Design and Validation of a Low Cost, Partial Flow Dilution Tunnel with Tapered Element Oscillating Microbalance

A Thesis

Presented in Partial Fulfillment of the Requirements for the

Degree of Master of Science

with a

Major in Mechanical Engineering

in the

College of Graduate Studies

University of Idaho

by

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May 2010

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Abstract

Accurate, repeatable measurement of tailpipe emissions is an important factor in the development of internal combustion engines and testing of alternative fuels. A dilution tunnel simulates the action of exhaust mixing with atmospheric gases and prevents condensation prior to gas and particulate measurements. In this work, a micro dilution tunnel was designed for the Small Engine Research Facility (SMERF) and experiments were conducted to establish the controllability and accuracy of the tunnel. The tunnel design implements partial flow, Constant Volume Sampling (CVS) using an ejector dilutor. In addition to a new 5 gas Horiba MEXA 584L analyzer, a Tapered Element Oscillating Microbalance (TEOM) has been deployed for real-time measurement of particulate emissions. Data from these instruments and the flow conditioning equipment are collected and logged by a National Instruments data acquisition system. For best results, the system should be operated at 700° F suction temperature and 35 psia motive pressure to maintain a dilution ratio of 11:1 with uncertainty of 3% at the 80% confidence level. A procedure has been developed for obtaining and verifying dilution ratios between 11:1 and 15:1 with a 1.9L Volkswagen TDI diesel. This new instrumentation will also be helpful in testing two-stroke snowmobile engines that typically produce elevated levels of hydrocarbons and particulates beyond the saturation range of many electro-chemical emissions analyzers.

Acknowledgements

First and foremost, I would like to thank my major professor Dr. Steven Beyerlein for his support and guidance throughout my time at the University of Idaho. Likewise, Dr. Judi Steciak has been an indispensable resource both in and out of the classroom during my research. Invaluable in day-to-day problem solving and brainstorming; I could not have completed this work without the assistance of Dr. Dan Cordon. Lastly, I would like to thank the National Institute for Advanced Transportation Technology (NIATT) and the Idaho Higher Education Research Council (HERC) for their generous financial support of this project.

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Chapter 1: Introduction

Emissions from internal combustion engines are a significant concern both as potential health hazards, and as contributors to environmental issues, such as photochemical smog and climate change. Of particular interest are nitrogen oxides, carbon dioxide, carbon monoxide, hydrocarbons, and particulate matter. These pollutants can be detected by numerous methods, using either raw exhaust treated to remove water or diluting the exhaust with air to lower the dew point of the mixture.

Dilution tunnels have been shown by Kittleson, et al., to mimic mixing of exhaust pollutants that occurs as the exhaust exits the tailpipe of a vehicle [1]. Additionally, the dilution process "freezes" the exhaust – preventing chemical decomposition of exhaust constituents. Most commercial solutions dilute the full exhaust flow, at a minimum of 4:1 dilution ratio. Full flow systems, however, can be very large and prohibitively expensive. Micro dilution tunnels only sample a small portion of the exhaust, which although less accurate, is significantly cheaper and smaller.

Development of a micro dilution tunnel at the University of Idaho was undertaken to expand research capabilities in engine research and emission analysis. Due to the large variety of internal combustion (IC) engine testing taking place at the University of Idaho, a dilution tunnel was chosen as the best instrument to be used in testing. Using a dilution tunnel, one can test anything from a diesel engine that generates high levels of particulate matter and NO_x, to a two-stroke engine that may release elevated levels of hydrocarbons that would saturate an ordinary gas analyzer. Additionally, the dilution tunnel does an excellent job of freezing the exhaust

composition, preventing possible line contamination or continuing reactions in the hot exhaust gas. Design of the dilution tunnel was centered on meeting these research needs and goals.

In Chapter 2, preliminary research into emission formation is introduced to better understand both the behavior of engine emissions, and the best practices of detecting emissions in a laboratory setting, including which sensors would work best for the application. This particularly applied to the case of engine soot or particulate matter detection, since this is an area in which technology is still developing. Additionally, the field of dilution tunnels was explored to determine best practices for design and construction of a micro-dilution tunnel. From this research, a preliminary dilution tunnel system was designed utilizing the most appropriate component choices for the application.

Guided by information obtained from this research, Chapter 3 details several design decisions that were made as to major components of the dilution tunnel. These components were critical to producing the functionality needed for IC engine research, and were central to the overall design of the dilution tunnel. Once the critical functional components were obtained, testing was done to determine methods for control of the functioning parts of the dilution tunnel, and means to log data via electronic data acquisition (EDAC). As a final step, the detailed design of the tunnel was completed with all functional components, and fabrication took place to construct the final testing platform. Upon completion of fabrication, all that remained to complete was calibration of the control systems and validation of the tunnel apparatus as a whole.

Chapter 4 presents the final design of the dilution tunnel. As constructed, the systems that controlled the dilution process needed to be calibrated to allow both control of the dilution, and accurate and repeatable measurements of the rate of dilution in the tunnel apparatus. This process was attempted with several methods, eventually resulting in a calibration process that both worked, and provided accurate and repeatable results. Once the calibration of the tunnel was completed, tests were performed on various gases to validate that the control scheme was, in fact, working as it should. These tests also served to help establish the limits of accuracy that the dilution tunnel is able to deliver. As final validation and testing, the dilution tunnel was used to sample engine exhaust from a Volkswagen TDI diesel engine. This data helped establish experimental error for the dilution tunnel and provided lessons that would help in future testing. Discussion of results and recommendations for tunnel operation are reported in Chapter 5, including confidence intervals on measured dilution ratios.

Chapter 2: Emissions Testing and Dilution Tunnels

In the design of any system, it is first necessary to understand both the behavior of the system, and the desired functional requirements of the design. Before attempting the design of an emission sensing apparatus, it was first necessary to understand the nature of emissions in general, and the principles involved in detecting emissions. The preliminary research presented in this section, was conducted into the two main types of emissions that IC engines produce. First, gaseous emissions such as CO, CO_2, and NO, were explored to understand general formation and methods of detection, rather than to develop a complete understanding of the chemical kinetics and equilibrium mechanism. Secondly, the formation and detection of engine soot or particulate matter was researched with emphasis on feasible methods of detection. Finally, the field of dilution tunnels was explored to determine best practices for design and construction of a micro-dilution tunnel. This research was used to guide design decisions, and assist in component selection for critical systems.

2.1 – Gaseous Emissions and Detection

Gaseous emissions of concern from internal combustion engines primarily include CO, CO_2, NO, and unburned hydrocarbons. Each of these emissions has its own environmental and human hazards, and method of detection.

The primary pollutant from any internal combustion engine burning a hydrocarbon fuel is carbon dioxide. This is because CO_2 is a necessary product of the combustion process. By itself, CO_2 is not an inherently dangerous emission. It is non-

toxic, except in very large concentrations, and causes no short-term environmental effects. However, CO_2 has been identified as a greenhouse gas, carrying with it global warming potential. Most notably, it has been announced recently that the United States is officially recognizing greenhouse gases as dangerous substances, promising to be the precursor to future legislation by the Environmental Protection Agency. For the purposes of most engine research however, CO_2 is a "least of all evils" emission; the more efficient the combustion, the more CO_2 created and the less unburned hydrocarbons and CO that will be released into the atmosphere. For this reason, emission measurement of CO_2 is primarily used as a measure of complete combustion [2], or for the purpose of determining total carbon output.

The majority of harmful emissions from internal combustion engines are in the form of NO, CO and unburned hydrocarbons, although there are small concentrations of SO_2 (from sulfur-containing fuel and lubricants) and other pollutants. These three pollutants are responsible for the majority of health and environmental harm that can be traced to internal combustion engine use. Detection of gaseous emissions is accomplished in a number of ways, using a number of sensor technologies. The simplest sensor technology is an electro-chemical sensor. This type of sensor contains electrolytic compounds (usually acids) that are reactive to a certain species of gas. When the sensor is exposed to the gas, reactions will occur proportionally to the concentration of the gas – causing an electrical potential difference in the sensor cell [2]. These sensors have the advantage of being inexpensive, and fairly accurate, but are consumable, subject to long-term sensor drift, and ultimately do not have the accuracy of a more expensive sensor.

Another common method of measurement is using infrared (IR) spectroscopy. This method takes advantage of the IR absorbing properties of gases by passing a beam of IR light through the gases, and measuring the amount of IR absorbed by the gases in certain areas of the IR spectrum. Figure 1 shows the absorption spectrum of CO_2.

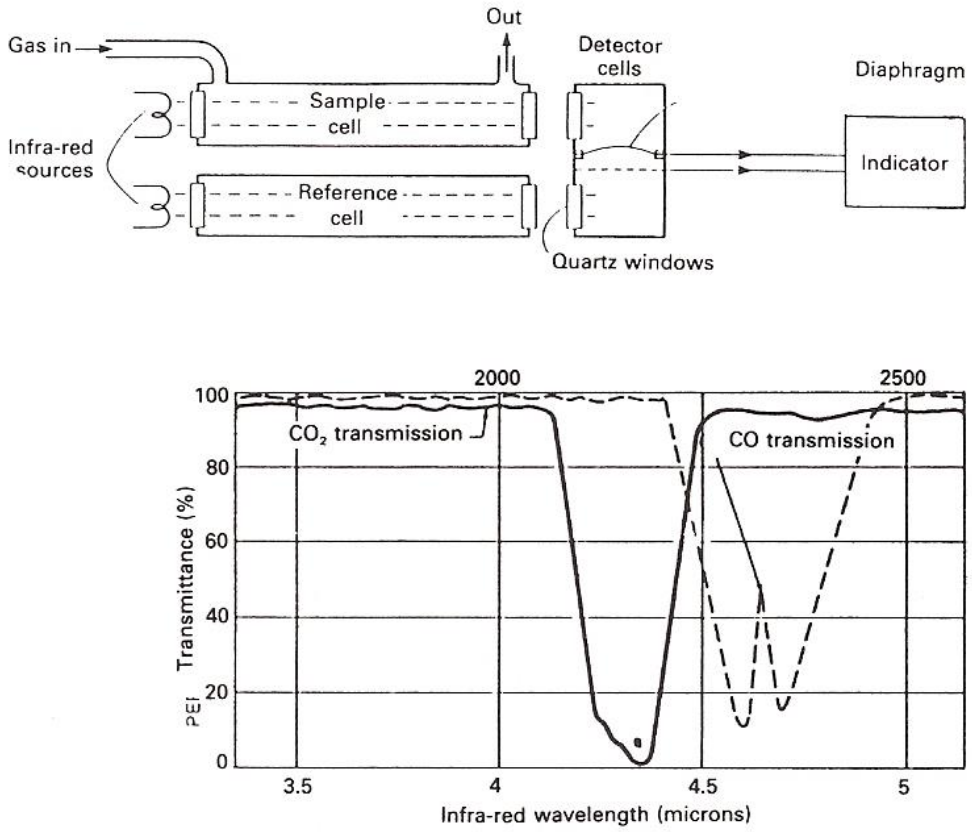

Figure 1: Operating principles of NDIR - CO_2 & CO absorption spectrum [2]

The infrared spectroscopy sensing technology most commonly used is the Non-Dispersive InfraRed sensor (NDIR). As previously described, NDIR sensors measure the spectrum and amplitude of infrared absorption and correlate it to relative amounts of species. NDIR can be calibrated to the absorption spectrums of CO_2, CO, and numerous hydrocarbons, and used to identify the relative quantities present in the sample.

However, for the NDIR sensor to work properly, one must be aware of and avoid crossover absorptions. The NDIR sensor measures only the amount of energy absorbed and, from its calibration, infers a concentration of gas. However, in the specific case of CO_2, water vapor also absorbs IR on some of the same wavelengths as CO_2, which can lead to significant error in the reading of CO_2 [2]. This means that unless water can be eliminated from the sample gas, the CO_2 measurement will be significantly inaccurate. Removal of water vapor from exhaust is most commonly accomplished by passing the exhaust gases through an ice bath to condense the water vapor. This sufficiently dries the sample to ensure that measurement of CO_2 will be accurate.

In some engine applications, emissions such as hydrocarbons and NO are in low enough concentrations that IR detection is not accurate enough. This means that additional sensing technologies are often needed to complete measurement of EPA regulated emissions. For unburned hydrocarbons, a very common sensor is Flame Ionization Detection (FID), which measures flame ionization changes when the sample is injected into fuel. This technology is more accurate than NDIR, but has the down side that the unburned hydrocarbon species (e.g. hexane, methane, etc.) cannot be determined – only the amount [2].

Nitrogen oxides (NO, NO_2, or NO_x for short) are the primary cause of photochemical smog. Detection of NO_x is most commonly done using a chemiluminescent NO_x sensor. Chemiluminescence is a process by which NO reacts with O_3 (ozone) and emits a photon after reaction. Exhaust is pretreated using catalysts or reducing agents to convert all NO_2 to NO before reaction. By measuring the amount of light emitted from the sample gas, NO_x concentration can be inferred in the sample

gases, although relative concentrations of NO and NO2 cannot be determined. Because effective detection of NO_x requires a dedicated sensor, it is common for many gas analyzers to add a simple and cheap electrochemical sensor to provide readings for NO_x.

In summary, detection of gaseous emissions can most accurately be performed by several dedicated instruments rather than one specific technology. For this reason, most emission sensing laboratories contain numerous sensors in a rack mounted analyzer setup. However, for general purposes, adequate measurements can be obtained using a NDIR sensor with a separate NO_x sensor.

2.2 – Particulate Formation and Detection

For purposes of this paper, we will define particulate as any non-gas substance that can be collected from engine exhaust by filtration, excepting water. Because of this broad definition, particulates include soot, smoke, unburned fuel particles, lubricating oil, and combinations thereof. However, this definition excludes what are known as nanoparticulates, very small particulate matter that are only beginning to be studied and understood.

In general, combustion in an internal combustion engine consists of a rapid oxidation reaction of a fuel air mixture. Ideally, all fuel reacts with oxygen and produces several exhaust gases. In practice, the oxidation reaction rarely reacts all of the available fuel in the time provided. Combustion in a CI engine occurs as auto-ignition, followed by flame as more fuel is injected into the cylinder. Injection of the fuel results in a spray of high velocity fuel particles inside the cylinder, which mix with the

air and combust. Particulates form primarily where large particles of fuel react with air, most often occurring near the nozzle of the injector, where there is an area of richer fuel-air ratio. Because there is not enough oxygen present locally to fully react the fuel, the fuel oxidizes partially, leaving a loose formation of carbon, and other unoxidized substances [2].

It should be recognized that particulate size distributions and composition will change as a result of changes in fuel, engine platform, RPM, injection timing, or a number of other factors. As such, we will be fairly general in descriptions in this section. The general composition of particulates can be seen in Figure 3.

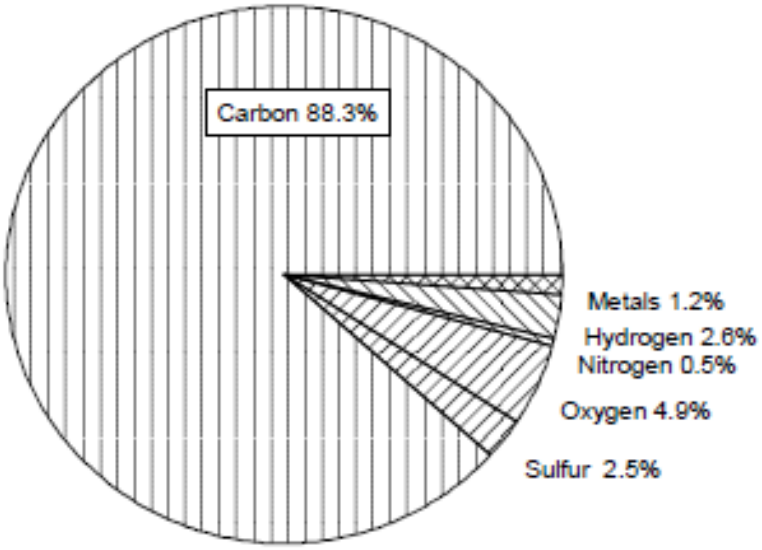

Figure 2: Particulate composition by mass [4]

Particulate matter in general consists of carbon matter, unburned fuel, unburned oil, and sulphates. Size of particulate is typically in the 0.1-2 μm range for naturally aspirated diesel engines, and roughly 75% of that size for turbocharged diesels. As noted earlier, the size and composition can vary significantly depending on test

platform, but in general, the biggest contributors to particulate formation appear to be fuel composition (specifically sulfur in fuel), engine lubricant [3], and engine design. As will be discussed further in the next section, the differences between turbocharged and naturally aspirated diesel engines can result in significantly less particulate matter for the turbocharged design.

By far, the most common (and EPA certified) method of detecting and measuring exhaust particulate is the gravimetric method. Simply put, gravimetric analysis consists of directing exhaust samples through one or more filters, and weighing the filters on a precision balance both before and after the test. The difference in mass before and after is the mass of particulate collected. This method has the advantage of being very accurate and repeatable, as transient changes are averaged out over the course of the test. However, this method is unable to provide any data on size or mass distribution, nor can it provide any data on transient emissions [6].

Gravimetric testing is most often used with Constant Volume Sampling (CVS) which considerably simplifies recording the volume of exhaust passed through the filter. CVS dilutes the exhaust with air at a set dilution ratio – providing a constant flow rate throughout the test. Once the test is complete, the filter is weighed and the particulate rate is calculated by the following equation:

$$Particulate\ Rate = \frac{Mass\ Particulate}{Volumetric\ flow * Time}$$

A major advantage to gravimetric testing is that it is stable and repeatable, and unaffected by water. After the test, the filters are allowed to equilibrate at controlled humidity, removing extraneous water, preventing erroneous data. The big disadvantage

of gravimetric detection is the slow testing rate, and sensitivity of testing [6]. Unless the system is automated, it is very possible for filters to be contaminated, throwing measurements off. Additionally, gravimetric testing can be very expensive and resource intensive due to the need for new filters each test.

Another method of measuring particulate is Laser Induced Incandescence (LII). This method uses a scanning laser to heat particulate matter in a gas stream to a temperature where the particle will emit incandescent light briefly as it cools. By measuring the duration of emitted light and making some assumptions about particle composition, this sensor can measure volume fraction of particulate in the exhaust flow. This measurement involves considerable amount of post-processing of data to produce measurements making LII somewhat impractical for general testing uses. Additionally, this technique relies on several assumptions about the density and constituency of particulate, meaning that mass measurements can be affected by changes in fuels, or engine platform. For these reasons, LII will probably continue to be more of a research tool than an EPA certification tool that can be easily used in a testing environment.

The final particulate measurement technology presented here is the Tapered Element Oscillating Microbalance or TEOM. A TEOM consists of a tapered, cantilever element forced to oscillate by an electronic feedback system. On the end of the cantilever element is a filter, through which the sample passes at a fixed volumetric flow rate. As the filter accumulates particulate mass, the frequency of the element oscillation changes, which gets picked up by the feedback system. This instrument can detect particulate concentration in a short sample time (as small as 0.21 sec [7]), giving

immediate readings of particulate mass. Figure 3 shows the basic features and operation of the TEOM.

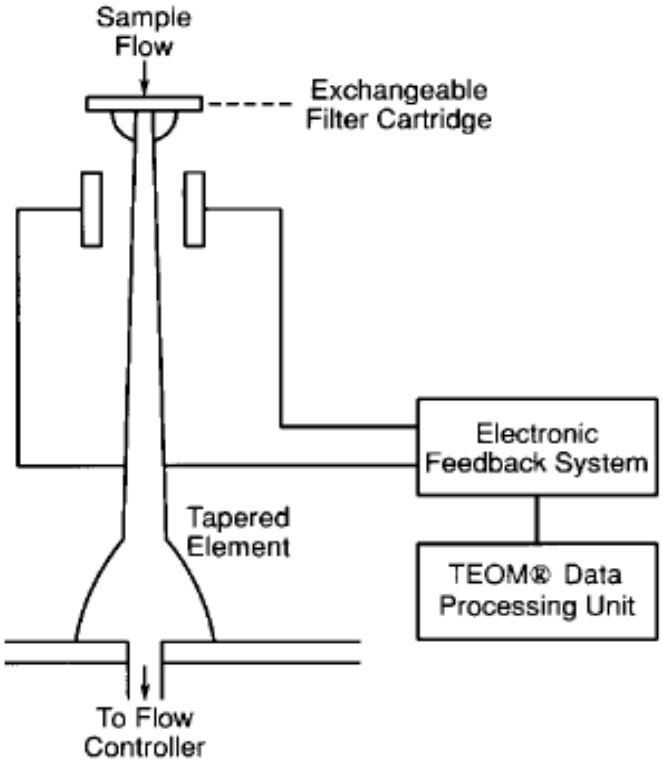

Figure 3: Internal features of Tapered Element Oscillating Microbalance [8]

Numerous studies [7;9;10;11] have been performed to determine the TEOM's ability to provide as accurate results as gravimetric particulate testing. In general, due to filter efficiencies, TEOMs seem to always read particle concentrations lower than equivalent gravimetric tests, mostly due to filter inefficiency collecting smaller particulates. As the technology has matured, the accuracy has improved from 9-14% [9] underreporting to about 6% [10] underreporting when compared with gravimetric results. This improvement can be linked primarily to improvements in filter efficiency due to improved filter media [10]. Additionally, original reports of inaccuracies in TEOM measurements can be at least partially attributed to vibration or moisture [11].

Some major drawbacks of TEOM measurements are loss of particulate matter, sensitivity to moisture, sensitivity to vibration, and susceptibility to saturation. The size and material of the filter leads to lower efficiency for smaller particulates when compared to gravimetric filter technology. Since a portion of the particulate can pass through the TEOM filters, this contributes to lower sensor resolution and underreporting by the instrument. Additionally, because the filter is not hydrophobic, particulate measurements can be affected by water vapor unless the sample is treated to reduce water, often resulting in particulate loss. Sensitivity to vibration can also cause large discrepancies in readings due to interference with the vibration of the tapered element. Lastly, if used on raw exhaust, the small face area of the filter (approximately 15mm in diameter) can become fouled in a short period of time, requiring frequent replacement. However, if the TEOM can be isolated from vibration and used to sample diluted exhaust, rather than raw exhaust, a TEOM can be an affordable and accurate substitute for gravimetric testing.

2.3 – Dilution Tunnel Sampling

The purpose of a dilution tunnel is to dilute raw engine exhaust with a cool gas, both to freeze composition, and lower dew point of the incoming gases. A dilution tunnel mixes the engine exhaust flow with a dilutant gas in a known ratio, called a dilution ratio as shown below.

$$Dilution\ ratio = \frac{Volume_{dilutant}}{Volume_{exhaust}}$$

As the engine exhaust is mixed with the dilutant stream, the exhaust is cooled rapidly. This has the effect of stopping reactions that are still occurring in the exhaust, "freezing" the chemical composition. Additionally, because the dilutant stream contains very little water, the dilution process lowers the dew point in the mixture to much lower levels than in raw exhaust. Lowering the dew point eliminates the need for heated lines or desiccant drying procedures to prevent water condensation inside sensors or handling apparatus. This results in improved cost, reliability, and reduction of potential sensor problems in downstream gas sensors. Figure 4 shows the effect of dilution ratio on downstream temperature and relative humidity when sampling exhaust at 900° F (Approx 500° C). We can see that at a dilution ratio of 10:1 and above, the resultant humidity will not cause condensation in sample lines or sensors.

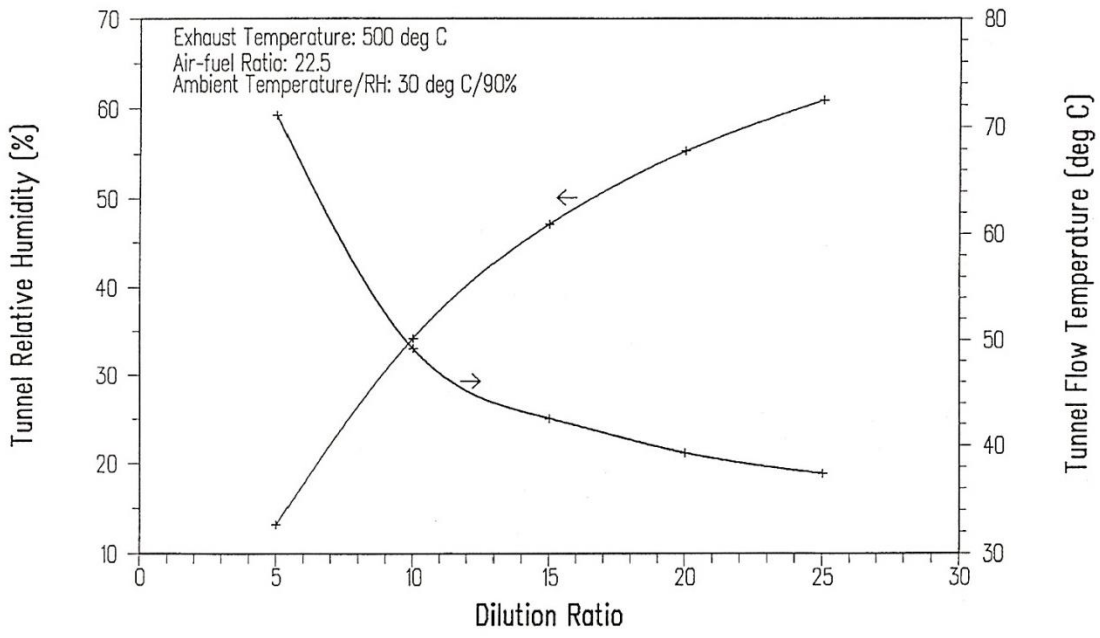

Figure 4: Dilution effects on diluted humidity and temperature [12]

Once the exhaust gas has been diluted, it can be sampled by an emission analyzer for quantities of pollutant. These quantities are then multiplied by the dilution ratio, resulting in raw concentrations of the measured emission. For example if a flow is diluted 10:1 and the diluted stream contains 50 ppm of NO, the exhaust stream must contain 50 ppm x 10 = 500 ppm of NO.

Dilution tunnels come broadly under two categories – full flow dilution tunnels, and partial flow tunnels. As the name implies, a full flow dilution tunnel samples the entire exhaust flow from an internal combustion engine and mixes it with a dilution gas[13]. Because of the volumes of exhaust, the dilutant is most commonly ambient air, and even with high flow components, the dilution ratios on a full flow tunnel will rarely reach as high as 10:1. Partial flow tunnels will take some portion of an internal combustion engine exhaust and dilute it with dilutant in the same way as a full flow tunnel, but in much smaller proportions.

Full flow dilution tunnels are most commonly used in emission testing facilities, where emissions are measured in total amounts as mandated by Federal Test Procedures (FTP). An internal combustion engine will be attached to a dynamometer and operated at specified RPMs and loads for given times, while emissions are collected and recorded. Because no exhaust is allowed to escape, the repeatability of measurements is generally agreed to be better than that obtained with a partial flow tunnel [13]. Additionally, because of the low dilution ratios, less sensitive equipment is necessary to measure emissions within the required accuracy. This is important in very sensitive measurements, such as those required to certify a vehicles emission level. The full flow tunnels require a large amount of air handling equipment in order to supply

the volume of air needed to dilute the entire flow of exhaust. Typically, for these lower dilution ratios, there are often issues with water fouling, as the dewpoint is still high enough to cause condensation in sample lines.

Partial flow tunnels are commonly used in smaller laboratory setups. Partial flow tunnels have many benefits over full flow tunnels, including size, cost, and maintenance. Partial flow systems can be considerably smaller than a full flow system, allowing them to be used in small lab or portable setups. By their nature, they sample only a portion of the exhaust gases, improving sensor response time by eliminating fluctuations in dilution ratio or flow rates. Because of the smaller volumetric rates, it is possible to achieve much higher dilution ratios in the partial flow tunnels; some tunnels can get as high as 10,000:1 ratios [1], although these ratios are typically detrimental to accurate readings, as the concentration of pollutants is orders of magnitude smaller than raw exhaust, and requires very sensitive instruments to detect.

One regrettable truth about partial flow tunnels is that there are always discrepancies in particulate matter when compared to full flow system. Much work has gone to understanding and quantifying these losses, however there are many factors to the losses. Several of the more significant reasons are transfer line effects, dilution ratio, air pump used, and residence times. Transfer line effects stem from two sources: a) wall cooling resulting in thermo-phoretic forces causing particulate deposition along the walls of the transfer line, and b) sudden expansions [14]. This can not only lower particulate readings, but can cause contamination of the testing if the deposits randomly re-enter the exhaust stream. Figure 5 illustrates the process of deposition by sudden expansion.

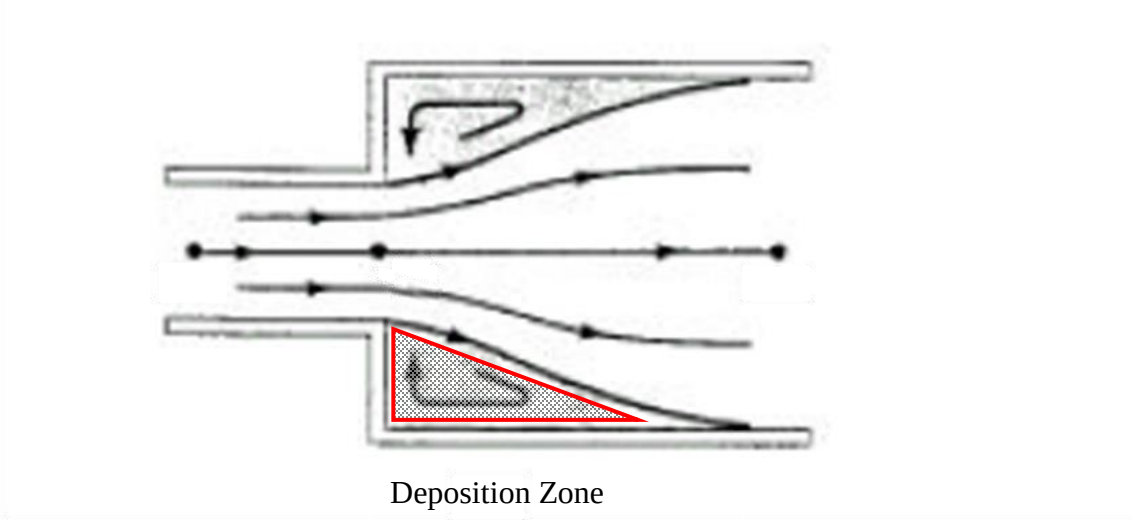

Figure 5: Deposition effects of sudden expansion [14]

In summary, partial flow dilution tunnels, while not as accurate as full flow tunnels, can provide accurate measurement of exhaust emissions in an economical and small package. In addition, partial flow micro dilution tunnels can prevent sensor saturation or fouling that might be experienced with either full flow tunnels or raw exhaust.

Chapter 3: Dilution Tunnel Design

3.1 - System Level Design

The design of the NIATT dilution tunnel was originally undertaken by a team of mechanical engineering seniors as part of their senior capstone design class. The team undertook preliminary analysis and research into dilution tunnel systems, and purchased the dilution device to be used in further work. Following from the work done by the senior design team, the overall design of the NIATT dilution tunnel was finalized according to both their recommendations and the analysis of existing dilution tunnel systems in Chapter 2 of this work.

The system level design for the dilution tunnel was chosen based on several objectives: a) economy, both of size and cost, b) overall functionality, and c) ease of use. It was decided to build a micro-dilution tunnel to keep the physical envelope small, a large factor in the already crowded engine research facility. As a dilution device, an ejector dilutor was determined to be the ideal component both due to the small physical size and the lack of moving parts. The simplicity of the ejector dilutor operation ensured both robust operation and ease of use on the overall system. Lastly, it was decided to purchase a TEOM and portable gas analyzer as a cost effective means of providing the most functionality for sensing both gaseous and particulate emissions. These major components would be tied together using a data acquisition system running National Instruments Labview software. This final piece was chosen for its ability to combine outputs from the other components into one easy to use interface

that also provides data logging in electronic form. This system level design can be seen in Figure 6.

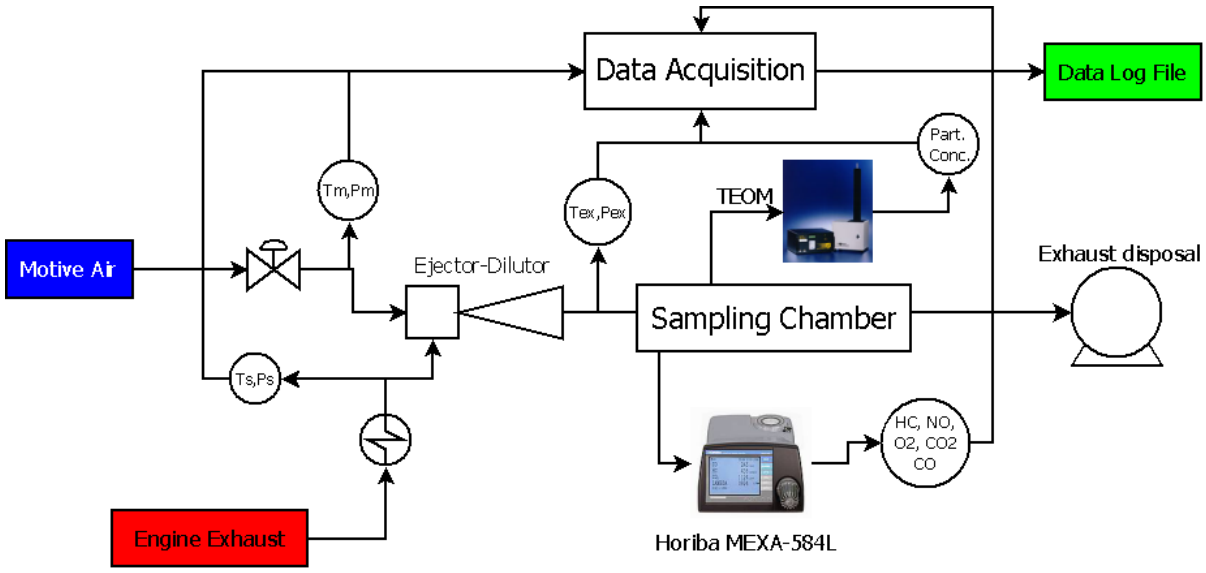

Figure 6: System diagram of dilution tunnel design

As shown in Figure 6, the NIATT micro dilution tunnel design dilutes a constant volume of exhaust with dilution gas. This lowers the dew point of the mixture, and enables instruments to test the mixture for pollutants without pretreatment that could modify the composition. A dilutant, which most commonly would be compressed air, is introduced as the motive flow in an ejector dilutor – drawing in engine exhaust from the suction line, and mixing it into the dilution stream; functioning as the only pumping input for the micro dilution tunnel. From the ejector dilutor, the diluted stream enters a sampling chamber, from which sample flows are drawn into various sensors.

Sample streams enter a gas analyzer, determining concentration of hydrocarbons, CO_2, and other pollutants. A TEOM also is connected to the tunnel, which can determine the concentration of particulate matter in the exhaust stream. Each of these components supplies

a signal to a data acquisition system that both displays the measurements and logs the data electronically. Once through the sampling chamber, the remaining dilution stream is directed out of the tunnel and into an exhaust collection system.

3.2 - Component Selection

The dilution device chosen for the NIATT dilution tunnel was an ejector venturi style pump. Ejector pumps are often used in the sampling of engine exhaust because of their lack of moving parts, and ability to withstand high heat. Pressurized gas is introduced into the motive side of the pump at a pressure range of 15-80 psig in common ejectors. This gas flow is referred to as the motive flow. This motive flow becomes choked in the truncated nozzle and creates a low pressure area inside the suction chamber causing suction gas to be drawn in and mixed with the motive flow. The diffuser section of the ejector mixes the stream and discharges the flow to the rest of the tunnel. Figure 7 shows the function of an ejector.

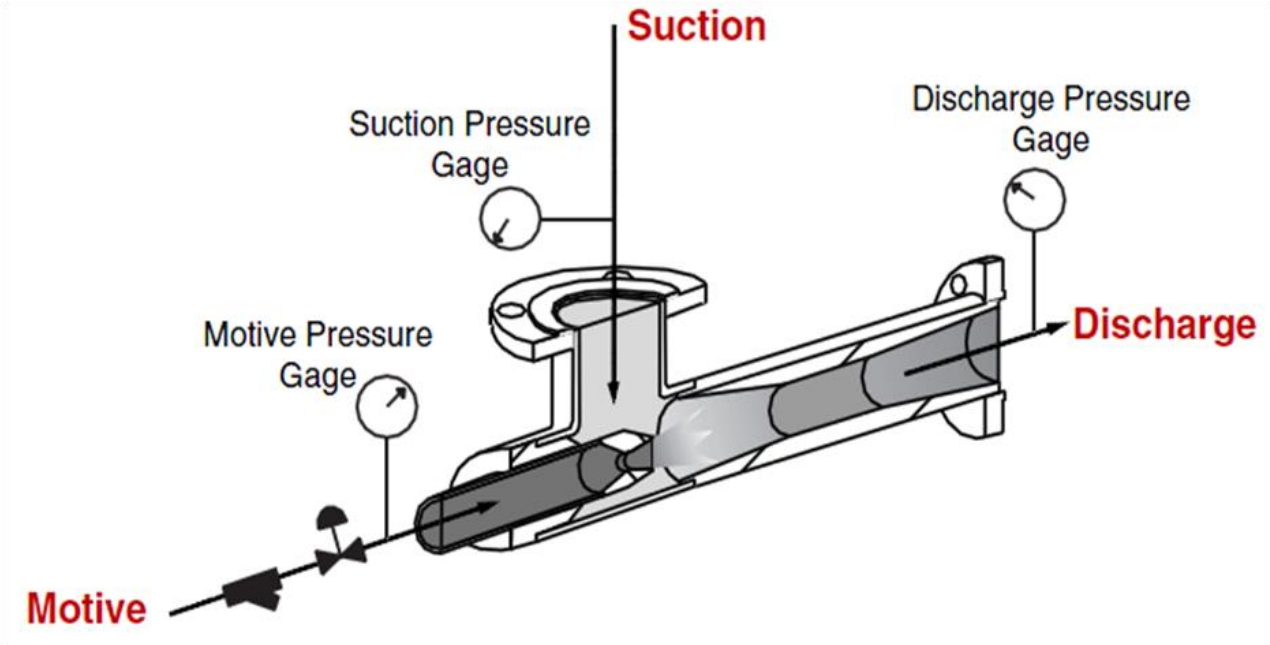

Figure 7: Ejector dilutor operating principals [15]

The ejector acquired for the NIATT dilution tunnel was purchased from Fox Valves, a manufacturer of custom critical flow venturi products. This ejector has a custom sonic choke designed for a set dilution ratio of 10:1 at a suction temperature of 1000° F, although later testing revealed that the actual dilution ratio was higher than advertised.

A critical functionality for the NIATT dilution tunnel was the ability to measure particulate matter. A TEOM model 1400ab was purchased from Thermo Scientific to deliver this functionality. This instrument was the primary model of TEOM manufactured by Thermo Scientific at time of purchase, and was recommended for use by engineers working for Thermo. Additionally, this model had been used in previous engine particulate studies with success [10]. The TEOM 1400ab can be seen in Figure 8.

Figure 8: Thermo Scientific TEOM model 1400ab [15]

Due to dilution of the exhaust gases, gas analyzers used on dilution tunnels must have higher resolution for pollutants than an analyzer used to test tailpipe emissions. The NIATT tunnel is nominally designed to dilute exhaust in a 10:1 volumetric ratio, which means that the relative concentrations for most pollutants will be 10 times smaller when sampled from the dilution tunnel than when sampled from the tailpipe of an engine. For this reason, in a dilution tunnel usage it is important to use an analyzer that has high resolution and precision, to keep from losing overall accuracy in the instrument. Three major elements were identified as being important features beyond the required precision of the analyzer: portability and physical footprint, ability to produce analog output for data acquisition, and capacity to sense all major species of pollutant (NO_x, O_2, CO_2, CO, and HCs).

Several quotations were obtained from different manufacturers of emission sensing equipment, and each was evaluated according to price and functionality as defined above. Eventually, the decision was made to purchase the Horiba MEXA-584L with added NO and O_2 functionality. This device is shown in Figure 9. Measurement of concentrations of CO, CO_2, and hydrocarbons with the MEXA-584L is accomplished with its Non-Dispersive Infra-Red cell (NDIR). Hydrocarbons measured by the MEXA-584 are reported using n-hexane equivalence. Addition of the electrochemical NO sensor was a cost effective alternative to purchasing a separate dedicated chemilumiscent NO_x sensor to accomplish a similar function. Additionally, the optional O_2 sensor was added to the purchased analyzer to add oxygen sensing capability.

The MEXA-584L was significant in its option for analog outputs, a feature not offered by many 5-gas analyzers. This allows for all of the sensor outputs to supply an analog 0-1 V signal to a data acquisition unit to be compiled with other data for a global picture of

the exhaust gas. Analog signal outputs, in combination with its small size and budget pricing were the deciding factors for eventually purchasing this sensor from Horiba in August 2009.

Figure 9: Horiba MEXA 584L 5-gas analyzer

In addition to sensing pollutants, this analyzer calculates the lambda parameter, and is capable of sensing engine speed (RPM) using an induction sensor. When integrated into the complete tunnel system, this analyzer provides output for acquisition and logging of pollutants, correlated to engine RPM. The Lambda(λ) parameter is the ratio of actual air-to-fuel ratio to stoichiometric , and can be expressed on a molar or, as below, mass basis.

$$\lambda = \frac{\left(\frac{\text{mass}_{\text{air}}}{\text{mass}_{\text{fuel}}}\right)_{\text{actual}}}{\left(\frac{\text{mass}_{\text{air}}}{\text{mass}_{\text{fuel}}}\right)_{\text{stoichiometric}}}$$

This parameter is used to determine whether the engine is running in a fuel lean condition ($\lambda > 1$) or fuel rich condition ($\lambda < 1$). The MEXA 584L can be used to calculate Lambda according to the formula below. Because of the O_2 present in dilutant air, this

calculation would necessitate the sensor being either removed from the dilution tunnel or the use of dry nitrogen as dilutant.

$$\lambda = \frac{[CO2] + \frac{[CO]}{2} + [O2] + \left\{\left(\frac{H_{cv}}{4} * \frac{3.5}{3.5 + \frac{[CO]}{[CO2]}} - \frac{O_{cv}}{2}\right) * ([CO2] + [CO])\right\}}{\left(1 + \frac{H_{cv}}{4} - \frac{O_{cv}}{2}\right) * \{([CO2] + [CO]) + (K1 * [HC])\}}$$

Where:

[ ]	is the concentration in % by volume, for HC only in ppm vol;
K1	is the conversion factor for HC expressed in ppmvol n-hexane (here 6 x 10^4)
H_{cv}	is the atomic ratio of hydrogen to carbon in the fuel
O_{cv}	is the atomic ratio of oxygen to carbon in the fuel

To collect and log measurements by the various components of the dilution tunnel, an electronic data acquisition system was required. The primary data acquisition for the dilution tunnel was chosen to be a Hewlett Packard VXI data acquisition unit shown in Figure 10. This unit is rather large, which resulted in a larger space footprint than previously planned. However, the VXI provides 30 channels of analog voltage input; bandwidth that allows all of the acquisition necessary for the NIATT dilution tunnel. To accomplish data acquisition and logging, each sensor input was connected to one of two multiplexer cards connected to the VXI that provide multiple terminals for sensing voltage. These terminals can be measured by the VXI's voltmeter, and scaled to provide a real time reading. The VXI unit is connected with a computer for acquisition and logging using National Instruments Labview software.

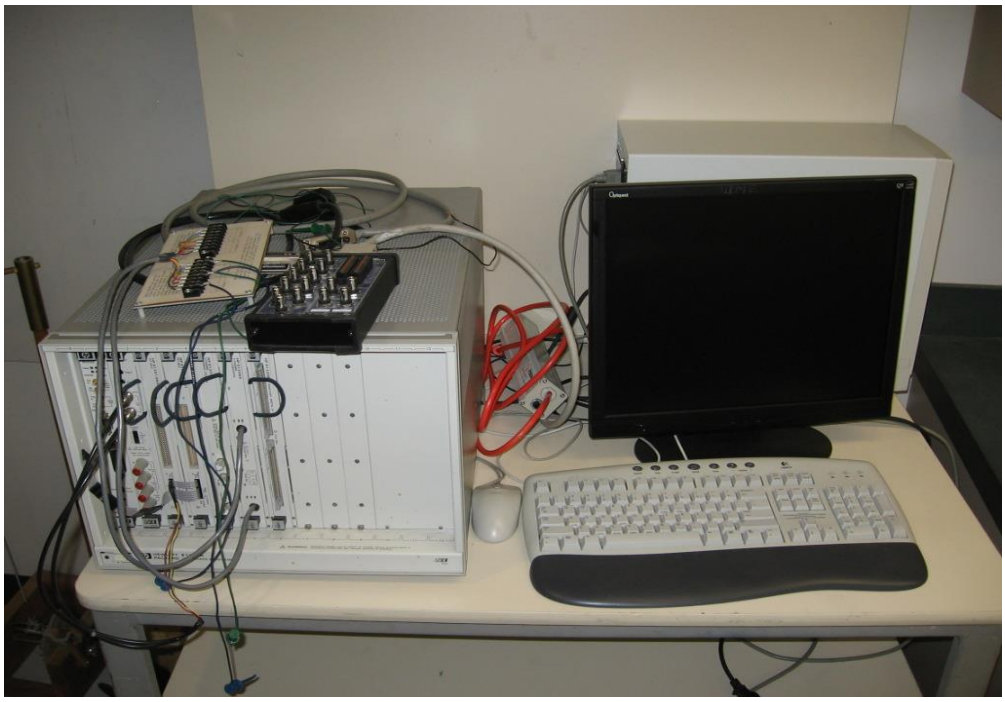

Figure 10: Hewlett Packard VXI Data acquisition unit

To be able to measure and log dilution ratio, the ejector dilutor was instrumented using 3 pressure transducers appropriately scaled to estimated readings, and 3 thermocouples, one instrument for each input or output from the ejector. The thermocouple inputs are directly read by the VXI using its onboard temperature compensation. The pressure transducers require voltage signals to be measured and scaled according to range and output as described in section 4.2.

3.3 - Dilution Ratio Control

As previously discussed, the ejector dilutor has a custom sonic choke designed for a set dilution ratio of 10:1 at a suction temperature of 1000° F and motive pressure of 35 psig. Unfortunately, this one-point calibration was not sufficient for this dilution tunnel, primarily because of temperature shifts in engine exhaust. Engine exhaust exits the cylinder at varied

temperatures depending on engine load and engine type, which means that controlling parameters to continually maintain this one point calibration would be difficult for steady state tests, and impossible for transient tests. In conversations with Fox Valve, engineers at Fox disclosed an equation they claimed could be used to determine ejector dilutor behavior under varying suction temperatures and motive pressures; this equation is shown below.

$$Dilution\ Ratio = \frac{1.76\left(\frac{P_{motive}}{49.7psia}\right)\sqrt{\frac{MW_{Motive}}{29}}}{.176\left(\frac{P_{suction}}{13.4\ psia}\right)\sqrt{\frac{T_{suction} * MW_{suction}}{1460°R * 29}}}$$

Preliminary design for controlling the dilution ratio was to parametrically control both the motive pressure and the suction temperature per the above equation. Pressure would be controlled using a valve, while temperature would be governed using a line heater; This consisted of a temperature controller driving heating tape on the exhaust inlet of the dilution tunnel. These two adjustment points would work as a "coarse" and "fine" adjustment of the dilution ratio, allowing the ejector to achieve anywhere from 5:1 dilution ratio to well above 20:1. Because the suction temperature ($T_{suction}$) of the suction is a square root term, even large variations in temperature would result in small variations of dilution ratio, allowing for fine control. Changes in motive pressure (P_{motive}), on the other hand, would result in fairly large changes in dilution ratio for even a small change in pressure, allowing a "coarse" control of the dilution ratio. Additionally, the equation above provides a term for adjustment of the dilution ratio with different dilutant gases and exhaust gases for different species of exhaust using the term for molecular weight of the motive or suction gas.

Control of the ejector dilutor required the ability to monitor temperature and pressures throughout the tunnel. The dilution tunnel system was instrumented with pressure transducers

and thermocouples as shown in Figure 6. These instruments were used to measure critical parameters for determining the dilution ratio and provide general diagnostics on the tunnel apparatus as a whole. Further discussion of the design of the dilution device can be found below in section 3.5.

3.4 - Data Acquisition Software

Most significant to the construction of a scientific instrument is the acquisition and logging of data. This aspect of this project was a driving factor in design and component selection for instrumentation. Each major component of the dilution tunnel design was either chosen to provide output for acquisition, or was instrumented to provide the necessary information to either control, or infer data that would be required in the operation of the tunnel.

While both the TEOM and the Horiba MEXA-584L provide analog output signals, the ejector dilutor does not. To make measurements critical to the determination of dilution ratio, the dilution tunnel was instrumented with thermocouples and pressure transducers on each inlet and outlet of the ejector to provide temperature and pressure data. Each of these transducers requires an excitation voltage to be able to output a signal. The data acquisition for the dilution tunnel was connected according to the schematic in Figure 11.

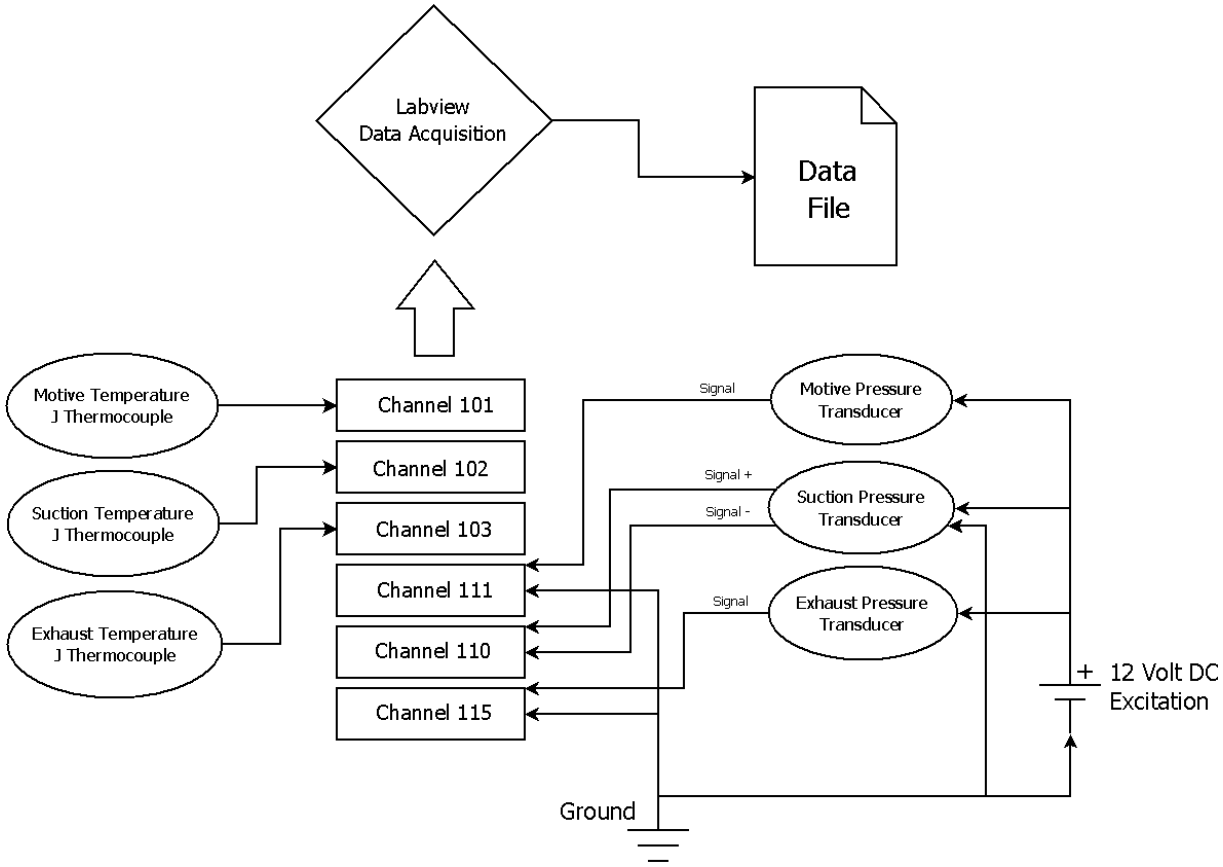

Figure 11: Circuit diagram of Dilution ratio acquisition system

A Labview program, or Virtual Instrument (VI), was created to interpret and log data from emissions instruments and collect it in a single data file. The data channels were assigned arbitrarily and are acquired according to Table 1 below:

Table 1: Table of analog channels on data acquisition

Channel Number	Channel Description	Signal Definition
Channel 100	Ambient Air Temperature (up to 1400 °F)	Type J Thermocouple
Channel 101	Suction Fluid Temperature (up to 1400 °F)	Type J Thermocouple
Channel 102	Motive Fluid Temperature (up to 1400 °F)	Type J Thermocouple
Channel 103	Exhaust Fluid Temperature (up to 1400 °F)	Type J Thermocouple
Channel 115	Exhaust Fluid Pressure (0-100 psia)	0-5 V DC
Channel 110	Suction Fluid Pressure (0-30 psia)	0-30 mV DC
Channel 111	Motive Fluid Pressure (0-100 psia)	0-5 V DC
Channel 201	Ch1 – Inst. Mass Concentration (0-500 $\mu g/m^3$)	0-10 V DC
Channel 202	Ch 2 - 30 min Mass Concentration (0-500 $\mu g/m^3$)	0-10 V DC
Channel 203	Ch 3 – Filter total mass (0-5000 $\mu g/m^3$)	0-10 V DC
Channel 208	Gas Analyzer - % CO (0-10%)	0-1 V DC
Channel 209	Gas Analyzer - % O_2 (0-25%)	0-1 V DC
Channel 210	Gas Analyzer – PPM HC (0-20000 PPM)	0-1 V DC
Channel 211	Gas Analyzer – PPM NO (0-5000 PPM)	0-1 V DC
Channel 212	Gas Analyzer - % CO_2 (0-25%)	0-1 V DC
Channel 213	Gas Analyzer – Lambda (0-9.999)	0-1 V DC
Channel 214	Gas Analyzer – RPM (0-9990 RPM)	0-1 V DC
Channel 215	Gas Analyzer – Oil Temperature (0-150 °F)	0-1 V DC

The Labview interface of the NIATT dilution tunnel was designed as the final interface for future users of the dilution tunnel. Primary design goals for this interface included: ease of use, data logging, modularity of function, and ease of access to calibration parameters. To accomplish these goals, the final Labview interface was constructed in modules that correspond to functionality, as shown in Figure 12.

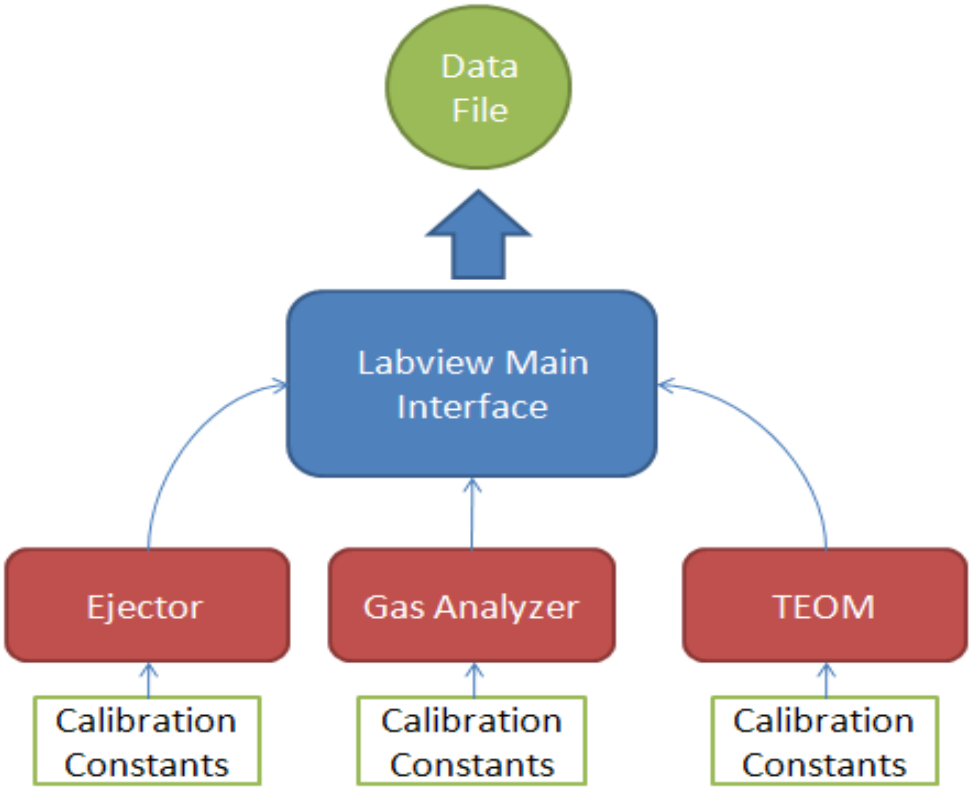

Figure 12: Schematic design of Labview interface

A separate program was created for calibration and acquisition of data from each of the three major subsystems: ejector, gas analyzer, and TEOM. Each of these modules contains its own interface for calibration, and outputs for interaction with the primary interface. This design enables a user in the future to easily access calibration parameters for each of the major systems if needed for future calibration due to instrument drift, or instrument failure. Users of the main interface do not have to view the lower modules unless necessary, as they are not displayed on the main interface. Instead, the user only has to press the start button on the Labview interface, specify a destination for the data file, and monitor the outputs as shown on Figure 13.

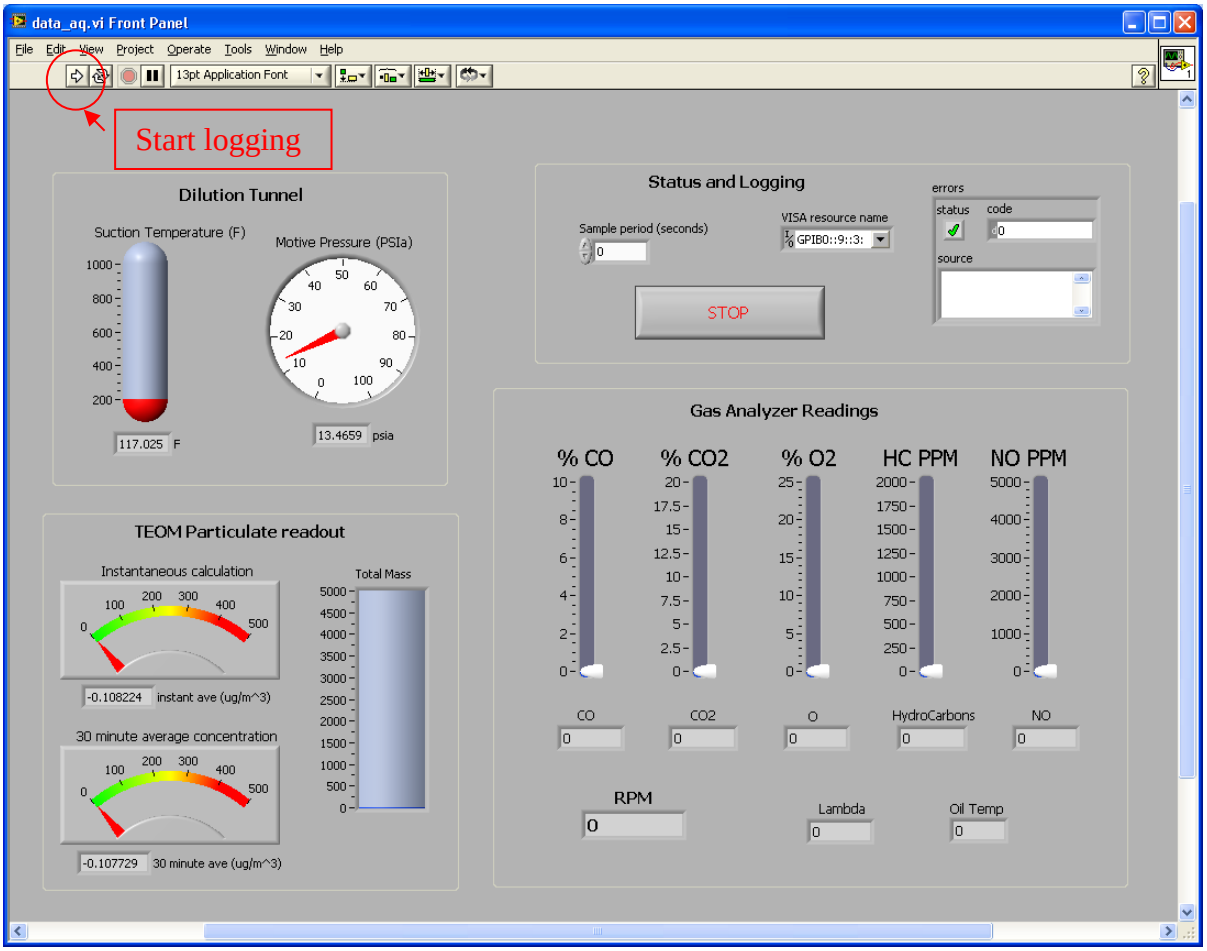

Figure 13: Main Labview interface for data acquisition using dilution tunnel

The main interface is divided into four main sections: Dilution Tunnel, TEOM readings, Gas Analyzer readings, and Status and Logging. The Dilution Tunnel box, in the upper left of the interface, provides readings on the two major adjustment points of the dilution ratio, motive pressure, and exhaust temperature. The TEOM Particulate readout, in the lower left of the interface, displays particulate concentration both immediate, and as a 30 minute average. In addition to these readings, the total mass of particulate on the filter is displayed, as a method to determine when the filter needs to be changed. In the lower right portion of the interface is the display of emissions obtained from the Horiba 5-gas analyzer. This area of the interface displays pollutants such as CO, CO_2, NO, O_2, and HCs as well as

the calculated parameter Lambda. Additionally, if the Horiba is connected to the inductive RPM sensor, or oil temp sensor, the interface will display this data as well.

Each of the sections previously referred to are available only as readouts of the interface; the fourth section, in the top right of the interface, is the Status and Logging box. This section is shown in Figure 14. The two primary controls in this section are the sample period and stop button. The sample period controls the delay in seconds between logging operations in the Labview program. This value can be modified depending on the type of emission monitoring required, with lower periods for short term measurements and higher periods for long term measurements. This value can be adjusted to keep data files from growing too large. The Stop button is the preferred method to stop the data logging process and reset the Labview program. The remaining controls are the VISA resource name and errors window. The VISA resource name is the method of specifying the VXI as the hardware resource to communicate with, and should not be changed from the default value of (GPIB0::9::3) unless the VXI acquisition setup on the dilution tunnel. Lastly, the errors window will communicate any errors in the program operation.

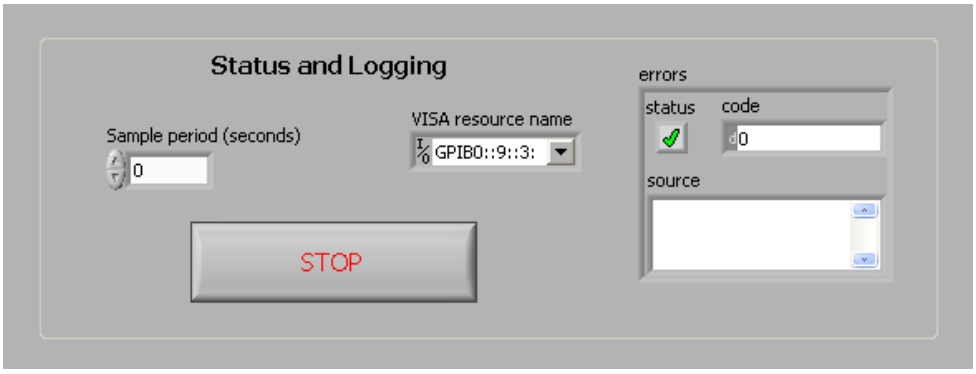

Figure 14: Status and Logging interface

Once logging has been started in the Labview interface, a file is either created, or appended to, depending on whether a new file or an existing file is chosen. This file is automatically created with a date and time stamp and tab separated columns in the order that data is logged, as shown in the example data file in Figure 15.

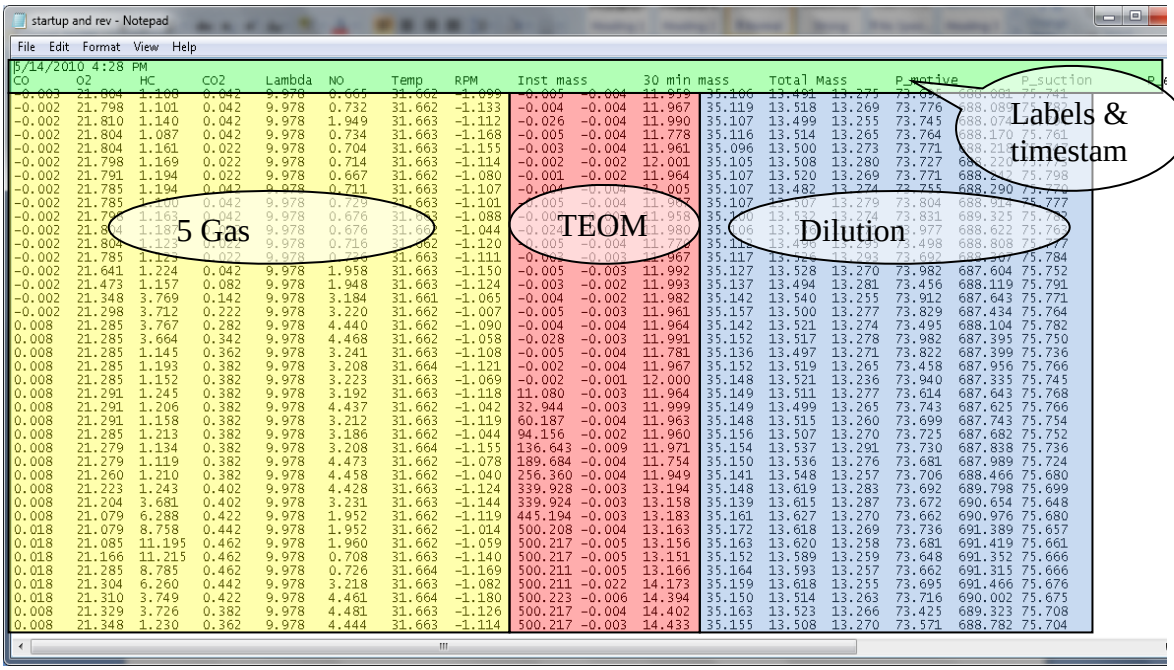

Figure 15: Sample data file created by Labview interface

The data file created by the Labview data acquisition program is grouped in three main sections corresponding to the three main functional components: Gas Analyzer, TEOM, and Dilution Tunnel. By arranging the data in tab separated format, this information can be copied and pasted directly into a numerical analysis program such as Microsoft Excel for further data analysis.

3.5 - Detail Design

Once the system level design of the dilution tunnel, shown in Figure 6, had been finalized, the detailed design and system integration commenced. This work fell into three general activities: dilution tunnel design and fabrication, instrumentation, and final assembly

and integration. Dilution tunnel fabrication encompassed the physical design and fabrication of the dilution tunnel apparatus. Once the apparatus was constructed, instrumentation of the tunnel was undertaken to place sensors and controls for the instrument. As the final stage of detail design, the apparatus was assembled in a single cart, with all operating components onboard, and all controls integrated into a functional platform for engine testing.

The primary task of the dilution tunnel design was to implement the parametric control strategy previously discussed in Section 3.3. A method was needed to control both motive pressure and suction temperature. The solution to the motive pressure control was simply to install a valve upstream of the motive input to regulate motive pressure. However, increasing suction temperature proved more difficult, requiring fabrication of a line heater to increase the temperature to the desired set point.

A stainless line heater was designed to heat the incoming exhaust up to a temperature of 1000 F. This heater can be seen in Figure 16 below. The exhaust enters the heater at a temperature lower than desired for the dilution ratio set point. On this end of the dilution tunnel is an expansion to slow the incoming gases while they are heated. An Omegalux SST high temperature heating tape was purchased from Omega with 600 watt heating capacity. This heating tape was wrapped around a section of thin-walled stainless tubing that along the body of the heater. Near the suction inlet, the heater is tapped with 1/8” pipe inputs for pressure transducer and thermocouple measurements as shown in Figure 16.

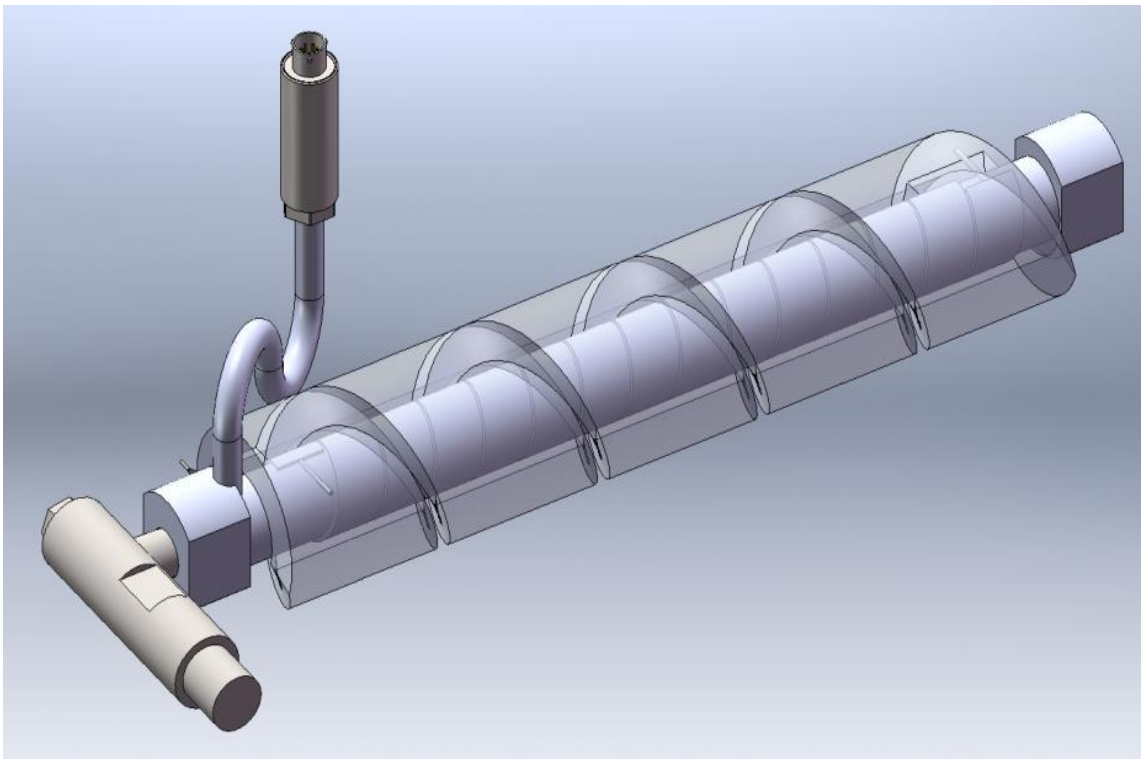

Figure 16: Line heater design with temperature and pressure sensor.

Due to the high temperature of the exhaust in the line heater (as high as 1200° F), it was necessary to place the pressure transducer away from the heater. This was accomplished using an "S" shaped stainless steel pressure tap, which kept the pressure transducer below its rated temperature of 450° F, while still allowing accurate pressure measurements. Additionally, due to the high temperatures, the line heater was surrounded with alumina silica ceramic fiber insulation for safety reasons.

Early testing on the ejector dilutor revealed that back pressure has a large effect on dilution ratio. As a result of this testing, care was taken to prevent back pressure downstream from the ejector dilutor. Each fitting was tapered inside with low angles to prevent pressure loss and flow separation. Fittings were added to allow the diluted flow to expand into the sampling chamber and contract to exit into an exhaust handling system. Barbed hose fittings

were inserted into the sampling chamber to allow sensors to draw off diluted flow for testing as shown in Figure 17 and 18. Once the sampling chamber was completed, the dilution tunnel portion was ready for instrumentation.

Figure 17: Tunnel body with transducer and sampling lines

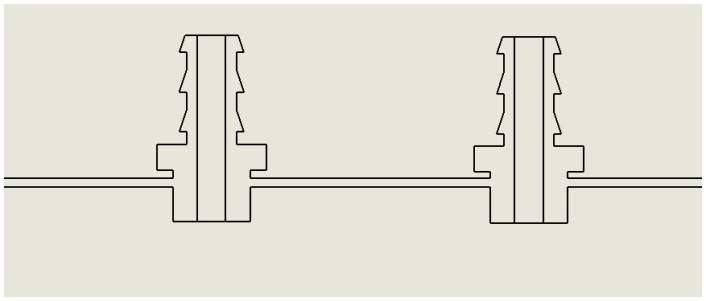

Figure 18: Side profile of sample line fittings.

To implement the control strategy, the dilution tunnel was instrumented with temperature sensing thermocouples and pressure transducers. Motive flow was instrumented by placing a two tee fittings in line with the motive air supply. A 0-100 psia pressure

transducer was connected to one of the tee fittings, while a J type thermocouple was connected to the other. As previously discussed, the suction temperature and pressure were instrumented by drilling and tapping directly into the fabricated line heater to add a thermocouple fitting and pressure tap. A 0-30 psia, high temperature, pressure transducer was attached to the top of the pressure tap. Lastly, the sampling chamber was instrumented with another 100 psia pressure transducer and J type thermocouple to provide data on the dilution stream. A 12 volt power supply was connected to the three pressure transducers to provide excitation voltage as shown in Figure 11 above. These sensors were connected to the VXI data acquisition unit as shown in Figure 11 and Figure 19.

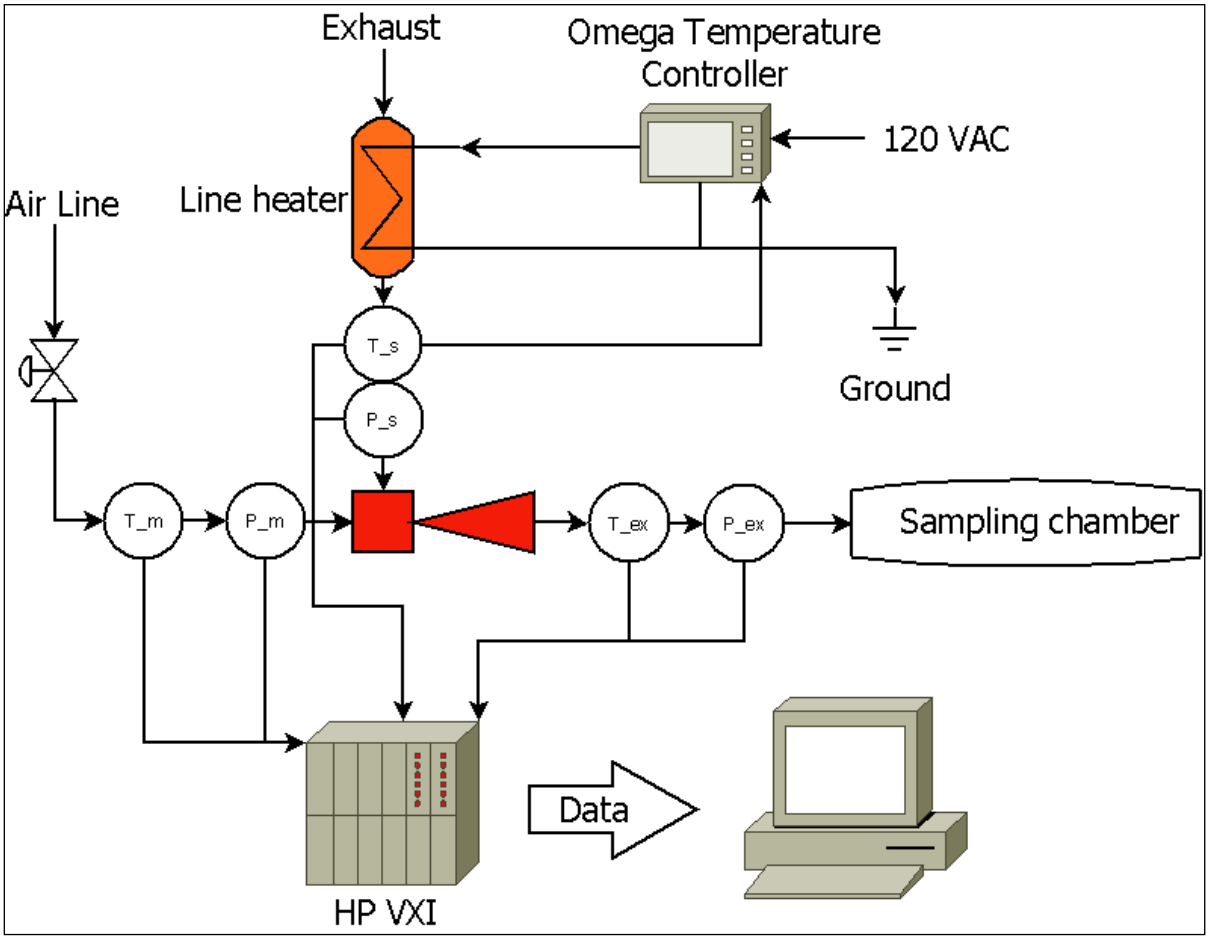

Figure 19: Control schematic for ejector dilutor

To control the suction line heater, an Omega CN2110-T10 PID temperature controller, as seen in Figure 20, was purchased and connected to the heating tape. The controller contains a 10 amp solid state relay that controls the power output to the SST heating tape, rated for 5.2 amps. This controller was connected to a switch to power the circuit. To provide temperature feedback, the controller was connected to a K type thermocouple inserted into the gas stream. This thermocouple allows the controller to monitor temperature in the suction line and adjust the power to the heating tape to maintain suction temperature.

Figure 20: Omega CN2110-T10 PID temperature controller with 10 amp solid state relay

The final stage of design and construction was to integrate all of the components together onto a single package. A single cart was designed to contain all of the working components of the dilution tunnel. An exception was made for the TEOM, which was kept separate from the tunnel cart to isolate the sensor from vibration. The final cart design, shown below in Figure 21, implemented a recessed, shielded compartment for the suction

line heater, and onboard power for line heater and computer and data acquisition. This cart concept was fabricated using steel square tube and sheet metal for construction materials. Additionally, a flexible stainless sample line was attached to the suction line to allow easy attachment to engine exhaust bungs welded into exhaust lines. The final cart setup is shown in Figure 21 and Figure 22.

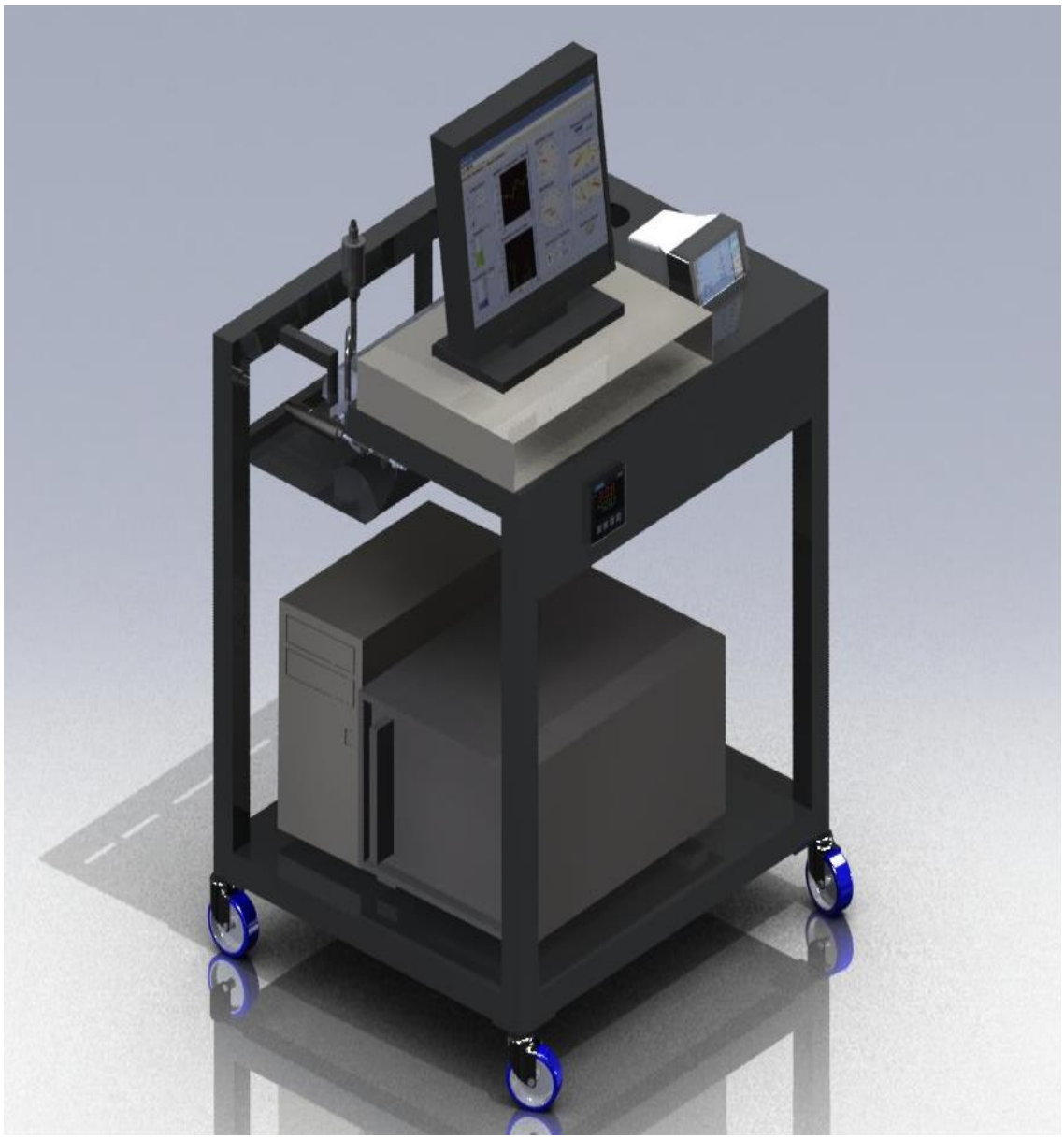

Figure 21: Detail design for dilution tunnel cart

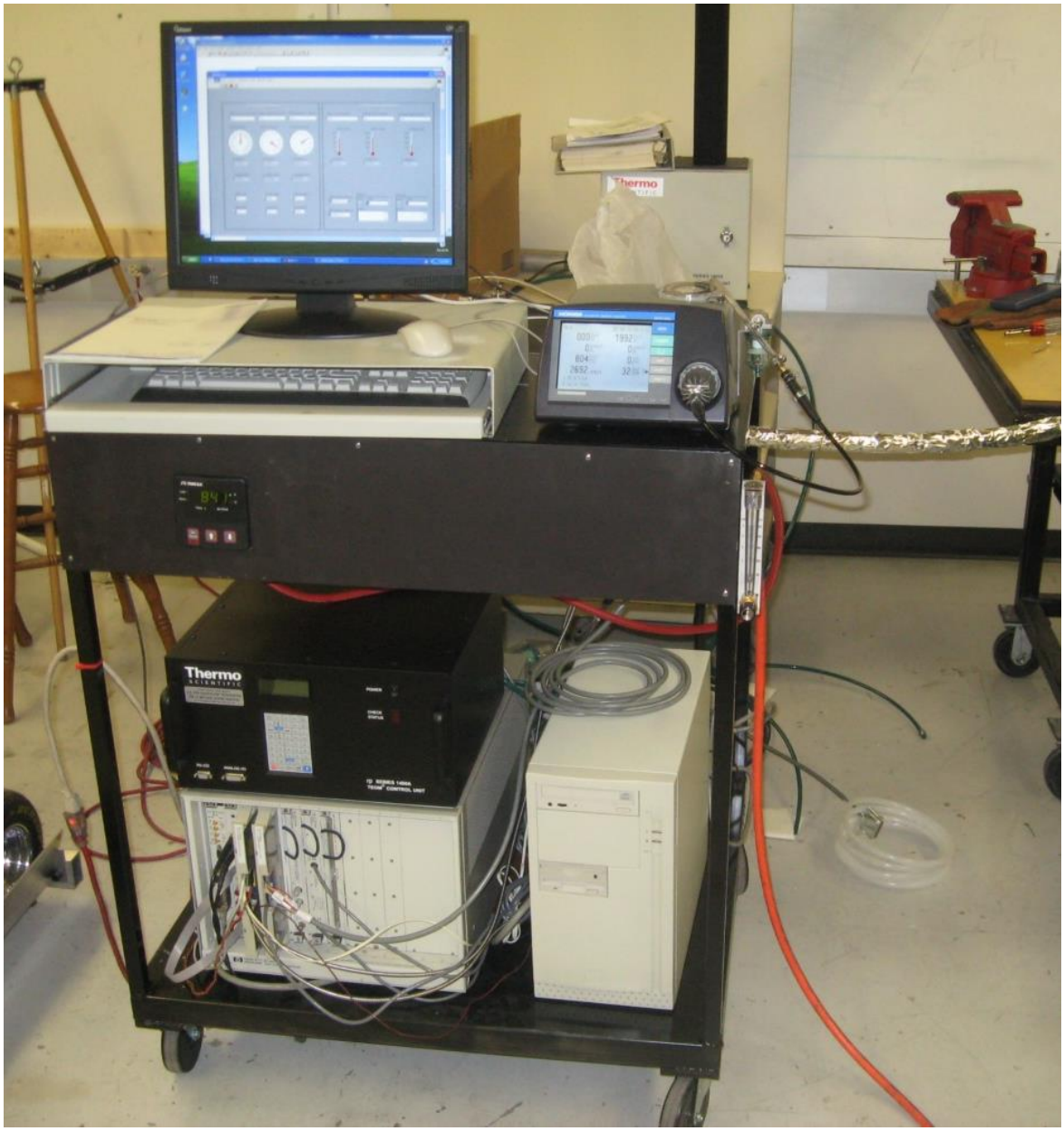

Figure 22: Dilution tunnel system cart

Chapter 4: Dilution Tunnel Validation

4.1 - Dilution Device Calibration

Arguably the most important measurement in a dilution tunnel is that of the dilution ratio. Error in the dilution ratio serves to magnify error in other instruments, such that at a certain level of uncertainty, the measurements would be almost useless. To calibrate the dilution device, several tests were performed to correlate temperature and pressure measurements around the ejector pump with overall dilution ratio through the dilution tunnel as described in Section 3.3. Ideally, this calibration would result in an overall equation or curve-fit for dilution ratio as a function of exhaust temperature and motive pressure as previously described in section 3.2. However, when initial testing commenced, it became obvious that this goal would not be as simple as it appeared. Initial test results, as illustrated in Figure 23, showed that the equation supplied by Fox Valve appeared to give not only

different answers for the dilution ratio as measured by rotameter flow meters, but the trend of dilution ratios between the calculation methods diverged considerably.

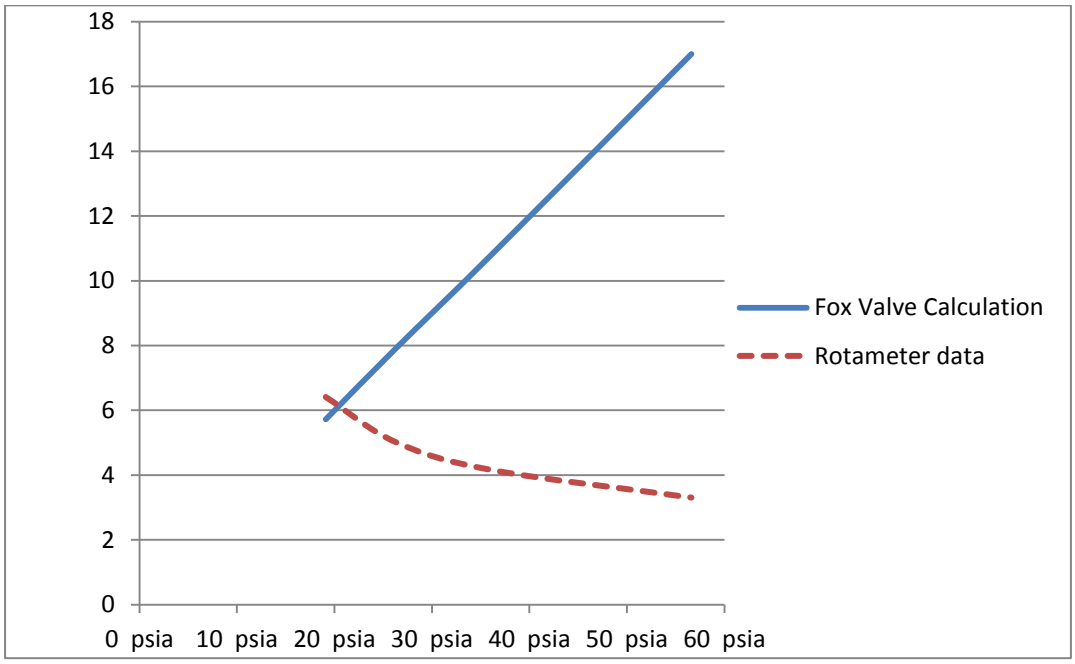

Figure 23: Dilution ratios at three different set points as calculated by two different methods

To resolve the issues with determining dilution ratio, a simpler and more robust test was conceived to determine dilution ratio. The suction of the ejector was connected to a supply of nearly pure CO_2 (99+%) at atmospheric pressure and allowed to draw the CO_2 in, the same way the ejector would sample exhaust. On the exhaust of the ejector, the Horiba MEXA-584L was positioned to sample the diluted stream. Since the MEXA was calibrated to ignore atmospheric levels of carbon dioxide, any CO_2 detected in the diluted stream would have been introduced to the stream via the ejector suction. By taking a volumetric measurement of the concentration of CO_2, the dilution ratio could be backed out using the following simple equation:

$$D_r = 1/(\%CO2)$$

This test setup proved to be much simpler and more accurate than previous methods due to the level of accuracy of the 5 gas analyzer.

During the CO_2 cal-gas dilution calibration, a number of constant temperature sweeps, and constant pressure sweeps were performed and plotted as a function of dilution ratio. The collected data can be seen in Figure 24 and Figure 25. One notable element of the data obtained using this method was that it did not substantiate any of the previous methods for measuring dilution ratio. However, unlike the previous data, the data obtained using CO_2 cal-gas dilution was both repeatable and, as shown later, fairly accurate.

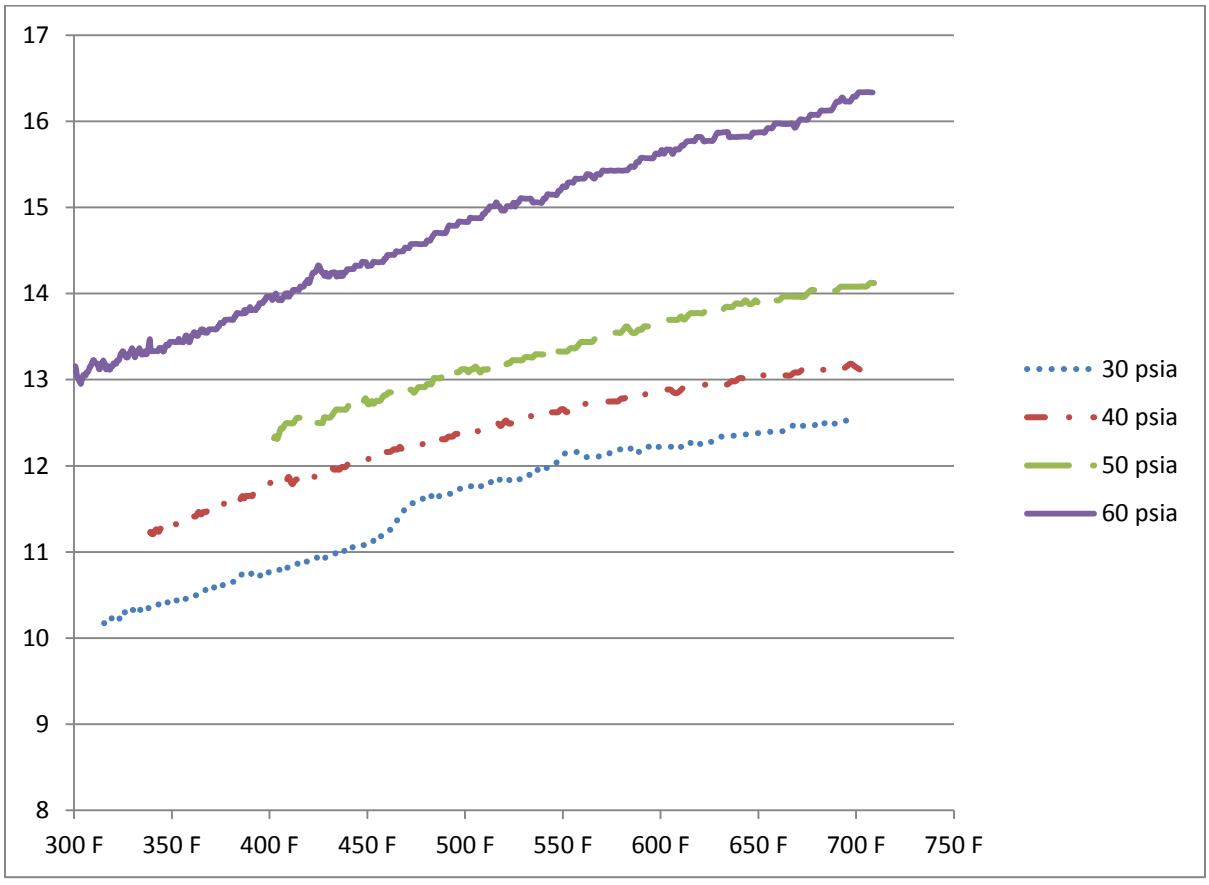

Figure 24: Dilution ratio as a function of suction temperature with constant motive pressure measured with CO_2 cal-gas dilution

Figure 24 is the raw data obtained using CO_2 cal-gas dilution, varying temperature while holding motive pressures constant. This data was obtained by heating the suction temperature to a 700 F, turning off the line heater, and logging data as the dilution tunnel cooled down. This data showed common trends of dilution ratios between data sets, and demonstrated the dilution ratio's low sensitivity to temperature shifts. Each set of data showed at most a shift of 1 point of dilution ratio per hundred degrees of temperature change.

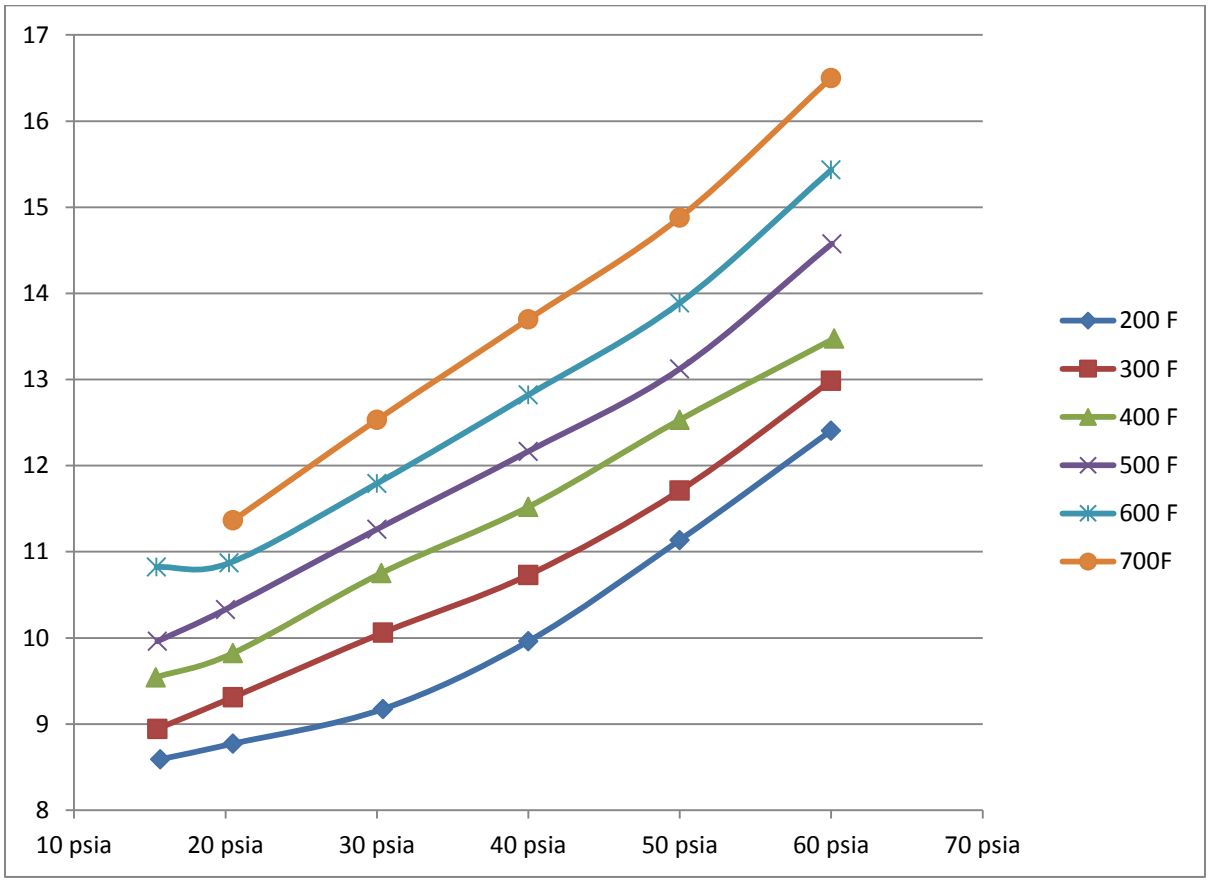

Figure 25: Dilution ratio as a function of motive pressure with constant temperature data sets measured using CO_2 cal-gas dilution

Figure 25 is data obtained using CO_2 cal-gas dilution, at constant temperatures while varying the motive pressures. This data was obtained by setting the suction temperature to a constant point, and varying the motive pressure while logging dilution ratios. This data

showed good correlation between different temperatures, and demonstrated the dilution ratio's high sensitivity to changing motive pressure. The dilution ratio at a given temperature was seen to vary approximately 5 points over a moderate pressure change of only 40 psi. These results validated the control scheme of using the motive pressure and suction temperature as "coarse" and "fine" control respectively.

One effect of using CO_2 injection to calibrate the dilution tunnel was that no definitive curve fit of the data could be obtained as a function of the two independent variables. This led to the establishing of various "run points" which are combinations of exhaust temperature and motive pressure that are correlated to a specific dilution ratio. This approach has an added benefit of stability, since it has been noted that at higher motive pressures, the dilution ratio is unstable. The selected run points are listed in Table 2. It should be noted that Set Point 1 should not be used for engine testing, as it can be very difficult to maintain stability in the measurement due to the low pressure. This set point was included due to the low suction volumetric flow that was necessary for the calibration described in Section 4.3.

Table 2: Measured set points for known dilution ratios

	Suction Temperature	Motive Pressure	Dilution Ratio
Set Point 1	700 F	18 psia	10:1
Set Point 2	700F	35 psia	12.5:1
Set Point 3	700 F	55 psia	15:1
Set Point 4	520F	60 psia	15:1

4.2 - Labview Calibration

Each of the major sections of the dilution tunnel was given its own Labview Virtual Instrument (VI) inside the overall VI. Sub-VIs are essentially sub-routines in the Labview programming language. They have their own interfaces and functions, but are only pieces of the larger program. By making sub-VIs for the TEOM, gas analyzer, and ejector instrumentation, each sub VI is both a readout of the data output of the instrument, and an interface to the calibration of the instrument. Since all inputs excepting thermocouples are linear voltage signals, each sensor must be supplied with a gain and a bias to properly calculate the measured parameter. As an example of a sub-VI, the sub-VI for the dilution tunnel portion of the instrument can be seen in Figure 26 with the areas for gain constants

and bias constants highlighted.

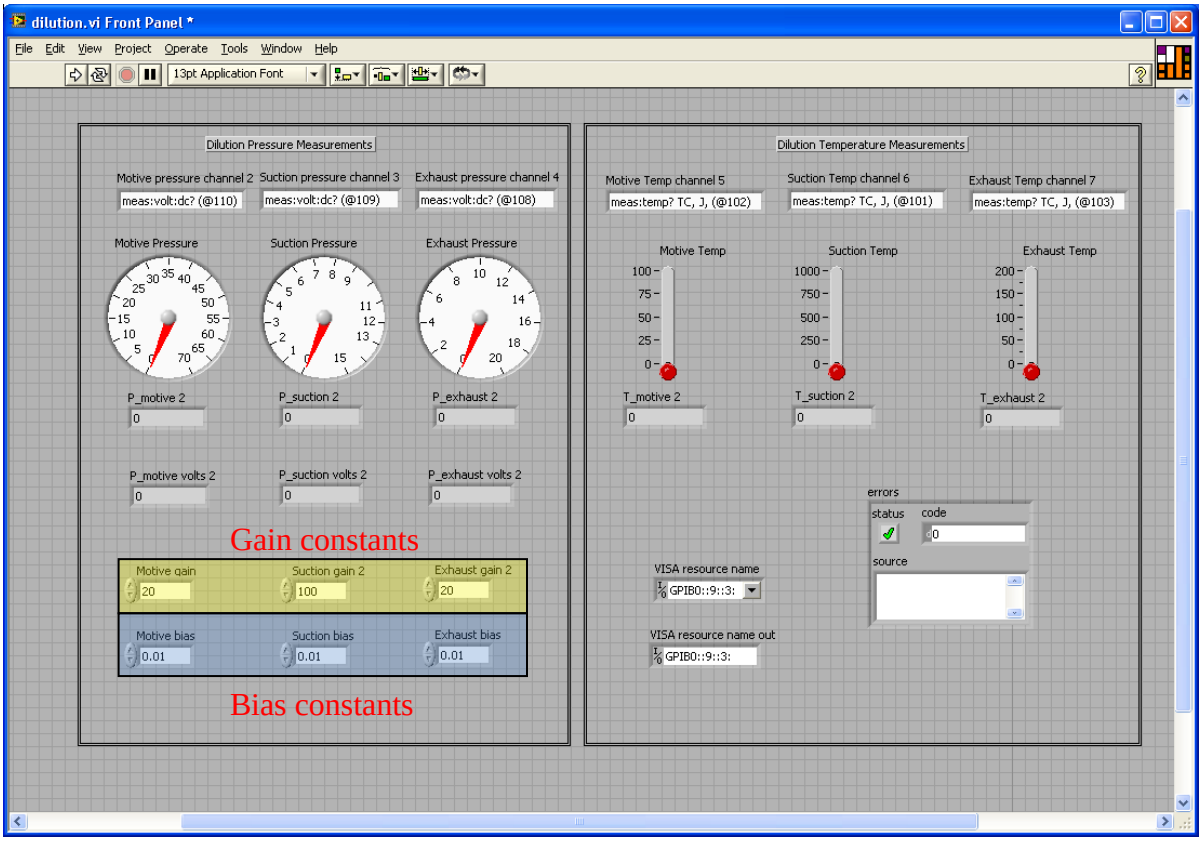

Figure 26: Sub-VI for calibration of the dilution tunnel sensors with gain and bias constants highlighted.

Determining calibration constants was accomplished by direct measurement or by using calibration data supplied by the manufacturer. Gain was determined by dividing the full scale measurement by the full scale signal voltage. For example, a pressure transducer with a range of 0-100 psia and an output of 0-5 volts DC will have a gain of (100/5=20). Once gain was specified, bias was determined by measuring the signal at zero output and adjusting the bias until the sensor reads zero. For example if exhaust pressure reads 15 psia, the bias would be 1.6 psia to bring the sensor to the correct ambient pressure of 13.4 psia. Once the calibration constants are specified, the VXI will measure DC voltage across the sensor,

multiply the voltage by the gain, and then subtract the bias to get a measurement of pressure in units of psia.

Although not pictured here, the sub VIs for both the gas analyzer and TEOM have nearly identical interfaces, and have been designed to work the same way as the interface shown in Figure 26. These interfaces can be found in Appendix B. The rationale for making these constants accessible through the Labview interface was to make recalibration easier. Recalibrations will not need to occur often, but over long periods of time, sensor outputs will often "drift", necessitating recalibration.

4.3 - Bench Testing with Calibration Gas

Upon completion of calibration, the dilution tunnel system as a whole needed to be tested to validate that it not only works as it is supposed to, but also provides accurate and repeatable data to the user. Validation procedure consisted of two separate trials: calibration gas validation, and dynamic engine validation.

Calibration gas, or cal-gas, bench testing was the first form of validation to be conducted on the NIATT dilution tunnel. The process of cal-gas validation is to introduce pure cal-gas into the suction port of the dilution tunnel and compare the measured concentrations as measured by the gas analyzer of the dilution tunnel. This process is compared to the results as the cal-gas is measured un-diluted by the gas analyzer. Given a known dilution ratio, these measurements should correlate well if the tunnel is working correctly.

To conduct the cal-gas validation, several containers of calibration gas were chosen from stores available to the Small Engine Research Facility. Four separate containers of cal-gas were chosen from the stores of SMERF for both their general spread of pollutant species,

and their relative concentrations of those pollutants. These gases and their constituents can be seen in Table 3. By choosing calibration containers that contain numerous species in relatively high concentrations, it was possible to more distinctly see the level of correlation in species and in concentrations. Additionally, more pollutant species present in a calibration gas led to reduced chance for sensor error in the gas analyzer. Since several separate sensors were being used in a single measurement, the likelihood for large error in all of the instruments together was significantly lower. By using these containers, if divergent readings were obtained on all species, it would be most likely attributed to a dilution tunnel problem, rather than inaccuracy in the gas analyzer. Results from these tests can be seen in Tables 4 through 8.

Table 3: Constituents of calibration gases used for validation

Calibration Gases	
Gas 1	1481 ppm Hexane, 5.03% O_2, 4.00% CO, 5.00% CO_2
Gas 2	100 ppm Hexane 100 ppm CO 2000 ppm CO_2
Gas 3	5.00% CO_2
Gas 4	201 ppm HC , 0.5% CO, 6.05% CO_2, 298 ppm NO

Table 4: Results from testing cal-gas 1

Cal-Gas 1		
CO Measured	CO2 Measured	HCs Measured
4.00	**5.00**	**1481**
4.1	4.9	1620
3.9	5.6	1540
4.2	5.0	1600

Table 5: Results from testing cal-gas 2

Cal-Gas 2		
CO Measured	CO2 Measured	HCs Measured
4.00	**0.20**	**100**
4.1	0.2	120
3.9	0.0	100

Table 6: Results from testing cal-gas 3

Cal-Gas 3
CO2 Measured
5.00
5.8
6.2

Table 7: Results from testing cal-gas 4

Cal-Gas 4			
CO Measured	CO2 Measured	HCs Measured	NO Measured
0.50	**6.05**	**1060**	**298**
0.3	5.4	900	270
0.4	6.8	1200	340

Results from cal-gas testing were varied. Calibration gas #2 in particular generated very poor results. This was primarily because the calibration gas had very low mass per unit volume of pollutants: 100 ppm HC, 0.01% CO, and 0.2% CO_2. Once diluted, the concentrations should look something like 10 ppm HC, 0.001% CO and 0.02% CO_2. This makes it unlikely that any reasonable degree of accuracy could be expected on this measurement, as it pushes the resolution of the gas analyzer beyond its accuracy limits. However, this data was important as an example of limitations of the dilution tunnel.

One limitation that likely inhibited more accurate readings was the sample rate. Cal-gas is highly expensive, and the containers of gases available for testing were fairly small. Additionally, the regulator for these gases was only able to supply up to 6 L/min of cal-gas for testing. This meant not only that allowing the analyzer to fully stabilize would involve using an entire container of cal-gas, but additionally meant that only dilution ratios that did not sample more than 6 L/min of suction gas could be tested with these gases. The exception to this was calibration gas #4, which was in a larger tank held at higher pressure and could be sampled longer and at other set points. Consequently, cal-gas validation could only be used to establish the general validity of the CO_2 cal-gas dilution ratios established.

4.4 – Engine Testing

As final validation of the dilution tunnel apparatus, testing was performed using an actual engine platform. This procedure consisted of connecting the dilution tunnel to a Volkswagen 1.9 L TDI diesel engine to provide a real operating scenario. The engine was set at a specific RPM and loaded using an alternator and set of resistor banks; this setup can be seen in Figure 27 . While maintaining that specific load point of the engine, raw exhaust emissions were measured using the Horiba 5 gas analyzer. Once the readings had stabilized,

the gas analyzer was reconnected to the dilution tunnel to sample the diluted stream. This provided a real-life scenario to validate dilution readings as compared to raw exhaust readings. Engine load points were arbitrarily chosen between the no-load condition and the maximum load available on the existing apparatus. Additionally, load settings and RPM could not be duplicated from test to test, since the TDI diesel did not have a tachometer to measure RPM and the throttle position sensor was not capable of fine adjustment.

Figure 27: Engine testing test setup

Engine testing using the dilution tunnel was conducted at three approximate load levels. These loads were at idle condition, approximately 1500 RPM, and approximately 2500 RPM. Raw exhaust measurements were compared to diluted measurements to validate and confirm the validity of the set points established in CO_2 cal-gas dilution testing. One significant issue was uncovered during engine testing was that the measured dilution effect

was significantly different from the previously measured set points. For example, at Set Point 3 shown in Table 2, the dilution measured using exhaust gases was around 11:1 rather than the expected 12.5:1 ratio measured with CO_2 cal-gas dilution. This effect was investigated for other dilution ratios and various engine speeds with the same result. The results of engine dilution ratios compared to CO_2 cal-gas dilution ratios at set points can be seen in Table 8:

Table 8: Dilution ratio correlation between engine exhaust and CO2 at 700° F suction temperature

Motive Pressure	Suction Temperature	CO_2 cal-gas dilution ratio	Engine exhaust dilution ratio	Engine/CO_2
35 psia	700° F	12.5	10.83	0.867
55 psia	700° F	15	12.52	0.834
60 psia	520° F	15	13.56	0.904

One notable fact about these measurements was that the measured dilution ratio with engine exhaust was consistently approximately 85-90% of the CO_2 cal-gas dilution set point. This trend could be explained by the different molecular weights of the gases, causing different flow characteristics in the dilutor. Additionally, these dilution measurements did not change as a function of engine RPM in the testing conducted at Set Points 2 and 3. This meant that the set point could be corrected to accommodate engine exhaust and used exactly as previously described. This testing data is shown in Table 9.

Table 9: Results of engine exhaust dilution measurements

	Set Point 2 35 psia, 700° F	Set Point 2 35 psia, 700° F	Set Point 3 55 psia, 700° F	Set Point 3 55 psia,700° F	Set Point 2 35 psia, 700° F
Run #	Run 1	Run 1	Run 2	Run 2	Run 3
Species used for calculation	CO_2	NO	CO_2	NO	CO_2
Idle engine speed ratio	10.62	11.41	12.52	12.65	11.14
~1500 RPM, 5 kW	10.77	11.72	12.50	12.52	No data
~2500 RPM 25kW	10.91	11.81	No data	No data	No data

Testing was conducted primarily at set points of 700° F suction temperature and both 35 psia and 55 psia motive pressures. The reason for using these set points was for stability of measurement. 700° F suction temperature was a very stable temperature to maintain, even when exhaust gases heated up as a result of increasing load. The dilution ratios in Table 5 were measured by comparing quantities of both CO_2 and NO in raw exhaust, and in diluted exhaust. Due to the associated error of the NO measurements, it was decided to base dilution ratios on measurements of exhaust CO_2, as these measurements have less systematic error. These measurements were used to establish the 80% confidence intervals shown in Table 10. This confidence interval was used to estimate error bounds on raw emission data compared to dilution data shown in Figure 28.

Table 10: Recommended set points for future tunnel operation, and associated error in dilution ratio

Set point conditions	Experimental dilution ratio (80% confidence)
700° F suction – 35 psia motive	10.83 ± 0.31
700° F suction – 35 psia motive	12.56 ± 0.26

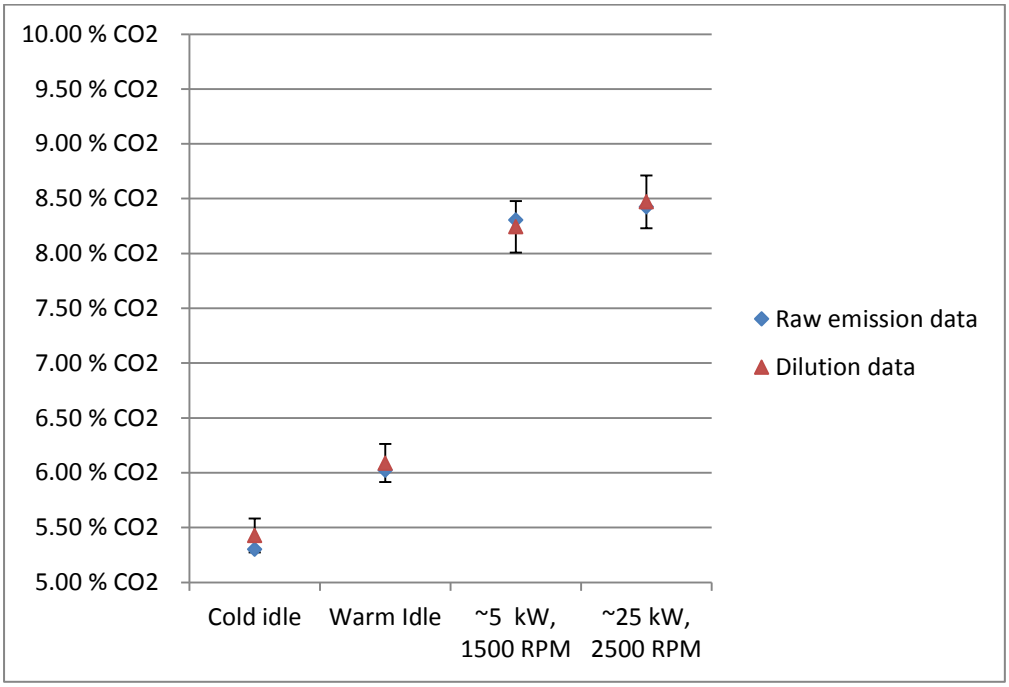

Figure 28: Exhaust gas CO_2 measurement at 700° F, 35 psia with 80% confidence interval

Chapter 5: Conclusions and Recommendations

As designed and fabricated, the NIATT dilution tunnel fulfills all of the design requirements previously discussed in section 3.1. The system is contained on a portable cart, making it ideal for the crowded environment of the Small Engine Research Facility at University of Idaho. It contains one easy-to-use interface that displays and logs all data for future use. All functions and controls necessary for operation of the dilution tunnel are located onboard the cart, meaning that the cart only needs to be connected to a power supply and air line to function. Final tunnel specifications can be found in Table 11. Additionally, several pictures of the NIATT dilution tunnel can be seen in Figure 29 through Figure 31.

Table 11: NIATT dilution tunnel specifications

Sample chamber volume	2.1 Liters
Diluted exhaust flow	40-150 L/min (dilution ratio dependent)
Particulate sensor flow rate	5-13 Liters/min
Gas analyzer flow rate	4 Liters/min
Residence time	3.2 - .85 seconds (dilution ratio dependent)
Measurement Capabilities	HC, CO, CO_2, O_2, NO_x, & Particulate mass concentration
Particulate Sensor	Thermo Scientific TEOM 1400-ab
Gas Analyzer	Horiba MEXA-584L w/ NO & O_2

Figure 29: NIATT dilution tunnel front view

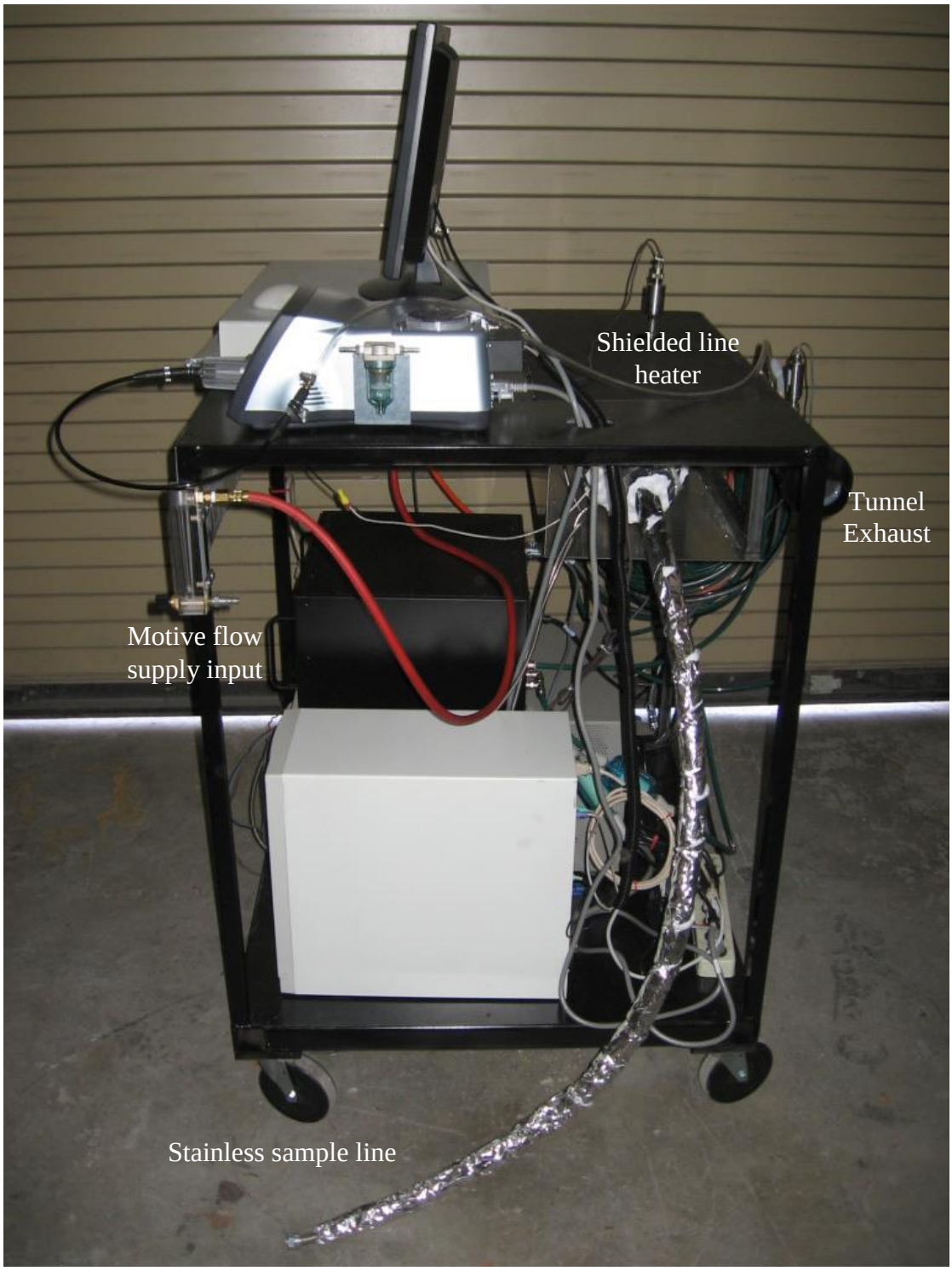

Figure 30: NIATT dilution tunnel right side view

Figure 31: NIATT dilution tunnel left side view

As discussed in Section 4.4, engine tests revealed two set points that should be used to set the dilution ratio at the start of testing with the dilution tunnel. Either set point can be used to good effect, although checking the dilution ratio, as described in Section 4.4 using raw exhaust comparison, is recommended before testing. These set points correspond to dilution ratios shown in Table 10, and have experimental error of ± 0.3. This experimental error was fairly close to the 3.4% root sum squared error based on the dilution ratio equation.

Some lessons were learned in the validation of the dilution tunnel that should be heeded by future users. For particulate testing, the primary lesson learned was how sensitive the TEOM is to particulate matter and vibration. Even slight bumps or vibration caused TEOM readings to fluctuate wildly for almost 5 minutes. Additionally, large quantities of particulate, such as a diesel engine produces at startup or acceleration, also create fluctuations in particulate readout that may or may not represent actual measurement of particles. Regardless of the efficacy of these measurements, the measurements exceed the scale of the analog output from the TEOM. This scale can be changed, but would drastically affect resolution of the measured particulate matter. In short, transient particulate testing will probably not be possible without further development on the dilution tunnel and further adjustment of the TEOM itself.

Another important lesson learned in engine testing is the necessity of carefully choosing sampling locations. There are two pitfalls to avoid in choosing an area to place a sampling port in the exhaust system: exhaust air mixing, and exhaust pressure. Exhaust ports should be placed at least 18 inches from the atmospheric exit of the exhaust stream to prevent induction of ambient air from the exhaust exit. Also, care must be taken to avoid pressure drops downstream of the sampling port. As engine RPM increases, this can cause back

pressure in the exhaust system that could pressurize the suction line. This can be eliminated by making sure that the exhaust is sampled shortly before it exits to atmosphere. If this is not possible, the pressure could be removed by installing a manual valve on the suction line, and creating enough pressure drop in the exhaust line to bring the suction pressure reading down to atmospheric pressure. However, this would not be desirable, due to the need to adjust this valve every time the RPM changes.

While the system meets the needs of current testing, there are some areas for improvement in the next generation. While prolonged usage may reveal more shortcomings, one of the biggest areas for improvement on the NIATT dilution tunnel is the addition of better, dedicated analyzers for the primary species of emissions. Ideally these sensors would be a NDIR sensor for detection of CO, CO_2, and HCs, and a dedicated chemiluminescent sensor for detecting nitrogen oxides, and separate dedicated O_2, and H_2 sensors. Higher functionality NDIR sensors can be calibrated to determine relative amounts of various species of molecule, having the potential to determine quantities of hydrocarbons of different species than the commonly measured hexane. This may especially be important in the analysis of emissions from engines combusting alternative fuels such as ethanol or biodiesel. Furthermore, acquisition of dedicated sensors for NO_x, O_2, and H_2 would expand capabilities for testing at the university that may only be envisioned in the future.

By purchasing more accurate equipment, it would be possible to attain greater accuracy in the dilution tunnel. This equipment could also potentially determine deficiencies in the dilution tunnel apparatus that are not possible to detect using current equipment. Moreover, separate dedicated sensors would allow for the gradual acquisition of better equipment as budget allows, rather than as an all-in-one expense.

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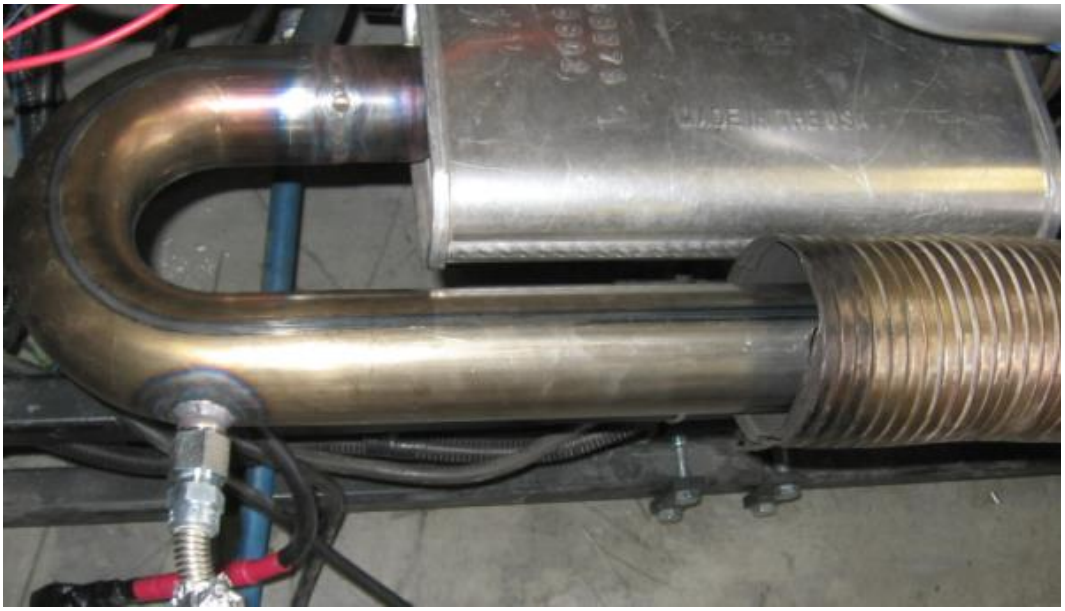
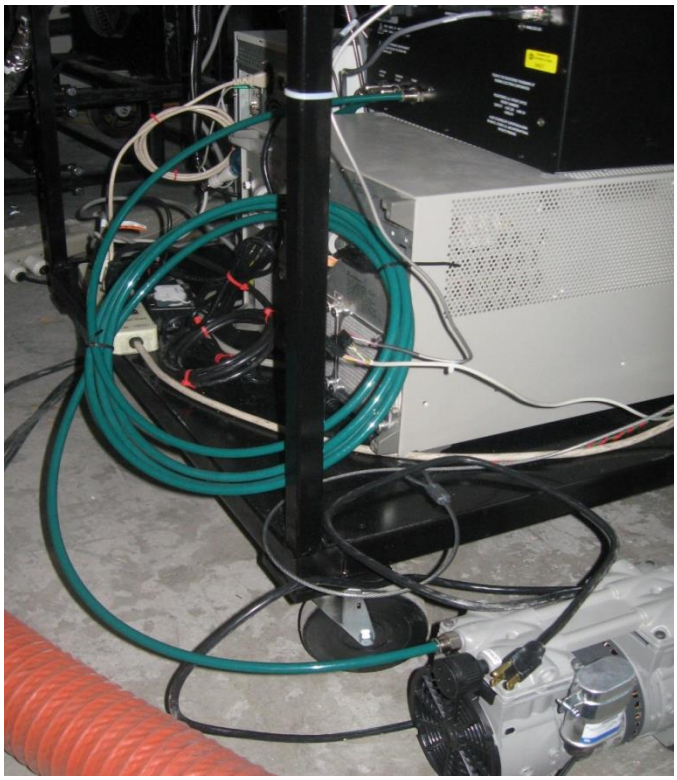
Appendix A: Dilution Tunnel Operating Procedures

1) Connect dilution tunnel suction inlet line to exhaust bung. This connection should ideally be a ½ inch NPT male connection welded into the exhaust section and should be at least 18” before the exit to atmosphere.



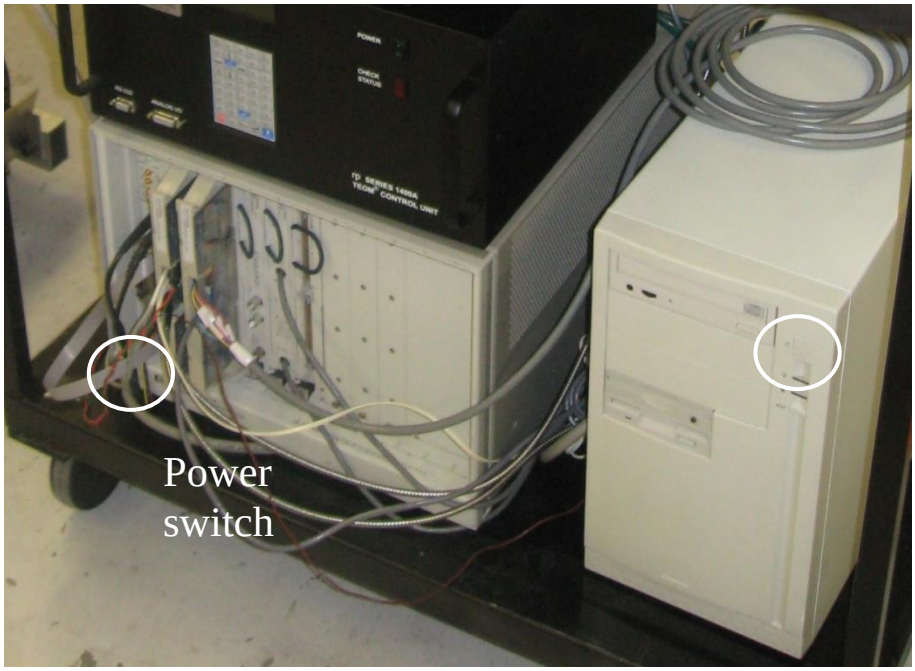
2) Connect TEOM sensor unit to control unit. This is done by connecting the data cable and black tube to the fittings on the side of the control unit.

3) Connect vacuum pump to control unit. This is done by connecting tubing to the fitting on the vacuum pump and the other side to the control unit

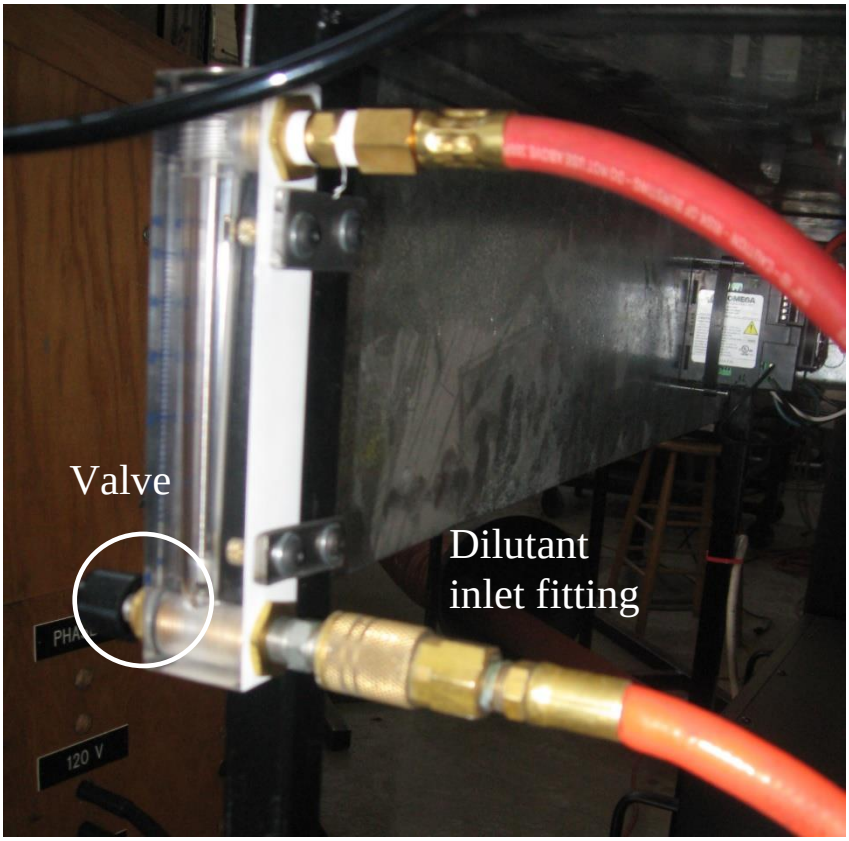


4) Turn on vacuum pump by plugging in the cord.
5) Turn on TEOM sensor unit by switching the front switch. The red check status light will turn on, indicating a temperature condition. This is not a system problem; it only indicates that the TEOM has not come up to temperature. Warm-up and initializing takes about 1 hour.

6) Turn on HP VXI data acquisition unit, and computer.

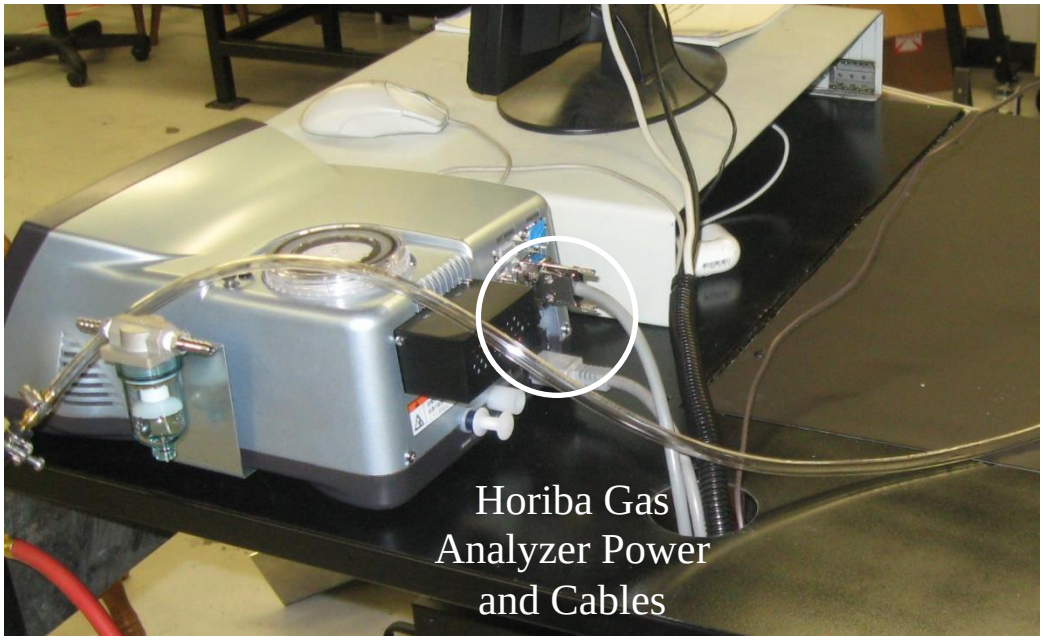


7) Connect dilutant supply to air fitting on motive pressure valve. Crack valve open to let a small amount of air begin flowing through the tunnel.

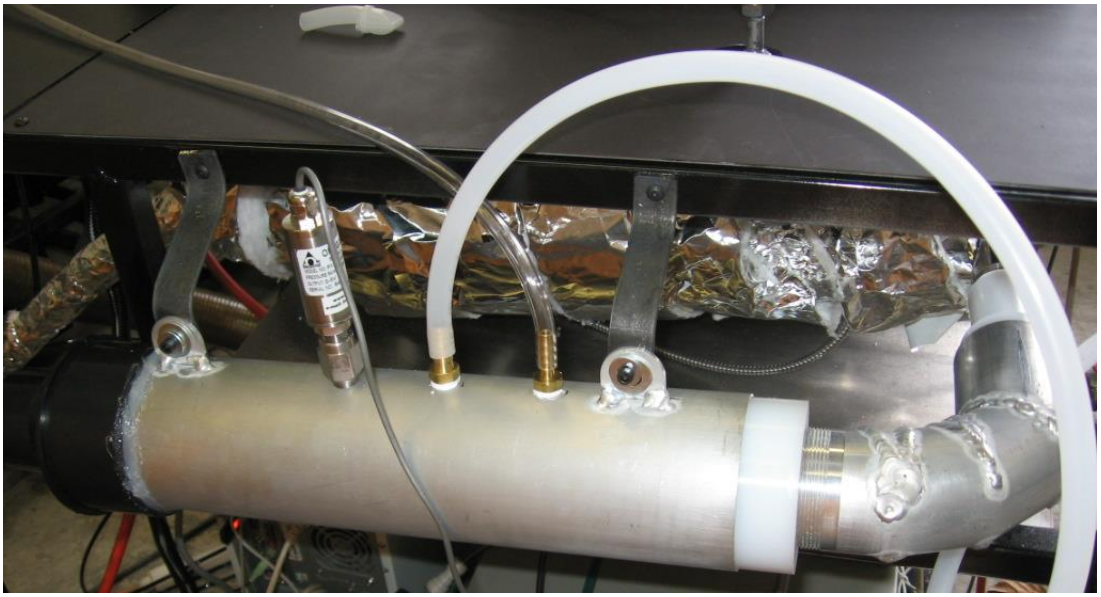


8) Turn on temperature controller. Set temperature to 820 F. This temperature corresponds to a suction temperature of 700 F. The temperature sensor on the temperature controller consistently reads higher due to being too close to the wall of the line heater.

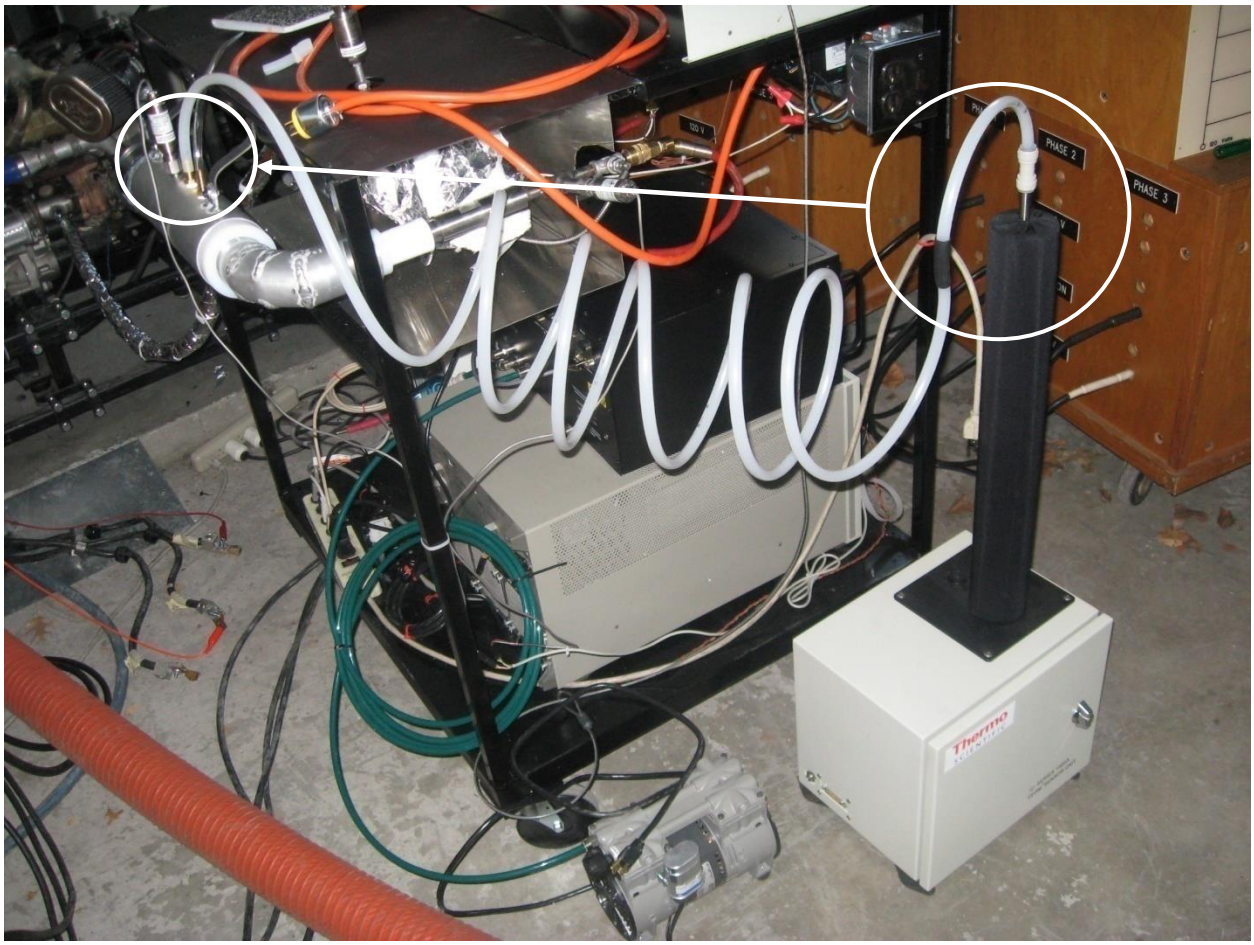
9) Turn on Horiba gas analyzer; if necessary, connect cable to analog out port.



10) Connect gas analyzer tubing to dilution tunnel sampling chamber.



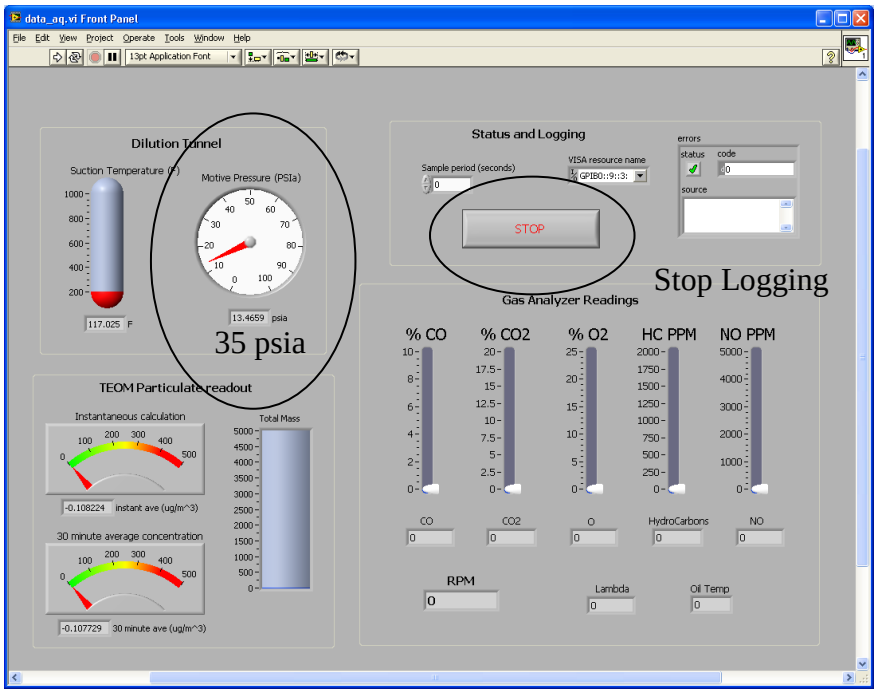
11) Connect TEOM outlet to dilution tunnel sampling chamber



12) Start Labview and load Dilution_tunnel.VI

13) Press MEAS on Horiba 5-gas analyzer. This starts gas measurements.

14) Start the Labview program Dilution_tunnel.VI and adjust the motive pressure to 35 psia.



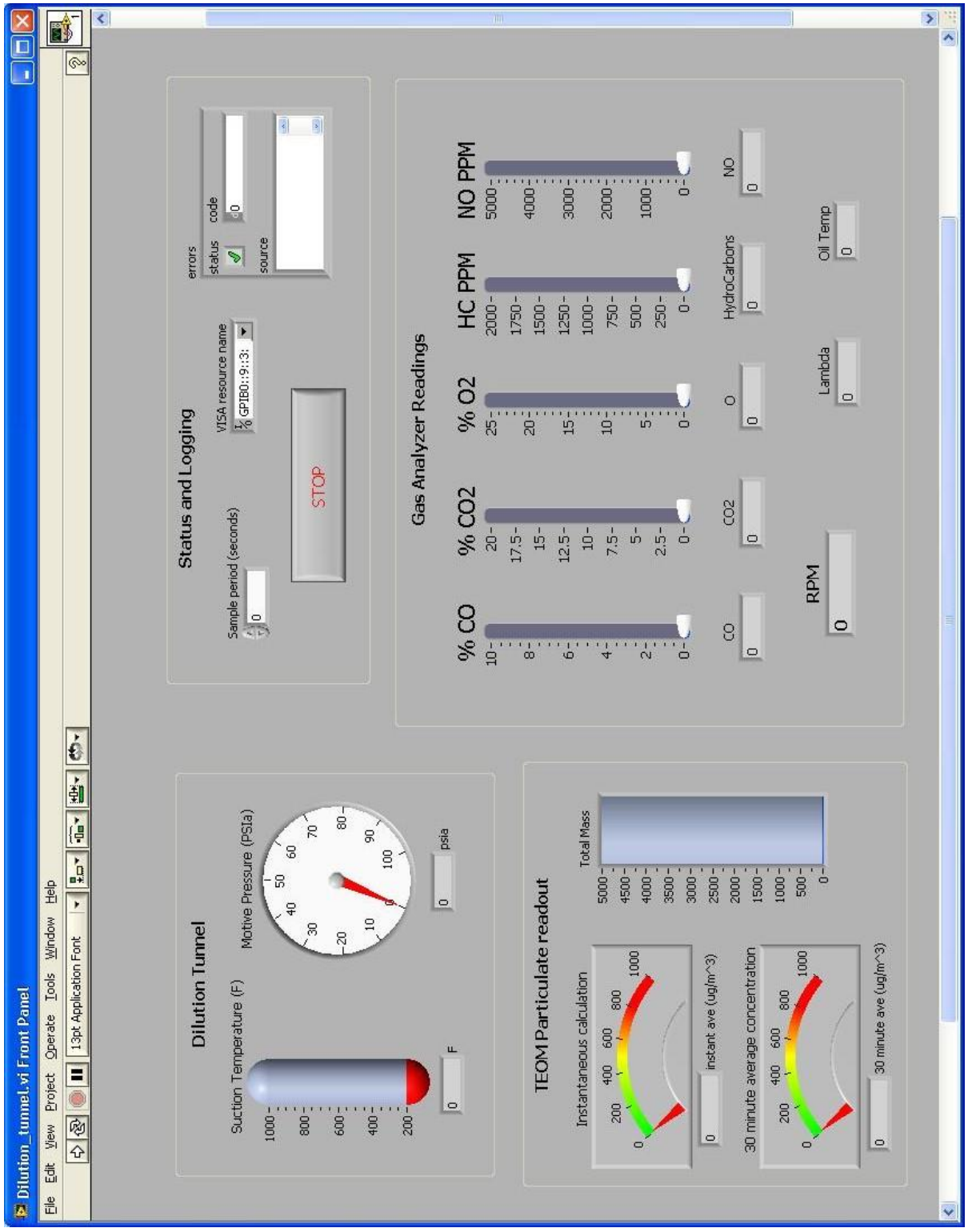
15) Connect Horiba MEXA 584L input to exhaust probe and insert probe into exhaust stream while engine is running for at least one minute. This will establish a raw exhaust baseline reading to use on dilution readings.
16) Stop logging on the Labview interface.
17) Connect Horiba MEXA 584L input to dilution tunnel line.
18) Start logging data from dilution tunnel for several minutes before stopping logging. This will establish a diluted exhaust baseline.

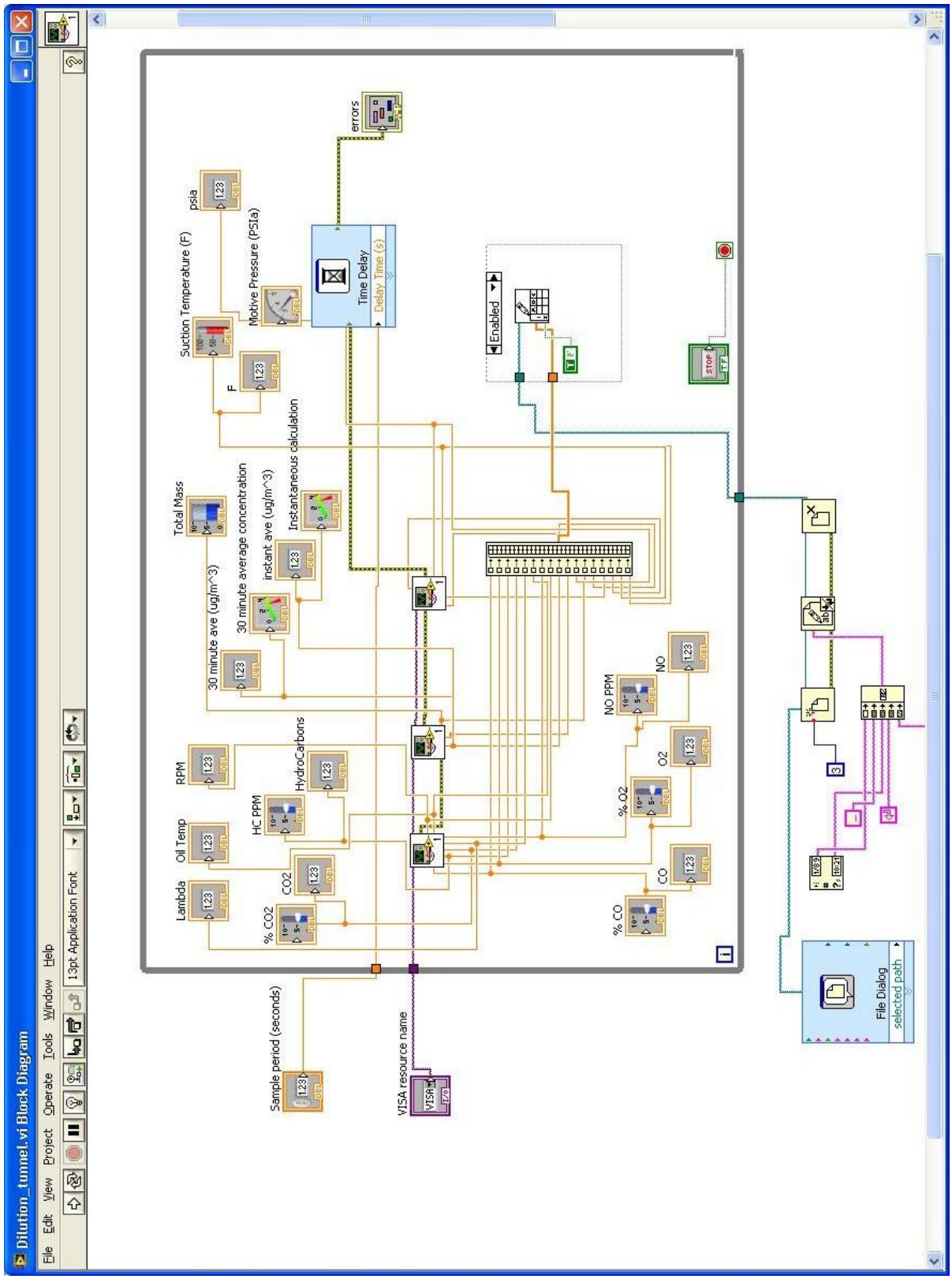
The dilution tunnel is now ready to take measurements. By comparing raw exhaust to diluted exhaust, one can determine a dilution ratio in the following way.

$$Dilution\ Ratio = \frac{\%\ CO2\ raw\ exhaust}{\%\ CO2\ diluted\ exhaust}$$

This ratio will be constant throughout testing, and can be used to convert diluted measurements into raw exhaust concentration.

Appendix B: Labview Interface

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30 minute ave (ug/m^3)
RPM
HydroCarbons
HC PPM
Oil Temp
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O2
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Sample period (seconds)
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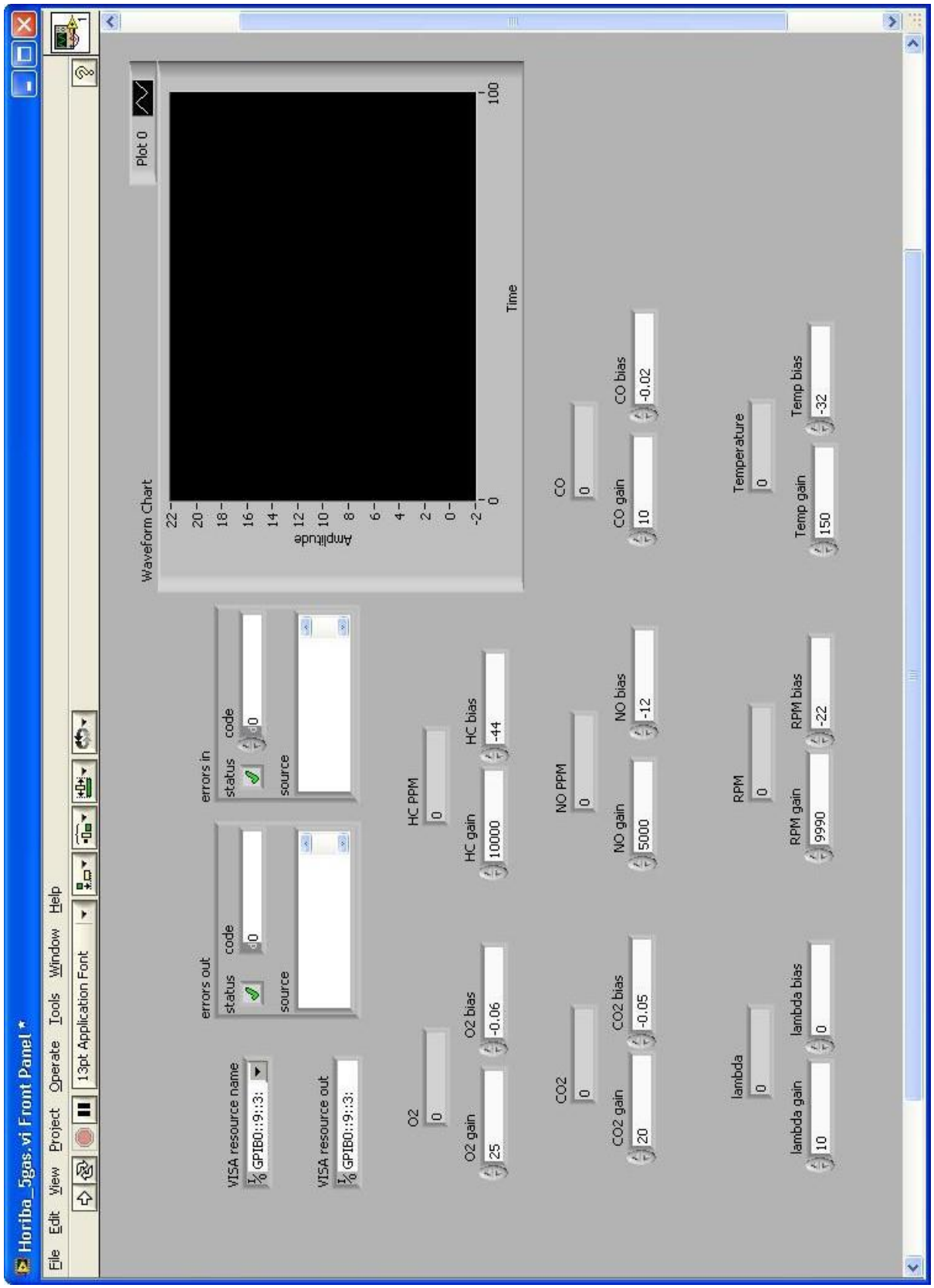
File Dialog
selected path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source
errors in
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VISA resource out
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O2 gain
O2 bias
HC PPM
HC gain
HC bias
CO2
CO2 gain
CO2 bias
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RPM
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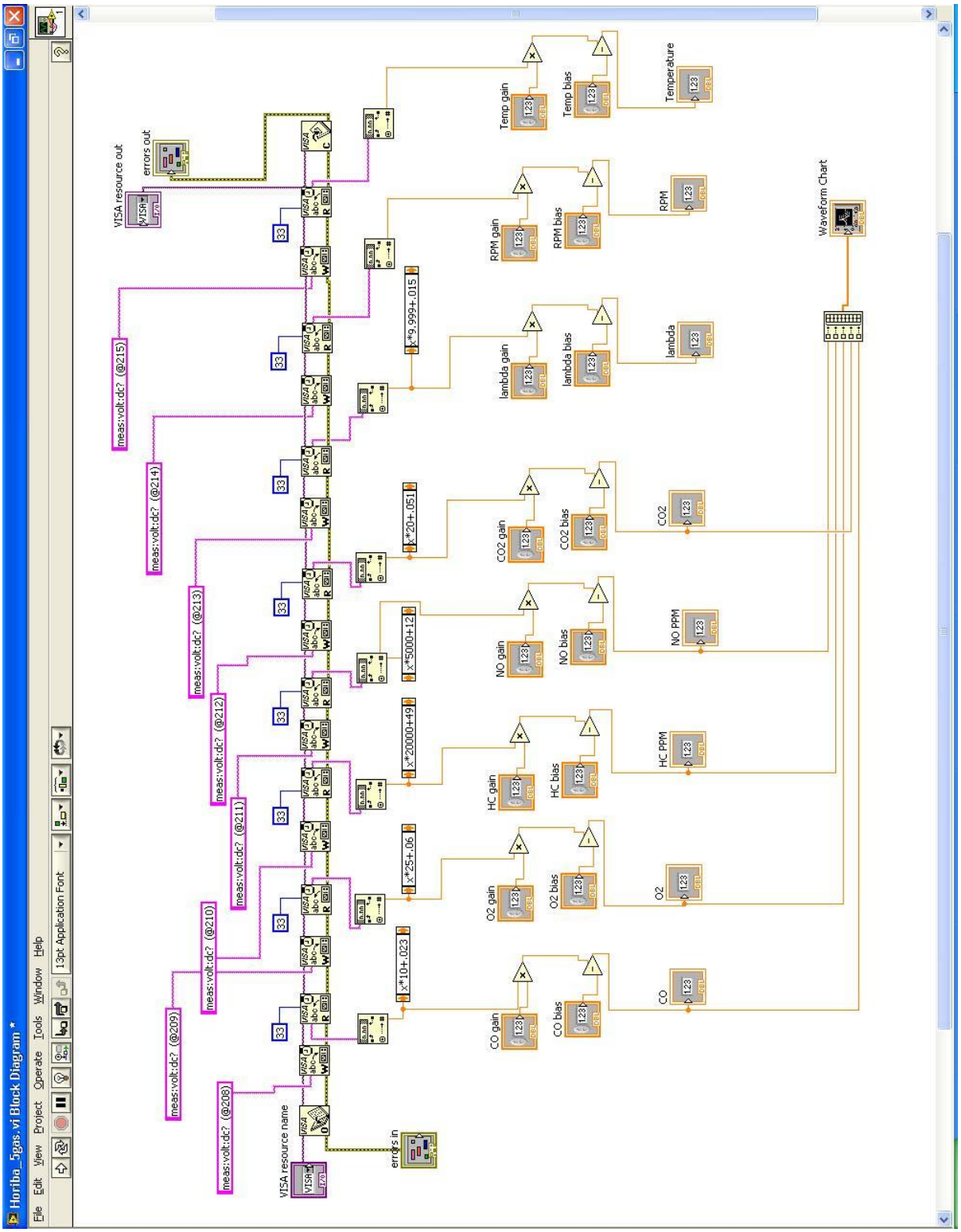
Temperature
Temp gain
Temp bias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x*20000+49
x*5000+12
x*20+.051
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CO bias
CO
O2 gain
O2 bias
O2
HC gain
HC bias
HC PPM
NO gain
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lambda bias
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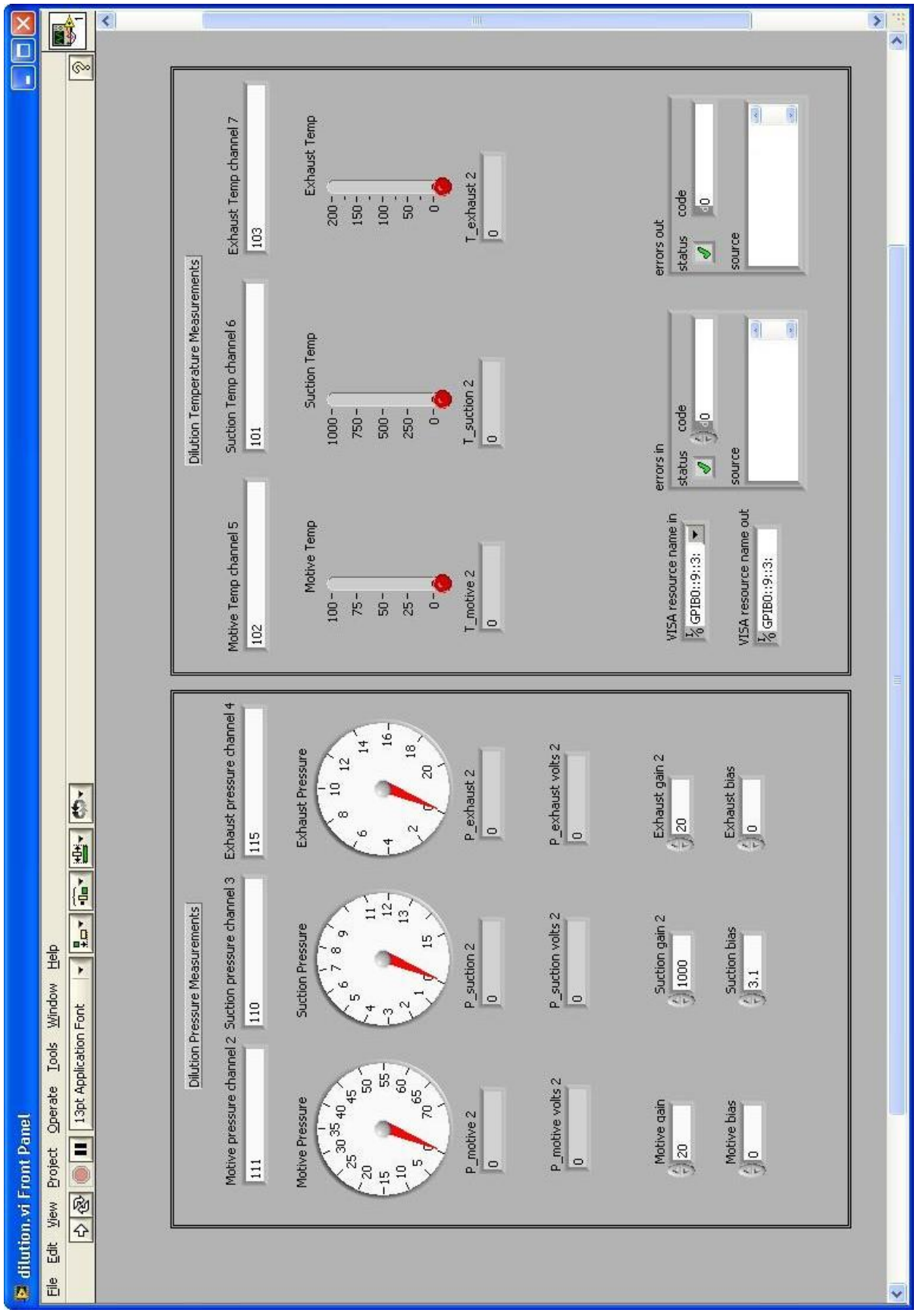
Temp gain
Temp bias
Temperature
Waveform Chart


dilution.vi Front Panel
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Dilution Pressure Measurements
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Suction pressure channel 3
110
Exhaust pressure channel 4
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Motive Pressure
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P_exhaust 2
P_motive volts 2
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P_exhaust volts 2
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Exhaust gain 2
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Exhaust bias
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Exhaust Temp channel 7
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Suction Temp
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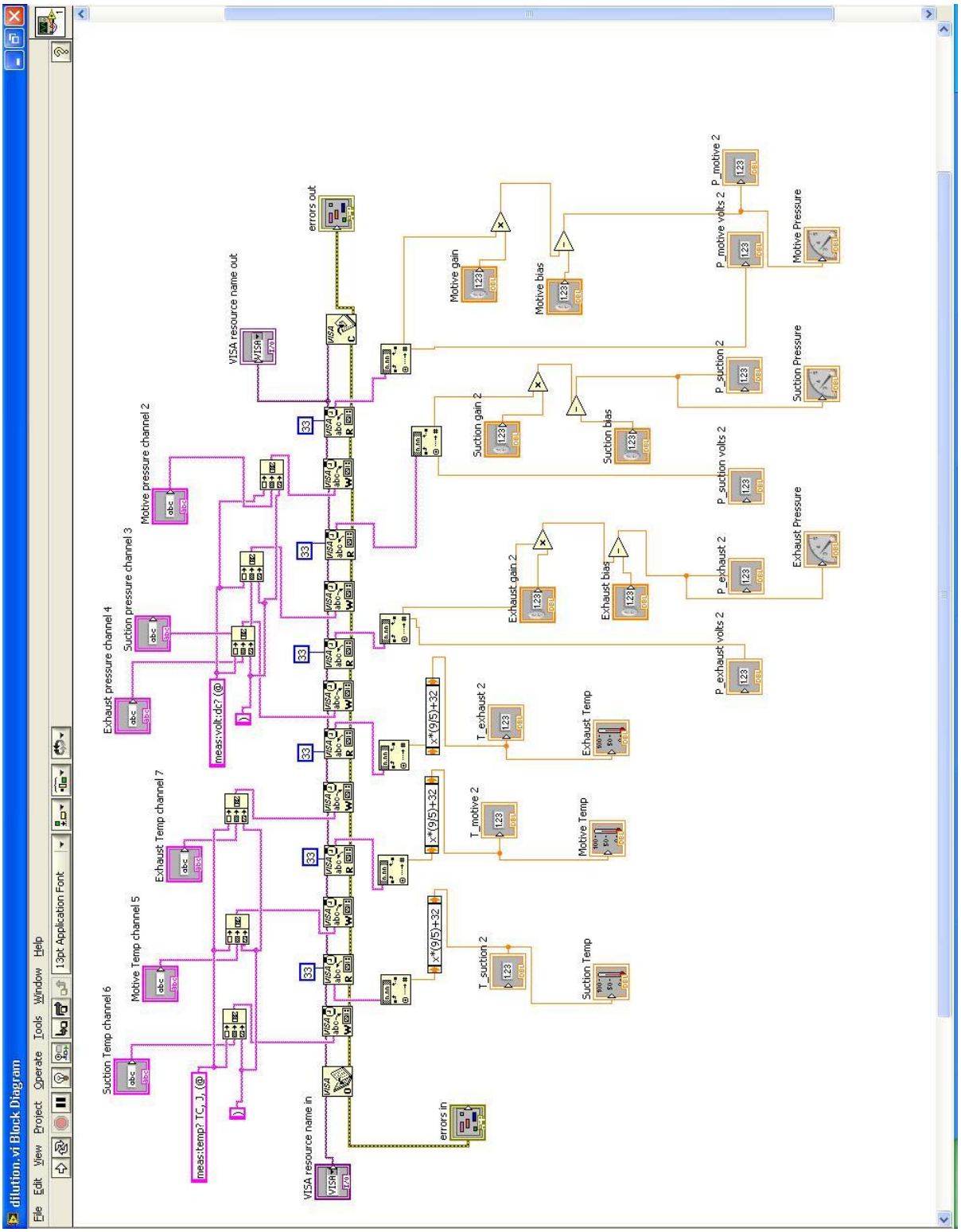
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Motive Temp channel 5
Exhaust Temp channel 7
Exhaust pressure channel 4
Suction pressure channel 3
Motive pressure channel 2
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T_motive 2
T_exhaust 2
Suction Temp
Motive Temp
Exhaust Temp
Suction gain 2
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Motive bias
Exhaust gain 2
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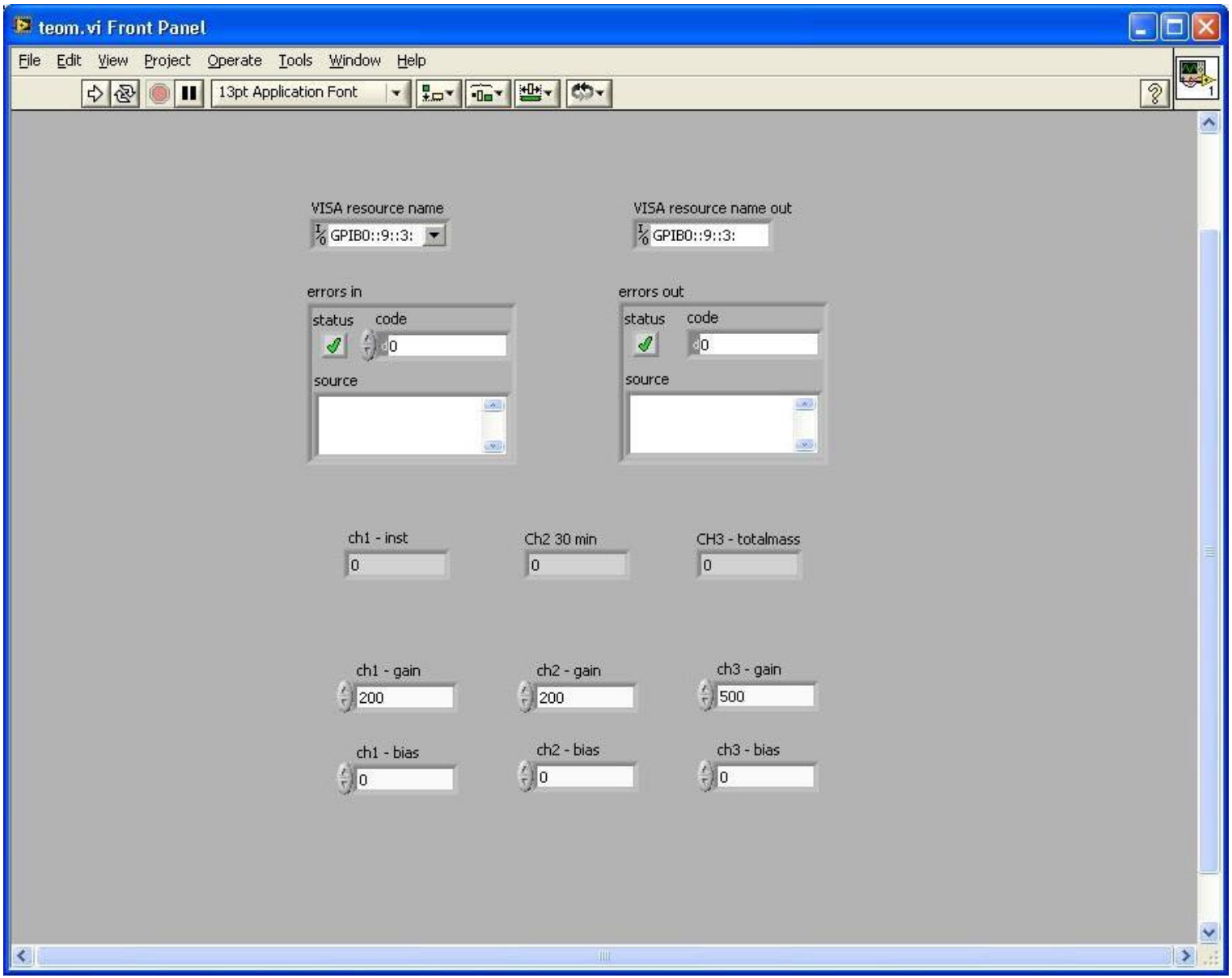
Motive Pressure
Exhaust Pressure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Ch2 30 min
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CH3 - totalmass
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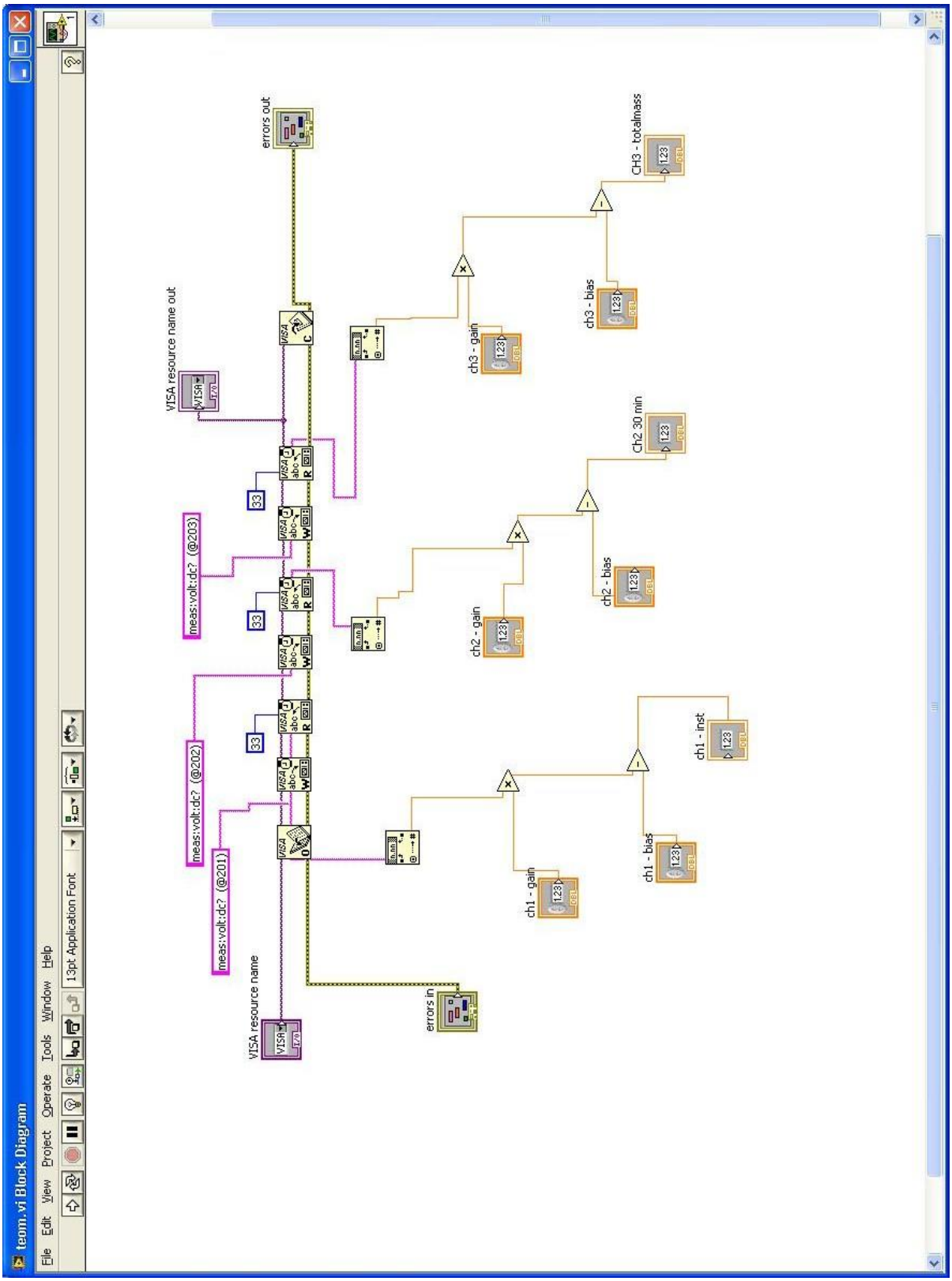
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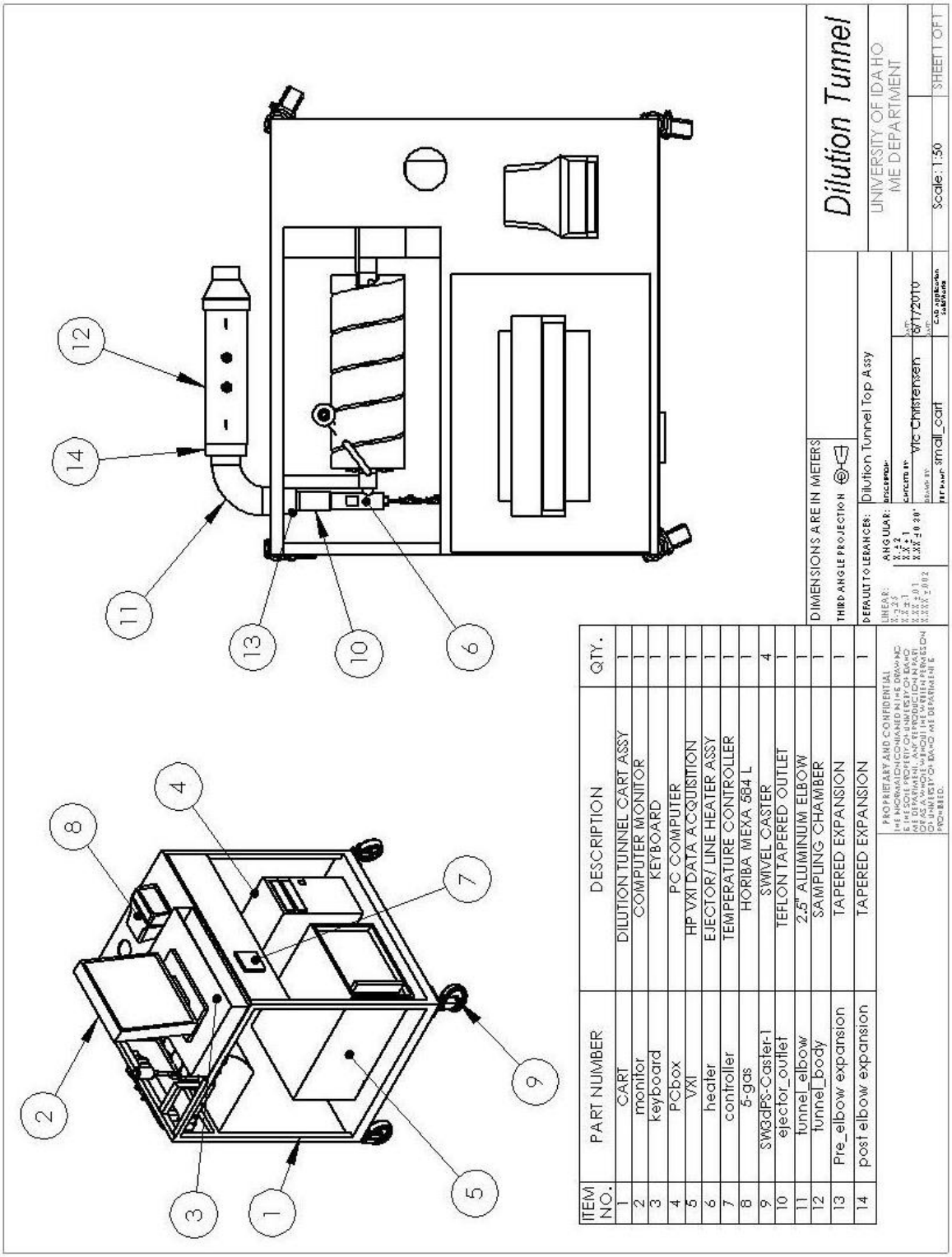
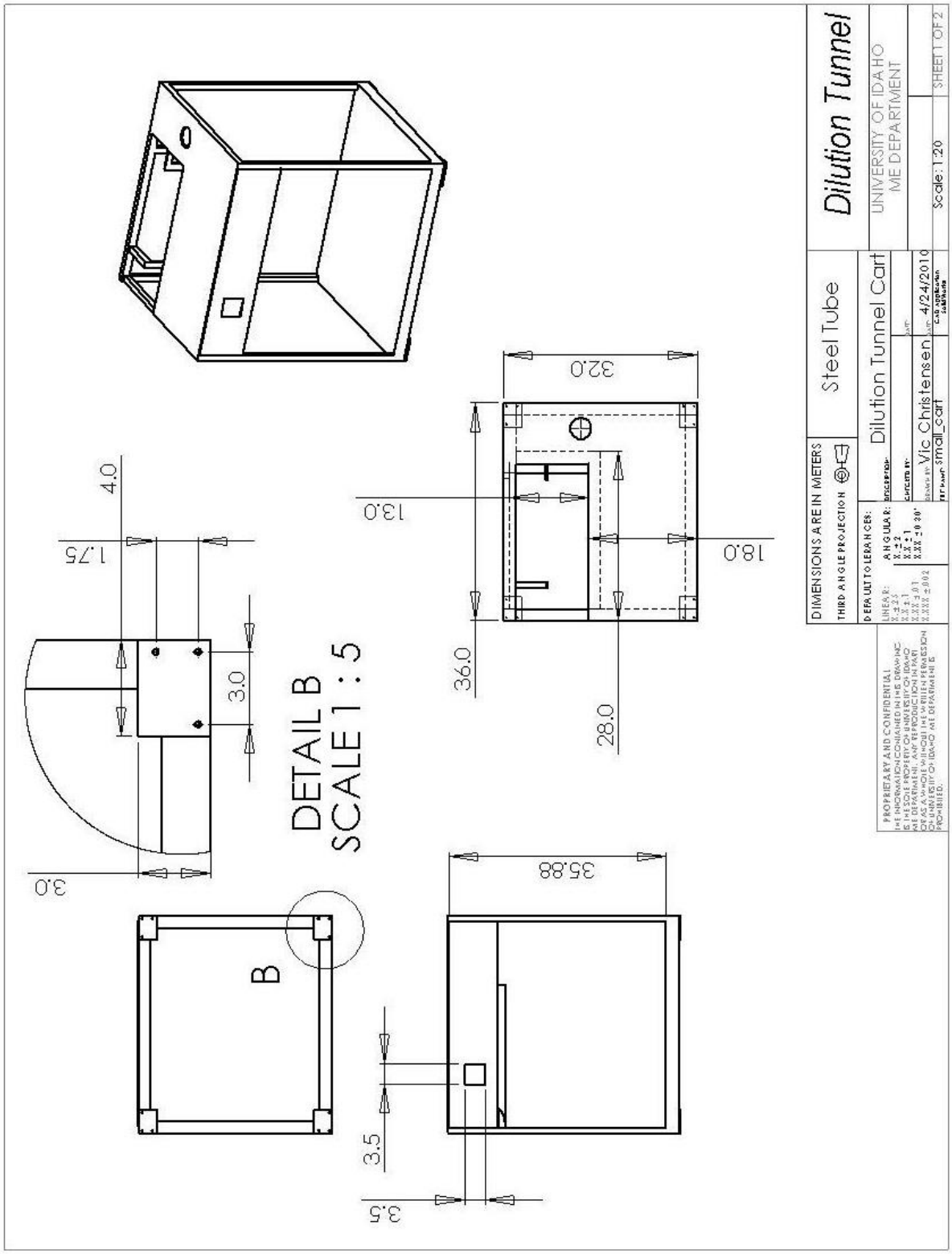
33
33
ch3 - gain
ch3 - bias
CH3 - totalmass
ch2 - gain
ch2 - bias
Ch2 30 min
ch1 - gain
ch1 - bias
ch1 - inst

Appendix C: Detail Drawings




Dilution Tunnel
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ME DEPARTMENT
Steel Tube
Dilution Tunnel Cart
DIMENSIONS ARE IN METERS
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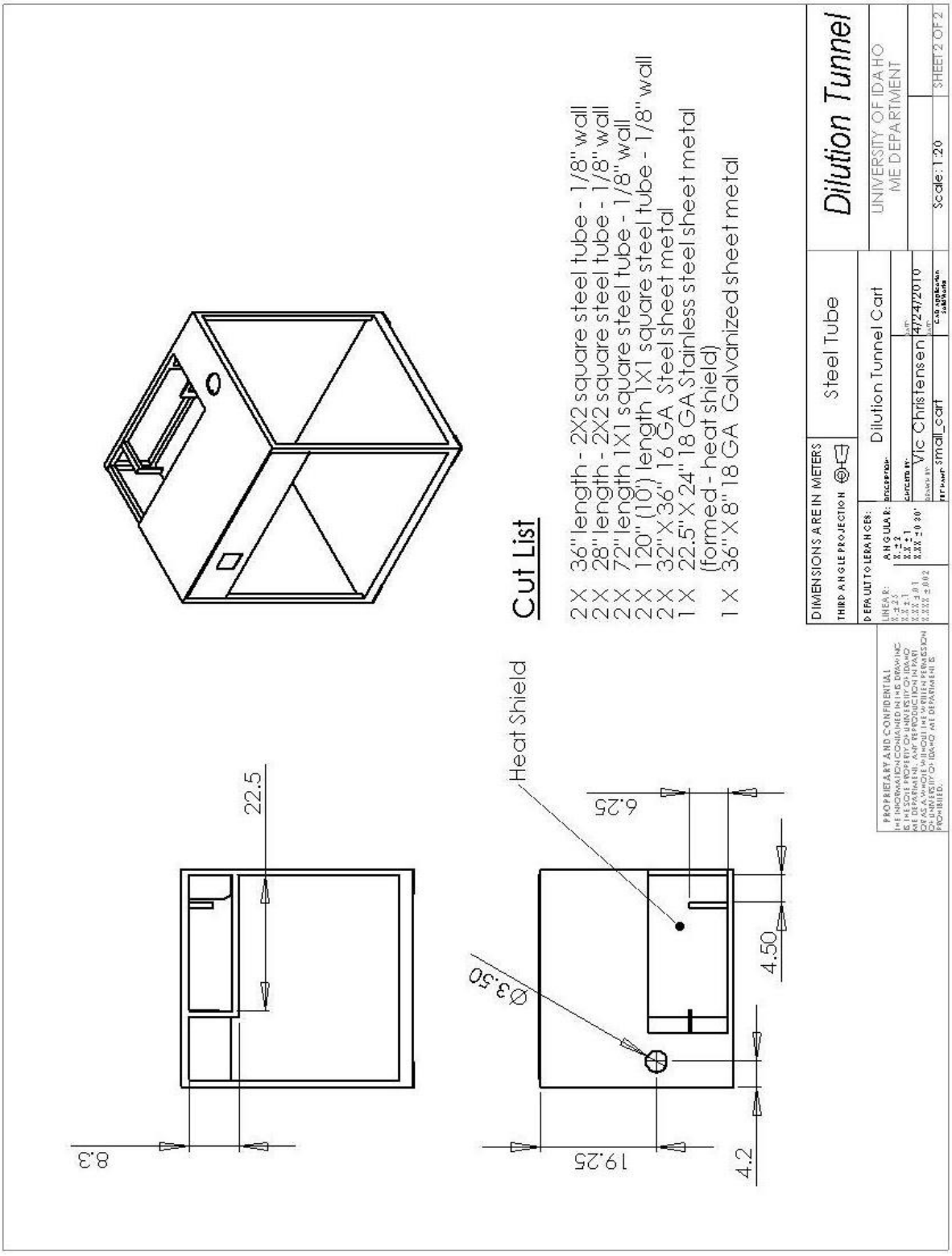
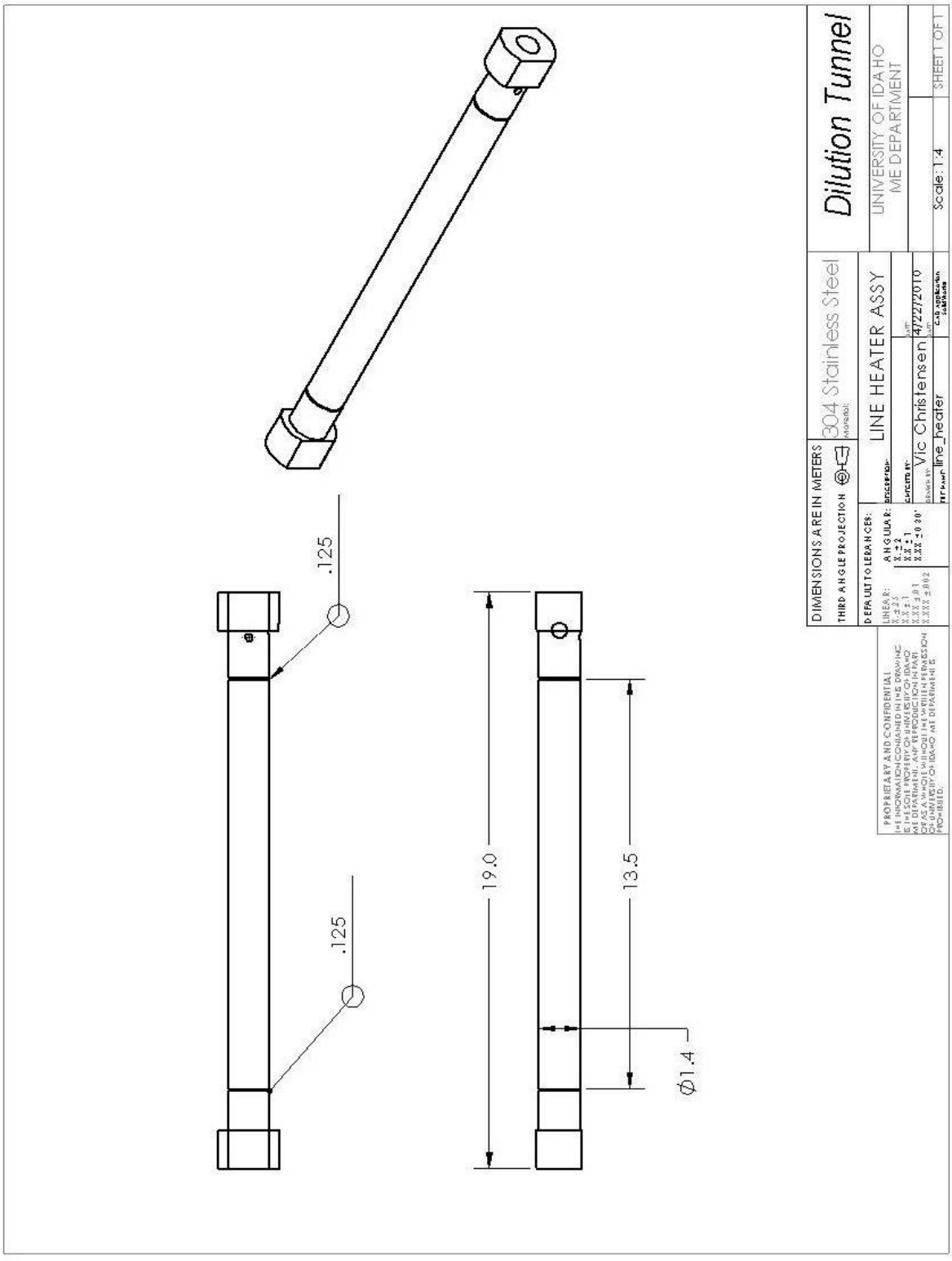
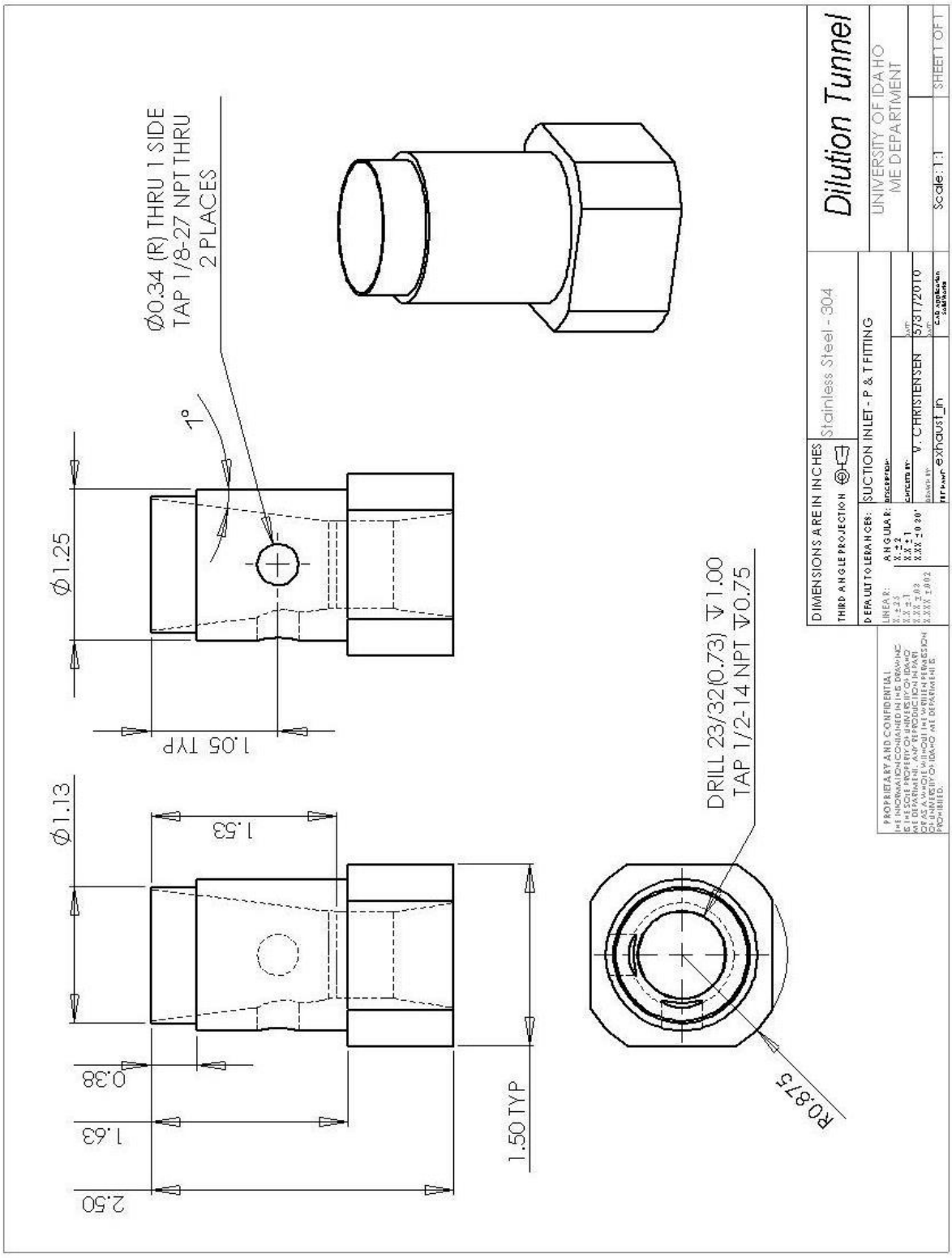
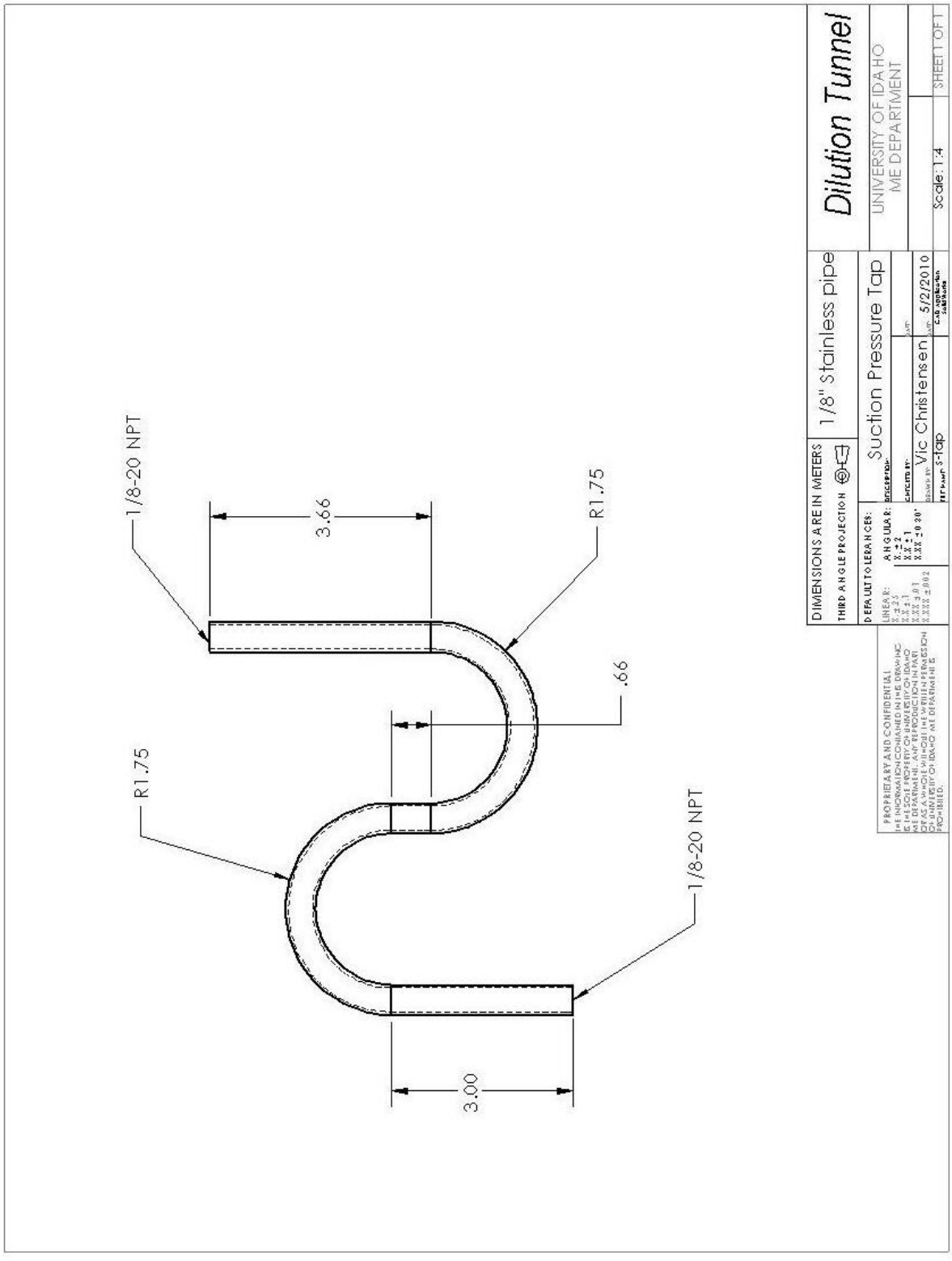
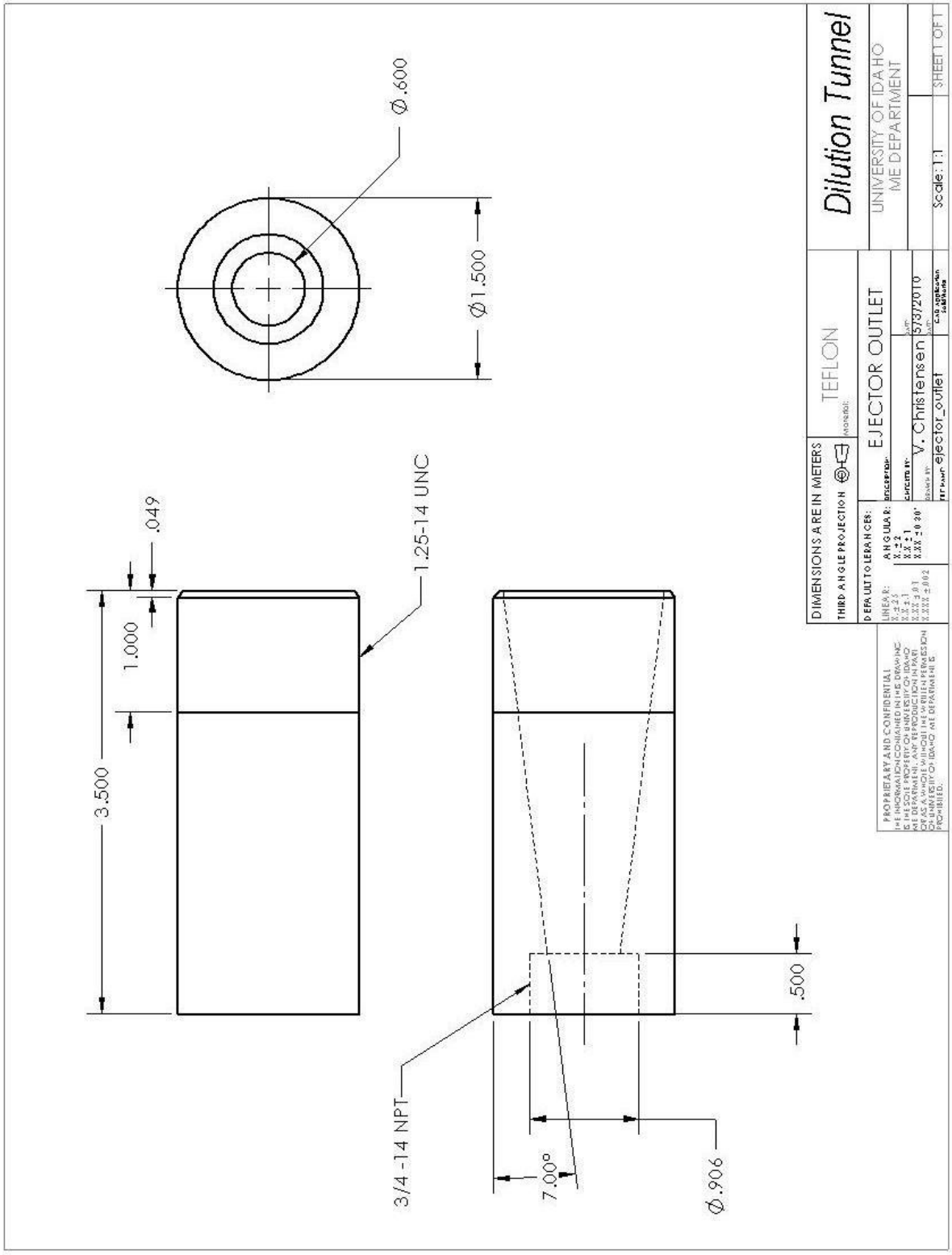
DEFAULT TOLERANCES:
LINEAR:
ANGULAR:
Vic Christensen
4/24/2010
small_cart
Scale: 1:20
SHEET 1 OF 2
PROPRIETARY AND CONFIDENTIAL
DETAIL B
SCALE 1 : 5
4.0
1.75
3.0
3.0
32.0
13.0
18.0
36.0
28.0
35.88
3.5
3.5
B

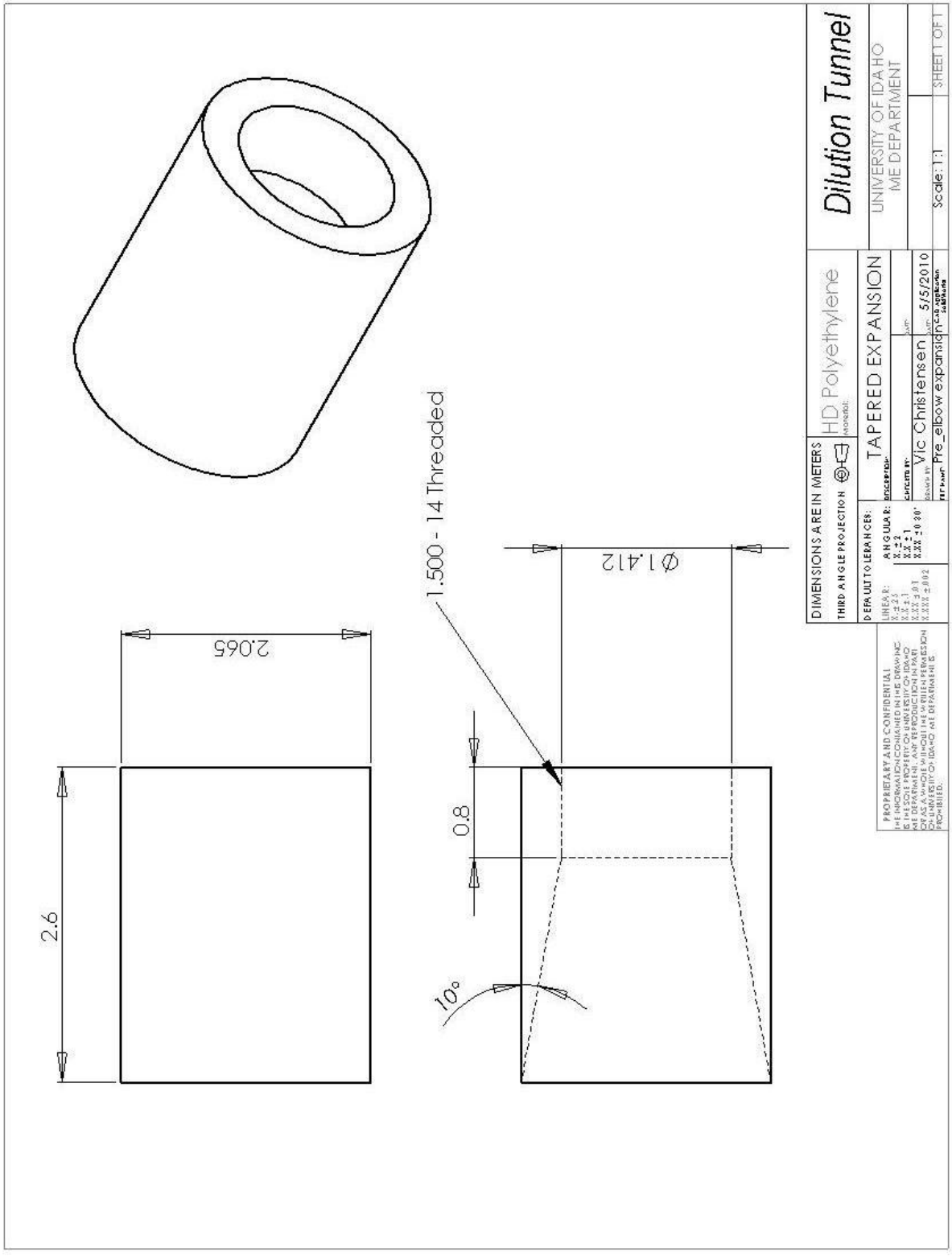

Cut List
2X 36" length - 2X2 square steel tube - 1/8" wall
2X 28" length - 2X2 square steel tube - 1/8" wall
2X 72" length 1X1 square steel tube - 1/8" wall
2X 120" (10') length 1X1 square steel tube - 1/8" wall
2X 32"X 36" 16 GA Steel sheet metal
1X 22.5"X 24" 18 GA Stainless steel sheet metal
(formed - heat shield)
1X 36"X 8" 18 GA Galvanized sheet metal
Heat Shield
Ø3.50
6.25
4.50
19.25
4.2
22.5
8.3
DIMENSIONS ARE IN METERS
THIRD ANGLE PROJECTION
Steel Tube
Dilution Tunnel
Dilution Tunnel Cart
Vic Christensen
4/24/2010
small_cart
Scale: 1:20
SHEET 2 OF 2
UNIVERSITY OF IDAHO
ME DEPARTMENT
PROPRIETARY AND CONFIDENTIAL

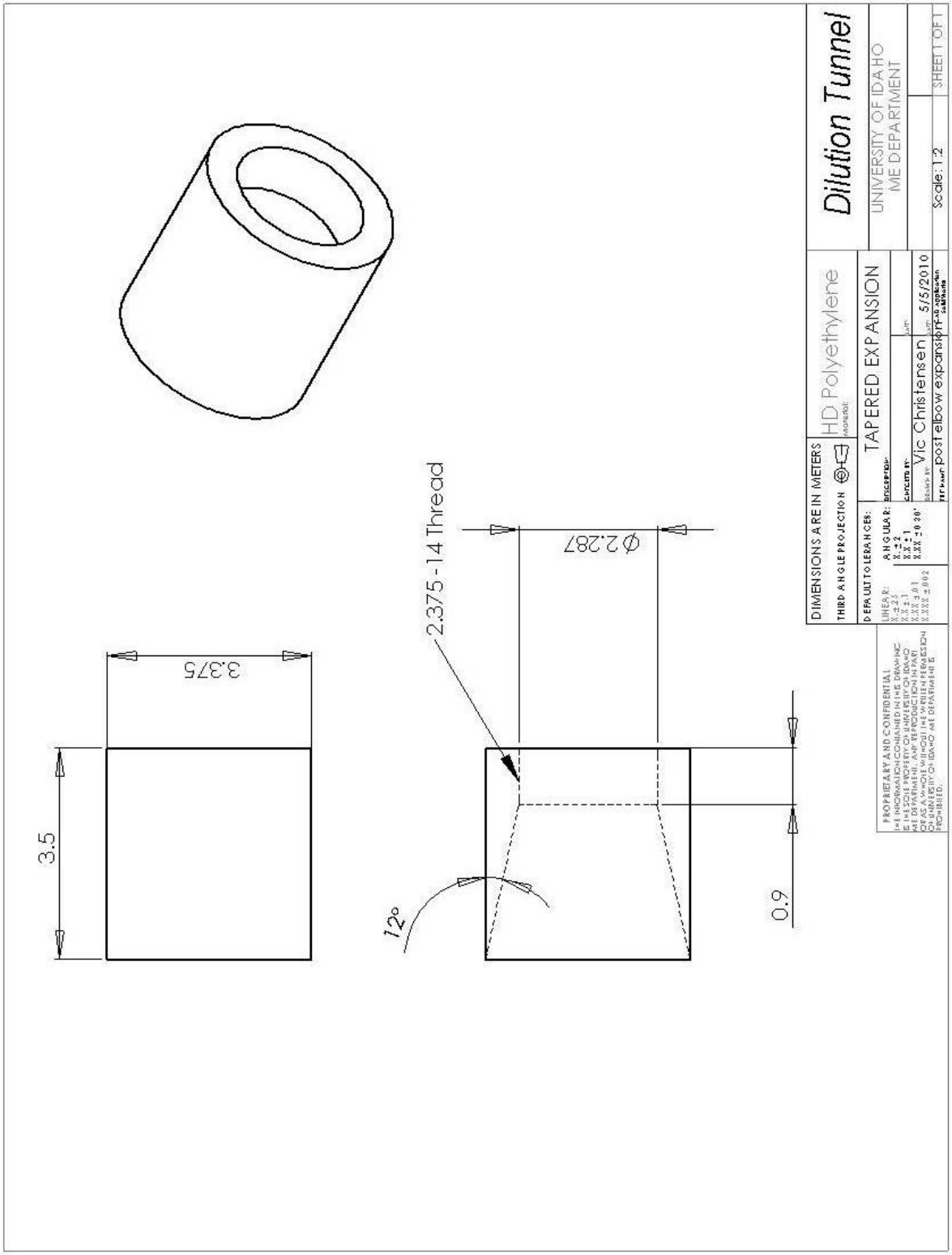

.125
.125
19.0
13.5
Ø1.4
Dilution Tunnel
304 Stainless Steel
LINE HEATER ASSY
Vic Christensen
4/22/2010
line_heater
UNIVERSITY OF IDAHO
ME DEPARTMENT
Scale: 1:4
SHEET 1 OF 1
DIMENSIONS ARE IN METERS
THIRD ANGLE PROJECTION
PROPRIETARY AND CONFIDENTIAL

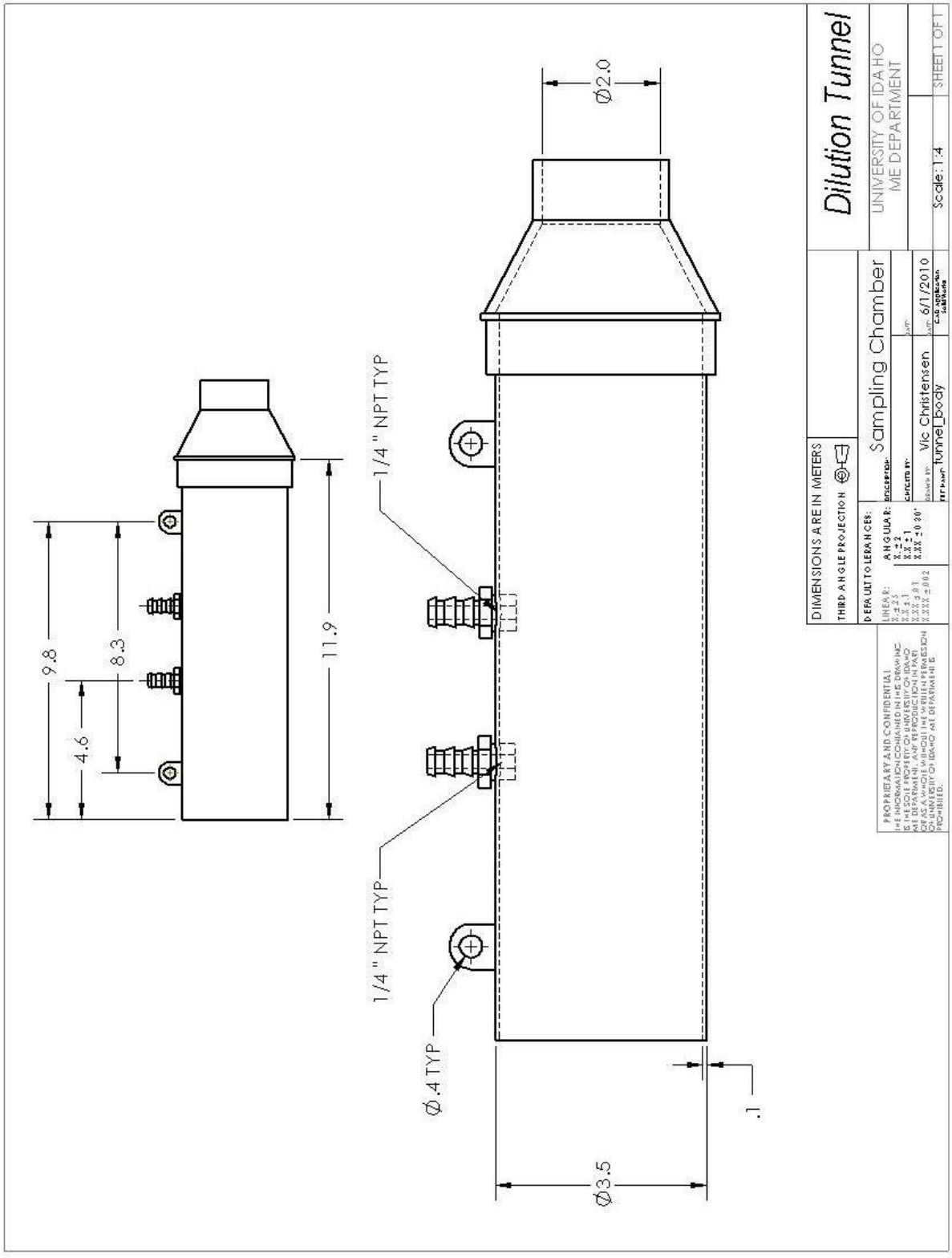

Ø0.34 (R) THRU 1 SIDE
TAP 1/8-27 NPT THRU
2 PLACES
1°
Ø1.25
1.05 TYP
Ø1.13
1.53
0.38
1.63
2.50
1.50 TYP
DRILL 23/32(0.73) ↧1.00
TAP 1/2-14 NPT ↧0.75
R0.875
DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION
Stainless Steel - 304
Dilution Tunnel
UNIVERSITY OF IDAHO
ME DEPARTMENT
DEFAULT TOLERANCES:
SUCTION INLET - P & T FITTING
ANGULAR:
V. CHRISTENSEN
5/31/2010
exhaust_in
Scale: 1:1
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL


1/8-20 NPT
3.66
R1.75
.66
R1.75
1/8-20 NPT
3.00
DIMENSIONS ARE IN METERS
THIRD ANGLE PROJECTION
1/8" Stainless pipe
Suction Pressure Tap
Vic Christensen
5/2/2010
Dilution Tunnel
UNIVERSITY OF IDAHO
ME DEPARTMENT
Scale: 1:4
SHEET 1 OF 1

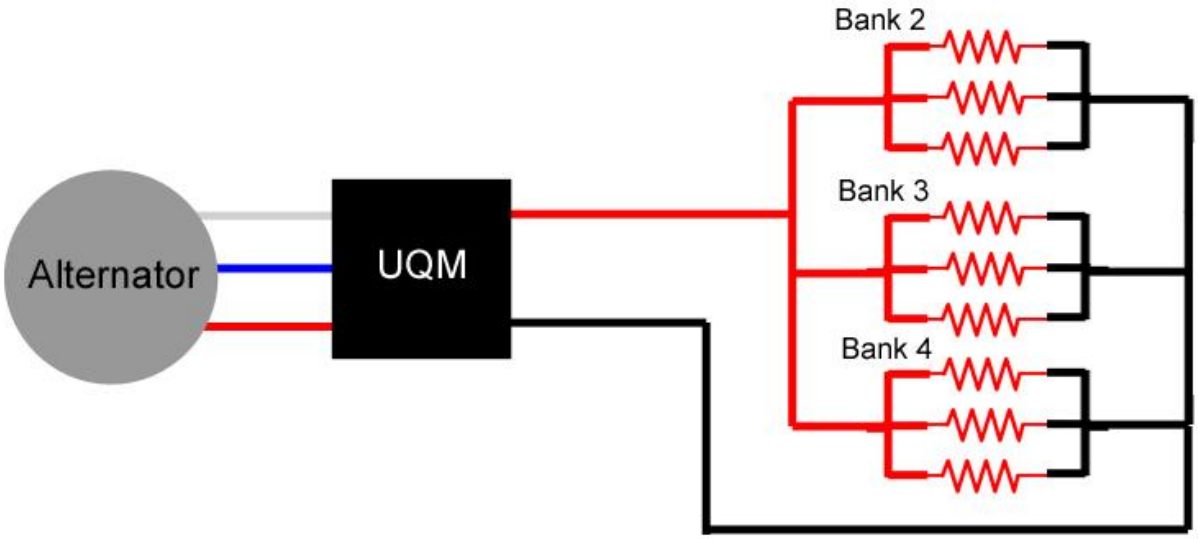

Ø.600
Ø1.500
.049
1.000
3.500
1.25-14 UNC
3/4 -14 NPT
7.00°
Ø.906
.500
Dilution Tunnel
UNIVERSITY OF IDAHO
ME DEPARTMENT
EJECTOR OUTLET
TEFLON
V. Christensen
5/31/2010
ejector_outlet
Scale: 1:1
SHEET 1 OF 1


Dilution Tunnel
UNIVERSITY OF IDAHO
ME DEPARTMENT
TAPERED EXPANSION
HD Polyethylene
DIMENSIONS ARE IN METERS
THIRD ANGLE PROJECTION
DEFAULT TOLERANCES:
LINEAR:
ANGULAR:
Vic Christensen
5/5/2010
Pre_elbow expansion
Scale: 1:1
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
1.500 - 14 Threaded
Ø1.412
2.065
2.6
0.8
10°

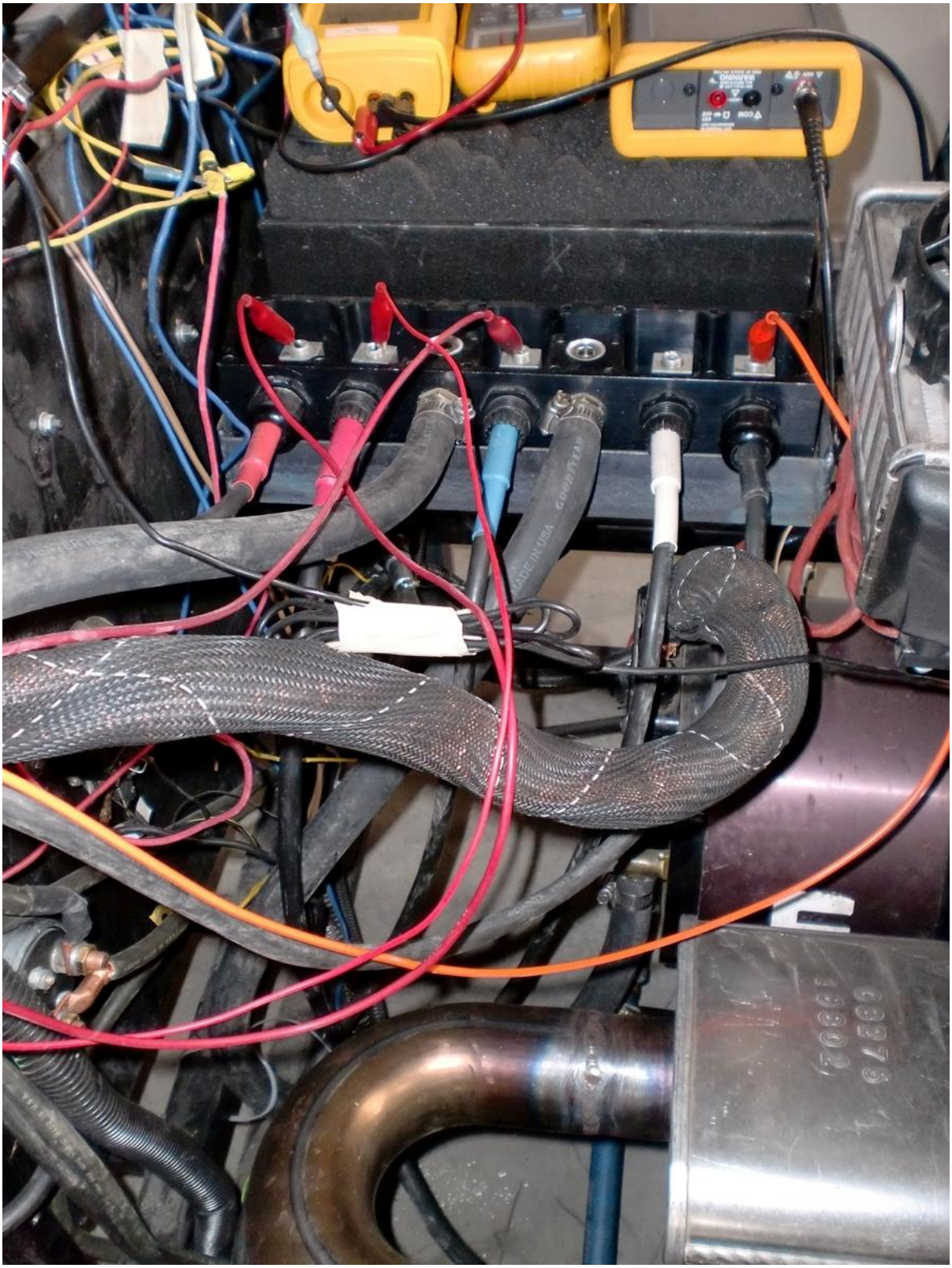

Dilution Tunnel
UNIVERSITY OF IDAHO
ME DEPARTMENT
DIMENSIONS ARE IN METERS
THIRD ANGLE PROJECTION
HD Polyethylene
TAPERED EXPANSION
Vic Christensen
5/5/2010
post elbow expansion
Scale: 1:2
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
3.375
3.5
2.375 - 14 Thread
Ø2.287
12°
0.9

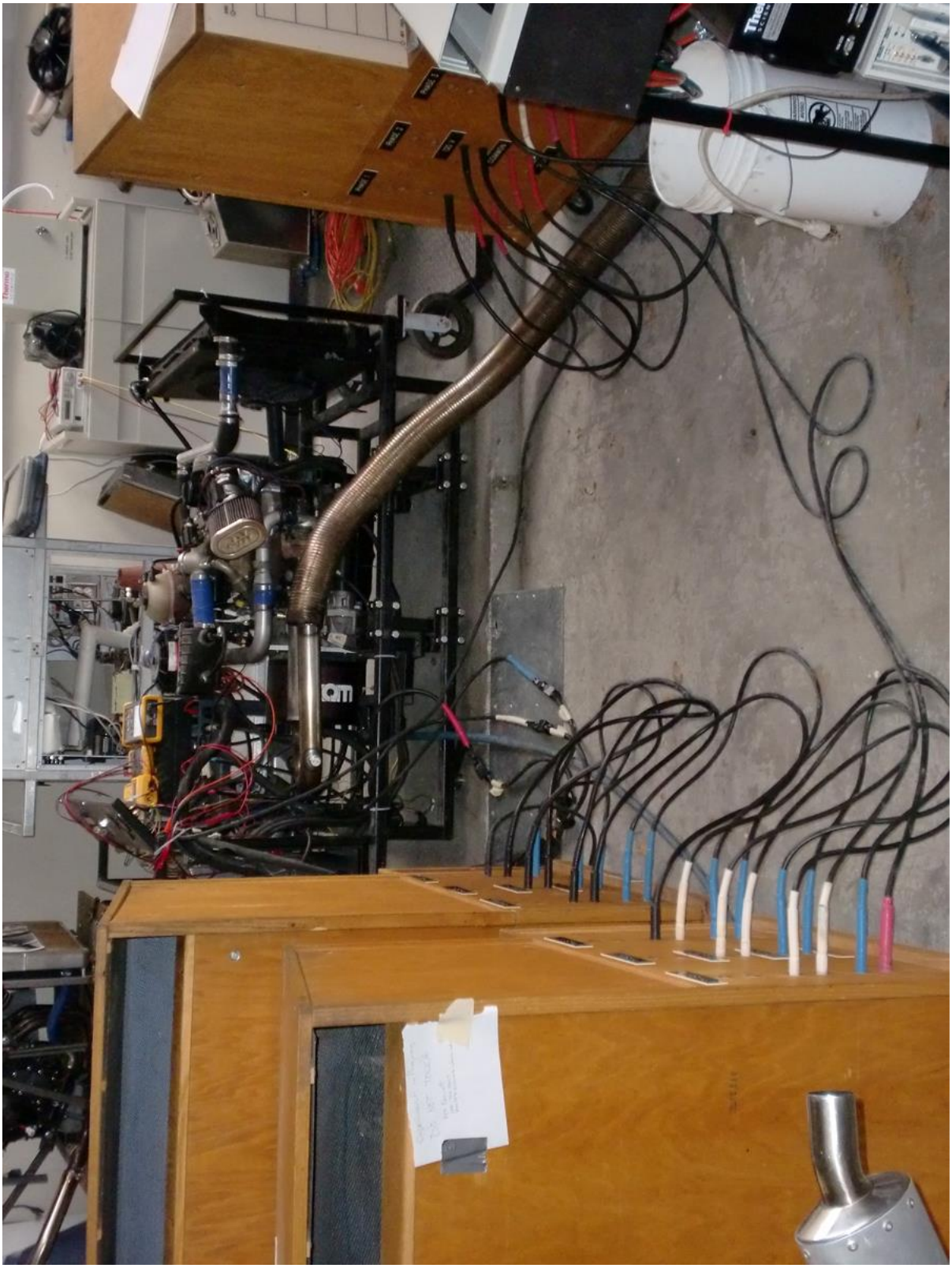

Dilution Tunnel
Sampling Chamber
Tunnel_body
Vic Christensen
6/1/2010
Scale: 1:4
SHEET 1 OF 1
UNIVERSITY OF IDAHO
ME DEPARTMENT
DIMENSIONS ARE IN METERS
THIRD ANGLE PROJECTION
DEFAULT TOLERANCES:
PROPRIETARY AND CONFIDENTIAL
Ø2.0
1/4 " NPT TYP
1/4 " NPT TYP
Ø.4 TYP
Ø3.5
.1
9.8
8.3
4.6
11.9

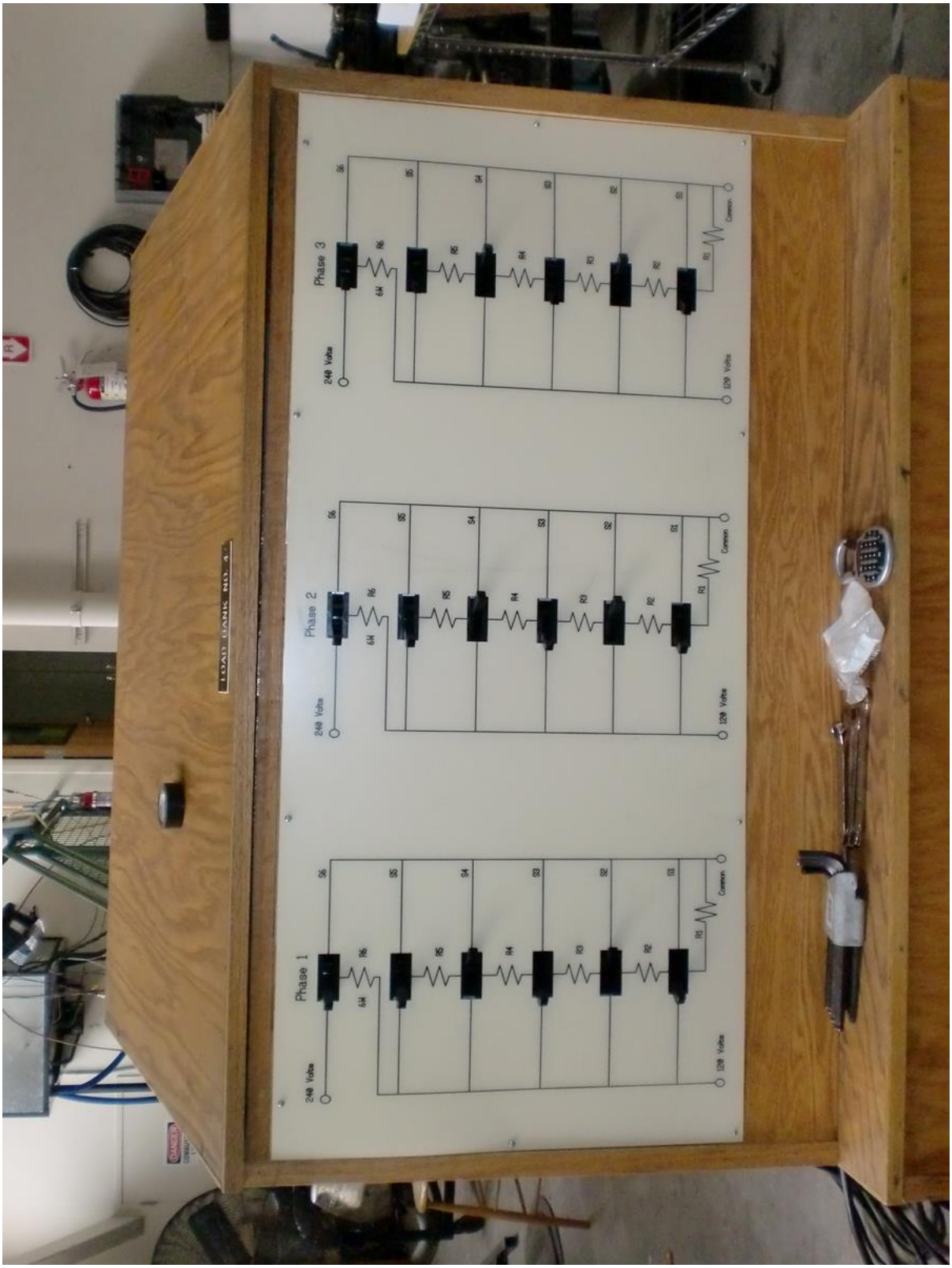
Appendix D: Resistor Bank Test Setup



To dissipate the power generated by the motor, the alternator coupled to the motor was connected to a UQM AC to DC power convertor. The DC power was routed to three resister banks each configured to have three effective resistors of 9 ohms. In all, there were 9 resistors in parallel, each having 9 ohms resistance. The theoretical total resistance is one ohm; the measured resistance was 1.3 ohms. With this configuration the resistor banks can cumulatively dissipate 30kW of power.



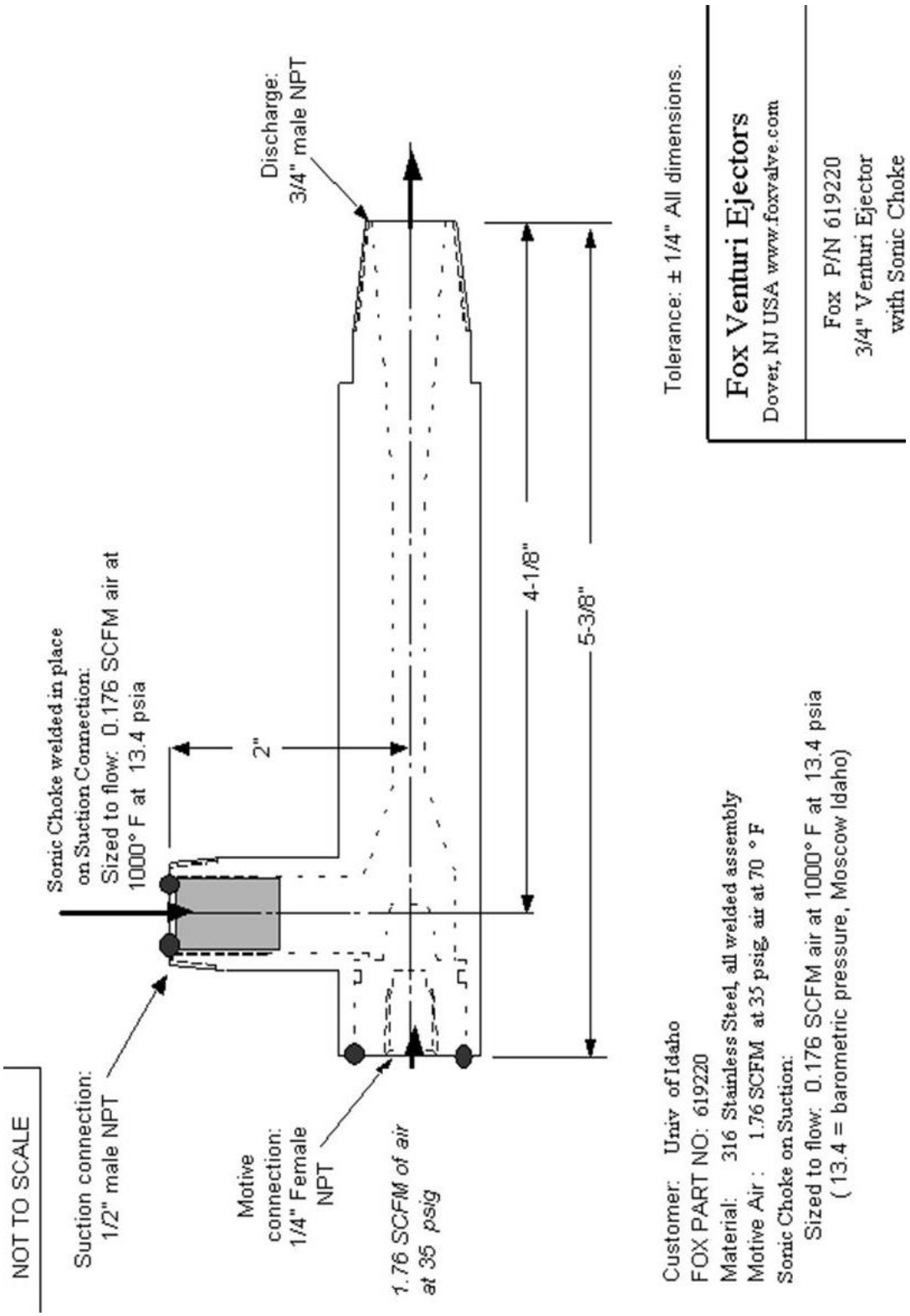



LOAD BANK NO. 4
Phase 3
240 Volts
120 Volts
Common
R1
R2
R3
R4
R5
R6
S1
S2
S3
S4
S5
S6
Phase 2
240 Volts
120 Volts
Common
R1
R2
R3
R4
R5
R6
S1
S2
S3
S4
S5
S6
Phase 1
240 Volts
120 Volts
Common
R1
R2
R3
R4
R5
R6
S1
S2
S3
S4
S5
S6


PHASE 3
PHASE 2
120 V
CO MON
PHASE 1

Appendix E: Component Specification Sheets

Fox Ejector Dilutor



Thermo Scientific TEOM 1400ab

Product Specifications

To maintain optimal product performance, you need immediate access to experts worldwide, as well as priority status when your air quality equipment needs repair or replacement. We offer comprehensive, flexible support solutions for all phases of the product life cycle. Through predictable, fixed-cost pricing, our services help protect the return on investment and total cost of ownership of your Thermo Scientific air quality products.

Ambient Particulate Monitor, TEOM 1400ab

Regulatory Designations	USEPA equivalency designation number EQPM-1090-079 as an equivalent PM-10 monitor, USEPA CACM for PM-2.5.
	German EPA approval for TSP, PM-10. Conforms with European continuous PM-10 monitoring requirements.
	Norms/approvals in Australia, Japan, Korea and Taiwan.
Safety/Electrical Designations	CE: EN550011 Group 1, Class B (Emissions); EN55082-1 (Immunity); EN61010-1 (Safety)
	ETL: UL- and CSA-equivalent approval
Standard System Configuration	TEOM Sensor Unit and TEOM Control Unit
	Menu-Driven Software for User Interaction via the Keypad
	ActiVolTM flow control using Automatic Mass Flow Controller(s) and supplied Ambient Temperature and Ambient Pressure Sensors
	Connecting and Interface Cables, and Vacuum Pump
	Consumables for average first year's operation (ambient)
	RPCOMM Software for Local or Remote Communication
	Support for the ACCUTM System
	System Configurations Include PM-10, PM-2.5, PM-1, TSP and basic
Instrument Performance (3 l/min, 1s, stable conditions)	Measurement Range: 0 to 5,000,000 µg/m³ (5 g/m³)
	Resolution: 0.1 µg/m³
	Precision: ±1.5 µg/m³ (1-hour ave), ±0.5 µg/m³ (24-hour ave)
	Minimum Detectable Limit for Mass Measurement: 10 nanograms, 0.06 µg/m³ (1-hour ave)
	Accuracy for Mass Measurement: ±0.75%
Data Averaging and Output	Real-time Mass Conc Averages: 10 min default, 10 to 3600 sec
	Long-Term Averaging: 30 min, 1, 8, and 24 hr
	Data Output Rate: every 2 sec
Operating Range	The temperature of the sampled air may vary between -40 and 60 °C.
	The TEOM Sensor and Control Units must be weather protected within the range of 2 to 40 °C.
	An optional Complete Outdoor Enclosure provides complete weather protection.
	Main Flow Rate: 0.5 to 4.0 l/min
	Auxiliary Flow Rate: 2.0 to 18.0 l/min
	Temperature of Mass Transducer: ambient to 70 °C
	Temperature of Internal Sample Tube: ambient to 70 °C
Data Storage	Internal data logging of 1 to 8 user-specified variables; capacity of 40 weeks of hourly mass concentration data.
Filter Media	Pallflex TX40, 13 mm effective diameter
Data Output and Input	Four-Line Display on TEOM Control Unit
	Two-way RS232 communication using the AK Protocol or German Ambient Network Protocol.
	3 User-Defined Analog Outputs (0-1, 0-2, 0-5 or 0-10 VDC)
	2 User-Defined Contact Closure Alarm Circuits
	7 Averaged Analog Inputs (± 2 VDC or ± 10 VDC) with user-defined conversion to engineering units, including vector-averaged wind velocity and direction.
Power Requirements	Sensor and Control Units: 120 VAC/60 Hz: 1 A; 240 VAC/50 Hz: 0.5 A
	Pump: 120 VAC/60 Hz: 4.25 A; 240 VAC/50 Hz: 2.25 A
Physical Dimensions	Base of TEOM Sensor Unit: W: 14" (36 cm) x D: 11" (28 cm) x H: 13" (33) cm;
	Heated Air Inlet of TEOM Sensor Unit: H: 26" (66 cm) x Diameter: 3.5" (9 cm); Weight: 40 lb (18 kg)
	TEOM Control Unit: W: 17" (43 cm) x D: 18" (46 cm) x H: 9" (22 cm) (rack mountable); Weight: 32 lb (15 kg)

This product is manufactured in a plant whose quality management system is ISO 9001 certified.

Lit_1400ABAQI_09/09

Air Quality Instruments
27 Forge Parkway
Franklin, MA 02038 USA
(866) 282-0430
(508) 520-0430
(508) 520-1460 fax
www.thermo.com/air

Thermo SCIENTIFIC

Horiba MEXA-584L

Specifications

- **Model:** MEXA-584L
- **Conformed standards :** • OIML Class 0 • CE • FCC
- **Application:** Exhaust gases in idling status from gasoline vehicle (two-wheel or four-wheel vehicle), LPG vehicle (four-wheel vehicle)
- **Principle:**
  - CO, HC, CO_2: non-dispersive infrared (NDIR)
  - Air-to-fuel ratio (AFR), Excess air ratio (λ, lambda): carbon balance method, or Brettshneider method (with O_2 measurement) *1
- **Measured/displayed components:**
  Measured components (standard):
  - CO: 0.00 % vol to 10.00 % vol
  - HC: 0 ppm vol to 10,000 ppm vol, or 0 ppm vol to 20,000 ppm vol *2 (as hexane equivalent value)
  - CO_2: 0.00 % vol to 20.00 % vol
  - AFR: 10.0 to 30.0
  - LAMBDA: 0.000 to 9.999

  External input components (optional):
  - O_2: 0.00 % vol to 25.00 % vol
  - NO: 0 ppm vol to 5,000 ppm vol
  - Engine speed (RPM): 0 rpm to 9999 rpm (Guaranteed range for linearity is 200 rpm to 6000 rpm)
  - Oil temperature (TEMP): 0 ℃ to 150 ℃
- **Monitor display:** LCD (black and white, 320 x 240 dot)
- **Input/outputs:**
  - Digital input/output: RS-232C (standard), RS-485 (option) *3
  - Printer: RS-232C
- **Calibration gas:**
  Dedicated cylinder
  - Mixed gas of CO, C_3H_8 and CO_2,
  - NO (for the instrument with NO analyzer (optional))
- **Environment:**
  - Ambient temperature:
    0 ℃ to 45 ℃
    5 ℃ to 40 ℃ (for OIML conformity)
  - Humidity: below 90 % as relative humidity
  - Ambient pressure: 80 kPa to 106 kPa
- **Power supply** *4: 100 V to 240 V AC
  50/60Hz, single phase
- **Power capacity:** Approx. 55 VA at stable state
- **Dimensions:**
  260(W) x 357(D) x 157(H) mm (without optional units)
- **Mass:** Approx. 4 kg (without optional units)
- **Response speed** *5, 6: Within 15 s, as Td + T95,
- **Repeatability** *5, 7:
  - CO: Within 0.01 % vol, or within 1.7 % of reading (whichever is larger)
  - HC: Within 3.3 ppm vol, or within 1.7 % of reading (whichever is larger)
  - CO_2: Within 0.17 % vol, or within 1.7 % of reading (whichever is larger)
- **Warm-up time:** 5 minutes

Options

- **O_2 sensor**
- **NO sensor**
- **Thermometer tachometer**
- **Tachometer**
- **Oil temperature sensor**
- **Serial printer**
- **Printer cable** (1.5 m)
- **Input/output cable**
  (RS-232C cable; 2.5 m, 5 m, 10 m)
- **Analog output board** (0 - 1 V)
- **Optional probe** (ϕ6/ϕ4 mm, copper pipe)
- **Drain separator** (Separately attached)
- **Motorcycle probe**

Printout example

■Remarks

*1 Air-to-fuel ration (AFR) and excess air ratio (λ) are calculated by the carbon balance method in standard configuration.
In case that an optional O_2 sensor is connected, the Brettshneider equation is applied for the calculation.
*2 For optional range for HC, 20,000 ppm vol, display resolution is 2 ppm vol within the range of 0 ppm to 4,000 ppm, and 20 ppm vol within the range of 4,000 ppm vol to 20,000 ppm.
*3 Contact HORIBA for quotation on RS-485 connection (optional). For connecting by USB, please use a RS232C/USB converter.
*4 For using the analyzer with a DC power source, please prepare a DC/AC inverter.
*5 Span gas for the performance test shall be approx. 0.5 % vol for CO, 200 ppm vol for C_3H_8 and 14 % vol for CO_2.
*6 When calibration gases are switched at sample inlet with the optional probe attached.
*7 Repeatability is described as the standard deviation of values of 20 repeated measurements. It is also corresponding with less than one third of the linearity.

Please read the operation manual before using this product to assure safe and proper handling of the product.

http://www.horiba.com e-mail: info@horiba.co.jp

Horiba continues contributing to the preservation of the global environment through analysis and measuring technology.

Omega CN2110 – T10

Specifications

Control Modes: On/off, PI-proportional with integral

Control Adjustments

Proportional Band: Sensor range
Automatic Reset: 0.0 to 99.9 repeats/min
Cycle Time: 0.1 to 60.0 sec
On/Off Deadband: 1° to 100°F or °C
Setpoint Upper Limit: Sensor range °F or °C
Setpoint Lower Limit: Sensor range °F or °C
Output Limit: 0 to 100%

Alarm Adjustments:

Type: Absolute, high or low
Setpoint: Sensor range °F or °C
Alarm Dead Band: 0 to 100°F or °C

Control/Alarm Outputs:

Relay (-R1): 1 A form A, 120/240 Vac
Relay (-R20): Form A, 120/240 Vac resistive loads at 30 s cycle time; 20 A, 500,000 operations; 15 A, 1 million operations; 5 A, 5 million operations
Solid State Relay Drive (-DC): 24 Vdc at 40 mA
Solid State Relay (-T1): 1 A, up to 240 Vac
Solid State Relay (-T5): 5 A, up to 240 Vac at 40°C
Solid State Relay (-T10): 10 A, up to 240 Vac at 40°C

Alarm: Form C, relay 5 A@ 120 Vac, 2.5 A at 240 Vac

Sensor Input: Switch selectable J, K thermocouple or RTD

Input Update Rate: 4 samples/s

Readout Stability:

J and K Thermocouple: ±1°F per 10°F change in ambient temperature
RTD: ±0.5 per 10°F change in ambient temperature

Open Sensor and Out-of-Range:

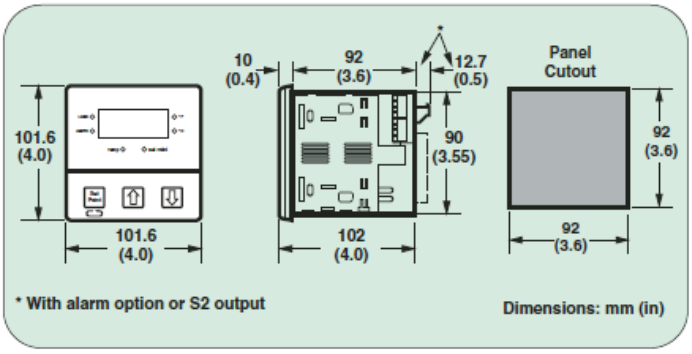
Conditions: Displays "SEnS", control output 0%

Instrument Power: 90 to 260 Vac ,<10 Va
Operating Environment: 0° to 65°C (32°to 150°F)
Enclosure Material: High-temperature ABS plastic rated for 0° to 175°F
Front Panel: NEMA 4X (IP65) construction
Influence of Line Voltage Variation: ±0.1% of sensor span per 10% change in nominal line voltage
Noise Rejection:

Common Mode Noise: <2°F with 230 Vac, 60 Hz applied from sensor input to earth ground
Series Mode Noise: <2°F with 100 mV, peak-to-peak series mode noise
RFI: Typically <0.5% of sensor span at distance of 1 m (3.1') from a transmitter of 4 W at 464 MHz

Sensor Leadwire Effect:

RTD: ±0.1% of sensor span per 20 Ω balanced leadwire resistance



* With alarm option or S2 output

Dimensions: mm (in)

Input Specifications

Input Specifications		Range °F	Range °C	Accuracy at 77°F ambient
J	Iron-Constantan	-100 to 1400°F	-73 to 760°C	0.2% span ±1 LSD
K	CHROMEGA®-ALOMEGA®	-300 to 2400°F	-184 to 1316°C	0.2% span ±1 LSD
RTD	100Ω Pt, 3-wire	-200 to 1000°F	-128 to 538°C	0.2% span ±1 LSD

MOST POPULAR MODELS HIGHLIGHTED!

To Order *(Specify Model Number)*

Model No.	Price	Description
CN2110-R1	$345	Relay, 1 A
CN2110-R20	350	Relay, 20 A
CN2110-DC	340	DC pulse 24 Vdc
CN2110-T1	345	AC SSR, 1 A
CN2110-T5	365	AC SSR, 5 A
CN2110-T10	390	AC SSR, 10 A

Comes complete with operator's manual.

Ordering Examples: CN2110-R1-AL,** controller with a 1 A relay and alarm, $345 + 25 = **$370. OCW-3,** OMEGACARE℠ extends standard 1-year warranty to a total of 4 years **($93),** $370 + 93 = **$463.

CN2110-T10,** controller with a 10 A ac SSR, **$390

Options

Order Suffix	Add'l Price	Description
-AL	$25	Alarm

Accessories* (Field Installable)

Model No.	Price	Description
2110X-R1	$55	1 A relay output module
2110X-R20	55	20 A relay output module
2110X-DC	45	DC pulse output module
2110X-T1	55	1 A, AC SSR output module
2110X-T5	110	5 A, AC SSR output module
2110X-T10	110	10 A, AC SSR output module
2110X-R1-AL	70	1 A relay output module, with alarm
2110X-R20-AL	80	20 A relay output module, with alarm
2110X-DC-AL	70	DC pulse output module, with alarm
2110X-T1-AL	70	1 A, AC SSR output module, with alarm
2110X-T5-AL	150	5 A, AC SSR output module, with alarm
2110X-T10-AL	150	10 A, AC SSR output module, with alarm
DPP-6	575	¼ DIN panel punch

Alarm relay built into output module. If ordering a replacement module for existing controller with alarm, must specify accessory module with "-AL**" suffix.*