

8.3 Long Term Recommendations

After ensuring that the engine functions as designed and all of the sensors have been installed, a more permanent solution for user input and engine operation would be desired. Ideally, the centralization of all power sources and hardwiring the engine control into the test stand. These are the two changes that are different than the short term goals and will provide the finishing touches to the test stand.

Regarding the power requirements for the operation of the engine, our recommendation is that the fuel pump, ECU, and user interface power come from a power supply that is connected to the main power strip inside of the test stand. Since standard wall voltages and currents are not appropriate for the electronics in question, a power supply, either stock if one can be found or have a custom one made, would be required. The advantages of this would be that there would no longer be any batteries to charge and that all of the electricity would be on one circuit and therefore one emergency stop. This addition would make the limiting factor for operation the fuel supplies and not the discharge time of the batteries.

For the user interface, a custom system would have to be designed. The system would have to include a throttle and trim input for the use of the user, electronics to convert those inputs into PWM signals, and then transfer those converted signals to the ECU. Due to the limitations of our skills, we do not have a specific design in mind, only that the system should have the ability to run the engine as designed and incorporate an emergency stop for the entire test stand.

9. Conclusions

The construction of a miniature gas turbine test stand was a challenging capstone design project designed to complete the Major Qualifying Project requirement for the Aerospace Degree at Worcester Polytechnic Institute. Our overall goal for this project was to construct a miniature gas turbine test stand that would be able to run, be controlled by the user, and visually display the desired data. While this proved to be a large feat for such a short time period, we were able to come very close to accomplishing this. With more time, we would have completed this project in full. While there are few written works online detailing projects such as this, enough resources are available to make a complete, accurate end product possible.

The most challenging section of this project for our Aerospace Engineering group was creating the control interface system, a task that requires a background in Electrical and Computer Engineering. While this project will come to full completion within the next year, having members with backgrounds in this area is critical to producing a well-constructed test stand interface. Although funds may be an issue, opting for a more up to date DAQ card will allow more freedom in sensor selection and installation. Construction of a silencer proved to be simple and required little funding with the added benefit of this attachment is well worth the time and cost.

Total fabrication of our test stand required many man hours, including time spent learning how to utilize the proper equipment. While we were able to finish the stand in time, it is essential to start this process as early as possible. The fabrication process was driven by the needs of the force balance and turbine selection, both of which are driven by aerodynamic and error analysis. These two areas of analysis were chokepoints for this project and should be started by the entire group as early as possible. Doing so will allow the most accurate and complete construction of a test stand in the future.

10. Recommendations

During the completion of our project there were several areas in which additional work is either required or would add a significant amount to the completion of the project. This additional work falls into the individual categories of the project itself. For the reference of future groups expanding on our accomplishments, our recommendations have been organized by their relevant section and presented below.

10.1 Fabrication Recommendations

There are some things left for the fabrication of the test stand to be fully complete. The stand requires the monitor mount attachment as well as the structure for the engine control box. The polycarbonate cover for the top of the stand needs to be cut and attached. The doors for the bottom of the stand need to be fabricated as well as all the siding to surround the lower portion of the stand. The stand needs to be leveled on an actual level surface. The finishing hardware such as handles and locks needs to be purchased and attached where appropriate on the stand.

10.2 Sensor Recommendations

One of the primary issues with sensor selection and purchasing was finding sensors that could properly interface with our DAQ cards. While we were able to eventually find sensors that would work with them, there were a few instances where we had to settle for sensors with less than ideal accuracy. This was also primarily due to financial constraints imposed by this project. If finances were not an issue, one of the largest improvements that could be made would be to acquire a more up-to-date DAQ card, and to make sure that it will interface with the proper sensors needed. While the sensors we selected still did the job, improved accuracy and ease of use with the DAQ card would go a long way in improving the end result of a test stand. This would also allow users to clean up the LabVIEW code. While there are other programs that can

do the same job as LabVIEW, we found it convenient to use and recommend its use for similar projects in the future.

10.3 Fire Science Laboratory Recommendations

Since our test stand will be operating in the Fire Science Laboratory at Worcester Polytechnic Institute, the stand and the experiments being performed must meet the existing specifications. Upon the decision to operate our stand in the Fir Science Laboratory, we requested all relevant material for creating an approved experiment. From this documentation we determined that our experiment, as we had designed it, would be acceptable for the laboratory with only a minimal amount of additional paperwork.

After the construction of the final test stand is complete, the following documentation will need to be completed. Following the master checklist for Fire Science Laboratory operation, the operator of the experiment will have to complete the necessary training. In addition to this the full experiment, from set up and start up to shut down and cleaning up, will have to be described exactly as they are to be performed. Any and all safety hazards need to be identified in addition to the measures being taken to mitigate them. Finally all documentation must be on file with the Fire Science Laboratory manager and all students participating in the lab must understand and undergo any relevant training. There may be additional safety and training measures required by the Fire Science department that would also have to be addressed.

10.4 Engine Control Recommendations

The detailed recommendations regarding the engine control system were presented in the relevant section above. To summarize what still needs to be done, the work falls into the two broad categories of power management and operator input. On the side of power management, a

power supply either needs to be created or procured to supply the required power for the fuel pump, ECU, and the operator control system. This operator control system, ideally, should be hard-wired and fully integrated into the test stand. This would prevent additional sources of malfunction as well as having the benefit of keeping the entire system integrated and therefore easier to safeguard.

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Appendices

Appendix A – Derivation of Equations

This appendix contains details of the derivation of the equations relevant to the design of the laboratory experiment. In order to keep the analysis as accurate as possible, the equations used to develop the laboratory exercise centered on the turbojet are based on the approach of non-ideal cycle analysis. The assumptions made include:

- The gas is calorically perfect upstream of the combustor with properties: c_{pc}, γ_c

- The gas is calorically perfect downstream of the combustor with properties: c_{pt}, γ_t

- The universal gas constant is constant throughout the engine: R

- All components, except the burner, are assumed to be adiabatic

- Efficiencies of the compressor and turbine can be described by means of constant polytropic efficiencies

- Bleed and leakage is neglected between all engine stations.

The station numbers in the following equations are in reference to Figure 1.

A.1: Mass Flow Rate

The derivation of the Mass Flow rate ($\dot{m}_1$), as given in equation (2) is as follows:

Starting with the conservation equation:

$$\dot{m}_1 = \rho_1 V_1 A_1 \tag{A1}$$

Taking the definition for stagnation pressure:

$$P_{t1} = P_1 + \frac{\rho_1 V_1^2}{2} \tag{A2}$$

Solving (A2) for ρ_1, substituting into (A1) and solving for V_1 yields:

$$V_1 = \frac{2(P_{t1} - P_1)A_1}{\dot{m}_1} \tag{A3}$$

Taking the equation of state:

$$P_1 = \rho_1 R T_1 \tag{A4}$$

In addition to the relationship between static and stagnation temperature:

$$T_1 = T_{t1} - \frac{V_1{}^2}{2C_{pc}} \tag{A5}$$

Substituting (A5) into (A4) and solving for ρ_1:

$$\rho_1 = \frac{2C_{pc}P_1}{2RC_{pc} - RV_1{}^2} \tag{A6}$$

Substituting (A6) into the conservation equation (A1):

$$\dot{m}_1 = \frac{2C_{pc}A_1 P_1 V_1}{2RC_{pc} - RV_1{}^2} \tag{A7}$$

Substituting (A3) into (A7):

$$\dot{m}_1 = \frac{2C_{pc}A_1 P_1 \left(\frac{2(P_{t1} - P_1)A_1}{\dot{m}_1}\right)}{2RC_{pc} - R\left(\frac{2(P_{t1} - P_1)A_1}{\dot{m}_1}\right)^2} \tag{A8}$$

Simplifying the complex fraction and rearranging (A8):

$$\dot{m}_1 = \left(\frac{4C_{pc}A_1{}^2 P_1(P_{t1} - P_1)}{\dot{m}_1}\right)\left(\frac{\dot{m}_1{}^2}{\dot{m}_1{}^2 2RC_{pc} - 4R(P_{t1} - P_1)}\right) \tag{A9}$$

Combining both fractions, simplifying and solving for $\dot{m}_1$ yields the final equation:

$$\dot{m}_1 = \frac{\left(4A_1{}^2\right)(P_{t1} - P_1)\left(C_{pc}P_1 + R(P_{t1} - P_1)\right)}{2RC_{pc}} \tag{A10}$$

A.2: Stagnation Pressure Ratio across Compressor

The derivation of the overall stagnation pressure ratio across the compressor (π_c), as given in

equation (9) is as follows:

Taking the definition for π_c, substituting the assumption of an the ideal diffuser yields:

$$\pi_c = \frac{P_{t3}}{P_{t2}} \qquad P_{t2} = P_{t0} = P_{t1}$$

$$\pi_c = \frac{P_{t3}}{P_{t1}} \qquad\qquad (B1)$$

Using the definition for stagnation pressure at station 3:

$$P_{t3} = P_3 + \frac{\rho_3 V_3{}^2}{2} \qquad\qquad (B2)$$

Then solving the conservation at station 3 for V_3 and substituting into (B2):

$$P_{t3} = P_3 + \frac{\rho_3 \left(\frac{\dot{m}_3}{\rho_3 A_3}\right)^2}{2} \qquad\qquad (B3)$$

Simplifying (B3) and dividing by P_{t1} yields the final expression:

$$\pi_c = \frac{P_3}{P_{t1}} + \frac{\dot{m}_3{}^2}{2 P_{t1} \rho_3 A_3{}^2} \qquad\qquad (B4)$$

A.3: Density at Station 3

In order to solve for both mass flow and the relevant pressures and temperatures an

expression for the density at station 3 (ρ_3) is required.

Starting with the conservation and Ideal Gas Law equations at station 3:

$$\dot{m}_3 = \rho_3 A_3 V_3 \qquad P_3 = \rho_3 R T_3$$

Then substituting into the definition for static temperature at station 3:

$$T_3 = T_{t3} - \frac{V_3{}^2}{2C_{pc}}$$

Yields:

$$T_3 = \frac{2C_{pc}T_{t3} - V_3{}^2}{2C_{pc}}$$

Solving the Ideal Gas Law equation for ρ_3 and substituting in (C1) yields: $(C2)$

$$\rho_3 = \frac{2C_{pc}P_3}{2C_{pc}RT_{t3} - RV_3{}^2}$$

Substituting (C2) into the conservation equation at station 3 and simplifying:

$$\dot{m}_3\left(2C_{pc}RT_{t3} - RV_3{}^2\right) = 2C_{pc}P_3A_3V_3 \qquad (C3)$$

Rearranging (C3) into a polynomial in terms of coefficients of V_3: $(C4)$

$$\left(\frac{\dot{m}_3R}{2C_{pc}}\right)V_3{}^2 - (P_3A_3)V_3 + T_{t3}\dot{m}_3R = 0$$

In order to find the expression for V_3, the quadratic equation was used:

$$V_3 = \left[\frac{A_3P_3 - \sqrt{A_3{}^2P_3{}^2 - \frac{2\dot{m}_3{}^2R^2T_{t3}}{C_{pc}}}}{\dot{m}_3R}\right] \qquad (C5)$$

Substituting (C5) back into the conservation equation and solving for ρ_3 yields:

$$\rho_3 = \left(\frac{\dot{m}_3}{A_3}\right)\left[\frac{A_3P_3 - \sqrt{A_3{}^2P_3{}^2 - \frac{2\dot{m}_3{}^2R^2T_{t3}}{C_{pc}}}}{\dot{m}_3R}\right]^{-1} \qquad (C6)$$

Appendix B – Design Models
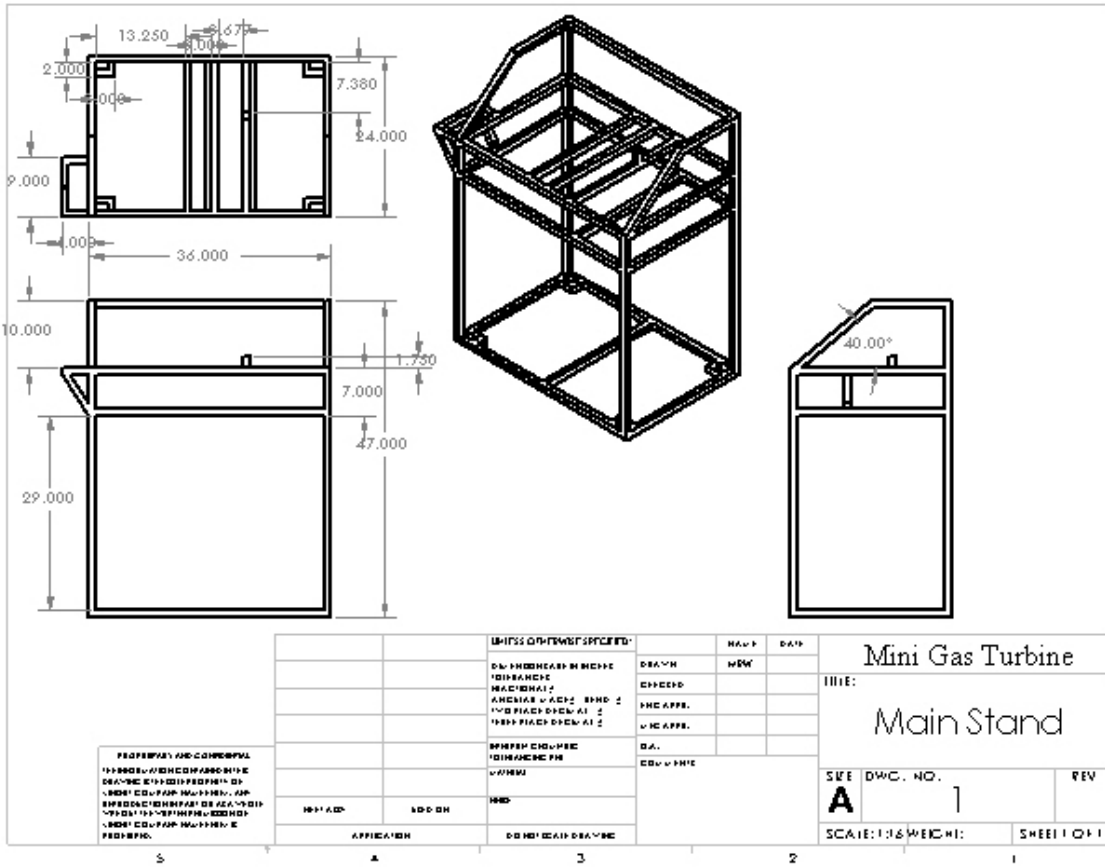
This drawing shows the primary frame of the test stand and gives dimensions for the different steel bar lengths. The modifications for attaching the casters to the frame can also be seen in this drawing in on the bottom corners of the isometric view.

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Mini Gas Turbine
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	MRW		
			CHECKED			TITLE:
			ENG APPR.			
			MFG APPR.			Cover Brace
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
			COMMENTS:			
		MATERIAL				SIZE A	DWG. NO. 2	REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:12	WEIGHT:	SHEET 1 OF 1

This CAD drawing shows the 'Cover Brace' part which is the frame for the polycarbonate hatch/door for the upper portion of the test stand.

UNLESS OTHERWISE SPECIFIED:			NAME	DATE	Mini Gas Turbine
DIMENSIONS ARE IN INCHES		DRAWN	MRW		TITLE:
TOLERANCES: FRACTIONAL±		CHECKED			
ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±		ENG APPR			Engine Mount
		MFG APPR			
INTERPRET GEOMETRIC TOLERANCING PER		Q.A.			
MATERIAL		COMMENTS:			
FINISH					SIZE A	DWG. NO. 3	REV
NEXT ASSY	USED ON	DO NOT SCALE DRAWING			SCALE: 1:4	WEIGHT:	SHEET 1 OF 1
APPLICATION							

This drawing provides the dimensions for the engine mount and a detailed view of how the load cell attaches to measure thrust.
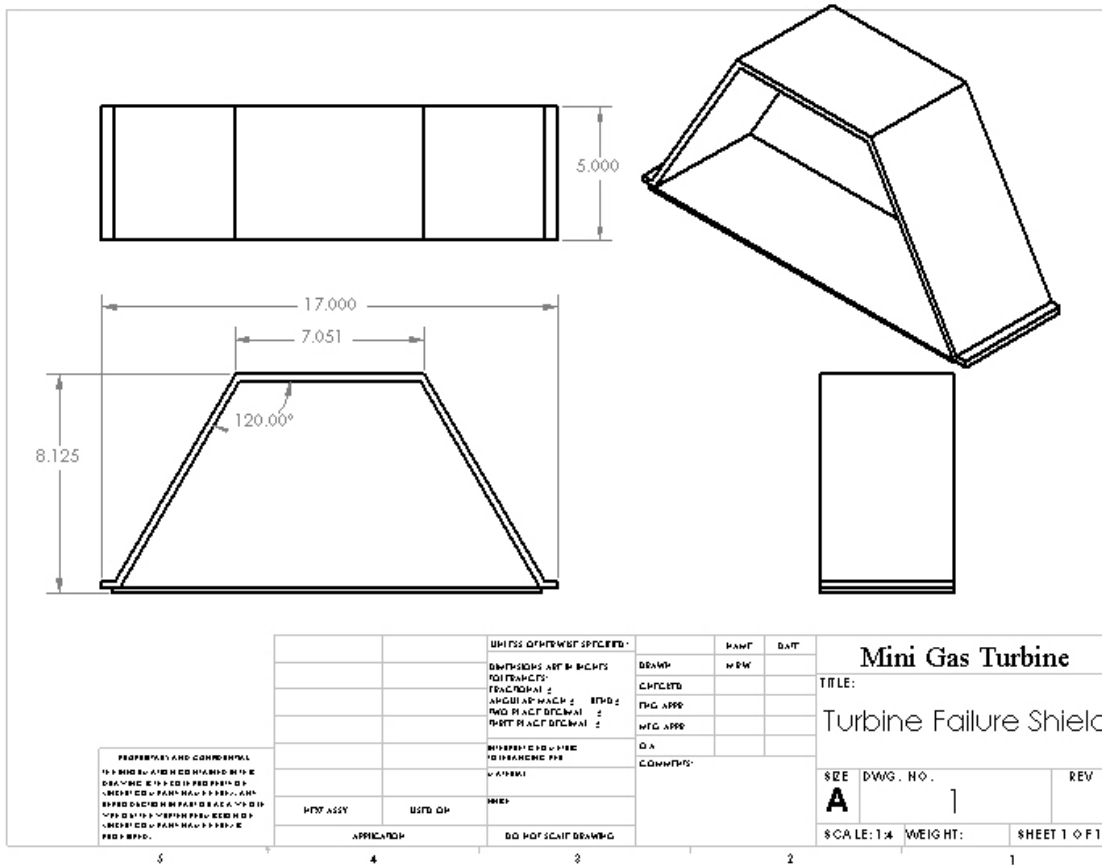
This drawing shows the turbine failure shield that will encompass the engine. The shape was determined because the thickness of the metal prevents the machining of a single piece semi-circular shield.
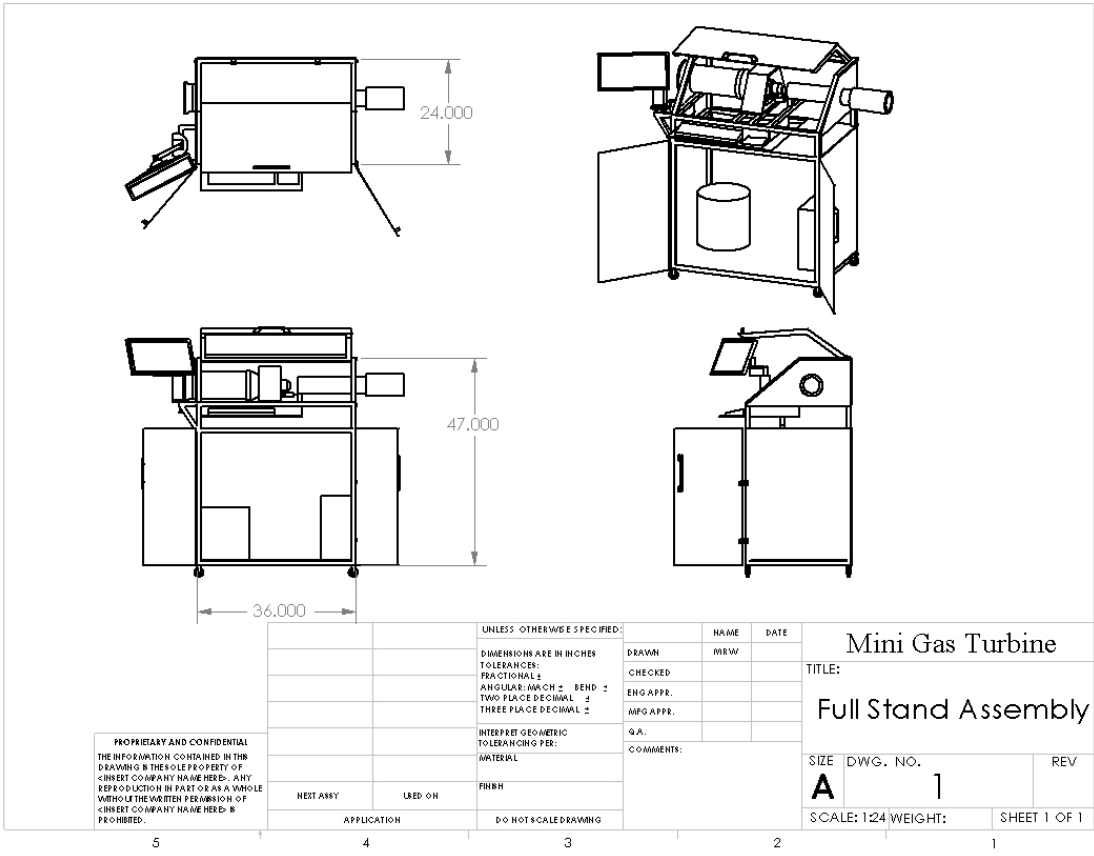
This drawing shows the concept of the full stand assembly giving basic dimensions to provide a scale.

Appendix C – Assembly Views

C.1 Isometric View of Fabricated Main Stand

C.4 Inlet View of Assembled Stand
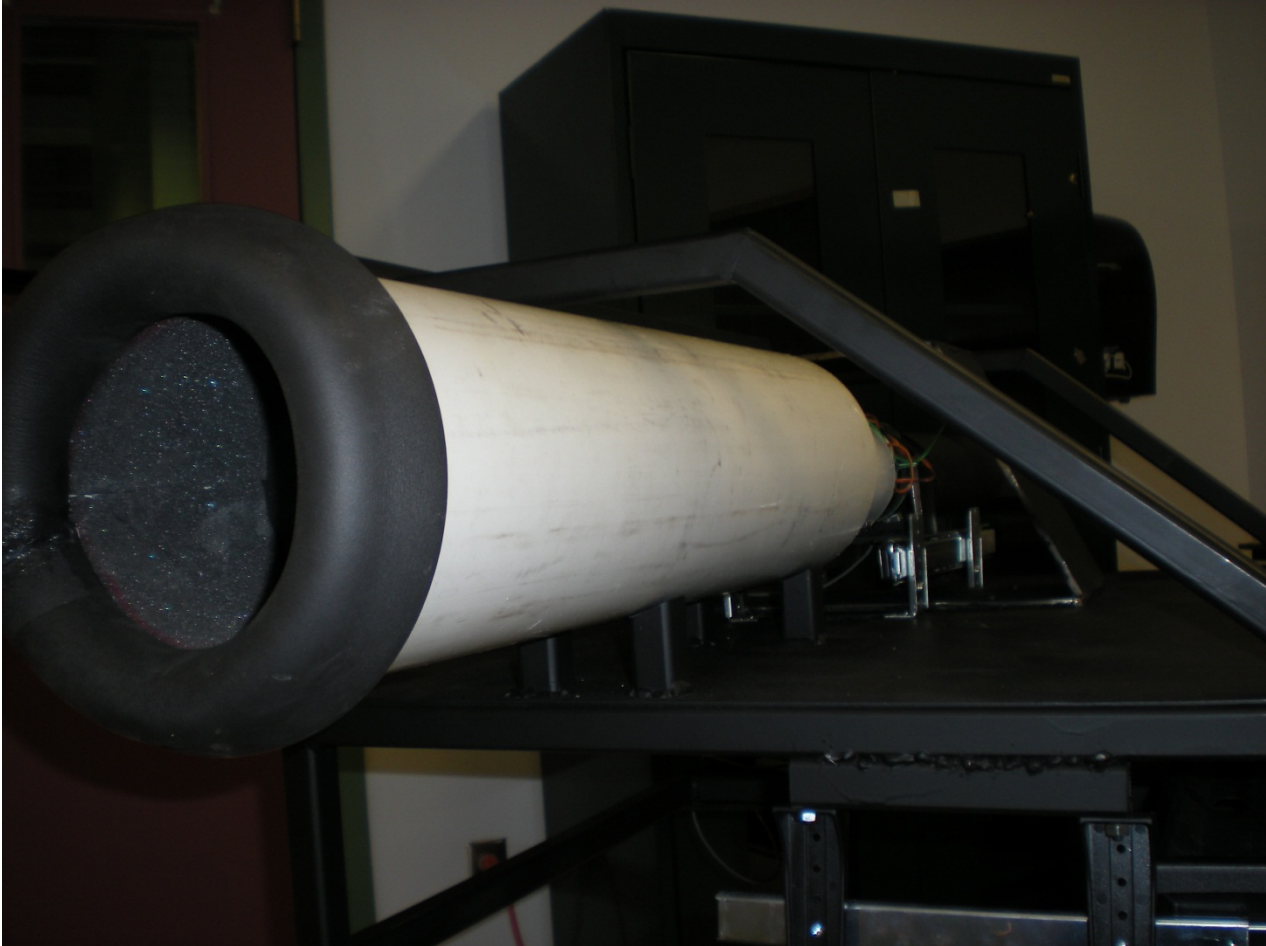
C.5 Exhaust View of Assembled Stand
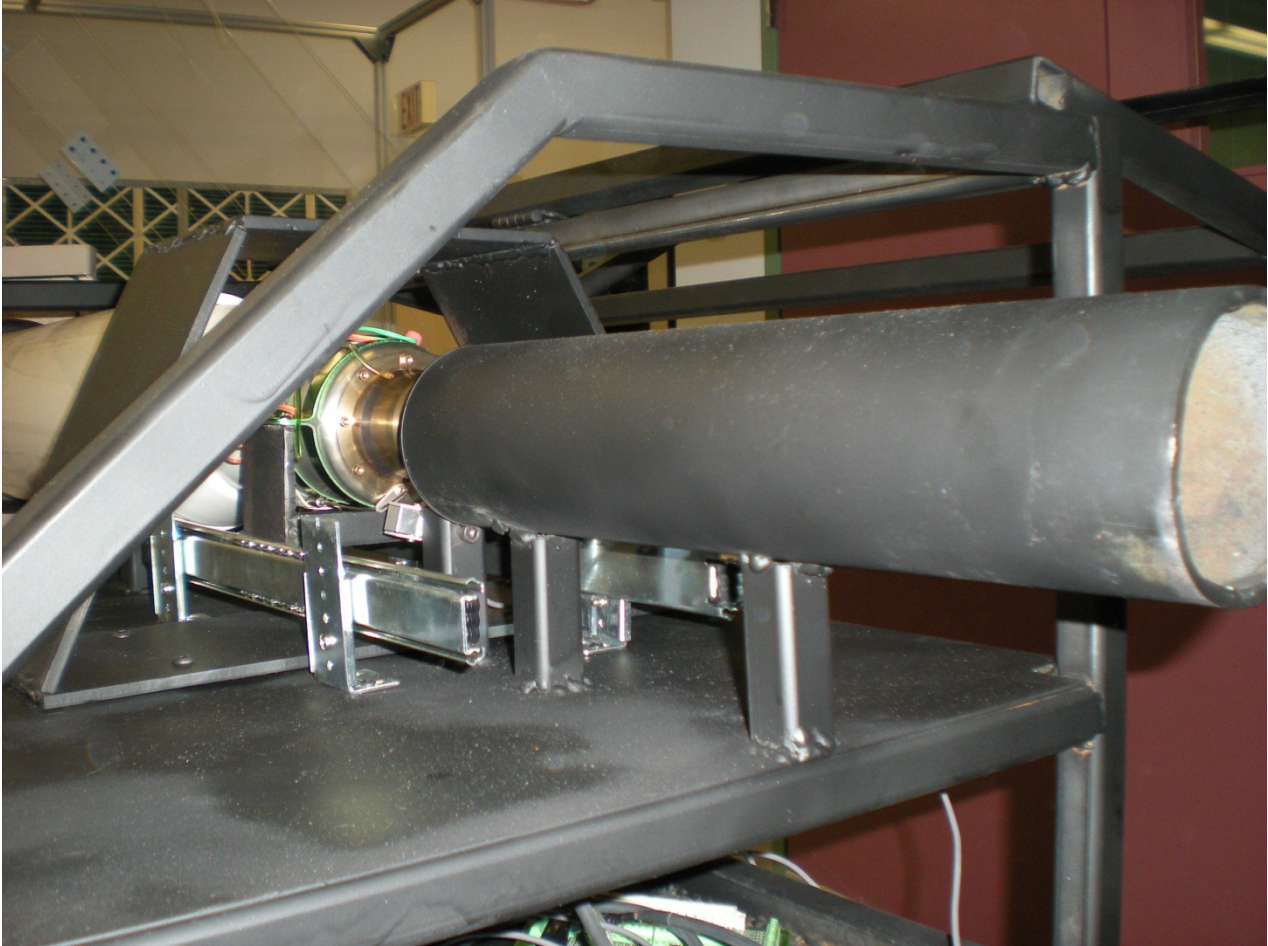
Appendix D – Sensor Specifications

This Appendix shows all the sensor specifications and calibration sheets. All of the sensors we chose for this project came from Omega Engineering, Inc.

D.1 Load Cell

MINIATURE LOW-PROFILE TENSION LINKS
LOW PROFILE 19 mm (0.75") TO 25 mm (1") HEIGHT
STANDARD AND METRIC MODELS

LC703/LCM703 Series
Tension/Compression Calibrated in Tension
10 lb to 1000 lb
5 kg to 500 kgf

1 Newton = 0.2248 lb
1 daNewton = 10 Newtons
1 lb = 454 g
1 t = 1000 kgf = 2204 lb

STANDARD
LC703-25, $295,
shown actual size.
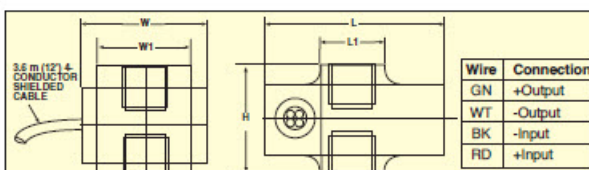
METRIC
LCM703-150, $295,
shown actual size.

Starts at
$295

MADE IN USA — NIST Standard — RoHS

LC703-100, $295,
shown larger than actual size.

✔ **Low Profile**
✔ **High Accuracy**
✔ **Rugged Industrial Design**

The LC703/LCM703 Series comprises economical universal (tension/compression) load cells with a low profile. Ranges above 100 lb are stainless steel; ranges below 100 lb are aluminum. The low profile and rugged design make LC703 and LCM703 suitable for many industrial applications, including robotics, automated weighing systems, and batch-process control systems.

3.6 m (12') 4-CONDUCTOR SHIELDED CABLE

Wire	Connection
GN	+Output
WT	-Output
BK	-Input
RD	+Input

SPECIFICATIONS
Excitation: 10 Vdc (15V max)
Output: 2 mV/V nominal
5-Point Calibration:
0%, 50%, 100%, 50%, 0%
Linearity:
10 to 100 lb: ±0.15%
>100 lb: ±0.10 FSO
5 to 50 kgf: ±0.15%
75 to 500 kgf: ±0.10%
Hysteresis:
10 to 100 lb: ±0.15%
>100 lb: ±0.10 FSO
5 to 50 kgf: ±0.15%
75 to 500 kgf: ±0.10%
Repeatability: ±0.05%
Zero Balance: ±1.0% FSO
Operating Temp Range:
-40 to 82°C (-40 to 180°F)

Dimensions: mm (in)

CAPACITY	L (MAX)	L1	W	W1	H	THREAD
10 lb / 5 kgf	38 (1.50)	14 (0.56)	14 (0.54)	9.5 (0.38)	19 (0.75)	10-32 x 0.20 / M5 x 0.8-6H
25 to 100 lb / 10 to 50 kgf	41 (1.62)	14 (0.56)	17 (0.66)	13 (0.50)	19 (0.75)	¼-28 x 0.23 / M6 x 1.00-6H
150 to 1K lb / 75 to 500 kgf	44 (1.75)	14 (0.56)	24 (0.93)	19 (0.75)	25 (1.0)	⅜-24 x 0.38 / M10 x 1.5-6H

Compensated Temp Range:
16 to 71°C (60 to 160°F)
Thermal Effects:
Zero: ±0.005% FSO/°F
Span: ±0.005% % FSO/°F
Protection Class: IP54
Safe Overload: 150% of capacity
Ultimate Overload: 300% of capacity
Output Resistance: 350 ±10 Ω

Input Resistance: 360 Ω minimum
Full Scale Deflection: 0.003" nominal
Construction:
≤100 lb: Aluminum
>100 lb: 17-4 PH stainless steel
≤50 kg: Aluminum
>50 kg: 17-4 PH stainless steel
Electrical: 3.6 m (12') shielded 4-conductor PVC cable

F-62

LOAD CELLS F

OMEGADYNE INC.

LOAD CELL
FINAL CALIBRATION

0.00 -   10.00 KgF
Excitation   10.000 Vdc

Job: RMLS8981   Serial: 284181
Model: LCM703-10   Tested By: PEARL
Date: 10/13/2010   Temperature Range: 16 TO 72 C.
Calibrated: 0.00 -   10.00 KgF   Specfile: LCM703

```
        Force        Unit Data
         KgF           mVdc
      -----------   -----------
          0.00         0.0000
          5.00        10.7698
         10.00        21.5608
          5.00        10.7709
          0.00         0.0056
```

```
Balance         0.1313    mVdc
Sensitivity    21.5608    mVdc
In  Resist     400.20     Ohms
Out Resist     350.90     Ohms
59K Shunt       14.8150    mVdc
```

ELECTRICAL LEAKAGE: PASS

ELECTRICAL WIRING/CONNECTOR: RED   = +INPUT (EXC)
                             BLACK = -INPUT (EXC)
                             GREEN = +OUTPUT
                             WHITE = -OUTPUT

This Calibration was performed using Instruments and Standards that are
traceable to the United States National Institute of Standards Technology.

S/N	Description	Range	Reference	Cal Cert
Station 3	100lb Dead-Weights	0 - 45.35924 KgF	C-2691	C-2691
US3612530	AT34401A DMM UUT	Unit Under Test	C-2462	100038

Q.A. Representative : Pearl Stowers   Date: 10/13/2010
This transducer is tested to & meets published specifications. After final
calibration our products are stored in a controlled stock room & considered in
bonded storage. Depending on environment & severity of use factory calibration
is recommended every one to three years after initial service installation date.
COMMENTS: FINAL TEST IN TENSION.

Omegadyne, Inc., 149 Stelzer Court, Sunbury, OH 43074   (740) 965-9340
http://www.omegadyne.com   email: info@omegadyne.com   (800) USA-DYNE

ALL STAINLESS STEEL TRANSDUCER
MULTIMEDIA COMPATIBILITY
HIGH-PERFORMANCE SILICON TECHNOLOGY

Engineered from 1 to 10,000 psi.

PX309 Series
Gage/Absolute Pressure
0 to 5 Vdc Output
0-1 to 0-10,000 psi
0-70 mbar to 0-690 bar

Starts at
$225

NIST Standard CE ☒ RoHS

PX309-100G5V, $225, shown actual size.

Cable style.

Twist-lock style.

PX329-100G5V, $275, shown actual size.

Fast Delivery!

Metric thread adaptors available, see section C.

PX319-100G5V, $225, shown actual size.

mini DIN style (connector included).

- 1, 2, and 5 psi Low Pressure Ranges
- Rugged, Solid State Design
- All Stainless Steel
- High Stability, Low Drift
- 0.25% Accuracy
- RoHS Compliant
- IP65 Protection Class

SPECIFICATIONS
Excitation: 9 to 30 Vdc (<10 mA) (reverse polarity and overvoltage protected)
Output: 0 to 5 Vdc
Accuracy: ±0.25% FS BSL at 25°C; includes linearity, hysteresis and repeatability
Zero Offset: ±2% FSO; ±4% for 1 and 2 psi ranges
Span Setting: ±2% FSO; ±4% for 1 and 2 psi ranges
Total Error Band: ±2% FSO, includes linearity, hysteresis, repeatability, thermal hysteresis and thermal errors (except 1 psi = ±4.5% and 2 psi = ±3%)
Long-Term Stability (1 Year): ±0.25% typical
Typical Life: 10 million cycles
Operating Temperature: -40 to 85°C (-40 to 185°F)
Compensated Temperature:
 >5 psi Range: -20 to 85°C (-4 to 185°F)
 ≤5 psi Range: 0 to 50°C (32 to 122°F)
Proof Pressure:
 psia and ≤50 psig: 3x capacity or 20 psi, whichever is greater
 ≥100 psi: 2x capacity

Burst Pressure: 5x capacity or 25 psi, whichever is greater
Response Time: <1 ms
Shock: 50 g, 11 ms half-sine shock
Vibration: ±20 g
Wetted Parts: 316 SS for all psia ranges and 1 to 50 psig; 17-4 PH SS for ranges 100 to 10,000 psig
Pressure Port: ¼-18 MNPT
Electrical Connections:
 PX309: 1.5 m (5') 3-conductor cable
 PX319: mini DIN connector with mating connector included
 PX329: Twist-lock connector, mating connector sold separately (PT06V-10-6S)
Weight: 155 g (5.4 oz) max

Note: Units 100 psig and above may be subjected to vacuum on the pressure port without damage
For alternative performance specifications contact Engineering.

Order a snubber to protect your pressure transducer!

PS-4G, $12.75, shown actual size.
Snubbers protect sensors from fluid hammers/spikes.

B-96

VOLTAGE OUTPUT PRESSURE TRANSDUCERS

B

RUGGED, GENERAL PURPOSE TRANSDUCER

5 Vdc Output Wiring

Wiring	Cable	Mini DIN	Twist-Lock
Excitation (+)	Red	Pin 1	Pin A
Excitation (-)	Black	Pin 2	Pin B
Output (+)	White	Pin 3	Pin C
NIC		Pin 4	Pin D
Spare			Pin E
Vent			Pin F

Dimensions: mm (in)

22 (0.88) DIA   ⅞" HEX

56 (2.2) max   16 (0.63) max
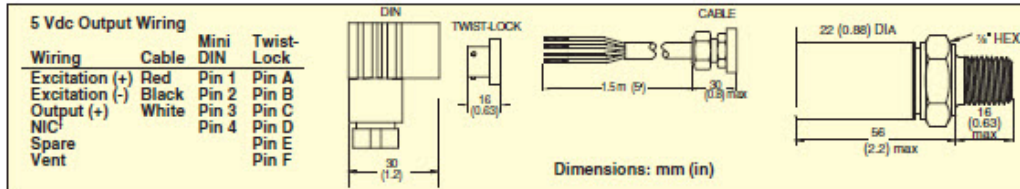
◻ LOW-PRESSURE RANGES HIGHLIGHTED

To Order *(Specify Model Number)*

RANGE bar	psi	1.5 m CABLE CONNECTION	PRICE	MINI DIN CONNECTION	PRICE	TWIST-LOCK CONNECTION	PRICE
ABSOLUTE PRESSURE							
0 to 0.34	0 to 5	PX309-005A5V	$325	PX319-005A5V	$325	PX329-005A5V	$350
0 to 1	0 to 15	PX309-015A5V	245	PX319-015A5V	245	PX329-015A5V	295
0 to 2.1	0 to 30	PX309-030A5V	245	PX319-030A5V	245	PX329-030A5V	295
0 to 3.4	0 to 50	PX309-050A5V	245	PX319-050A5V	245	PX329-050A5V	295
0 to 6.9	0 to 100	PX309-100A5V	245	PX319-100A5V	245	PX329-100A5V	295
0 to 14	0 to 200	PX309-200A5V	245	PX319-200A5V	245	PX329-200A5V	295
0 to 21	0 to 300	PX309-300A5V	245	PX319-300A5V	245	PX329-300A5V	295
GAGE PRESSURE							
0 to 0.07	0 to 1	PX309-001G5V	$345	PX319-001G5V	$345	PX329-001G5V	$370
0 to 0.14	0 to 2	PX309-002G5V	325	PX319-002G5V	325	PX329-002G5V	350
0 to 0.34	0 to 5	PX309-005G5V	300	PX319-005G5V	300	PX329-005G5V	325
0 to 1	0 to 15	PX309-015G5V	225	PX319-015G5V	225	PX329-015G5V	275
0 to 2.1	0 to 30	PX309-030G5V	225	PX319-030G5V	225	PX329-030G5V	275
0 to 3.4	0 to 50	PX309-050G5V	225	PX319-050G5V	225	PX329-050G5V	275
0 to 6.9	0 to 100	PX309-100G5V	225	PX319-100G5V	225	PX329-100G5V	275
0 to 10	0 to 150	PX309-150G5V	225	PX319-150G5V	225	PX329-150G5V	275
0 to 14	0 to 200	PX309-200G5V	225	PX319-200G5V	225	PX329-200G5V	275
0 to 21	0 to 300	PX309-300G5V	225	PX319-300G5V	225	PX329-300G5V	275
0 to 34	0 to 500	PX309-500G5V	225	PX319-500G5V	225	PX329-500G5V	275
0 to 69	0 to 1000	PX309-1KG5V	225	PX319-1KG5V	225	PX329-1KG5V	275
0 to 138	0 to 2000	PX309-2KG5V	225	PX319-2KG5V	225	PX329-2KG5V	275
0 to 207	0 to 3000	PX309-3KG5V	225	PX319-3KG5V	225	PX329-3KG5V	275
0 to 345	0 to 5000	PX309-5KG5V	225	PX319-5KG5T	225	PX329-5KG5V	275
0 to 517	0 to 7500	PX309-7.5KG5V	225	PX319-7.5KG5V	225	PX329-7.5KG5V	275
0 to 690	0 to 10,000	PX309-10KG5V	225	PX319-10KG5V	225	PX329-10KG5V	275

ACCESSORIES

MODEL NO.	PRICE	DESCRIPTION
CAL-3	150.00	Recalibration: 5-point NIST traceable
PT06V-10-6S	26.50	Mating twist-lock connector for PX329
CA-39-4PC22-5	90.00	Mating twist-lock connector with 1.5 m (5') cable for PX329
CX5302	15.00	Extra mating mini DIN connector for PX319

¼ NPT Pressure Snubbers: $12.75
PS-4G = Gas
PS-4E = Lt Oil
PS-4D = Dense Lq
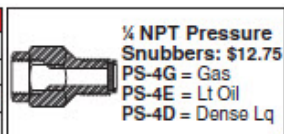
Comes complete with 5-point NIST-traceable calibration.
Ordering Examples: *PX309-100G5V, 100 psi gage pressure transducer with 0 to 5 Vdc output and 1 m cable termination, $225.*
PX319-015A5V, 15 psi absolute pressure transducer with 0 to 5 Vdc output and mini DIN termination, $300. PX329-3KG5V, 3000 psi gage pressure transducer with 0 to 5 Vdc output and twist-lock termination, $275. Mating connector sold separately; order PT06V-10-6S, $26.50.

B-97

OMEGADYNE INC.

PRESSURE TRANSDUCER
FINAL CALIBRATION

0.00 - 50.00 PSIA
Excitation 28.000 Vdc

Job: TN1469   Serial: 121909I079
Model: PX309-050A5V   Tested By: JP
Date: 10/28/2010   Temperature Range: 4 to 185 F.
Calibrated: 0.00 - 50.00 PSIA   Specfile: PX309-5V+=15-50G-=3C

Pressure   Unit Data
PSIA   Vdc
----------   -----------
  0.00   0.014
 25.00   2.512
 50.00   5.015
 25.00   2.512
  0.00   0.014

Balance   0.013   Vdc
Sensitivity   5.001   Vdc

        ELECTRICAL LEAKAGE: PASS
PRESSURE CONNECTION/FITTING: 1/4-18 NPT Male
ELECTRICAL WIRING/CONNECTOR: BLACK = -EXC
                            WHITE = SIG
                            RED   = +EXC

    This Calibration was performed using Instruments and Standards that are
    traceable to the United States National Institute of Standards Technology.
    S/N   Description   Range   Reference   Cal Cert
1742/94-8   AUTO 150 PSI DRUCK   0 - 150 PSIA   C-2509   0906251742
MY44026132   AT34970A DMM   UUT   Unit Under Test   C-1310   908949730

Q.A. Representative : John Piendl   Date: 10/28/2010
This transducer is tested to & meets published specifications. After final
calibration our products are stored in a controlled stock room & considered in
bonded storage. Depending on environment & severity of use factory calibration
is recommended every one to three years after initial service installation date.

Omegadyne, Inc., 149 Stelzer Court, Sunbury, OH 43074   (740) 965-9340
http://www.omegadyne.com   email: info@omegadyne.com   (800) USA-DYNE

CERTIFICATE OF CONFORMANCE 0 TO 5 VDC DOCUMENT A012503

PX 309, 319, 329 0 TO 5VDC PRESSURE SENSOR	MODEL NUMBER INTERPRETATION										PRESSURE RANGE	SUPPLY VOLTAGE	OUTPUT	COMPENSATED TEMPERATURE	THERMAL EFFECTS
	PRODUCT SERIES	ELECTRICAL CONNECTOR			RANGE CODE			GAGE	ABSOLUTE	0 TO 5 VDC OUTPUT					
PART # :	PX	X1	X2	X3	X4	X5	X6	X7 GAGE	X7 ABSOLUTE	X8	PSI	VDC	VDC	°C	±% FS
	CABLE	3	0	9	0	0	1	G	N/A	5V	1	9 TO 30	0 TO 5	0-50	4.5
	DIN	3	1	9	0	0	2	G	N/A	5V	2	9 TO 30	0 TO 5	0-50	3
	BENDIX	3	2	9	0	0	5	G	A	5V	5	9 TO 30	0 TO 5	0-50	1.5
					0	1	5	G	A	5V	15	9 TO 30	0 TO 5	-20 TO 85	1
					0	3	0	G	A	5V	30	9 TO 30	0 TO 5	-20 TO 85	1
					0	5	0	G	A	5V	50	9 TO 30	0 TO 5	-20 TO 85	1
					1	0	0	N/A	A	5V	100	9 TO 30	0 TO 5	-20 TO 85	1
					2	0	0	N/A	A	5V	200	9 TO 30	0 TO 5	-20 TO 85	1
					3	0	0	N/A	A	5V	300	9 TO 30	0 TO 5	-20 TO 85	1
					1	0	0	G	N/A	5V	100	9 TO 30	0 TO 5	-20 TO 85	1
					1	5	0	G	N/A	5V	150	9 TO 30	0 TO 5	-20 TO 85	1
					2	0	0	G	N/A	5V	200	9 TO 30	0 TO 5	-20 TO 85	1
					3	0	0	G	N/A	5V	300	9 TO 30	0 TO 5	-20 TO 85	1
					5	0	0	G	N/A	5V	500	9 TO 30	0 TO 5	-20 TO 85	1
						1	K	G	N/A	5V	1000	9 TO 30	0 TO 5	-20 TO 85	1
						2	K	G	N/A	5V	2000	9 TO 30	0 TO 5	-20 TO 85	1
						3	K	G	N/A	5V	3000	9 TO 30	0 TO 5	-20 TO 85	1
						5	K	G	N/A	5V	5000	9 TO 30	0 TO 5	-20 TO 85	1
					7	5	K	G	N/A	5V	7500	9 TO 30	0 TO 5	-20 TO 85	1
					1	0	K	G	N/A	5V	10000	9 TO 30	0 TO 5	-20 TO 85	1

GENERAL SPECIFICATION

INPUT	VDC SEE TABLE
OUTPUT	0 TO 5 VDC SEE TABLE
OVER PRESSSURE	1 TO 50 PSI GAGE AND 5 TO 300 PSI ABSOLUTE: 3 TIMES RATED OR 20 PSI WHICHEVER IS GREATER
OR	100 TO 10,000 PSIG : 2 TIMES RATED PRESSURE
BURST PRESSSURE	1 TO 50 PSI GAGE AND 5 TO 300 PSI ABSOLUTE: 5 TIMES RATED OR 25 PSI WHICHEVER IS GREATER
OR	100 TO 10,000 PSIG : 2 TIMES RATED PRESSURE
ACCURACY	COMBINED LINEARITY, HYSTERISIS AND REPEATABILITY ±0.25% BSL
SETTING ACCURACY ZERO	±2.0% FS (±4.0% FOR 1 AND 2 PSI)
SETTING ACCURACY SPAN	±2.0% FS (±4.0% FOR 1 AND 2 PSI) CALIBRATION IN VERTICAL DIRECTION WITH FITTING DOWN
LONG TERM STABILITY	±0.25% FS TYPICAL (1 YEAR)
DURABILITY	10 MILLION MINIMUM
MEDIA COMPATABILITY	PRESSURE RANGES LESS THAN OR EQUAL TO 50PSI GAGE 300PSI ABSOLUTE : 316 ST ST
OR	PRESSURE RANGES 100PSI GAGE TO 10,000 PSI GAGE : 17.4 ST ST

0 TO 5 VDC EXTERNAL WIRING CODES

	CABLE PX309	MINI DIN PX319	TWIST LOCK PX329
SUPPLY (+)	RED	PIN 1	PIN A
SUPPLY (-)	BLACK	PIN 2	PIN B
SIGNAL	WHITE	PIN 3	PIN C
NC*		PIN 4	PIN D
SPARE			PIN E
VENT			PIN F
* FACTORY PIN: DO NOT CONNECT TO PIN			FILE0038

MICRO-MACHINED SILICON TRANSDUCERS
WET/DRY DIFFERENTIAL PRESSURE MODELS

NEW

PX409 Series
mV/V, 0 to 5 or 0 to 10 Vdc, or 4 to 20 mA Outputs
Uni-Directional Ranges
0-10 inH₂O to 0-1000 psid

Fast Delivery! Stock to 2 Weeks On Most Models

Starts at
$625

High 0.08% Accuracy

MADE IN USA · NIST · C E · RoHS

Cable style.

Metric thread adaptors and snubbers available, see section C.

✓ 5-Point NIST Traceable Calibration
✓ Precision Micro-Machined Silicon Core
✓ High Stability, Low Drift
✓ Welded Stainless Steel Construction
✓ 316L SS Wetted Parts on Wet Side–
   Clean Dry Gases in Dry Side
✓ Premium Temperature Performance
✓ Broad Compensated Temperature Range
✓ Durable, 1 Million Cycle Life
✓ Ruggedized with Secondary
   Containment
✓ Customized Specifications Available

These rugged stainless steel transducers are ideal for industrial, automotive, or aerospace applications where only one side of the transducer is exposed to wet media. These wet/dry transducers deliver the great performance characteristics of the Micro-Machined Silicon Series Transducers at a lower price than the wet/wet models. They can be used in test benches, filter monitoring, air flow, factory or pneumatic air, pitot tubes, air speed and other industrial or aerospace applications requiring a very rugged wet/dry transducer. The solid state silicon core will provide long, reliable service life with excellent long term stability.

COMMON SPECIFICATIONS

Accuracy: 0.08% BSL linearity, hysteresis and repeatability combined

Minimum Resistance Between Transducer Body and Any Wire: 100 MΩ

Operating Temperature:
   mV/V and 5 to 10 Vdc Output: -45 to 121°C (-49 to 250°F)
   mA Output: -45 to 115°C (-49 to 239°F)

Compensated Temperature Range:
   10 inH₂O to 5 psi: -17 to 85°C (1 to 185°F)
   15 to 1000 psi: -29 to 85°C (-20 to 185°F)

Thermal Accuracy: Zero   Span
% Span Shift over compensated temperature range
   10 inH₂O to 1 psi: ±1.00%   ±1.00%
   2.5 to 1000 psi: ±0.50%   ±0.50%

Pressure Cycles: 1 million minimum

Long Term Stability (1-Year):
±0.1% FS typical

PX409-015DDUV, 15 psid range,
10 mV/V output $625, shown actual size.

Four Electrical Termination Styles

IP67 environmental rating.

IP65 gage, IP67 absolute environmental rating.

PX409, 2 m (6') cable.

PX419, mini DIN.

IP67 environmental rating.

PX409C, conduit cable.

IP65 environmental rating.

PX429, twist-lock.

DIFFERENTIAL PRESSURE TRANSDUCERS

B

MICRO-MACHINED SILICON TRANSDUCERS
WET/DRY DIFFERENTIAL PRESSURE MODELS

NEW

MADE IN USA

Bandwidth: DC to 1 kHz typical

Response Time: <1 ms

CE Complient: Meets EN1326-1: 2006 for industrial locations

Shock: 50 g, 11 ms, half-sine shock (under test)

Vibration: ±20 g (under test)

Media Compatibility:
   High Side: All fluids and gases compatible with 316L SS
   Low Side: Clean, dry, non-ionic gases

Line/Static Pressure: 500 psi max applied to both sides simultaneously

Proof Pressure (Differential):
   10 inH$_2$O range = 10 times range
   1 psi range = 6 times range
   2.5 to 750 psi ranges = 4 times range
   1000 psi range = 3 times range

Hi Side Containment Pressure (Differential):
   Ranges 10 inH$_2$O to 5 psi: to 1000 psi
   Ranges 15 to 1000 psi: to 3000 psi

Pressure Ports: ¼ NPT male

Electrical Terminations:
   PX409: 2 m (6') cable
   PX409C: 2 m (6') cable with ½ NPT conduit thread
   PX419: mini DIN (mating connector included)
   PX429: Twist-lock, (mating connector sold separately)
   PX429 Mating Connector: PT06F10-6S, $26.50

Weight: 200 g (7 oz) max

Conduit backend PX409C
27.9 (1.1)   ½ NPT TH'D

Integral cable backend PX409
5.08 (0.2)

Twist-lock backend PX429
5.08 (0.2)

Mating Connector PT06F10-6S $26.50

mini DIN backend PX419
5.08 (0.2)

Dimensions: mm (in)

Dimensions: mm (in)
ø = diameter

ø22.8 (0.9)

68.5 (2.7)

22.8 (0.875) hex each end

¼ - 18 NPT each end

Serial # and range identify high port

50.8 (2.0)
78.7 (3.1)

30 psid and above

ø22.8 (0.9)

71.1 (2.8)

25.4 (1.0) hex each end

¼ - 18 NPT each end

Serial # and range identify high port

50.8 (2.0)
78.7 (3.1)

15 psid and below

B-233

WET/DRY DIFFERENTIAL PRESSURE MODELS
UNI-DIRECTIONAL RANGES WITH mV/V OUTPUTS

NEW

UNI-DIRECTIONAL mV/V SPECIFICATIONS
Output: 10 mV/V ratiometric
Supply Voltage: 5 to 10 Vdc
Current Draw: 5 mA @ 10 Vdc
Input Impedance: 1000 to 5000 Ω
Output Impedance: 5000 Ω ±10% typical
Zero Balance:
  Ranges ≤ 1psi: ±1% typ (2% max)
  Ranges > 1psi: ±0.5% typ (1% max)
Span Setting:
  Ranges ≤ 1psi: ±1% typ (2% max)
  Ranges > 1psi: ±0.5% typ (1% max)

MADE IN **USA**

Cable style.

Fast Delivery! Stock to 2 Weeks On Most Models

Metric thread adaptors and snubbers available, see section C.

PX409-030DDUV, 30 psid range, 10 mV/V output, $625, shown actual size.

CABLE TERMINATION*

To Order (Specify Model Number)
10 mV/V OUTPUT, ¼ NPT MALE CONNECTORS

RANGE	METRIC	MODEL NO.	PRICE
0 to 10 inH$_2$O	25 mbar	PX409-10WDDUV	$675
0 to 1 psi	70 mbar	PX409-001DDUV	675
0 to 2.5 psi	170 mbar	PX409-2.5DDUV	675
0 to 5 psi	350 mbar	PX409-005DDUV	625
0 to 15 psi	1 bar	PX409-015DDUV	625
0 to 30 psi	2 bar	PX409-030DDUV	625
0 to 50 psi	3.5 bar	PX409-050DDUV	625
0 to 100 psi	7 bar	PX409-100DDUV	625
0 to 150 psi	10 bar	PX409-150DDUV	625
0 to 250 psi	17.5 bar	PX409-250DDUV	625
0 to 500 psi	35 bar	PX409-500DDUV	625
0 to 750 psi	50 bar	PX409-750DDUV	625
0 to 1000 psi	70 bar	PX409-1.0KDDUV	625

* To order conduit fitting backend change model number from "PX409" to "PX409C", no additional charge.

MINI DIN TERMINATION
10 mV/V OUTPUT, ¼ NPT MALE CONNECTORS

RANGE	METRIC	MODEL NO.	PRICE
0 to 10 inH$_2$O	25 mbar	PX419-10WDDUV	$675
0 to 1 psi	70 mbar	PX419-001DDUV	675
0 to 2.5 psi	170 mbar	PX419-2.5DDUV	675
0 to 5 psi	350 mbar	PX419-005DDUV	625
0 to 15 psi	1 bar	PX419-015DDUV	625
0 to 30 psi	2 bar	PX419-030DDUV	625
0 to 50 psi	3.5 bar	PX419-050DDUV	625
0 to 100 psi	7 bar	PX419-100DDUV	625
0 to 150 psi	10 bar	PX419-150DDUV	625
0 to 250 psi	17.5 bar	PX419-250DDUV	625
0 to 500 psi	35 bar	PX419-500DDUV	625
0 to 750 psi	50 bar	PX419-750DDUV	625
0 to 1000 psi	70 bar	PX419-1.0KDDUV	625

TWIST-LOCK TERMINATION**

MOST POPULAR MODELS HIGHLIGHTED!

10 mV/V OUTPUT, ¼ NPT MALE CONNECTORS

RANGE	METRIC	MODEL NO.	PRICE
0 to 10 inH$_2$O	25 mbar	PX429-10WDDUV	$675
0 to 1 psi	70 mbar	PX429-001DDUV	675
0 to 2.5 psi	170 mbar	PX429-2.5DDUV	675
0 to 5 psi	350 mbar	PX429-005DDUV	625
0 to 15 psi	1 bar	PX429-015DDUV	625
0 to 30 psi	2 bar	PX429-030DDUV	625
0 to 50 psi	3.5 bar	PX429-050DDUV	625
0 to 100 psi	7 bar	PX429-100DDUV	625
0 to 150 psi	10 bar	PX429-150DDUV	625
0 to 250 psi	17.5 bar	PX429-250DDUV	625
0 to 500 psi	35 bar	PX429-500DDUV	625
0 to 750 psi	50 bar	PX429-750DDUV	625
0 to 1000 psi	70 bar	PX429-1.0KDDUV	625

**Mating connector sold separately, order PT06F10-6S, $26.50 each. Comes complete with 5-point NIST traceable calibration certificate.

Ordering Examples: PX409C-100DDUV, 0 to 100 psi uni-directional wet/dry differential pressure range, 10 mV/V output, 0.08% accuracy, ¼ NPT fitting, 2 m (6) cable with ½ NPT conduit fitting, **$625.**
PX419-015DDUV, 0 to 15 psi uni-directional wet/dry differential pressure range, 10 mV/V output, 0.08% accuracy, ¼ NPT fitting, mini DIN connector, **$625.**
PX429-10WDDUV, 0 to 10 inH$_2$O uni-directional Wet/Dry differential pressure range, 10 mV/V output, 0.08% accuracy, ¼ NPT termination, twist-lock connector plus **PT06F10-6S,** mating connector, $675 + 26.50 = **$701.50.**

CONNECTIONS—mV/V OUTPUT

PX429 TWIST-LOCK		PX419 MINI DIN		PX409 CABLE	
Pin A	+EXC	Pin 1	+EXC	Red	+EXC
Pin B	-EXC	Pin 2	-EXC	Black	-EXC
Pin C	+SIG	Pin 3	+SIG	White	+SIG
Pin D	-SIG	Pin 4	-SIG	Green	-SIG
Pin E	No Connection				
Pin F	No Connection				

OMEGADYNE INC.
CERTIFICATE OF CALIBRATION

Model Number: PX409-10WDDUV

Serial Number: 417549
Date: 1/21/2010
Job: R1082

Capacity: 10.00 in H2O
Excitation: 10.00 Vdc
Technician: CHARLES

Pressure Connection: 1/4-18 NPT Male

WIRING CODE

Electrical Connection: BLACK = - EXCITATION
                                  WHITE = + SIGNAL
                                  GREEN = - SIGNAL
                                  RED = + EXCITATION

CALIBRATION WORKSHEET

Pressure in H2O	OUTPUT mVdc
0.00	0.077
5.00	50.115
10.00	100.234
5.00	50.164
0.00	0.067

NIST Traceable Number(s): C-1954, C-2466

Omegadyne Inc. certifies that the above instrumentation has been calibrated and tested to meet or to exceed the published specifications. This calibration was performed using instrumentation and standards that are traceable to the National Institute of Standards and Technology. This document also ensures that all testing performed complies with MIL-STD 45662-A, ISO 10012-1, and ANSI/NCSL Z540-1-1994 requirements. After Final Calibration our products are stored in an environmentally controlled stock room and are considered in bonded storage. Depending on environmental conditions and severity of use, factory calibration is recommended every one to three years after the initial service installation date.

Bruce Lott

Accepted and Certified By

1/21/2010
Date

PX 409, 419, 429   mV/V DIFFERENTIAL PRESSURE SENSOR
CERTIFICATE OF CONFORMANCE   DOCUMENT A012650

MODEL NUMBER INTERPRETATION

PX	PRODUCT SERIES	ELECTRICAL CONNECTOR		RANGE CODE			WET WET DIFF UN	WET DRY DIFF UN	MW OUTPUT	PRESSURE RANGE (PSI)	SUPPLY VOLTAGE (VDC)	OUTPUT MV	COMPENSATED TEMPERATURE (C)	ZERO SHIFT +/-%SPAN	SPAN SHIFT +/-%SPAN	OVER PRESSURE (TIMES)	CONTAINMENT · SIDE PSI
	X1	X2	X3	X4	X5	X6	X7		X8								
CABLE	4	0	9	1	0	W	DWU	DDU	V	10"H2O	10	100	-17 TO 85	1.00	1.00	10	1000
DIN	4	1	9	0	0	1	DWU	DDU	V	1	10	100	-17 TO 85	1.00	1.00	6	1000
BENDIX	4	2	9	0	0	2	DWU	DDU	V	2.5	10	100	-17 TO 85	0.50	0.50	4	1000
CONDUIT	4	0	9C	0	0	5	DWU	DDU	V	5	10	100	-17 TO 85	0.50	0.50	4	1000
				0	1	5	DWU	DDU	V	15	10	100	-29 TO 85	0.50	0.50	4	3000
				0	3	0	DWU	DDU	V	30	10	100	-29 TO 85	0.50	0.50	4	3000
				0	5	0	DWU	DDU	V	50	10	100	-29 TO 85	0.50	0.50	4	3000
				1	0	0	DWU	DDU	V	100	10	100	-29 TO 85	0.50	0.50	4	3000
				1	5	0	DWU	DDU	V	150	10	100	-29 TO 85	0.50	0.50	4	3000
				2	5	0	DWU	DDU	V	250	10	100	-29 TO 85	0.50	0.50	4	6000
				5	0	0	DWU	DDU	V	500	10	100	-29 TO 85	0.50	0.50	4	6000
				7	5	0	DWU	DDU	V	750	10	100	-29 TO 85	0.50	0.50	4	6000
				1	0	K	DWU	DDU	V	1000	10	100	-29 TO 85	0.50	0.50	4	6000

GENERAL SPECIFICATION

|		
INPUT		DC ONLY 5 TO 10 V OPERATING
OUTPUT		MV/V SEE TABLE
OVER PRESSSURE		SEE TABLE
CONTAINMENT		SEE TABLE
ACCURACY		COMBINED NON-LINEARITY, HYSTERISIS AND NON- REPEATABILITY ±0.08% BSL
SETTING ACCURACY ZERO		± 5% FS TYP 1% MAX (± 5% TYP ±2% MAX FOR 2.5 PSI AND BELOW)
SETTING ACCURACY SPAN		± 5% FS TYP 1% MAX (± 5% TYP ±2% MAX FOR 2.5 PSI AND BELOW)
		CALIBRATION IN HORIZONTAL DIRECTION WITH ELECTRICAL CONNECTOR UP.
LONG TERM STABILITY		±0.1% FS TYPICAL (1 YEAR)
DURABILITY		10 MILLION MINIMUM
MEDIA COMPATABILITY	DWU	ALL WETTED MATERIALS 316 (L) STAINLESS STEEL POSITIVE AND NEGATIVE PORTS
	DDU	POS : 316 (L) ST ST POSITIVE. NEG 316L ST ST , GLASS, STRUCTURAL ADHESIVE, SILICON.
LINE PRESSURE		500PSI
EMC COMPATABILITY (CE)		EC DIRECTIVE 2004/108/EC (CONSOLIDATED 89/336): STANDARD IEC 61326 2006 FOR INDUSTRIAL LOCATIONS
ROHS		YES

mV/V EXTERNAL WIRING CODES

	CABLE PX409 AND PX409C	MINI DIN PX419	TWIST LOCK PX429
EXCITATION (+)	RED	PIN 1	PIN A
OUTPUT (+)	WHITE	PIN 3	PIN C
OUTPUT (-)	GREEN	PIN 4	PIN D
EXCITATION (-)	BLACK	PIN 2	PIN B
SPARE			PIN E
SPARE			PIN F

We certify that this sensor is in full conformance with all written specifications as contained in this data sheet.

FILE0070

A

Nextel®-Covered Flexible Thermocouple Elements
High Temperature!

XC Series Starts at
$20
300 mm

MADE IN USA

Length
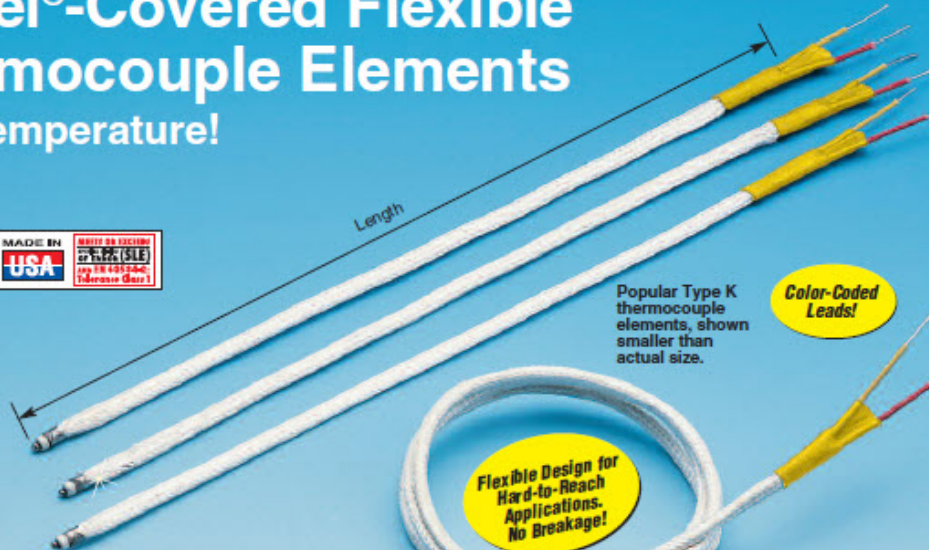
Popular Type K thermocouple elements, shown smaller than actual size.

Color-Coded Leads!

Flexible Design for Hard-to-Reach Applications. No Breakage!

✔ **Standard 300 mm (12") Long Thermocouple Elements**
✔ **Available in Type K, E, and J Calibrations**
✔ **Insulation Temperature Rating Up to 1200°C (2200°F)**

OMEGA® Nextel ceramic-insulated thermocouples are easy-to-use precise temperature elements manufactured to meet the highest industry standards. The Nextel ceramic insulation is rated for 1200°C (2200°F) continuous use, or 1425°C (2600°F) short term. These highly versatile elements are ideal for many high-temperature applications. If requested, OMEGA® can combine these elements with thermowells and industrial heads to produce a complete head and well assembly, available for fast delivery.

Available in 3 wire sizes, 14, 20, and 24 gage, the standard element configuration is 300 mm (12") long, with a general purpose welded bead, an exposed-junction thermocouple, plus a 13 mm (0.5")

Actual size.

stripped end termination. Calibration Types K (CHROMEGA®-ALOMEGA®), E (CHROMEGA®-constantan), J (iron-constantan), and N (OMEGALLOY®-NICROSIL-NISIL) are available. For additional abrasion protection, order stainless steel or Inconel® overbraiding. Consult Sales for more information.

Discount Schedule
1 to 10 . . . . .Net
11 to 24 . . . . .5%
25 to 49 . . . . .10%
50 and up 15%

PTRS-1628-600 ceramic protection tube, $700, shown larger than actual size, see page A-141.
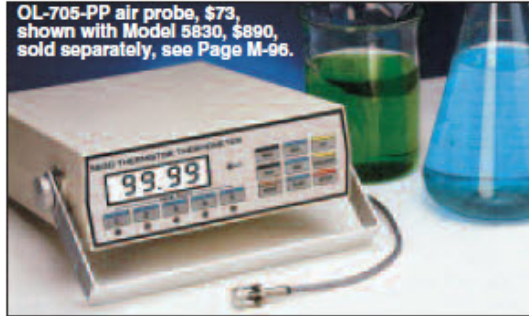
Complete Your Thermocouple Assembly!
A complete selection of OMEGA® ceramic protection tubes is available, see page A-139.
Compatible wells also available in section B.

☐ **MOST POPULAR MODELS HIGHLIGHTED!**

To Order *(Specify Model Number)*
300 mm (12") Long with Insulation, Plus 13 mm (0.5") Stripped Ends Standard *(Other Lengths Available)*

AWG Wire Size	Type K Temp Range -185 to 1250°C (-300 to 2300°F)	Price 300 mm (12") Length	Price Add'l 150 mm (6") or Fraction	Type E Temp Range -185 to 850°C (-300 to 1600°F)	Price 300 mm (12") Length	Price Add'l 150 mm (6") or Fraction	Type J Temp Range -185 to 750°C (-300 to 1400°F)	Price 300 mm (12") Length	Price Add'l 150 mm (6") or Fraction
14	XC-14-K-12	$21	$3	XC-14-E-12	$21	$3	XC-14-J-12	$21	$3
20	XC-20-K-12	20	2	XC-20-E-12	20	2	XC-20-J-12	20	2
24	XC-24-K-12	20	2	XC-24-E-12	20	2	XC-24-J-12	20	2

To order longer elements, change "-12" to indicate actual length required. Temperature limitation is by type of thermocouple material selected.
Note: Available with silica insulation. Change the "XC" to "XS", no additional cost.
Ordering Example: XC-20-J-12 is a 20 AWG thermocouple, Type J, 12" long with Nextel ceramic fiber insulation, $20.

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Linear Thermistor Components and Probes

OL-705-PP air probe, $73, shown with Model 5830, $890, sold separately, see Page M-96.

Linear Response Components

For applications requiring thermistors with linear response to temperature change, OMEGA offers linear components. These unique devices consist of a thermistor composite for temperature sensing and an external resistor composite for linearizing.

Thermistor composites 44018 and 44019 each contain two thermistors packaged in a single sensor (Figures 1A and 1B). Thermistor composite 44020 contains three thermistors packaged in a single sensor (Figure 1C).

Resistor composites for use with 44018 and 44019 thermistor composites consist of two metal film resistors of the size shown in Figure 2. Resistor composites for use with the 44020 thermistor composite consist of three of the same type metal film resistors.

Linear components are manufactured with different values for different temperatures ranges. When they are connected in networks shown in Figures 3 (A and B) and 4 (A and B), they produce a varying voltage or resistance which is linear with temperature.

One of the basic network manifestations is a voltage divider as in Figure 3A for components other than #44212, and as shown in Figure 3B for component #44212. The area within the dashed lines represents the thermistor composite. The network hookup for linear resistance versus temperature is shown in Figure 4A for linear components except #44212, and in Figure 4B for #44212.
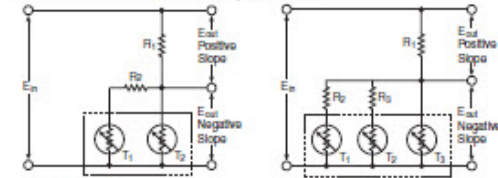
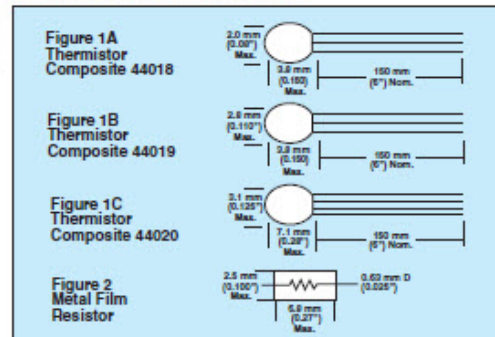Following is a description of why these networks produce linear information. The equation for a voltage divider network, consisting of R and R_0 in series, is:

$$E_{out} = E_{in} \frac{R}{R + R_0}$$

where E_{out} is the voltage drop across R. If R is a thermistor, and E_{out} is plotted versus temperature, the total curve will be essentially non-linear and of a general "S" shape, with linear or nearly linear portions near the ends and in the center.

Figure 1A Thermistor Composite 44018

Figure 1B Thermistor Composite 44019

Figure 1C Thermistor Composite 44020

Figure 2 Metal Film Resistor

If R is modified by the addition of other thermistors and resistors, linearity of the center section of the curve, where sensitivity is greatest, can be extended to cover a wide range of temperatures. This section follows the general equation for a straight line, y = mx + b or in terms of a linear component:

For Voltage Mode
$$E_{out} = \pm MT + b$$
where M is slope in volts/°T, T is temperature in °C or °F, and b is the value of E_{out} when T = 0°

For Resistance Mode
$$R_t = MT + b$$
where M is slope in ohms/°T, T is temperature in °C or °F, and b is the value of the total network resistance, R_t, in ohms when T = 0°
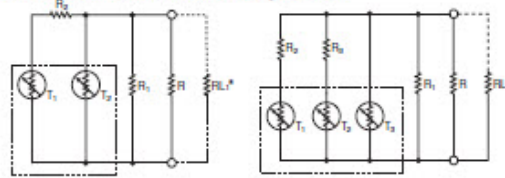
Linear Voltage vs. Temperature

Figure 3A

Figure 3B

Note: *Model 5830 precision benchtop thermometer includes linearized circuitry, refer to section M.*

Linear Resistance vs. Temperature

Figure 4A

*RL$_1$ may be any value as long as a new R$_1$ value (R$_{1A}$) is selected to satisfy the relationship:

Figure 4B

$$R_{1A} = \frac{R_1 \times RL_1}{RL_1 - R_1}$$

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Sensitivity is 400 times greater than an IC thermocouple. Thermistor values as high as 30 mV/°C are common. In addition, output voltage can be applied to a recorder or digital voltmeter to produce a precise, sensitive, direct reading thermometer.

Multiplexing
The 44018 thermistor composite is used in four of the linear components. The part that changes in each component is the resistor composite, which determines the temperature range. Therefore, the 44018 thermistor composite can be used over the entire -30 to 100°C temperature range by simply changing resistor composites. Its accuracy and interchangeability over the full range is ±0.15°C. It is not mandatory that OMEGA® resistor composites be used with the 44018 thermistor composite. Any 0.1% resistors of the proper values and with a temperature

coefficient of 30 PPM or less may be substituted. In other situations, it is frequently desirable to have thermistor composite temperature sensors at more than one location. When this is required, it is not necessary to have a separate resistor composite for each

thermistor composite. It is possible to multiplex any number of thermistor composites through a single resistor composite for greater design flexibility

To Order (Specify Model Number)

Linear Kit[†] Model No.	Price	Thermistor Composite Model No.	Price	Resistor Composite Model No.	Price
44201	$37	44018	$28	44301	$12
44202	37	44018	28	44302	12
44203	37	44018	28	44303	12
44204	37	44018	28	44304	12
44211A	57	44019	42	44311A	12
44212	90	44020	64	44312	19

See the next page for more information.
Ordering Examples: **44203**, linear kit, **44018**, dual thermistor composite plus **44303**, resistor composite sensor, $37 + 28 + 12 = **$77**.
44202, linear kit, **44018**, dual thermistor composite plus **44302**, resistor composite sensor, $37 + 28 + 12 = **$77**.

Component Specifications

	°C	°F	°C	°F
† Linear Components Kit Model No.	44201		44202	
Range	0 to 100°C	32 to 212°F	-5 to 45°C	23 to 113°F
Thermistor Composite Model No.	44018		44018	
Resistor Composite Model No.	44301		44302	
Resistor Composite Values	$R_1 = 3200\ \Omega$, $R_2 = 6250\ \Omega$		$R_1 = 5700\ \Omega$, $R_2 = 12000\ \Omega$	
Thermistor Accuracy & Interchangeability	±0.15°C -30 to 100°C	±0.27°F -22 to 212°F	±0.15°C -30 to 100°C	±0.27°F -22 to 212°F
E_0 Positive Slope	$E_{out} =$ $(+0.0053483\ E_{in})\ T$ $+0.13493\ E_{in}$	$E_{out} =$ $(+0.00297127\ E_{in})\ T$ $+0.03985\ E_{in}$	$E_{out} =$ $(+0.0056846\ E_{in})\ T$ $+0.194142\ E_{in}$	$E_{out} =$ $(+0.00315851\ E_{in})\ T$ $+0.093083\ E_{in}$
E_0 Negative Slope	$E_{out} =$ $(-0.0053483\ E_{in})\ T$ $+0.86507\ E_{in}$	$E_{out} =$ $(-0.00297127\ E_{in})\ T$ $+0.96015\ E_{in}$	$E_{out} =$ $(-0.0056846\ E_{in})\ T$ $+0.805858\ E_{in}$	$E_{out} =$ $(-0.00315851\ E_{in})\ T$ $+0.906917\ E_{in}$
Resistance Mode	$R_t =$ $(-17.115)\ T +2768.23$	$R_t =$ $(-9.508)\ T +3072.48$	$R_t =$ $(-32.402)\ T +4593.39$	$R_t =$ $(-18,001)\ T +5169.42$
*Ein MAX	2.0 Volts		3.5 Volts	
*I$_T$ MAX	625 µA		615 µA	
***Load Resistance Minimum R.L.	3 MΩ		10 MΩ	
Linearity Deviation	±0.216°C	±0.388°F	±0.065°C	±0.12°F

* **Ein Max** and ***I$_T$ Max** values have been assigned to control thermistor self-heating errors so they do not enlarge the component error band; i.e., the sum of the linearity deviation plus the probe tolerances. The values were assigned using a thermistor dissipation constant of 8MW/°C in stirred oil. If better heat-sink methods are used or if an enlargement of the error band is acceptable, Ein Max. and I$_T$ Max values may be exceeded without damage to the thermistor probe.
*** See Figure 1, example 1 on typical linear component application page D-45.
†† Kit includes thermistor composite and resistors.

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	°C	°F	°C	°F
Linear Components Kit Model Number[†]	44203		44204	
Range	-30 to 50°C	-22 to 122°F	-2 to 38°C	+30 to 100°F
Thermistor Composite Model Number	44018		44018	
Resistor Composite Model Number	44303		44304	
Resistor Composite Values	$R_1 = 18,700\ \Omega$ $R_2 = 35,250\ \Omega$		$R_1 = 5700\ \Omega$ $R_2 = 12,400\ \Omega$	
Thermistor Accuracy & Interchangeability	±0.15°C -30 to 100°C	±0.27°F -22 to +212°F	±0.15°C -2 to +38°C	±0.27°F -22 to +212°F
E_0 Positive Slope	$E_{out} =$ $(+0.0067966\ E_{in})\ T$ $+0.34893\ E_{in}$	$Eo_{out} =$ $(+0.00377588\ E_{in})\ T$ $+0.228102\ E_{in}$	$E_{out} =$ $(+0.00563179\ E_{in})\ T$ $+0.192439\ E_{in}$	$E_{out} =$ $(+0.0031289\ E_{in})\ T$ $+0.09232\ E_{in}$
E_0 Negative Slope	$E_{out} =$ $(-0.0067966\ E_{in})\ T$ $+0.65107\ E_{in}$	$E_{out} =$ $(-0.00377588\ E_{in})\ T$ $+0.771898\ E_{in}$	$E_{out} =$ $(-0.00563179\ E_{in})\ T$ $+0.807563\ E_{in}$	$E_{out} =$ $(-0.0031289\ E_{in})\ T$ $+0.90768\ E_{in}$
Resistance Mode	$R_t = (-127.096)\ T$ $+12175$	$R_t = (-70.608)\ T$ $+14435$	$R_t = (-32.1012)\ T$ $+4603.1$	$R_t = (-17,834)\ T$ $+5173.8$
Ein MAX*	3.0 Volts		4 Volts	
I$_T$ MAX***	475 µA		685 µA	
Load Resistance Minimum R.L.***	10 MΩ		10 MΩ	
Linearity Deviation	±0.16°C	±0.29°F	±0.03°C	±0.055°F
Linear Components Kit Model Number[†]	44211A		44212	
Range	-55 to 85°C	-67 to 185°F	-50 to 50°C	-58 to 122°F
Thermistor Composite Model Number	44019		44020	
Resistor Composite Model Number	44311A		44312	
Resistor Composite Values	$R_1 = 3550\ \Omega,$ $R_2 = 6025\ \Omega$		$R_1 = 23,100\ \Omega$ $R_2 = 88,200\ \Omega$ $R_3 = 38,000\ \Omega$	
Thermistor Accuracy & Interchangeability	±0.4°C, 0 to 85°C ±0.8°C, -55 to 0°C	±0.72, 32 to 185°F ±1.44, -67 to 32°F	±0.1°C -50 to 50°C	±0.18°F - 58 to 122°F
E_0 Positive Slope	$E_{out} =$ $(+0.005068\ E_{in})\ T$ $+0.3411\ E_{in}$	$E_{out} =$ $(+0.002816\ E_{in})\ T$ $+0.2510\ E_{in}$	$E_{out} =$ $(+0.00559149\ E_{in})\ T$ $+0.40700\ E_{in}$	$E_{out} =$ $(+0.00310638\ E_{in})\ T$ $+0.30760\ E_{in}$
E_0 Negative Slope	$E_{out} =$ $(-0.005068\ E_{in})\ T$ $+0.6589\ E_{in}$	$E_{out} =$ $(-0.002816\ E_{in})\ T$ $+0.7490\ E_{in}$	$E_{out} =$ $(-0.00559149\ E_{in})\ T$ $+0.59300\ E_{in}$	$E_{out} =$ $(-0.00310638\ E_{in})\ T$ $+0.69240\ E_{in}$
Resistance Mode	$R_t = (-17.99)\ T$ $+2339$	$R_t = (-9.994)\ T$ $+2658.8$	$R_t = (-129.163)\ T$ $+13698.23$	$R_t = (-71.757)\ T$ $+15994.5$
Ein MAX.*	2.0 Volts		3.5 Volts	
I$_T$ MAX.***	833 µA		700 µA	
Load Resistance Minimum R.L.***	10 MΩ		10 MΩ	
Linearity Deviation	±1.1°C	±2°F	±0.15°C (condition A)** ±0.08°C (condition B)**	±0.27°F (A) ±0.15°F (B)

** The maximum error at any point is the algebraic sum of the thermistor manufacturing tolerances, plus linearity deviation, a fixed network behavior. Condition "A" is the worst case linearity deviation of ±0.15°C and may occur with the ±0.1% resistors supplied. Condition "B" exists when the three resistors are whin ±0.02% of nominal, which reduces linearity deviation to ±0.08°C.

Note: The time required for a thermistor composite to indicate 63% of a newly impressed temperature is one second in "well stirred" oil and ten seconds in free , still air.

†† Kit includes thermistor composite and resistors.

D

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Typical Linear Component Applications

Example 1:

To measure and record on a 100 mV recorder temperature in the range 30 to 40°C.

1. Select Part number 44202 (temperature range -5°to +45°C)
   basic equation $E_{out1} = (-0.0056846\ E_{In})\ T + 0.805858\ E_{In}$
2. Calculate E_{In} for 10°C equal to 100 mV

Figure 1

$$(E_{out},\ @30°C - E_{out1}\ @\ 40°C) = 100\ mV$$
$$[(-0.0056846\ E_{In})\ 30°C + 0.805858\ E_{In}] - [(-0.0056846\ E_{In})\ 40°C + 0.805858\ E_{In}] = 100\ mV$$
$$0.056846\ E_{In} = 100\ mV$$
$$E_{In} = 1.7591\ Volts$$

3. Using the Linear network as two legs of a Wheatstone bridge add the two additional legs, R_3 and R_4 so that $E_{out2} = 0$ when T = 30°C. (See Figure 1.) R_3 and R_4 are calculated from five known conditions.
   (1) The voltage drop across R_4 (E_{R4}) should equal E_{out1} at 30°C for E_{out2} to equal zero.
   (2) $E_{In} = 1.7591$ Volts
   (3) 1000 ohms $\le R_3 + R_4 \le 5000$ ohms. (If $R_3 + R_4$ is less than 1 K, excessive battery drain may occur. If $R_3 + R_4$ is more than 5 K, some degradation of linearity will occur.)
   (4) $E_{R4} = \dfrac{E_{In}\ R_4}{R_3 + R_4}$

   (5) $E_{out1} = -0.0056846\ (1.7591\ Volts)\ (+30°C) + 0.805858\ (1.7591\ Volts) = 1.1180$ Volts

   $E_{R4} = E_{out1} = E_{R4} = \dfrac{E_{In}\ R_4}{R_3 + R_3}$ or $1.1180 = \dfrac{R_4\ 1.7591}{R_3 + R_4}$ and let us choose $R_3 + R_4 = 1000$ ohms.

   Solve for R_3 and R_4 $1.1180 = \dfrac{R_4\ 1.7591}{R_4 + 100 - R_4}$ $R_4 = 635.55$ ohms $R_3 = 364.45$ ohms

4. Apply E_{out2} to the recorder input terminals and the result is a direct reading 10°C full scale thermometer.

Example 2:

To make a 4 digit 100 mV sensitivity digital voltmeter into a direct reading differential thermometer whose ambient range is -30 to 40°C;

1. Select Part number 44203 (temperature range -30 to 50°C)
   basic equation Eout = (-0.0067966 Ein) T +0.65107 Ein
2. Calculate Ein so that 10 mV equals one degree C. (This is done so that the Digital Volt Meter will read directly in temperature with 0.01°C readability)

Figure 2

$$(E_{out},\ @ -30°C - E_{out},\ @ +40°C) = 0.700\ Volts$$
$$[(-0.0067966\ E_{In})(-30) + 0.65107\ E_{In}] - [(-0.0067966\ E_{In})\ (40) + 0.65107\ E_{In}] = 0.700$$
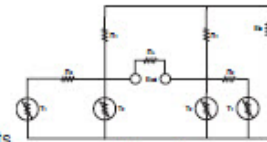$$0.47576\ E_{In} = 0.700$$
$$E_{In} = 1.4713\ Volts$$

3. Connect two linear networks (#44203) as shown in Fig. 2.
4. Apply E_{out} to the Digital Volt Meter input terminals for a direct reading differential thermometer.

Example 3:

To make a 2-wire system from a 3-wire system using any Linear component:
1. For voltage mode, connect R_2 to the thermistor composite. (See Figure 3.) This unit can function as the temperature sensor and be located remote from the signal conditioning circuit by up to distance "D".
2. The resistance mode differs from the voltage mode only by removal of the power source. (See Figure 4.)
3. Acceptable distance "D" varies according to the temperature range. Using #22 wire "D" may be as follows without loss of accuracy in both 2-wire and 3-wire systems. Where distance "D" is greater than indicated, heavier gauge wire may be used.

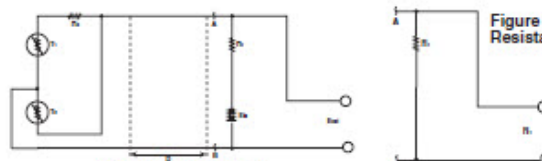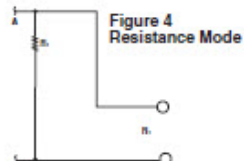| Temperature Range	Distance "D"
0 to 100°C	30 m (100')
-5 to 45°C	91 m (300')
-30 to 50°C	91 m (300')
30 to 100°C	91 m (300')

Figure 3 Voltage Mode

Figure 4 Resistance Mode

Example 4:

Multiplexing to connect any number of thermistor composites to a single signal conditioning circuit. (See Figure 5.) Multiplexing can be accomplished much more easily with a two-wire system, such as shown in Figure 5.

Figure 5

Lead Colors:
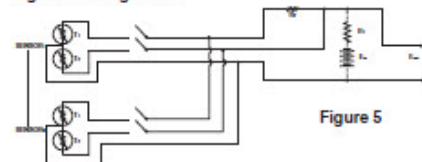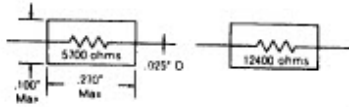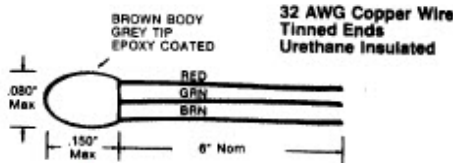**Green:** Common to T1 & T2
**Brown:** T1   **Red:** T2

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OMEGA RESISTOR COMPOSITE 44304

OMEGA THERMISTOR COMPOSITE 44018

BROWN BODY
GREY TIP
EPOXY COATED

32 AWG Copper Wire
Tinned Ends
Urethane Insulated

RED
GRN
BRN

.080" Max
.150" Max
6" Nom

#44204 30° to 100°F $R_T = (-17.834) T + 5173.7$	R_T Ohms
30	4638.71
35	4550.41
40	4461.23
45	4371.60
50	4281.83
55	4192.17
60	4102.74
65	4013.6
70	3924.72
75	3836.02
80	3747.35
85	3658.55
90	3569.48
95	3479.99
100	3389.70

The values tabulated above are compiled using nominal thermistor values and may differ from values calculated by the stated equation. The differences constitute the Linearity Deviation Curve.
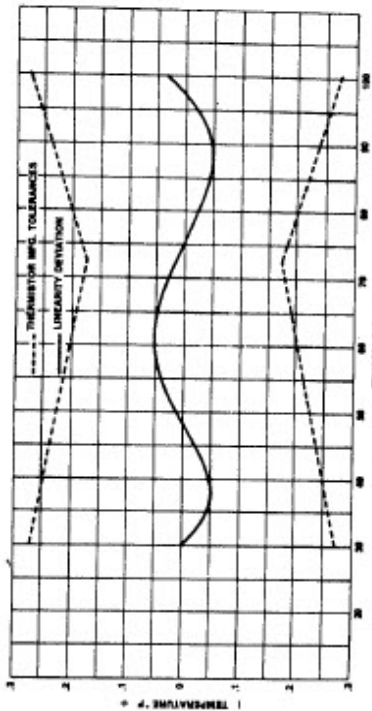
The maximum error at any point is the algebraic sum of the thermistor manufacturing tolerances plus the linearity deviation, a fixed network balance. Since the linearity deviation is a known quantity, it may be eliminated from the error statement by consulting the linearity deviation curve at the temperature in question, and making the appropriate adjustment.

Manufactured under U.S. Patent #'s 2970411 and 3316765 and various foreign patents.

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08M31402
OMEGA® LINEAR RESPONSE THERMISTOR
COMPONENT KIT

ΩEOMEGA® 44204

44204 PARTS INCLUDED:

Thermistor composite 44018
Resistor (R_1)   5.7 KΩ
Resistor (R_2)   12.4 KΩ

RANGE 30° to 100°F

This Linear Response Thermistor Network is a composite device consisting of resistors and precise thermistors which produce an output voltage linear with temperature, see Fig. 1, or a linear resistance with temperature, see Fig. 2. The precise thermistors can either be the OMEGA #44018 (as included in the #44204) or they can be an OMEGA 700 Series Probe since they are electrically identical.

Equations which describe the behavior of the device are: (Refer to Fig. 1)

$Eout_1 = (-0.0031289 \text{ Ein}) T + 0.90768 \text{ Ein}$
$Eout_2 = (+0.0031289 \text{ Ein}) T + 0.09232 \text{ Ein}$
(Refer to Fig. 2)
$R_T = (-17.834) T + 5173.7$
$T = °F$

	Voltage Mode	Resistance Mode
Thermistor Absolute Accuracy and Interchangeability:	±0.27°F	±0.27°F
Linearity Deviation:	±0.055°F	±0.98 ohms
***Ein Max**	4 Volts	
***I_T Max**		685 µA
Sensitivity:	0.0031289 Ein/°F	17.834 ohms/°F
Load Resistance:	10 Megohm min.	
Time Constant:	The time required for the thermistor to indicate 63% of a new impressed temperature, in "well stirred" oil, 1 sec.; in free still air, 10 sec.	
Storage Temperature:	−112° to +250°F (−80 to +120°C)	

Fig. 1   Fig. 2
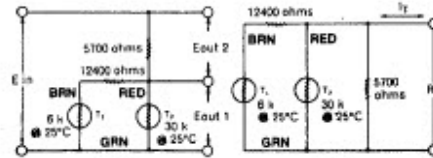
***Ein Max. I_T Definition:**

Ein Max. I_T Max values have been assigned to control the thermistor self-heating errors so that they do not enlarge the component error band; i.e., the sum of the linearity deviation plus the probe tolerances.

Ein Max, I_T Max values are assigned using a thermistor dissipation constant of 8MW/°C in stirred oil. If better heat-sink methods are used or if an enlargement of the error band is acceptable, Ein Max, I_T Max values may be exceeded without damage to the thermistor probe.

WARNING

Use heat sinks when soldering or welding to thermistor leads.

M112/0390