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The Design of an Exhaust Sampling System for the Measurement of Diesel Exhaust Constituents

By

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ABSTRACT

The exhaust sampling system using California Analytical Instruments (CAI) analyzers was re-designed to provide increased functionality, reduced down time, and reduced maintenance costs. The project phases consist of concept formulation, initial design formulation, detailed design, and final assembly. The performance of the sampling system is verified by conducting a dynamometer test using a diesel engine as an exhaust source. Data was acquired on two different days to eliminate any unforeseeable issues that may have arisen from the design and fabrication process. Simple design changes were made after the first trial and those changes were validated through the second test trial. It was concluded that a functional sampling system can be designed and constructed in-house. It was also demonstrated that the thermoelectric sample gas chillers used in the design of the sampling system are capable in delivering a consistently dry sample provided the sample pressure and ambient temperature are kept stable.

DEDICATION

I dedicate this work to my parents, Hana and Nadiya, whom without their continuous love, support, guidance, and believing in the importance of one’s education; graduate studies would not have been possible.

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I would like to express my gratitude and appreciation to my advisors, Dr. J. Tjong and Dr. A. Sobiesiak for their guidance and continued support. I would also like to thank my committee members, Dr. G. Rankin, Dr. P. Henshaw, and Dr. B. Minaker for their support and comments.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

BCB	Polycyclic Biphenyls
BOM	Bill of Material
CAAA	Clean Air Act Amendments
CARB	California Air Resources Board
CLD, HCLD	Chemiluminescent Detector
EEP	Essex Engine Plant
EGR	Exhaust Gas Re-circulation
ELR	European Load Response
EPA	Environmental Protection Agency (USA)
ESC	European Stationary Cycle
ETC	European Transient Cycle
EU	European Union
EUDC	European Urban Driving Cycle
FID	Flame Ionization Detector
FTIR	Fourier-Transformed Infrared
FTP	Federal Test procedure
GVWR	Gross Vehicle Weight Rating
HCHO	Formaldehyde
HHDDE	Heavy Heavy-Duty Diesel Engines
LAFY	Los Angeles Freeway Cycle
LANF	Los Angeles Non-Freeway Cycle
LDV	light-Duty Vehicles
LEV	Low Emission Vehicle
LFR	Lean Flame-out Region
LHHDE	Light Heavy-Duty Diesel Engines
LPM	Liters per Minute
MDPV/MDV	Medium-Duty Passenger Vehicles
MHDDE	Medium Heavy-Duty Diesel Engines
NDIR	Non-Dispersive Infrared Detector
NEDC	New European Driving Cycle
NMHC	Non-Methane Hydrocarbons
NMOG	Non-Methane Organic Gas
NOx	Nitrogen Oxides Emissions (Grouped)
NYNF	New York Non-Freeway Cycle
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
PPM	Parts Per Million
PTC	Poly-chlorinated terphenyls
PTFE	Polytetraflouroethylene (Teflon^{TM})
SBC	Standard Bench Cycle
SCFM/CFM	Standard Cubic Feet per Minute

SFTP	Supplemental Federal Test Procedure
SO4	Sulphate Particles
SOF	Soluble Organic Fraction
SOL	Particulate Matter Solid Fraction
SRC	Standard Road Cycle
SUV	Sport Utility Vehicle
THC	Total Hydrocarbons
TLEV	Traditional Low Emission Vehicle
TPM	Total Particulate Matter
ULEV	Ultra Low Emission Vehicle
ULSD	Ultra Low Sulfur Diesel
ZEV	Zero Emission Vehicle

1 INTRODUCTION

1.1 Introduction

The latest emissions targets mandated by government regulating bodies such as the EPA and the European Commission are much lower than the regulations already in place today. By 2010; automakers and engine manufacturers must meet these targets to avoid legal problems, bad press, production disruptions, and heavy taxation. Arguably, the hardest task falls upon diesel engine manufacturers. Historically, diesel engines have been the most popular choice for public transit, off-highway construction machinery, and medium- to heavy-duty trucks due to their excellent fuel economy, durability and low maintenance. However, diesel engines; while emitting fewer emissions by volume than gasoline engines; have been more polluting than their counterparts. This is due to the difficulties faced when dealing with diesel exhaust. Diesel exhaust varies widely in temperature; making it very hard to apply traditional catalytic conversion methods as they require high temperature and near stoichiometric air/fuel ratio. The approach taken by engine manufacturers to "clean" diesel exhaust is to heavily invest in new technology requiring continuous and expensive development and testing. Extensive dynamometer testing utilizing advanced emissions analyzers and sampling systems are required to determine the effect of the new technology on the emissions produced. This constitutes long hours of testing, sometimes up to 2000 hours per test to accurately determine the effectiveness of such devices as EGR coolers, particulate filters, and diesel catalysts.

However, the diesel exhaust is considered to be corrosive and if not conditioned properly during the sampling phase; it can be very harmful to the emission analysis instruments. These instruments are sensitive and precise equipment and require the exhaust sample to be supplied at a specific temperature range, pressure, and mostly moisture-free. The current sampling systems of the emissions analyzers used at the Powertrain Engineering Research and Development Center (PERDC) were examined in order to determine the best possible design for a sampling system that will ensure long hours of uninterrupted operation for these analyzers. This sampling system will also have to be robust, easy to maintain, and were ensure that the sample delivered to the analyzers will be filtered, pressure-regulated, moisture-free, and within the acceptable temperature range. The proposed emissions analyzer bench was tested to verify the integrity and the safety of the design

1.2 Research Methodology

The methodology utilized in this thesis was as follows (detailed in chapter 3):

1. Finalize a design concept based on the literature reviewed and observations made and lessons learned at the Powertrain Engineering Research and development Center (PERDC).
2. Provide detailed drawings and specifications for all the systems and components used in the sampling system.
3. Select and order the necessary components.
4. Fabricate and machine the necessary components.
5. Assemble the emissions bench and connect the emissions analyzers to the sampling system and to the electrical system.
6. Validate and test the various sub-systems or sub-assemblies. Make the necessary changes or improvements based on the results of these tests.
7. Conduct final testing in an engine test cell to verify that the complete system is functional and meets requirements.

1.3 Testing and Data Collection

The testing phase of this project consisted of several stages:

1. The first stage was to test the new emissions bench for proper installation and workmanship. This was performed outside the test cell to verify that all the systems were working properly and that there are no leaks. The three emissions analyzers were calibrated before engine testing.

2. An engine test was setup cell with a 6.4L turbo-diesel V8 engine and the emissions bench was connected to the exhaust stream via a specially-designed sampling probe assembly. Exhaust data was collected over a period of time to test for stability and robustness of the design under continuous testing. This phase also allowed for the verification of the different sampling system components and that they were performing as intended, such as, the chillers, heated transfer lines, and temperature controllers. The exhaust emission data was collected using a state-of-the-art data acquisition system supplied by ETAS Group and setup specifically for the emission bench.

1.4 Thesis Outline

A brief look into emission standards is presented in the literature review section. The literature review also examines the composition of diesel exhaust and what distinguishes it from gasoline exhaust. Finally, the review section finishes with a detailed examination of the technology behind the exhaust analyzer instruments used in the experimental work of this thesis and why it is so important to protect against the corrosiveness of diesel exhaust. Chapter three details design concept formulation and the methodology used to arrive at the proposed design. Chapter four discusses the detailed design of the sampling system using the CAI emissions analyzers. Chapter five details component fabrication and the assembly process of the exhaust bench. Chapter six describes the commissioning process and the data that were acquired are presented, followed by conclusions and final recommendations in chapter seven.

2 REVIEW OF LITERATURE

This chapter is a review of the technology and the scientific facts related to this research. The sections below start by discussing the emission regulations that are the main catalyst driving engine technology. It also reviews the composition of diesel exhaust and finishes with a detailed examination of emission measurement and analysis technology and its underlying fundamentals.

2.1 Exhaust Emissions Regulations in the United States

Automotive exhaust emissions in the United States are regulated by the Environmental Protection Agency (EPA) and the California "Air Resources Board" (CARB) [1]. California is the only state with the authority to establish its own emissions regulations; the other states have the choice of adopting the federal standards regulated by the EPA or adopting California's own standards that are put forth by CARB [7]. Emission thresholds were first enacted into law in 1968 through the introduction of the Clean Air Act. These standards were later updated in 1977 introducing further restrictions that helped reduce emissions by 90% compared to the levels of 1973 [1]. The Clean Air Act was amended again in 1990; which is the most recent update [7].

The Clean Air Act amendments of 1990 define two sets of standards [7]:

- Tier 1: These standards where published in 1991 and phased in between 1994 and 1997.
- Tier 2: This set of standards was adopted in 1999 and phased in between 2004 and 2009.

The Tier II standards are structured into 11 certification levels, 8 permanent and three temporary levels, all called certification bins. In order to ease the phasing period for manufacturers, they are required to certify their products into any of these bins [7]. However, when these standards were implemented in 2009; the average NOx emissions for the entire light-duty vehicle (LDV) fleet sold had to meet the average NOx standard of 0.07 g/mile. The temporary bins (9, 10, and 11) had more relaxed standards and were expired after the 2008 model year (MY) [10]. Table 2.1 shows the emission standards for all bins tested using the Federal Test Procedure (FTP 75) for cars and light-duty trucks and are measured in g/mile. From this table we can see that manufacturers have the choice to certify for an intermediate life of 5 years or 50,000 miles whichever comes first, or for a full useful life of 150,000 miles.

Table 2.1: Tier II Emission Standards for Cars and Light-Duty Trucks, FTP 75, g/mi [7]

Bin#	Intermediate life (5 years/50,000 mi)					Intermediate life (5 years/50,000 mi)				
	NMOG*	CO	NOx	PM	HCHO	NMOG*	CO	NOx†	PM	HCHO
Temporary Bins										
11 MDPV[s]						0.280	7.3	0.9	0.12	0.032
10[a,b,d,f]	0.125 (0.160)	3.4 (4.4)	0.4	-	0.015 (0.018)	0.156 (0.230)	4.2 (6.4)	0.6	0.08	0.018 (0.027)
9[a,b,e,f]	0.075 90.140)	3.4	0.2	-	0.015	0.090 (0.180)	4.2	0.3	0.06	0.018
Permanent Bins										
8	0.100 (0.125)	3.4	0.14	-	0.015	0.125 (0.156)	4.2	0.20	0.02	0.018
7	0.075	3.4	0.11	-	0.015	0.090	4.2	0.15	0.02	0.018
6	0.075	3.4	0.08	-	0.015	0.090	4.2	0.10	0.01	0.018
5	0.075	3.4	0.08	-	0.015	0.090	4.2	0.07	0.01	0.018
4	-	-	-	-	-	0.070	2.1	0.04	0.01	0.011
3	-	-	-	-	-	0.055	2.1	0.03	0.01	0.011
2	-	-	-	-	-	0.010	2.1	0.02	0.01	0.004
1	-	-	-	-	-	0.000	0.0	0.00	0.00	0.000

* for diesel fueled vehicle, NMOG (non-methane organic gases) means NMHC (non-methane hydrocarbons)

† average manufacturer fleet NOx standard is 0.07 g/mi for Tier 2 vehicles

a- Bin deleted at the end of 2006 model year (2008 for HLDTs)

b- The higher temporary NMOG, CO and HCHO values apply only to HLDTs and MDPVs and expire after 2008

c- An additional temporary bin restricted to MDPVs, expire after model year 2008

d- Optional temporary NMOG standard of 0.195 g/mi (50,000) and 0.280 g/mi (full useful life) applies for qualifying LDT4s and MDPVs only

e- Optional temporary NMOG standard of 0.100 g/mi (50,000) and 0.130 g/mi (full useful life) applies for qualifying LDT2s only

f- 50,000 mile standard optional for diesels certified to bins 9 or 10

Heavy-duty diesel trucks and buses have their own set of standards to adhere to. These standards for this vehicle category, with the exception of PM, were virtually unchanged during the period of 1988-2003. However, in 1997 EPA adopted new standards to be implemented starting in 2004 and it gave the manufacturers the flexibility to certify their engines or vehicles in to any of the two categories listed in table 2.2:

Table 2.2: EPA Emission Standards for MY 2004 and later HD Diesel Engines, g/bhp.hr [7]

Option	NMHC +NOx	NMHC
1	2.4	n/a
2	2.5	0.5

Starting in 2007, the EPA introduced new emission standards for heavy-duty engines. These standards are very stringent and are to be phased in by 2010. The changes cover emission standards and diesel fuel regulation [7]. The new emission standards are as follows:

- PM – 0.01 g/bhp.hr
- NOx – 0.20 g/bhp.hr
- NMHC – 0.14 g/bhp.hr

All diesel engines are to meet the PM standard in the 2007 MY. However, NOx and NMHC standards will be phased in between 2007 and 2010. This would be based on a percentage of sales; meaning; 50% of engines sold from 2007 to 2009 must meet the new standards with full compliance in 2010. The case is very similar to gasoline engines, with the difference being 50% compliance in 2008 and full compliance by 2009 [7].

2.2 Exhaust Gas Composition in Diesel Engines

In order to design a robust and effective exhaust gas sampling system, it is imperative to understand the composition of the exhaust gas produced by diesel engines and how that composition differs from other fuels, such as, gasoline. Real combustion is incomplete and during this process; carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM) are produced in addition to the typical products of a complete combustion of hydrocarbon fuels (CO_2, H_2O, and N_2) [8]. Figure 2.1 shows the differences in the composition of raw SI and diesel exhaust. We can see that diesel engines emit about a fifth of the amount emitted by spark-ignition (SI) engines [8]. We can also see that the NOx levels are almost the same and diesel engines emit far more particulate matter than SI engines.

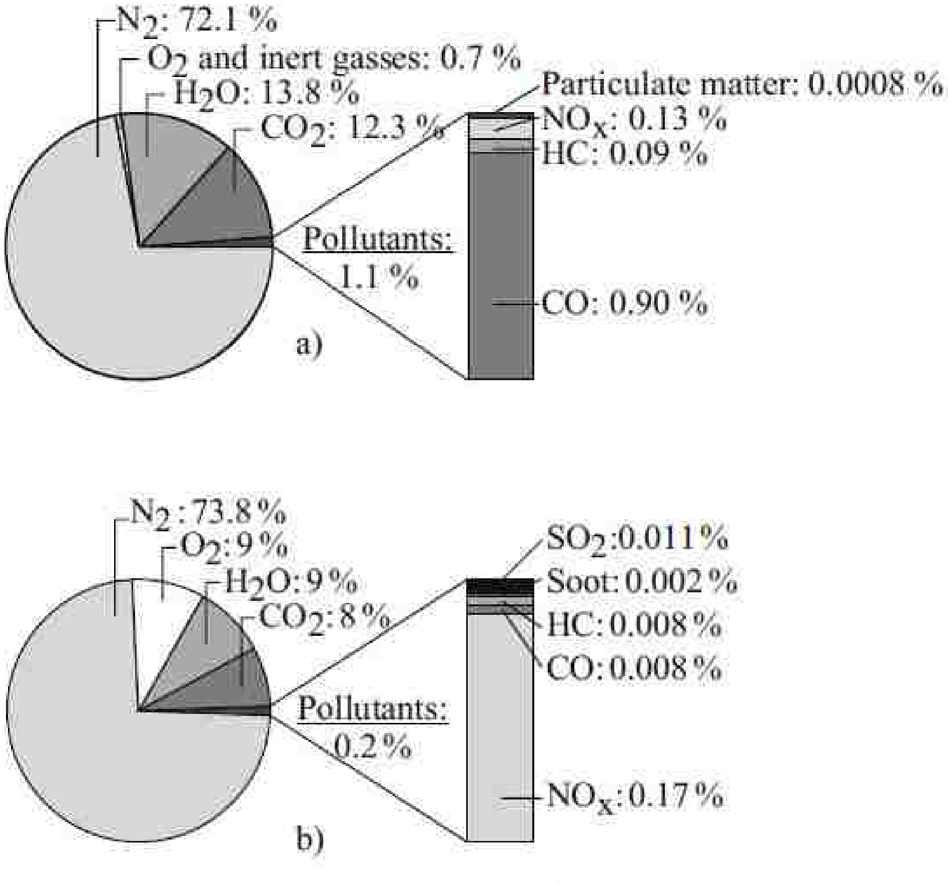


Figure 2.1: Raw Emissions in percent by volume. a) SI engine and b) diesel engine adapted from: Simulating Combustion, Simulation of Combustion and Pollutant Formation for Engine Development. Pg. 117 [8]

Looking at the exhaust composition of diesel engines, it is important to pay attention to the particulate matter fraction in order to insure the robustness of the sampling system. Particulates are very harmful to the exhaust gas analyzers and tend to contaminate the instruments causing poor performance, false readings, and in some cases, instrument failure. This becomes a major issue if the analyzers are being used for an extended period of time (continuously). Therefore, proper protection must be designed into the sampling system in the form of multiple stages of filtration. The gas temperature is also a major issue. Gasoline engines tend to operate at relatively higher exhaust temperatures than diesel engines; also, diesel exhaust temperatures have a wider temperature window than gasoline exhaust, which poses additional problems during the sampling process. Other issues, such as water content, also affect the sampling process as excessive moisture has to be removed from the sample in order for the sample to be acceptable for certain instruments, such as non-dispersive infrared detectors (NDIR), and dry Chemiluminescent detectors (CLD).

2.3 Exhaust Analysis Instruments

There are many different instruments used to analyze the contents of automotive exhaust gas. The most common approach that is used by automotive companies and suppliers is the use of dedicated exhaust gas analyzers, such as non-dispersive infrared detector (NDIR), flame ionization detector (FID), and the chemiluminescence detector (CLD). These devices are designed to detect a certain compound or a family of compounds. Another common tool used to analyze automotive exhaust is the Fourier-Transform Infrared Detector (FT-IR). This device is designed to detect a wide range of compounds and molecules based on the principles of infrared spectroscopy. This device is mainly used in the research and development field as it yields very accurate results when used to measure NO, NO_2, CO, CO_2, short-chain alcohols, hydrocarbons, and aldehydes, such as, methanol, ethanol, and formaldehyde. However, Majewski and Khair [9] state that FT-IR is not suitable for longer chain hydrocarbons that are typical of diesel engines. The next sections describe the various instruments in detail.

2.3.1 Non-Dispersive Infrared Detector

This type of detector utilizes the infrared (IR) principle to detect a specific compound or more. Particular wavelengths corresponding to certain compounds, such as, CO and CO_2 are isolated using special filters in order to only detect these compounds. The instrument detects the absorbance of CO and CO_2 at 2170 and 2350 wavenumbers (cm^{-1}) respectively [10]. These devices are intended for target applications and do not record a spectrum similar to the FT-IR detectors [10].

A typical NDIR instrument consists of an infrared light source, a chopper, a sample measuring cell, and a detector filled with a mixture containing the gas to be measured. Figure 2.2 shows a generic NDIR layout.

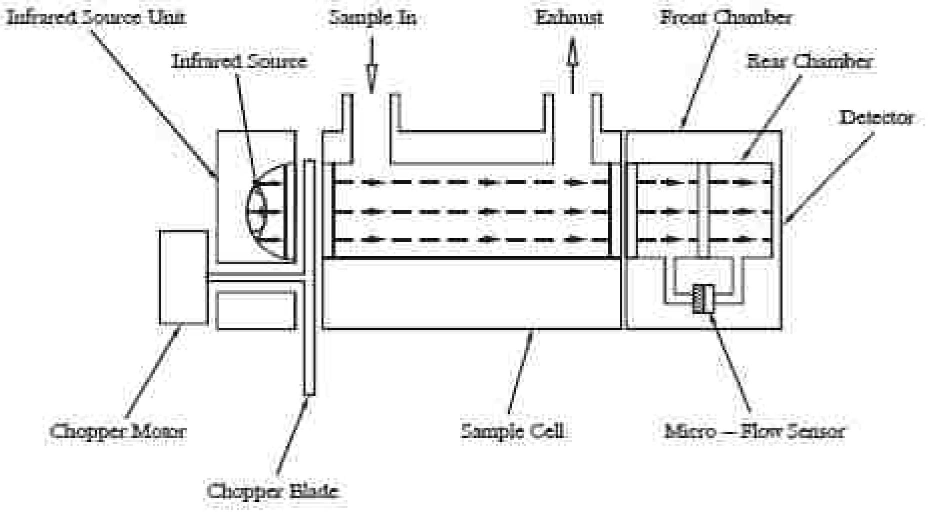


Figure 2.2: General NDIR Detector [4]

The light source is actually an infrared emitter that acts like a black body radiating over a wide range of wavelengths. The chopper is used to modulate the light source at a certain frequency [9]. Usually, the light beam generated passes through the sample cell where a portion of it is absorbed by the gas to be analyzed [4]. The light beam then reaches the detector front chamber where the light beam is partially absorbed in the front chamber and the residual beam is absorbed in the rear chamber of the detector. As a result; the pressure is increased in both of the chambers [4]. The detector is designed to produce a differential pressure between the two chambers and this pressure is measured by a special pressure sensor that converts the pressure to an AC voltage. This voltage is later conditioned and rectified into a DC voltage where it can be converted into the corresponding concentration of the gas to be analyzed [4].

The NDIR detector is capable of detecting CO, CO_2, SO_2, CH_4, NO, N_2O, HCl and C_3H_8 [4, 9]. However, the flame ionization detector is the main tool to detect hydrocarbons in the automotive industry due to faster and more accurate response and the NDIR is mainly used to detect CO and CO_2.

The NDIR detector is very sensitive to pressure; therefore, care must be taken in maintaining constant pressure and flow during calibration and sampling [9]. Also, the instrument is very sensitive to water vapor as it contaminates the internal components of the detector and affects some of the materials used in the construction of the detector, such as alkaline earth halogenide windows [9]. In order to insure proper performance of the detector; the sample is delivered to the analyzer dry after passing through a gas chiller (dryer).

2.3.2 Chemiluminescence Detector (CLD)

The chemiluminescence detector or CLD is used to detect the levels of nitrogen oxides (NOx) in a sample. The principle of operation is based on the chemical reaction between nitric oxide and ozone [9]:

$$NO + O_3 = NO_2^* + O_2 = NO_2 + O_2 + \text{photon}$$

Ozone is produced on-board in the instrument in an ozonator through a high-voltage discharge in oxygen [9] or using an ultraviolet lamp [2]. The excited nitrogen dioxide that is produced by the reaction returns to its normal state spontaneously. This leads to a red light emission of photons in the range of 0.6 to 3 μm [9]. This light is filtered to eliminate interference from other compounds, such as, CO, SO_2 and hydrocarbons. The light is later measured by a photomultiplier (photodiode) [2, 9] and the resulting signal is proportional to the NO concentration in the sample [9]. In order to measure total NOx in a sample ($NO+NO_2$); the sample has to first pass through a converter to convert NO_2 to NO before being reacted with ozone. This is accomplished by passing the sample through a stainless steel or molybdenum heated furnace that leads to the decomposition of NO_2 to NO. Ultra-violet converters are also used. The efficiency of such devices is usually in the range of 95-98% [2, 9].

The common chemiluminescence detector requires a cold, dry sample to prevent condensation and dissolving of NO_2 in the condensate [9]. The detector is also available in a heated version that can operate with wet, hot exhaust samples [9].

2.3.3 Flame Ionization Detector (FID)

The flame ionization detector (FID) is a non-selective instrument [11]; it is used to detect the concentration of unburned hydrocarbons in a sample. The principle of operation is based on the production of ions and electrons during the combustion of hydrocarbons in a hydrogen flame [9]. The detector only responds to the carbon-hydrogen bonds that are present in almost every organic compound [11], however, it has no response to compounds that don't have the C-H bonds, such as, carbon disulfide, carbon tetrachloride, carbonyl, alcohol, and halogen [10, 11]. The FID is considered a mass-sensitive, rather than a concentration-sensitive device. As an advantage; a change in flow rate has little effect on the response of the detector [10], however; it is maintained constant. In order for the FID to operate; two gases are needed. H_2/He gas is considered the fuel and it is usually supplied at a 40/60 ratio respectively. The fuel gas is mixed with air and burned in a special burner. The resulting flame is non-ionized and the detector does not register a response. However, once a sample containing hydrocarbons is introduced into the burner; it burns producing ions and electrons and it generates a current in the range of 10 pA [9]. This current is a function of the carbon atoms that are burned through the flame [9]. The results are reported in units of ppmC (parts per million by volume of carbon) [9]. The FID does not respond to water vapor and has little or no response to most inorganic compounds, such as, CO_2, SO_2, and NOx [10]. One of the disadvantages of flame ionization detectors is that the detector will produce a slightly different response to two different molecules having the same number of carbon atoms. This is the result of differences in the molecular structure of these compounds [5]. During testing; the detector will probably be calibrated with an alkane compound (methane or propane) and then used to measure diesel or gasoline exhaust. This represents a significant problem as the unburned hydrocarbons present in the exhaust sample are made up of different families, some of which are not similar to the calibration gas [5]. This is further illustrated in Table 2.3. It shows the current output of the FID for different hydrocarbon families.

Table 2.3: Sensitivity of FID Detector Current Output to Hydrocarbon Type [5]

Hydrocarbon Family	Current Output Relative to methane
Methane	1.00
Alkanes	1.00 x N
Alkenes	0.95 x N
Alkynes	1.30 x N
Aromatics	1.00 x N

2.3.4 Paramagnetic Detector

This type of detector is used to measure the oxygen concentration in diesel or gasoline exhaust. The principle of operation of this analyzer is based on the fact that certain gases exhibit paramagnetic properties, such as oxygen and nitrogen oxides [9].

2.4 Exhaust Sampling Systems

An exhaust sampling system is needed to condition the raw exhaust sample prior to introducing this sample to the exhaust analyzers. In order for the exhaust sample to be ready for the analyzers; it has to undergo specific processes to render it acceptable. These processes include filtration, gas drying, pressure and flow regulation and maintaining proper gas temperatures. The US EPA requires that the sampling system used during engine testing and certification meets certain specifications. These specifications and regulations are described in the CFR Title 40: Protection of the Environment, Part 1065: Engine-Testing Procedures, Subpart B: Equipment Specifications [12]. An ideal sampling system consists of the following stages:

- **Filtration stage**: Ideally; this stage should consist of two filters in series. The first filter is used to remove the larger particulate matter particles and is followed by a finer filter to achieve further filtration. These filters and the sample transfer lines should also be maintained at a temperature of 191°C in order to prevent any hydrocarbon condensation in the lines or filter housings.

- **Drying Stage**: This stage is used to dry the exhaust sample in order to remove as much water vapor as possible. The gas chiller or dryer should be positioned after the filters and upstream of the NDIR and CLD analyzers as these devices require dry sample as moisture contaminates the internal components and has a significant influence on the results obtained. The chiller should be able to produce an output gas sample at a dew point of 2-4°C during different engine running conditions and the EPA also specifies that the dryer should pass a NO_2 penetration test designed to insure that NO_2 removal during drying is low and acceptable [12].

- **Pressure and Flow Regulation Stage**: This stage is crucial to the optimal performance of the exhaust gas analyzers. The analyzers are designed to operate at specific sample pressures and flow rates. This is important because in order to have the analyzer perform as advertised; the flow rate of the sample and the inlet pressure should be met. Failure to accomplish this step will result in false readings as the analyzer will be over-pressurized or starved of adequate sample flow.

- **Temperature Regulation Stage**: This stage starts as the exhaust sample enters the sampling system as ends as the sample exits. It is extremely important to maintain the exhaust sample at 191°C ±11°C prior to introducing the sample to an FID detector. An exhaust sample at lower temperatures will result in lower false readings as some hydrocarbon molecules will condensate in the transfer lines. Also, the gas temperature should be approx. 120-130°C at the inlet of the gas dryer to ensure that vapor condensation occurs only in the dryer as it is designed to dry the gas while having minimal effects on other constituents, such as, NO_2.

All these stages have to be available in a sampling system if accurate satisfactory results are to be obtained from an experiment. The poor execution of one of these stages will result in erroneous results.

2.4.1 EPA Sampling System Requirements

EPA regulations published in 40 CFR, Part 1065 specifies the requirements of emission sampling hardware [12]. Below are some of these recommendations as they pertain to exhaust sampling equipment:

- **Sample Probes**: A probe is the first part of a sampling system and it protrudes in to the exhaust stream to extract a sample. EPA recommends that the probe be heated to 190°C if the probe is used to extract hydrocarbons for THC or NMHC measurements in order to minimize hydrocarbon deposition and condensation. EPA also recommends that probes that are used to extract NOx from diluted exhaust be temperature-controlled to prevent aqueous condensation.

- **Transfer Lines:** Transfer lines are used to transfer an exhaust sample from the probe to the rest of the sampling system or the analyzers. However; care must be taken to minimize the total length of the line and avoid 90° bends, elbow fittings, tees, and cross fittings as much as possible. It is also recommended that the radius of any unavoidable bend be maximized. If gaseous samples are being transferred; the transfer line inner surfaces are to be made from a 300 series stainless steel, PTFE, or Viton. Inline filters can also be used if they have the same specifications as the transfer lines and meet the same temperature requirements as follows:

1. If the transfer lines are used upstream of an NO_2-to-NO converter or a gas chiller; the sample must be maintained at a temperature that prevents moisture condensation.
2. If the lines are used to transfer THC samples; the inner wall temperature of the line must be maintained at a temperature of 191±11°C.

- **Optional sample-conditioning components:** The following components may be used in the process of transferring a gas sample from an exhaust stream to the analyzers:

1. NO_2 –to-NO Converter may be used if it meets the efficiency performance test specified by EPA.
2. A gas dryer (chiller) can also be used to extract moisture from the exhaust sample. The most common type of dryer used is the thermal dryer. These dryers must meet an NO_2-loss performance check to verify that they have a minimum 95% NO_2 penetration capacity. If the chiller does not meet this requirement; it should not be used upstream of a NOx analyzer or can only be used after the NO_2 converter to minimize the negative effect on the NO_2 concentration to an acceptable level. EPA also specifies that a chiller may not be used upstream of a THC detector or upstream of PM sample filters.
3. Sampling pumps can be used upstream of any analyzer unit; however, care must be taken to ensure that they are maintained at adequate temperatures to prevent aqueous condensation or at 191±11°C if they are used upstream of a THC analyzer. Also, the inner surfaces of the pump must be made of 300 series stainless steel, PTFE, or Viton to prevent the sample from reacting with the pump materials. Figure 2.3 shows a typical double-

headed and a single headed pump both heated and temperature-controlled at 191±11°C.

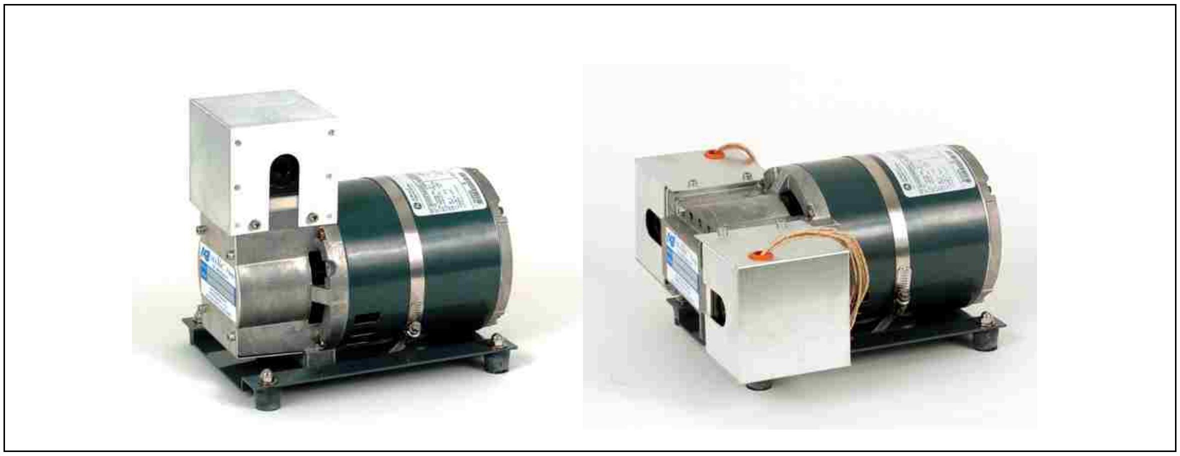


Figure 2.3: Diaphragm Pumps used to Sample Exhaust Gas [22]

Figure 2.4 shows a complete sampling system used by HORIBA to condition the exhaust gas prior to introducing the sample through the analyzers.

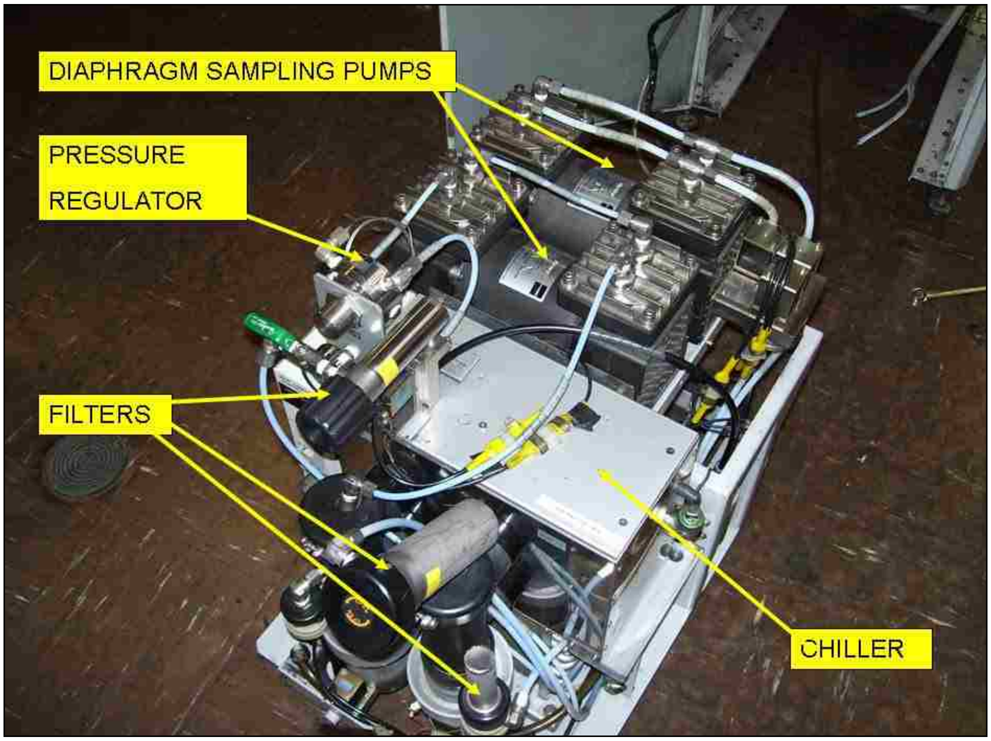


Figure 2.4: HORIBA Sampling System

3 DESIGN INTENT AND METHODOLOGY

3.1 Sampling System Deficiencies

A poorly designed, operated or maintained sampling system will have significant negative effects on the response (results) of an experiment. Test engineers must be familiar with the working principles and the operating conditions of the sampling system. The system should also be fully instrumented with pressure transducers, flow meters, and thermocouples in the proper locations to maintain an acceptable level of transparency that makes error detection and problem solving easy and fast. It is also important to know the state of the exhaust sample as it travels through the sampling system so errors and uncertainties linked to the operating conditions of the analyzers or sampling system components can be determined. A non-instrumented sampling system does not provide data that can supplement the measured emission data to ensure the accuracy and the associated error of the results.

The first step in improving the efficiency of the exhaust sampling system is to fully study and understand the operating principles of the different exhaust gas analyzers (NDIR, FID, and CLD), which were explained in the literature review section of this thesis. Each analyzer type is designed to sample the exhaust at very specific conditions and these devices tend to have very little tolerance to samples that are outside the requirements specified by the manufacturer. Each analyzer has specific requirements for temperature, pressure, flow, filtration, and moisture level that have to be met in order to obtain meaningful results and avoid damaging the analyzer.

PERDC utilizes two different commercial exhaust analyzer stacks, Horiba and California Analytical Instruments. Horiba and CAI provide emission analyzers that use the same technologies to analyze exhaust samples. Horiba supplies the analyzers along with a sampling and conditioning system specifically designed to deliver the optimal sample to the analyzers. Furthermore; the FID oven that is used to detect total hydrocarbon concentrations is located outside the main analyzer in a stand-alone unit while the other analyzers (NDIR, CLD, and a paramagnetic detector) are located in the main unit. This configuration has the advantage of added simplicity to the main unit design as a heated sample to 191°C is not required since the main unit is only used to measure CO, CO_2, NOx, and O_2. These constituents require a dry sample only. The sample lines and heated filters leading to the FID oven are maintained at 191°C to prevent hydrocarbon condensation. Figure 3.1 below shows the Horiba emission analyzer main unit and the FID oven.

Figure 3.1: HORIBA Emissions Analyzer Main Unit (A) and FID Oven (B)

California Analytical Instruments supply single analyzer units without the sampling system. The sampling and conditioning systems for the CAI analyzers were designed and built in-house at PERDC. Since the first CAI exhaust bench was assembled; the design of the sampling system has evolved and a few more iterations of the sampling system have been produced. However, the fundamental design of the sampling system has not changed since the first bench was put into service. All the changes that have been made to this system represent "Band-Aid" solutions and do not address the actual deficiencies of the system. Figure 3.2 details the schematic representing a CAI analyzer bench complete with the sampling system.

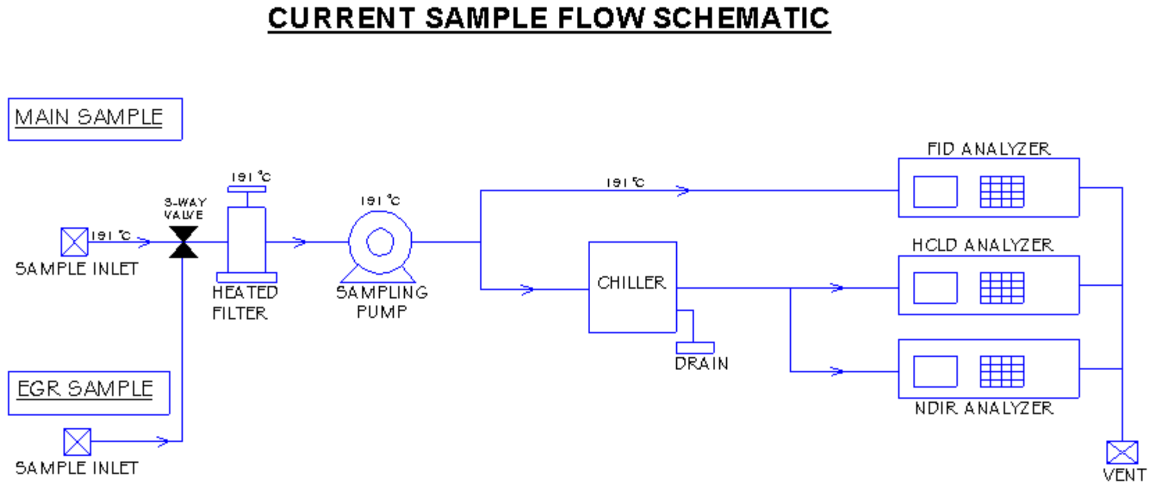


Figure 3.2: Current CAI Analyzer Bench with Sampling System

The main sample travels through a single path in order to reach any of the three analyzers. This requires the sampling pump to be heated to 191ºC along with the inline filters and the transfer lines all the way to the gas chiller. The reason for this is to prevent the heavier hydrocarbons in the sample from condensation. Therefore, the sample is introduced into the chiller at higher temperatures than desired resulting in excess water buildup downstream of the chiller. This is due to the fact that the chiller does not extract enough heat to bring the temperature down to condense all the water. In order to prevent the water from reaching the analyzers; a water separator is sometimes used. Figure 3.3 shows a common setup with the water separator at the inlet of the analyzers. Although, this solution does work in eliminating excess moisture in the sample, it does not address the chiller itself. This solution also requires that the water separator to be serviced periodically by an operator to drain the accumulated water. Failure to do so would result in some water being delivered to the analyzer.

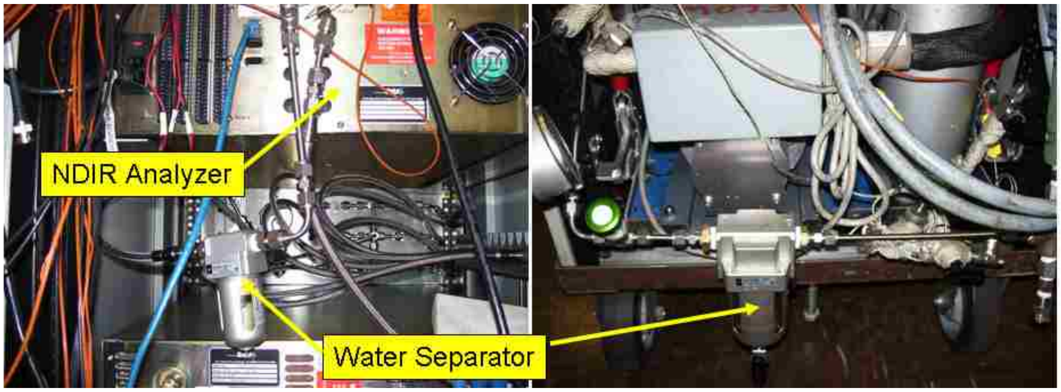


Figure 3.3: Water Separators used in CAI Sampling System

The chiller used in the CAI sampling system is a vapor-compression type with a maximum input temperature of 75ºC. Another problem with the current setup is that the sample pressure is neither monitored nor controlled upstream of the analyzers. The CAI emissions analyzers use electronic flow control devices that are designed to operate with input sample pressure of 8-25 PSIG. This allows for the sample flow to be regulated inside the analyzers; a very crucial requirement if correct analyzer performance is in order. The current system utilizes a single sampling pump that delivers the sample to all three analyzers (FID, NDIR, and CLD). Also, since the sample pressure is not regulated; the sampling pump delivers the sample at maximum output pressure that easily exceeds the analyzer requirements. This is due to the fact that the pump is being restricted by the flow regulation devices inside the analyzers resulting in excessive pressure build up at the analyzer inlets. Figure 3.3 shows the gas dryer used in all the CAI sampling systems. Heating most of the components to 191°C also results in excessive heat emitted inside the bench cabinet. This becomes an issue if the bench is to be used continuously for extended hours inside the test cell. The analyzers have a maximum operating temperature of no more than 40°C and it is not difficult to reach this temperature inside the test cell when testing diesel aftertreatment devices. Therefore; it is a good practice to operate the bench at lower temperatures when possible.

As we can see from the schematic in Figure 3.2; the system does not include a dedicated EGR line that would allow real-time EGR measurements. Rather; the EGR sample is redirected through the only sampling line by means of a 3-way valve operated manually. Basically, the EGR sample is introduced into the analyzer bench manually by an operator when EGR data is to be acquired. This might be adequate in certain tests where continuous EGR control and monitoring is not required; however, this system cannot be used when EGR control is required as real-time data become necessary.

Figure 3.4: Gas Chiller used in CAI Sampling System

3.1.2 Requirements for the New Sampling System / Emissions Bench

This project was commissioned to address performance deficiencies present in the exhaust analyzer equipment currently in service. The finished product would boost improved performance in the following categories:

1. The sampling system would be capable of delivering an exhaust sample that meets the requirements specified by the exhaust analyzer manufacturer, such as, temperature, pressure, filtration, and moisture.

2. The sampling system would be capable of providing two separate exhaust samples simultaneously. The second sample would serve as a real-time EGR sample.
3. The system would provide the capability to acquire exhaust gas data during the sampling process, such as, temperatures and pressures at key points throughout the system to ensure compliance.
4. Provide a development platform for exhaust sampling technologies that would be developed in the future to improve the sampling system. Such improvements in filtration, heating, or drying could be utilized in a future design that would provide a better performance.
5. The sampling system would be cost-effective when compared to other similar commercial systems that are supplier as turn-key systems.
6. The new sampling system would be a reproducible design. This means that this system is not assembled for the completion of this thesis only, but would serve as a complete product that can be used for long-term operation in a testing facility.

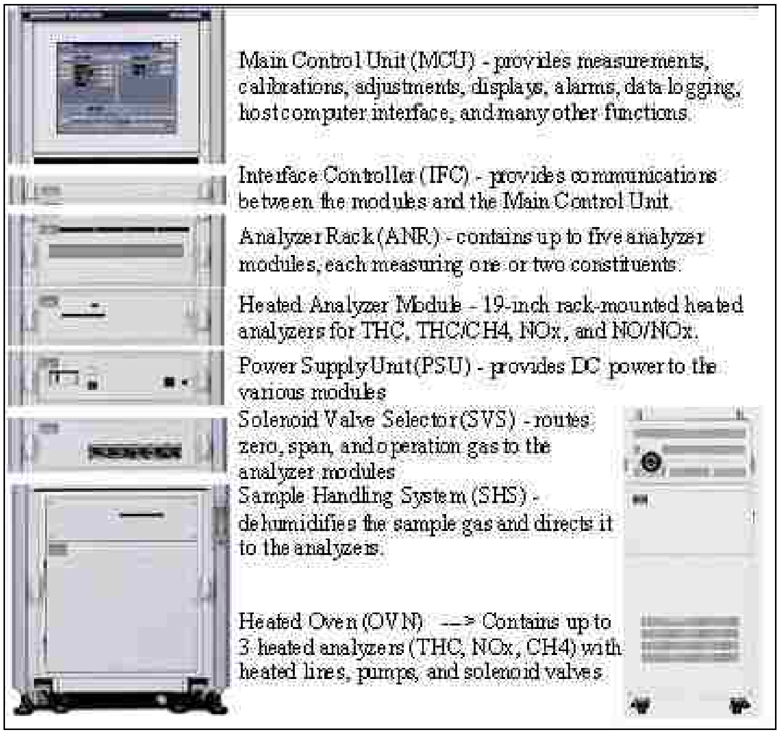
3.2 Emissions Bench Selection

Given the deficiencies of the current CAI analyzer benches and the need to provide additional emission analysis equipment for the lab; the need arose for a solution that is functional, robust, cost-effective, and safe. Research was conducted to determine the viability of the different options available to PERDC. The advantages and disadvantages of these options were weighed in an effort to make a decision. The next sections describe the selection process

3.2.1 Horiba MEXA-7500 Analyzer System

Horiba is considered the benchmark in emission analysis equipment. The MEXA-7500 would be the model of choice for PERDC as it is configured for direct exhaust sampling without the need for dilution. The advantages of this system are:

- Turn-Key system. This unit is purchased, therefore, very minimal setup and fabrication is required.
- It is capable of sampling two dedicated samples and an EGR sample simultaneously making it ideal for diesel aftertreatment testing. The analyzer can measure all the regulated exhaust emission constituents like THC, NOx, and CO. It also measures unregulated substances that are necessary for engine performance analysis, such as, CO_2 and O_2.
- Innovative configuration for the sampling system as the THC and NOx detectors are housed in a single heated oven while the rest of the analyzers are placed in a separate unit [13].



Main Control Unit (MCU) - provides measurements, calibrations, adjustments, displays, alarms, data logging, host computer interface, and many other functions.

Interface Controller (IFC) - provides communications between the modules and the Main Control Unit.

Analyzer Rack (ANR) - contains up to five analyzer modules, each measuring one or two constituents.

Heated Analyzer Module - 19-inch rack-mounted heated analyzers for THC, THC/CH4, NOx, and NO/NOx.

Power Supply Unit (PSU) - provides DC power to the various modules

Solenoid Valve Selector (SVS) - routes zero, span, and operation gas to the analyzer modules

Sample Handling System (SHS) - dehumidifies the sample gas and directs it to the analyzers.

Heated Oven (OVN) ---> Contains up to 3 heated analyzers (THC, NOx, CH4) with heated lines, pumps, and solenoid valves

Figure 3.5: HORIBA MEXA-7500 Emission Analyzer System [13]

The disadvantage of this system is the cost. The purchase price for this is approximately $414,000. This requires a significant capital investment. Also, this system would have to be serviced by Horiba personnel every year or as needed.

3.2.2 Modified CAI Analyzer System

A current CAI emissions analyzer system could be modified to meet the requirements of testing diesel aftertreatment devices. This means that the system should be capable of sampling a dedicated EGR sample along with the main sample simultaneously. This requires a complete redesign of the current sampling system to improve the performance and the functionality of the current sampling system. A second sampling pump as well as a second dedicated gas chiller for the EGR sample would be required. The new modifications would boost the following advantages:

- An upgraded sampling system that would allow for a dedicated EGR line for real-time data acquisition.
- Added protection to the analyzers through double-stage filtration, improved moisture removal, and pressure regulation to ensure longer service life for the analyzers and reduced OEM repairs.
- Improved data acquisition through ETAS modules that are setup into the analyzer rack that would send temperature, pressure, and emission concentration data to a remote computer. An Ethernet setup is also available for a second method of data transfer.
- The availability of CAI analyzers at the EEP laboratory means that only a sampling system would have to be fabricated. This reduces the total cost of the project significantly. Also; upon the successful completion of this project; the current CAI analyzer systems can be upgraded to the proposed system in this thesis by modifying them either in-house or by sending them to the manufacturer.

This option also has its disadvantages:

- The CAI analyzer system is only capable of sampling two direct samples including the EGR sample compared to the three samples handled by the Horiba system. This would require the addition of a second analyzer system if two simultaneous samples are required.
- Due to the added EGR stream into the NDIR analyzer; the unit lacks a paramagnetic detector for oxygen measurement. Therefore, the CAI analyzer can not provide O_2 data. The CAI NDIR analyzer can only have three detectors present in the unit. These detectors for this project are the main CO2, main CO, and the EGR CO2 detectors.
- The fabrication process may consume significant labor hours and add strain to the machining and sheet metal departments at PERDC.

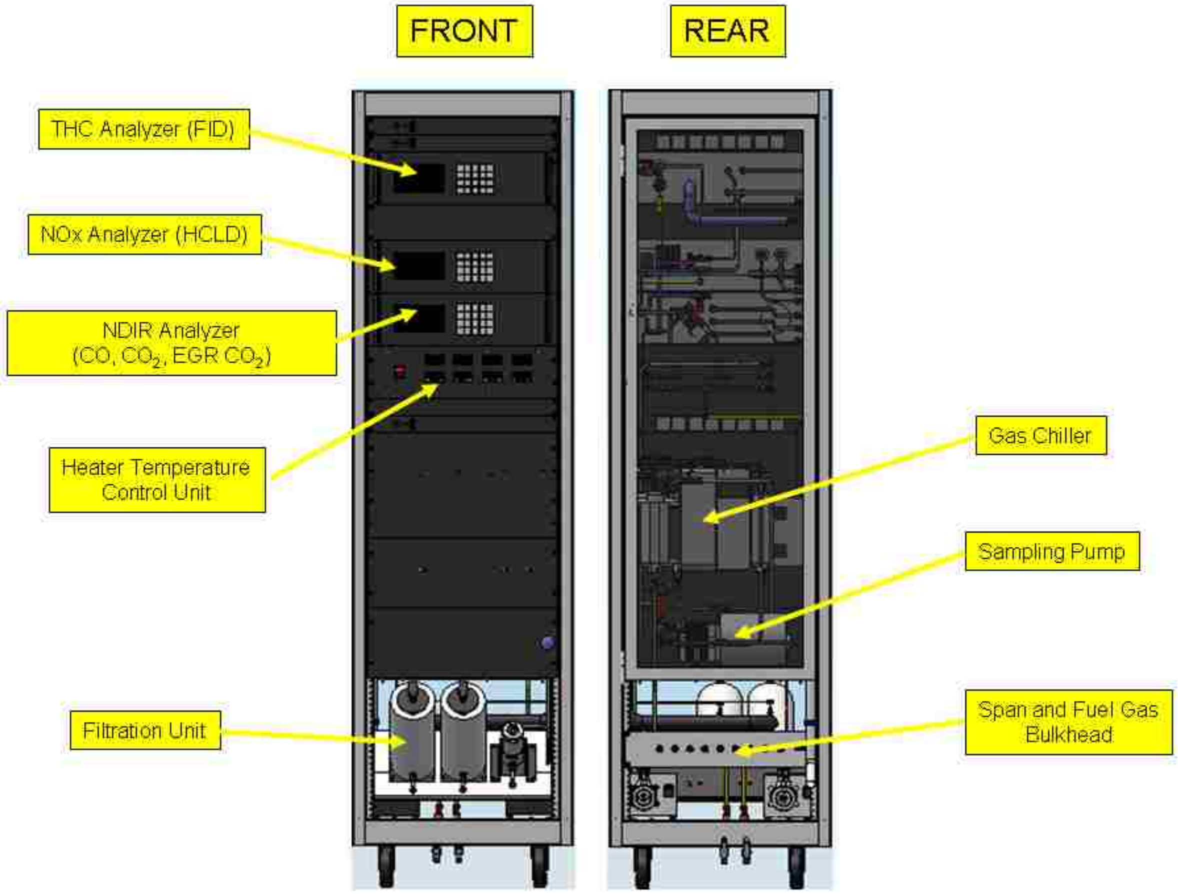


Figure 3.6: Modified CAI Emission Analyzer System

3.2.3 Selection of Emissions Bench

To aid in the selection process, Table 3.1 was constructed to put both options into perspective. Table 3.1 details the pros and the cons of considering the Horiba or the CAI option.

Table 3.1: HORIBA Analyzer System vs. CAI Analyzer System Comparison

	HORIBA MEXA-7500	MODIFIED CAI ANALYZER	CHOICE
1	Measures 2 Direct Lines + EGR	Measures 1 Direct Line + EGR	HORIBA
2	Measures All Common Exhaust Constituents (THC, NOx, CO, CO_2, O_2)	Can Measure All Common Constituents except for O_2	HORIBA
3	Costs Approximately $415,000	Costs Approximately $60,000 Including The Cost of The Analyzers	CAI
4	Requires training and new investment in spare parts and maintenance filters	No training required, spare parts and maintenance filters are already in use at EEP lab	CAI
5	Complex and usually requires service performed by HORIBA technicians.	Simple enough to perform most of the service in house. This system can also serve as a development platform for future models	CAI

This table clearly shows that the Horiba system is the winner when functionality is concerned. It is also the industry standard in the field of automotive emissions analysis and engine and vehicle certification. However, the price of this system is extremely high compared to the CAI system. Also, the emissions bench resulting from this project would not be used for certification purposes; rather, it would be used for development testing. This makes the CAI system a very viable option since a factory-certified system is not required. The CAI system can also be improved in the future to accommodate an O_2 detector to make this system a more complete solution for engine testing. The findings of this project can greatly aid in that category. Therefore, the choice for this project is to proceed with the modified CAI emissions Analyzer System. The major factors influencing this decision being cost and the assumption that the short-comings of the CAI system, in terms of functionality and robustness, will be addressed in the new system proposed in the next chapter.

4 DETAILED DESIGN OF MODIFIED CAI EMISSIONS ANALYZER

An ideal sampling system was designed and a schematic drawing was produced before starting the purchasing and building phase of the project. A precise blueprint was needed to ensure that the focus remained on the design goals and objectives and that the project cost and timeline are maintained as the blueprint would allow for a timeline and an approximate cost to be established by constructing a valid bill of materials (BOM). Therefore, significant time was dedicated to establish a 3D CAD model that was inclusive of the major systems and components, such as, analyzers, filters, chillers, sampling pumps, and the data acquisition system. This step minimizes unforeseeable issues that can arise from packaging constraints. The conceptual design process, schematics, blueprints, and part selection are also detailed in this chapter.

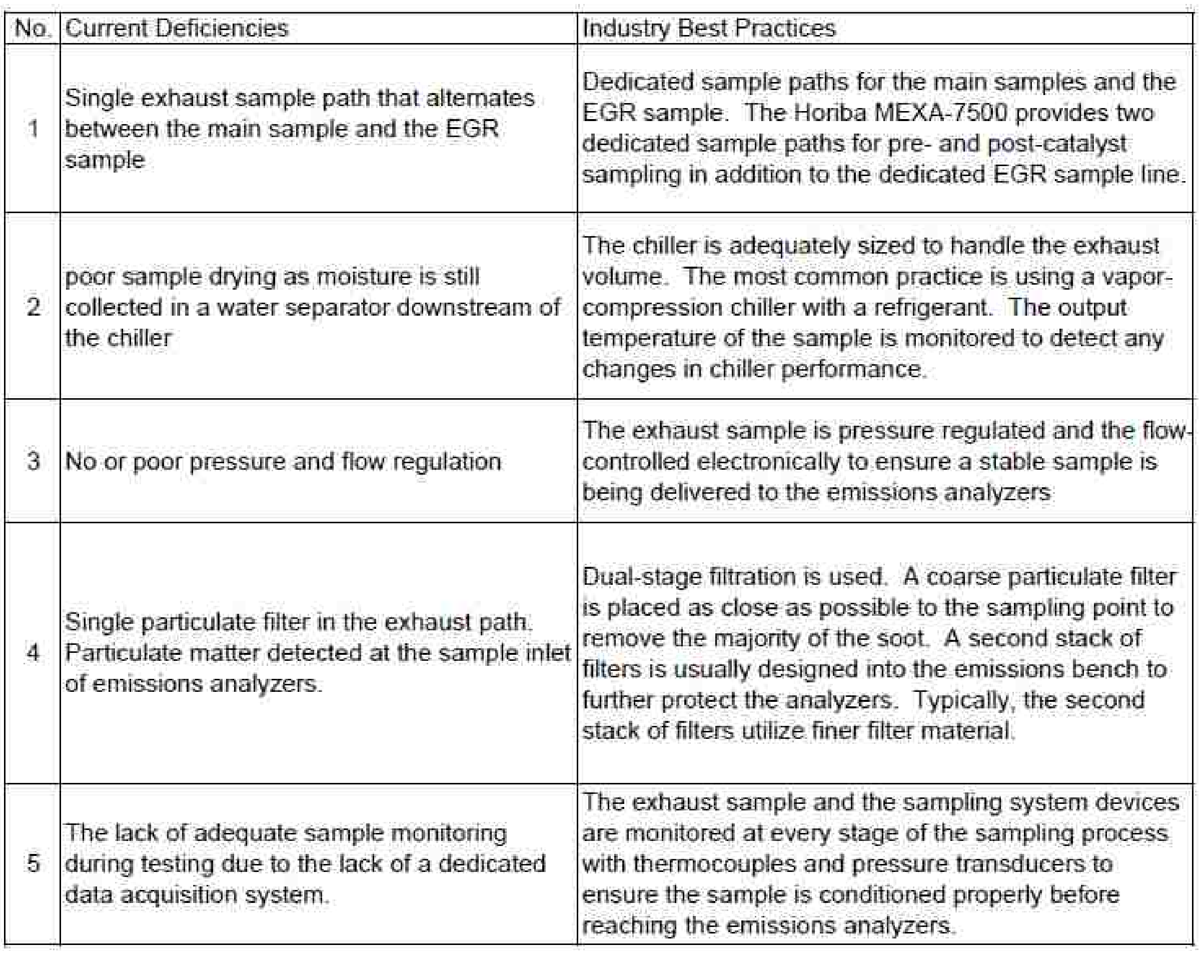
4.1 Initial Concept Development

A decision was made to go back to the drawing board and establish a clean-sheet design instead of modifying an existing in-service CAI analyzer bench. The first step was to examine the requirements of the CAI analyzer units separately and determine if these requirements could be met. Generally, all emissions analyzers require the supplied sample to be precisely controlled in terms of temperature, pressure, moisture, and filtration.

Figure 4.1: Typical CAI Emission Analyzer Instrument. [3]

Figure 4.1 shows a typical CAI emissions analyzer. It can be mounted directly on a standard 19” rack. The deficiencies outlines in section 3.1 were summarized in Table 4.1 along with the industry best practices that are used to remedy these issues. Table 4.2 details the exhaust sample requirements that would have to be met in order to ensure proper analyzer performance and durability. These types of instruments are extremely sensitive and can be damaged easily if proper attention is not paid to how the sample is handled.

Table 4.1: Current Sampling System Deficiencies vs. Industry Best Practices



No.	Current Deficiencies	Industry Best Practices
1	Single exhaust sample path that alternates between the main sample and the EGR sample	Dedicated sample paths for the main samples and the EGR sample. The Horiba MEXA-7500 provides two dedicated sample paths for pre- and post-catalyst sampling in addition to the dedicated EGR sample line.
2	poor sample drying as moisture is still collected in a water separator downstream of the chiller	The chiller is adequately sized to handle the exhaust volume. The most common practice is using a vapor-compression chiller with a refrigerant. The output temperature of the sample is monitored to detect any changes in chiller performance.
3	No or poor pressure and flow regulation	The exhaust sample is pressure regulated and the flow-controlled electronically to ensure a stable sample is being delivered to the emissions analyzers
4	Single particulate filter in the exhaust path. Particulate matter detected at the sample inlet of emissions analyzers.	Dual-stage filtration is used. A coarse particulate filter is placed as close as possible to the sampling point to remove the majority of the soot. A second stack of filters is usually designed into the emissions bench to further protect the analyzers. Typically, the second stack of filters utilize finer filter material.
5	The lack of adequate sample monitoring during testing due to the lack of a dedicated data acquisition system.	The exhaust sample and the sampling system devices are monitored at every stage of the sampling process with thermocouples and pressure transducers to ensure the sample is conditioned properly before reaching the emissions analyzers.

Table 4.2: CAI Analyzer System Sample Requirements [2, 3, 4]

	Flame Ionization Detector (FID)	Non-Dispersive Infrared Detector (NDIR)	Chemiluminescence Detector (CLD)
Filtration	0.1 micron for the sample and 0.7 micron for the span and fuel gases.	Dust must be removed completely, final filter to remove objects larger than 4 micron.	Dust must be removed completely, final filter to remove objects larger than 4 micron.
Condensation	Caution must be taken to insure the sample does not condense as the moisture can damage the analyzer.	Sample dew point of 2-4ºC or less.	The sample dew point must be lower than the instrument dew point; the sample must pass through a dryer with a 95% NO_2 penetration or better.
Gas Temperature	Maximum rating of the gas temperature is 385 ºF (196 ºC). Also, the heated transfer lines and filters leading to the analyzer must be maintained at 191 ± 11°C.	Can not exceed maximum rating of the instrument 104ºF (50 ºC).	Can not exceed maximum rating of the instrument 212ºF (100 ºC).
Pressure and Flow Rates	Without optional sampling pump: 8-25 PSIG at a maximum 3 liters/min flow rate. Sample can not exceed 2 PSIG if using the optional sampling pump.	Without optional sampling pump: 8-25 PSIG at a maximum 3 liters/min flow rate. Sample can not exceed 2 PSIG if using the optional sampling pump.	Without optional sampling pump: 8-25 PSIG at a maximum 3 liters/min flow rate. Sample can not exceed 2 PSIG if using the optional sampling pump.

A schematic drawing was established to address the requirements above. Figure 4.2 shows the schematic for the proposed sampling system for the CAI emissions analyzers. Examining this schematic; we can see that filtration, sample moisture, sample temperature, and sample pressure are addressed. Sample flow rate is regulated internally in the analyzers provided that the sample pressure is regulated to the desired specifications listed in the CAI User Manuals [2, 3, 4]. This is done by using flow controllers inside the analyzers that require a specific input pressure in order to meter the sample flow properly. Another factor affecting the pressure and flow rate of the sample is the proper venting of the exhaust sample once it has been analyzed. Any restrictions to the analyzer vents would affect the readings of the instruments as sample flow requirements would not be met [2, 3, 4].

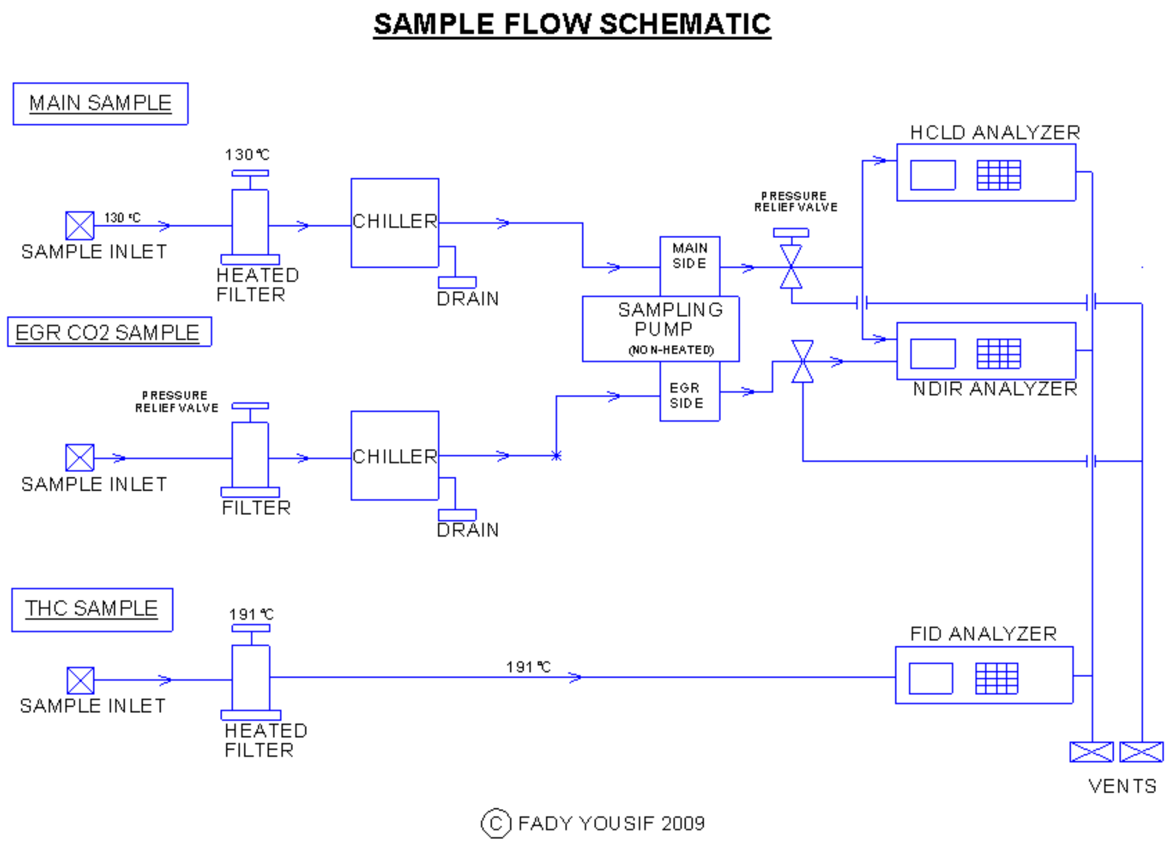


Figure 4.2: Modified CAI Emission Analyzer System

Before discussing the major components of the sampling system; it is important to shed some light on the major modification of this system. As previously mentioned; the THC sample stream is separated from the main sample. This modification will:

1. Reduce the transfer lines heating requirement for the main sample from 191°C to 130°C. This can reduce the amount of work the chillers would have to do to cool the sample to reduce the dew point to 2-4°C.
2. By having a separate THC sample stream; the main sampling pump is not used to deliver the THC sample; therefore, allowing for the use of the optional sampling pump inside the CAI flame ionization detector that is designed specifically to deliver the THC sample to the FID oven.
3. Allow for the placement the main sampling pump downstream of the chillers. This is advantageous for two reasons: The first benefit is using the pump without

heating it as it would only process a dry sample and since it is not used to deliver a THC sample. This can reduce the total heat emitted inside the analyzer cabinet and is beneficial to the chillers that are placed in the vicinity of the sampling pump. The second advantage is the ability to run the chillers in a different configuration; namely in a vacuum setup instead of a pressurized setup. This configuration is recommended by the chiller manufacturer [17].

Therefore, a dedicated sample stream for the FID was setup as shown in the bottom of Figure 4.2. The sample passes through the heated ATMO/SEAL heated filter housing before being routed to the FID oven. A diaphragm-type sampling pump mounted inside the FID analyzer pulls the exhaust sample through to the electronic pressure controller inside the oven. Figures 4.3 and 4.4 show the internal parts of the CAI HFID 600 and the FID oven respectively.

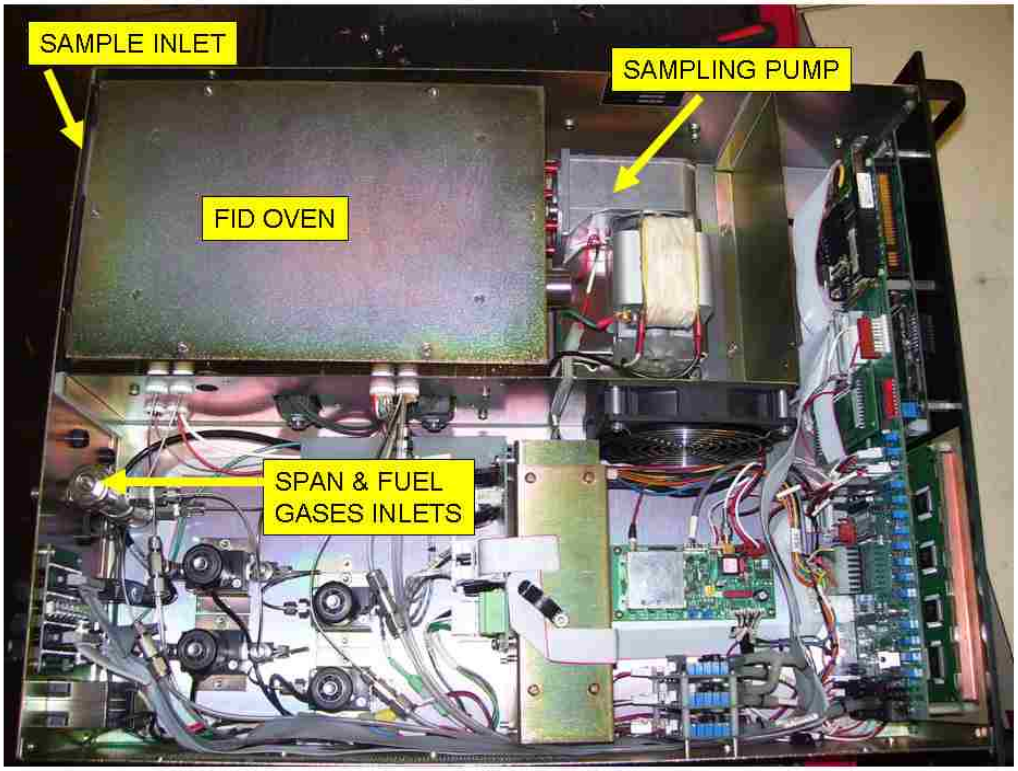


Figure 4.3: The Internal Components of CAI HFID 600 THC Analyzer

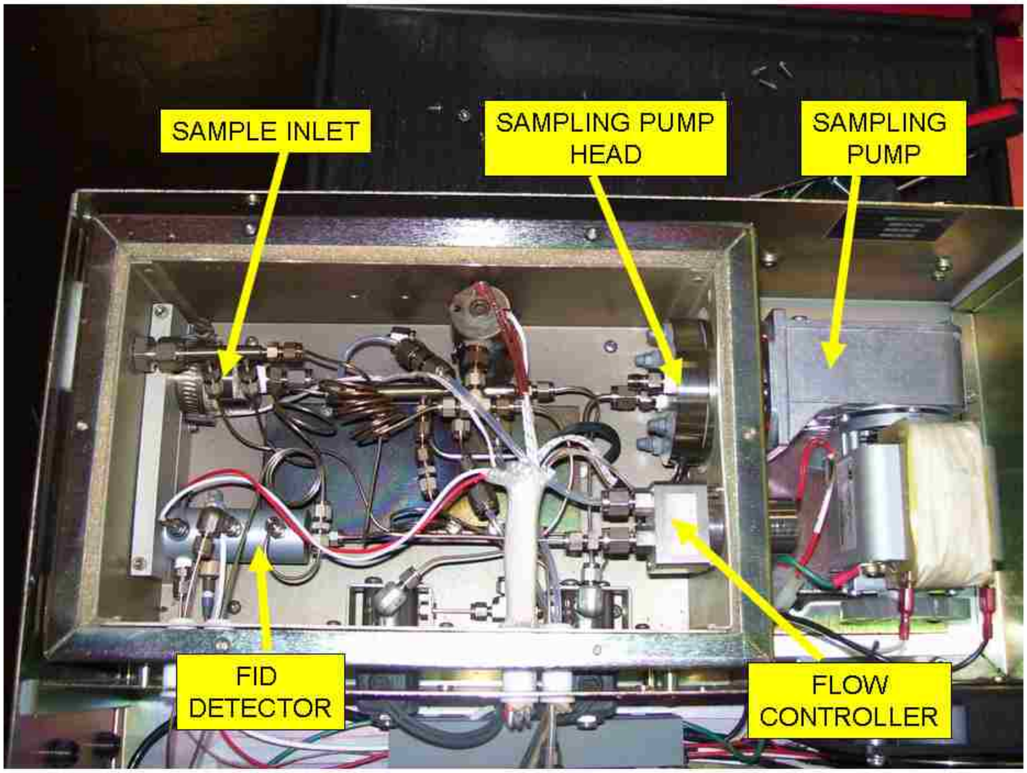


Figure 4.4: The CAI HFID 600 THC Analyzer Oven

4.2 Cabinet and Electrical System Design

The first challenge encountered was accommodating the extra component needed for the added functionality within the existing frame of the current CAI analyzer system. The decision to use the existing cabinet was influenced by the following factors:

- The availability of standard 19.00” rack cabinets at PERDC. This provided a significant cost saving as the list price for a new cabinet is approximately $1000.
- The ease of mobility of the current bench. One of the requirements of the CAI system is to be mobile and transferable from one test cell to another. The height of the current bench can not be increased as it would limit the movement of the bench through certain sections of the laboratory.

The cabinet selected for this project is the Economizer model ER-16525 supplied by BUD Industries. This cabinet can accommodate any standard 19.0" rack-mounted instruments, such as, the CAI analyzers. The mountable area measures 70" in length and 30" in depth, which should provide adequate space for all the equipment [14]. Figure 4.5 shows the Economizer ER-16525 cabinet.

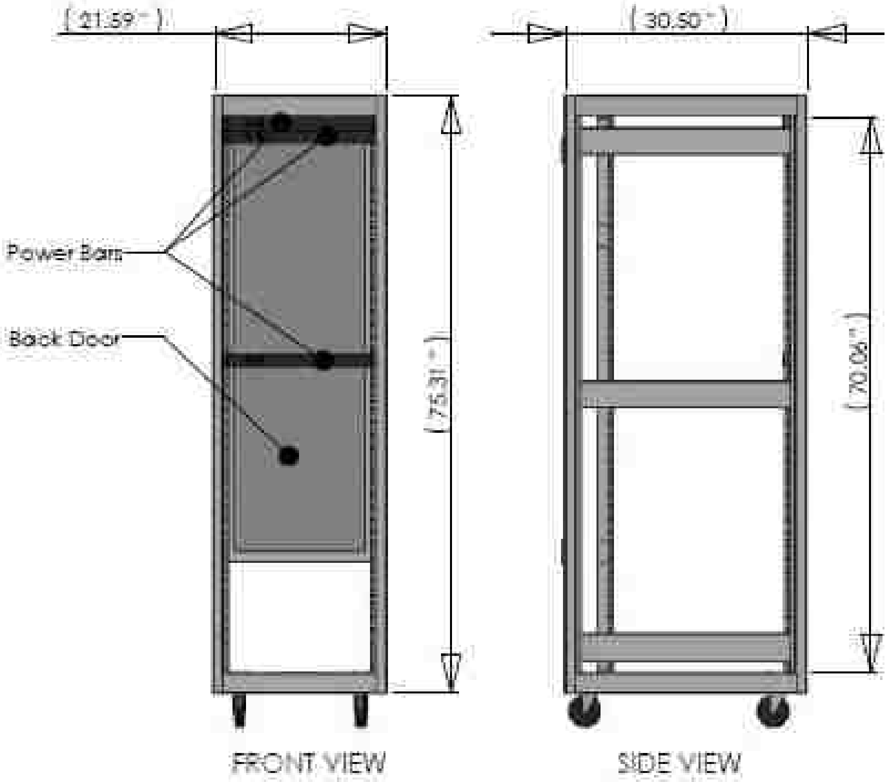
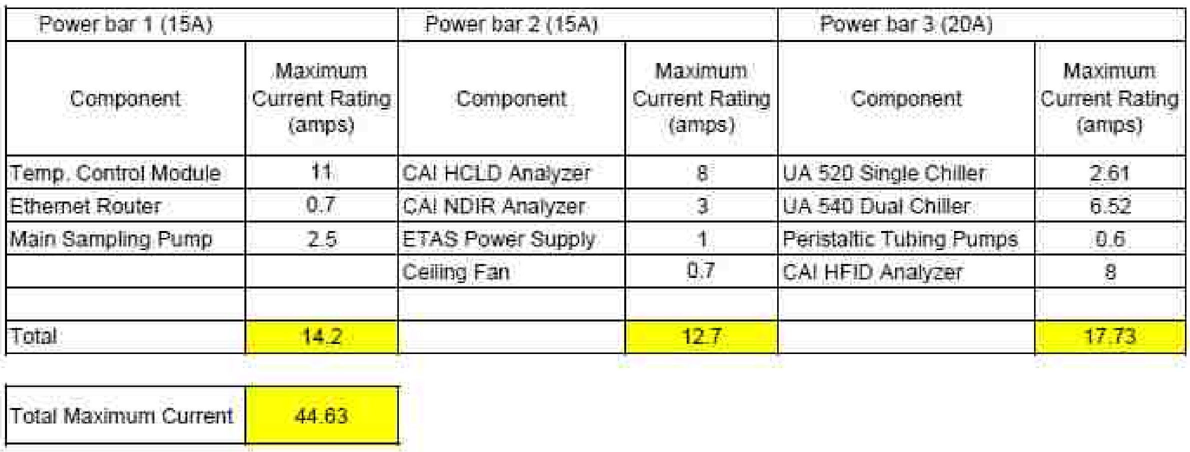


Figure 4.5: ER-16525 Standard 19" Rack Cabinet [14]

The first task was to establish the electrical requirements of the emissions bench and determine whether the test cells can accommodate these requirements. Examining the dynamometer test cells at PERDC; it was determined that the cell can accommodate two emissions benches at 50 Amps per bench. The power consumption data for all the different instruments and components were summed to establish a maximum power rating for the emissions bench. Table 4.3 detailed the maximum current consumption in Amps at 115 V for the different components in the emissions bench and the corresponding power bars that these components are connected to. The total number was divided between the three power bars installed in the cabinet and care was taken to ensure the maximum current rating of each power bar was not exceeded.

Table 4.3: Maximum Current Rating for CAI Emissions Bench Components



Power bar 1 (15A)		Power bar 2 (15A)		Power bar 3 (20A)	
Component	Maximum Current Rating (amps)	Component	Maximum Current Rating (amps)	Component	Maximum Current Rating (amps)
Temp. Control Module	11	CAI HCLD Analyzer	8	UA 520 Single Chiller	2.61
Ethernet Router	0.7	CAI NDIR Analyzer	3	UA 540 Dual Chiller	6.52
Main Sampling Pump	2.5	ETAS Power Supply	1	Peristaltic Tubing Pumps	0.6
		Ceiling Fan	0.7	CAI HFID Analyzer	8
Total	14.2		12.7		17.73

Total Maximum Current	44.63

Figure 4.6 shows the electrical system configuration. The main disconnect had three output lines to the power bars to power the bench components. The electrical power is supplied to the main disconnect via two 14 AWG power cables that are mated to 20A and 30A plugs respectively.

After the cabinet selection; sub-assemblies are designed to meet certain parts of the requirements specified in Table 4.2. A detailed look into these sub-assemblies is provided in the subsequent sections of this chapter.

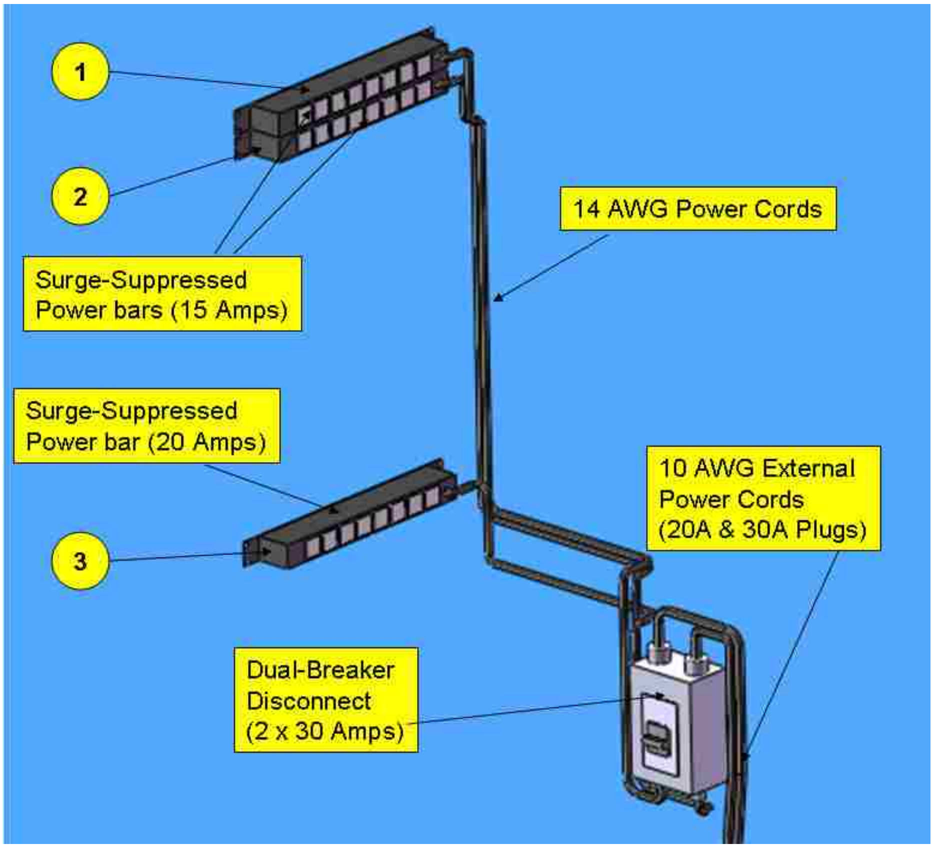


Figure 4.6: CAI Bench Electrical Power System

4.3 Sample Filtration Assembly

The schematic in Figure 4.1 shows that filtration is the first stage of the sampling system. A filter is needed for each one of the separate sampling lines (THC, main sample, and EGR). However, the heating requirements are different and depend on the analysis to be conducted on that particular sample. The inner surfaces of the THC sample lines and filters must be maintained continuously at 191ºC ± 11 ºC according to EPA recommendations [12]. The main sample lines and filters for NOx, CO_2, and CO must also be heated to prevent aqueous condensation; however, they do not need to be heated to 191°C since they only need to be hot enough to prevent aqueous condensation [12]. This would prevent NO_2 from being absorbed into water droplets. Since the main chiller is designed to accommodate an input sample temperature of 351°C; the heated filter and line leading to the chiller is maintained at 191°C as well to provide a safety buffer for the temperature in the event of temperature fluctuation due to the nature of operation of the temperature controller. The EGR sample would not have to be heated as CO_2 concentrations are not affected by moisture in the sample [9].

Figure 4.7 below shows the final design of the filtration system. It consists of three filter housings for three separate sample streams. Two of the filter housings are heated. The third (smaller) filter housing is not heated as is intended for the EGR sample. The only constituent measured in the EGR sample is CO_2 as it is compared to the main sample CO_2 and an EGR value is established. Appendix A.1 details the design and specifications of the sample filtration system.

Appendix A.1 contains detailed plans for the stainless steel bracket and the filter housings.

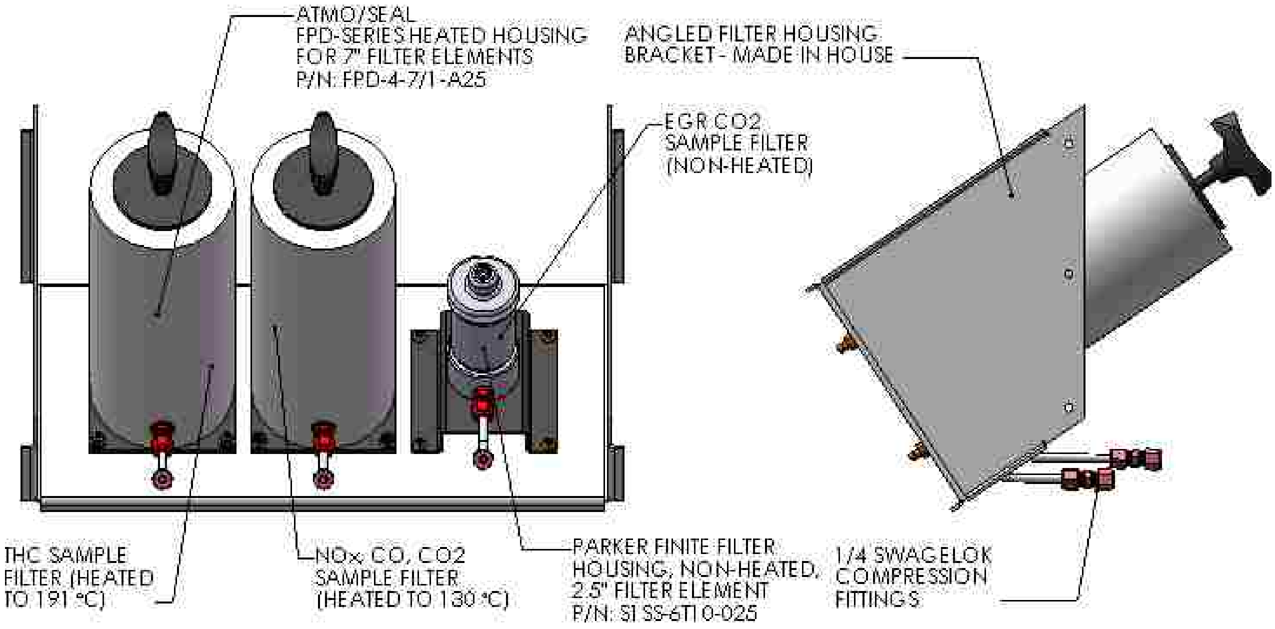


Figure 4.7: Sample Filtration Assembly

4.4 Exhaust Sample Dryers (Chillers)

There are two chillers used in this system. The first chiller is used for the main sample stream and the other for the EGR sample stream. The chillers are manufactured by Universal Analyzers Inc. and they are of the thermoelectric type. The chiller used for the main sample stream is the UA Model 540 Dual Channel Sample Cooler. It consists of two separate, insulated heat exchangers that are routed in series to achieve optimum cooling. Figure 4.8 shows the Universal Analyzer Model 540 main sample cooler.

The 540 model is used in the main sample stream to condition the sample to the desired dew point (2-4°C or lower) before routing the sample to the NDIR and the CLD analyzers. The NDIR analyzer used in this system is capable of analyzing two separate CO_2 samples simultaneously. Therefore, it was decided to use this analyzer to provide the real-time EGR capability. The second chiller is used in the EGR sample stream. This sample is also routed to the NDIR analyzer. Figure 4.9 shows the single-channel 520 model.

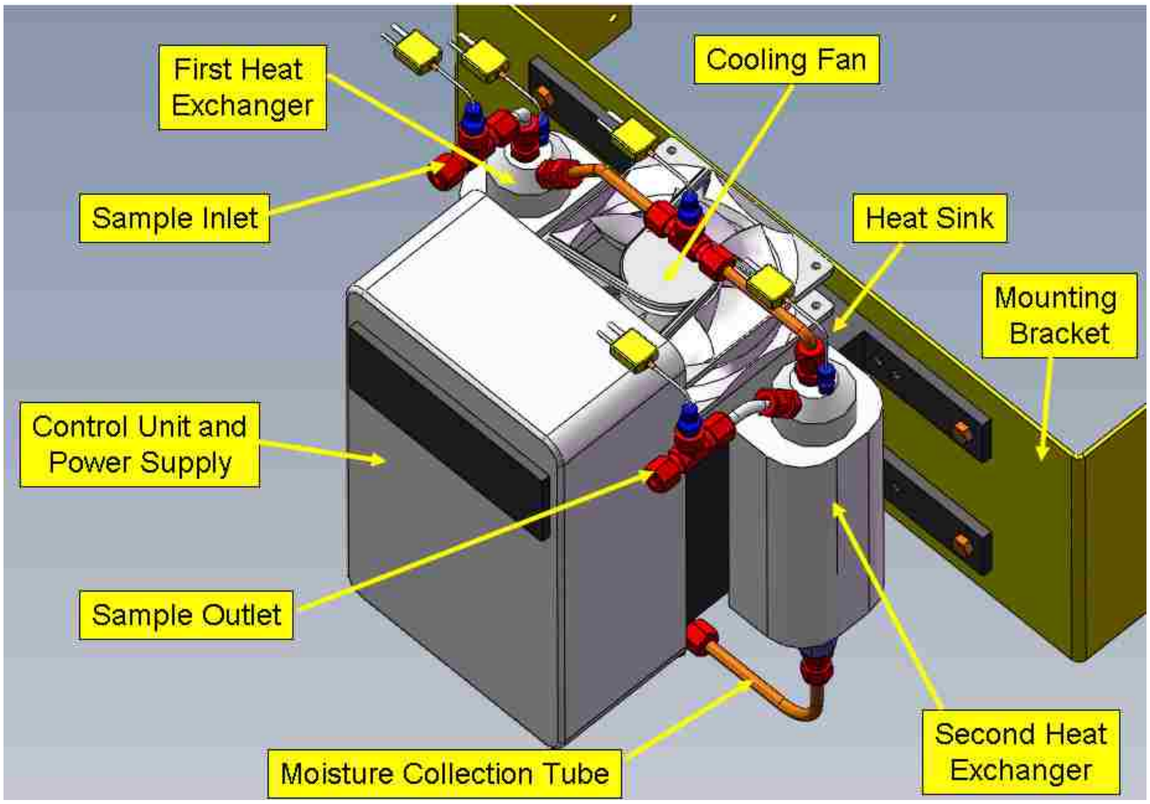


Figure 4.8: Universal Analyzers Model 540 Dual Channel Sample Cooler

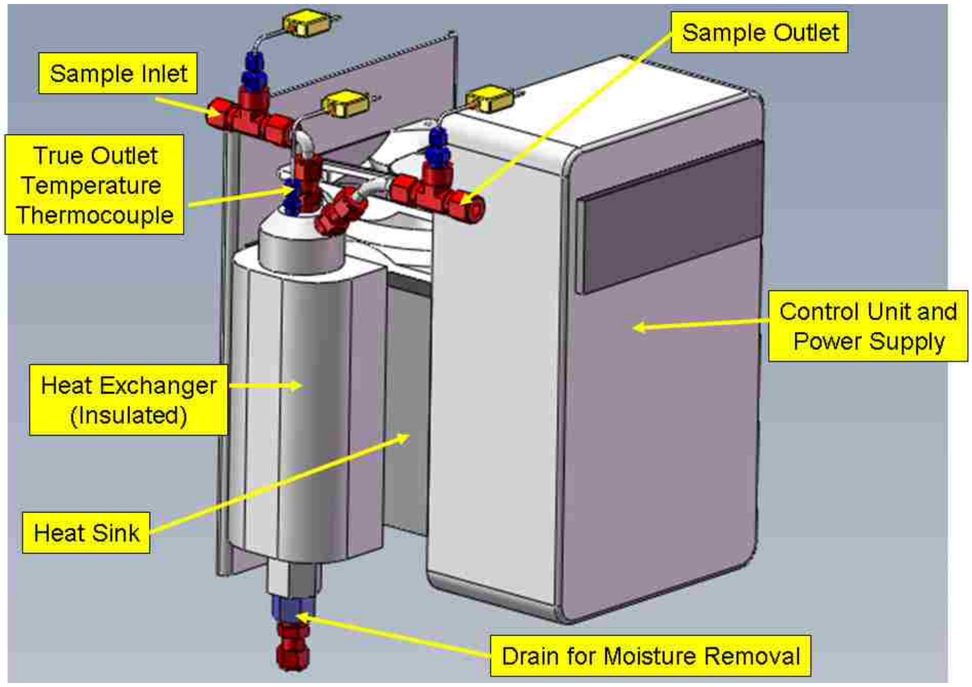


Figure 4.9: Universal Analyzers Model 520 Single Channel Sample Cooler

The operating principle of these chillers is based on thermoelectric cooling. A thermoelectric module (Peltier Junction) is mounted on aluminum blocks that house the heat exchanger. When current is supplied to this module at a specific voltage a cooling effect occurs as one side of the module drops in temperature and the other side's temperature increases. Figure 4.10 shows a typical commercial single-stage Peltier module.

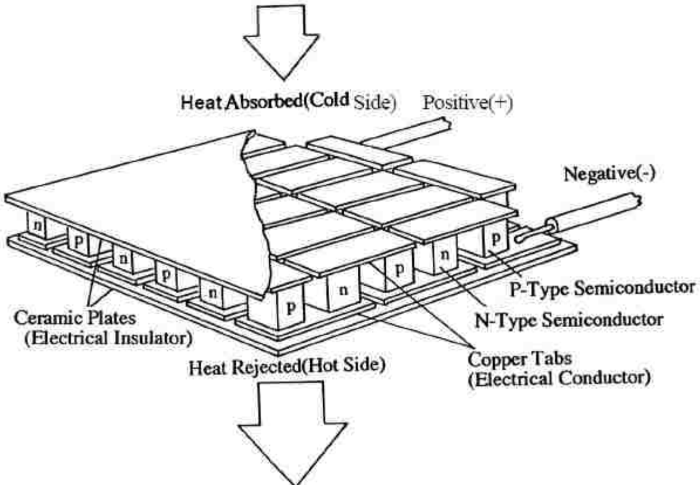


Figure 4.10: Commercial single-stage Peltier junction [18]

These modules are designed and manufactured in different sizes, cooling capacities, and power ratings. They are common in applications where space conservation is critical and when no moving parts are required [18]. A Peltier module consists of many thermoelectric couples that are connected electrically in series and thermally in parallel. These couples are placed between two ceramic plates that act as the hot and cold surfaces [18]. These modules are rigid and require optimal surface mounting to perform properly. A single Peltier module is used for each heat exchanger in the Universal Analyzer chillers. Figure 4.11 shows the detail of the configuration used in the chillers. The 540 model utilizes two such configurations routed in series. The 520 model consists of one heat exchanger.

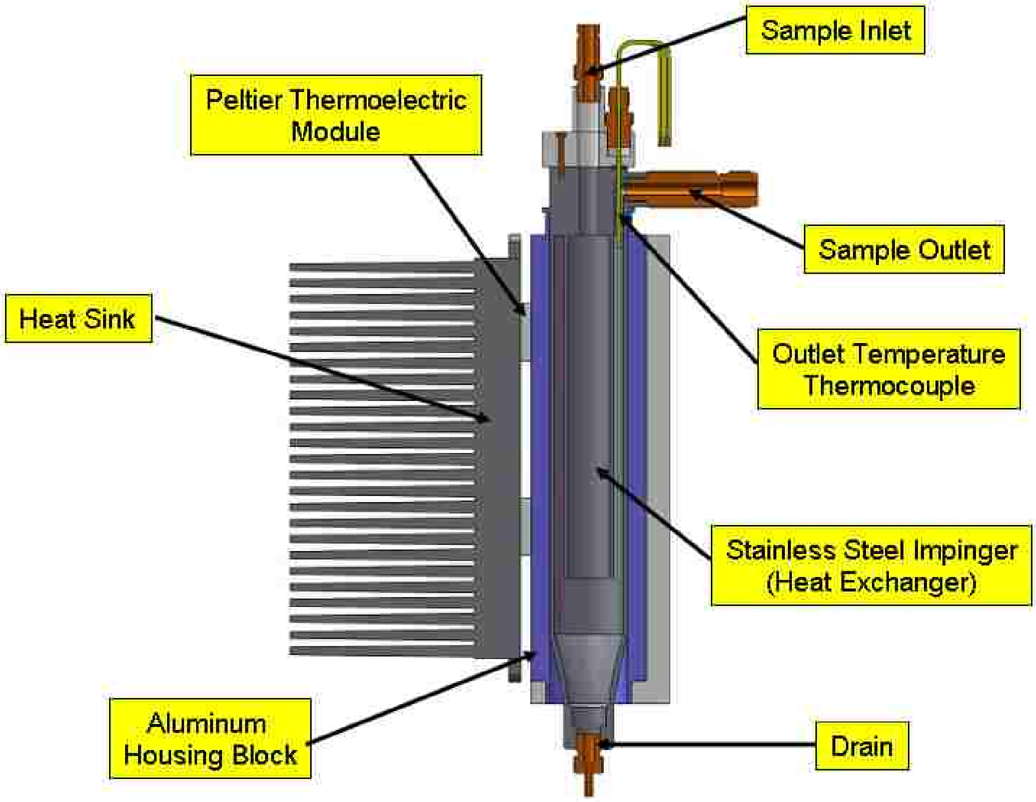


Figure 4.11: Heat Exchanger Setup for the UA Chillers

This type of cooling has many advantages. The Table 4.4 compares the specifications of the Universal Analyzer 540 model (dual-channel) to the currently used CAI OEM chiller model 1100.

Table 4.4: Universal Analyzer Model 540 vs. CAI OEM Chiller Model 1100 [17, 19]

Category	Universal Analyzer Model 540	CAI OEM Chiller Model 1100
Method of Cooling	Thermoelectric Module	Refrigeration Cycle Using R-134a
Sample Flow rate	0-4 Liters/Min	Up to a Maximum of 10 Liters/Min
Ambient Temperature	1 - 41 °C	5 - 35 °C
Maximum Inlet Temperature	351 °C	70 °C
Power Requirement	740 Watts (Maximum)	300 Watts
Operating Relative humidity	50%	100%
Weight	24 lbs (11 Kg)	41 lbs 918.6 Kg)
Outlet Sample Dew Point	40 °F (4 °C) Adjustable	34 °F

Since the chiller would have to supply a dry sample to two of the three analyzers; the maximum sample flow rate of the UA chiller is adequate for this system and if the heat exchangers are connected in series; the flow rate can be as high as 15 LPM [17]. The maximum ambient temperature and maximum inlet temperature of the UA chiller are also favorable to the CAI OEM 1100 chiller. The sample inlet temperature is very critical to the successful operation of the sampling system. Having the ability to heat the transfer lines to 191°C prevents accidental condensation upstream of the chiller and allows the sample moisture to condense in the chiller only where it is designed to remove the water efficiently while having minimal effect on exhaust constituents' concentrations. This is not feasible with the currently in-service CAI OEM 1100 chiller. In order not to exceed the 70°C maximum inlet temperature of the CAI 1100 chiller; the temperature of the transfer lines connected to the chiller's inlet has to be reduced. Also, supplying a gas sample higher than the recommended maximum inlet temperature would overload the refrigeration cycle of the chiller and may leave a significant amount of water still present in the sample at the outlet. This shortcoming is the main reason for using water separators downstream of the chiller as indicated in Figure 3.3. The Universal Analyzer model 540 chiller has the following soluble gas removal rates [17]:

- NO = 0% Loss
- NO_2 = <10% Loss
- SO_2 = <2% Loss
- CO = 0% Loss
- CO_2 = <2% Loss

Appendix A.2 lists the manufacturer's documentation for UA model 520 and 540.
In order for the UA chiller to perform as intended; the moisture removed by the chiller must be disposed of properly. Failure to remove the collected moisture will result in poor performance in the form of excessive condensate collecting in the chiller's heat exchanger leading to water being present in the sample after the chiller. To accomplish this task; a peristaltic pump drive connected to a condensate tank on the outlet was used.

4.5 Exhaust Sampling Pumps

The CAI sampling system utilizes two sampling pumps for the handling of three separate sample streams. The first pump is dedicated to the THC sample line and is enclosed in the CAI HFID 600 analyzer. The FID internal sampling pump is provided by KNF Neuberger Inc. and the model is N010ST.16I. Below are the specifications of this pump [21]:

- 316 stainless steel head construction.
- 9 liter/min (0.32 SCFM) maximum flow.
- 22 psig maximum continuous pressure.
- Solid Teflon diaphragm and valves construction.
- 115VAC (60 Hz), 2.1A maximum power rating.

Figure 4.12 on the next page shows the N010ST.16I diaphragm sampling pump. Appendix A.3 lists additional technical specifications regarding this pump.

Figure 4.12: KNF Sampling Pump Model N010ST.11I [21]

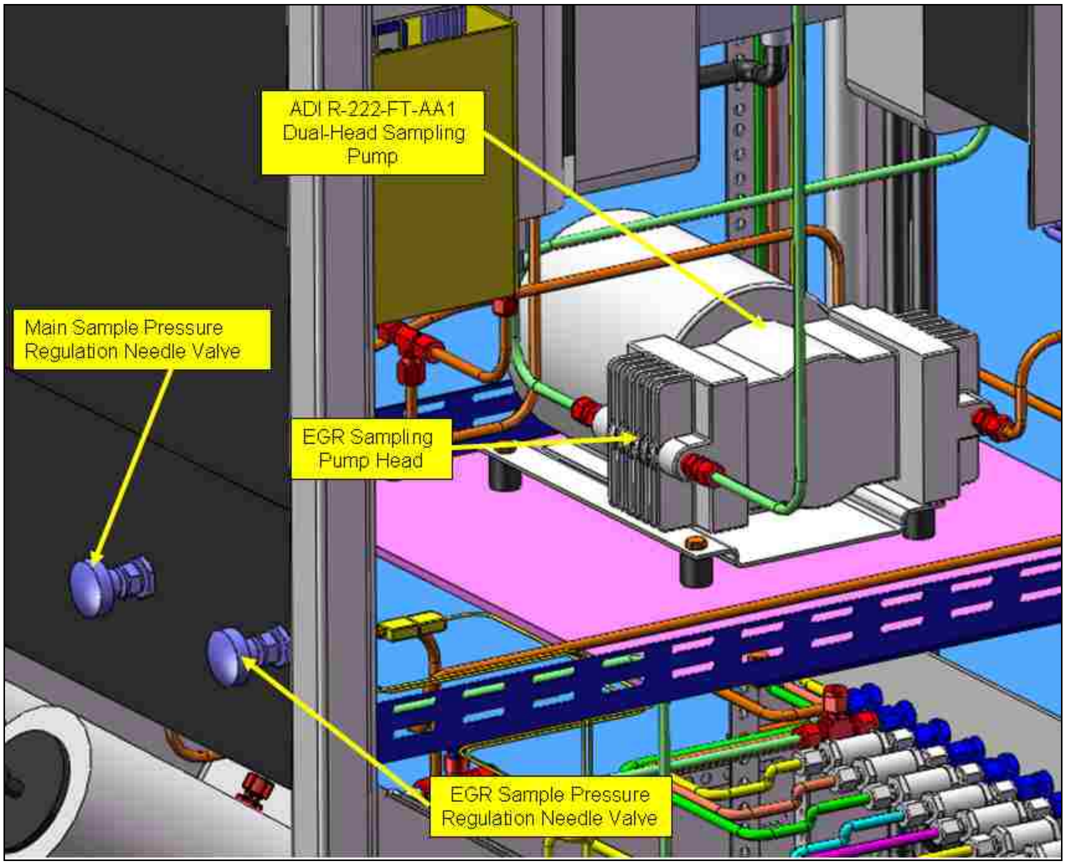
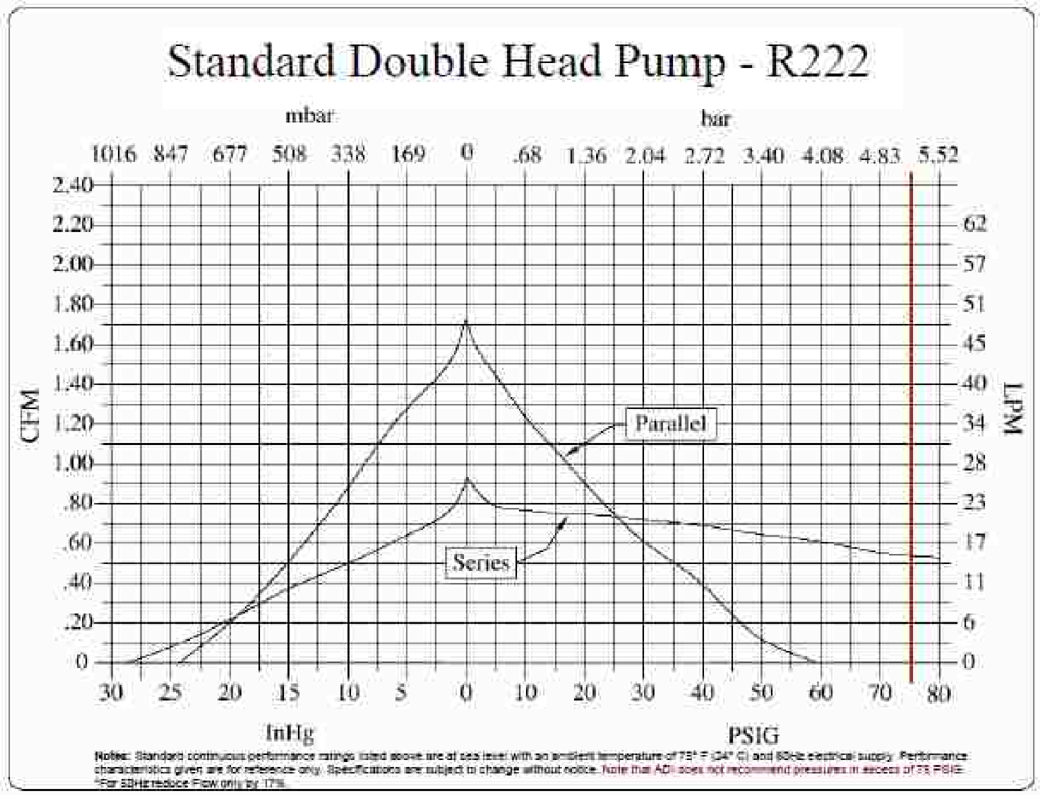


Figure 4.13: ADI Dual-Head Sampling Pump Used in the Sampling System

The second sampling pump is used for the remaining two sample streams; the main sample and the EGR sample. The main sampling pump is manufactured by Air Dimensions Inc. (ADI) and the model used is Dia-Vac R222-FT-AA1. This pump is of the diaphragm type and consists of two pump heads. This pump (pictured in figure 4.13 above) is also not heated. This pump has the following specifications [22]:

- Maximum Outlet Pressure = 53 PSIG (3.66 bar)
- Ultimate Vacuum = 24.0 inHg
- Maximum Flow rate = 0.92 CFM (26.0 LPM)

In order to establish that this pump meets the pumping requirements for the sampling system; the pump chart for this specific pump had to be reviewed. Figure 4.14 shows the R-222 generic pump chart [22]:

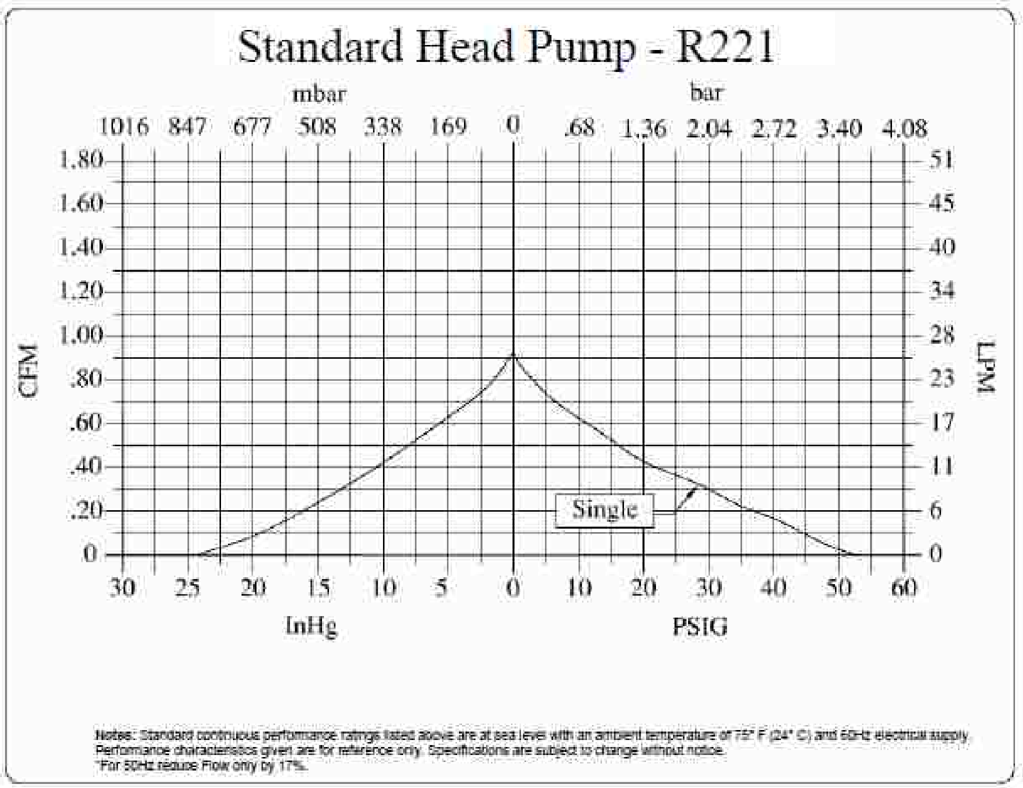


Notes: Standard continuous performance ratings listed above are at sea level with an ambient temperature of 75° F (24° C) and 60Hz electrical supply. Performance characteristics given are for reference only. Specifications are subject to change without notice. Note that ADI does not recommend pressures in excess of 75 PSIG.
*For 50Hz reduce Flow only by 17%.

Figure 4.14: ADI R-222 Pump Chart [22]

The purpose of this chart was to quickly verify the flow rate of the pump at specific outlet pressure or inlet vacuum conditions. This chart is designed specifically for parallel or series configurations of this pump. However, this pump will not be used in this fashion. The R-222 pump heads are used independently of each other and therefore, this chart cannot be used to verify the flow rate of each pump head separately. The choice was made to consult the R-221 pump chart (Figure 4.15) instead, as this chart is suited for a single-head pump that has the same specifications as each of the heads on the R-222 pump. When examining the R-221 pump chart; the following conclusion is made:

When restricting the pump outlet pressure to the range of 10-15 PSIG; the flow rate was observed to be in the range of 15-18 LPM.



Notes: Standard continuous performance ratings listed above are at sea level with an ambient temperature of 75° F (24° C) and 60Hz electrical supply. Performance characteristics given are for reference only. Specifications are subject to change without notice.
*For 50Hz reduce Flow only by 17%.

Figure 4.15: ADI R-221 Pump Chart [22]

This pressure range is considered safe according to the analyzer manufacturer [2, 3, 4] while at the same time delivering the exhaust sample at an adequate flow rate as 15-18 LPM is considered satisfactory when keeping in mind that it would supply 4 separate detectors in the main sample stream (CO_2_Exh, CO_2_EGR, CO, and NOx). The second pump head would supply the EGR stream as stated before. However, proper testing is needed to determine if the pump is needed in diesel applications as the EGR sample is usually under considerable pressure due to turbocharger boost. The EGR pump can still be used when using the analyzer bench for gasoline applications.

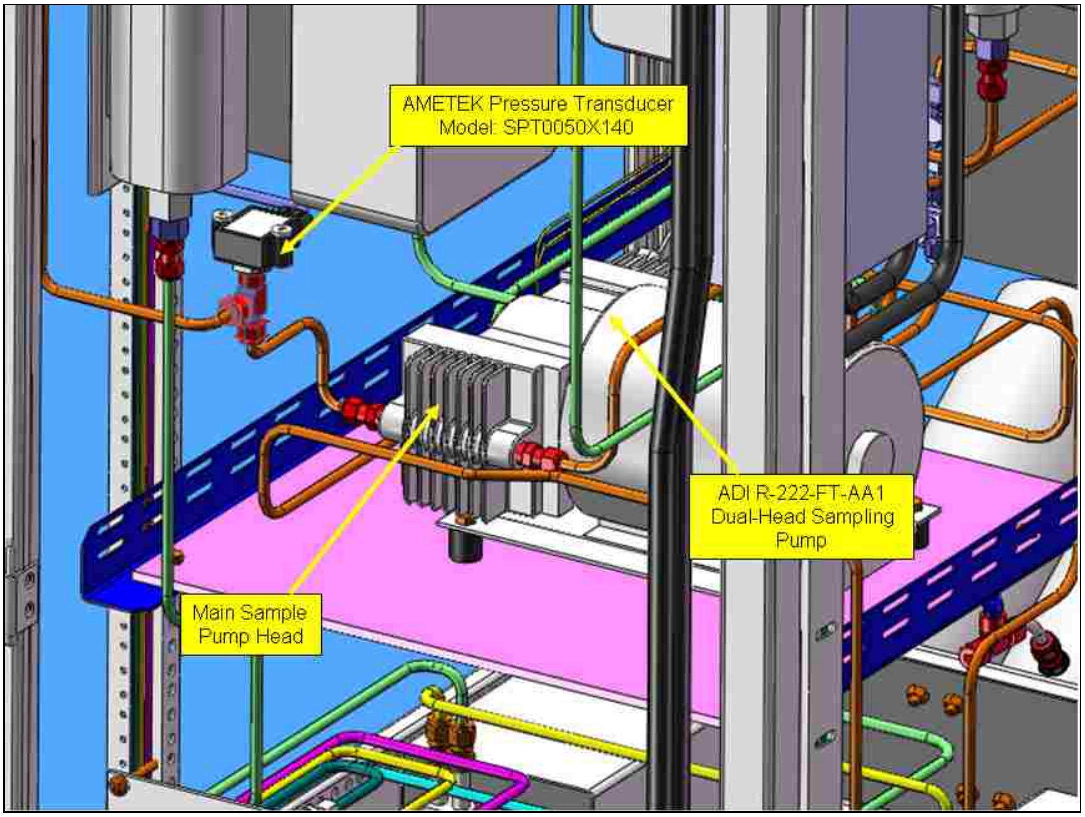


Figure 4.16: The Main Sample Side of the ADI Sampling Pump

The output pressure is monitored by an electronic pressure transducer manufactured by Ametek US. Gauge, model: SPT0050X140. This pressure transducer has a range of 0-50 psig and it is discussed in further detail in section 4.7.1. This pressure transducer is used to monitor the sample pressure at the inlet of the NDIR and CLD analyzers as well. It is shown in Figure 4.16.

4.6 Span and Fuel Gas Bulkhead System

The span fuel gases necessary for the performance of the CAI analyzer system are delivered to the bench through a bulkhead assembly that would ensure ease of use and that the filtration requirements for these gases are met. The manufacturer recommends that the fuel gases are filtered using a 2-4 micron filter. Figure 4.17 shows the details of the bulkhead.

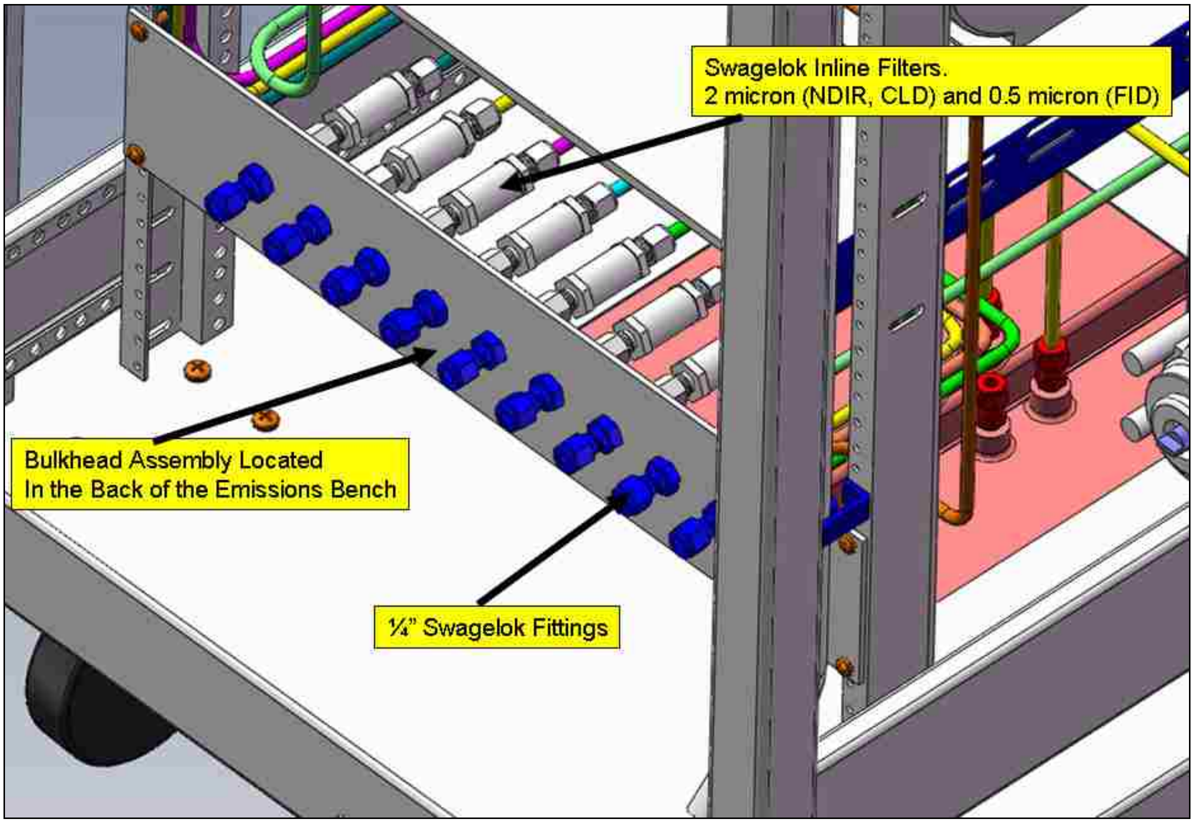


Figure 4.17: Span and Fuel Gas Bulkhead System

4.7 Data Acquisition System

A data acquisition system (DAQ) is needed to collect vital information during the operation of the analyzers, such as, exhaust sample temperatures and pressures in various stages throughout the sampling system and also to collect exhaust concentration data through the analog output channels of the three analyzers. The DAQ is manufactured by ETAS and it consists of different modules each designed to collect specific types of data. Figure 4.18 shows the module stack employed in the CAI analyzer system. These modules are connected to a central hub (ES600.1), which in turn can connect to a remote computer via an Ethernet cable.

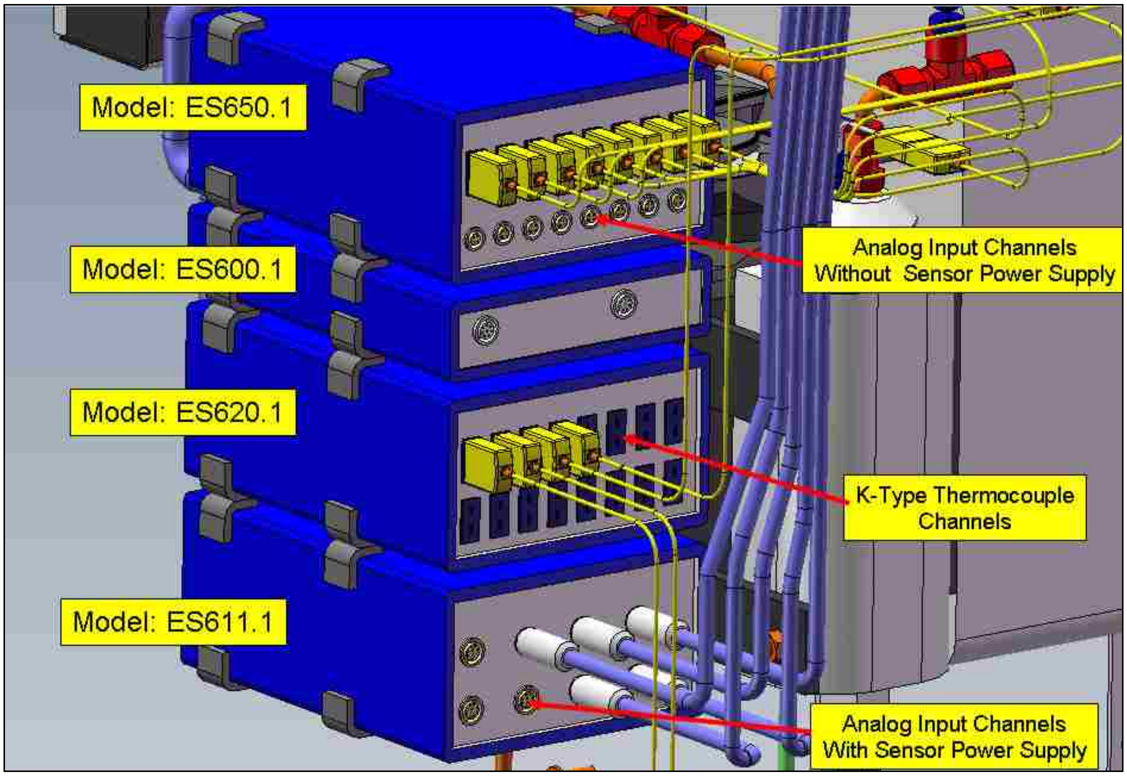


Figure 4.18: ETAS Data Acquisition Modules

This system is designed to collect the following data from the sampling system:

1. Exhaust gas temperature after the filtration stage for the THC and main samples.
2. Exhaust gas temperature through the main and EGR chiller to monitor chiller performance.
3. Exhaust gas pressure at the inlet of the NDIR and CLD analyzers to ensure maximum pressure rating is not exceeded and to be used as a feedback when regulating the sample pressure using the pressure regulation needle valve.
4. Exhaust gas pressure at the outlet of the main pump head to help achieve proper flow rate through the chiller.
5. Analog output data from the three analyzers.
6. Exhaust gas temperature through the transfer lines and heated filter upstream of the emissions bench in order to monitor the exhaust gas and detect any issues that may arise, such as, a failed transfer line or filter.

Table 4.5: Specifications of the ETAS Modules Used in the Data Acquisition System [23, 24, 25, 26]

Model: ES650	
Analog Voltage Inputs	
Resolution	16 bits, higher at slower sampling rates
Sampling Rate	0.5 to 2000 samples/sec
Input Voltage range	-10V to +10V or -60V to +60V
Maximum Inaccuracy	0.05%
Power Supply	
Operating Voltage	6 to 32 V DC
Current Consumption	Approx. 270 mA (Operational) and 5 mA (Standby) at 12V
Thermocouple Inputs	
Resolution	21 bits, corresponding to 0.1 K for K-Type Thermocouples
Sampling Rate	0.1 to 10 Samples/sec
Measuring Range	-210 to +1372 C (Type K)
Maximum Inaccuracy	0.005 K/K for Type K Thermocouples

Model: ES620	
Power Supply	
Operating Voltage	6 to 32 V DC
Current Consumption	Approx. 220 mA (Operational) and 5 mA (Standby) at 12V
Thermocouple Inputs	
Resolution	21 bits, corresponding to 0.1 K for K-Type Thermocouples
Sampling Rate	0.1 to 10 Samples/sec
Measuring Range	-210 to +1372 C (Type K)
Maximum Inaccuracy	0.005 K/K for Type K Thermocouples

Model: ES611	
Analog Voltage Inputs	
Resolution	16 bits, higher at slower sampling rates
Sampling Rate	0.5 to 2000 samples/sec
Sampling rate (Ch. 4,8)	0.5 to 20000 samples/sec
Input Voltage range	-10V to +10V or -60V to +60V
Maximum Inaccuracy	3 mV + Uin * 0.05%
Power Supply	
Operating Voltage	6 to 32 V DC
Current Consumption	Approx. 1.7A (Operational) and 5 mA (Standby) at 12V
Sensor Supply	
Resolution	12 bit
Output Voltage (Vout)	0V to -15V, 0V to +15V
Maximum Error	25 mV

4.7.1 Pressure Transducer Selection and Location

There are six pressure transducers installed in the sampling system to monitor exhaust sample pressure at different stages of the system. The six locations are:

1. Sample input of the chemiluminescence analyzer (CLD)
2. Sample input of the main CO_2 detector of the NDIR analyzer
3. Sample input of the main CO detector of the NDIR analyzer
4. Sample input of the second CO_2 detector of the NDIR analyzer that serves at the EGR CO_2 detector
5. The main sampling pump head outlet port

The pressure transducer selected is the Ametek SPT Series model SPT0050X140 manufactured by Ametek US. Gauge. This transducer is made of 316L stainless steel internal parts that make it compatible with exhaust gas. Below are some of the specifications of this transducer [27]:

• Model:	SPT0050X140.
• Range:	0 to 50 PSIG.
• Voltage Output:	1-6 VDC.
• Input Excitation:	8 to 15 VDC.
• Accuracy:	±0.25% Full Scale.
• Response Time:	Less than 20 milliseconds.
• Connection Type:	1/8” Male NPT Connection.

These pressure transducers are connected to the ETAS ES611.1 module. This ETAS module is capable to supplying the required power to this transducer while acquiring the analog voltage. Therefore, it is not necessary to supply power to the transducer through a separate power supply. The output signal of this pressure transducer is also amplified through a circuit placed in the transducer enclosure. Therefore; a charge amplifier is not needed in this case. Figure 4.19 shows the Ametek SPT pressure transducer.

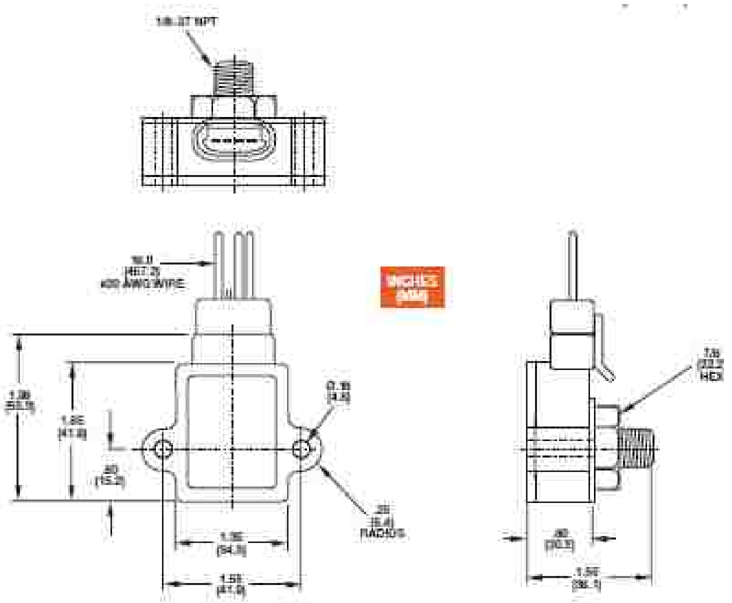


Figure 4.19: Ametek SPT Pressure Transducer [27]

Figure 4.20 shows the pressure transducers used in the CAI emissions bench.

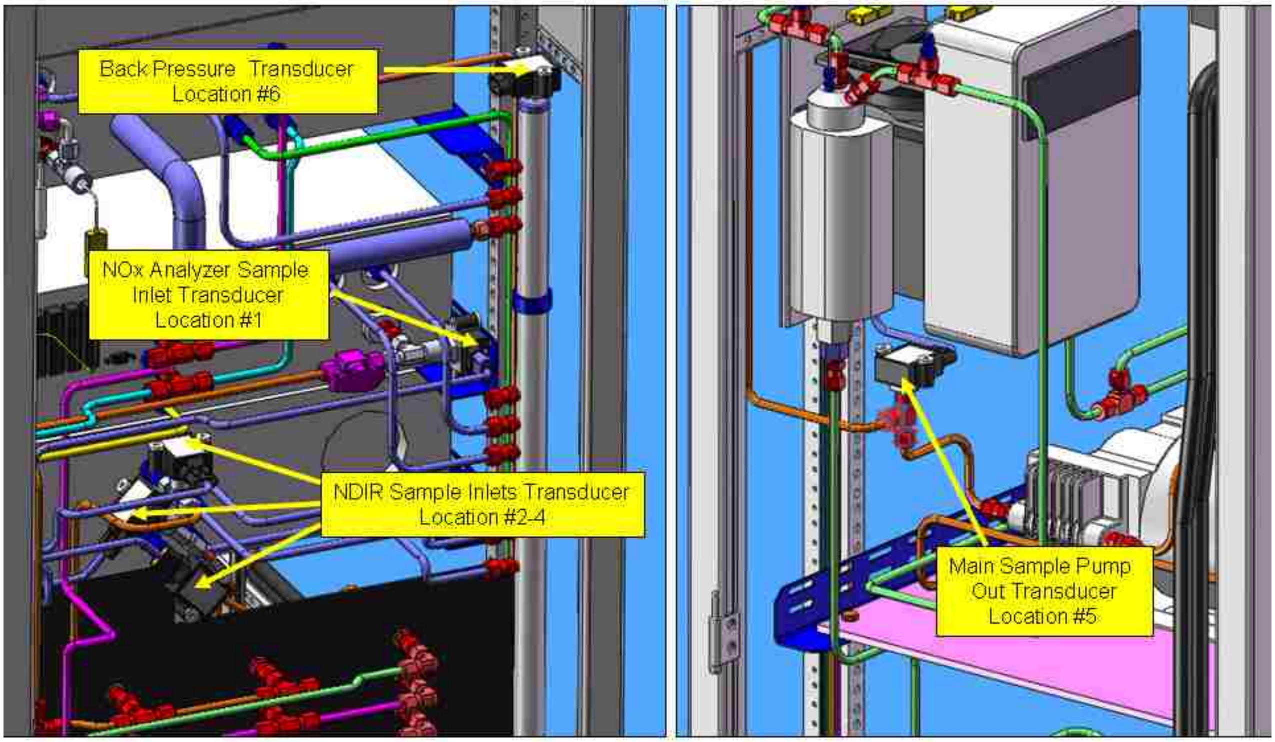


Figure 4.20: Pressure Transducers Connected to NDIR and CLD Analyzers

4.7.2 Thermocouple Selection and Location

Thermocouples are installed in different stages of the sampling system to observe the temperature of the exhaust gas as it flows through the system. This allows the operator to detect problems within the sampling system at an earlier stage than the current system. The temperature data can be acquired by the ETAS data acquisition system and can be used to demonstrate that the sampling system was operating within the required parameters during testing. Table 4.6 lists the locations of the K-Type thermocouples used in the CAI emissions bench.

Table 4.6: Thermocouple Locations

TC No.	Location
1	FID Sample Inlet
2	CLD and NDIR Sample Inlet
3	FID Sample Post Heated Filter
4	Main Sample Post Heated Filter
5	Main Chiller Sample Inlet
6	Main Chiller First Impinger Out Temp
7	Main Chiller Sample Mid Temp
8	Main Chiller Second Impinger Out Temp
9	Main Chiller Sample Outlet
10	Main Chiller Cooling Air Temp
11	EGR Chiller Sample Inlet
12	EGR Chiller Impinger Out Temp
13	EGR Chiller Sample Outlet
14	EGR Chiller Cooling Air Temp
15	Sample Temp at Sampling Point
16	Sample Temp Post First FID Heated Filter
17	Sample Temp Post First Main Heated Filter

As stated above; the thermocouple type used in this project is the K-type. This is the standard type used at PERDC and it has the following specifications [28]:

- Temperature range: -200°C to 1250°C (-328°F to 2282°F).
- Std. limits of error: greater of 2.2°C or 0.75%.
- 1/16” Probe OD with mini-connector type.
- Nickel-Aluminum grade (Yellow) extension cables.

The locations of the thermocouples are pictured in Appendix A.4.

4.8 Final Assembly

All the sub-systems discussed in this chapter so far will have to be connected together to arrive at the final product. This is achieved by connecting the component together by using one of the following three methods:

- Stainless steel tubing – Grade 304, 0.25” OD, 0.17” ID.
- Teflon Tubing – 0.25” OD, 0.19” ID
- Heated Transfer lines. These lines are supplied by Atmo/Seal Inc. The inner tube is a 0.25”OD Teflon tube. This is used when the sample temperature needs to be controlled at a specific temperature.

Also, stainless steel Swagelok fittings are used where needed, such as, tees, straight fittings, and needle valves. Figures 4.21 and 4.22 show the main sample path and the EGR sample path.

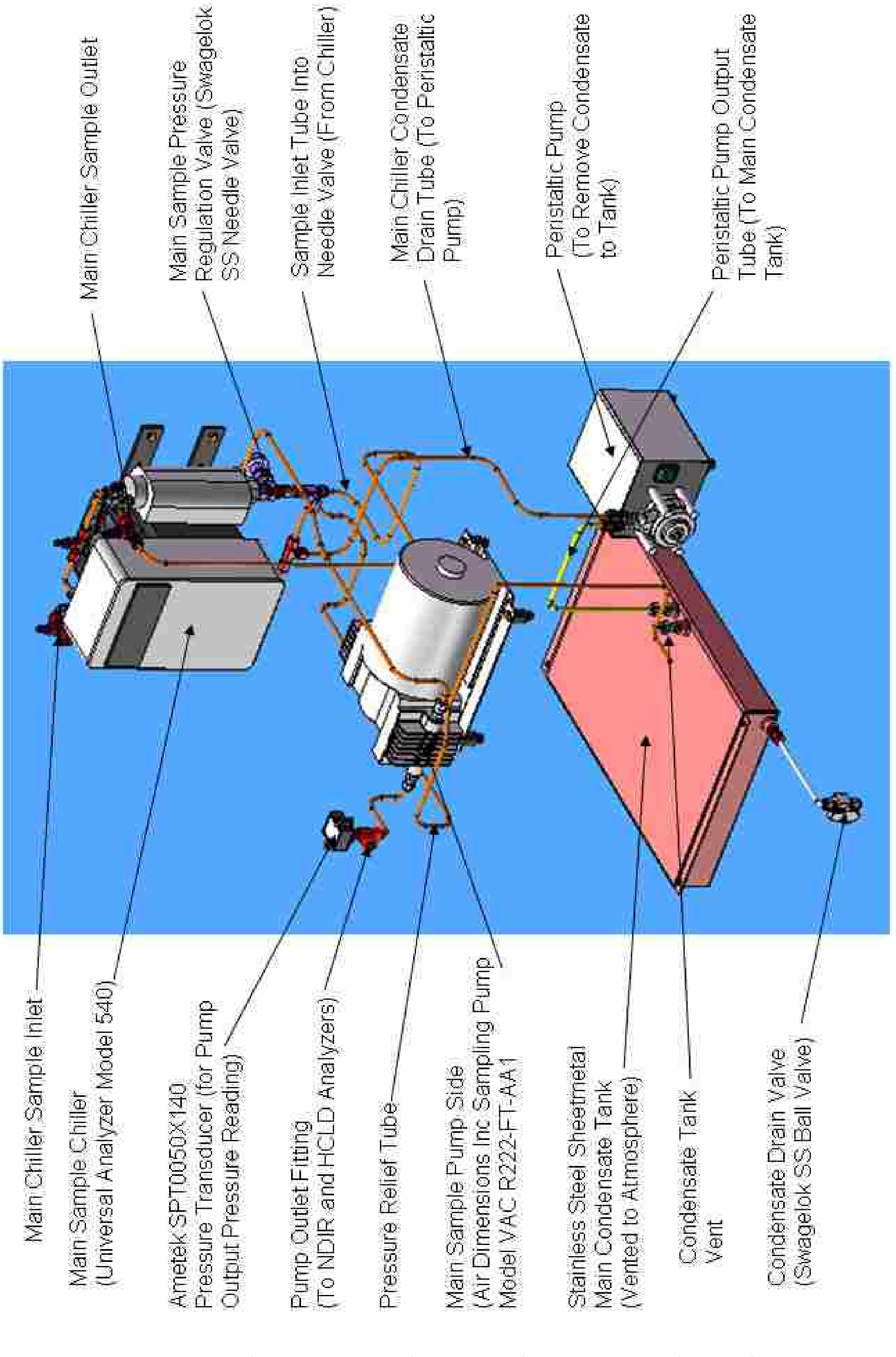


Figure 4.21: Main Sample (NDIR+CLD) Path Starting at the Chiller Sample Inlet

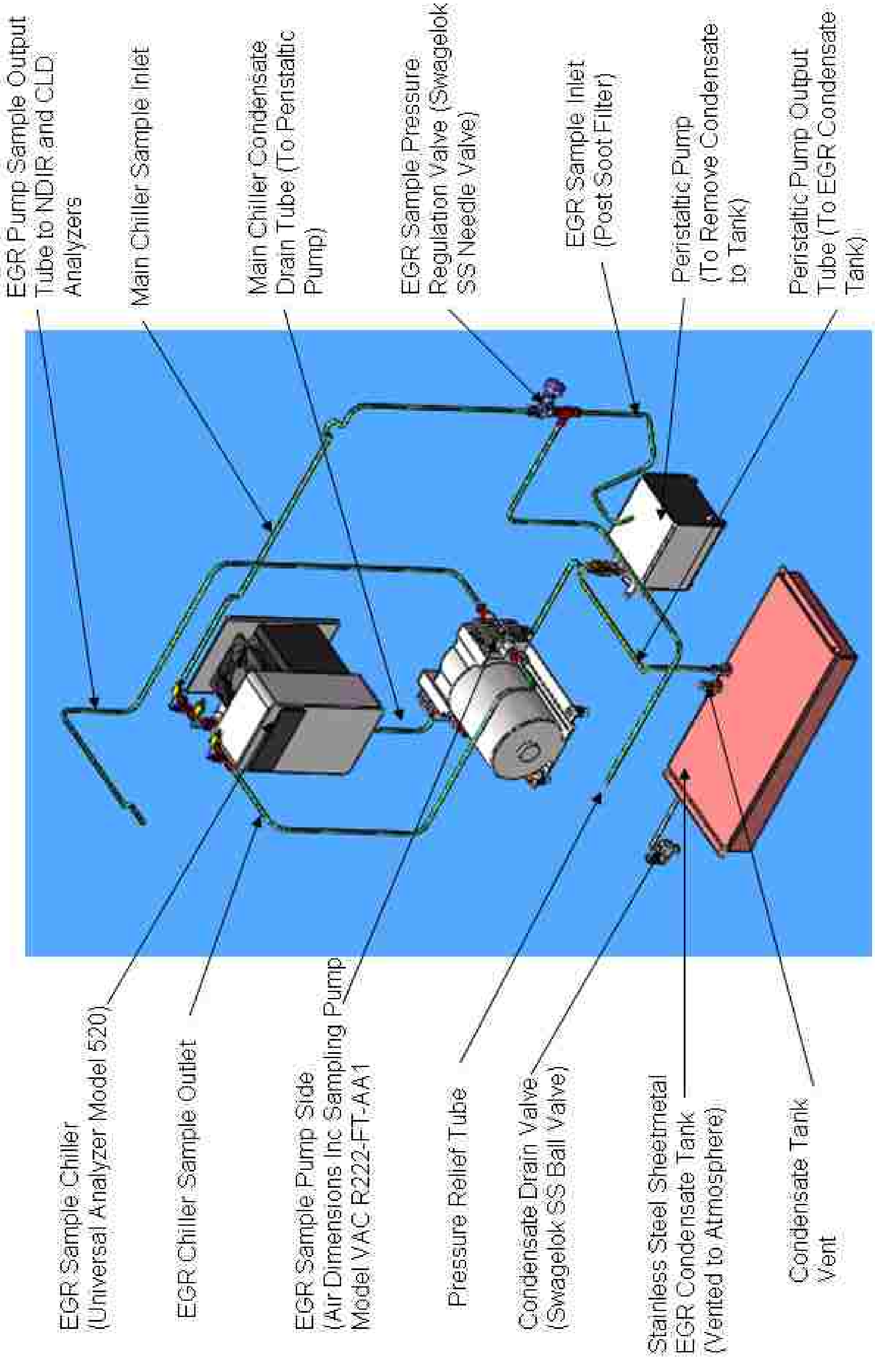


Figure 4.22: EGR Sample Path Starting at the Chiller Sample Inlet

5 FABRICATION AND ASSEMBLY

This chapter details the fabrication of the components that are designed in-house. Also, the final assembly is detailed in this chapter and the commissioning of the final product.

5.1 Component Fabrication

This section details the components and systems that were fabricated in-house. This includes brackets, enclosures, temperature controller units, and transfer lines.

5.1.1 Transfer Lines and Junction Heaters

The transfer lines used in this project fall into three categories as discussed in chapter 4. The first category is the heated transfer lines used to transfer the sample from the exhaust sampling point to the CAI emissions bench and then within the emissions bench itself upstream of the main chiller to prevent aqueous condensation. A heated transfer line is also used to transfer the sample from the FID heated filter to the FID instrument to prevent hydrocarbon condensation. These lines are maintained at 191°C internal wall temperature as per EPA requirements [12]. The heated transfer lines have the following specifications [15]:

1. 0.25” OD Teflon Sample tube for added flexibility.
2. The internal sample tube is insulated with a special felt material. The outside diameter measures 1.5”.
3. Electrical requirements: 120V/60Hz - 2 Amps.
4. This transfer line requires a temperature controller to function properly.
5. The heater element is sleeved in an extruded layer of silicon, rated at 200°C continuous operation with 250°C maximum temperature.

Figure 5.1 below details the internal components of the heated transfer lines used [15]:

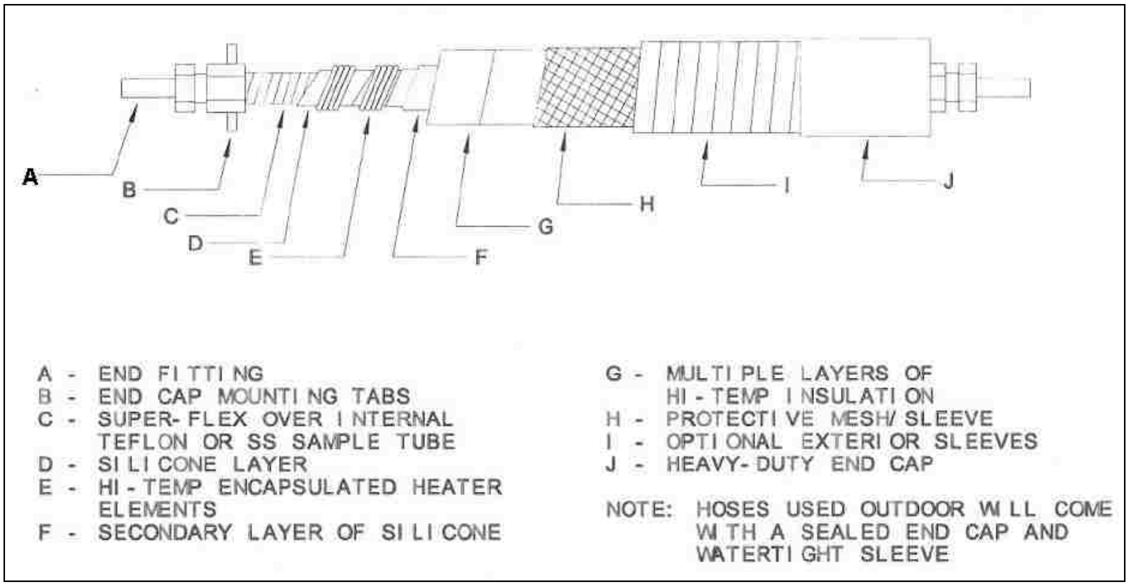


Figure 5.1: Atmo/Seal Heated Sample Transfer Line [15]

Figure 5.2 below shows the heated transfer lines used inside the bench and to deliver the sample to the bench.

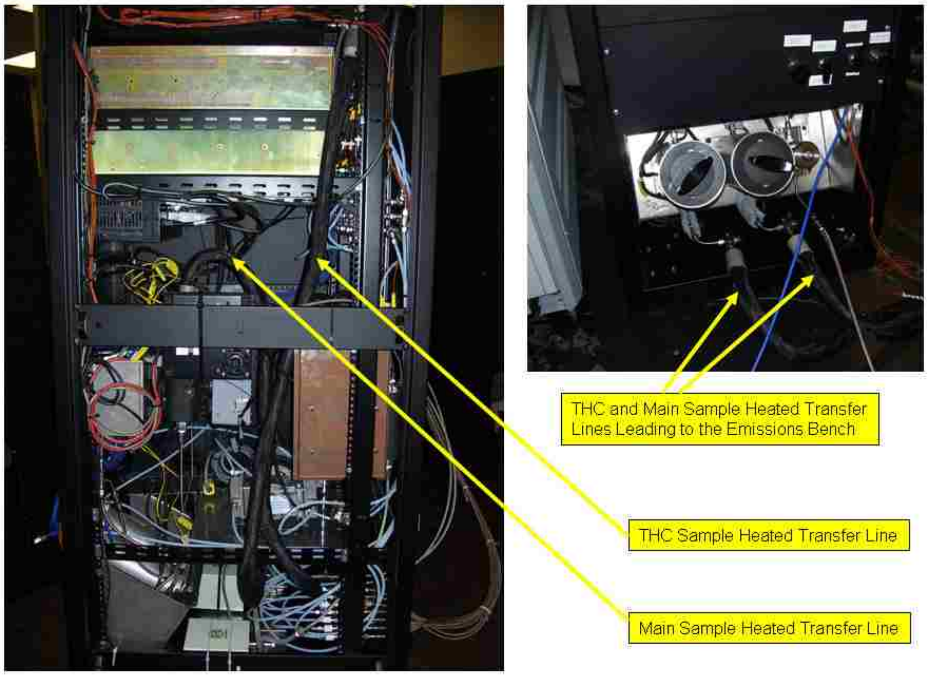


Figure 5.2: Heated Transfer Lines Used

The other two categories of transfer lines are the solid stainless steel tubing and the flexible Teflon tubing. These two kinds of transfer lines are used when sample temperature does not need to be regulated as it flows through the line. The Teflon tubing was used as the preference due to its flexibility and ease of installation. It also meets EPA requirements as specified in CFR 40: Part 1065 (Engine testing procedures) [12]. Figure 5.3 below shows the stainless steel and the Teflon tubing:

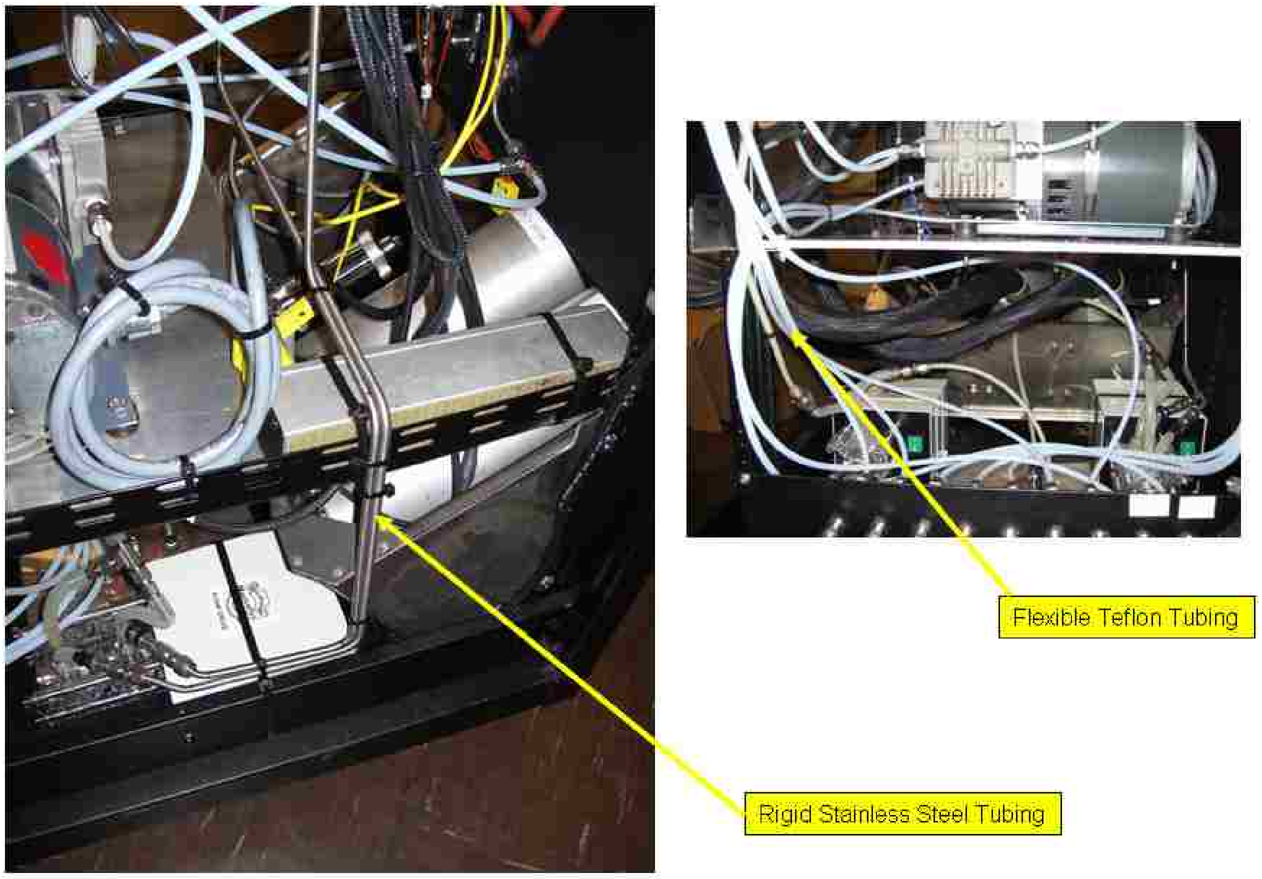


Figure 5.3: Stainless Steel and Teflon Tubing

Swagelok 0.25” compression fittings are used at the ends of all transfer lines. These fittings are 316-grade stainless steel. The heated transfer line fittings are also heated using special junction heaters that are designed to clip over tee or straight fittings. This is done to eliminate any “cold spots” from the sample path that may lead to sample condensation resulting in false results. These junction heaters follow the same principle as the heated transfer lines. They are also manufactured by Atmo/Seal and are rated for

200°C continuous operation [15]. They require an external thermocouple to be installed in order to sense the junction temperature as a feedback signal to the temperature controller. Figure 5.4 shows a junction heater fully assembled with the connector and the thermocouple female connector to accommodate a K-Type thermocouple.

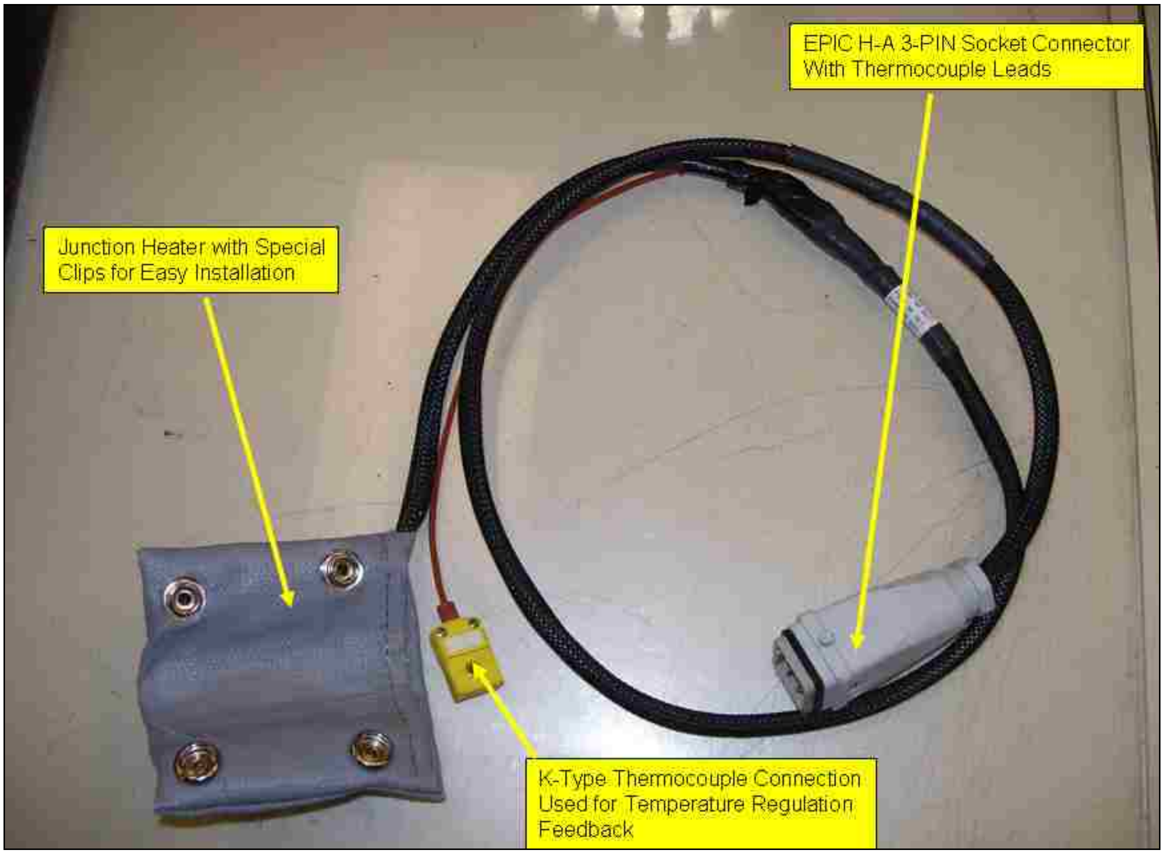


Figure 5.4: Atmo/Seal Junction Heater Fully Assembled

Figures 5.5 and 5.6 show the junction heaters installed in the CAI emissions bench. In Figure 5.5; the junction heaters are installed across the heated particulate filters. In figure 5.6; the junction heater is installed on the exposed stainless steel tube leading to the FID sample inlet. This setup eliminates the cold spot between the two devices. This cold spot was previously wrapped with insulating wrap to prevent heat dissipation; however, this did not solve the problem as heat was not added to the junction to maintain the 191°C temperature requirement.

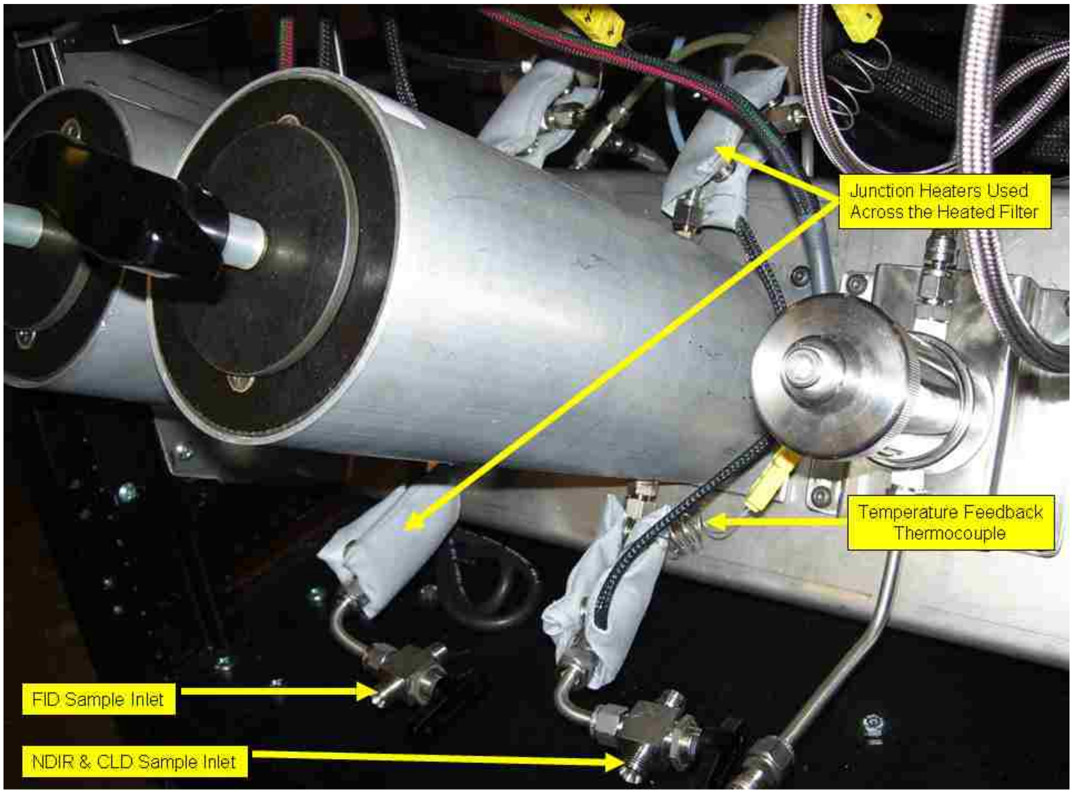


Figure 5.5: Junction Heaters Installed Across the Heated Particulate Filters

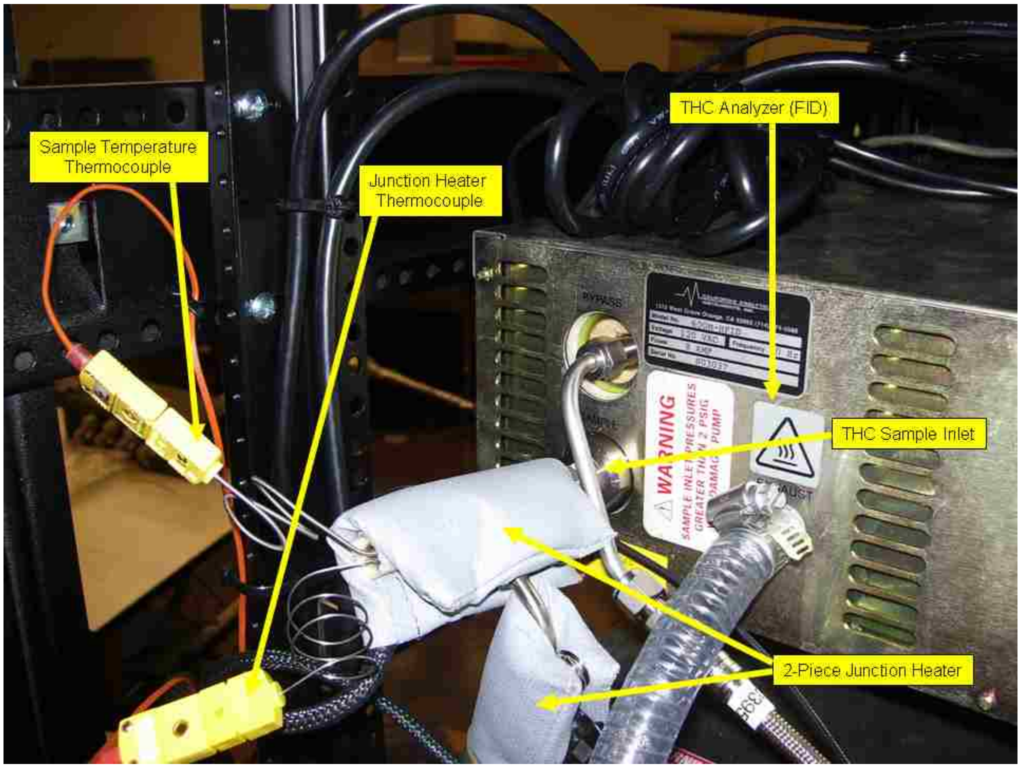


Figure 5.6: Junction Heaters Installed At the Flame Ionization Detector Sample Inlet

There are three junction heaters used in the CAI emissions bench. Two of the junction heaters are used across the heated filters in the front of the bench. The third heater is used at the sample inlet of the THC analyzer (FID) to eliminate the cold spots from exposed stainless steel tubing and fittings.

5.1.2 Temperature Controller Unit

A temperature controller unit was designed to provide temperature control for the heated components, such as, transfer lines, heated filters and junction heaters. This unit was designed to fit in a 19” standard mounting rack and provide a user interface showing the temperature controller screens. Table 5.1 lists the main required parts to assemble the temperature controller unit. Figures 5.6 and 5.7 show the unit fully assembled.

Table 5.1: Temperature Controller Unit Required Parts

Item No.	Part Number	Description	Quantity
1	17252-A-B1-0	Volex Power Receptacle	1
2	HKP-15A	Bussman HKP Series Fuse Holder	1
3	WRG32F2BBRLN	Cherry WR Series Rocker Switch	2
4	OPTO22-240D10	Solid State Relay	8
5	E5GN-Q1TC	Omron Temperature Controller	8
6	EPIC H-A 3-PIN	EPIC Female Connector	8
7	BUD	BUD Series Plastic Enclosure -19"	1
8	In-House	Front Plate	1
9	In-House	Back Plate	1
10	In-House	Relay Bottom Tray	1

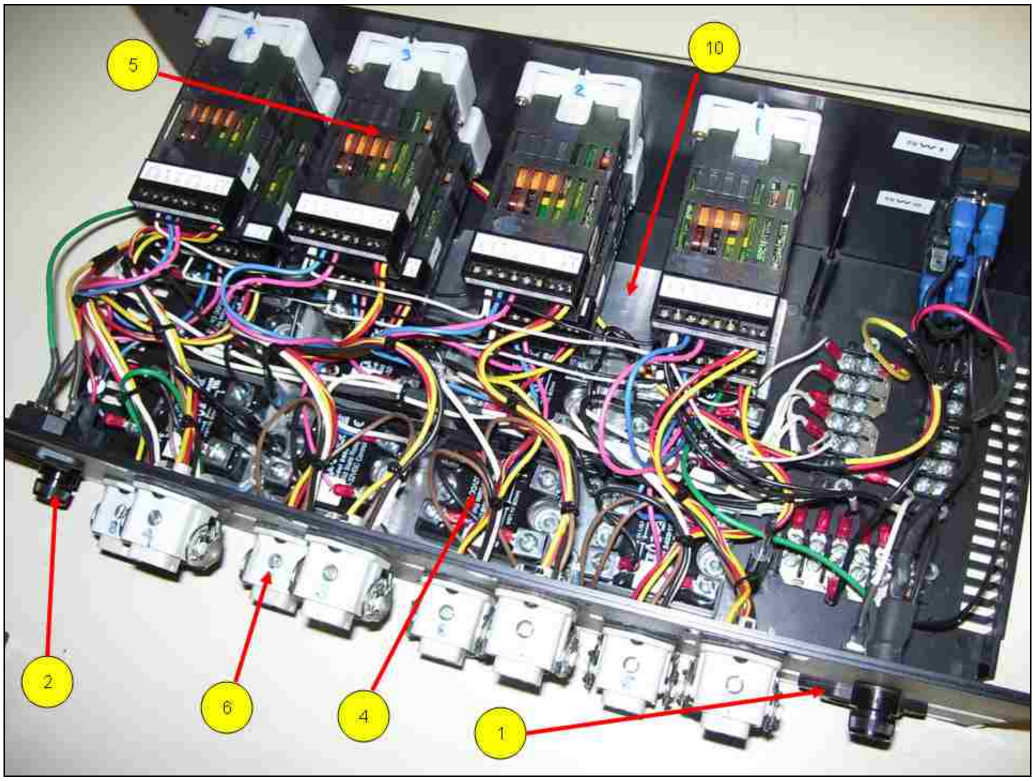


Figure 5.7: Temperature Controller Unit with Top Cover Removed (Numbered Items Identified in Table 5.1)

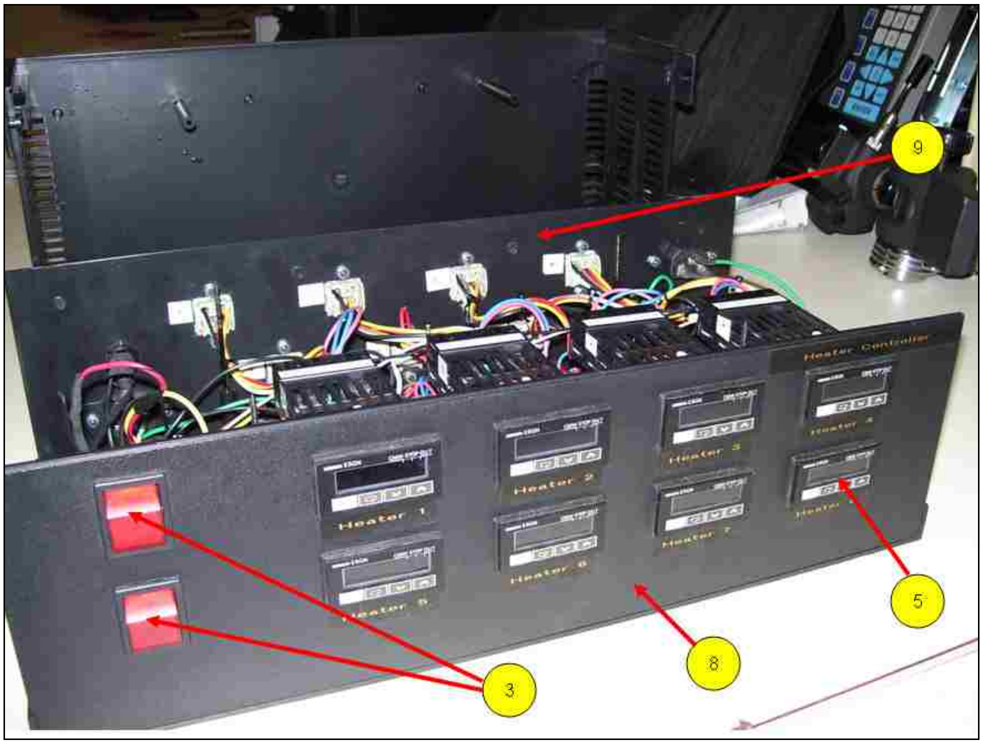


Figure 5.8: Temperature Controller Unit (Front View) (Numbered Items Identified in Table 5.1)

Figure 5.9 shows the wiring schematic for one temperature controller. This setup was duplicated eight times to produce a controller unit capable of providing temperature control for eight different heated devices simultaneously. The power requirements for the controller unit are the standard 120V. It connects to one of the three power bars used in the emissions bench. It also has the capability of operating only four of the temperature controllers if needed. This is due to the fact that there is a dedicated rocker switch for every four temperature controllers (see Figure 5.7). This device is also designed and fabricated following all the electrical safety regulations and is inspected by Ontario's Electrical Safety Authority (ESA) and certified as electrically-safe. Appendix A.5 shows the drawings for the fabricated parts of the temperature controller unit, such as, the front and the back plates and the relay tray.

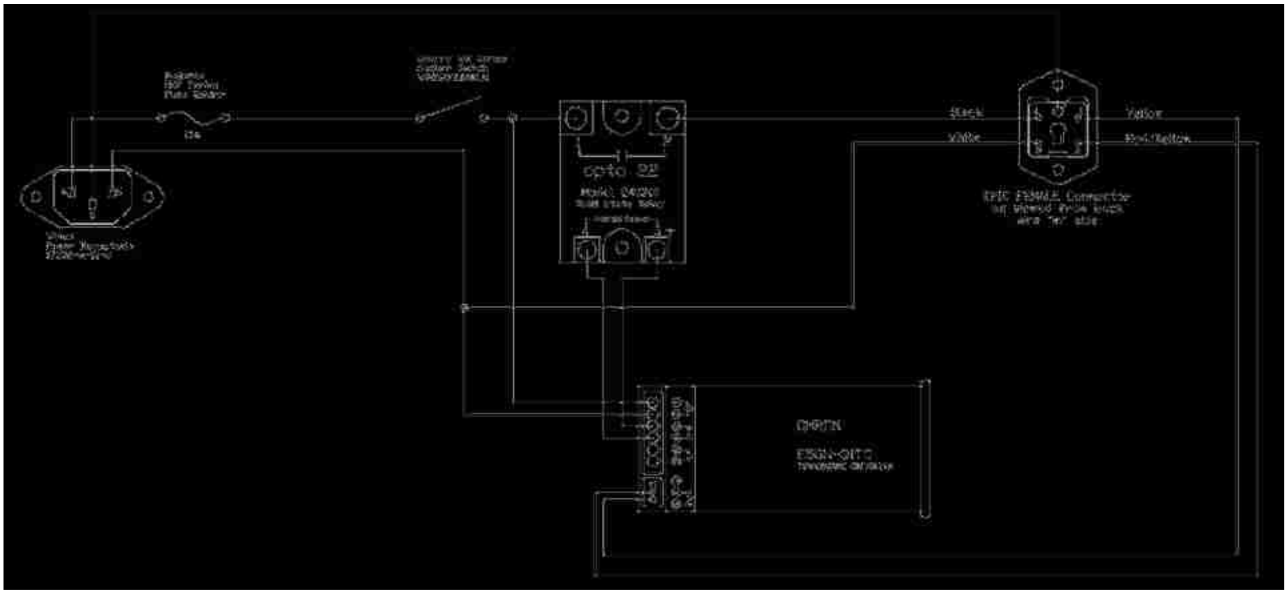


Figure 5.9: Temperature Controller Wiring Schematic (Showing One Controller)

5.1.3 Gas Collection Manifold

A manifold to collect the exhaust gases exiting the analyzers was fabricated. The body of the manifold is made from a 1.0” stainless steel circular tubing stock; capped from one end and open at the bottom to allow for a venting hose to be connected to the emissions bench. This hose vents the exhaust gas to the test cell collection facility. The exhaust gas exiting the analyzers must be disposed of safely as it can pose some health risks to the operators in the vicinity of the emissions bench. Figures 5.10 and 5.11 show the gas collection manifold installed in the emissions bench and the assembly drawing respectively.

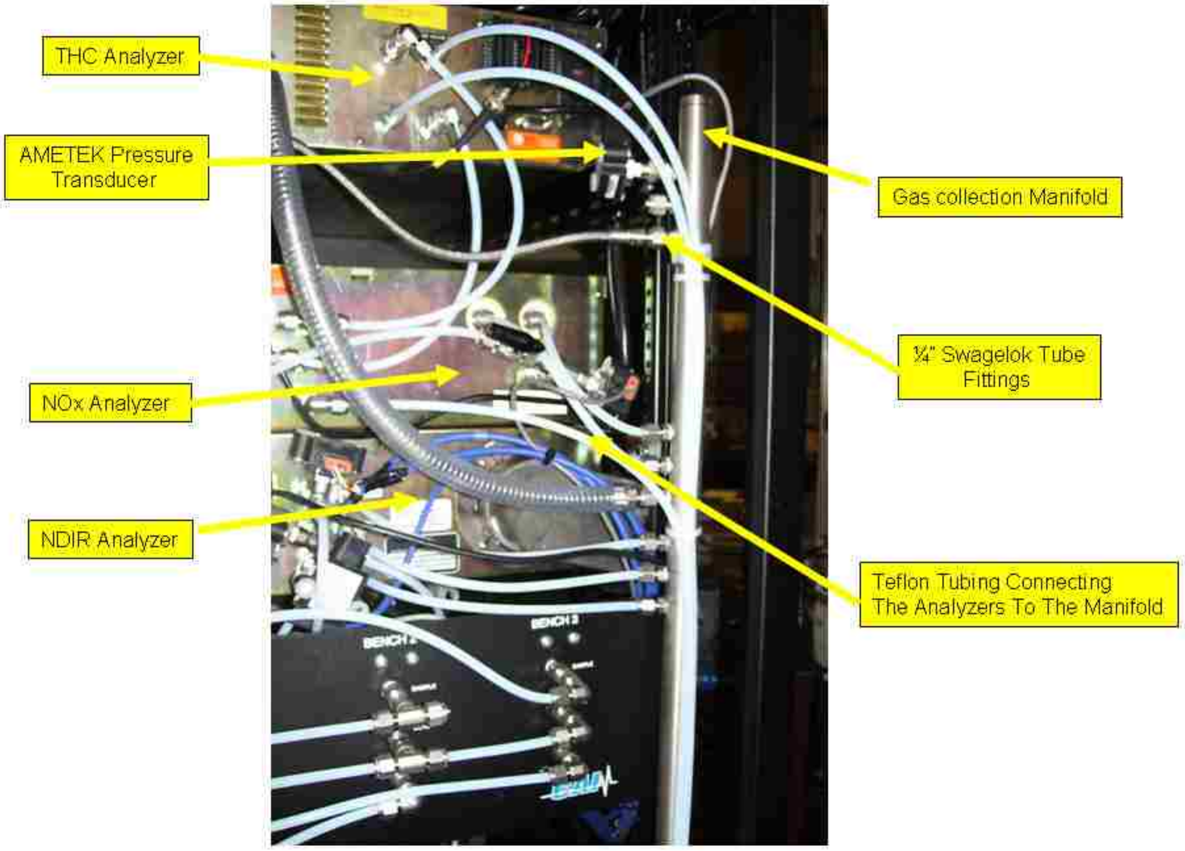


Figure 5.10: Gas Collection Manifold Installed in the Back of the CAI Emissions Bench

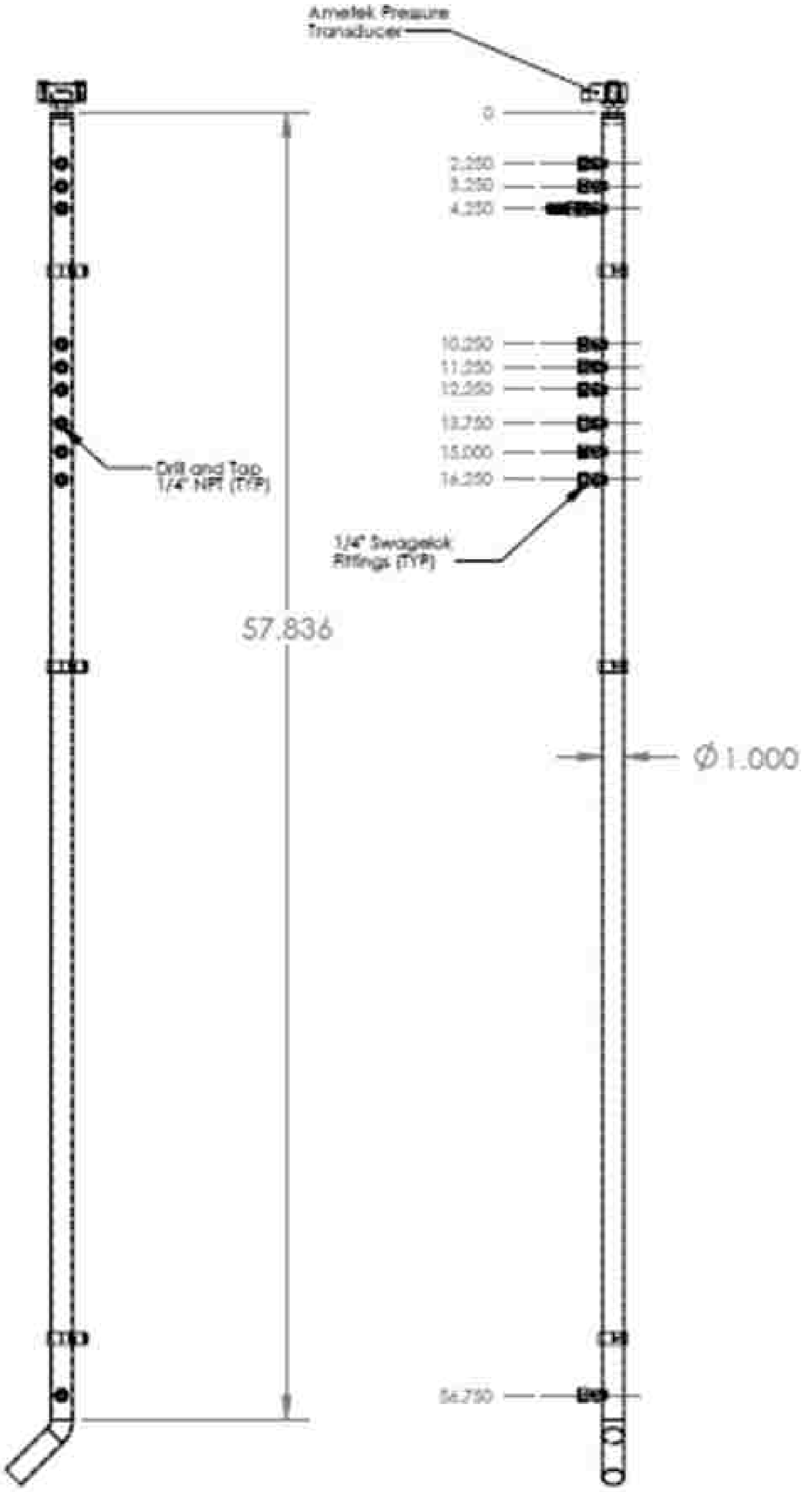


Figure 5.11: Gas Collection Manifold Assembly Drawing

5.1.4 Sampling Pump Installation

The dual-headed sampling pump is installed on a tray designed to securely fasten the pump. The tray is made from 0.25" Aluminum sheet and it was fabricated in-house. Figure 5.12 shows the pump tray and the sampling pump installed in the emissions bench. The sampling pump is seated on special rubber mounts to reduce the level of vibration transferred from the pump to the bench chassis during operation. Appendix A.3 includes the drawing for the pump tray. The sampling pump is connected to a dedicated power bar so the pump can be switched off during analyzer calibration.

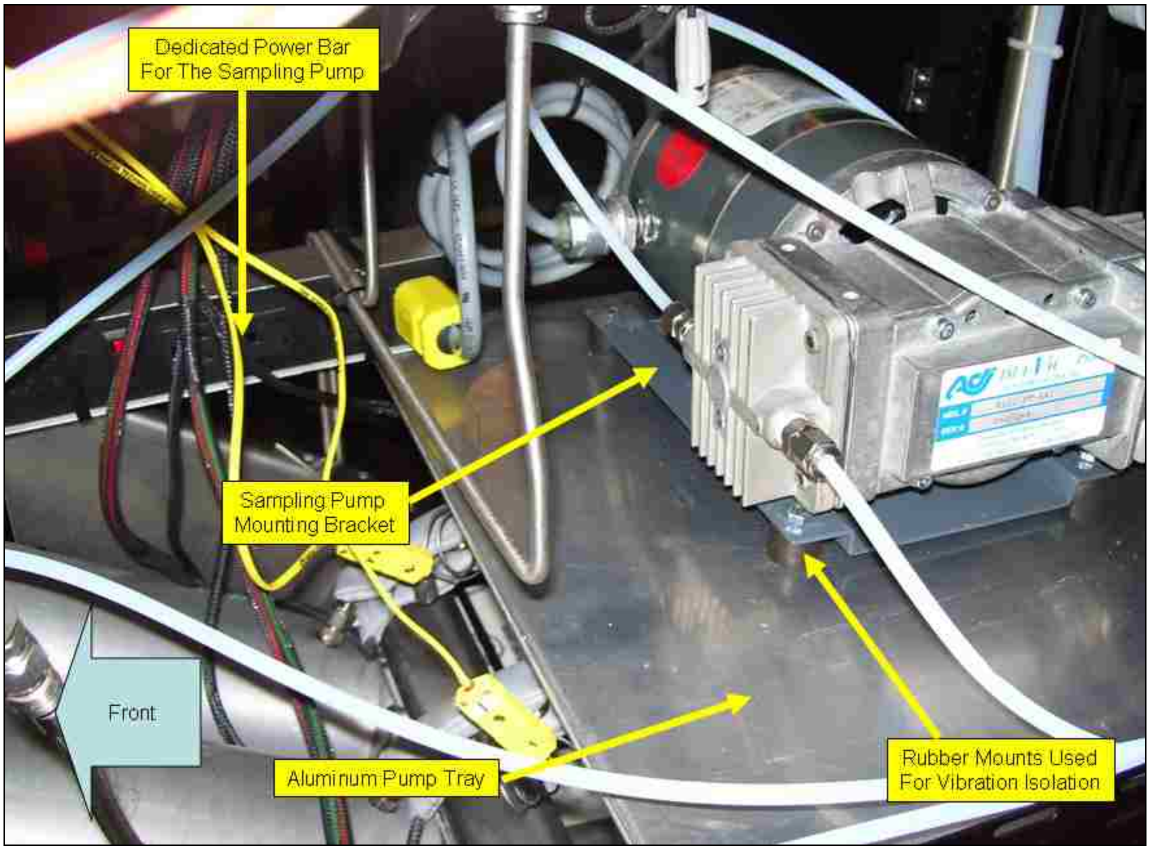


Figure 5.12: Gas Collection Manifold Assembly

5.1.5 Analyzer Heat Removal

When the analyzers are switched on they generate a significant amount of heat. This heat energy is transferred out of the analyzers via fans. It was observed during the initial startup and commissioning phase that the internal ambient temperature of the bench was relatively high compared to its surroundings. Thermocouples were installed at the bottom of both chillers to examine the ambient temperature closer. It was noticed that the room air surrounding the chillers was as high as 37°C for the main chiller and 33°C for the EGR chiller since it is closer to the back of the bench. This has adverse effects on the chiller performance since ambient temperature is critical for the operation of the thermoelectric devices to function properly. The chiller rejects the heat absorbed from the sample stream through forced convection from a fan mounted on top of the heat sink (see Figure 4.8). Higher ambient temperatures in the vicinity of the chillers reduce the cooling efficiency of the chillers. Therefore, every effort has been made to reduce the heat rejected into the emissions bench. Two of the heat sources contributing to this are the NDIR and CLD analyzers. Figure 5.13 shows the air vents of these two analyzers. Special diffusers and channels were fabricated to direct the heat rejected from these analyzers outside the emissions bench.

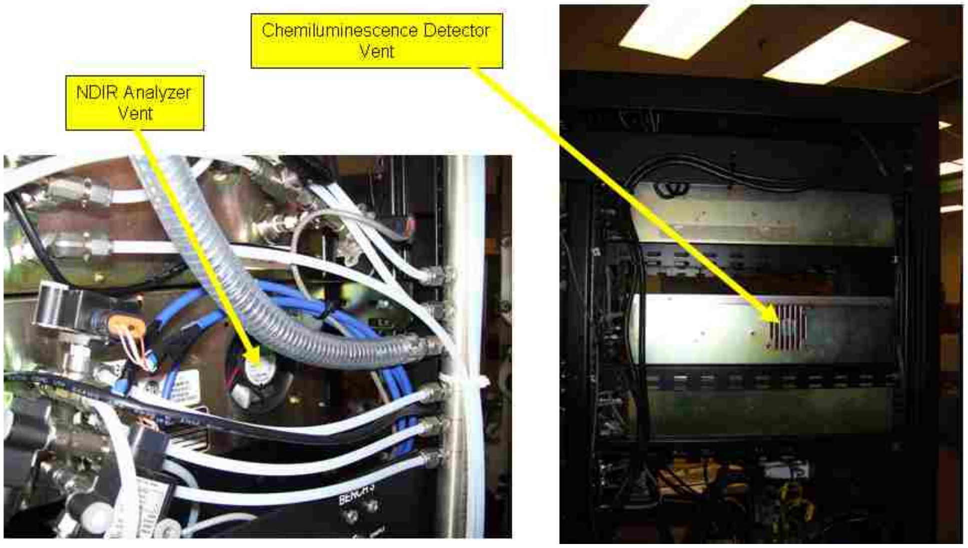


Figure 5.13: NDIR and CLD Analyzer Vents

Figure 5.14 shows the sheetmetal channels that were fabricated in-house to direct the hot air exiting the analyzer to the outside of the emissions bench. Figure 5.15 shows the NDIR channel installed.

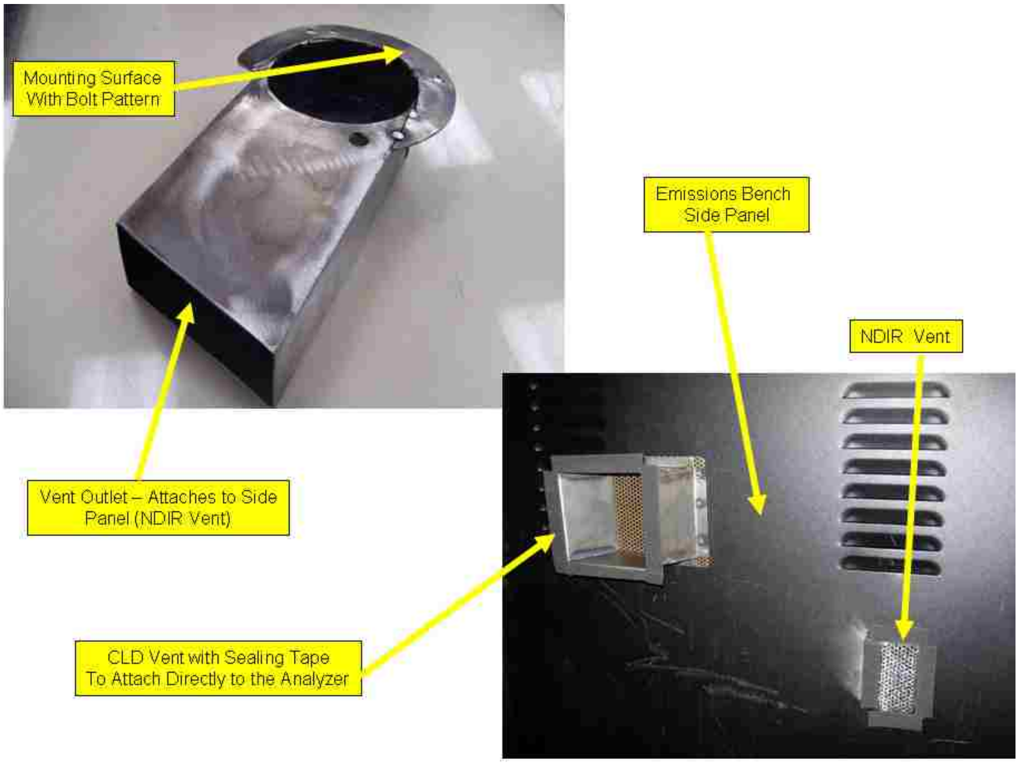


Figure 5.14: Fabricated Channels to Be Attached To the Vents in Figure 5.13

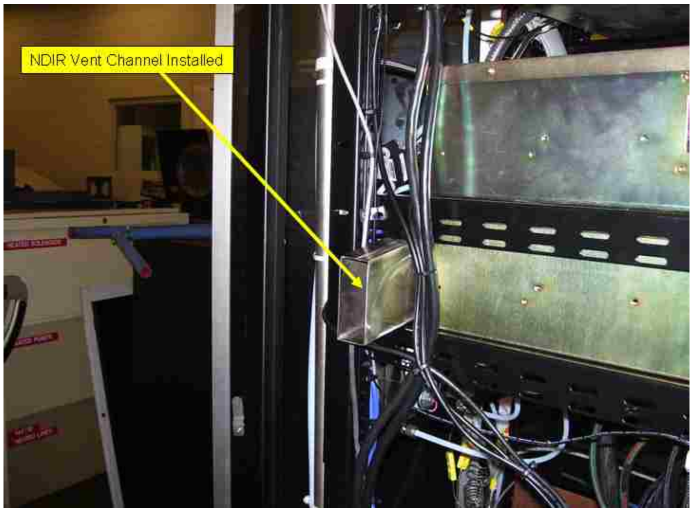
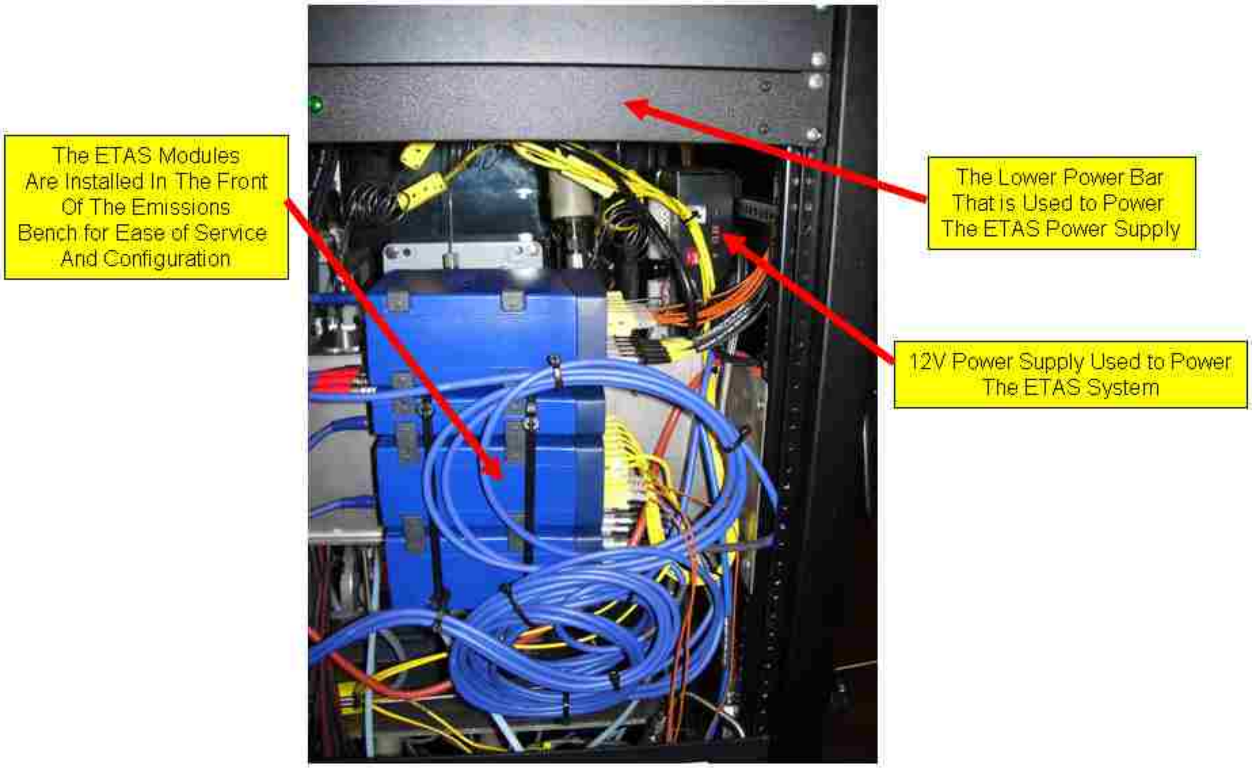


Figure 5.15: NDIR Channel Installed

5.2 Data Acquisition System Configuration

Once all the components and sub-assemblies were installed; the data acquisition system must be installed and configured. The data acquisition system consists of the ETAS modules pictured in Figure 4.18; the thermocouples installed in the bench and outside the bench to monitor exhaust gas temperature en route to the emissions bench, and the AMETEK pressure transducers used to monitor exhaust gas pressure at various stages of the process. The ETAS modules were installed in the front of the emissions bench for ease of modification and changing of modules or channels if needed. The module stack is secured to the back of the main chiller supporting bracket using heavy-duty plastic ties. This makes it easy to remove the entire stack if needed. Figure 5.16 shows the ETAS module stack in place. The ETAS system is powered by a dedicated 12V power supply that is also pictured in Figure 5.16. This power supply is connected to the lower 20A power bar pictured in Figure 4.6.



The ETAS Modules Are Installed In The Front Of The Emissions Bench for Ease of Service And Configuration

The Lower Power Bar That is Used to Power The ETAS Power Supply

12V Power Supply Used to Power The ETAS System

Figure 5.16: ETAS Module Stack Installed

Figure 5.17 shows all the channels connected to the modules. The ETAS ES650.1 module pictured at the top of the stack is a thermocouple/analog input device. Therefore; all the analog output signals from the analyzers are connected to this module. This delivers the emission concentrations to the ETAS experiment resulting in a single graphical user window that encompasses all the acquired data. Some of the thermocouples monitoring the chiller performance are also connected to this module. The ETAS ES620.1 in the middle of the stack is a thermocouple module. All the remaining thermocouples in the system are connected to this module. The ETAS ES611.1 module in the bottom of the stack is an 8-channel analog input module with internal power supply for the devices connected. The six Ametek pressure transducers used in the emissions bench are connected to this module. Each channel is configured to supply 0-14V power to the pressure transducer connected to it. Finally, the ETAS ES 600.1 is the main hub where all the modules are connected. This provides a single-point connection for the entire stack and makes it easy to connect the whole system to a remote computer via an Ethernet cable; also pictured in figure 5.17.

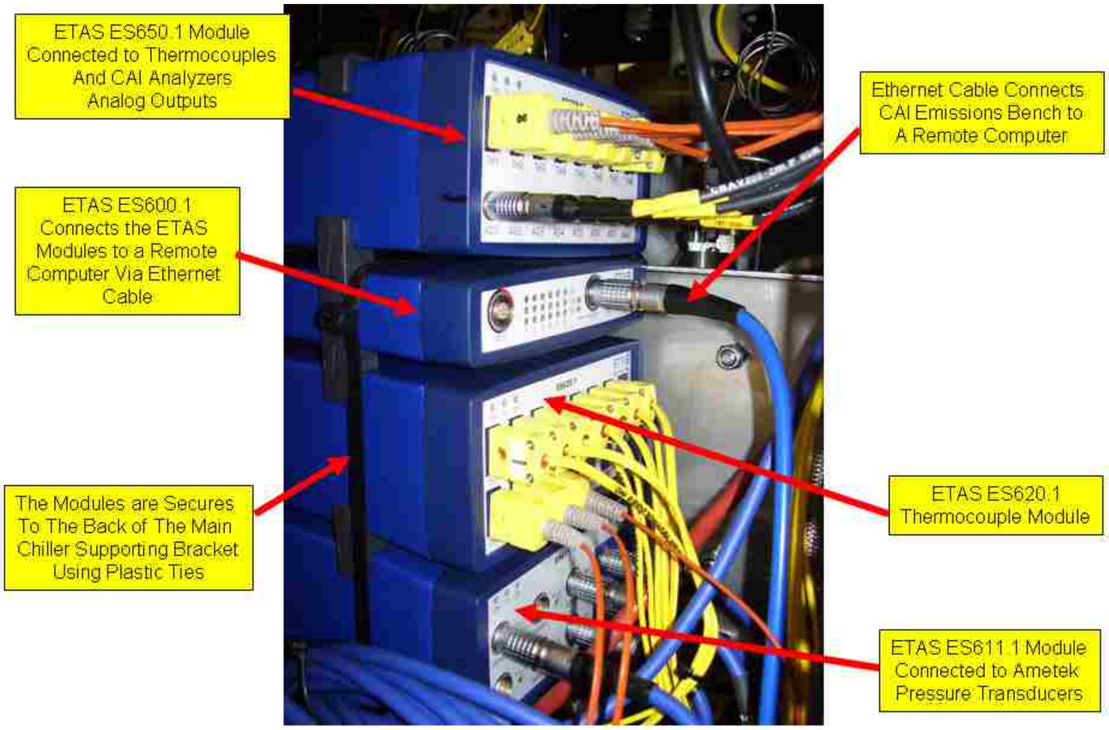
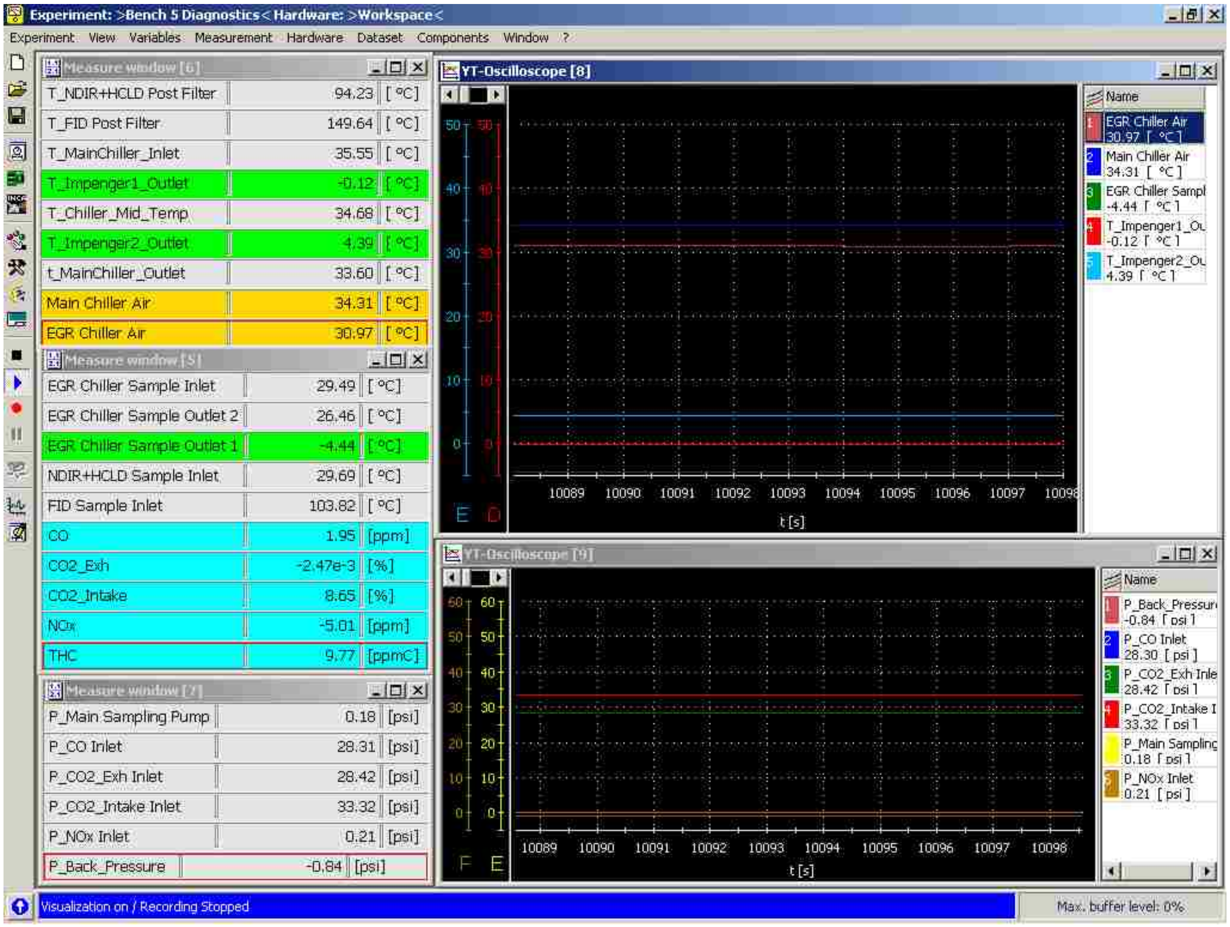


Figure 5.17: ETAS Module Stack Channels Installed

Once the hardware is installed; the ETAS software is setup. The advantage of this setup is that this experiment can be inserted as a page into an existing ETAS experiment that is used to run the engine. This adds a level of convenience and transparency to the process as all the necessary data can be acquired by logging a single file. Figure 5.18 shows a screen shot of the ETAS experiment. The experiment contains two streaming graphs of some the data being acquired to the left of the screen. The green-highlighted lines show the chiller impinger data as this is the true temperature of the exhaust gas exiting the chiller heat exchangers. The yellow-highlighted lines show the ambient temperature of the air at the bottom of the chiller. It is very important to keep these temperatures as low as possible. Table 5.2 on the next page details the signal names used in the ETAS experiment and what they represent.



Measure window [6]

T_NDIR+HCLD Post Filter	94.23	[°C]
T_FID Post Filter	149.64	[°C]
T_MainChiller_Inlet	35.55	[°C]
T_Impenger1_Outlet	-0.12	[°C]
T_Chiller_Mid_Temp	34.68	[°C]
T_Impenger2_Outlet	4.39	[°C]
t_MainChiller_Outlet	33.60	[°C]
Main Chiller Air	34.31	[°C]
EGR Chiller Air	30.97	[°C]

Measure window [5]

EGR Chiller Sample Inlet	29.49	[°C]
EGR Chiller Sample Outlet 2	26.46	[°C]
EGR Chiller Sample Outlet 1	-4.44	[°C]
NDIR+HCLD Sample Inlet	29.69	[°C]
FID Sample Inlet	103.82	[°C]
CO	1.95	[ppm]
CO2_Exh	-2.47e-3	[%]
CO2_Intake	8.65	[%]
NOx	-5.01	[ppm]
THC	9.77	[ppmC]

Measure window [7]

P_Main Sampling Pump	0.18	[psi]
P_CO Inlet	28.31	[psi]
P_CO2_Exh Inlet	28.42	[psi]
P_CO2_Intake Inlet	33.32	[psi]
P_NOx Inlet	0.21	[psi]
P_Back_Pressure	-0.84	[psi]

Figure 5.18: ETAS Experiment Screen Shot

Table 5.2: ETAS Experiment Channels

Channel Name	Description	Units	Sampling Rate
T_NDIR+HCLD Post Filter	The Main Sample Temperature After the Heated Filter	℃	100 ms (10 Hz)
T_FID Post Filter	The THC Sample Temperature After the Heated Filter	℃	100 ms (10 Hz)
T_MainChiller_Inlet	The Sample Temperature at the Inlet of the Main Chiller	℃	100 ms (10 Hz)
T_Impinger1_Outlet	The Sample Temperature at the Outlet of the First Impinger of the Main Chiller	℃	100 ms (10 Hz)
T_Chiller_Mid_Temp	The Sample Temperature Between the Two Heat Exchangers of the Main Chiller	℃	100 ms (10 Hz)
T_Impinger2_Outlet	The Sample Temperature at The Outlet of the Second Impinger of the Main Chiller	℃	100 ms (10 Hz)
T_MainChiller_Outlet	The Sample Temperature at the Outlet of the Main Chiller	℃	100 ms (10 Hz)
Main Chiller Air	The Ambient Air Temperature at the Bottom of the Main Chiller Heat Sink	℃	100 ms (10 Hz)
EGR Chiller Air	The Ambient Air Temperature at the Bottom of the EGR Chiller Heat Sink	℃	100 ms (10 Hz)
EGR_Chiller Sample Inlet	The Sample Temperature at the Inlet of the EGR Chiller	℃	100 ms (10 Hz)
EGR_Chiller Sample Outlet2	The Sample Temperature at the Outlet of the EGR Chiller	℃	100 ms (10 Hz)
EGR_Chiller Sample Outlet1	The Sample Temperature at the Outlet of the Impinger of the EGR Chiller	℃	100 ms (10 Hz)
NDIR+HCLD Sample Inlet	The Main Sample Temperature Before it Splits Between the NDIR and the HCLD	℃	100 ms (10 Hz)
FID Sample Inlet	The THC Sample Temperature at the Inlet of the FID Oven	℃	100 ms (10 Hz)
CO	CO Concentration from the NDIR Analyzer	ppm	10 ms (100 Hz)
CO2_Exh	The main Sample CO_2 Concentration from the NDIR Analyzer	%	10 ms (100 Hz)
CO2_Intake	The EGR Sample CO_2 Concentration from the NDIR Analyzer	%	10 ms (100 Hz)
NOx	The NOx Concentration of the Main Sample	ppm	10 ms (100 Hz)
THC	The THC Concentration of the Main Sample	ppmC	10 ms (100 Hz)
P_Main Sampling pump	The Pressure at the Outlet of the Main Pump Head	PSIG	10 ms (100 Hz)
P_CO Inlet	The Pressure of the CO Sample Stream at the Back of The NDIR Analyzer	PSIG	10 ms (100 Hz)
P_CO2_Exh Inlet	The Pressure of the Main CO_2 Sample Stream at the Back of The NDIR Analyzer	PSIG	10 ms (100 Hz)
P_CO2_Intake Inlet	The Pressure of the EGR CO_2 Sample Stream at the Back of The NDIR Analyzer	PSIG	10 ms (100 Hz)
P_NOx_Inlet	The Pressure of the NOx Sample Stream at the Back of the HCLD analyzer	PSIG	10 ms (100 Hz)
P_Back_Pressure	The Pressure at the Back Gas Manifold	PSIG	10 ms (100 Hz)

6 COMMISSIONING

The commissioning phase is intended to test the final product and ensure that all the systems and components are operating as intended. During this stage of the project the final assembled product is tested to identify potential areas of improvement. Certain components or systems within the CAI emissions bench might need to be modified to deliver the required performance. This stage also serves a validation that the final product is ready to be used commercially or conclude that the design needs to be adjusted.

6.1 Experimental Setup

An experiment was setup in a dynamometer test cell, where a diesel engine was installed in order to generate an exhaust stream for the CAI emissions bench to sample. The engine in the experiment had the following specifications:

- 6.4L V8 Turbo Diesel Engine.
- 4 Valves / Cylinder.
- Piezo-Electric Common Rail Fuel Injection.
- Dual-Stage Turbo-Charging.
- Bore x Stroke: 3.87” x 4.134” (98.2 x 105 mm).
- Dual EGR Coolers.

The main exhaust sample is drawn from a custom-made sensor ring that is used to allow for multiple sampling probes to be installed at the same plane. There are two sampling probes installed in the sampling ring to account for the main sample and the THC sample. There is also a sampling line installed into the intake manifold of the diesel engine to extract the EGR sample for EGR CO_2 measurement. The THC and main sample transfer lines are heated using an external temperature controller unit similar to the one used in the emissions bench. There are also two heated particulate filters used as a first line of defense upstream of the CAI emissions analyzer. This helped keep the transfer lines downstream of the filters as clean as possible and reduce particulate “hang-up” that may occur on the inner walls of the transfer lines. These filters use a 0.01 micron fiber filter with 75% filtration efficiency. The distance of the sensor ring from the engine was approximately 70 inches and the length of the heated transfer lines from the sampling point to the sample inlet on the emissions bench was approximately 25 feet. This included two transfer lines for each sample stream measuring 12 feet in length each and the heated filter assembly connected between them. The effect of this distance is considered negligible during this experiment as the CAI emissions bench is intended for steady-state testing. During transient testing this distance would have to be reduced as much as possible to improve the analyzer response time. Typically, the engine was started and allowed to warm up and reach normal operating conditions for the given test parameters. During the engine warm-up period the CAI emissions bench was started and allowed to warm up for one hour as per manufacturer’s recommendations [2, 3, 4]. This warm-up period was necessary for the following reasons:

- The FID oven has to reach a minimum temperature of 180°C before the ignition sequence is initiated to establish the flame.
- The internal components of the NOx analyzer need to reach proper temperatures as well, such as, the reaction chamber (80°C) and the NOx Converter (200°C).
- The heated transfer lines and filters used internally and to transfer the exhaust gas to the emissions bench need to reach a temperature of 191°C.
-

Before the start of the test, the CAI emissions bench was calibrated using a set of span gases with known concentrations. Also, specific ranges were set for the different detectors. Table 6.1 lists the known concentration values of the span gases and the sampling ranges.

Table 6.1: Span Gas Concentrations and Analyzer Ranges

	Unit	Span Gas Value	Range
THC	ppmC1	468	600
NOx	ppm	967	1200
CO	ppm	930	1200
CO_2_MAIN	% vol.	9.06%	15%
CO_2_EGR	% vol.	9.06%	15%

Also, to calibrate the zero point of analyzers, pure nitrogen gas was used. A calibration procedure from the manufacturer was followed and 55 data points were acquired. The calibration results are detailed in Table 6.2.

Table 6.2: Analyzer Calibration Data

	Units	Mean	Std. Dev.	COV	Min	Max
THC	ppmC1	450.246	0.309	0.0007	449.400	450.750
NOx	ppm	967.799	0.237	0.0002	967.150	968.260
CO	ppm	930.919	0.554	0.0006	930.140	931.980
CO_2_MAIN	% vol.	9.075	0.006	0.0006	9.060	9.080
CO_2_EGR	% vol.	9.063	0.005	0.0005	9.060	9.070

The standard deviation values in Table 6.2 represent the uncertainty of each detector. When these values are expressed in percent uncertainty they can be related to the manufacturer-published uncertainty values. The manufacturer states that all three instruments have an accuracy of 99% or more [3, 4,5]. The THC data is used to express the uncertainty in percentage as an example:

$$\% \text{ Uncertainty (THC)} = (\text{Std. Dev.} / \text{Mean}) * 100$$

$$= (0.309 / 450.246) * 100 = 0.07 \%$$

Given that the COV values represent the standard deviation divided by the mean and since they are very similar, a conclusion can be made that all the detectors meet or exceed the manufacturer’s specifications of 1% uncertainty or lower. Figure 6.1 shows the schematic for the experimental setup of the commissioning phase of the project. It mainly details the components used between the diesel engine and the CAI emissions bench.

Next, the span gases were applied to the various detectors in 10% increments from 0% to 100% span gas value using a gas divider. The concentrations at these increments were recorded and the data was plotted. Figures 6.1 to 6.5 show the desired linear response of the detectors compared to the actual detector response at the different span gas increments. This gives us a closer look at the detector's performance in the measured exhaust concentration region. Examining the THC data in Figure 6.1, we can see that the detector's poor response in the 0-30% span gas region and that it improves as the span concentration is increased. This can be attributed to the elected range (in this case 600 ppmC1) and the span concentration used (468 ppmC1). The selected range is too wide for the measured THC value and the span gas concentration is too high to provide a much accurate THC reading at lower concentrations. This is one of the disadvantages of using a single span gas concentration for calibration purposes.

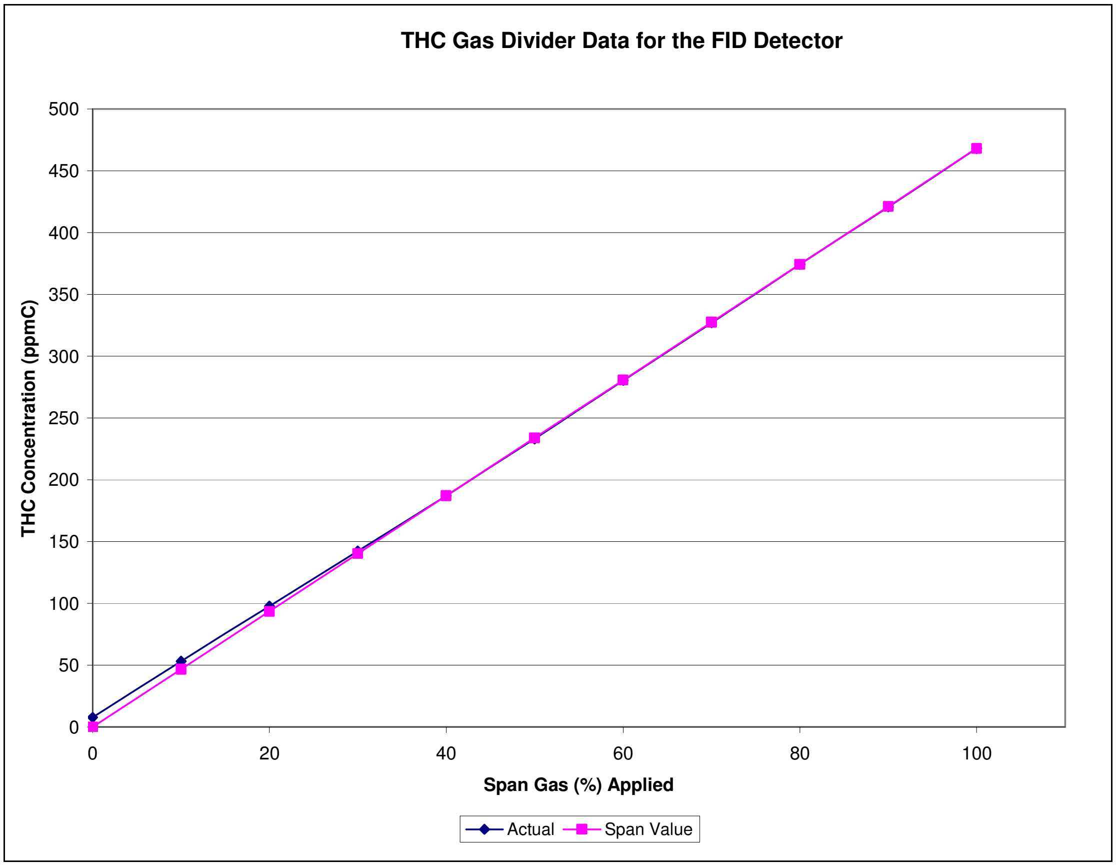


Figure 6.1: THC Actual Concentration vs. Applied Span Gas (%)

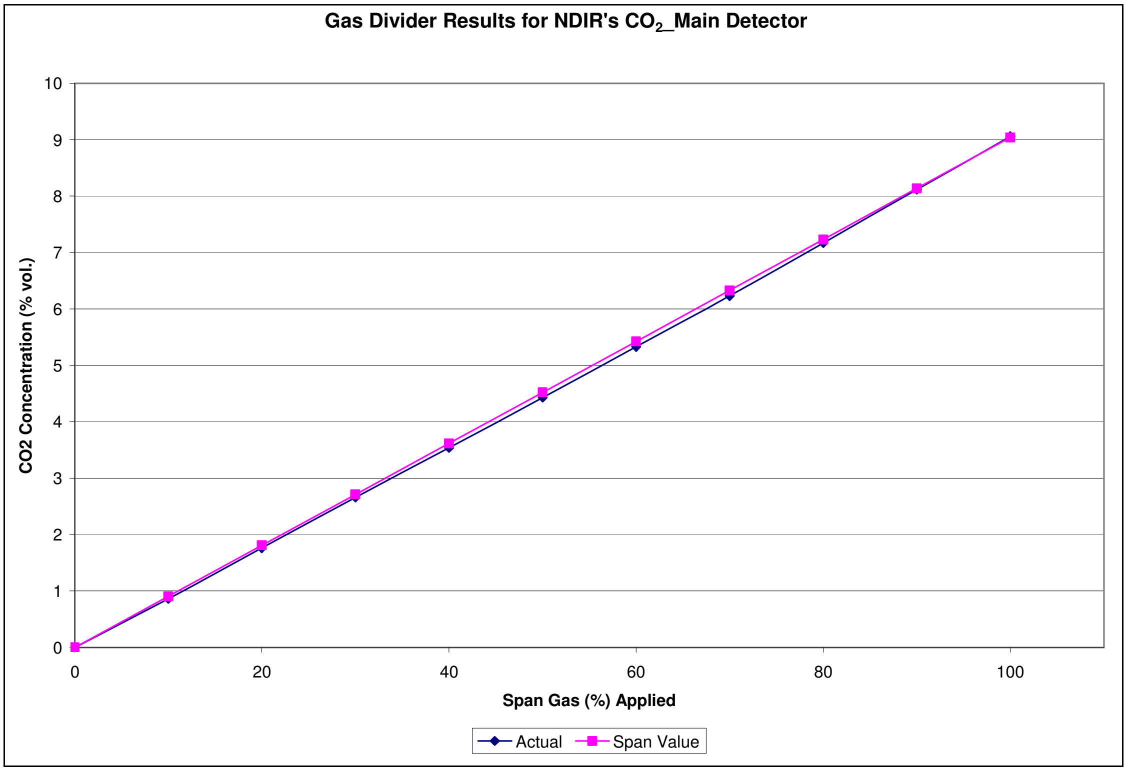


Figure 6.2: CO_2_Main Actual Concentration vs. Applied Span Gas (%)

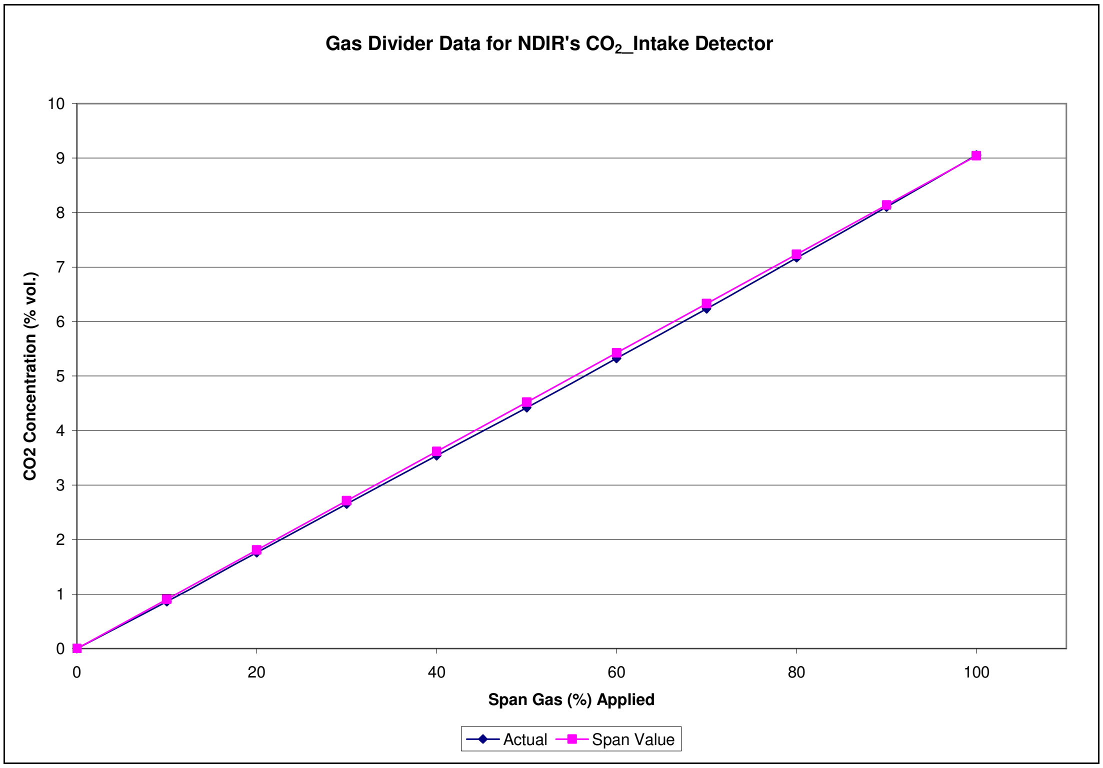


Figure 6.3: CO_2_Intake Actual Concentration vs. Applied Span Gas (%)

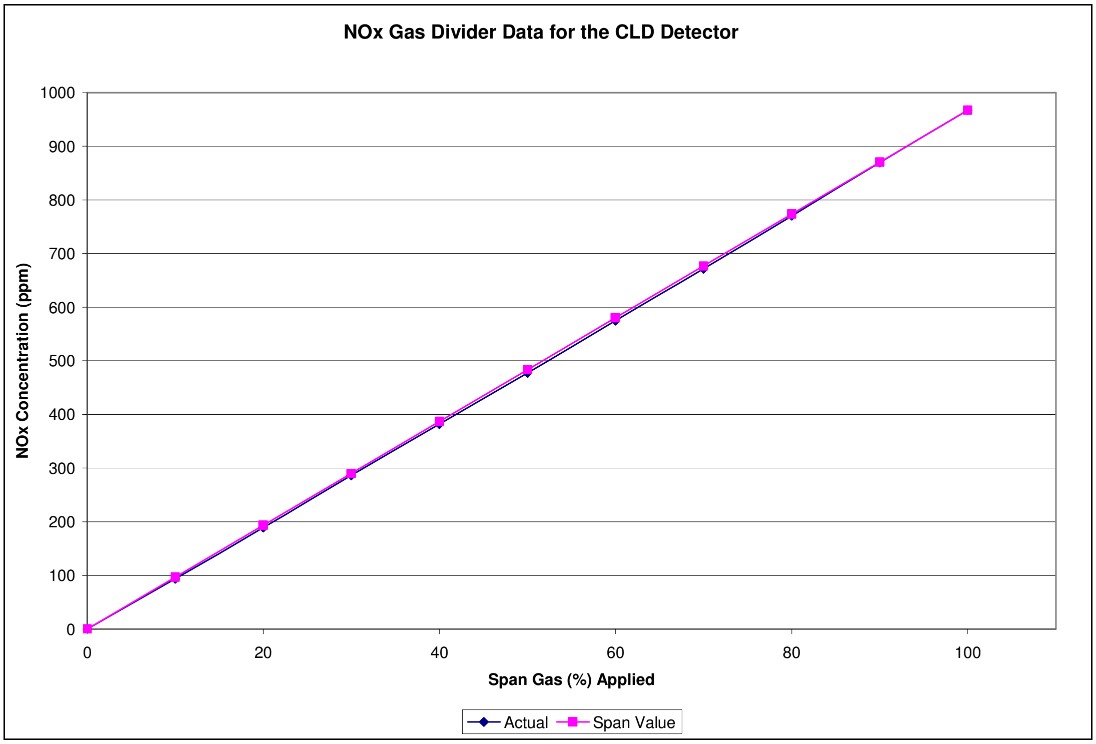


Figure 6.4: NOx Actual Concentration vs. Applied Span Gas (%)

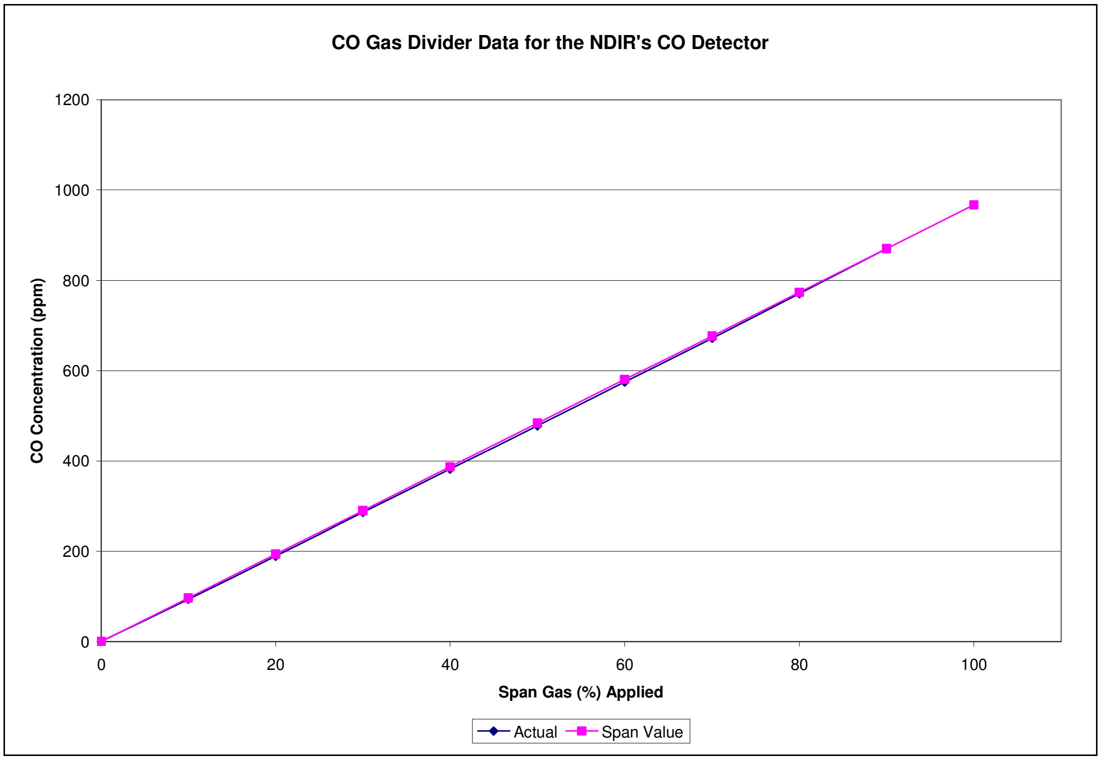


Figure 6.5: CO Actual Concentration vs. Applied Span Gas (%)

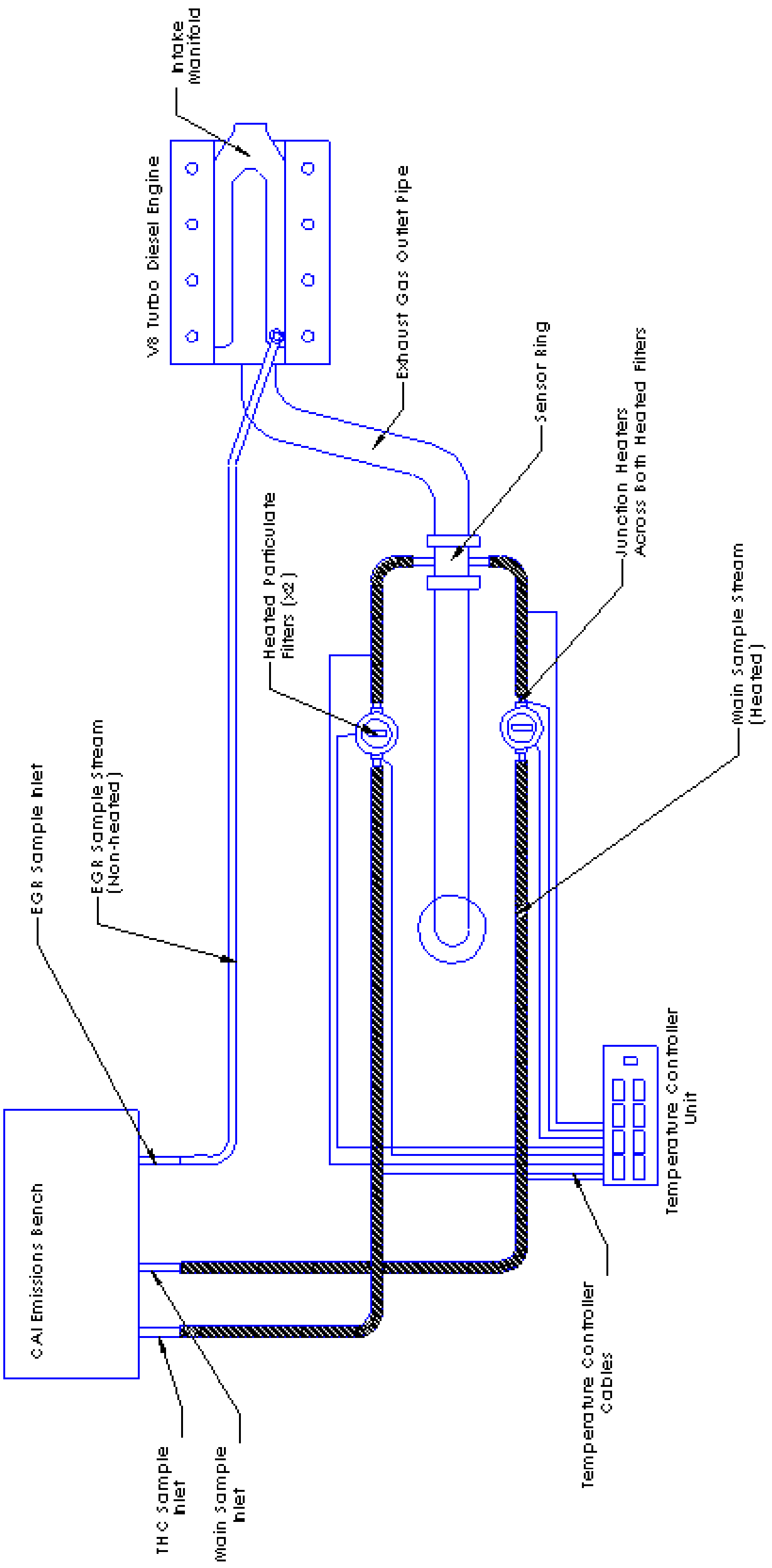


Figure 6.6: The Experiment Schematic of the Commissioning Phase

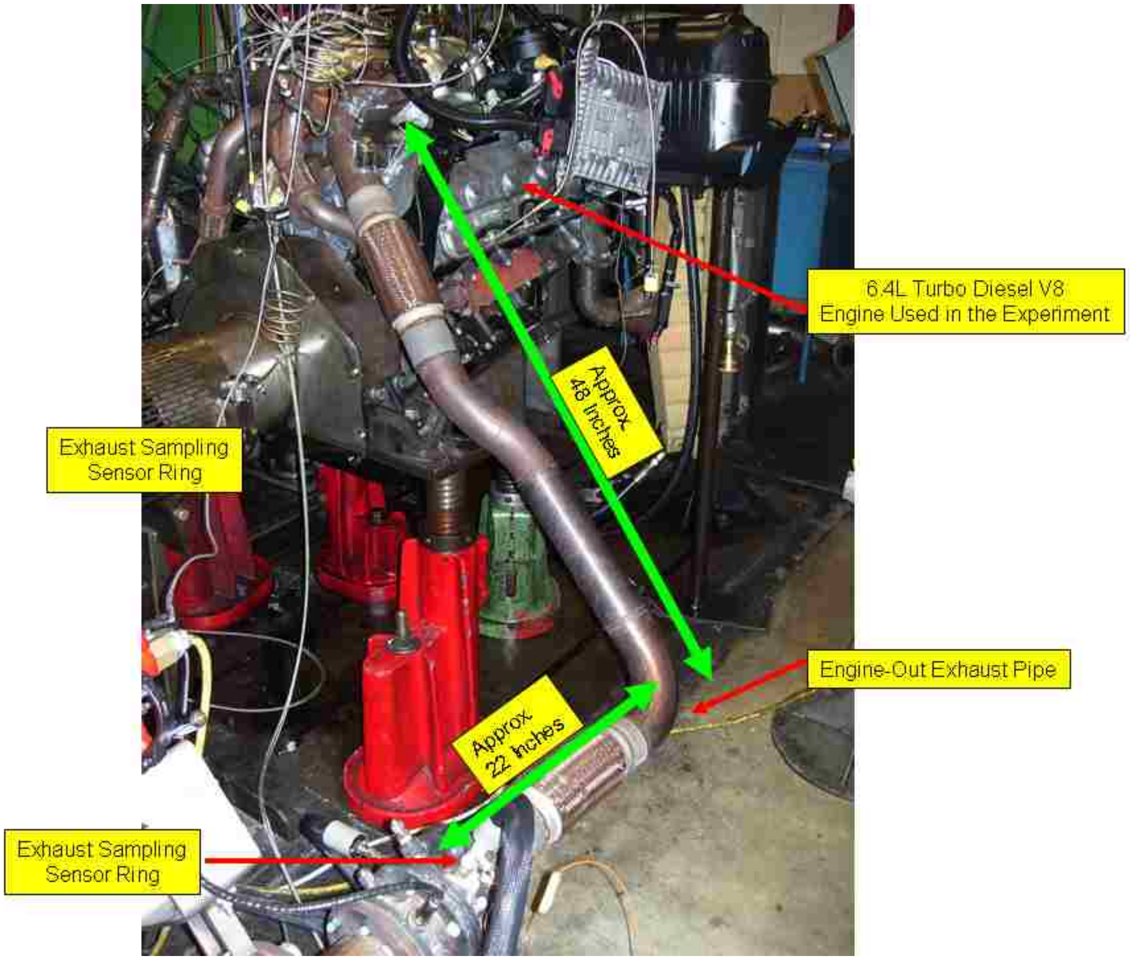


Figure 6.7: Engine Setup and Distance from the Sensor Ring

Figure 6.6 describes the basic setup of the experiment. Figure 6.7 shows part of the experimental setup including the engine, the exhaust output pipe, and the sampling sensor ring. Details of the sensor ring at the main sampling point are also shown in Figure 6.8. Figure 6.9 shows the setup of the heated particulate filters and the associated junction heaters upstream of the CAI emissions bench. Also, all the necessary lines were connected to the CAI emissions bench, such as, the sample transfer lines in the front of the bench, the span and fuel gas lines in the back of the bench, and the exhaust vent and pressure relief lines also in the back of the bench. Figures 6.10 and 6.11 show the CAI emissions bench fully prepped for testing with all the necessary lines connected.

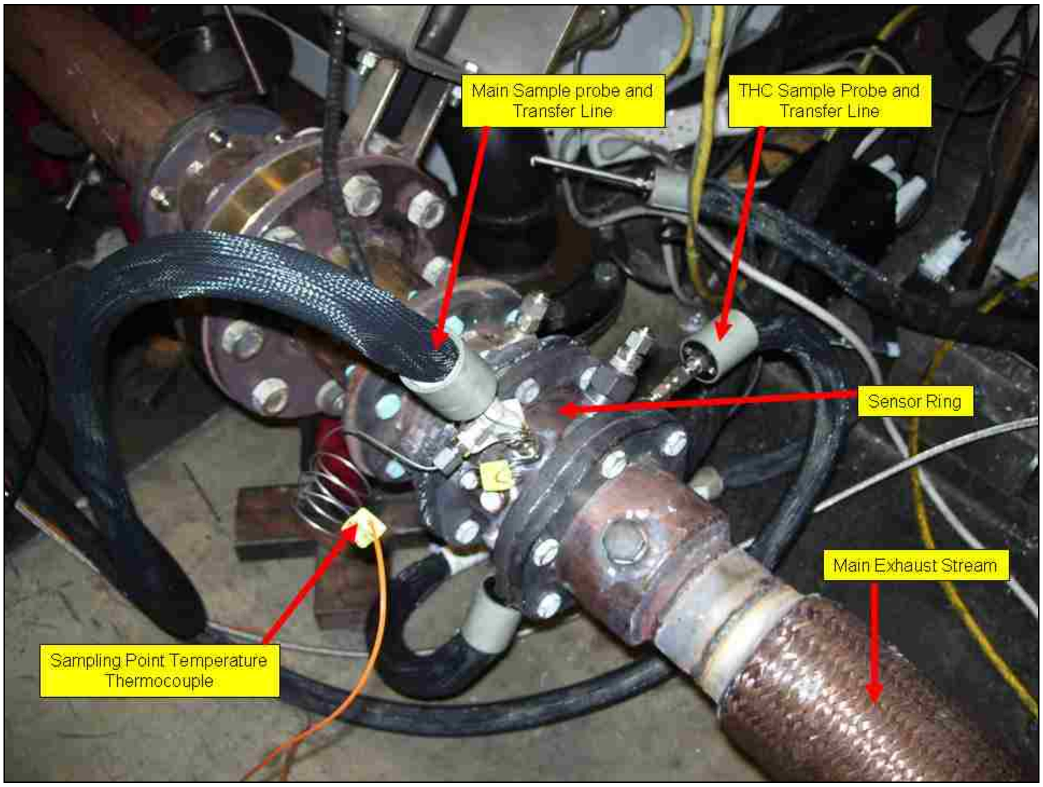


Figure 6.8: Sensor Ring Setup for Exhaust Sampling

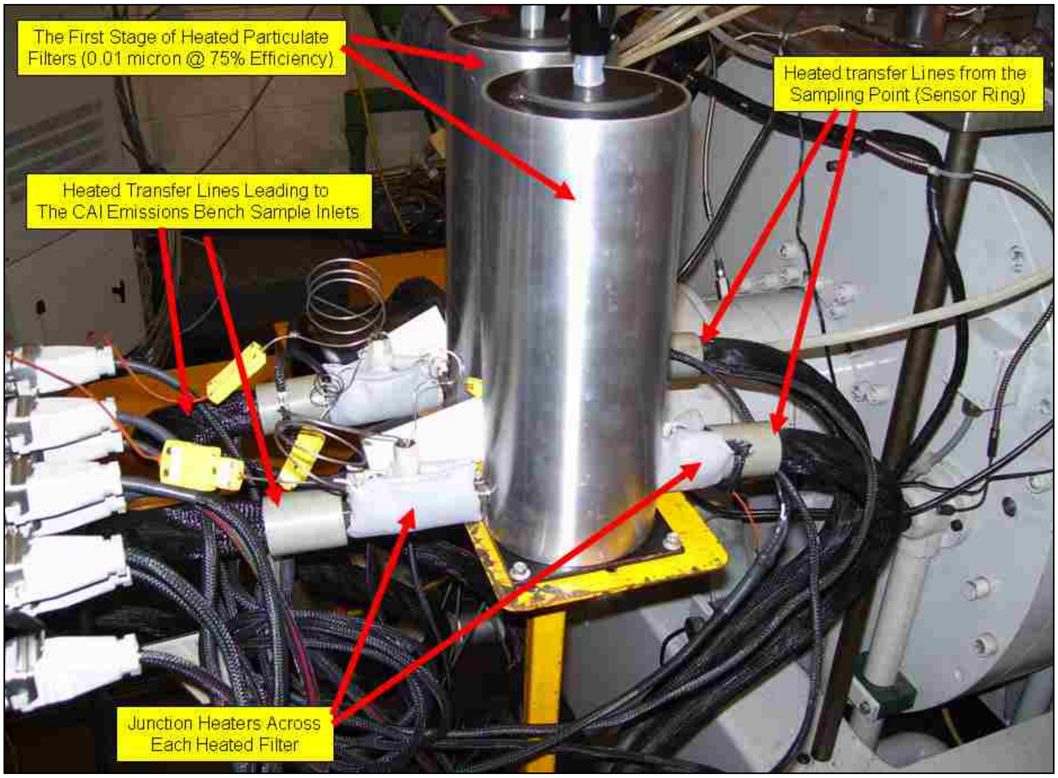


Figure 6.9: The External Heated Filters Used Upstream of the CAI Emissions Bench

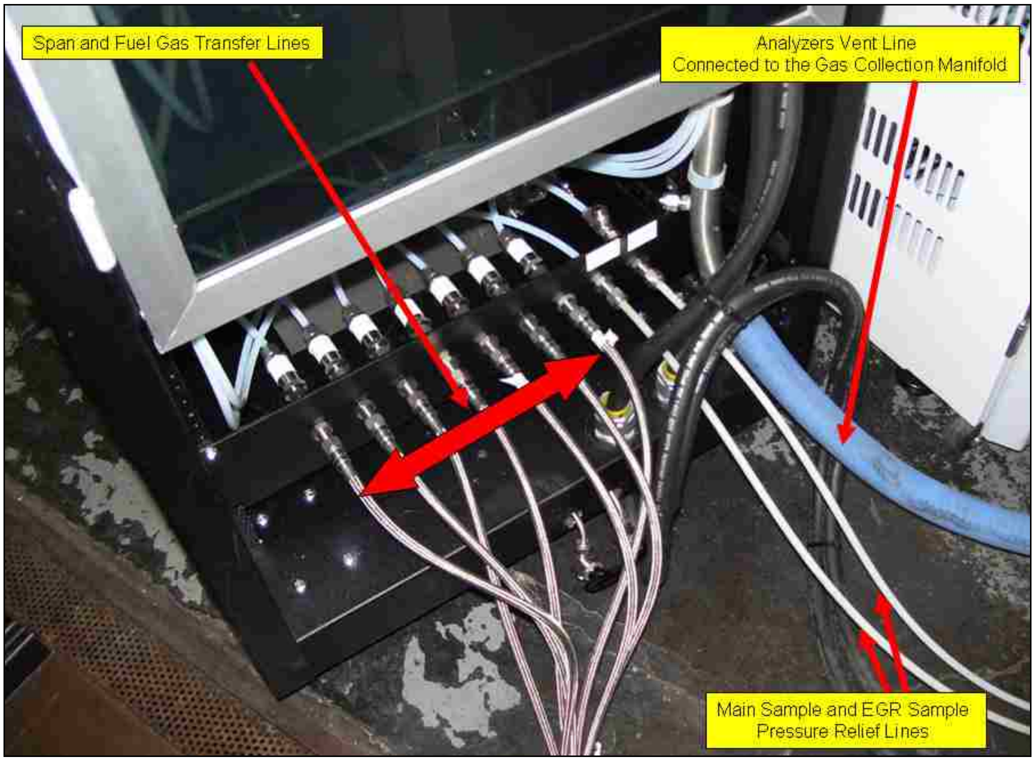


Figure 6.10: Span and Fuel Gas Connections and the Exhaust Pressure Relief Lines in The Back of the CAI Emissions Bench

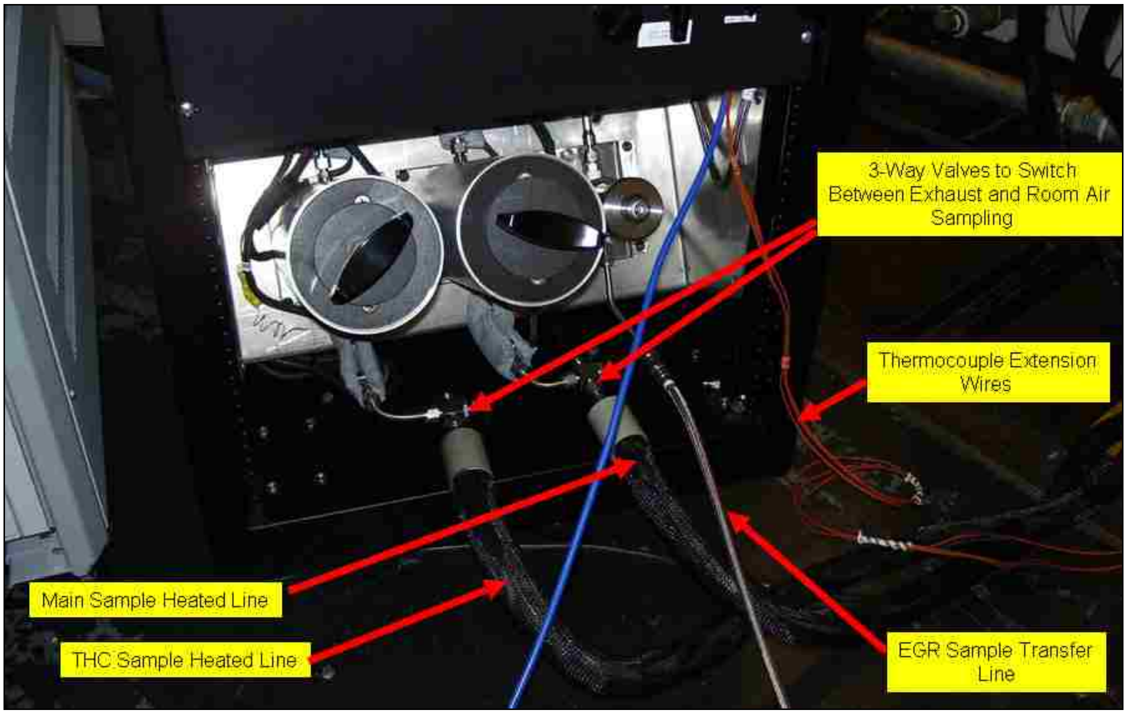


Figure 6.11: Sample Transfer Lines Connected to the Front of the CAI Emissions Bench

6.2 Data Collection

The first set of data was collected on January 26, 2010 (Trial #1). The CAI analyzer was setup inside of cell #1 and 64 data points were acquired during approximately three hours of operation. The data was acquired every 2.5 minutes. The second set of data was acquired on Jan 27; 2010 (Trial #2). This time, the emissions bench was placed outside of the cell. The reason for this was to provide a lower and more stable room temperature. The ambient temperature inside the test cell increases slightly over time and it depends on the engine operating conditions. During the first test run; the air conditioning unit was not operating inside the test cell. Therefore, the ambient temperature differed from one area of the test cell to another. The range of the ambient temperature was approx. 27-32°C. Every data point consisted of all the parameters outlined in Table 5.2. The data was then tabulated in Excel and the mean and standard deviation of each parameter was presented to determine the stability of the data. The engine was operated at the following conditions on both test dates:

- Engine Speed: 2000 rpm
- Engine Torque: 200 N.m
- EGR: Approx. 21%
- Engine Coolant Temperature: 180°F

The EGR valve was actuated manually by applying a 20% EGR set point using ETAS INCA software that is used for calibration purposes. The EGR ratio was calculated from the CO_2 data collected to verify the result. The following equation was used:

$$\mathbf{EGR\% = (CO_2\_Intake / CO_2\_Exh) * 100}$$

Table 6.3 below shows the mean, standard deviation, min and max values calculated for the first set of data points collected for trial #1. Appendix C1 lists the complete data sets for all the trials.

Table 6.3: Trial #1 CAI Emissions Bench Data

Signal	Units	Mean	Std. Dev.	COV	Min.	Max.
CO	ppm	743.85	9.47	0.013	728.37	766.45
CO2_Exh	% vol.	5.18	0.02	0.003	5.16	5.23
CO2_Intake	% vol.	1.06	0.02	0.018	1.03	1.1
EGR_Chiller_Air	°C	35.41	0.32	0.009	34.68	36.1
T_EGR_Chiller_Sample_Inlet	°C	35.33	0.54	0.015	34.34	35.93
T_EGR_Chiller_Impenger1_Outlet	°C	4.29	1.88	0.437	1.16	7.4
EGR_Chiller_Sample_Outlet	°C	15.54	0.52	0.033	14.58	17.25
FID_Sample_Inlet	°C	167.89	0.66	0.004	166.82	169.01
Main_Chiller_Air	°C	38.07	0.27	0.007	37.48	38.63
NDIR+HCLD Sample Inlet	°C	33.49	0.34	0.010	32.94	33.99
NOx	ppm	237.11	1.05	0.004	234.29	239.47
P_Back_Pressure	PSIG	-0.84	0.00	0.000	-0.84	-0.84
P_CO_Inlet	PSIG	12.50	3.27	0.261	6.08	18.43
P_CO2_Exh_Inlet	PSIG	12.59	3.27	0.260	6.16	18.52
P_CO2_Intake_Inlet	PSIG	12.87	3.34	0.260	4.96	21.24
P_Main Sampling_Pump	PSIG	12.47	3.23	0.259	6.12	18.34
P_Nox_Inlet	PSIG	12.57	3.27	0.260	6.15	18.5
T_Chiller_Mid_Temp	°C	30.67	0.40	0.013	29.61	31.19
T_FID_Post_Filter	°C	153.51	1.91	0.012	151.98	158.74
T_Main_Chiller_Impenger1_Outlet	°C	19.06	0.34	0.018	18.55	19.97
T_Main_Chiller_Impenger2_Outlet	°C	5.52	0.06	0.011	5.44	5.73
T_MainChiller_Inlet	°C	90.90	2.20	0.024	89.06	96.91
t_MainChiller_Outlet	°C	17.99	0.54	0.030	16.63	18.56
T_NDIR+HCLD_Post_Filter	°C	152.86	3.69	0.024	140.46	155.8
T_Post_HFilter_FID	°C	163.37	2.43	0.015	156.53	165.27
T_Post_HFilter_Main	°C	156.10	2.18	0.014	151.5	157.75
T_Sampling_Point	°C	139.91	1.20	0.009	138.13	143.19
THC	ppmC1	122.83	2.16	0.018	120.23	129.29

The uncertainty for the emissions concentration values acquired in Trial #1 can be determined by the same approach used in calculating the span gas measurements uncertainty. The uncertainty of each exhaust constituent is expressed in percentage next:

Table 6.4: Exhaust Constituents Uncertainty Values for Trial #1

Exhaust Constituent	Units	Mean	Standard Deviation	% Uncertainty
THC	ppmC1	122.83	2.16	1.76
NOx	ppm	237.11	1.05	0.44
CO	ppm	743.85	9.47	1.27
CO_2_Main	% vol.	5.18	0.02	0.39
CO_2_Intake	% vol.	1.06	0.02	1.89

Figures 6.12 and 6.13 show the emissions concentrations for Trial #1. Figure 6.14 shows the pressure readings at the sample inlet of the NDIR and the HCLD analyzers. The THC analyzer does not require pressure monitoring as it has a dedicated internal sampling pump. Figure 6.15 shows the main chiller performance versus the main pump output pressure. The main sample pressure was very difficult to regulate manual as stated above. However, the main and EGR sample pressure values were maintained in the range of 10-15 PSIG for the majority of the test, which is, the recommended sample pressure by the chiller manufacturer. The main chiller performance was stable; however, the true outlet temperature of the sample (impinger 2) was higher than desired. Figure 6.16 details the EGR chiller performance and clearly shows the effect of the sample line pressure on the output temperature. Also, it was observed that as the ambient temperature inside the emissions bench increased, so did the inlet and outlet temperatures of the EGR chiller (slightly). The complete trial #1 data is listed in Appendix C.

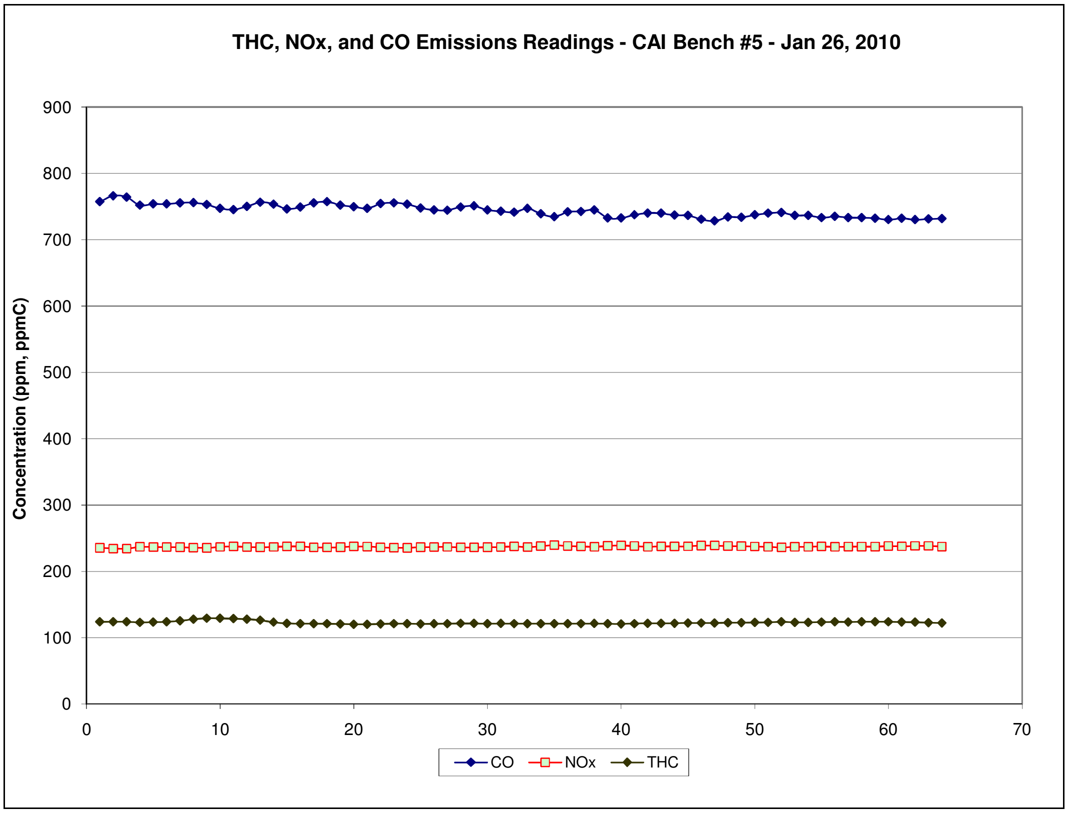


Figure 6.12: THC, NOx, and CO Values during Trail #1

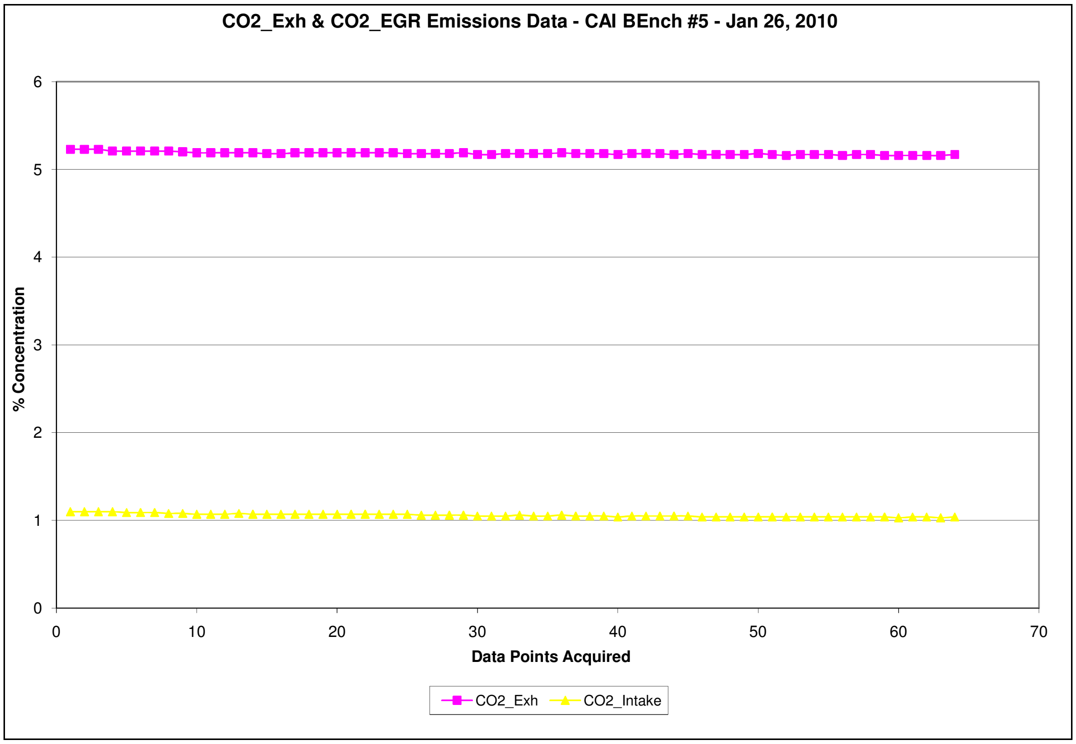


Figure 6.13: CO_2_Exh and CO_2_Intake during Trial #1

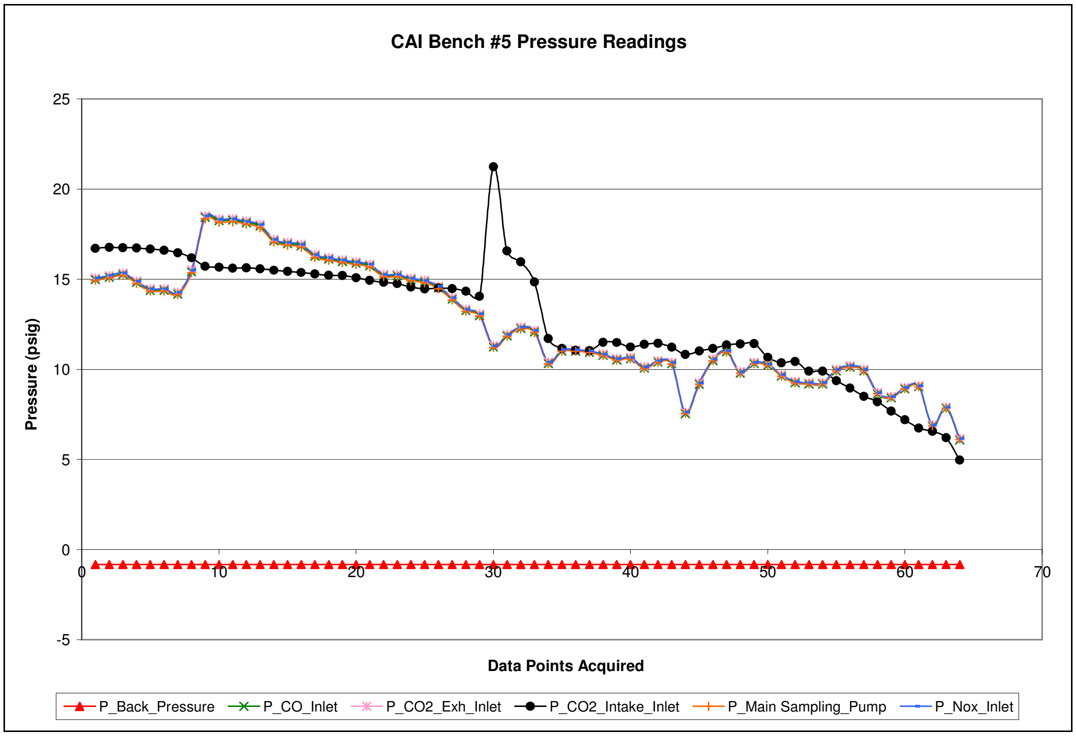


Figure 6.14: Analyzer (NDIR & HCLD) Inlet Pressure Readings during Trial #1

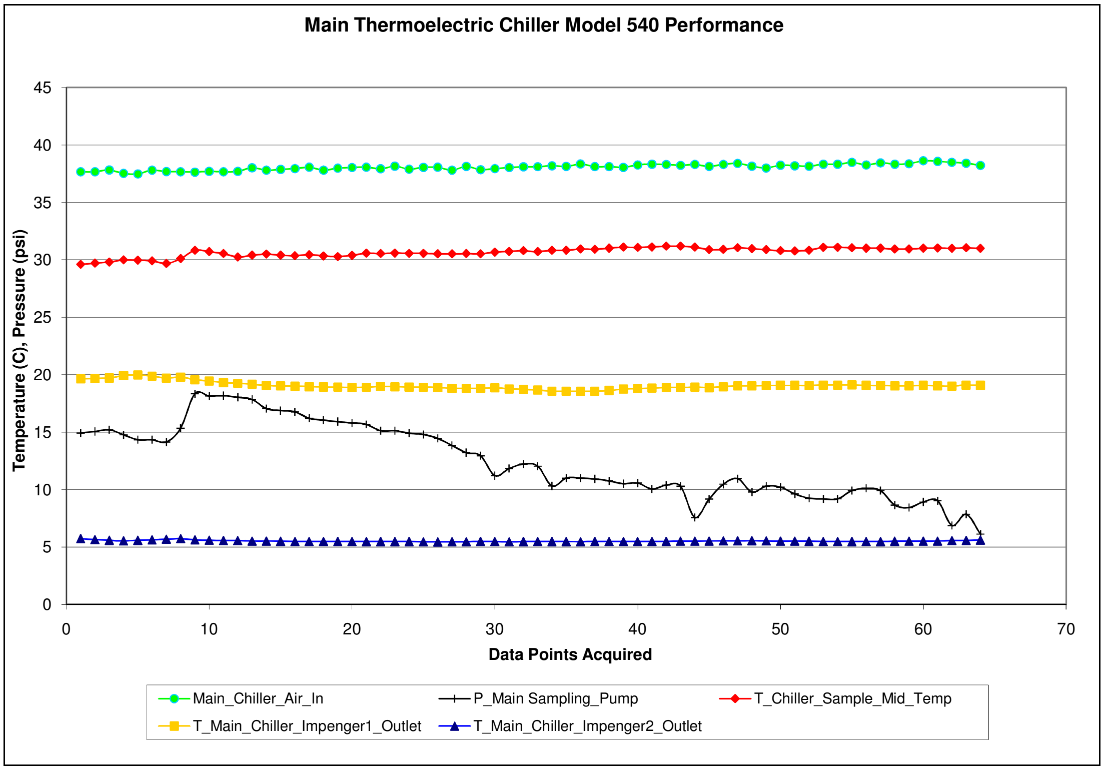
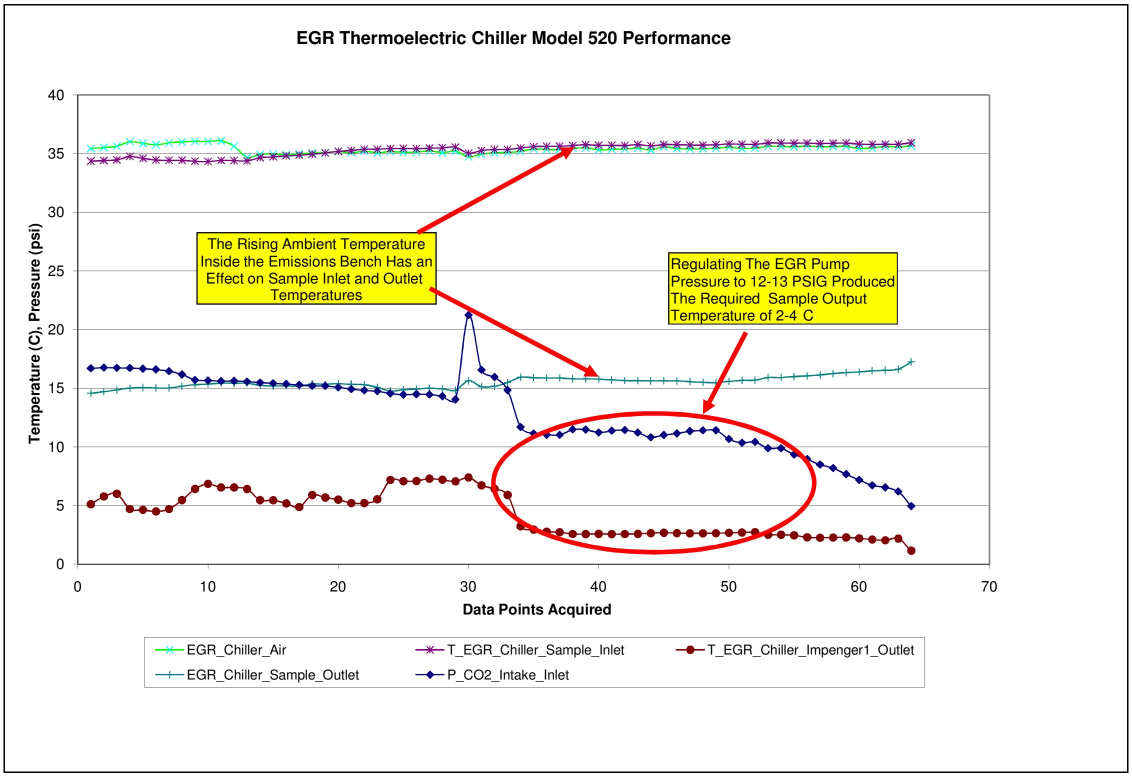


Figure 6.15: Main Chiller Performance during Trial #1



The Rising Ambient Temperature Inside the Emissions Bench Has an Effect on Sample Inlet and Outlet Temperatures

Regulating The EGR Pump Pressure to 12-13 PSIG Produced The Required Sample Output Temperature of 2-4 C

Figure 6.16: EGR Chiller Performance during Trial #1

After examining the collected data for the first trial a few observations were made:

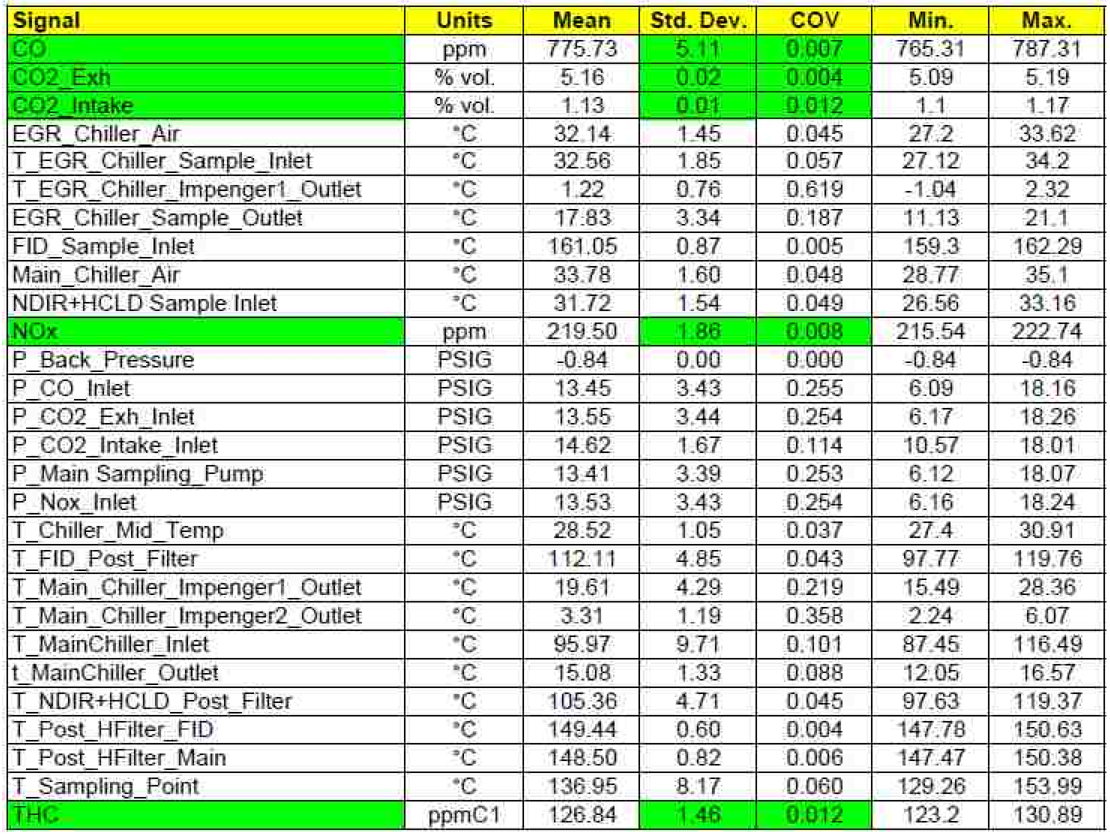
1. The standard deviation values of the emissions concentrations (highlighted in green) were acceptable. However, once the uncertainty was calculated for the various detectors, the results were higher than the 1% uncertainty specified by the manufacturer.
2. The main chiller air and the EGR chiller air temperature values were 38.06°C and 35.41°C respectively. These values represent the ambient air temperature in the vicinity of the chillers and are measured at the top of the heat sink fan before the air is channeled through the heat sink. These values are high compared to the actual test cell room temperature (27-32°C). It was concluded that the devices inside the emissions bench were generating a significant amount of heat that was not being dispose of properly.
3. The sampling pump pressure measurements (main and EGR sample) fluctuated significantly. The intended output pressure of the sampling pump was 15 PSIG. However, it was extremely difficult to achieve this set point. A manual needle valve was used to regulate the pressure for each sample stream. This was achieved by relieving a portion of the sample after the sampling pump to reduce the pump output pressure to the desired value. However, all the pressure values exhibited a downward trend, indicating either a leak in the lines or a faulty pump. The testing was stopped when the sample pressures reached approx. 6 psig as this was not enough to operate the internal electronic proportional valves inside the NDIR and HCLD analyzers.
4. The chillers output temperature (impinger outlet temperatures) were as follows:
    - Main chiller = 5.44°C - 6.12°C
    - EGR chiller = 1.16°C – 7.4°C

    These values increased as the internal ambient temperature increased. The required range is 2-4°C in order to meet the analyzers' manufacturer requirements.
5. The heated transfer lines, filters, and junction heaters all operated as intended and maintained the desired temperatures.

A Few modifications were made to reduce the ambient temperature inside the emissions bench. The parts described in section 5.1.5 were installed to help in the rejection of the heat generated by the NDIR and the HCLD analyzers. A second set of data was collected on January 27, 2010 to compare the results with the previous set of data (Trial #1). The same operating conditions were applied in Trial #2. The engine was operated at 2000 rpm, 200 N.m, and 20% EGR valve set point. Table 6.4 shows the summary of the data acquired during Trial #2. During this trial 76 data points were acquired at 2.5-minute intervals for a total test time of approximately 3.2 hours. The complete data set acquired in Trial #2 is listed in Appendix C.

We can see from Table 6.5 that the emissions concentrations are very comparable to trial #1 values. Also, the standard deviations of the emissions concentrations were lower than in Trial #1. Table 6.6 details the uncertainty analysis for the exhaust constituent values.

Table 6.5: Trial #2 CAI Emissions Bench Data



Signal	Units	Mean	Std. Dev.	COV	Min.	Max.
CO	ppm	775.73	5.11	0.007	765.31	787.31
CO2_Exh	% vol.	5.16	0.02	0.004	5.09	5.19
CO2_Intake	% vol.	1.13	0.01	0.012	1.1	1.17
EGR_Chiller_Air	°C	32.14	1.45	0.045	27.2	33.62
T_EGR_Chiller_Sample_Inlet	°C	32.56	1.85	0.057	27.12	34.2
T_EGR_Chiller_Impenger1_Outlet	°C	1.22	0.76	0.619	-1.04	2.32
EGR_Chiller_Sample_Outlet	°C	17.83	3.34	0.187	11.13	21.1
FID_Sample_Inlet	°C	161.05	0.87	0.005	159.3	162.29
Main_Chiller_Air	°C	33.78	1.60	0.048	28.77	35.1
NDIR+HCLD Sample Inlet	°C	31.72	1.54	0.049	26.56	33.16
NOx	ppm	219.50	1.86	0.008	215.54	222.74
P_Back_Pressure	PSIG	-0.84	0.00	0.000	-0.84	-0.84
P_CO_Inlet	PSIG	13.45	3.43	0.255	6.09	18.16
P_CO2_Exh_Inlet	PSIG	13.55	3.44	0.254	6.17	18.26
P_CO2_Intake_Inlet	PSIG	14.62	1.67	0.114	10.57	18.01
P_Main Sampling_Pump	PSIG	13.41	3.39	0.253	6.12	18.07
P_Nox_Inlet	PSIG	13.53	3.43	0.254	6.16	18.24
T_Chiller_Mid_Temp	°C	28.52	1.05	0.037	27.4	30.91
T_FID_Post_Filter	°C	112.11	4.85	0.043	97.77	119.76
T_Main_Chiller_Impenger1_Outlet	°C	19.61	4.29	0.219	15.49	28.36
T_Main_Chiller_Impenger2_Outlet	°C	3.31	1.19	0.358	2.24	6.07
T_MainChiller_Inlet	°C	95.97	9.71	0.101	87.45	116.49
t_MainChiller_Outlet	°C	15.08	1.33	0.088	12.05	16.57
T_NDIR+HCLD_Post_Filter	°C	105.36	4.71	0.045	97.63	119.37
T_Post_HFilter_FID	°C	149.44	0.60	0.004	147.78	150.63
T_Post_HFilter_Main	°C	148.50	0.82	0.006	147.47	150.38
T_Sampling_Point	°C	136.95	8.17	0.060	129.26	153.99
THC	ppmC1	126.84	1.46	0.012	123.2	130.89

Table 6.6: Exhaust Constituents Uncertainty Values for Trial #2

Exhaust Constituent	Units	Mean	Standard Deviation	% Uncertainty
THC	ppmC1	126.84	1.46	1.15
NOx	ppm	219.5	1.86	0.85
CO	ppm	775.73	5.11	0.66
CO_2_Main	% vol.	5.16	0.02	0.39
CO_2_Intake	% vol.	1.13	0.01	0.88

Table 6.6 shows that the uncertainty values for the exhaust gas concentrations improved in Trial #2. Therefore, these values will be chosen to calculate the total uncertainty of the exhaust gas constituents. The total uncertainty is expressed as the summation of the span gas uncertainties:

- THC = 1.15 + 0.07 = 1.22 %
- NOx = 0.85 + 0.02 = 0.87 %
- CO = 0.66 + 0.06 = 0.72 %
- CO2_Main = 0.39 + 0.06 = 0.45 %
- CO2_Intake = 0.88 + 0.05 = 0.93%

Figure 6.17 and Figure 6.18 show the emissions concentrations during the second trial. Figure 6.19 shows the main chiller performance. Figure 6.20 shows the EGR chiller performance.

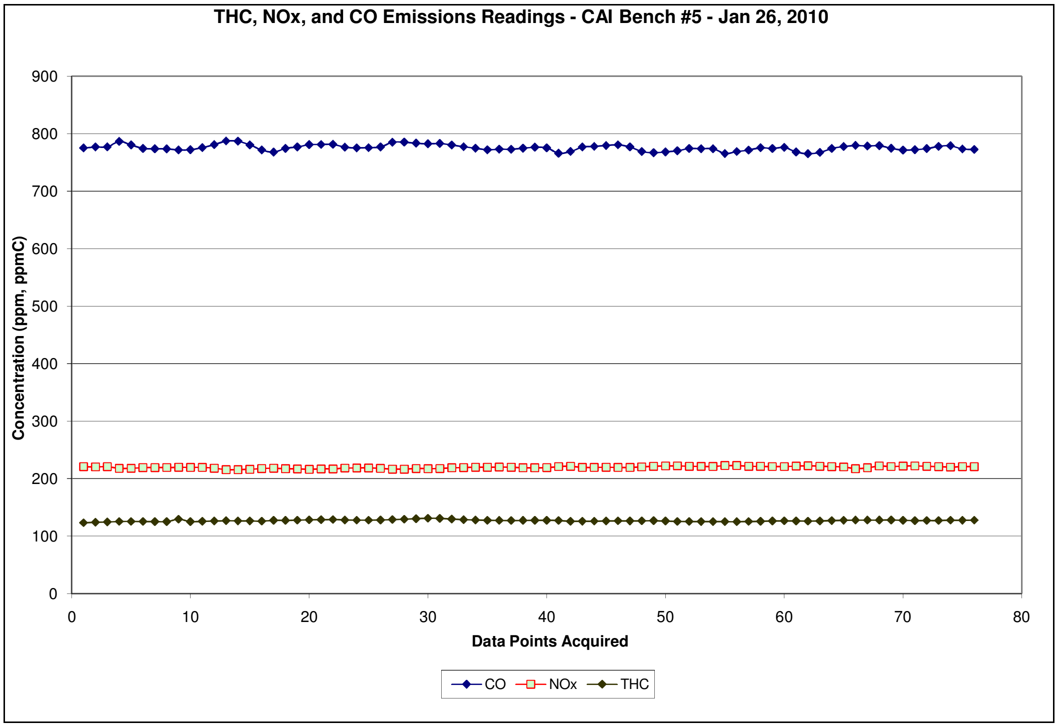


Figure 6.17: THC, NOx, and CO Concentrations during Trial #2

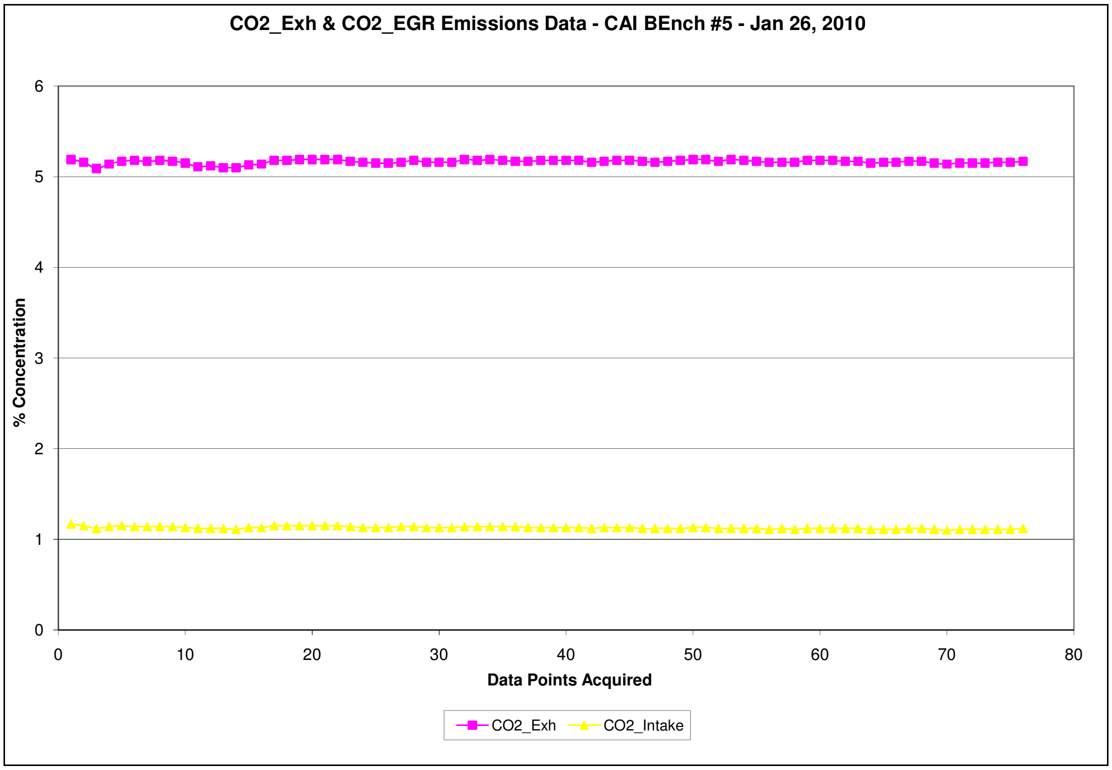


Figure 6.18: CO_2_Exh and CO_2_Intake Concentrations during Trial #2

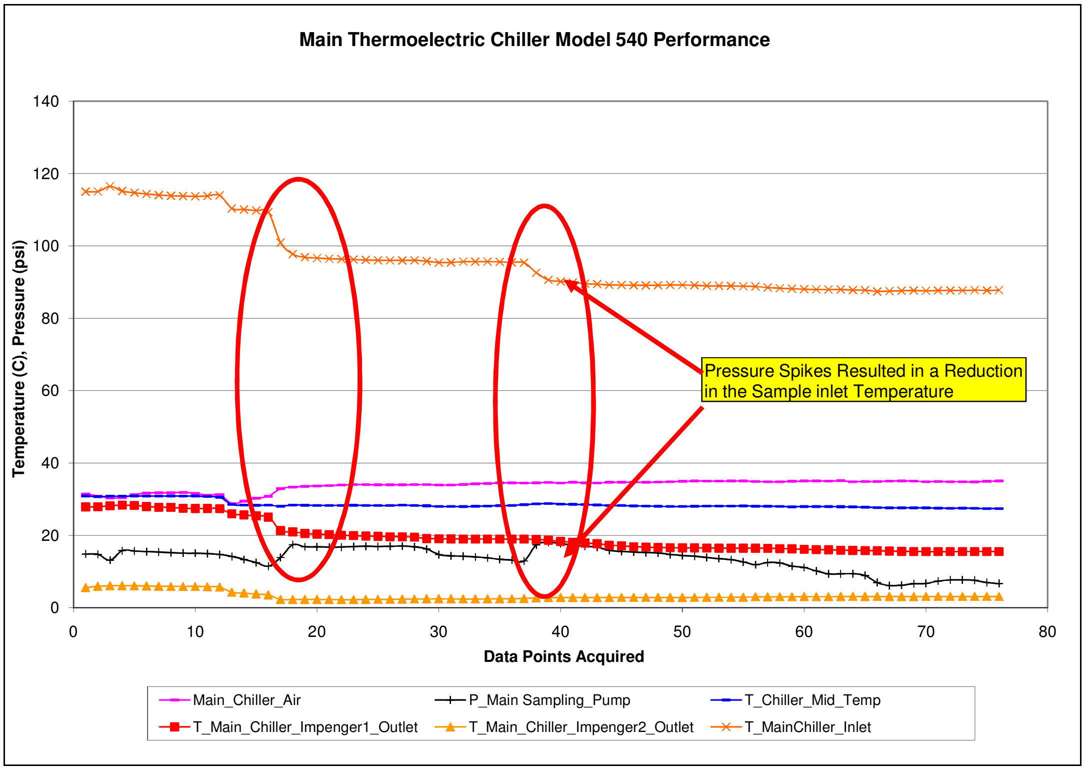


Figure 6.19: Main Chiller Performance during Trial #2

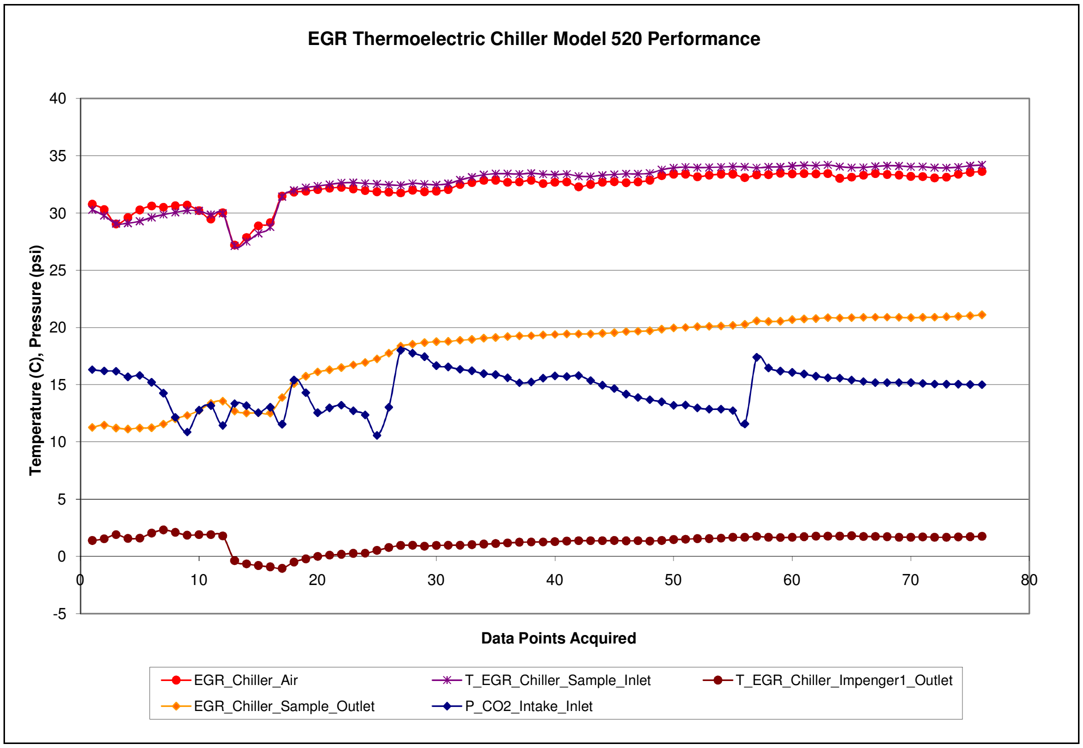


Figure 6.20: EGR Chiller Performance during Trial #2

The following observations were made after the second trial:

1. The ambient temperature in the vicinity of the main and EGR chillers was lower than in Trial #1. The main chiller ambient temperature mean value was reduced from 38.06°C to 33.54°C and the EGR ambient mean temperature was reduced from 35.41°C to 31.89°C as a result of the venting installed in Trial #2. Also, the test cell air conditioning unit was not operational again. It is safe to assume that this contributed to the higher than usual ambient room temperature in the test cell (27-33°C). The reduction in the internal ambient temperature of the emissions bench in Trial #2 was very beneficial. The true sample output temperature of both chillers was significantly lower than in the first trial. The sample output mean values were reduced from 5.53°C to 3.35°C (main chiller) and 4.32°C to 1.13°C (EGR chiller). These values are well within the manufacturer's recommendations.
2. The main and EGR sample line pressure values were still volatile. The manual pressure regulation valves proved too time-consuming and did not have adequate resolution to achieve precise and fast pressure regulation. The pressure fluctuation in the main chiller affected the sample input temperature. This can be observed in Figure 6.19. The EGR sample pressure was also fluctuating significantly; however, it remained in the required range of 10-15 PSIG.
3. The uncertainty values for the exhaust constituents improved considerably over the values obtained in Trial #1. The calculated uncertainties were in the 1% range specified by the manufacturer except for the THC value. The resulting higher uncertainty value for THC could be attributed to the low level

7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Conclusions

The following conclusions were formulated from the CAI Emissions Bench project:

1. It was demonstrated that a functional emissions analyzer bench can be designed, fabricated, and assembled in-house at a fraction of the cost of a commercial turn-key system, such as, HORIBA. However, this project has to be considered the first iteration in a possible series of modifications and fine-tuning to achieve a robust, commercially-usable product.
2. One of the main components of the CAI emissions bench that is under scrutiny is the thermoelectric chiller. In this bench; two thermoelectric chillers are used to remove excess moisture from the exhaust sample. It was concluded that this type of chiller is very sensitive to the surrounding conditions. The ambient temperature must be kept as low as possible and as stable as possible. This would increase the heat transfer through the heat sink. Also, it would be ideal if the CAI emissions bench is kept outside of the test cell while sampling the exhaust gas. This is a typical arrangement that is found in other laboratories. The advantage of this setup is that the room temperature becomes stable and it is not affected by the heat generated by the engine inside the test cell. This is also recommended by the manufacturer of the emissions analyzers as excessive heat is detrimental to the electronic components in these analyzers. The disadvantage of placing the emissions bench outside the test cell is the increased length of the sample transfer lines that would be needed to deliver the exhaust sample. This would be a major issue if transient testing was conducted. However, this would have minimal effect on steady-state testing.
3. The pressure regulation mechanism used in this bench proved unsatisfactory. The manual needle valves used as pressure relief valves are far from ideal and do not

posses the necessary resolution to reach the correct pressure values. The feedback mechanism used to verify the pressure readings was inadequate as the pressure transducers were not in the vicinity of the needle valves and therefore there was a significant lag time that further complicated the pressure regulation task.

4. The data acquisition system proved instrumental in quickly identifying potential issues or bottlenecks. This helped reduce down time and provided the needed transparency at every stage of the sampling system from the sampling point to the analyzer sample inlets. The data sets acquired can also serve as a proof that the emissions readings acquired were in fact accurate by determining that the sampling system was performing as intended.
5. The span gases used in the calibration of the CAI analyzers were not matched correctly with the measured values during the commissioning phase. Since, the ranges in the analyzers have to be matched with the available span gases, they, also, were not matched correctly with the measured values. This is the result of having single span gas concentration per exhaust constituent for calibration purposes.

7.2 Future Recommendations

Given certain performance short-comings and design considerations; the following recommendations are made for future consideration when further developing this emissions bench.

1. Further chiller testing should be conducted. The thermoelectric chiller should be benchmarked against the traditional chiller used in the current CAI emission benches. The current chiller is a vapor-compression type that can be used in conjunction with sample pressure regulation to determine the true performance value of this design as the current CAI emissions benches do not utilize pressure regulation.
2. If the current sampling system design is to be adopted; more work needs to be done in the area of pressure regulation. Electronic proportional valves should be

used with an adequate feedback system to eliminate the volatility that is associated with manual valve control.

3. Due to the complexity of the proposed sampling system design in this project thought was given to a different approach. If the emission analyzers were all fitted with the optional OEM internal sampling pumps, then many components can be eliminated from this design without sacrificing performance. In reality if the sampling pump and the associated pressure regulation hardware were eliminated and the task of sampling and pressure regulation was delegated to the analyzers performance gains can then be realized while significantly simplifying the overall design and cost. This approach was proven to be successful by examining the THC analyzer operation. The THC data was stable and repeatable. However, further testing is required before concluding that this approach is a feasible alternative.
4. Another approach that can be recommended is the design of a remote sampling system that can be left in the test cell and connected to an analyzer rack placed outside of the test cell. This setup would protect the analyzers from the environmental effects of the test cell. Basically, the remote sampling system would consist of the particulate filters and the chillers only as the exhaust sampling and pressure regulation would be performed by the emission analyzers themselves.
5. There must be new span gas bottles added to the collection of calibration gases with different concentrations to cater to different ranges. For example, we currently use a 468 ppmC1 THC span bottle with a selected range of 600 ppmC1. This is adequate when sampling in the 50-100% range of this span gas. However, if we need to sample in the lower regions (0-200 ppmC1) then a new span gas with a lower concentration would be needed (250 ppmC1).

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APPENDIX A: Detailed Design Documentation

A.1 Filter Assembly Design

The filter housings selected for this design are the ATMO/SEAL FPD-4-7/1-A25 and the Parker Finite Series S1SS-6T10-025. The specifications for the ATMO/SEAL filter housing are as follows [15]:

- Maximum heating capacity of 225 °C.
- Power rating: 2A, 120V.
- Must be controlled by a temperature controller or a PID controller.
- Equipped with K-Type thermocouple for control purposes.
- Aluminum Exterior construction.
- Stainless steel inner construction.
- Inlet and outlet ports are ¼ compression fittings (Swagelok).
- Houses a 1" OD Filter x 7" in length.
- Bayonet-style plunger for filter removal and replacement.

Figure A.1 shows the ATMO/SEAL filter housing. This housing is heated using a heating element and controlled by a temperature controller. An OMRON E5GN basic type temperature controller is used for this purpose. The third filter housing is a Parker Finite Series S1SS-6T10-025. This filter housing has the following specifications [16]:

- Complete stainless steel construction with small-volume bowl.
- ¼" Compression Fittings for inlet and outlet ports.
- ¼" drain port with plug if needed.
- Screw-type cap for filter replacements.
- Houses a 2.5" fiber filter.
- The filter used is 6T10-025. This filter has a removal efficiency of 99.97% for 0.3 to 0.6 micron particles.

- The filter used has a pressure drop of 1.0 psi when the filter media is dry and 2-3 psi when the filter media is wet with 10-20 wt. oil.

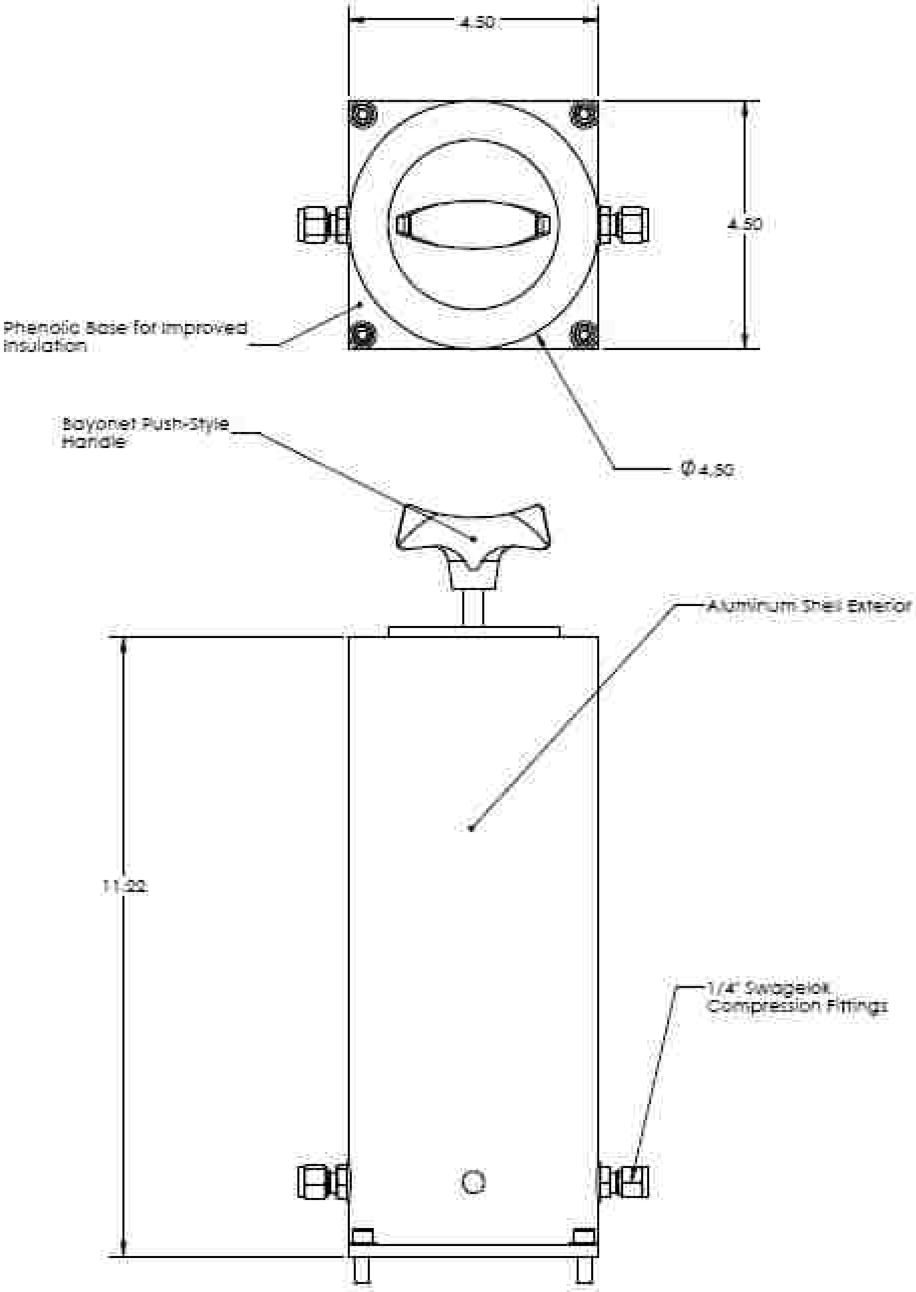


Figure A.1: ATMO/SEAL FPD-4-7/1-A25 Heated Filter Housing [15]

Figure A.2 shows the Parker S1SS-6T10-025:

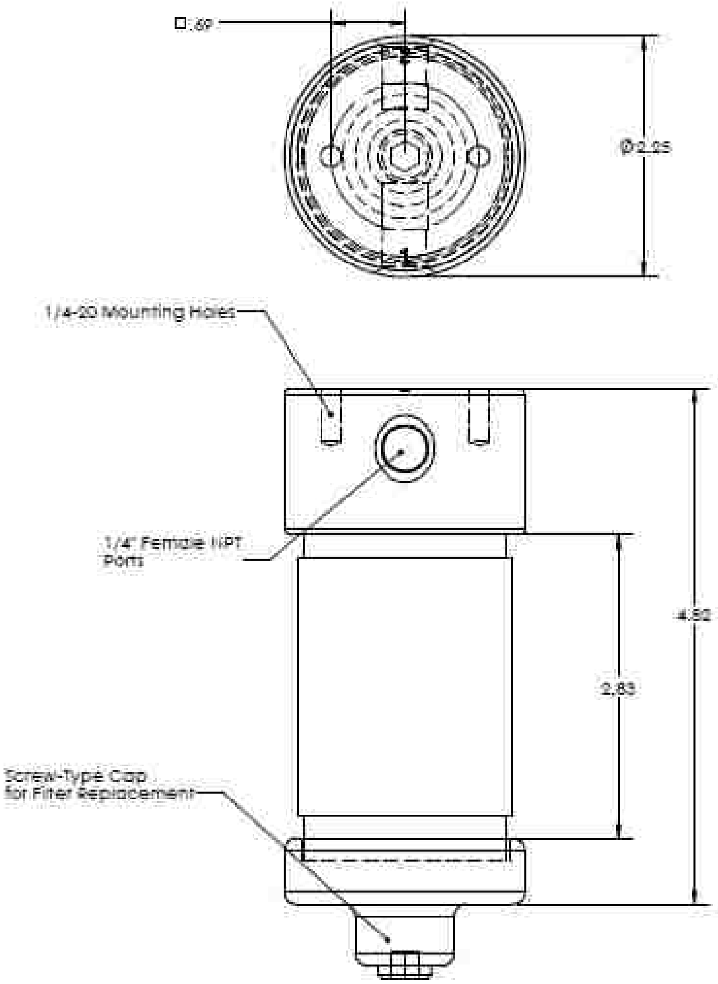


Figure A.2: Parker Finite S1SS-6T10-025 Filter Housing [16]

These three filter housings are mounted on a stainless steel bracket that was designed and fabricated in house. Figure A.3 shows the drawing of the filter housing bracket. The material used to construct this bracket is stainless sheet metal with the thickness of 0.1046 inch (12-Gauge). An inclination angle of 30 degrees was chosen to improve the handling of the filters by the operator. Typically; these filter housings are mounted either vertically or horizontally inside the cabinet and this arrangement has proven unpractical at times when trying to remove the filter.

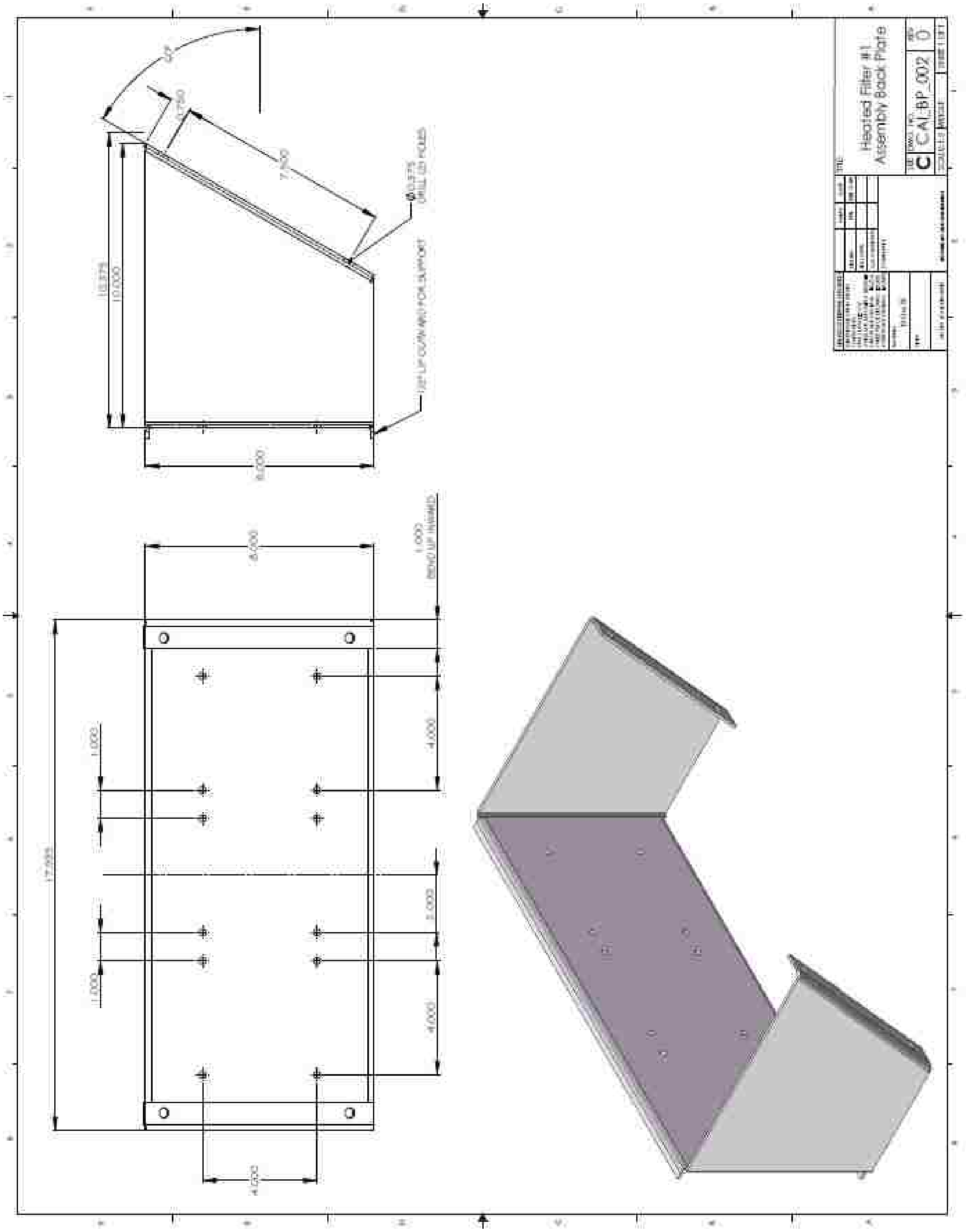


Figure A.3: Filter Housing Bracket

A.2 Exhaust Gas Dryers – Design and Configuration

The Universal Analyzer chillers are used to remove excess moisture from the sample stream except the THC sample. The dual-channel model 540 is used for the main sample stream that delivers the exhaust sample to the NDIR and the CLD analyzers. The single-channel chiller is used to de-humidify the EGR sample before reaching the NDIR analyzer. These chillers are based on the thermoelectric cooling principle. Thermoelectric modules (also called Peltier junctions) are used to extract the heat from a special housing that the sample passes through. Below are the specifications of the dual-channel 540 model and the single-channel 520 model. Figures A.4 and A.5 show the details of the UA 540 and UA 520 models:

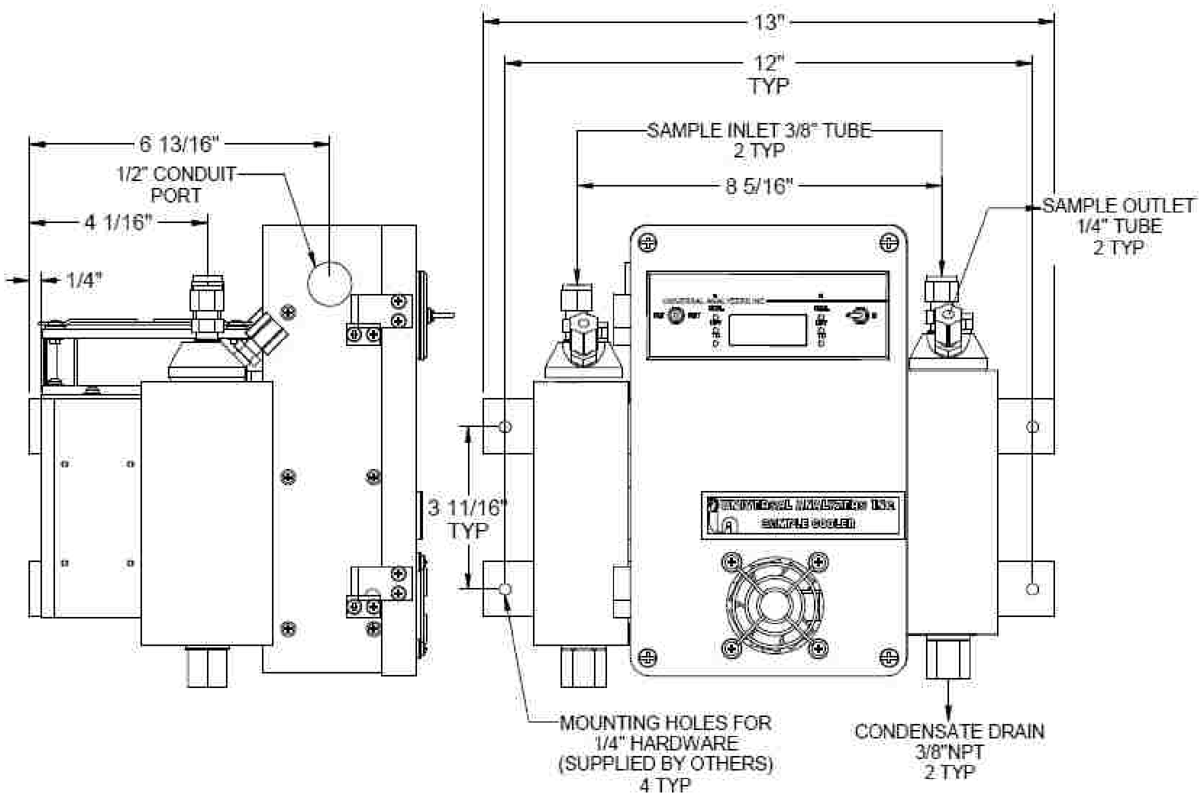


Figure A.4: Universal Analyzer Model 540 Dual-Channel Gas Sample Chiller [17]

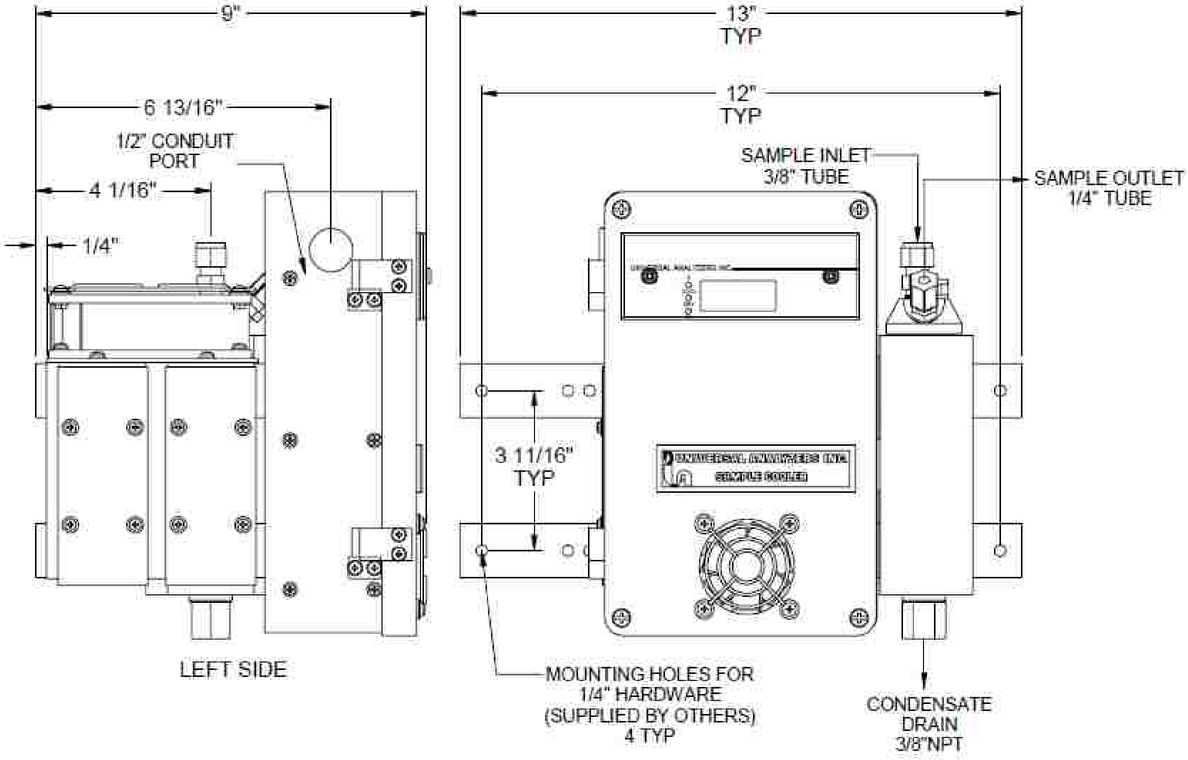


Figure A.5: Universal Analyzer Model 520 Single-Channel Gas Sample Chiller [20]

The water removal takes place in the impingers on the sides of the heat sink. Figure A.6 shows the typical design of the 5” impingers used in these chillers. Using this chiller in a sampling system requires the use of a sampling pump downstream the chiller to draw the sample through. Also, the sample pressure and flow rate has to be regulated in order for the chiller to operate properly. This can be accomplished with the use of a needle valve to relief the sample pressure. The needle valve is placed at the sampling pump outlet and the excess exhaust gas is routed through a ¼” Teflon tube to the test cell gas collection manifold. Figure A.5 shows the setup and location of the needle valve.

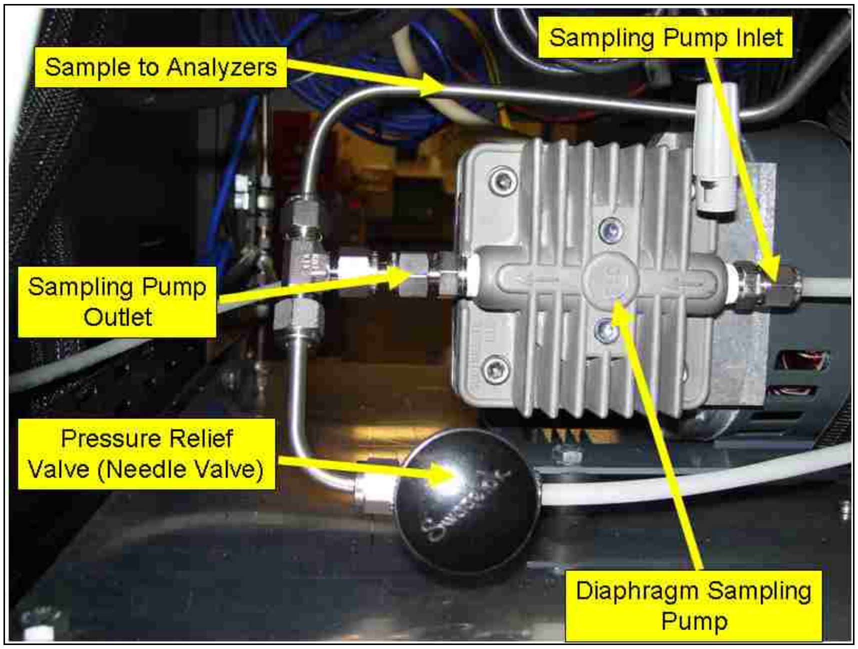


Figure A.5: Pressure Regulation of the Exhaust Main Sample

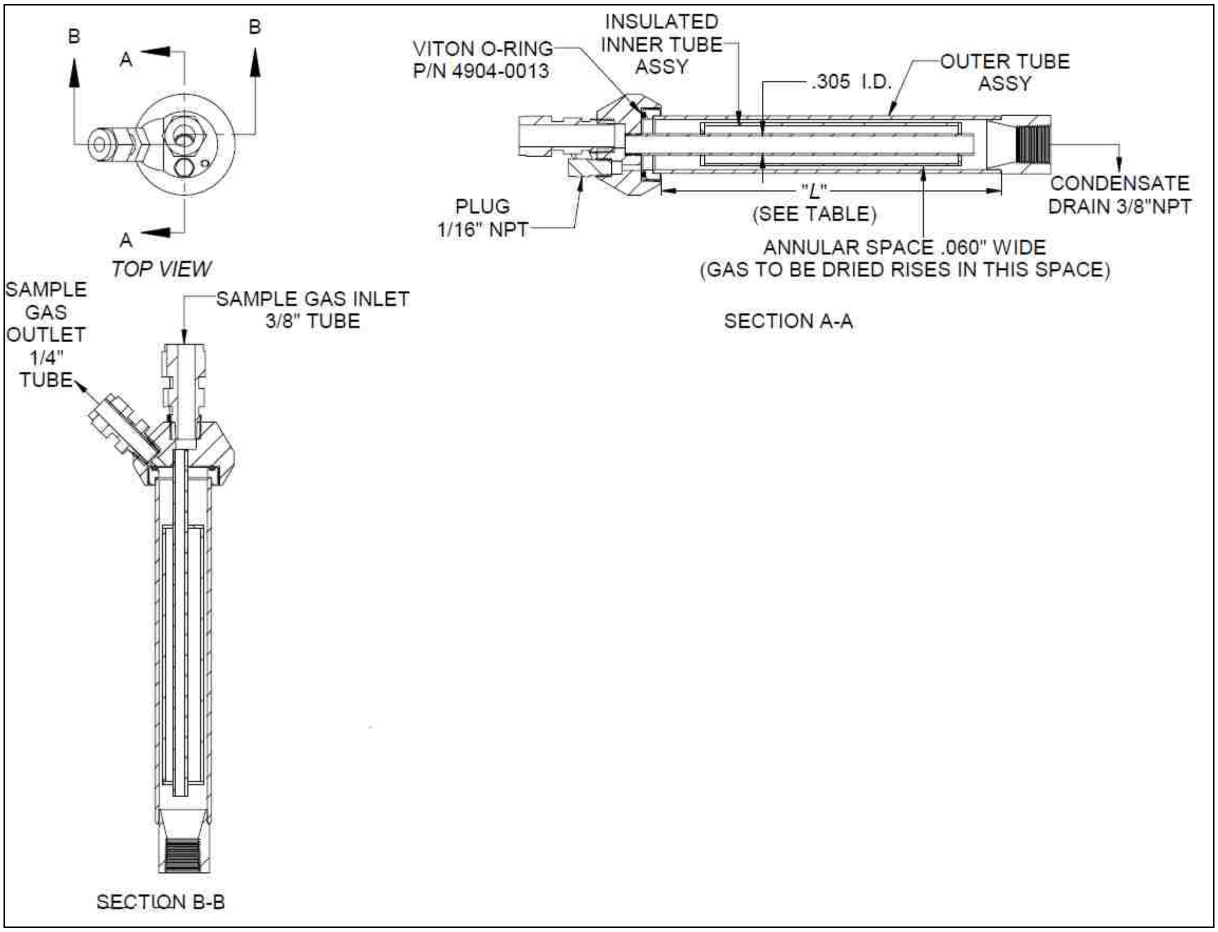
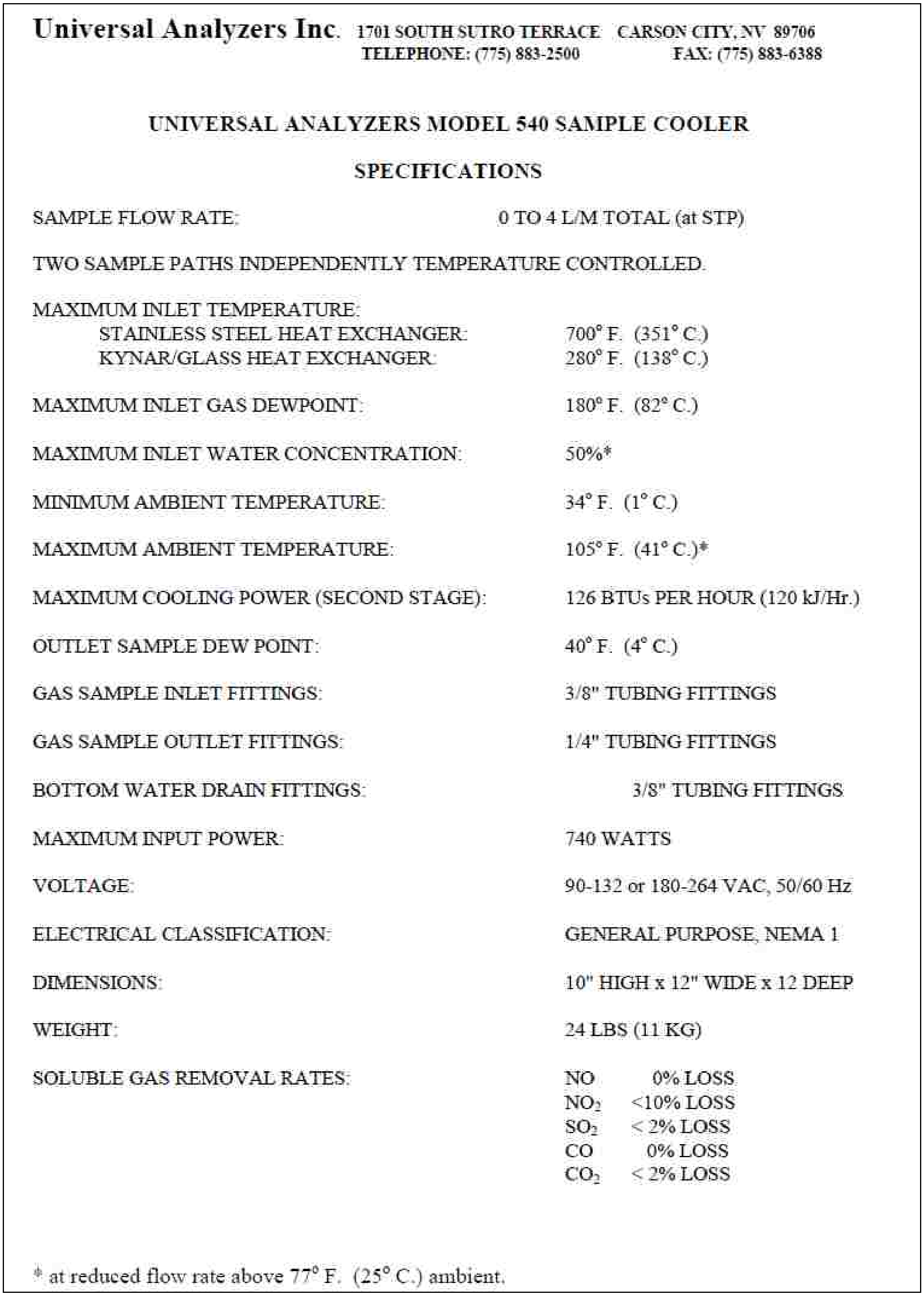


Figure A.6: Universal Analyzer Stainless Steel Impinger Design [17]



Universal Analyzers Inc. 1701 SOUTH SUTRO TERRACE CARSON CITY, NV 89706
TELEPHONE: (775) 883-2500 FAX: (775) 883-6388

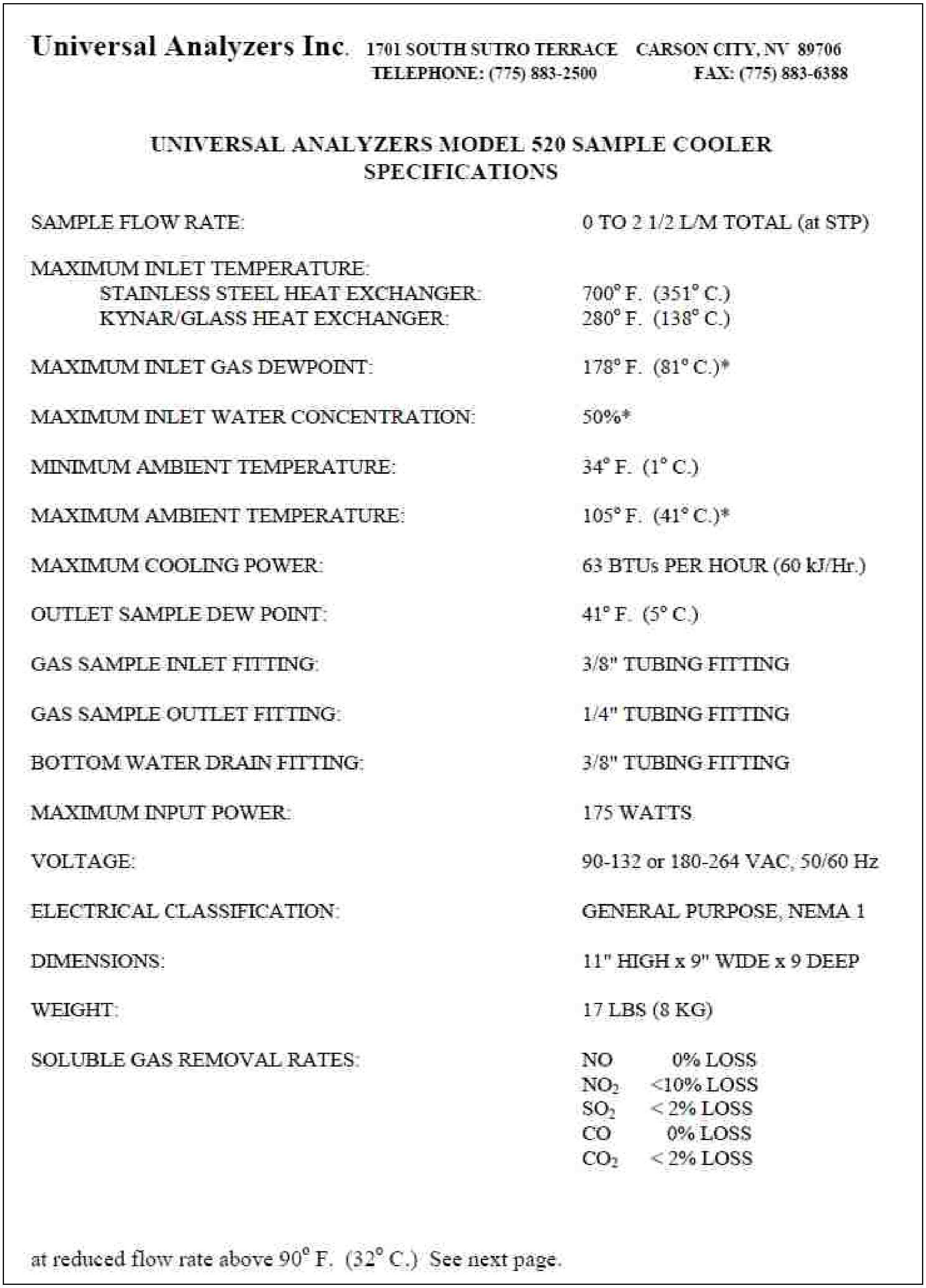
UNIVERSAL ANALYZERS MODEL 540 SAMPLE COOLER

SPECIFICATIONS

SAMPLE FLOW RATE:	0 TO 4 L/M TOTAL (at STP)	
TWO SAMPLE PATHS INDEPENDENTLY TEMPERATURE CONTROLLED.		
MAXIMUM INLET TEMPERATURE:		
STAINLESS STEEL HEAT EXCHANGER:	700° F. (351° C.)	
KYNAR/GLASS HEAT EXCHANGER:	280° F. (138° C.)	
MAXIMUM INLET GAS DEWPOINT:	180° F. (82° C.)	
MAXIMUM INLET WATER CONCENTRATION:	50%*	
MINIMUM AMBIENT TEMPERATURE:	34° F. (1° C.)	
MAXIMUM AMBIENT TEMPERATURE:	105° F. (41° C.)*	
MAXIMUM COOLING POWER (SECOND STAGE):	126 BTUs PER HOUR (120 kJ/Hr.)	
OUTLET SAMPLE DEW POINT:	40° F. (4° C.)	
GAS SAMPLE INLET FITTINGS:	3/8" TUBING FITTINGS	
GAS SAMPLE OUTLET FITTINGS:	1/4" TUBING FITTINGS	
BOTTOM WATER DRAIN FITTINGS:	3/8" TUBING FITTINGS	
MAXIMUM INPUT POWER:	740 WATTS	
VOLTAGE:	90-132 or 180-264 VAC, 50/60 Hz	
ELECTRICAL CLASSIFICATION:	GENERAL PURPOSE, NEMA 1	
DIMENSIONS:	10" HIGH x 12" WIDE x 12 DEEP	
WEIGHT:	24 LBS (11 KG)	
SOLUBLE GAS REMOVAL RATES:	NO	0% LOSS
	NO_2	<10% LOSS
	SO_2	< 2% LOSS
	CO	0% LOSS
	CO_2	< 2% LOSS

* at reduced flow rate above 77° F. (25° C.) ambient.

Figure A.7: Universal Analyzer Model 540 Sample Chiller Specifications [17]



Universal Analyzers Inc. 1701 SOUTH SUTRO TERRACE CARSON CITY, NV 89706
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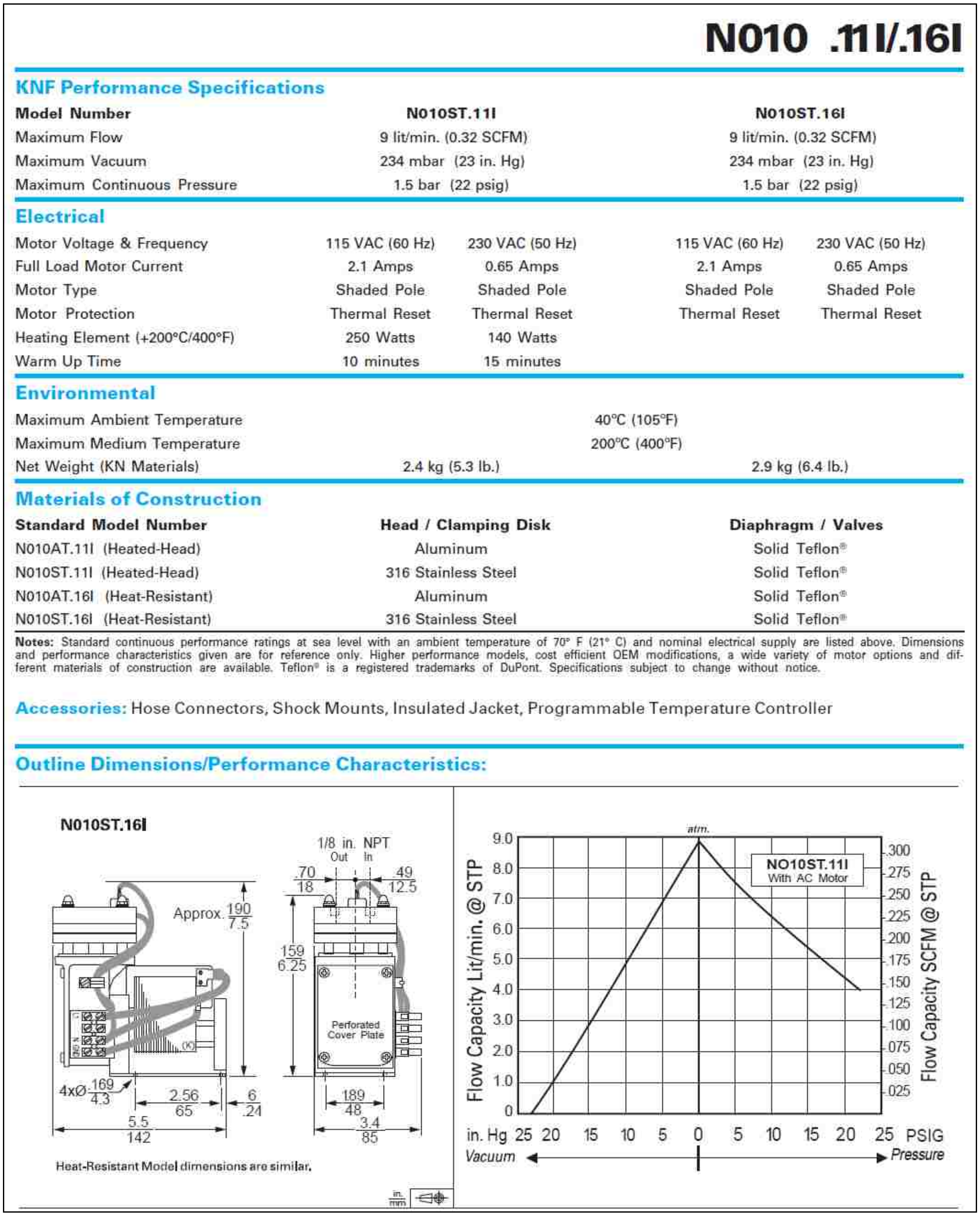
UNIVERSAL ANALYZERS MODEL 520 SAMPLE COOLER SPECIFICATIONS

SAMPLE FLOW RATE:	0 TO 2 1/2 L/M TOTAL (at STP)
MAXIMUM INLET TEMPERATURE:	
STAINLESS STEEL HEAT EXCHANGER:	700° F. (351° C.)
KYNAR/GLASS HEAT EXCHANGER:	280° F. (138° C.)
MAXIMUM INLET GAS DEWPOINT:	178° F. (81° C.)*
MAXIMUM INLET WATER CONCENTRATION:	50%*
MINIMUM AMBIENT TEMPERATURE:	34° F. (1° C.)
MAXIMUM AMBIENT TEMPERATURE:	105° F. (41° C.)*
MAXIMUM COOLING POWER:	63 BTUs PER HOUR (60 kJ/Hr.)
OUTLET SAMPLE DEW POINT:	41° F. (5° C.)
GAS SAMPLE INLET FITTING:	3/8" TUBING FITTING
GAS SAMPLE OUTLET FITTING:	1/4" TUBING FITTING
BOTTOM WATER DRAIN FITTING:	3/8" TUBING FITTING
MAXIMUM INPUT POWER:	175 WATTS
VOLTAGE:	90-132 or 180-264 VAC, 50/60 Hz
ELECTRICAL CLASSIFICATION:	GENERAL PURPOSE, NEMA 1
DIMENSIONS:	11" HIGH x 9" WIDE x 9 DEEP
WEIGHT:	17 LBS (8 KG)
SOLUBLE GAS REMOVAL RATES:	NO 0% LOSS NO_2 <10% LOSS SO_2 < 2% LOSS CO 0% LOSS CO_2 < 2% LOSS

at reduced flow rate above 90° F. (32° C.) See next page.

Figure A.8: Universal Analyzer Model 520 Sample Chiller Specifications [20]

A.3 Exhaust Sampling Pumps



N010 .11I/.16I

KNF Performance Specifications

Model Number	**N010ST.11I**	**N010ST.16I**
Maximum Flow	9 lit/min. (0.32 SCFM)	9 lit/min. (0.32 SCFM)
Maximum Vacuum	234 mbar (23 in. Hg)	234 mbar (23 in. Hg)
Maximum Continuous Pressure	1.5 bar (22 psig)	1.5 bar (22 psig)

Electrical

Motor Voltage & Frequency	115 VAC (60 Hz)	230 VAC (50 Hz)	115 VAC (60 Hz)	230 VAC (50 Hz)
Full Load Motor Current	2.1 Amps	0.65 Amps	2.1 Amps	0.65 Amps
Motor Type	Shaded Pole	Shaded Pole	Shaded Pole	Shaded Pole
Motor Protection	Thermal Reset	Thermal Reset	Thermal Reset	Thermal Reset
Heating Element (+200°C/400°F)	250 Watts	140 Watts		
Warm Up Time	10 minutes	15 minutes		

Environmental

Maximum Ambient Temperature	40°C (105°F)	
Maximum Medium Temperature	200°C (400°F)	
Net Weight (KN Materials)	2.4 kg (5.3 lb.)	2.9 kg (6.4 lb.)

Materials of Construction

Standard Model Number	**Head / Clamping Disk**	**Diaphragm / Valves**
N010AT.11I (Heated-Head)	Aluminum	Solid Teflon®
N010ST.11I (Heated-Head)	316 Stainless Steel	Solid Teflon®
N010AT.16I (Heat-Resistant)	Aluminum	Solid Teflon®
N010ST.16I (Heat-Resistant)	316 Stainless Steel	Solid Teflon®

Notes: Standard continuous performance ratings at sea level with an ambient temperature of 70° F (21° C) and nominal electrical supply are listed above. Dimensions and performance characteristics given are for reference only. Higher performance models, cost efficient OEM modifications, a wide variety of motor options and different materials of construction are available. Teflon® is a registered trademarks of DuPont. Specifications subject to change without notice.

Accessories: Hose Connectors, Shock Mounts, Insulated Jacket, Programmable Temperature Controller

Outline Dimensions/Performance Characteristics:

Figure A.9: KNF Diaphragm Sampling Pump Model N010ST.16I [21]

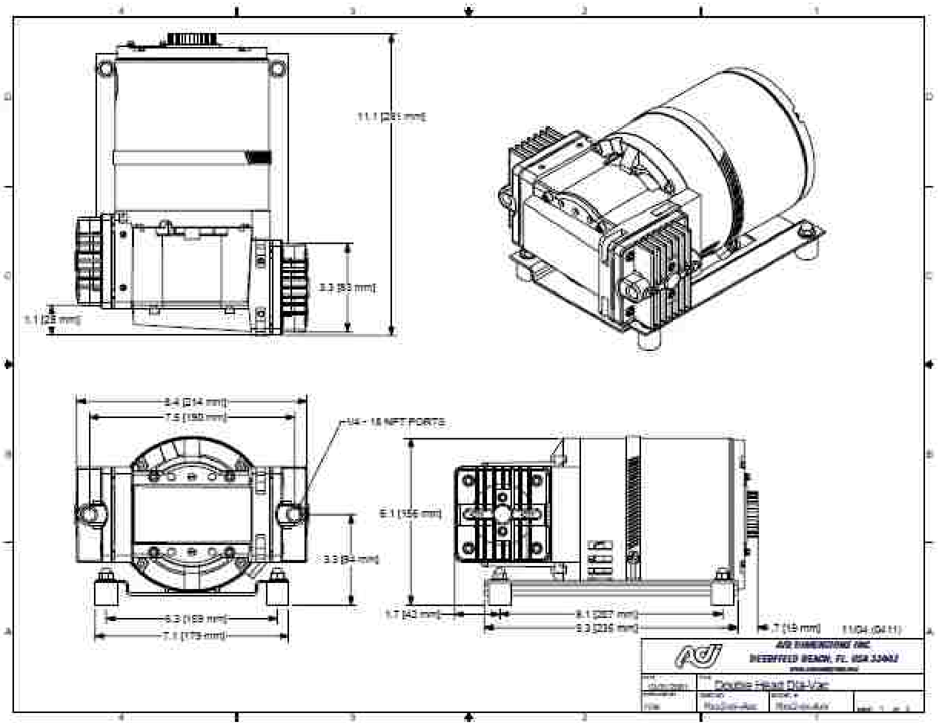


Figure A.10: ADI Diaphragm Sampling Pump Model R222-FT-AA1 [22]

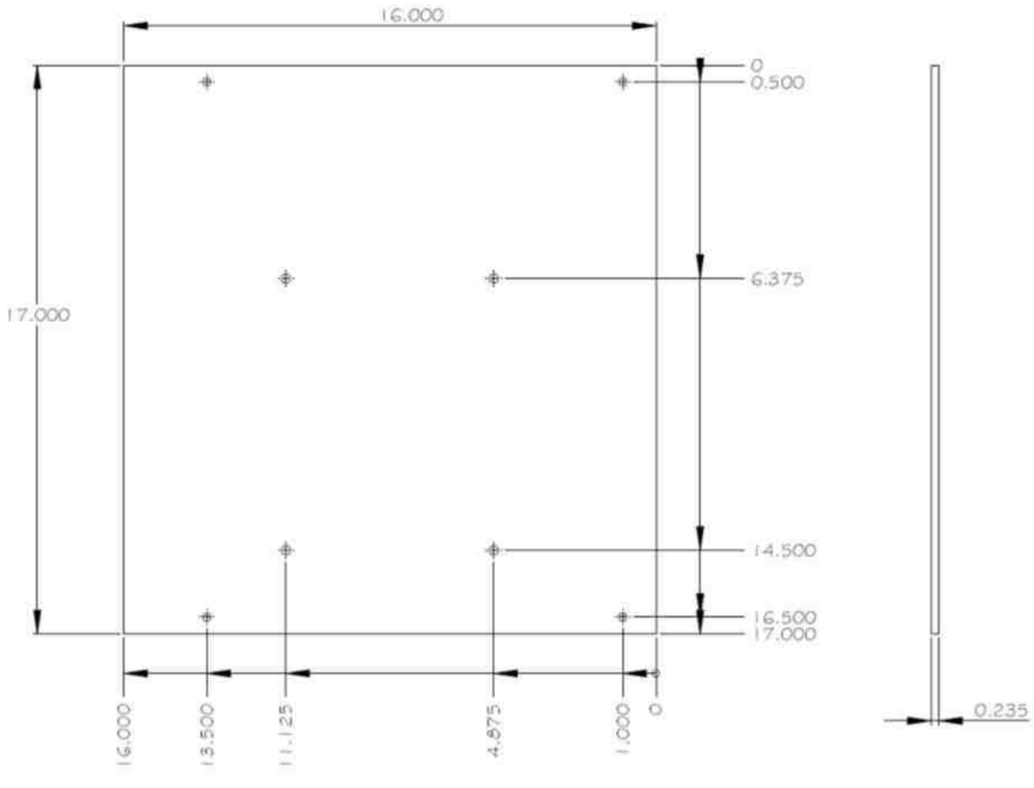


Figure A.11: Sampling Pump Mounting Tray Drawing

A.4 Thermocouple Locations

The pictures below detail the locations of the thermocouples used in the CAI Emissions Analyzer bench (The balloon numbers correspond to Table 4.5):

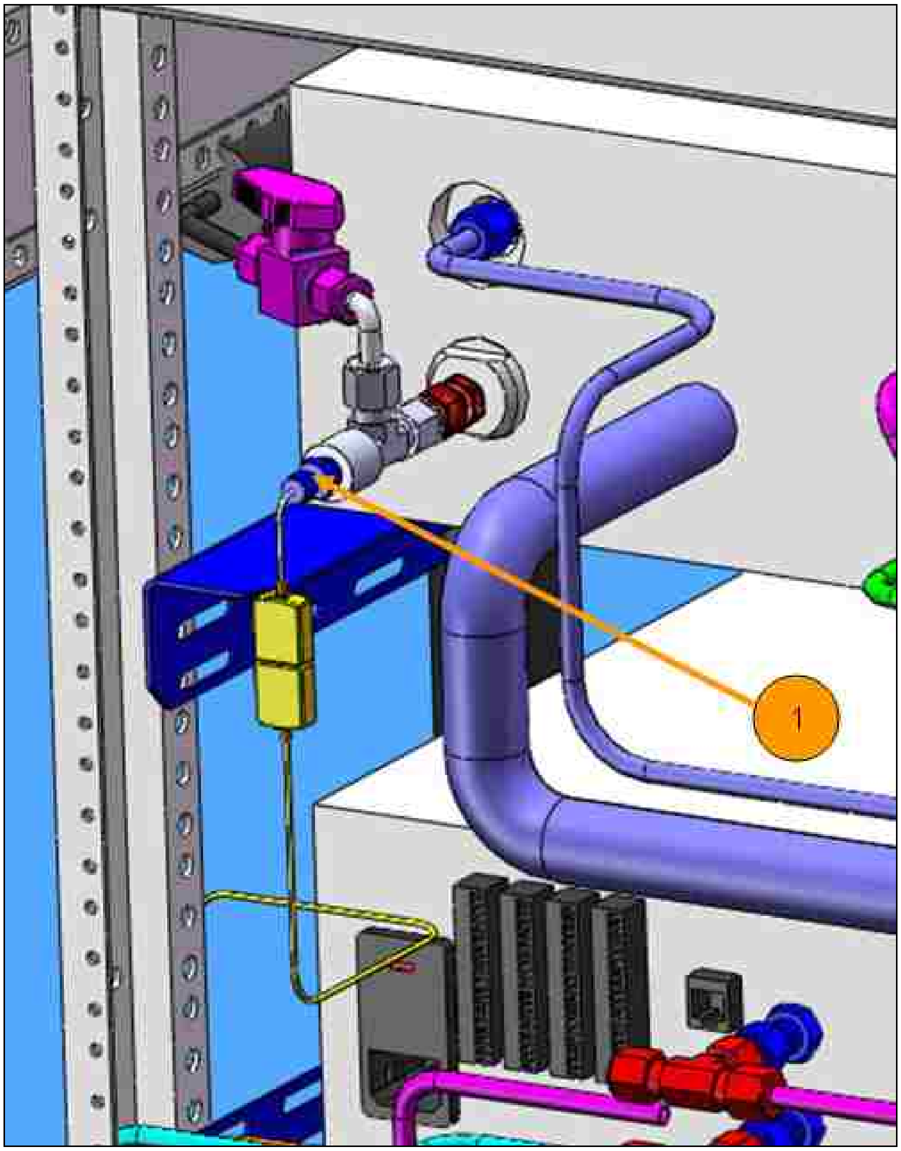


Figure A.11: Thermocouple Locations (FID Sample Inlet)

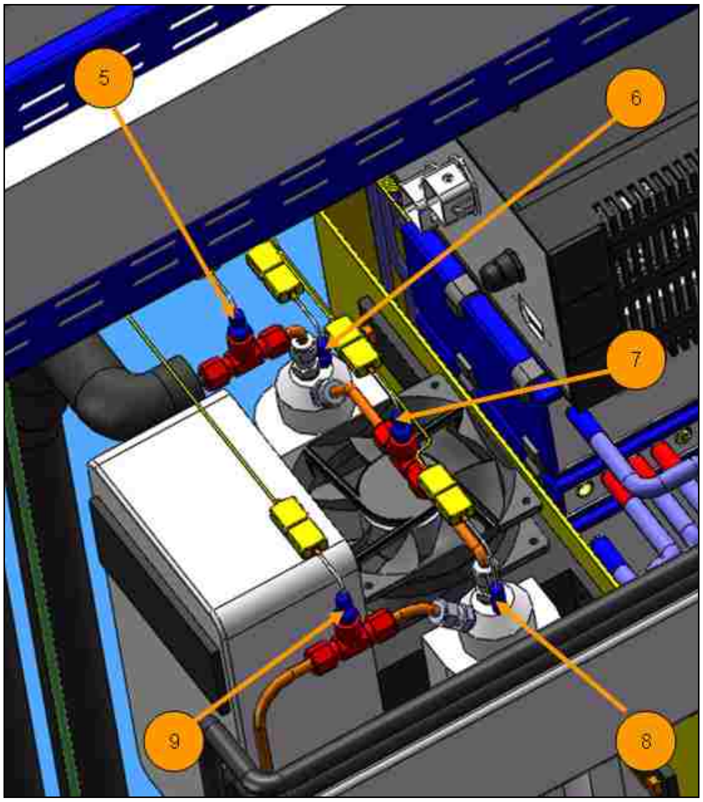


Figure A.12: Thermocouple Locations (Main Sample Chiller)

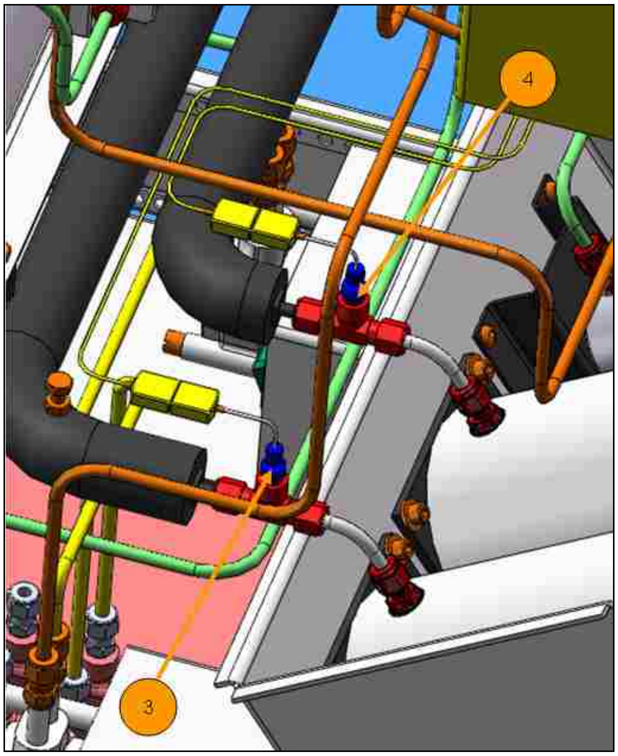


Figure A.13: Thermocouple Locations (FID and Main Sample – post heated filter)

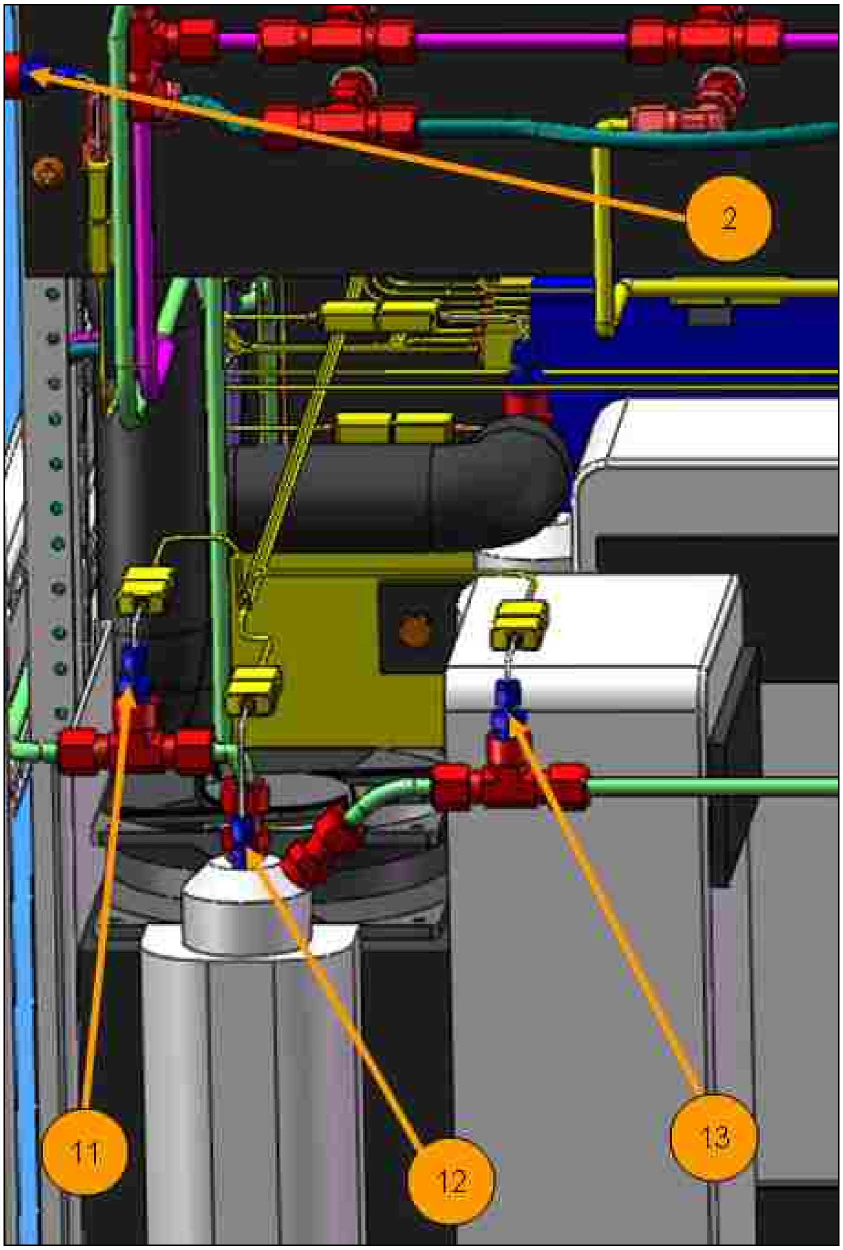


Figure A.14: Thermocouple Locations (EGR Sample Chiller)

A.5 Temperature Controller Unit Drawings

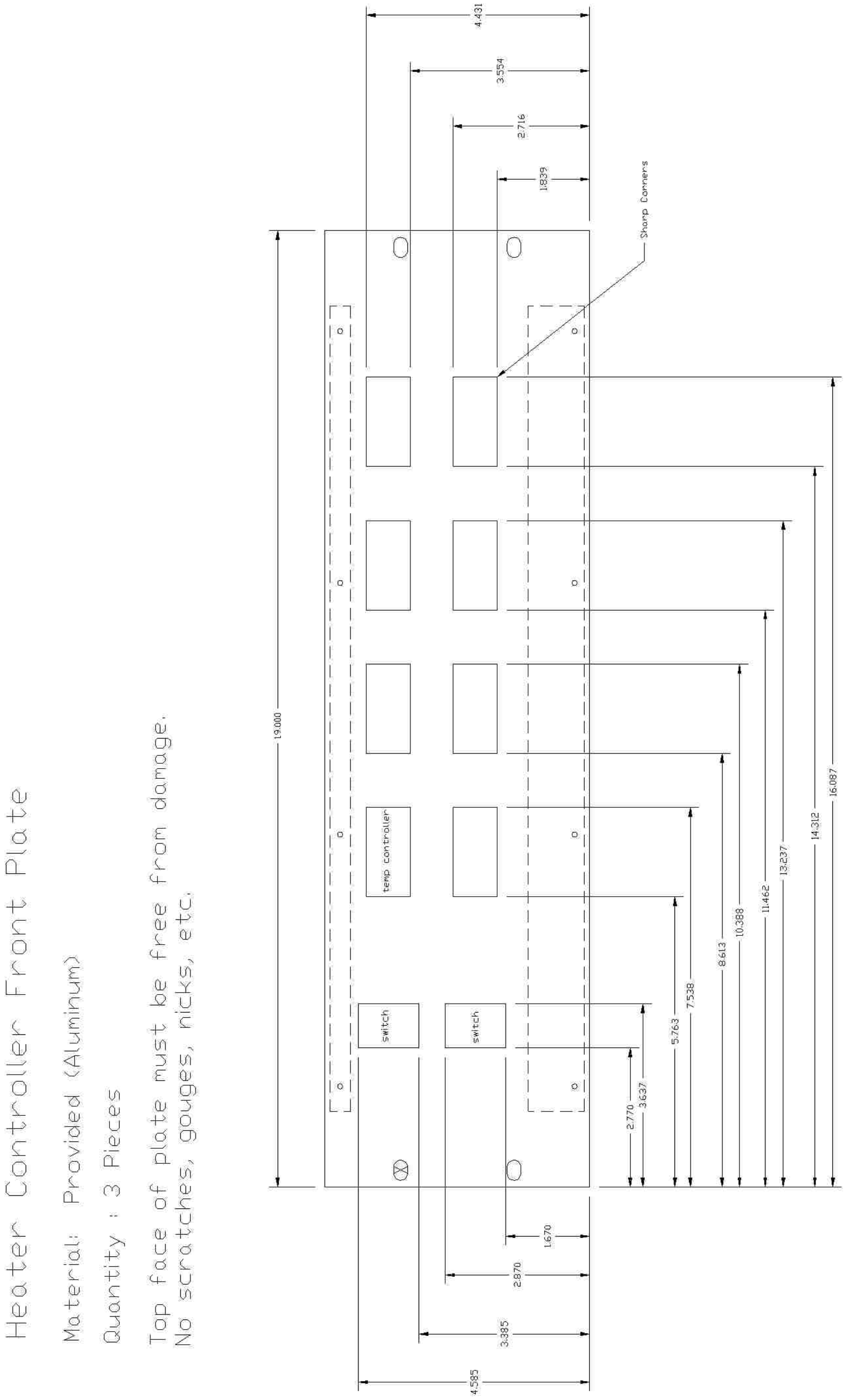


Figure A.15: Temperature Controller Unit Front Plate

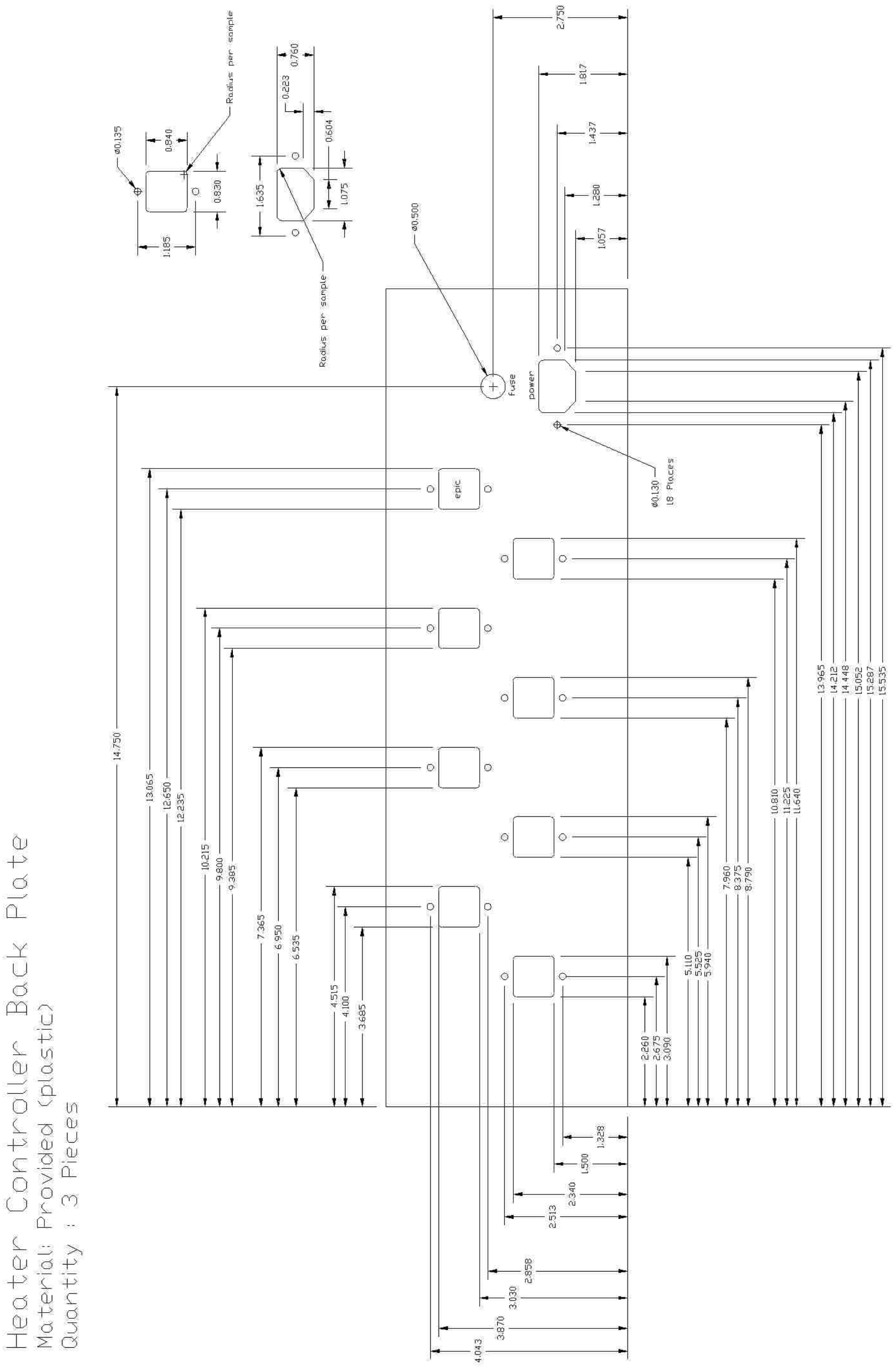


Figure A.16: Temperature Controller Unit Back Plate

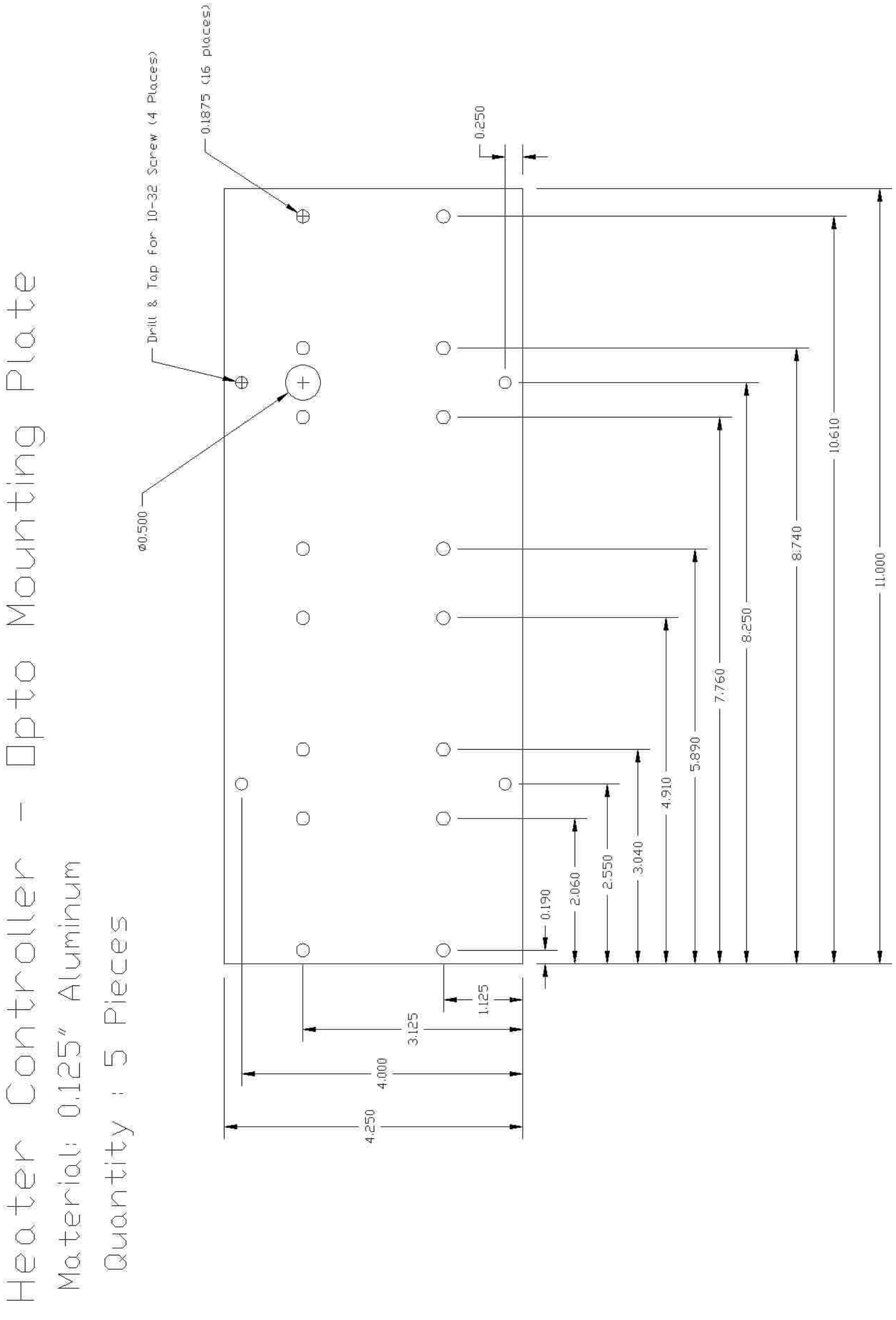
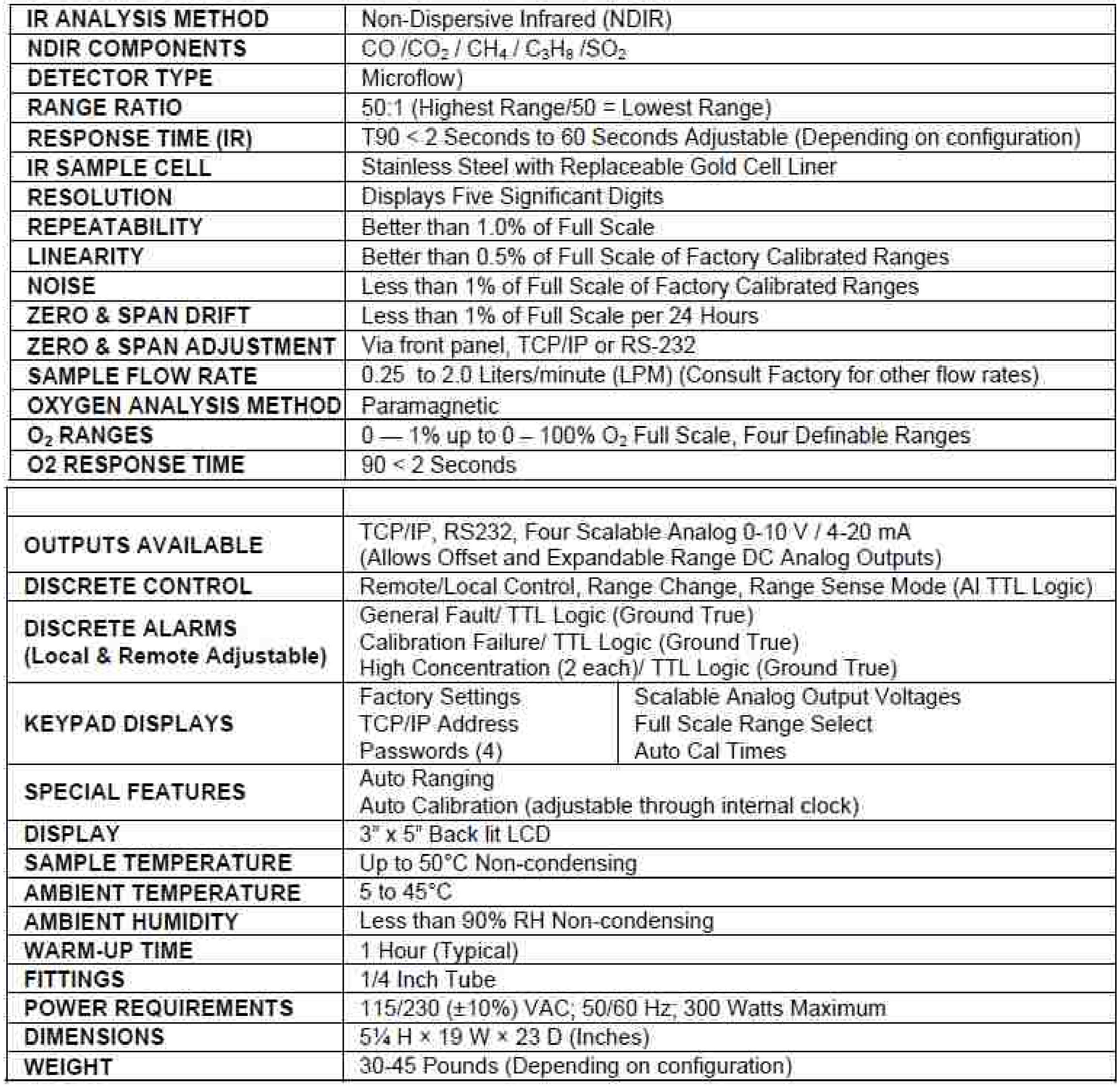


Figure A.17: Temperature Controller Unit Relay Mounting Plate

APPENDIX B: CAI Exhaust Gas Analyzers Specifications

B.1 MODEL 601/601P/602/602P/603 NDIR

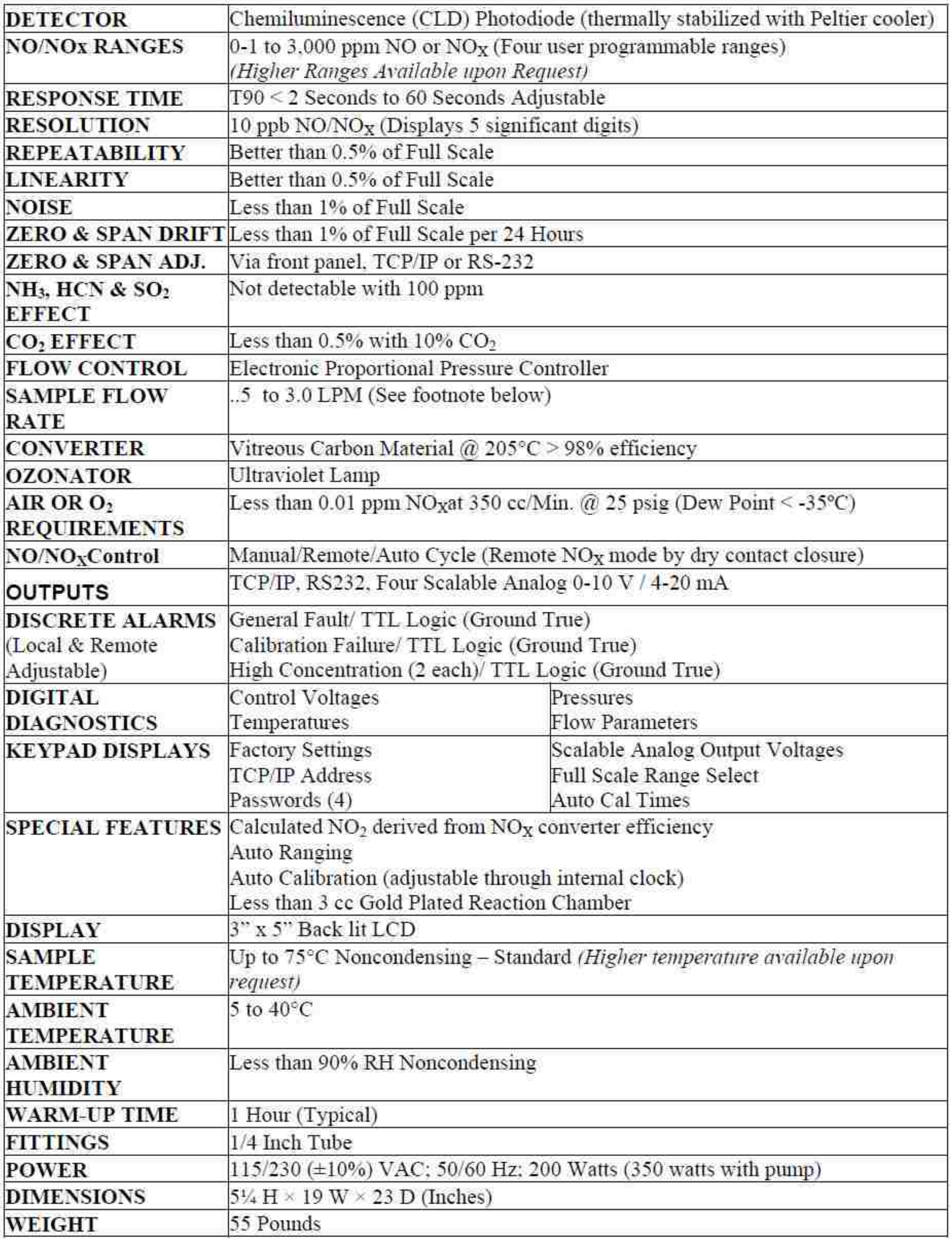
Table B.1: Model 600 NDIR Specifications and Features [4]:



IR ANALYSIS METHOD	Non-Dispersive Infrared (NDIR)
NDIR COMPONENTS	CO /CO_2 / CH_4 / C_3H_8 /SO_2
DETECTOR TYPE	Microflow)
RANGE RATIO	50:1 (Highest Range/50 = Lowest Range)
RESPONSE TIME (IR)	T90 < 2 Seconds to 60 Seconds Adjustable (Depending on configuration)
IR SAMPLE CELL	Stainless Steel with Replaceable Gold Cell Liner
RESOLUTION	Displays Five Significant Digits
REPEATABILITY	Better than 1.0% of Full Scale
LINEARITY	Better than 0.5% of Full Scale of Factory Calibrated Ranges
NOISE	Less than 1% of Full Scale of Factory Calibrated Ranges
ZERO & SPAN DRIFT	Less than 1% of Full Scale per 24 Hours
ZERO & SPAN ADJUSTMENT	Via front panel, TCP/IP or RS-232
SAMPLE FLOW RATE	0.25 to 2.0 Liters/minute (LPM) (Consult Factory for other flow rates)
OXYGEN ANALYSIS METHOD	Paramagnetic
O_2 RANGES	0 — 1% up to 0 – 100% O_2 Full Scale, Four Definable Ranges
O2 RESPONSE TIME	90 < 2 Seconds
OUTPUTS AVAILABLE	TCP/IP, RS232, Four Scalable Analog 0-10 V / 4-20 mA (Allows Offset and Expandable Range DC Analog Outputs)
DISCRETE CONTROL	Remote/Local Control, Range Change, Range Sense Mode (Al TTL Logic)
DISCRETE ALARMS (Local & Remote Adjustable)	General Fault/ TTL Logic (Ground True) Calibration Failure/ TTL Logic (Ground True) High Concentration (2 each)/ TTL Logic (Ground True)
KEYPAD DISPLAYS	Factory Settings TCP/IP Address Passwords (4) Scalable Analog Output Voltages Full Scale Range Select Auto Cal Times
SPECIAL FEATURES	Auto Ranging Auto Calibration (adjustable through internal clock)
DISPLAY	3" x 5" Back lit LCD
SAMPLE TEMPERATURE	Up to 50°C Non-condensing
AMBIENT TEMPERATURE	5 to 45°C
AMBIENT HUMIDITY	Less than 90% RH Non-condensing
WARM-UP TIME	1 Hour (Typical)
FITTINGS	1/4 Inch Tube
POWER REQUIREMENTS	115/230 (±10%) VAC; 50/60 Hz; 300 Watts Maximum
DIMENSIONS	5¼ H × 19 W × 23 D (Inches)
WEIGHT	30-45 Pounds (Depending on configuration)

B.2 MODEL 600 HCLD

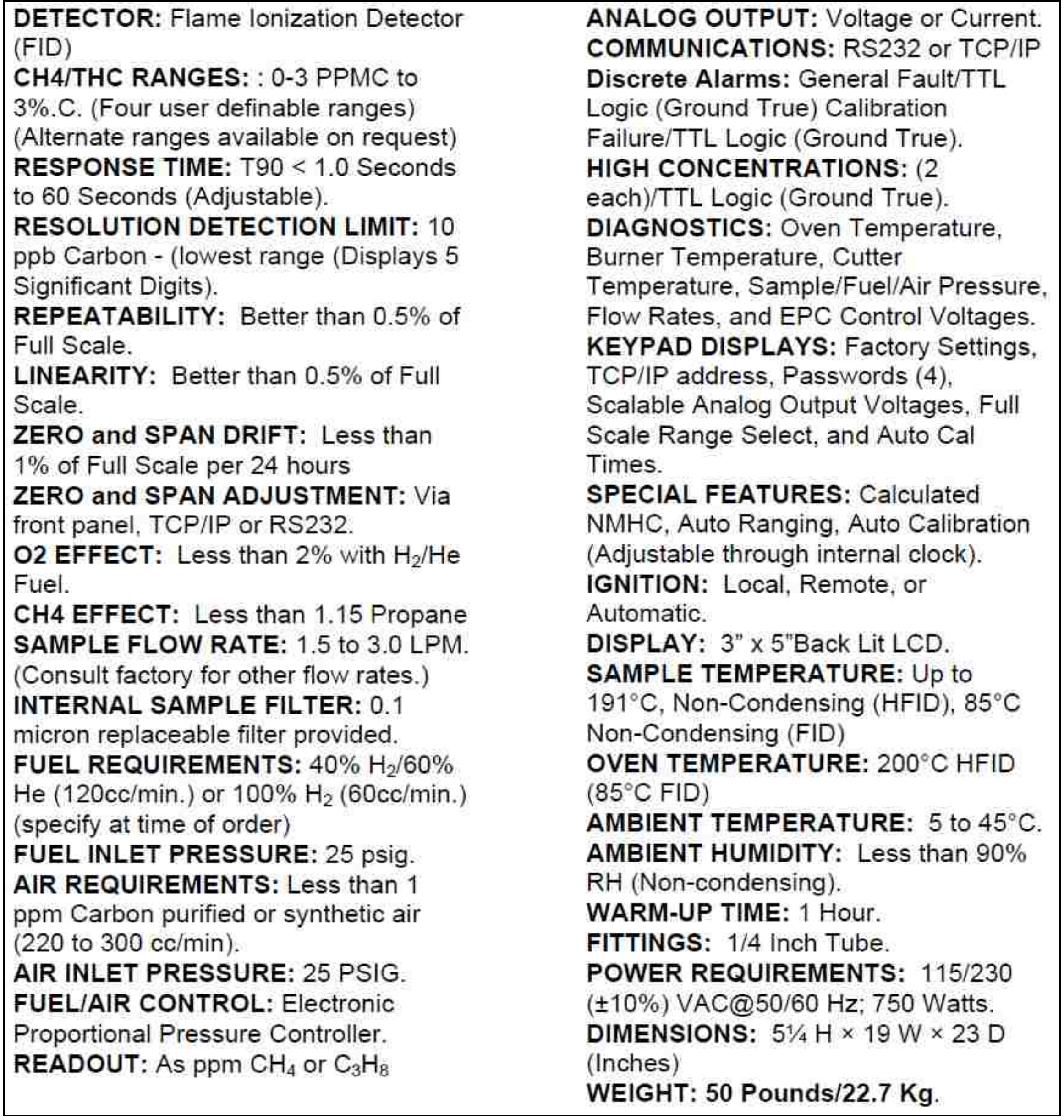
Table B.2: Model 600 HCLD Specifications and Features [2]:



DETECTOR	Chemiluminescence (CLD) Photodiode (thermally stabilized with Peltier cooler)	
NO/NOx RANGES	0-1 to 3,000 ppm NO or NO$_X$ (Four user programmable ranges) *(Higher Ranges Available upon Request)*	
RESPONSE TIME	T90 < 2 Seconds to 60 Seconds Adjustable	
RESOLUTION	10 ppb NO/NO$_X$ (Displays 5 significant digits)	
REPEATABILITY	Better than 0.5% of Full Scale	
LINEARITY	Better than 0.5% of Full Scale	
NOISE	Less than 1% of Full Scale	
ZERO & SPAN DRIFT	Less than 1% of Full Scale per 24 Hours	
ZERO & SPAN ADJ.	Via front panel, TCP/IP or RS-232	
NH_3, HCN & SO_2 EFFECT	Not detectable with 100 ppm	
CO_2 EFFECT	Less than 0.5% with 10% CO_2	
FLOW CONTROL	Electronic Proportional Pressure Controller	
SAMPLE FLOW RATE	..5 to 3.0 LPM (See footnote below)	
CONVERTER	Vitreous Carbon Material @ 205°C > 98% efficiency	
OZONATOR	Ultraviolet Lamp	
AIR OR O_2 REQUIREMENTS	Less than 0.01 ppm NO$_X$at 350 cc/Min. @ 25 psig (Dew Point < -35°C)	
NO/NO$_X$Control	Manual/Remote/Auto Cycle (Remote NO$_X$ mode by dry contact closure)	
OUTPUTS	TCP/IP, RS232, Four Scalable Analog 0-10 V / 4-20 mA	
DISCRETE ALARMS (Local & Remote Adjustable)	General Fault/ TTL Logic (Ground True) Calibration Failure/ TTL Logic (Ground True) High Concentration (2 each)/ TTL Logic (Ground True)	
DIGITAL DIAGNOSTICS	Control Voltages Temperatures	Pressures Flow Parameters
KEYPAD DISPLAYS	Factory Settings TCP/IP Address Passwords (4)	Scalable Analog Output Voltages Full Scale Range Select Auto Cal Times
SPECIAL FEATURES	Calculated NO_2 derived from NO$_X$ converter efficiency Auto Ranging Auto Calibration (adjustable through internal clock) Less than 3 cc Gold Plated Reaction Chamber	
DISPLAY	3" x 5" Back lit LCD	
SAMPLE TEMPERATURE	Up to 75°C Noncondensing – Standard *(Higher temperature available upon request)*	
AMBIENT TEMPERATURE	5 to 40°C	
AMBIENT HUMIDITY	Less than 90% RH Noncondensing	
WARM-UP TIME	1 Hour (Typical)	
FITTINGS	1/4 Inch Tube	
POWER	115/230 (±10%) VAC; 50/60 Hz; 200 Watts (350 watts with pump)	
DIMENSIONS	5¼ H × 19 W × 23 D (Inches)	
WEIGHT	55 Pounds	

B.3 MODEL 600 HFID

Table B.3: Model 600 HFID Specifications and Features [3]:



DETECTOR: Flame Ionization Detector (FID)

CH4/THC RANGES: : 0-3 PPMC to 3%.C. (Four user definable ranges) (Alternate ranges available on request)

RESPONSE TIME: T90 < 1.0 Seconds to 60 Seconds (Adjustable).

RESOLUTION DETECTION LIMIT: 10 ppb Carbon - (lowest range (Displays 5 Significant Digits).

REPEATABILITY: Better than 0.5% of Full Scale.

LINEARITY: Better than 0.5% of Full Scale.

ZERO and SPAN DRIFT: Less than 1% of Full Scale per 24 hours

ZERO and SPAN ADJUSTMENT: Via front panel, TCP/IP or RS232.

O2 EFFECT: Less than 2% with H_2/He Fuel.

CH4 EFFECT: Less than 1.15 Propane

SAMPLE FLOW RATE: 1.5 to 3.0 LPM. (Consult factory for other flow rates.)

INTERNAL SAMPLE FILTER: 0.1 micron replaceable filter provided.

FUEL REQUIREMENTS: 40% H_2/60% He (120cc/min.) or 100% H_2 (60cc/min.) (specify at time of order)

FUEL INLET PRESSURE: 25 psig.

AIR REQUIREMENTS: Less than 1 ppm Carbon purified or synthetic air (220 to 300 cc/min).

AIR INLET PRESSURE: 25 PSIG.

FUEL/AIR CONTROL: Electronic Proportional Pressure Controller.

READOUT: As ppm CH_4 or C_3H_8

ANALOG OUTPUT: Voltage or Current.

COMMUNICATIONS: RS232 or TCP/IP

Discrete Alarms: General Fault/TTL Logic (Ground True) Calibration Failure/TTL Logic (Ground True).

HIGH CONCENTRATIONS: (2 each)/TTL Logic (Ground True).

DIAGNOSTICS: Oven Temperature, Burner Temperature, Cutter Temperature, Sample/Fuel/Air Pressure, Flow Rates, and EPC Control Voltages.

KEYPAD DISPLAYS: Factory Settings, TCP/IP address, Passwords (4), Scalable Analog Output Voltages, Full Scale Range Select, and Auto Cal Times.

SPECIAL FEATURES: Calculated NMHC, Auto Ranging, Auto Calibration (Adjustable through internal clock).

IGNITION: Local, Remote, or Automatic.

DISPLAY: 3" x 5"Back Lit LCD.

SAMPLE TEMPERATURE: Up to 191°C, Non-Condensing (HFID), 85°C Non-Condensing (FID)

OVEN TEMPERATURE: 200°C HFID (85°C FID)

AMBIENT TEMPERATURE: 5 to 45°C.

AMBIENT HUMIDITY: Less than 90% RH (Non-condensing).

WARM-UP TIME: 1 Hour.

FITTINGS: 1/4 Inch Tube.

POWER REQUIREMENTS: 115/230 (±10%) VAC@50/60 Hz; 750 Watts.

DIMENSIONS: 5¼ H × 19 W × 23 D (Inches)

WEIGHT: 50 Pounds/22.7 Kg.

APPENDIX C: Commissioning Test Data

Table C.1 : Trial #1 Data Points Acquired on January 26, 2010

Signal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
CO	757.43	766.45	764.43	752.12	764	753.94	765.76	756.87	753.11	747.28	745.57	750.32	756.54	753.79	746.51	749.29
CO2_Exh	5.23	5.23	5.23	5.21	5.21	5.21	5.21	5.21	5.2	5.19	5.19	5.19	5.19	5.19	5.18	5.18
CO2_Intake	1.1	1.1	1.1	1.1	1.09	1.09	1.09	1.08	1.08	1.07	1.07	1.07	1.08	1.07	1.07	1.07
EGR_Chiller_Air	35.44	35.53	35.64	36.02	35.88	35.76	35.93	36	36.06	36.04	36.1	35.63	34.88	34.95	34.96	34.92
T_EGR_Chiller_Sample_Inlet	34.37	34.43	34.48	34.77	34.61	34.47	34.44	34.44	34.36	34.34	34.43	34.42	34.4	34.57	34.73	34.82
T_EGR_Chiller_Impenger1_Outlet	5.12	5.78	6.01	4.71	4.64	4.5	4.71	5.47	6.43	6.86	6.55	6.55	6.41	5.47	5.46	5.19
EGR_Chiller_Sample_Outlet	14.58	14.71	14.87	15.01	15.07	15.03	15.03	15.18	15.31	15.36	15.44	15.43	15.43	15.26	15.2	15.22
FID_Sample_Inlet	166.82	166.9	166.97	167.18	167.3	167.38	167.36	167.48	167.51	167.49	167.45	167.37	167.39	168	168.27	168.49
Main_Chiller_Air	37.67	37.67	37.82	37.53	37.48	37.61	37.68	37.67	37.64	37.7	37.67	37.7	38.02	37.8	37.88	37.95
NDIR+HCLD Sample Inlet	32.96	32.96	33	33.16	33.05	32.97	32.94	33.03	33.01	33.03	33.06	33.04	33.03	33.11	33.14	33.18
NOx	235.54	234.39	234.29	237.07	236.8	236.55	236.43	236.82	235.45	236.87	237.74	236.66	236.36	236.87	237.61	237.59
P_Back_Pressure	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84
P_CO_Inlet	14.96	15.11	15.26	14.81	14.36	14.38	14.17	15.4	18.43	18.24	18.27	18.13	17.94	17.13	16.96	16.85
P_CO2_Exh_Inlet	16.07	15.2	15.35	14.9	14.47	14.47	14.27	15.51	18.52	18.33	18.37	18.23	18.03	17.22	17.06	16.94
P_CO2_Intake_Inlet	16.7	16.76	16.74	16.73	16.67	16.6	16.46	16.18	15.71	15.67	15.61	15.63	15.57	15.49	15.43	15.37
P_Main Sampling_Pump	14.93	15.06	15.21	14.77	14.34	14.34	14.14	15.35	18.34	18.15	18.16	18.04	17.85	17.05	16.88	16.77
P_Nox_Inlet	15.06	15.19	15.34	14.88	14.45	14.45	14.25	15.49	18.5	18.31	18.34	18.2	18.01	17.2	17.03	16.92
T_Chiller_Mid_Temp	29.61	29.71	29.82	30	29.97	29.92	29.69	30.11	30.83	30.72	30.55	30.25	30.41	30.51	30.41	30.36
T_FID_Post_Filter	156.14	156.01	156.4	156.46	156.7	156.93	157.2	157.78	158.72	158.74	158.27	156.17	155.76	154.36	154.05	154.09
T_Main_Chiller_Impenger1_Outlet	19.64	19.67	19.72	19.92	19.97	19.67	19.7	19.76	19.57	19.45	19.31	19.24	19.15	19.06	19.03	18.99
T_Main_Chiller_Impenger2_Outlet	5.73	5.64	5.58	5.53	5.56	5.62	5.66	5.73	5.62	5.59	5.56	5.56	5.52	5.52	5.5	5.48
T_MainChiller_Inlet	96.23	96.18	96.18	95.6	95.1	95.43	96.91	96.77	92.59	92.45	92.11	91.96	91.76	91.52	91.42	91.38
t_MainChiller_Outlet	16.77	16.69	16.65	16.63	16.66	16.75	16.81	17.07	17.56	17.57	17.66	17.7	17.72	17.82	17.84	17.87
T_NDIR+HCLD_Post_Filter	140.46	141.66	142.56	144.47	145.46	146.23	146.82	147.63	148.86	149.36	150.44	150.63	150.43	151.24	152.03	152.08
T_Post_HFilter_FID	156.63	156.92	157.24	158.38	158.75	159.04	159.2	159.6	160.12	160.22	160.38	160.45	160.62	161.33	161.76	162.2
T_Post_HFilter_Main	151.9	151.87	151.79	151.5	151.5	151.56	151.67	152.1	152.54	152.71	152.93	153.04	153.28	154.05	154.42	154.77
T_Sampling_Point	138.62	139.86	140.8	142.61	142.79	143	142.88	143.19	141.29	141.24	141.29	141.32	140.96	140.48	140.75	140.58
THC	123.92	124.17	124.07	123.05	123.49	124.18	125.54	127.69	129.29	129.26	128.76	127.86	126.4	123.34	121.66	121.11

Table C.1 : Trial #1 Data Points Acquired on January 26, 2010 - Con't

Signal	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
CO	755.7	757.3	752.31	749.93	747.22	754.45	755.79	753.6	747.91	744.67	744.54	749.39	751.03	744.72	742.93	741.46
CO2_Exh	5.19	5.19	5.19	5.19	5.19	5.19	5.19	5.19	5.18	5.18	5.18	5.18	5.19	5.17	5.17	5.18
CO2_Intake	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.06	1.06	1.06	1.06	1.05	1.05	1.05
EGR_Chiller_Air	34.98	35.06	35.08	35.16	35.07	35.22	35.08	35.18	35.12	35.14	35.24	35.09	35.22	34.73	34.95	35.08
T_EGR_Chiller_Sample_Inlet	34.88	34.97	35.07	35.2	35.27	35.38	35.38	35.44	35.45	35.43	35.47	35.5	35.55	35.84	35.27	35.38
T_EGR_Chiller_Impenger1_Outlet	4.88	5.91	5.69	5.51	5.21	5.22	5.54	7.19	7.08	7.1	7.3	7.21	7.07	7.4	6.73	6.43
EGR_Chiller_Sample_Outlet	15.17	15.37	15.36	15.4	15.34	15.31	15.08	14.77	14.88	14.94	15.01	14.95	14.83	15.64	15.14	15.18
FID_Sample_Inlet	168.65	168.85	168.95	168.99	167.88	166.89	167.09	167.35	167.58	167.76	167.97	168.14	168.24	168.56	168.68	168.77
Main_Chiller_Air	38.06	37.81	37.98	38.04	38.07	37.93	38.15	37.9	38.05	38.06	37.81	38.13	37.88	37.94	38.04	38.1
NDIR+HCLD Sample Inlet	33.21	33.27	33.29	33.32	33.35	33.42	33.39	33.41	33.4	33.39	33.42	33.43	33.43	33.28	33.25	33.3
NOx	236.2	235.99	236.41	237.57	227.42	236.23	235.61	236.59	236.53	236.76	236.89	236.16	236.05	236.53	236.67	237.73
P_Back_Pressure	-0.54	-0.84	-0.84	-0.54	-0.84	-0.34	-0.54	-0.54	-0.54	-0.54	-0.34	-0.54	-0.54	-0.84	-0.34	-0.84
P_CO_Inlet	16.26	16.11	15.98	15.88	15.74	15.19	15.15	14.97	14.85	14.51	13.89	13.25	12.98	11.23	11.86	12.27
P_CO2_Exh_Inlet	16.37	16.2	16.07	15.97	15.83	15.28	15.28	15.06	14.94	14.61	13.98	13.34	13.07	11.32	11.94	12.36
P_CO2_Intake_Inlet	15.29	15.21	15.2	15.08	14.93	14.82	14.75	14.56	14.46	14.5	14.47	14.32	14.05	21.24	16.57	15.96
P_Main Sampling_Pump	16.21	16.04	15.92	15.81	15.67	15.13	15.13	14.91	14.8	14.46	13.84	13.22	12.95	11.21	11.63	12.23
P_Nox_Inlet	16.35	16.16	16.08	15.95	15.81	15.26	15.25	15.04	14.92	14.59	13.96	13.32	13.06	11.3	11.93	12.33
T_Chiller_Mid_Temp	30.45	30.35	30.29	30.4	30.58	30.55	30.6	30.67	30.57	30.52	30.52	30.55	30.53	30.68	30.74	30.8
T_FID_Post_Filter	153.84	153.58	153.52	153.22	153.45	152.79	152.99	152.64	152.95	152.53	152.83	152.5	152.78	152.57	152.62	152.88
T_Main_Chiller_Impenger1_Outlet	18.96	18.93	18.92	18.89	18.91	18.96	18.96	18.92	18.91	18.89	18.81	18.82	18.81	18.86	18.77	18.72
T_Main_Chiller_Impenger2_Outlet	5.48	5.49	5.48	5.48	5.47	5.47	5.47	5.47	5.43	5.44	5.45	5.45	5.49	5.46	5.45	5.47
T_MainChiller_Inlet	91.26	91.25	91.24	91.21	91.22	91.18	91.14	91.11	91.07	91.02	90.94	90.89	90.82	90.05	89.55	89.48
t_MainChiller_Outlet	17.91	17.89	17.89	17.89	17.86	17.87	17.9	17.91	17.87	17.85	17.89	17.92	17.96	18.03	18.13	18.19
T_NDIR+HCLD_Post_Filter	152.07	152.63	152.71	152.56	153.12	153.3	153.74	154.14	153.63	153.96	154.6	154.27	154.06	154.44	154.28	154.66
T_Post_HFilter_FID	162.53	162.82	163.06	163.25	163.45	163.93	164.08	164.32	164.48	164.61	164.7	164.76	164.78	164.91	164.97	164.98
T_Post_HFilter_Main	155.06	155.34	155.6	155.86	156.07	156.46	156.57	156.74	156.88	157.01	157.16	157.3	157.37	157.44	157.38	157.38
T_Sampling_Point	140.5	140.53	140.46	140.57	140.79	140.68	140.5	140.57	140.15	140.04	140.15	140.43	140.72	139.24	139	139.06
THC	121.17	120.99	120.57	120.37	120.23	120.9	121.06	121.08	120.86	120.96	121.14	121.47	121.5	121.2	121.41	121.37

Table C.1 : Trial #1 Data Points Acquired on January 26, 2010 - Con't

Signal	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
CO	747.16	739.06	734.6	742	742.74	744.92	732.86	732.76	737.5	740.29	739.98	737.05	736.76	730.63	725.37	734.28
CO2_Exh	5.18	5.18	5.18	5.19	5.18	5.18	5.18	5.17	5.18	5.18	5.18	5.17	5.18	5.17	5.17	5.17
CO2_Intake	1.06	1.05	1.05	1.06	1.05	1.05	1.05	1.04	1.05	1.05	1.05	1.05	1.05	1.04	1.04	1.04
EGR_Chiller_Air	35.11	35.2	35.39	35.36	35.35	35.45	35.49	35.32	35.37	35.39	35.45	35.31	35.59	35.44	35.4	35.42
T_EGR_Chiller_Sample_Inlet	35.37	35.45	35.6	35.63	35.63	35.7	35.76	35.72	35.72	35.7	35.77	35.67	35.78	35.77	35.74	35.73
T_EGR_Chiller_Impenger1_Outlet	5.91	3.24	2.96	2.77	2.73	2.58	2.57	2.59	2.57	2.58	2.59	2.66	2.69	2.66	2.64	2.64
EGR_Chiller_Sample_Outlet	15.49	15.95	15.9	15.88	15.86	15.81	15.8	15.78	15.72	15.66	15.65	15.64	15.65	15.63	15.57	15.51
FID_Sample_Inlet	168.86	168.89	168.85	168.86	168.96	169.01	168.87	168.64	168.58	168.5	168.45	168.29	168.19	168.12	168.01	167.9
Main_Chiller_Air	38.11	38.19	38.13	38.34	38.12	38.12	38.08	38.26	38.33	38.3	38.23	38.31	38.14	38.31	38.39	38.15
NDIR+HCLD Sample Inlet	33.33	33.49	33.56	33.6	33.63	33.66	33.72	33.74	33.74	33.74	33.77	33.75	33.77	33.79	33.78	33.75
NOx	236.62	238.12	239.47	238.18	237.7	237.06	238.55	239.06	238.28	237.14	237.58	237.73	237.83	238.88	239.04	238.21
P_Back_Pressure	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84
P_CO_Inlet	12.07	10.32	11.01	11.01	10.94	10.77	10.51	10.36	10.06	10.4	10.3	7.54	9.17	10.48	10.97	9.79
P_CO2_Exh_Inlet	12.16	10.41	11.1	11.09	11.03	10.65	10.6	10.66	10.14	10.48	10.39	7.63	9.25	10.57	11.05	9.87
P_CO2_Intake_Inlet	14.84	11.7	11.15	11.05	11.03	11.49	11.48	11.23	11.38	11.44	11.22	10.82	11.02	11.15	11.35	11.41
P_Main Sampling_Pump	12.04	10.32	11	11	10.93	10.76	10.51	10.57	10.05	10.35	10.29	7.57	9.17	10.47	10.95	9.79
P_Nox_Inlet	12.14	10.39	11.08	11.08	11.01	10.84	10.58	10.65	10.12	10.47	10.37	7.62	9.24	10.55	11.03	9.88
T_Chiller_Mid_Temp	30.73	30.93	30.84	30.95	30.92	31.02	31.11	31.08	31.13	31.19	31.19	31.11	30.89	30.91	31.06	30.98
T_FID_Post_Filter	152.54	152.6	152.53	152.6	152.21	152.46	152.13	152.07	152.14	152.16	152.35	152.34	152.07	152.28	152.28	152.24
T_Main_Chiller_Impenger1_Outlet	18.66	18.56	18.58	18.55	18.56	18.62	18.74	18.79	18.83	18.86	18.86	18.92	18.87	18.96	19.02	19.03
T_Main_Chiller_Impenger2_Outlet	5.48	5.47	5.47	5.46	5.48	5.48	5.48	5.48	5.49	5.49	5.51	5.51	5.52	5.53	5.53	5.55
T_MainChiller_Inlet	89.42	89.4	89.41	89.38	89.39	89.39	89.38	89.37	89.36	89.33	89.46	89.43	89.49	89.47	89.4	89.38
t_MainChiller_Outlet	18.24	18.31	18.31	18.32	18.3	18.31	18.3	18.34	18.37	18.4	18.39	18.41	18.41	18.46	18.49	18.47
T_NDIR+HCLD_Post_Filter	154.33	154.63	154.77	155.18	154.61	154.87	155.63	154.89	155.19	155.32	154.59	155	155.45	154.94	154.81	155.15
T_Post_HFilter_FID	164.96	165.03	165.08	165.12	165.14	165.21	165.27	165.34	165.21	165.15	165.11	165.06	165	164.98	164.95	164.89
T_Post_HFilter_Main	157.39	157.54	157.64	157.68	157.63	157.62	157.67	157.74	157.73	157.75	157.73	157.58	157.56	157.51	157.53	157.49
T_Sampling_Point	139.05	139.57	139.43	139.22	139.27	139.09	139.21	139.23	139.31	139.21	139.21	139.2	138.96	139.13	139.08	139.02
THC	121.25	121.14	121.12	121.23	121.38	121.41	121.11	120.88	121.3	121.79	121.67	121.88	122.31	122.31	122.28	122.64

Table C.1 : Trial #1 Data Points Acquired on January 26, 2010 - Con't

Signal	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
CO	733.96	737.54	739.96	741.08	736.75	736.75	733.47	735.11	733.43	733.2	732.44	730.21	732.33	730.22	731.26	732.06
CO2_Exh	5.17	5.18	5.17	5.16	5.17	5.17	5.17	5.16	5.17	5.17	5.16	5.18	5.16	5.16	5.16	5.17
CO2_Intake	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.03	1.04	1.04	1.03	1.04
EGR_Chiller_Air	35.46	35.55	35.44	35.48	35.63	35.63	35.59	35.64	35.59	35.6	35.52	35.45	35.49	35.63	35.56	35.68
T_EGR_Chiller_Sample_Inlet	35.76	35.83	35.8	35.8	35.91	35.91	35.89	35.9	35.86	35.89	35.91	35.82	35.8	35.81	35.81	35.93
T_EGR_Chiller_Impenger1_Outlet	2.65	2.68	2.71	2.74	2.52	2.52	2.47	2.3	2.26	2.26	2.29	2.21	2.11	2.04	2.19	1.16
EGR_Chiller_Sample_Outlet	15.46	15.59	15.66	15.7	15.92	15.92	16.01	16.06	16.14	16.26	16.34	16.4	16.49	16.54	16.63	17.25
FID_Sample_Inlet	167.74	167.88	167.61	167.58	167.54	167.54	167.49	167.45	167.41	167.3	167.27	167.18	167.13	167.12	167.16	167.14
Main_Chiller_Air	38	38.24	38.19	38.15	38.32	38.32	38.48	38.26	38.44	38.33	38.37	38.63	38.57	38.49	38.41	38.22
NDIR+HCLD Sample Inlet	33.79	33.82	33.81	33.82	33.87	33.87	33.9	33.91	33.9	33.92	33.94	33.92	33.92	33.92	33.92	33.99
NOx	237.88	237.52	236.96	236.97	237.08	237.08	237.56	237.05	237.29	237.35	237.31	238.17	237.78	238.43	238.44	237.3
P_Back_Pressure	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84
P_CO_Inlet	10.31	10.22	9.62	9.25	9.18	9.18	9.91	10.12	9.91	8.63	8.41	8.91	9.03	6.84	7.83	6.08
P_CO2_Exh_Inlet	10.39	10.3	9.7	9.33	9.26	9.26	9.99	10.2	9.99	8.71	8.49	8.99	9.1	6.92	7.91	6.16
P_CO2_Intake_Inlet	11.42	10.67	10.36	10.43	9.89	9.89	9.38	8.96	8.5	8.2	7.68	7.19	6.73	6.55	6.2	4.96
P_Main Sampling_Pump	10.3	10.21	9.62	9.25	9.19	9.19	9.91	10.11	9.91	8.65	8.43	8.92	9.03	6.87	7.86	6.12
P_Nox_Inlet	10.38	10.28	9.69	9.31	9.25	9.25	9.98	10.19	9.98	8.7	8.48	8.98	9.09	6.91	7.9	6.15
T_Chiller_Mid_Temp	30.89	30.8	30.77	30.85	31.1	31.1	31.05	31.02	31.02	30.94	30.96	31.02	31.04	31.01	31.06	31.01
T_FID_Post_Filter	152.25	152.07	152.22	151.98	152.17	152.17	152.36	152.04	152.43	152.17	152.48	152.19	152.37	152.28	152.62	152.44
T_Main_Chiller_Impenger1_Outlet	19.05	19.07	19.07	19.06	19.1	19.1	19.11	19.07	19.06	19.03	19.03	19.07	19.03	19	19.09	19.09
T_Main_Chiller_Impenger2_Outlet	5.53	5.51	5.52	5.5	5.48	5.48	5.47	5.46	5.47	5.5	5.51	5.51	5.52	5.56	5.57	5.61
T_MainChiller_Inlet	89.46	89.41	89.42	89.41	89.3	89.3	89.45	89.39	89.35	89.34	89.41	89.43	89.3	89.35	89.45	89.06
t_MainChiller_Outlet	18.42	18.4	18.36	18.3	18.38	18.38	18.38	18.4	18.41	18.44	18.4	18.44	18.5	18.49	18.54	18.56
T_NDIR+HCLD_Post_Filter	155.72	155.12	155.03	155.44	155.31	155.31	155.8	155.47	155.01	155.19	155.62	155.71	154.96	154.88	155.31	155
T_Post_HFilter_FID	164.83	164.78	164.77	164.79	164.75	164.75	164.74	164.75	164.77	164.74	164.72	164.71	164.71	164.74	164.74	164.7
T_Post_HFilter_Main	157.48	157.42	157.44	157.51	157.58	157.58	157.61	157.63	157.63	157.57	157.61	157.7	157.67	157.67	157.67	157.5
T_Sampling_Point	139.26	139.27	139.22	138.93	138.68	138.68	138.96	139.06	139.11	139.3	139.02	139.04	138.72	138.51	138.49	138.13
THC	122.79	122.94	123.3	123.97	123.24	123.24	123.59	123.93	123.81	123.96	124.13	124.08	123.81	123.42	122.81	122.36

Table C.2 : Trial #2 Data Points Acquired on January 27, 2010

Signal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
CO	775.28	776.98	777.2	786.55	760.58	774.45	773.82	773.63	771.63	772.28	775.84	781.06	787.31	786.96	780.56	771.84	768.06
CO2_Exh	5.19	5.16	5.09	5.14	5.17	5.18	5.17	5.18	5.17	5.15	5.11	5.12	5.1	5.1	5.13	5.14	5.16
CO2_Intake	1.17	1.15	1.12	1.14	1.15	1.14	1.14	1.14	1.14	1.13	1.12	1.12	1.12	1.11	1.13	1.13	1.15
EGR_Chiller_Air	30.75	30.31	29.04	29.6	30.27	30.61	30.5	30.64	30.69	30.21	29.47	30.02	27.2	27.86	28.88	29.16	31.47
T_EGR_Chiller_Sample_Inlet	30.29	29.77	29.08	29.11	29.28	29.61	29.67	30.05	30.23	30.18	29.86	29.97	27.12	27.5	28.21	28.77	31.43
T_EGR_Chiller_Impenger1_Outlet	1.39	1.54	1.9	1.58	1.6	2.04	2.33	2.11	1.96	1.9	1.9	1.8	-0.36	-0.65	-0.79	-0.91	-1.04
EGR_Chiller_Sample_Outlet	11.28	11.46	11.22	11.13	11.22	11.35	11.57	12.03	12.32	12.75	13.36	13.57	12.7	12.54	12.55	12.53	13.89
FID_Sample_Inlet	159.84	159.95	160.13	159.95	159.94	159.93	159.94	159.95	159.96	160.01	160.06	160.14	160.1	159.69	159.42	159.3	160.08
Main_Chiller_Air	31.43	30.87	30.39	30.41	31.26	31.65	31.79	31.77	31.88	31.6	31.05	31.25	28.77	29.45	30.28	30.81	32.92
NDIR+HCLD Sample Inlet	30.83	30.36	29.5	29.43	29.55	29.73	29.64	29.91	30.04	30.04	29.78	29.63	26.66	26.9	27.48	27.84	30.18
NOx	220.73	220.41	220.74	217.81	217.91	218.96	219.18	219.24	219.62	219.47	219.39	218.12	215.57	215.54	216.06	217.42	218.06
P_Back_Pressure	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84
P_CO_Inlet	14.83	14.78	13.14	15.85	15.73	15.96	15.44	15.24	15.11	15.09	14.97	14.77	14.2	13.38	12.5	11.5	13.54
P_CO2_Exh_Inlet	14.90	14.88	13.24	15.96	15.83	15.67	15.54	15.34	15.21	15.19	15.07	14.67	14.31	13.48	12.59	11.6	14.04
P_CO2_Intake_Inlet	16.31	16.2	16.17	15.69	15.81	15.21	14.26	12.15	10.86	12.78	13.17	11.44	13.35	13.16	12.55	13.03	11.54
P_Main Sampling_Pump	14.8	14.75	13.12	15.9	15.68	15.52	15.39	15.2	15.07	15.06	14.93	14.73	14.16	13.34	12.47	11.49	13.89
P_Nox_Inlet	14.92	14.87	13.23	15.94	15.81	15.65	15.62	15.32	15.19	15.16	15.05	14.85	14.29	13.46	12.56	11.56	14.01
T_Chiller_Mid_Temp	30.91	30.7	30.87	30.84	30.88	30.87	30.86	30.89	30.86	30.91	30.74	30.54	28.56	28.39	28.33	28.36	28.07
T_FID_Post_Filter	112.88	109.13	118.54	117.73	117.02	117.21	116.34	116.49	115.96	113.78	110.2	109.03	98.41	97.77	98.99	100.62	110.91
T_Main_Chiller_Impenger1_Outlet	27.87	27.89	28.19	28.36	28.27	27.98	27.78	27.76	27.5	27.43	27.43	27.41	25.96	25.64	25.37	25.06	21.33
T_Main_Chiller_Impenger2_Outlet	5.53	5.92	6.06	6.07	6.04	5.98	5.92	5.86	5.85	5.86	5.79	5.68	4.26	4.03	3.76	3.53	2.29
T_MainChiller_Inlet	115.04	115.07	116.49	115.19	114.74	114.36	114.07	113.88	113.8	113.72	113.87	113.99	110.41	110.09	109.81	109.35	100.98
t_MainChiller_Outlet	13.21	13.36	13.15	13.43	13.53	13.64	13.72	13.79	13.84	13.83	13.68	13.66	12.32	12.15	12.05	12.06	13.25
T_NDIR+HCLD_Post_Filter	113.39	110.7	119.37	117.75	116.67	116.08	114.54	114.39	113.25	110.81	107.76	107.24	97.95	97.63	99.21	100.38	105.36
T_Post_HFilter_FID	147.78	148.37	148.63	148.38	148.36	148.36	148.44	148.57	148.73	148.63	148.87	148.97	148.71	148.57	148.55	148.89	148.57
T_Post_HFilter_Main	149.27	149.66	149.67	149.56	149.5	149.68	149.81	149.94	150.1	150.18	150.24	150.38	150.13	150.06	150.1	150.13	148.64
T_Sampling_Point	153.33	153.78	153.96	151.32	152.55	153.15	153.46	153.76	153.99	153.54	152.62	152.47	146.64	146.27	146.33	146.27	139.64
THC	123.2	123.95	124.44	125.33	125.45	125.32	125.09	125.18	129.29	125.17	126.52	126.11	126.63	126.38	126.36	125.89	127.36

Table C.2 : Trial #2 Data Points Acquired on January 27, 2010 - Con't

Signal	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
CO	774.5	777.83	781.01	781.29	781.57	776.61	775.36	775.74	777.02	785.15	785.41	783.56	782.47	783.02	780.36	777.4	774.77
CO2_Exh	5.18	5.19	5.19	5.19	5.19	5.17	5.16	5.15	5.15	5.16	5.16	5.16	5.16	5.16	5.19	5.18	5.19
CO2_Intake	1.15	1.15	1.15	1.15	1.15	1.14	1.13	1.13	1.13	1.14	1.14	1.13	1.13	1.13	1.14	1.14	1.14
EGR_Chiller_Air	31.82	31.9	32.05	32.17	32.24	32.11	31.95	31.86	31.82	31.75	31.99	31.86	31.91	32.06	32.49	32.66	32.84
T_EGR_Chiller_Sample_Inlet	31.97	32.22	32.36	32.49	32.63	32.66	32.59	32.53	32.46	32.42	32.59	32.52	32.46	32.57	32.86	33.14	33.34
T_EGR_Chiller_Impenger1_Outlet	-0.49	-0.21	0	0.11	0.18	0.27	0.28	0.53	0.78	0.97	0.98	0.9	0.96	0.98	0.98	1.03	1.08
EGR_Chiller_Sample_Outlet	15.1	15.74	16.12	16.3	16.5	16.74	16.95	17.26	17.75	18.38	18.54	18.67	18.76	18.78	18.89	18.95	19.07
FID_Sample_Inlet	160.33	160.49	160.59	160.71	160.84	160.96	161.04	161.13	161.19	161.32	161.36	161.42	161.4	161.42	161.48	161.56	161.68
Main_Chiller_Air	33.34	33.55	33.64	33.79	33.94	34.04	34.03	33.96	34	33.98	34.02	34.04	33.91	33.95	34.11	34.28	34.37
NDIR+HCLD Sample Inlet	30.75	31.11	31.26	31.45	31.6	31.68	31.69	31.66	31.61	31.59	31.7	31.65	31.57	31.64	31.9	32.1	32.29
NOx	216.96	216.63	216.13	216.81	216.54	218.28	218.4	218.5	217.77	216.45	216.57	217.38	217.22	217.51	218.63	219.13	219.62
P_Back_Pressure	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84
P_CO_Inlet	17.48	16.91	16.91	16.8	16.64	16.97	17.06	17	17.04	17.12	16.9	16.31	14.75	14.39	14.29	14.09	13.82
P_CO2_Exh_Inlet	17.59	17.01	17	16.9	16.94	17.07	17.16	17.1	17.14	17.22	17	16.41	14.85	14.48	14.39	14.18	13.91
P_CO2_Intake_Inlet	15.41	14.3	12.85	12.98	13.21	12.72	12.36	10.57	13.03	18.01	17.75	17.44	16.66	16.56	16.34	16.21	15.96
P_Main Sampling_Pump	17.41	16.84	16.83	16.72	16.77	16.89	16.98	16.92	16.97	17.04	16.82	16.24	14.7	14.33	14.24	14.04	13.77
P_Nox_Inlet	17.57	16.99	16.96	16.87	16.92	17.04	17.14	17.08	17.12	17.19	16.97	16.38	14.83	14.46	14.37	14.16	13.89
T_Chiller_Mid_Temp	28.37	28.35	28.29	28.28	28.29	28.3	28.29	28.26	28.25	28.37	28.28	28.19	28	27.99	27.97	28.05	28.12
T_FID_Post_Filter	113.65	113.06	113.31	113.36	113.15	112.13	110.48	109.28	108.08	106.72	107.07	105.84	105.26	105.61	107.82	109.11	110.41
T_Main_Chiller_Impenger1_Outlet	20.98	20.53	20.36	20.22	20.02	19.92	19.81	19.73	19.64	19.54	19.49	19.15	19.05	19.01	18.98	18.96	18.97
T_Main_Chiller_Impenger2_Outlet	2.3	2.29	2.27	2.25	2.24	2.26	2.28	2.31	2.34	2.37	2.42	2.44	2.45	2.44	2.42	2.42	2.44
T_MainChiller_Inlet	97.79	96.89	96.67	96.5	96.39	96.27	96.17	96.07	96.03	96.01	96.08	95.82	95.43	95.46	95.57	95.66	95.68
t_MainChiller_Outlet	13.74	13.93	14	14.06	14.13	14.21	14.29	14.34	14.37	14.41	14.42	14.48	14.51	14.56	14.61	14.66	14.74
T_NDIR+HCLD_Post_Filter	106.75	105.56	105.72	105.73	105.41	104.19	102.85	101.81	100.9	99.63	100.11	98.81	98.43	99.03	101.51	102.49	103.63
T_Post_HFilter_FID	148.72	148.82	148.92	149.02	149.12	149.21	149.26	149.3	149.38	149.52	149.54	149.39	149.46	149.45	149.46	149.34	149.65
T_Post_HFilter_Main	148.44	148.28	148.15	148.06	148.07	148.11	148.13	148.2	148.15	148.09	148.09	148.04	147.82	147.8	147.71	147.67	147.68
T_Sampling_Point	138.34	138.12	138.3	138.34	138.42	138.09	137.57	137.26	136.94	136.42	136.38	135.9	134.97	135.11	135.68	136.04	136.53
THC	127.17	127.62	128.16	128.5	128.73	127.96	127.62	127.64	127.91	128.66	129.27	130	130.89	130.78	129.48	128.5	128.03

Table C.2 : Trial #2 Data Points Acquired on January 27, 2010 - Con't

Signal	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
CO	772.02	773.09	772.94	774.79	776.63	775.44	766.13	769.13	776.67	777.96	779.48	780.67	777.08	769.05	767.07	768.42	770.33
CO2_Exh	5.18	5.17	5.17	5.18	5.18	5.16	5.18	5.16	5.17	5.18	5.18	5.17	5.16	5.17	5.18	5.19	5.19
CO2_Intake	1.14	1.14	1.13	1.13	1.13	1.12	1.13	1.12	1.13	1.13	1.13	1.12	1.12	1.12	1.12	1.13	1.13
EGR_Chiller_Air	32.86	32.69	32.71	32.83	32.57	32.69	32.71	32.29	32.5	32.69	32.74	32.65	32.72	32.86	33.27	33.4	33.39
T_EGR_Chiller_Sample_Inlet	33.43	33.43	33.4	33.47	33.39	33.36	33.4	33.22	33.16	33.3	33.37	33.42	33.41	33.48	33.76	33.95	34.01
T_EGR_Chiller_Impenger1_Outlet	1.13	1.18	1.24	1.26	1.26	1.29	1.36	1.36	1.37	1.37	1.4	1.36	1.37	1.35	1.39	1.48	1.5
EGR_Chiller_Sample_Outlet	19.13	19.21	19.26	19.28	19.34	19.36	19.43	19.43	19.44	19.49	19.54	19.64	19.67	19.71	19.85	19.96	20
FID_Sample_Inlet	161.75	161.8	161.86	161.91	161.91	161.93	161.91	160.55	159.83	159.88	160.07	160.48	160.62	160.79	161.08	161.21	161.48
Main_Chiller_Air	34.5	34.53	34.48	34.53	34.62	34.47	34.7	34.52	34.49	34.66	34.7	34.75	34.69	34.72	34.83	34.94	35.04
NDIR+HCLD Sample Inlet	32.39	32.4	32.4	32.44	32.35	32.34	32.38	32.21	32.16	32.25	32.3	32.36	32.38	32.44	32.7	32.84	32.91
NOx	219.83	220.13	219.76	218.82	218.62	219.01	220.93	221.48	219.5	219.38	219.58	219.3	219.39	220.45	221.44	222.05	222.2
P_Back_Pressure	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84
P_CO_Inlet	13.41	13.2	12.96	17.45	18.16	17.76	17.42	17.04	16.76	15.92	15.64	15.42	15.32	15.16	14.77	14.49	14.3
P_CO2_Exh_Inlet	13.51	13.3	13.06	17.58	18.26	17.86	17.52	17.14	16.86	16.02	15.74	15.52	15.42	15.28	14.87	14.58	14.39
P_CO2_Intake_Inlet	15.88	15.51	15.17	15.23	15.58	15.77	15.71	15.8	15.36	14.95	14.66	14.17	13.86	13.68	13.51	13.19	13.22
P_Main Sampling_Pump	13.37	13.17	12.93	17.37	18.07	17.67	17.33	16.97	16.69	15.85	15.57	15.36	15.26	15.12	14.71	14.43	14.24
P_Nox_Inlet	13.49	13.28	13.04	17.54	18.24	17.83	17.49	17.12	16.84	16	15.71	15.5	15.39	15.26	14.85	14.57	14.37
T_Chiller_Mid_Temp	28.2	28.28	28.3	28.72	28.62	28.65	28.59	28.53	28.42	28.29	28.25	28.17	28.1	28.05	27.96	27.98	28.04
T_FID_Post_Filter	110.59	110.09	110.22	111	110.15	110.44	110.46	108.91	108.64	109.09	109.11	108.49	108.37	108.55	111.82	113.04	113.1
T_Main_Chiller_Impenger1_Outlet	18.98	18.96	18.97	18.88	18.64	18.34	18.09	17.9	17.59	17.29	17.12	16.87	16.75	16.64	16.58	16.55	16.54
T_Main_Chiller_Impenger2_Outlet	2.47	2.49	2.55	2.69	2.77	2.8	2.8	2.81	2.83	2.81	2.84	2.84	2.86	2.84	2.83	2.83	2.86
T_MainChiller_Inlet	96.8	96.47	96.37	92.63	90.64	90.2	89.93	89.61	89.45	89.24	89.19	89.13	89.11	89.14	89.23	89.21	89.16
t_MainChiller_Outlet	14.83	14.91	14.97	15.4	15.7	15.76	15.83	15.88	15.9	15.96	16	16.05	16.05	16.05	16.06	16.1	16.13
T_NDIR+HCLD_Post_Filter	103.92	103.2	102.97	103.34	102.3	102.67	102.72	101.25	101.22	101.46	101.39	100.6	100.48	100.79	103.94	105.19	105.08
T_Post_HFilter_FID	149.68	149.73	149.7	149.66	149.52	149.66	149.68	149.69	149.74	149.68	149.71	149.75	149.79	149.75	149.7	149.64	149.67
T_Post_HFilter_Main	147.77	147.64	147.76	147.57	147.47	147.5	147.59	147.73	147.78	147.86	147.98	147.94	147.91	147.87	147.75	147.76	147.88
T_Sampling_Point	136.58	136.33	136.08	134.41	132.84	132.35	132.25	131.58	131.25	131.28	131.11	130.86	130.54	131.01	131.79	132.09	132.36
THC	127.39	127.16	127.01	127.17	127.31	127.44	127.01	125.75	125.83	125.94	126.34	126.42	126.37	126.41	126.67	126.06	125.44

Table C.2 : Trial #2 Data Points Acquired on January 27, 2010 - Con't

Signal	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68
CO	774.36	773.53	773.92	765.62	769.03	771.59	776.73	774.36	776.24	768.36	766.31	767.5	774.43	777.74	779.71	778.53	779.21
CO2_Exh	5.17	5.19	5.18	5.17	5.16	5.16	5.16	5.18	5.18	5.18	5.17	5.17	5.15	5.16	5.16	5.17	5.17
CO2_Intake	1.12	1.12	1.12	1.12	1.11	1.12	1.11	1.12	1.12	1.12	1.12	1.12	1.11	1.11	1.11	1.12	1.12
EGR_Chiller_Air	33.17	33.3	33.35	33.39	33.09	33.32	33.34	33.47	33.41	33.44	33.41	33.45	33.03	33.14	33.29	33.45	33.36
T_EGR_Chiller_Sample_Inlet	33.96	33.98	34.01	34.05	34.03	33.94	34.02	34.02	34.11	34.16	34.14	34.2	34.05	33.96	33.98	34.07	34.13
T_EGR_Chiller_Impenger1_Outlet	1.56	1.56	1.6	1.67	1.67	1.75	1.68	1.65	1.67	1.73	1.77	1.77	1.76	1.81	1.74	1.75	1.72
EGR_Chiller_Sample_Outlet	20.07	20.1	20.13	20.18	20.27	20.57	20.52	20.54	20.68	20.75	20.76	20.86	20.83	20.86	20.86	20.9	20.9
FID_Sample_Inlet	161.64	161.71	161.83	161.93	161.93	161.36	162.07	162.14	162.26	162.29	162.27	162.19	162.07	162.07	162.06	162.09	162.14
Main_Chiller_Air	35.02	35	35.04	35.05	34.92	34.83	34.83	34.97	35.03	35.08	35.01	35.1	34.86	34.91	34.88	35.01	35.03
NDIR+HCLD Sample Inlet	32.89	32.92	32.96	33	32.95	32.53	32.93	32.91	32.98	33.06	33.06	33.12	32.96	32.95	32.95	33.06	33.06
NOx	221.45	221.22	221.08	222.74	222.5	221.47	221.27	220.88	220.91	221.83	222.34	221.44	220.53	220.29	217.18	218.73	221.97
P_Back_Pressure	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84
P_CO_Inlet	13.91	13.61	13.33	12.7	11.91	12.53	12.4	11.5	11.14	10.16	9.36	9.37	9.38	8.88	6.91	6.09	6.19
P_CO2_Exh_Inlet	14.01	13.7	13.42	12.79	12	12.63	12.49	11.58	11.22	10.25	9.44	9.45	9.46	8.96	6.99	6.17	6.27
P_CO2_Intake_Inlet	12.97	12.86	12.86	12.73	11.57	17.4	16.46	16.19	16.07	15.93	15.73	16.6	16.57	15.41	15.28	15.18	15.18
P_Main Sampling_Pump	13.87	13.56	13.29	12.56	11.88	12.5	12.36	11.47	11.12	10.15	9.36	9.37	9.38	8.88	6.94	6.12	6.22
P_Nox_Inlet	13.99	13.68	13.41	12.77	11.98	12.61	12.47	11.57	11.21	10.23	9.43	9.44	9.45	8.95	6.96	6.16	6.26
T_Chiller_Mid_Temp	28.11	28.1	28.11	28.15	28.08	28.05	28.02	27.91	27.96	27.93	27.95	27.92	27.88	27.8	27.69	27.62	27.63
T_FID_Post_Filter	112.49	112.78	113.05	112.9	112.41	113.6	115.52	117.85	117.53	117.31	117.25	117.23	116.93	115.22	116.65	117.58	117.4
T_Main_Chiller_Impenger1_Outlet	16.5	16.45	16.42	16.42	16.45	16.41	16.33	16.29	16.14	16.07	16.01	15.91	15.84	15.79	15.74	15.67	15.59
T_Main_Chiller_Impenger2_Outlet	2.85	2.85	2.88	2.9	3.01	2.97	3.01	3.03	3.06	3.05	3.06	3.07	3.1	3.06	3.11	3.09	3.09
T_MainChiller_Inlet	89	88.98	88.97	88.91	88.82	88.49	88.33	88.17	88.09	87.98	87.95	87.98	87.84	87.8	87.45	87.58	87.66
t_MainChiller_Outlet	16.21	16.22	16.25	16.3	16.27	16.36	16.29	16.36	16.34	16.44	16.44	16.49	16.47	16.45	16.46	16.52	16.51
T_NDIR+HCLD_Post_Filter	104.05	104.47	104.54	104.34	103.74	104.7	106.55	108.31	108.29	107.81	107.23	107.16	105.54	104.96	105.65	107.61	107.14
T_Post_HFilter_FID	149.73	149.76	149.81	149.76	149.54	149.62	149.5	149.64	149.71	149.81	149.86	149.88	149.88	149.9	149.9	149.91	149.96
T_Post_HFilter_Main	148.02	148.14	148.04	148.03	148.04	148.02	148	148.11	148.22	148.34	148.32	148.38	148.41	148.43	148.5	148.51	148.6
T_Sampling_Point	131.91	131.99	131.91	131.67	131.08	130.63	130.24	130.82	131.19	131.24	131.09	131.03	130.47	129.94	129.75	129.92	129.77
THC	125.3	125.25	125.2	125.04	124.91	125.37	125.71	126.19	126.42	126.16	126.02	126.33	126.94	127.5	127.7	127.73	127.71

Table C.2 : Trial #2 Data Points Acquired on January 27, 2010 - Con't

Signal	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85
CO	774.73	771.58	772.31	774.13	777.96	779.09	773.54	772.68									
CO2_Exh	5.15	5.14	5.16	5.15	5.15	5.16	5.16	5.17									
CO2_Intake	1.11	1.1	1.11	1.11	1.11	1.11	1.11	1.12									
EGR_Chiller_Air	33.31	33.2	33.18	33.07	33.13	33.38	33.55	33.62									
T_EGR_Chiller_Sample_Inlet	34.11	34.04	34.04	33.96	33.95	34.01	34.13	34.2									
T_EGR_Chiller_Impenger1_Outlet	1.68	1.68	1.71	1.68	1.67	1.71	1.72	1.76									
EGR_Chiller_Sample_Outlet	20.88	20.88	20.89	20.9	20.93	20.97	21.02	21.1									
FID_Sample_Inlet	162.16	162.28	161.02	160.27	160.29	160.6	160.97	161.38									
Main_Chiller_Air	35.02	34.88	34.92	34.83	34.88	34.82	34.93	35.07									
NDIR+HCLD Sample Inlet	33.06	32.98	32.98	32.92	32.9	32.97	33.07	33.16									
NOx	220.91	221.75	222.03	221.48	220.72	219.94	220.76	220.77									
P_Back_Pressure	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84	-0.84									
P_CO_Inlet	6.8	6.67	7.35	7.63	7.63	7.38	5.92	6.63									
P_CO2_Exh_Inlet	6.68	6.75	7.43	7.71	7.71	7.54	7	6.71									
P_CO2_Intake_Inlet	15.19	15.18	15.11	15.06	15.05	15.06	15.01	15									
P_Main Sampling_Pump	6.63	6.7	7.37	7.65	7.65	7.58	6.95	6.66									
P_Nox_Inlet	6.68	6.74	7.42	7.7	7.7	7.63	6.99	6.7									
T_Chiller_Mid_Temp	27.54	27.59	27.54	27.48	27.54	27.45	27.41	27.4									
T_FID_Post_Filter	117.49	117.01	116.66	116.21	115.89	117.93	119.52	119.76									
T_Main_Chiller_Impenger1_Outlet	15.54	15.49	15.49	15.51	15.52	15.52	15.53	15.51									
T_Main_Chiller_Impenger2_Outlet	3.09	3.11	3.11	3.12	3.11	3.1	3.1	3.1									
T_MainChiller_Inlet	87.69	87.63	87.71	87.69	87.7	87.81	87.73	87.79									
t_MainChiller_Outlet	16.51	16.5	16.5	16.49	16.49	16.49	16.53	16.57									
T_NDIR+HCLD_Post_Filter	106.88	106.14	106.06	105.61	105.51	107.53	109.43	110.63									
T_Post_HFilter_FID	150.06	150.16	150.22	150.34	150.38	150.46	150.53	150.53									
T_Post_HFilter_Main	148.67	148.77	148.8	148.75	148.77	148.82	148.95	149.11									
T_Sampling_Point	129.71	129.44	129.34	129.28	129.33	129.52	129.99	130.4									
THC	127.85	127.32	126.5	127.07	127.03	127.59	127.51	127.63									

Table C.3: Gas Divider Data for The CAI Exhaust Analyzers

Span Gas -->	THC (ppmC1)		NOx (ppm)		CO_2_Exh (% vol.)		CO_2_EGR (% vol.)		CO (ppm)	
% Span	Span Value	Actual	Span Value	Actual	Span Value	Actual	Span Value	Actual	Span Value	Actual
0	0	7.8	0	0.5	0	0	0	0	0	0.5
10	46.8	53.2	96.7	93.8	0.904	0.88	0.904	0.86	96.7	93.8
20	93.6	97.8	193.4	189.2	1.808	1.76	1.808	1.78	193.4	189.2
30	140.4	142.3	290.1	286.3	2.712	2.66	2.712	2.65	290.1	286.3
40	187.2	187.2	386.8	382	3.616	3.54	3.616	3.54	386.8	382
50	234	233.2	483.5	477.6	4,52	4.43	4.52	4.42	483.5	477.6
60	280.8	280.4	580.2	574.8	5.424	5.33	5.424	5.32	580.2	574.8
70	327.6	327	676.9	671.4	6.328	6.23	6.328	6.23	676.9	671.4
80	374.4	374.3	773.6	770.4	7.232	7.17	7.232	7.17	773.6	770.4
90	421.2	420.8	870.3	869.8	8.136	8.12	8.136	8.1	870.3	869.6
100	468	468	967	967	9.04	9.06	9.04	9.05	967	967

APPENDIX D: Test Engine Specifications

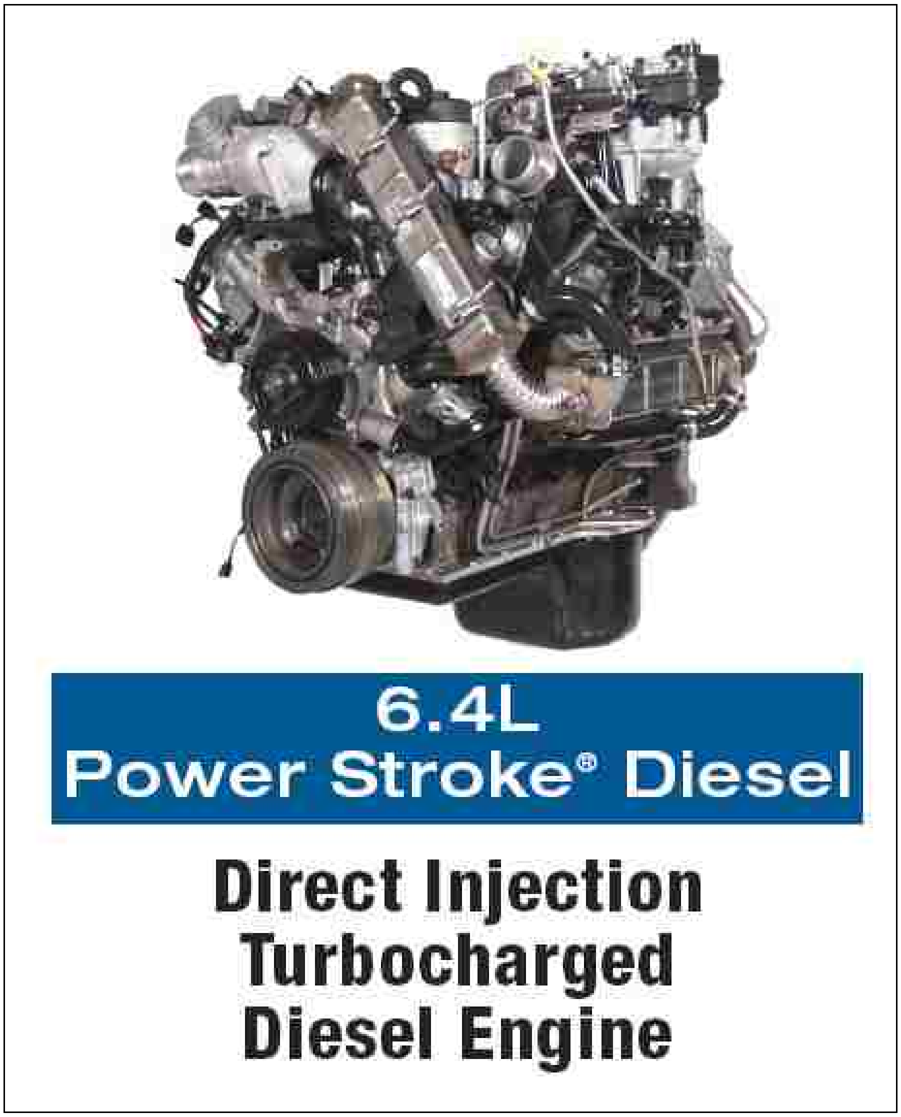


Figure D.1: ITEC 6.4L V8 Diesel Engine [6]

Table D.1: ITEC 6.4L V8 Diesel Engine Specifications [6]

6.4L POWER STROKE® DIESEL OVERVIEW

6.4L Power Stroke Diesel Specifications

Engine Type	Diesel, 4 Cycle
Configuration	4 OHV/1 Cam-In-Crankcase-V8
Displacement	390 cu. in. (6.4L)
Bore & Stroke	3.87 X 4.134 (98.2 X 105 mm)
Compression Ratio	17.5:1
Aspiration	Series Sequential Turbo with CAC
Rated Power @ RPM	350 @ 3000 RPM
Peak Torque @ RPM	650 @ 2000 RPM
Engine Rotation, Facing Flywheel	Counter Clockwise
Combustion System	High Pressure Common Rail Direct Injection
Total Engine Weight (auto with oil)	1130 lb. (486.85 kg)
Coolant Flow (to radiator)	125 gal/min (473 L/min) @ 3000 RPM
Air Flow @ RPM (compressor inlet)	744 CFM (21.1 m3/min) @ 3000 RPM
Exhaust Flow @ RPM (engine outlet)	1962 CFM (55.6 m3/min) @ 3000 RPM
Oil Flow @ RPM	13 gal/min (50 L/min) @ 3000 RPM
Cooling System Capacity (engine only)	25.3 qts (24 L)
Lube System Capacity (including filter)	15 qts. (14.2 L)
Firing Order	1-2-7-3-4-5-6-8

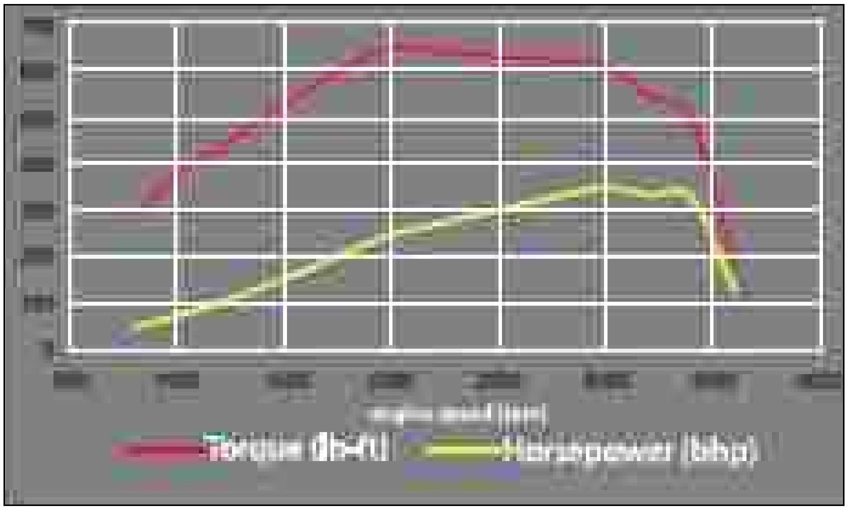


Figure D.2: 6.4L Diesel Engine Power & Torque Curves [6]

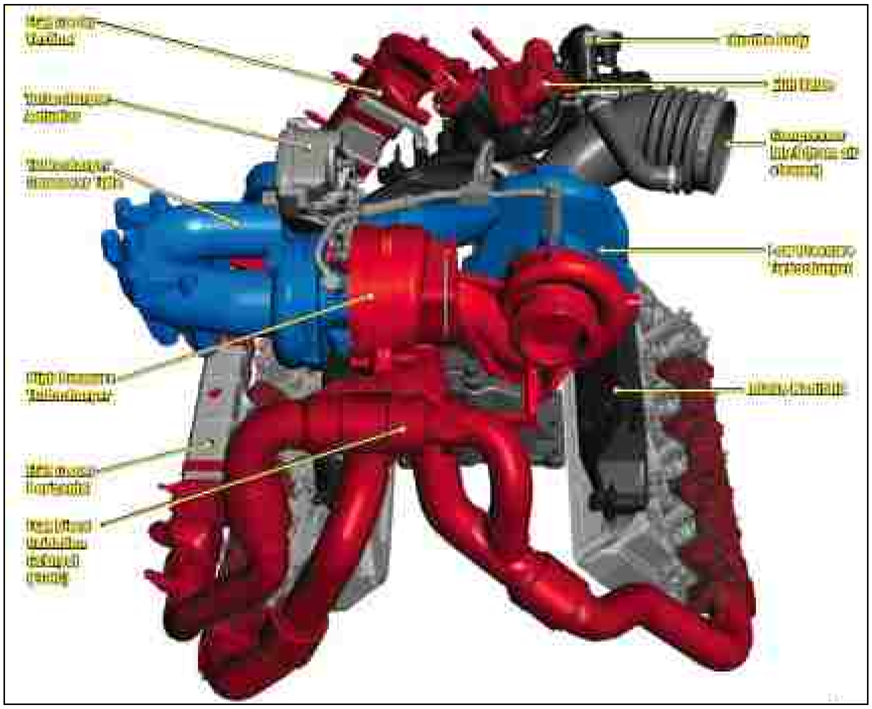


Figure D.3: Air Management System [6]

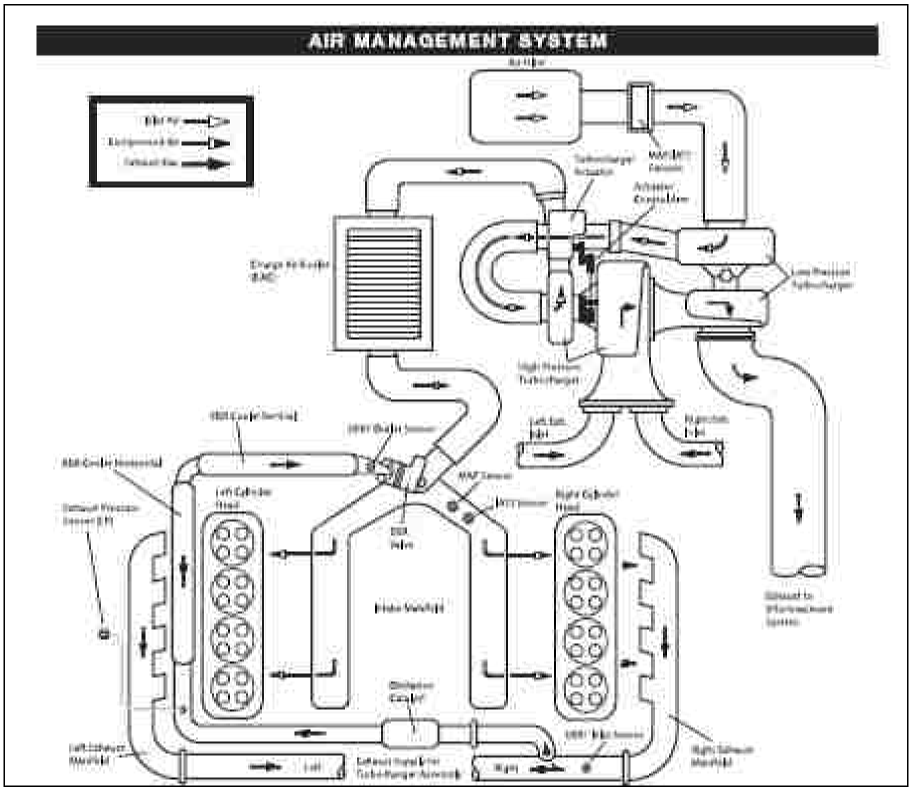
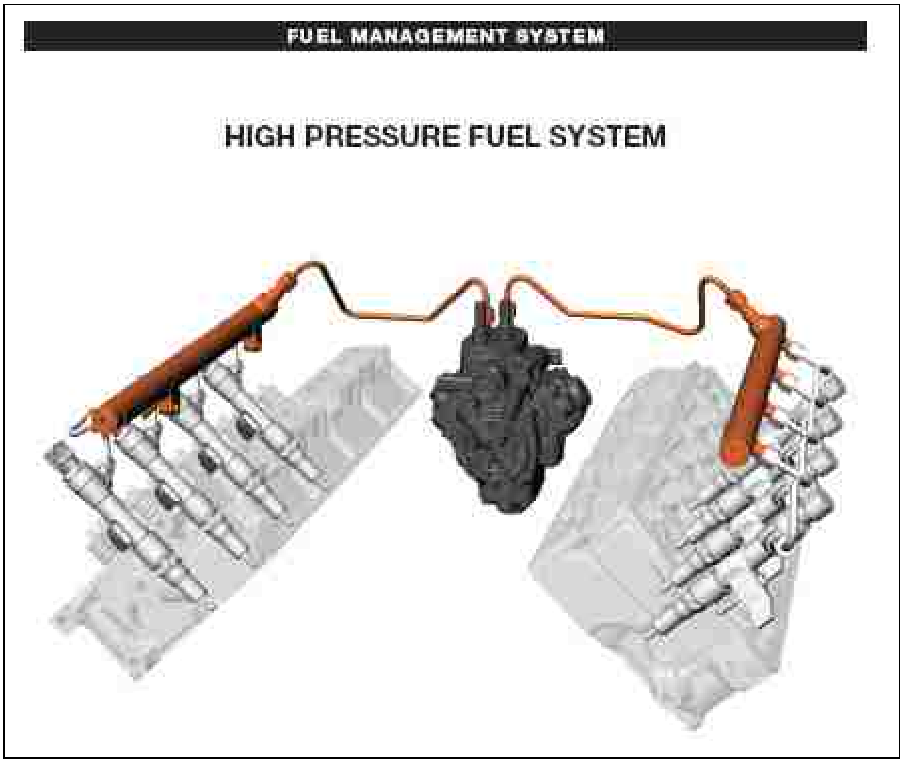


Figure D.4: Engine Air Flow [6]



FUEL MANAGEMENT SYSTEM

HIGH PRESSURE FUEL SYSTEM

Figure D.5: Fuel Injection System [6]

VITA AUCTORIS

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