

QUALITY ASSURANCE PROJECT PLAN FOR A RUMINANT EMISSION
MEASUREMENT SYSTEM

BY

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THESIS

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Abstract

Ruminant animals produce methane through metabolic processes, with implications for production efficiency and contributions to atmospheric accumulation of greenhouse gases. A Ruminant Emission Measurement System (REMS) was designed, constructed and tested at the Metabolism Unit of the Beef Cattle and Sheep Field Laboratory at the University of Illinois at Urbana-Champaign to quantify these emission rates for varying dietary components. REMS is a hyperbaric positive-pressure ventilated hood-type open-circuit respiration chamber system and measures and compares instantaneous methane concentrations between gas entering and exiting a chamber in order to calculate emission rate produced by beef cattle. A series of pumps, sampling tubes, solenoids, connections and chambers are utilized in the measuring process, and therefore many opportunities for dilution or leakage exist. Quality control is crucial in the application of this system to ensure the reliability of the emissions measurements, and a Quality Assurance Project Plan (QAPP) was developed to ensure consistency and reliability during testing. The QAPP presented in this document includes an introduction to all components within this system, quality control tests for each of those components, and general guidelines on the use and maintenance of the system. The document is arranged in four sections followed by the appendix, arranged in chapters for this thesis.

The first chapter provides a general introduction to this document, including a description of a Quality Assurance Project Plan and its implementation.

The second chapter gives a general description of the system that was constructed, including all the components that make up this system and their functionality. The components include: the gas sampling multiplexer for switching between and directing gas samples to the analyzer; six

orifice meters for measuring and controlling ventilation rates; six individual chambers, in each of which the head of one animal is placed during monitoring; a Heating, Ventilating and Cooling (HVAC) system for maintaining comfortable temperature and humidity inside the chambers; the gas analyzer; and system control software.

The third chapter focuses on quality assurance tests that were done in order to validate the performance of each component. One crucial assumption for the system operation is that the chamber and other components do not allow inward leakage to occur, thus a leakage test was conducted on the multiplexer, each chamber and the sampling line. In order to show that the chambers maintain positive pressure during test conditions, an internal pressure map was conducted. A calibration was completed for the orifice meters to ensure reliability of ventilation measurements. A calibration was also completed for the gas analyzer to ensure reliability of gas concentration measurement. A tracer-gas recovery test was conducted to validate the performance of the overall system for measuring generation of gas within each chamber.

The fourth chapter covers usage and related topics, including the necessary preparations before a test, physical or remote monitoring during a test and data analysis upon concluding a test.

General maintenance issues are also discussed and should be followed closely to ensure the well-being of the equipment and integrity of data collected during experiments.

The appendices cover specific instructions on using the system control software, conducting a multiplexer leakage test, calibrating the gas analyzer, conducting a system evaluation test, conducting a system performance test, preparations for experiments and operation of the building ventilation system.

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Chapter 1: Thesis Introduction

1.1 Quality Assurance Overview

A Quality Assurance Project Plan (QAPP) documents the design, construction and testing procedures for a project, including quality assurance steps to ensure the system behaves according to design. It integrates all the technical and quality aspects of the project in order to provide a "blueprint" for obtaining the type and quality of data and information needed for a specific decision or use. In addition to the proper usage of the system, regular maintenance issues are also discussed and should be closely followed.

A QAPP is necessary for any innovative system that requires special attention to its design, use and maintenance. It will contain important information regarding the proper usage and handling of equipment. It will be used by all the people that might work with any piece of the system, regardless of how minor their role is. It will also be used by people who may need to duplicate all or part of the system for a different project, maybe even implement changes or improvements to the system in order to suit their project goals.

Having a complete, precise and accurate QAPP will reduce time, cost and labor in the operation of the system. Users of the current system will have the resource to ensure uniformity in system operations and produce valid results on each trial. The information presented here can serve as a foundation on which to base new procedures for validating similar systems. For the users of other systems, parts of this document contains several Standard Operating Procedures (SOPs) for implementing this system in a completely separate application, as most of the quality assurance steps will be similar.

Previous implementations of quality assurance documents for ruminant emissions show specific conditions at which the experiments were conducted, however they do not show the underlying basis for how a QAPP should be presented (Johnson et al., 2007).

This document was prepared with the help of A Quality Assurance Project Plan for Monitoring Gaseous and Particulate Matter Emissions from Boiler Housing (Moody et al., 2008).

1.2 Organizational Introduction

This document was prepared for conducting experiments using the REMS with live animals. Chapter 2 outlines the components that are contained in REMS. Chapter 3 outlines the Quality Assurance (QA) tests that were conducted to validate the measurements of REMS. Chapter 4 outlines general maintenance issues associated with keeping each component of REMS at experimental conditions.

Chapter 2: Ruminant Emission Measurement System Components

2.1 System Description

A Ruminant Emission Measurement System (REMS) was conceptualized, designed, and assembled in the animal metabolism laboratory located at the University of Illinois Beef/Sheep Research Facility. The REMS is a state of the art greenhouse gas measurement system that will be used for quantification of methane emissions from enteric fermentation in beef cattle, and to evaluate nutrition, genetics, and management strategies on those emissions. Previous work has indicated enteric emissions are greatly affected by animal diet and genetics (Smith et al., 2007). The complete REMS consists of six main subsystems: a Gas Sampling Subsystem (GSS), a Fresh Air Supply and Measurement Subsystem (FASMS), a Thermal Environmental Controller Subsystem (TECS), six Ventilated Hood Chambers, an Infrared Photoacoustic Spectroscopy (IR-PAS) Multi-Gas analyzer, and Instrument Control Subsystem (ICS). Figure 2.1 is an operational schematic showing how each component interconnects with the others.

Within the GSS, a multiplexer was designed and constructed to allow sampling from seven locations (six chambers and the background) to be directed to a single gas analyzer (Section 2.2) by switching each solenoid between routing air flow to the analyzer or exhausting to the building. The system control software controls a relay to energize the solenoids as needed to sequentially switch to the desired sample.

Within the FASMS, in order to provide a stable, known air flow into the six metabolic chambers, low-cost orifice meters were designed, calibrated, and implemented to measure the supply ventilation into each chamber (Ramirez et al., 2013). The orifice meters were designed using the

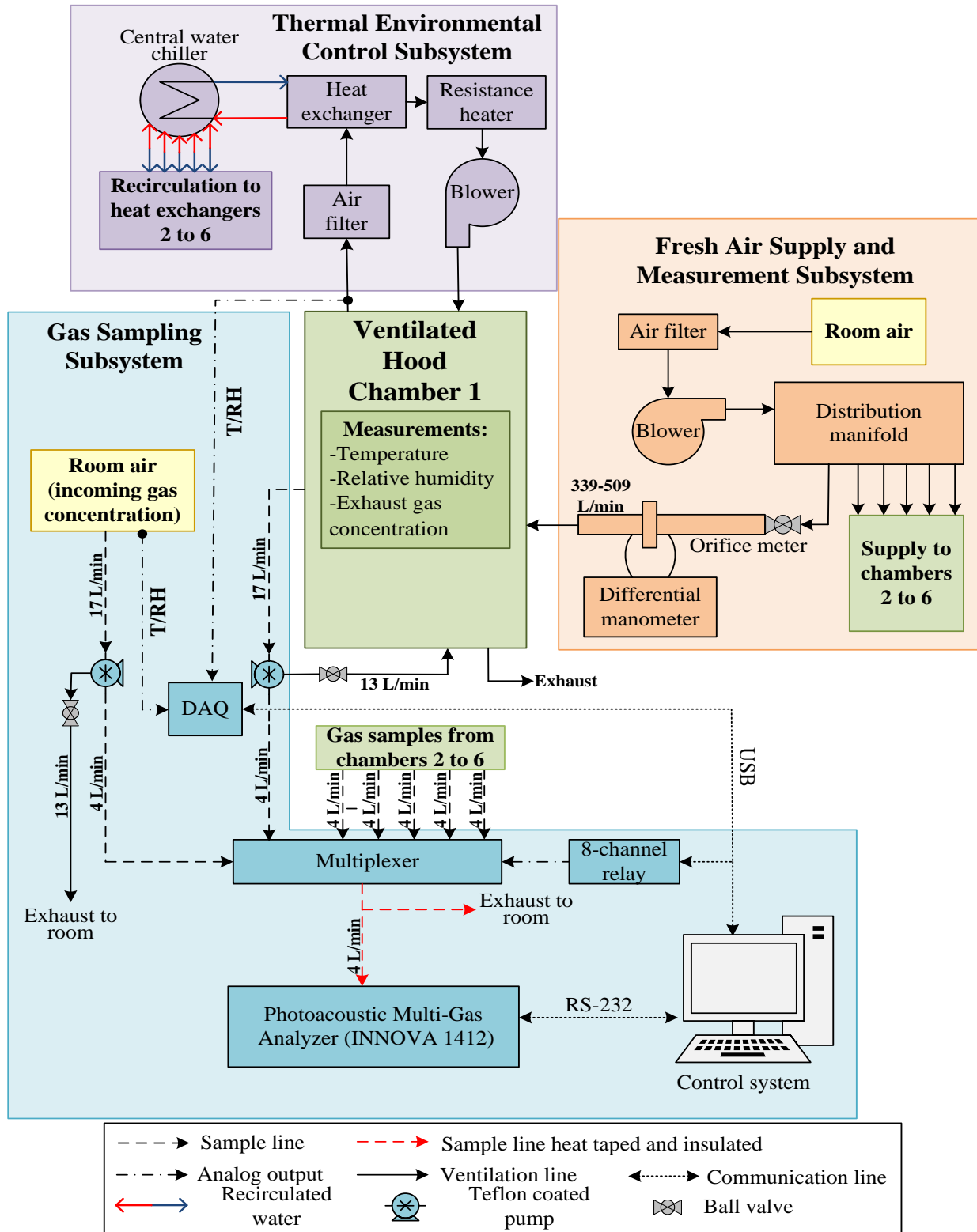


Figure 2.1: Schema of the Ruminant Emission Measurement System with a detailed breakdown for one chamber. Five more identical chambers are part of the complete system. Each chamber has an individual Chamber Air Conditioning Unit. Cold water is supplied by a common water chiller, and all orifice meters are supplied by a common blower.

existing ventilation system and provide precise ventilation rates (Section 2.3). Bernoulli's principle was the underlying basis for the design of these orifices; as a measureable pressure drop occurs as air passes through a sudden reduction in cross sectional area (Rhinehart et al., 2011).

Within the TECS, six individual Chamber Air Conditioning Units (CACU) condition the air within each chamber and provide comfortable air temperature and humidity in the chambers for the animals during emissions monitoring. Temperature and relative humidity are also recorded for use in emission rate calculations (Section 2.4).

The Ventilated Hood Chambers of the REMS provide an enclosed space for the animal's head which captures the gases generated by eructation and respiration (Section 2.5). The animal is secured by an existing stanchion in the building. Animals have the ability to stand up or lie down, eat and drink, but restrict movement while in the stanchion. A canvas hood attaches to the opening of the chamber and secures around the animal's neck to keep eructated gases inside the chamber space.

An IR-PAS multi-gas analyzer accurately measures and records methane concentration (Section 2.6). Our specific model was chosen for this application because of its accuracy, ability to simultaneously read multiple gases and minimal maintenance requirements compared to other gas analyzers.

The ICS developed using LabVIEW controls the switching of solenoids, records data from the temperature/relative humidity sensor and concentrations from the gas analyzer and calculates emission rates. The PC containing LabVIEW is connected to the data acquisition unit and relay

inside the multiplexer via USB and the gas analyzer via RS-232. It serves as the central control unit for operating the REMS and recording data.

2.2 Gas Sampling Subsystem (Multiplexer)

2.2.1 Approach

The following section documents the overall design parameters of the Gas Sampling Subsystem. Section 2.2.2 covers specific details regarding the components.

The multiplexer directs air samples from the chambers to the gas analyzer for gas concentration analysis, and is necessary because there are six chambers plus a background sample but only one analyzer. The multiplexer consists of a series of seven solenoid valves, one for each chamber and one for the background, with stainless-steel tubing connections. Each solenoid is wired such that the normally-open (NO) end leads to the exhaust while the normally-closed end leads to the gas analyzer. In this setting, the de-energized solenoid will direct the gas samples back to the building and the energized solenoid will direct the gas samples to be analyzed. Relays 1 through 6 are connected to the six 3-way solenoid valves corresponding to the 6 chambers. Relay 7 switches the solenoid collecting the background air sample. The multiplexer also houses an USB-based 8-channel relay to control the solenoids, a 9V, 1A regulated power source for the relay and a Data Acquisition Unit (DAQ) for receiving temperature and relative humidity levels. The relay provides eight single-pole double-throw (SPDT) Form C electromechanical relays. The relay operates on 5V DC power while everything else runs on AC, thus requiring a power supply to convert AC to DC. The DAQ sends the temperature and relative humidity to the software which displays the information on the computer screen and saves it to a data file. Only one solenoid should be activated at a time, since the air from only one chamber or the background can be analyzed. The background is sampled after each chamber to obtain a background concentration with which to calculate emission rate.

From the multiplexer, a single sample is routed to the analyzer. The sample line is split, with one line connected to the analyzer and the other exhausted to the equipment room. A rotameter attached to the exhaust measures the exhausted flow rate, typically around 4.0 lpm when the analyzer is not sampling (all solenoids closed). A reading of 2.0 lpm and above should be read when the analyzer is sampling to guarantee sufficient air flow to the analyzer. Under normal experiment conditions, an excess amount of air is pumped from the chambers to ensure that sufficient sample is available to the analyzer.

From each chamber, the air is drawn through a vacuum/pressure pump and directed through Teflon tubing to its respective solenoid valve. The pump is located on the inlet side of the multiplexer to create a positive pressure from the pump to the gas analyzer. Under this arrangement, if a leak occurs, it will not be a source of dilution. The only potential source of leakage is at the connection fitting between sampling inlet and the pump, which is under negative pressure. This crucial point should be tested for leakage coherent with the general maintenance issues discussed in Section 4.1, before every recovery test. Figure 2.2 demonstrates the layout of the multiplexer for routing the air samples from each chamber. The system control software controls relays inside the multiplexer unit to determine which solenoid to activate.

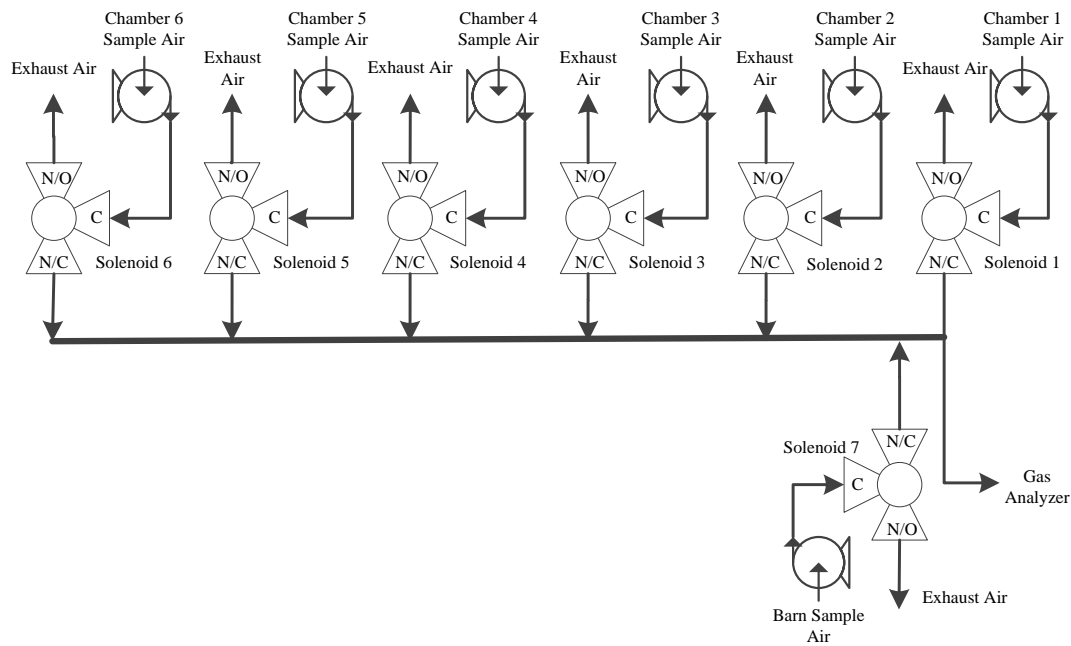


Figure 2.2: Multiplexer schematic showing components inside multiplexer for directing gas samples to the gas analyzer, including relay, power supply for relay, data acquisition unit and solenoids. Direction of gas flow is indicated by arrows, while solenoid positions are depicted with N/O (normally open), N/C (normally closed) and C (common).

2.2.2 Construction and Instrumentation

A sealed plastic enclosure (J Box Type 4X, QR Clear Cover, Hoffman Inc., Anoka, MN) measuring 584 mm x 400 mm x 184 mm (23" x 15-3/4" x 7-1/4"), houses the solenoids (Type 0330, Burkert, Ingelfingen, Germany, Figure 2.3), relay (USB-ERB08, Measurement



Figure 2.3: 3-way Solenoid Type 0330 (Image taken from <http://www.bermad.com/product/product=3-way-solenoid-valve-ww/cat=54118>, 2013).

Computing, Norton, MA), relay power source (Condor GLC40, SL Power Electronics Corp., Ventura, CA) and data acquisition unit (USB-1608G Series, Measurement Computing, Norton, MA). A series of 22.2mm (7/8") nominal diameter holes were drilled on either side of the box to allow for stainless-steel tube connections between each chamber and its solenoid. The holes were made slightly greater than the diameter of the connectors such that they could be mounted. Silicone was later applied in between the gaps to provide a sealed multiplexer unit (Figure 2.4).

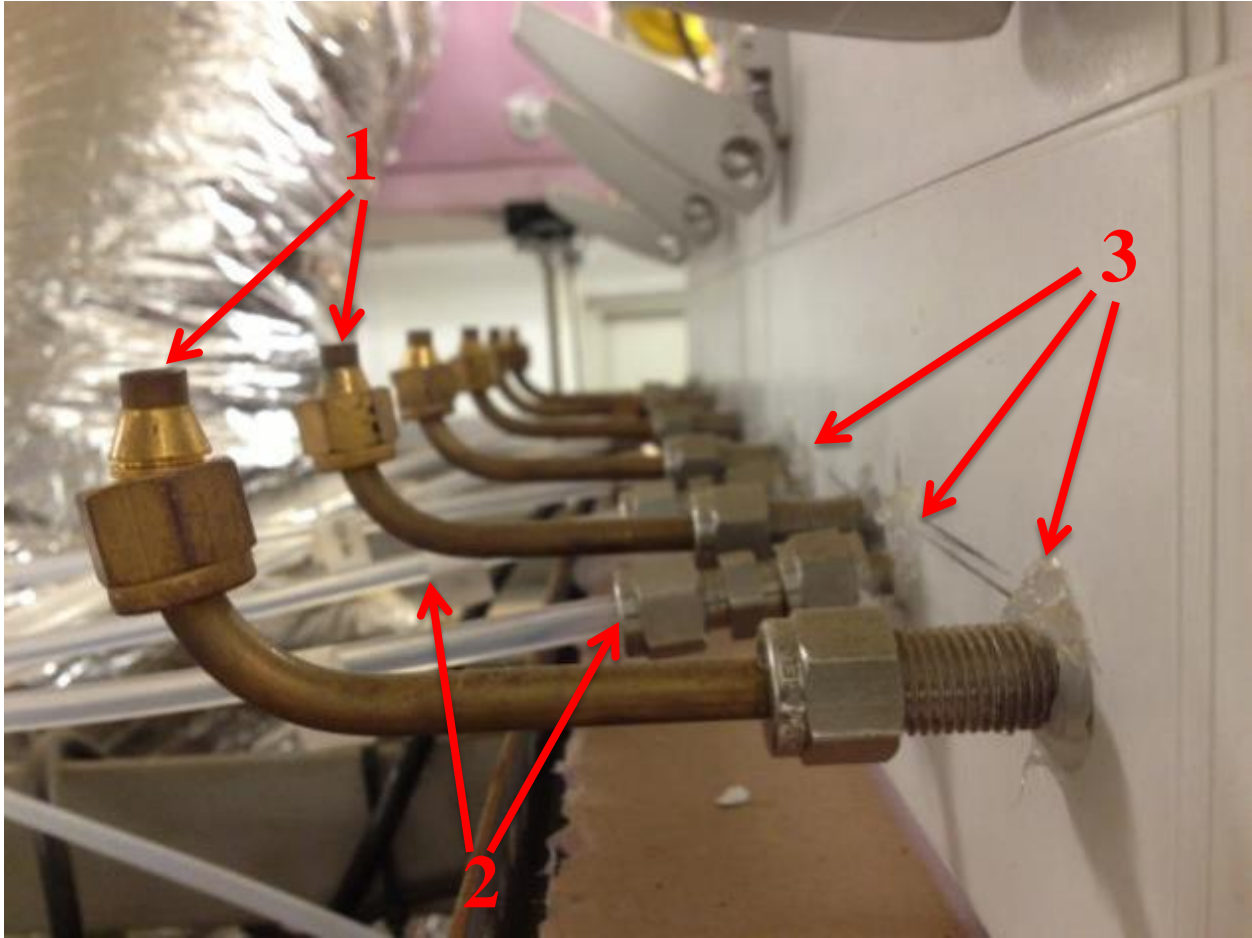


Figure 2.4: Picture showing exhaust (1) and sampling (2) lines of multiplexer. Also showing areas where silicon (3) was applied.

Solenoids are mounted onto individual custom plates attached to a larger base plate which is mounted inside the enclosure to facilitate access for repairs and maintenance. From each solenoid, three compression fittings (1/4" OD, 316SS, Swagelok, Solon, Ohio) provide air-tight connections to the inlet, exhaust and sampling line. All sampling lines are constructed using Teflon tubes (3.175 (1/8") ID x 6.35mm (1/4") OD, Cole-Parmer, Inc., Vernon Hills, IL). All connections within the enclosure are custom fit with stainless-steel tubing and various compression fittings (Figure 2.5). Stainless steel was selected due to its superior resistance to

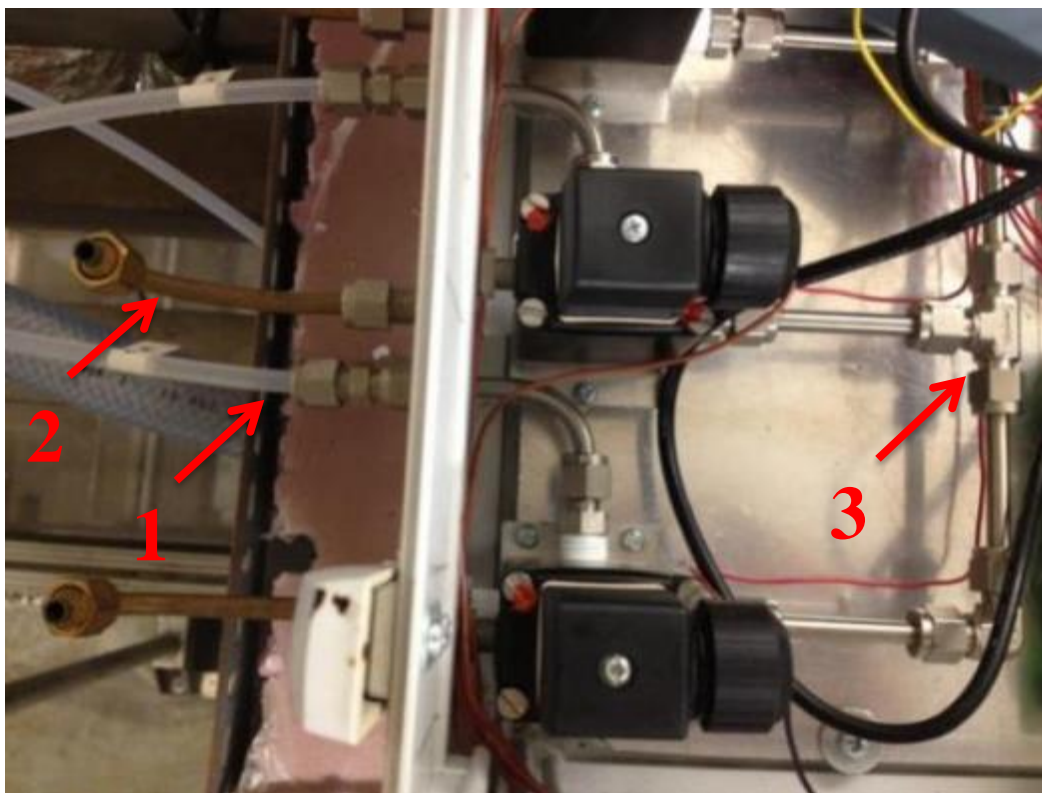


Figure 2.5: Picture showing solenoid connections from chamber (1), to exhaust (2) and to sampling line (3).

reaction, absorption or permeation with common gases that will be of interest for REMS. Brass tubing also manufactured by Swagelok provides exhaust outlets. Seven amber 4.0 mm (5/32") LED lights (Model No. 001-204, Paneltronics, Hialeah Gardens, FL) mounted in the enclosure wall and visible from the outside indicate which solenoid is activated (6 for the chambers, 1 for the background) and provide a quick verification of which chamber's sample air is currently being analyzed. Seven commercial Temp/RH sensors (HMP50, -40 °C to +60 °C, 0-98%RH, Vaisala, Helsinki, Finland) were wired to the DAQ inside the enclosure, while the physical sensors were placed one inside each chamber and one inside the building. Seven vacuum/pressure diaphragm pump (PTFE-coated, model EW-79200-30, Cole-Parmer, Inc., Vernon Hills, IL. Figure 2.6)



Figure 2.6: Vacuum pump located on the inlet side of the multiplexer.

placed outside and upstream of the multiplexer provide suction for the gas sampling line. Figure 2.7 shows the electrical wiring diagram of the multiplexer.

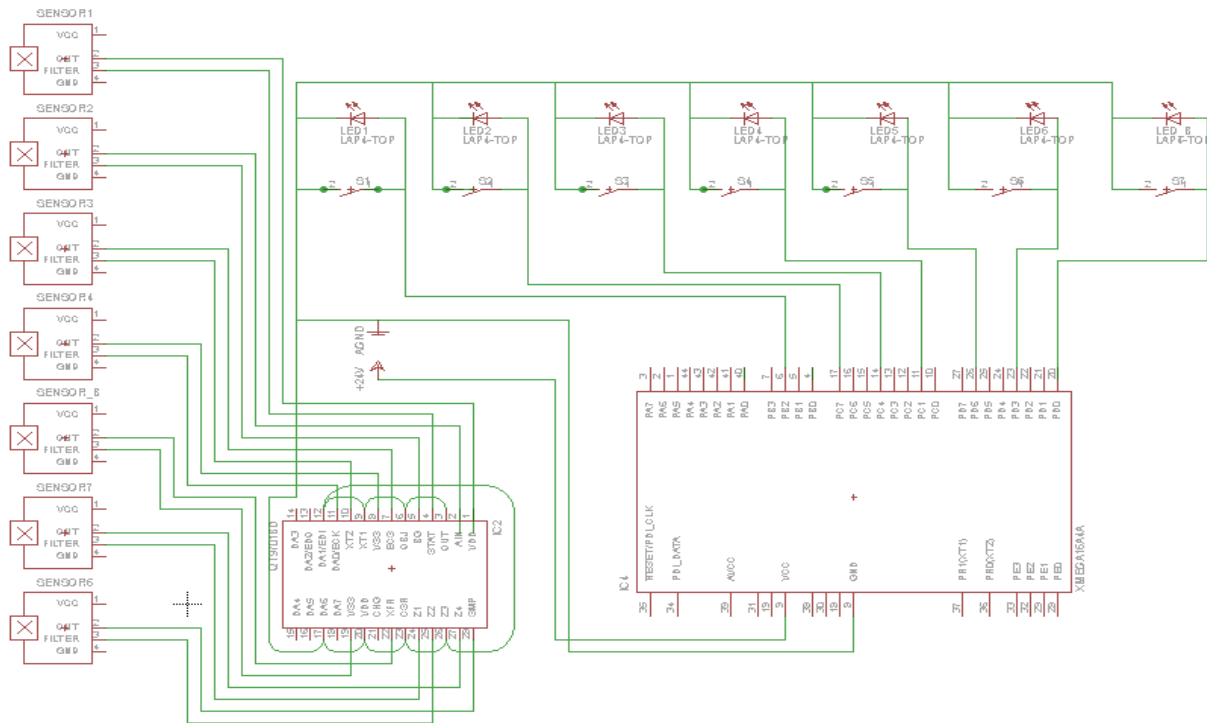


Figure 2.7: Multiplexer internal wiring scheme including wiring for each solenoid, LED, temperature and relative humidity sensors, data acquisition unit and relay.

2.3 Fresh Air Supply and Measurement Subsystem (Orifice Meter)

2.3.1 Approach

The following section documents the overall design parameters of the Fresh Air Supply and Measurement Subsystem. Section 2.3.2 covers specific details regarding the components.

Ramirez et al. (2013) documents the development and implementation of this system with greater detail.

For each metabolic chamber, a custom-designed and constructed orifice meter measures ventilation flow rate for providing fresh air into the chamber. An orifice plate is strategically placed after the entrance of the meter. When air passes through orifice meter, the smaller dimension of the orifice plate opening restricts flow and causes a pressure drop across the orifice plate. The orifice meter is equipped with an oil manometer that measures the pressure drop across the orifice plate. The relationship between the pressure difference across the orifice and the theoretical volumetric flow rate is shown by Equation 2.1. A calibration test that will be later introduced (Section 3.3) documents the correction for the relationship between this differential pressure and actual volumetric flow rate (Rhinehart et al., 2011).

$$Q_{OM}^{theoretical} = \frac{\pi}{4} d^2 \sqrt{\frac{2\Delta P_{OM}}{\rho_{ma}(1-\beta^4)}} \quad (\text{Equation 2.1})$$

Where:

$Q_{OM}^{theoretical}$ = theoretical flow rate of orifice meter ($m_{ma}^3 s^{-1}$)

ΔP_{OM} = static pressure drop across orifice plate (Pa)

ρ_{ref} = moist air density ($kg m^{-3}$)

d = orifice diameter (m)

β = ratio of orifice diameter to pipe diameter (m)

This formula takes into account orifice diameter, length and internal surface coefficient. Since all emission calculations are directly based on flow rate, and each orifice meter will have different calibration correction equation due to differences in assembly, it is crucial for each orifice to behave predictably and consistently.

2.3.2 Design and Construction

Each orifice is made from 50.8 (2") Schedule 40 PVC pipe, with a 508 mm (20") long entry pipe and 254 mm (10") long exit pipe. Entrance section length was specified to be 10 times the pipe diameter to ensure a fully developed flow entering the orifice. Similarly, the minimum allowable exit section length was 5 times the pipe diameter. The pipes connect to two thick-walled easy-connect Schedule 80 PVC flanges (4881K236, McMaster-Carr Supply Company, Elmhurst, IL), between which is sealed a 3.2 mm (1/8") acrylic orifice plate using rubber gaskets and silicone.

A 20.6 mm (13/16") orifice diameter was selected based on the design flow rate and the diameter

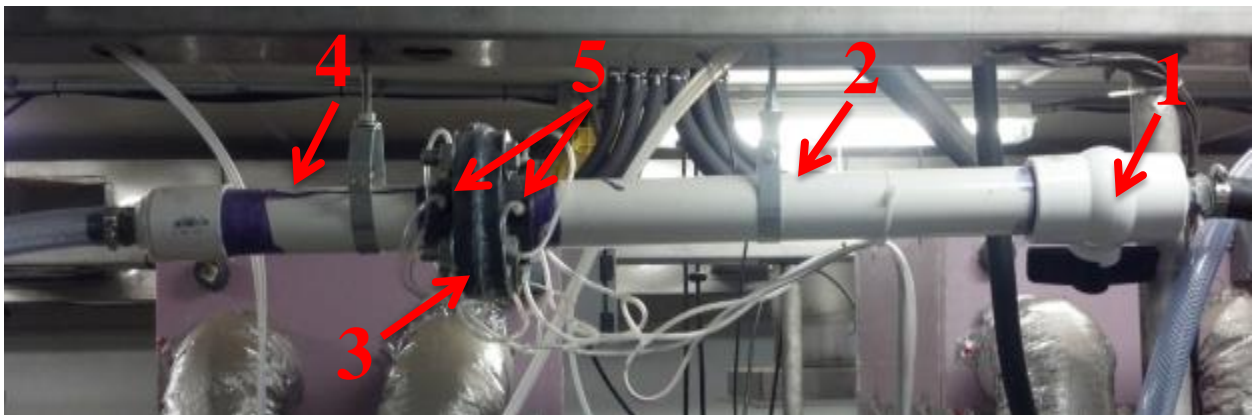


Figure 2.8: Physical construction of orifice meter, including ball valve (1), entrance pipe (2), orifice plate (3), exit pipe (4) and flange taps (5).

of the entrance pipe such that the ratio was between 0.4 and 0.8. Eight flange taps were strategically placed on the flanges, 4 upstream and 4 downstream to measure pressure difference

across orifice plate (ASME 2004). An inclined-vertical oil manometer (Series Mark II, Dwyer Instruments, Inc., Michigan City, Indiana, USA. Figure 2.9) was used to measure the



Figure 2.9: Inclined-vertical manometer with adjuster and level.

differential pressure by averaging the 4 measurements. A 50.8 mm (2") PVC ball valve was fitted at the entrance of the orifice to control air flow. Variable lengths of 25.4 mm (1") OD clear rubber hoses were connected to either end of the orifice, directing air from the ventilation supply, through the meter, and to the chamber.

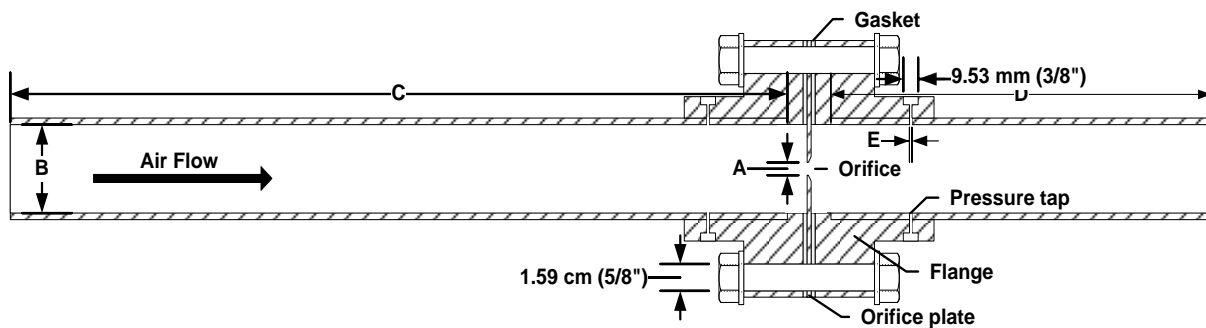


Figure 2.10: Internal schematic of orifice meter showing dimensions and location of orifice plate.

2.4 Thermal Environmental Control Subsystem (Chamber Air Conditioning Unit)

2.4.1 Approach

The following section documents the overall design parameters of the Thermal Environmental Control Subsystem. Section 2.4.2 covers specific details regarding the components.

Temperature and humidity are controlled in each chamber with a Thermal Environmental Control Subsystem (TECS, Figure 2.1), with a separate Chamber Air Conditioning Unit (CACU) located above each chamber, a common chilled water source and an external blower, both located in the Equipment room. Each CACU contains a filter to capture particulates, heat exchanger coils for cooling and dehumidifying, an electric resistance heater to raise the temperature back to supply set-point conditions, and an internal blower to provide constant air circulation within the chambers. The chiller supplies cold water to each individual CACU for moisture control. The external blower supplies background air through a manifold and the orifice meters to the chambers, providing fresh air for the animals. These components are all identified in Figure 2.11.

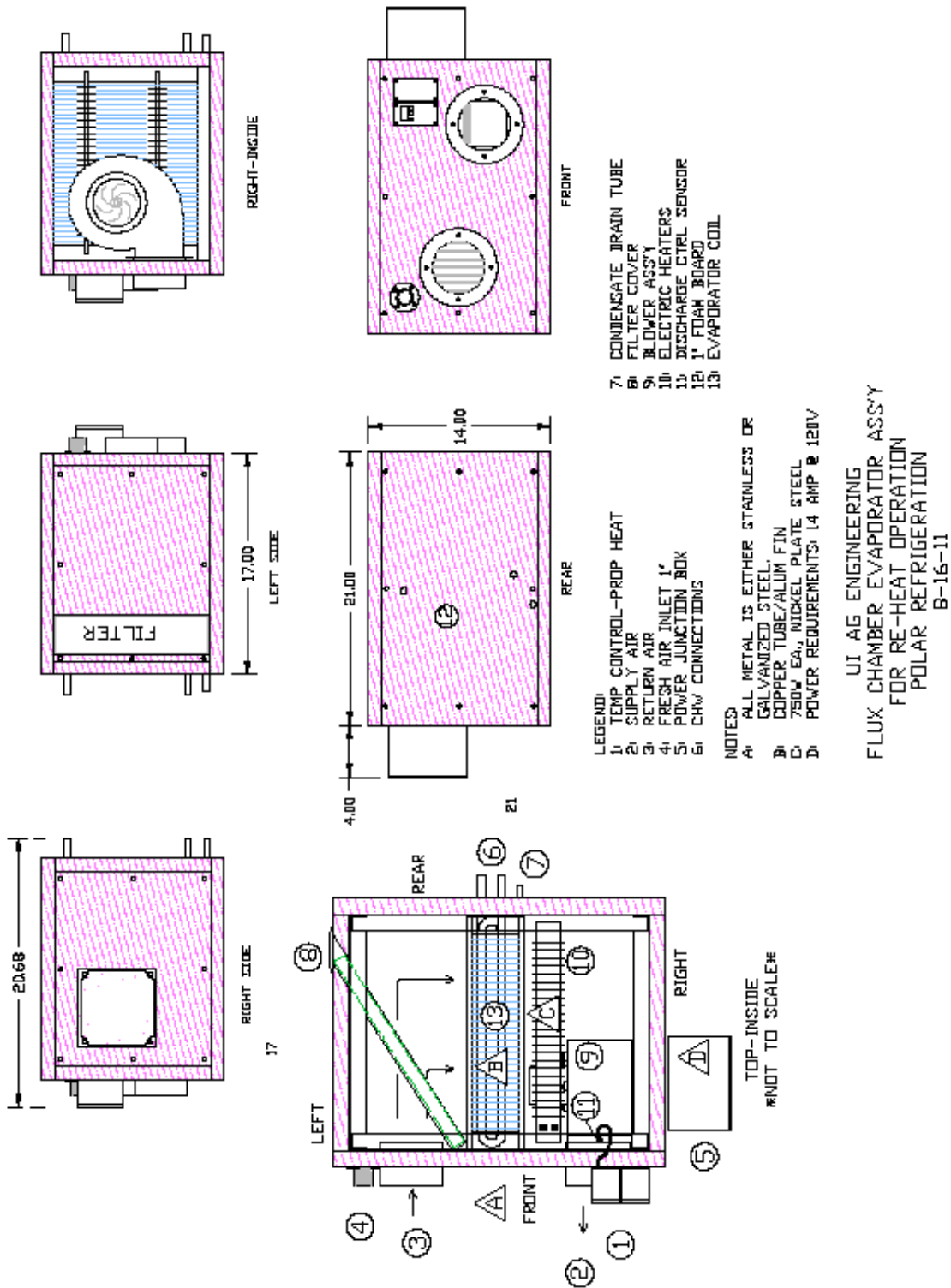


Figure 2.11: Schematic of air-conditioning
 0-1 = 1/4" SCALE

Figure 2.12 is a schematic of the psychrometric processes for air treatment in the CACU. Upon entering the heat exchanger, the air passes through a heat exchanger coil that cools the air down to saturation (1). When the relative humidity reaches 100%, the air is further cooled to condense moisture and lower the humidity ratio (2). Finally, the saturated air is heated up again to reach a user-defined supply air set-point (3). This set-point is lower than the set-point temperature for the chamber because it will mix with the air in the chamber, which is of higher temperature due to the sensible and latent heat produced by the animals. No fresh air (other than that from potential leakage) is added by the CACU, which only provides cooling, dehumidification and heating to the recirculation air. Fresh air is provided by the external blower and flow is measured by the orifice meter (Section 2.3).

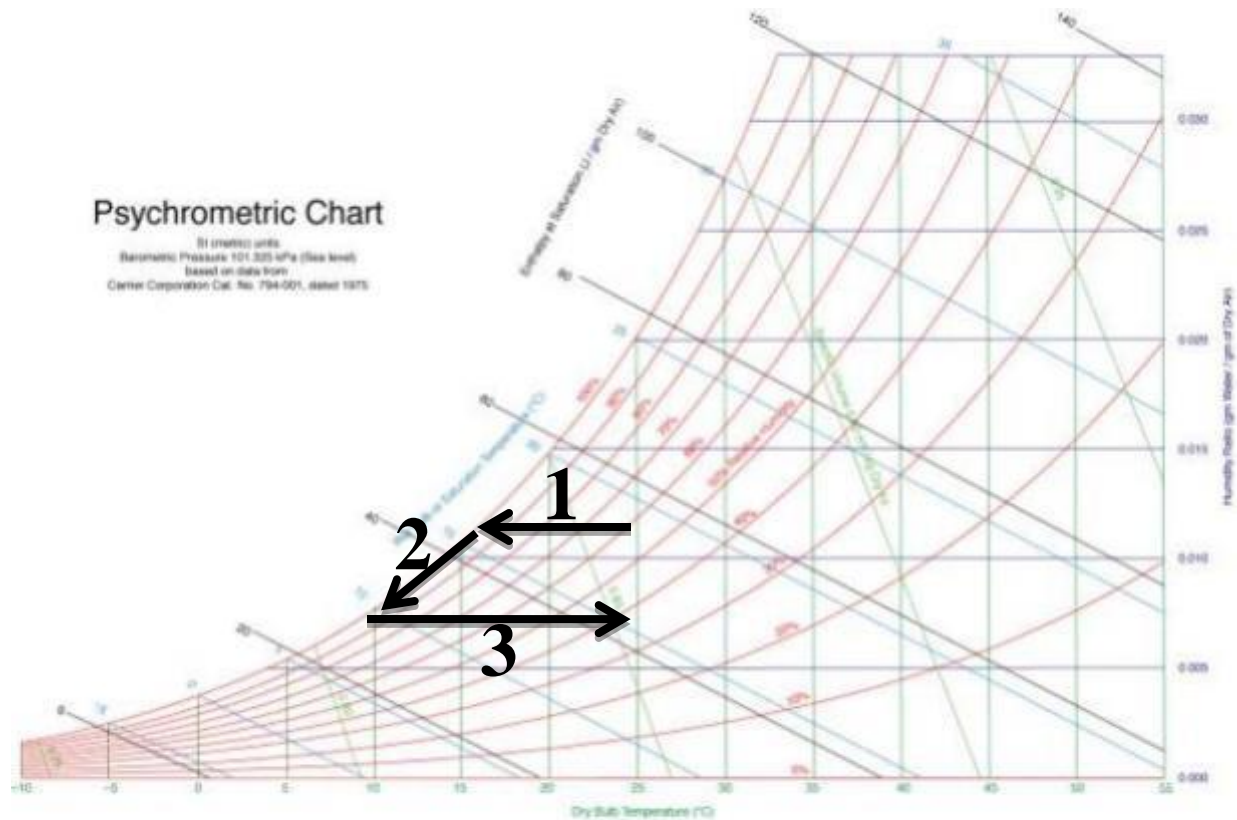


Figure 2.12: Psychrometric chart showing the air conditioning process: (1) cooling; (2) cooling with dehumidification; and (3) reheat. (Image taken from <http://commons.wikimedia.org/wiki/File:PsychrometricChart-SeaLevel-SI.jpg>. Accessed June, 2013).

2.4.2 Construction

The REMS TECS was custom-constructed based on a set of design criteria, and installed by a local contract company (Polar Refrigeration Heating & Cooling Inc., Urbana, IL). The system consists of six individual CACUs for each chamber, a central chiller and an external blower. A self-contained air-cooled chiller (Dimplex SV3000, Koolant Kooler, Kalamazoo, MI) with a capacity of 10.56 kW is located in the mechanical room adjacent to the animal space. In the main animal space, one CACU is mounted above each of the six chambers. Flexible tubing with 25.4 mm (1”) OD connects the supply/return lines from the chiller to the CACUs, with insulation

(25.4 mm (1") Armaflex, Armacell, Münster, Germany) to prevent condensation. The supply/return manifold is equipped with flow bypass to ensure adequate flow being supplied to other chambers when one or more chambers are shut. Likewise, 12.7 mm (1/2") flexible tubing with insulation (12.7 mm (1/2") Armaflex, Armacell, Münster, Germany) provides cold water supply/return lines to each individual chamber from the main line. Each conditioning box is constructed within a steel frame with insulating 12.7 mm (1/2") foam-board covering. A pleated filter measuring 305 mm x 457 mm x 25.4 mm (12" x 18" x 1"), fitted vertically, prevents any particulates from entering the heat exchanging coils. Single-circuit, double-rowed cooling coils recirculate the chilled water, providing continuous air cooling for the removal of excess moisture. After the air reaches near saturation, a 750 W electrical resistance heater (2XEF7, Tempco Electrical Heater Corp., Wood Dale, IL) reheats the air when necessary. Finally, a blower (1TDR3, Grainger, Lake Forest, IL) recirculates the air into the chambers. Temperature and humidity control is modulated by a controller with analog outputs (System 450 Series, Johnson Controls, Milwaukee, WI). A thermostat placed immediately before the supply duct monitors supply air temperature from the box to the chamber. This ensures that the air temperature being measured is the same as that being pushed into the chamber.

2.5 Ventilated Hood Metabolic Chamber

2.5.1 Approach

The following section documents the overall design parameters of the Ventilated Hood Metabolic Chambers. Section 2.5.2 covers specific details regarding the components.

The underlying basis on which the REMS operates is that the concentrations measured by the system represent the change in concentration due to contributions from the animal. This is only true if no infiltration occurs in any part of the system, including the housing unit. In order to prevent infiltration, the chambers must be kept at positive pressure continuously. Positive pressure between inside and outside the chamber force air to escape outwards, reducing the potential for sample contamination with unintended outside air infiltration. This guarantees that the concentration of whatever gas is being sampled is diluted only by the known quantity of supplied fresh air through the orifice meter, which is being measured. A canvas hood connects to the rear of the chamber and allows for closure around an animal's head while placed in the chamber. The opening size is large enough to fit a fully mature animal and the drawstring at the end of the hood can be tightened for smaller animals (Figure 2.13). A ventilation port for connection to the orifice meter provides constant fresh air for the animal (Figure 2.14). An automatic bowl-type drinker dispenses water whenever an animal pushes the nozzle, and a removable feed bin (Figure 2.15) allows easy access, weighing, and cleaning. For ease of transportation and cleaning, the chambers are made from polycarbonate panels and aluminum frames and set on rubber wheels. A transparent material was used to minimize blockage of the viewing area for the animals. Animal size was also considered in determining the chamber dimensions. Figure 2.16 depicts a completed chamber.



Figure 2.13: Picture of chamber interior showing drinker, feed bin and canvas hood.



Figure 2.14: Internal picture of chamber top showing ventilation port and air conditioning unit return air duct.



Figure 2.15: Front view of feed bin with handles.



Figure 2.16: Front view of completed chamber with removable door

2.5.2 Construction

Each chamber was constructed according to design specifications provided to ShapeMaster Inc., a fabrication company based in Ogden, IL, using transparent polycarbonate panels mounted in aluminum framing with rubber gasket seals at all joints. These materials were chosen for their versatility, durability and air-tightness. The chambers are mounted on four identical rubber wheels set on aluminum casters. The drinker (C20103N, Nasco Inc., Fort Atkinson, WI) is mounted in the corner of the chamber and is connected to a water line from the top of the chamber (Figure 2.13). The custom-constructed acrylic removable feed bin (30" x 24" x 10", Figure 2.15) suspends from a lip around the top of the bin placed on an aluminum frame flange near the bottom of the chamber. The feed bin, drinker, and the head of the animal in the chambers may be accessed through a hinged door (3/4 the height of the chamber) with rubber seals around the edges and latches along the non-hinged side. The door is easily removable if needed (Figure 2.16). A drain on the bottom of each chamber was incorporated as a safety feature in the event of a burst water pipe, to prevent the chamber from filling with water. The back of the chamber is constructed using aluminum sheet with an opening for the animal's head. A zippered canvas hood is bolted to a frame attached to the sheet metal with a drawstring opening to create an enclosure around the animal's head. The animal can stand and lie down while secured with its head inside the chamber. Ventilation and gas sampling ports are located in the top of each chamber. Dimensions are shown in Figure 2.17.

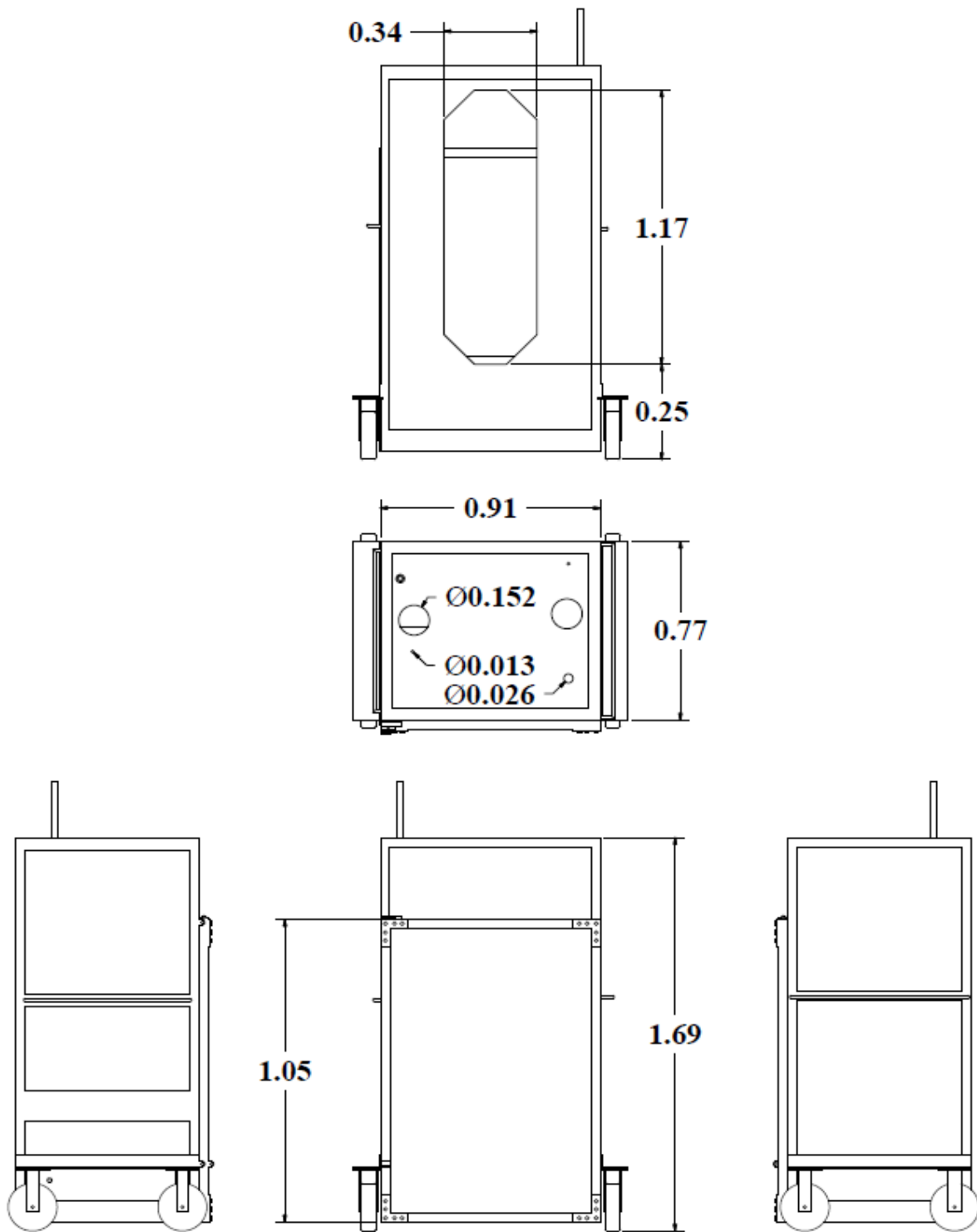


Figure 2.17: Back, top, side and front views of chamber (1.69m * 0.91m * 0.77m), including dimensions.

2.6 Infrared Photoacoustic Spectroscopy Multi-Gas Analyzer (INNOVA 1412i)

2.6.1 Approach

The following section documents the sampling sequence and frequency settings of the gas analyzer. Section 2.6.2 covers specific details regarding the internal working of the INNOVA. During normal usage of REMS, 5 gases may be sampled: nitrous oxide (N_2O), carbon dioxide (CO_2), sulfur hexafluoride (SF_6), ammonia (NH_3) and methane (CH_4). For both chamber and background concentration measurement, the sampling time is approximately seven minutes to sample all gases. This time requirement may be reduced if fewer gases are measured. For all gases, a total of 14.43 minutes (866 seconds) is required for each chamber-background sequence. For each chamber, 10 measurements are taken over a course of 433 seconds (43.3 seconds per measurement) and the average of the last four measurements is considered the considered to be representative of the sample concentration. The raw data and average are all saved by the control software. Following sample measurements, 10 measurements of the background air are collected, which is used as the background concentration for the emissions calculation (Figure 2.18). In the emissions calculations, the last four measurements from the background are averaged and subtracted from the average of the last four measurements from each chamber to calculate emission rate. Each sample takes 43.3 seconds due to the time it takes to rotate between filters for each gas, which is done automatically inside the INNOVA gas analyzer. One complete REMS iteration of all 6 chambers and background concentration takes approximately 86 minutes to complete.

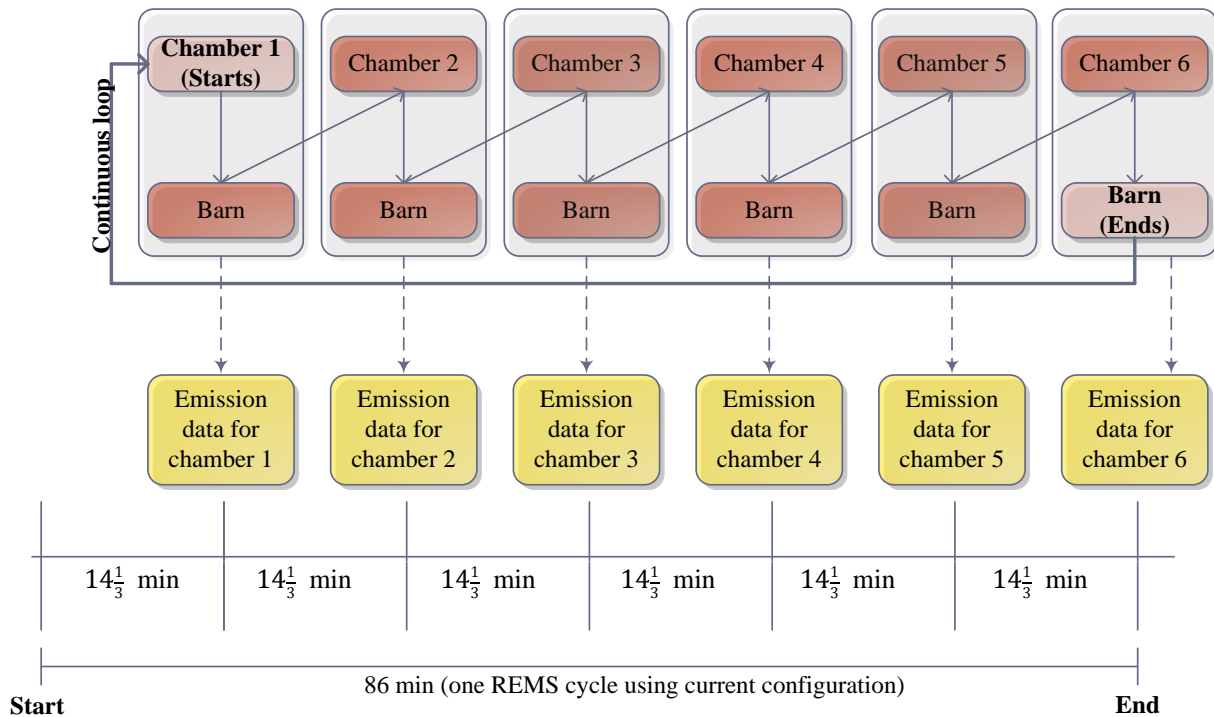


Figure 2.18: REMS sampling setup showing sampling sequence and time. Note the background air is sampled after each chamber, providing a more reliable background concentration for emission calculations.

2.6.2 Equipment

The LumaSense Photoacoustic Gas Monitor (INNOVA 1412i, LumaSense Technologies, Inc., Santa Clara, CA) is a highly accurate, reliable and stable quantitative field gas monitor. It uses the photoacoustic infrared detection method for measuring the sampled gas, allowing it to measure almost any field gas that absorbs infrared light. With a unique cross-compensation feature the gas analyzer compensates for interference between the measured field gases.

Appropriate optical filters are installed in the INNOVA 1412i's filter carousel so that it can selectively measure the concentration of up to 5 component gases and water vapor in any air

sample. For the purposes of this experiment, the filters required are listed in the following table (Table 2.1). The INNOVA 1412i can compensate for interference between the measured field

Table 2.1: Gas measurement capabilities selected for the INNOVA 1412i implemented in the REMS, including required filters and detection limit for each gas.

Gas	Molar Mass	Optical Filter No.	Sample Integration Time (SIT)(s)	Detection limit (ppm)
N ₂ O	44.013	985	1	0.066
CO ₂	44.01	985	1	154
SF ₆	146.06	975	1	0.022
NH ₃	17.031	976	5	0.2
CH ₄	16.04	969	5	0.4

gases, using the unique cross-compensation and water vapor compensation feature. The gas analyzer detection limit is gas-dependent, and it can detect methane emission as low as 0.4 ppm.

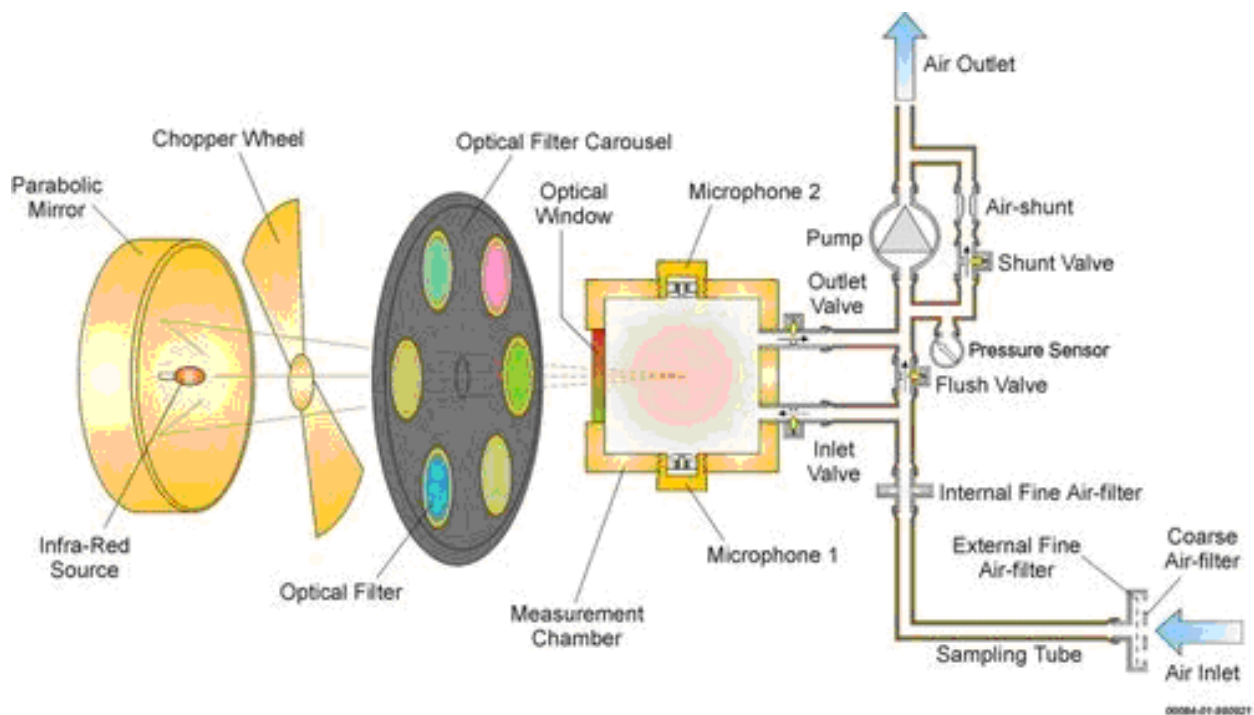


Figure 2.19: (Internal workings of the photoacoustic analyzer) (Reprinted from LumaSense, 2013).

2.7 Instrument Control Subsystem (LabVIEW)

2.7.1 Approach

LabVIEW (Version 8.2.1, National Instruments, Austin, TX), short for Laboratory Virtual Instrument Engineering Workbench uses a visual programming language “G” to create graphical block diagrams that correspond to physical pieces of the system for interface, data acquisition, and control. In the REMS system, there are three versions of software to implement in various operations of the system. The various versions of the control software are capable of: (1) receiving and recording the dry bulb temperature, dew point temperature and relative humidity outputs collected by the data acquisition unit; (2) outputting on/off signals to the relay which controls each solenoid; (3) transferring data to and from the gas analyzer and recording concentration measurements; and (4) calculating and recording emission rates as the necessary data are collected. The user interface is designed to be easy to understand and simple to use.

2.7.2 Implementation

The goal of the ICS created and operated in LabVIEW is to provide an easy way of controlling the solenoids and a clear way of recording and displaying measurement results for automation of the REMS instrumentation. For the purpose of REMS operation, three programs were developed. Appendix A and Appendix E offer additional description and details on the software and operation of the system. In order to initiate operation of each program, the “Run” arrow block near the top left side of the window should be clicked. In order to end the program, the button labeled “STOP” in the lower or upper right-hand side of the window should be clicked. The “Stop” block along the top left should not be clicked to end the program.

(1) "XDOUT.VI" controls only the solenoids inside the multiplexer. The physical relay interface is configured with 4 double-ended channels, and the controls are separated into two ports. The first 4 solenoids are controlled by the low side of the channel ("FIRSTPORTCL") while the rest are controlled by the high side ("FIRSTPORTCH"). For our operation, the channels are controlled individually. Manually clicking the switch in this interface energizes the solenoid selected. Only one solenoid may be turned on at once, and each solenoid must be turned off before exiting the program. Figure 2.20 shows the user interface for "XDOUT.VI". This code does not collect or record any data and is typically used for system troubleshooting. It is also useful for conducting system tests when it requires steps not available in existing programs.

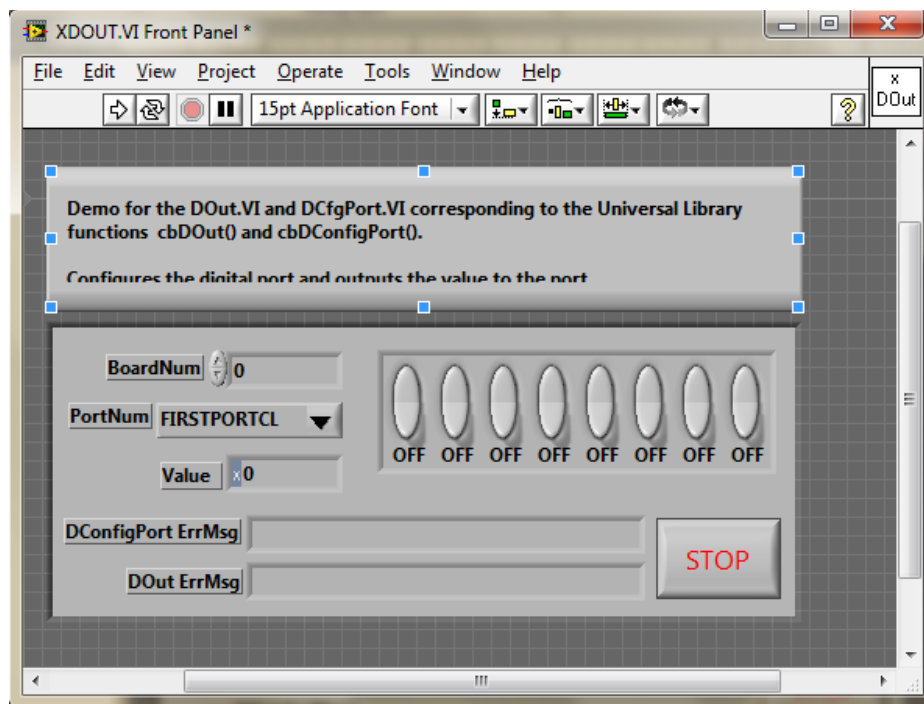


Figure 2.20: Screenshot of "XDOUT.VI" showing FIRSTPORTCL, which provides manual control to energize and de-energize solenoids 1-4.

(2) "Project(2).vi" should be operated for emissions studies with all six chambers active. The program follows the sampling strategy for all six chambers, as described in Section 2.6. The solenoids are automatically controlled based on the status of the gas analyzer. All parameters necessary for calculating emission rate are collected and recorded in a text file, and emission rates are automatically calculated and recorded as well. The only user inputs required are the flow rates for each orifice meter and barometric pressure. The emissions equation in this file is known to have an error, so emissions should be manually calculated following data collection when using this version.

(3) "Project(3).vi" should be operated for emissions studies with one active chamber at a time, such as recovery tests. Only one chamber (and background) will be sampled for the entire sequence. The user defines which chamber should be sampled using the pull-down chart on the upper right corner prior to initiating the program. This program does not allow the user to input orifice meter flow rates or barometric pressure, nor does it perform emission rate calculations. Users should record test conditions manually and complete calculations after running the test. "Project(3).vi" allows for 10 samples (433.3 seconds) from the background followed by 90 samples (3899.7 seconds) from the chamber, then repeats this cycle for the duration of the test. One cycle was completed in roughly 4333 seconds, or 1.2 hours. All gas concentration, temperature and relative humidity raw data are recorded in the saved data file.

In "Project(X).vi", LabVIEW receives temperature and relative humidity sensor outputs that were collected by the data acquisition unit and concentration readings from the gas analyzer. These readings are displayed onto the screen in real time on the "Display" page (Figure 2.21).

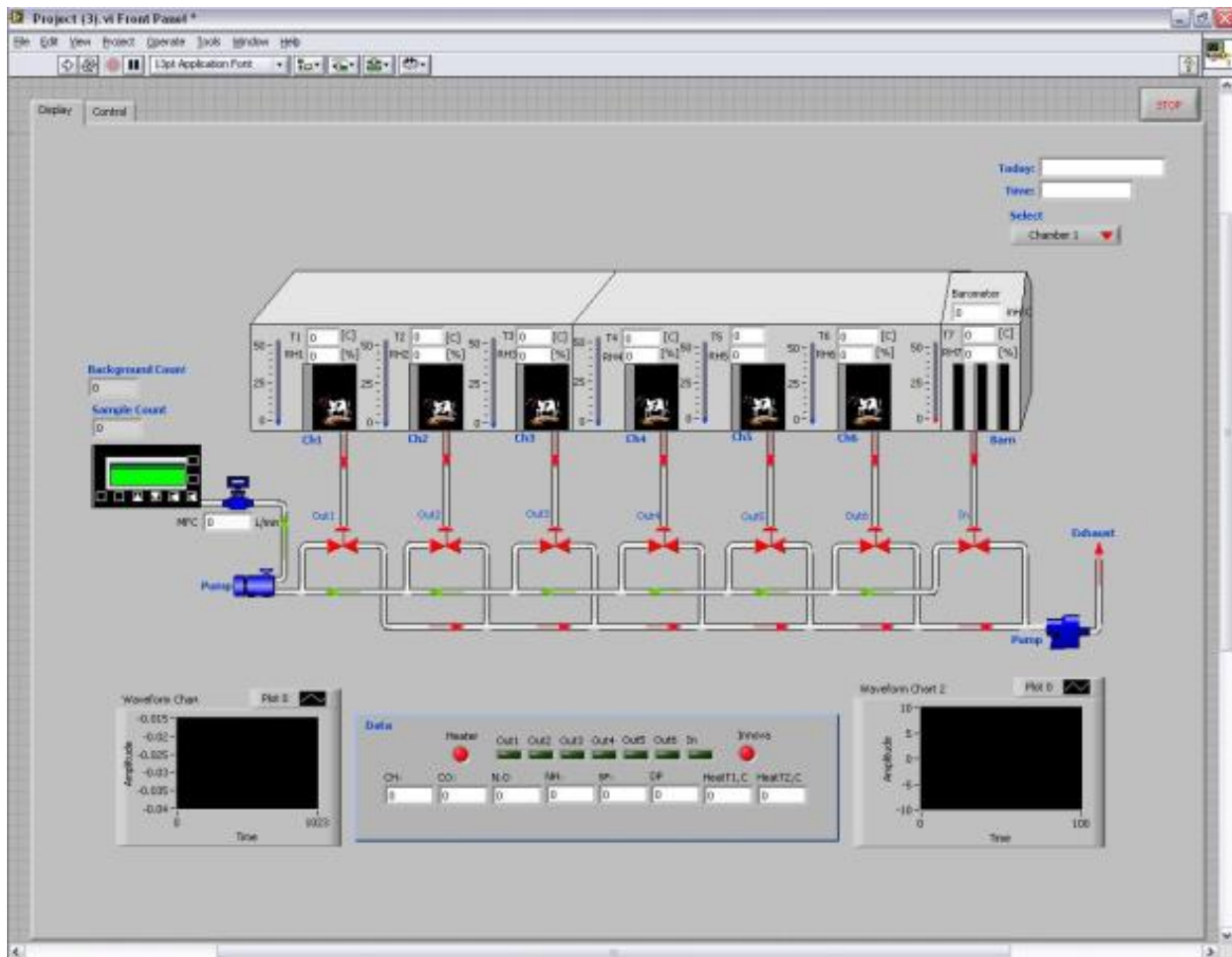


Figure 2.21: First page (Display) of "Program(2).vi" with date and time, gas concentrations and sampling counter shown. Arrows show direction of gas flow, the color green indicates active status while red indicates stand-by status.

Barometric pressure and orifice flow rates are manually entered on the “Control” page (Figure 2.22) and are essential for emissions calculations. For barometric pressure, the current reported measure should be accessed from www.noaa.gov for Champaign County immediately before initializing experiment. Orifice flow rates can be read from vertical-inclined manometers next to each chamber (For specific location and details on converting pressure to flow rate, refer to Section 2.3 and 3.3.4). The sampling sequence and frequency are automatically followed when

the program is started. A counter shows which chamber (or background) is being sampled, along with the number of samples already completed in the current sampling cycle.

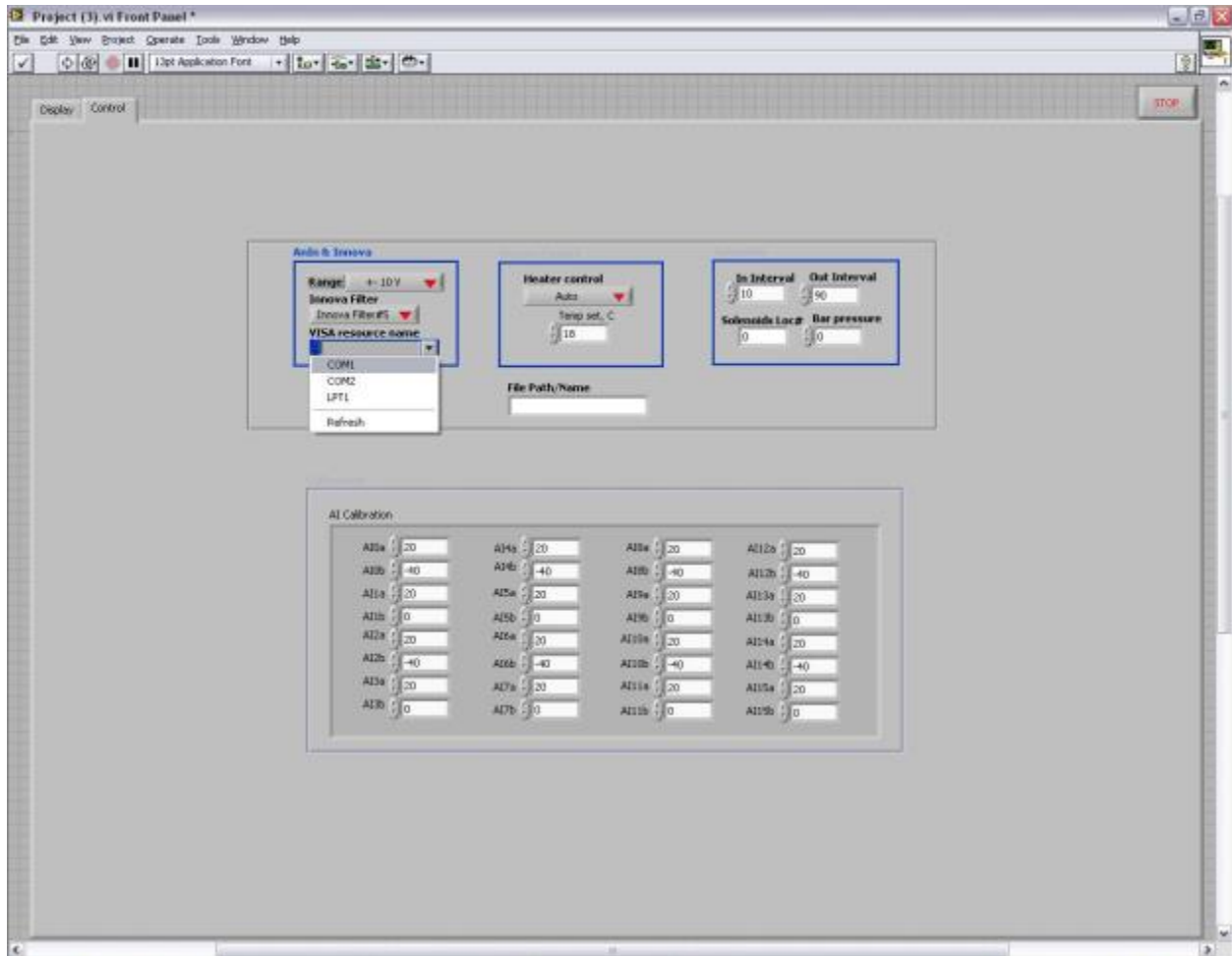


Figure 2.22: Second page (Control) of "Program(2).vi", allowing user to choose VISA resource name and temperature set-point.

A waveform data chart displays current and previous concentration readings so simple visual assessments can be made.

2.7.3 Alert System

For the safety of animals and integrity of experiment, a series of alerts were implemented into the LabVIEW program. Upon breaching a set threshold of environmental conditions, such as an upper and lower acceptable limit on CO₂, an alarm email is sent out to predetermined address, which can be directed to one or more computers or mobile phones. CO₂ levels are constantly measured by this system. CO₂ levels that are too high may indicate a faulty ventilation system and cause animals to suffocate. Likewise, CO₂ levels that are too low may indicate a cow that has pulled itself out from the chamber, causing useless concentration readings and false emission rates. This system will serve to prevent accidental loss of livestock and time.

2.7.4 Limitations

In “XDOUT.VI”, the user must remember to deactivate each solenoid after use. Clicking the “STOP” button terminates the program but has no effect on the state of each individual solenoid. In order to check whether each solenoid activated, refer to Section 4.1.4.

In “Project(2).vi”, the emission rate equation is incorrect. Gas concentration, temperature and relative humidity raw data should be downloaded from saved files and used to calculate emission rate using Equation 4.1. Pressure difference from the inclined-vertical oil manometers should be recorded on a separate excel sheet, also needed for ER calculations. Sampling time and sequence is set and can only be changed in the code.

In “Project(3).vi”, there is no input location for manometer readings. Gas concentration, temperature and relative humidity raw data should be downloaded from saved files and used to calculate emission rate using Equation 4.1. Pressure difference should be recorded on a separate

excel sheet, also needed for ER calculations. Sampling time is set and can only be changed in the code. Chamber to be sampled can be chosen in the first (Display) page.

Chapter 3: Quality Control and Performance Evaluations

3.1 Description of Tests

In order to satisfy quality assurance needs, a series of quality control tests were completed, including component leakage tests, equipment calibration, chamber pressure mapping and gas recovery tests.

A leakage test was conducted on the gas sampling system to demonstrate integrity of the gas samples taken from each chamber by verifying that each part of the sampling system was adequately sealed. This is performed by measuring both the quantity of air entering the supply side of the multiplexer and exiting the exhaust side and comparing the two values for discrepancy.

Calibration was completed for each orifice meter. Following the ASHRAE Fundamentals Handbook and ASME Flow Measurement protocols, a reference Chamber-Nozzle Airflow System (CNAS) for calibrating orifice meters was custom designed and assembled using a performance standard from ANSI/AMCA Laboratory Methods of Testing Fans for Certified Aerodynamic Performance Rating (Ramirez et al, 2013).

A chamber uniform air distribution test was conducted to ensure the uniformity of air distribution within each chamber by observing the mixing of gases inside the chambers and verifying any points of leakage into the chamber. This serves to show representative gas concentration is obtained at any location inside the chamber.

A chamber internal static pressure validation test was conducted to confirm that positive static pressure is maintained inside all chambers at all times. A total of 15 readings (5 readings from 3 heights each) inside each chamber were taken to sufficiently map a pressure chart.

Calibration was done for the INNOVA 1412i gas analyzer. With reference to Moody et al. (2008), a revised calibration method was followed and reported. This revised method takes humidity interference into account by using Nafion tubing during calibration.

A component leakage test was done to validate the integrity of the REMS sampling line and locate possible areas of sample contamination or dilution. This test was used to compare the concentration of gas before and after entering the REMS sampling line.

A system performance validation test was conducted to quantify the accuracy of the REMS emission calculations. This test shows the reliability of the whole system to detect a known quantity of injected gases.

3.2 Multiplexer Leakage

3.2.1 Approach

The following section documents the approach and method of conducting the multiplexer leakage test. For step-by-step instructions, refer to Appendix B.

A pump (PTFE-coated, model EW-79200-30, Cole-Parmer, Inc., Vernon Hills, IL), a rotameter (RMB-50D-BV, Series RCC, Dwyer Instruments, Inc., Michigan City, IN), the gas sampling multiplexer unit and another rotameter (EW-32460-44, Cole-Parmer, Inc., Vernon Hills, IL), were arranged in series. The first rotameter was placed between the pump and inlet port of solenoid 1 through 6, respectively. The second rotameter was either placed after the exhaust manifold or between the energized side of each solenoid and the gas analyzer. An adjustable bleeder was placed at a T-junction between the pump and rotameter to allow for control of air flow rate being provided. The solenoids were tested under two configurations:

1: Non-energized solenoids. Each solenoid was tested in its non-energized position (open to exhaust, closed to analyzer). The pump was started, allowing gas to flow through the multiplexer inlet of one chamber, pass through the solenoid and exit from the exhaust manifold. This test was done on each solenoid separately. The gas sampling line inside the multiplexer, including the solenoid, was deemed leak-free if reading from Rotameter 1 was identical (within the accuracy of the rotameters) to that from Rotameter 2. Rotameter 1 and 2 were operated in both locations for this test to ensure identical readings.

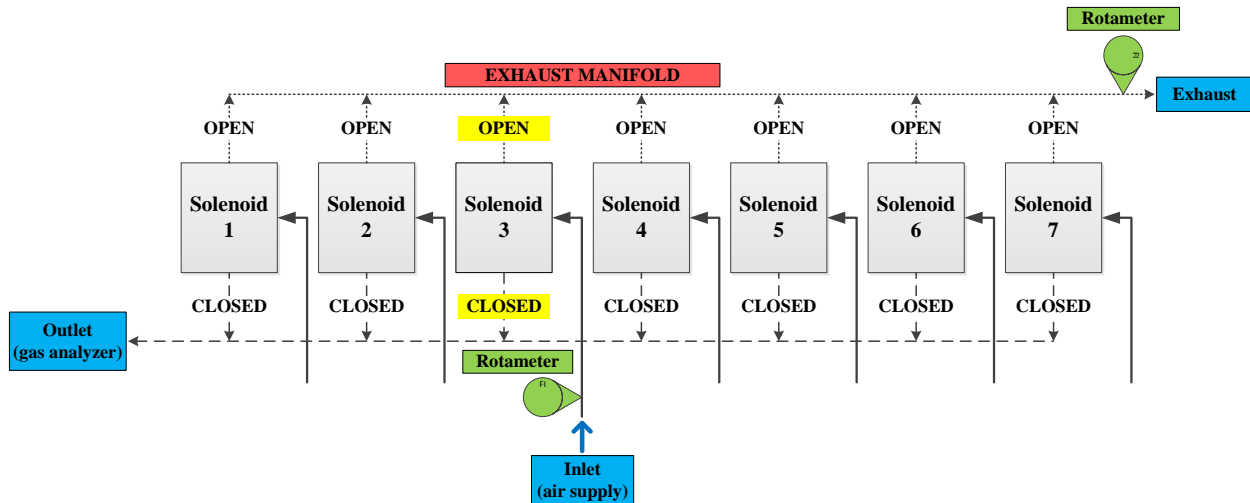


Figure 3.1: Multiplexer leakage test configuration for non-energized solenoids (example for Solenoid 3): Rotameter 1 was shown connected to Solenoid 3, with solenoid off and in its normally-off condition. Rotameter 2 was connected to the exhaust manifold. All other solenoids were sealed.

2: Energized solenoids. Each solenoid was individually tested in the energized state (closed to exhaust and open to analyzer). Once each solenoid was turned on, the airflow was directed to the gas analyzer supply line instead of the exhaust to the room. The pump was started, allowing gas to flow through the multiplexer inlet of one chamber, pass through the solenoid and exit through the sampling line leading to the gas analyzer. The system was allowed to remain on for 5 minutes before conducting the test. Readings from Rotameter 1 and 2 were recorded. The sampling line inside the multiplexer, including the solenoid, was deemed leak-free if reading from Rotameter 1 was identical (within the accuracy of the rotameters) to that from Rotameter 2. Rotameter 1 and 2 were operated in both locations for this test to ensure identical readings.

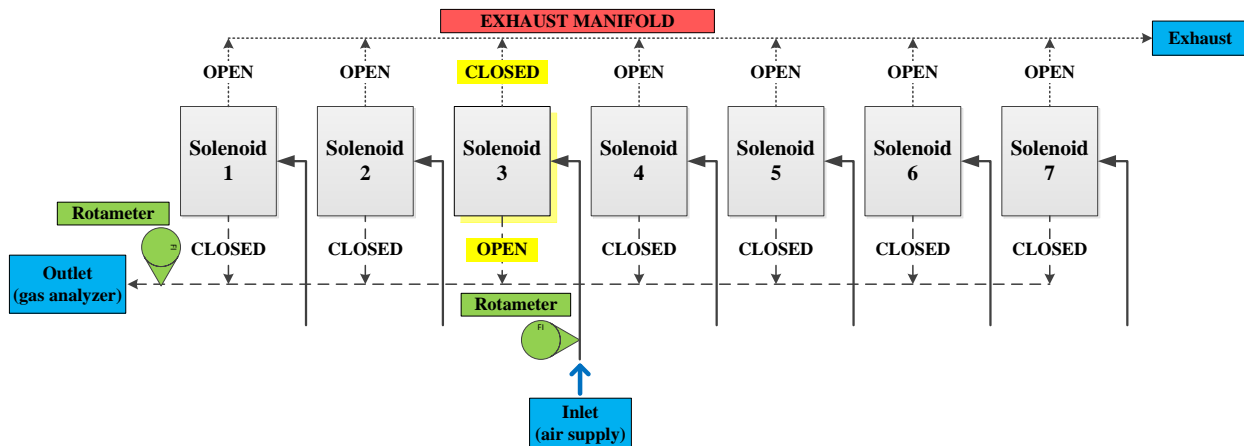


Figure 3.2: Multiplexer leakage test configuration for energized solenoids (example for Solenoid 3): Rotameter 1 was connected to Solenoid 3, with solenoid on, directing flow to the gas analyzer through the sampling line. Rotameter 2 was connected to the multiplexer outlet directing the sample to the gas analyzer inlet.

Note that the rotameters did not require calibration for this test. This is justifiable by means of a simple test. Assuming that a test line is challenged with a standard flow rate of 4 lpm, the uncalibrated rotameter is placed at the inlet of the test line is reading 5 lpm. This test line is considered leak-free if the rotameter flow rate remains at 5 lpm after being moved to the outlet of the line. As long as rotameter readings match at different locations along the sampling line, they do not need to be accurate.

3.2.2 Results

For testing the gas sampling lines for directing samples to the exhaust, the readings from Rotameter 1 were equal to those from Rotameter 2 for all seven gas sampling configurations. This result indicates that the sampling lines in the multiplexer, including the solenoid, for each of the seven gas samples, are leak-free.

For testing the gas sampling lines for directing samples to the analyzer, the readings from Rotameter 1 were equal to those from Rotameter 2 (state +/- accuracy – based on precision of

rotameter scales, ½ of smallest division) for all seven gas sampling configurations. This result indicates that the sampling lines in the multiplexer, including the solenoid, for each of the seven gas samples are leak-free.

3.3 Orifice Meter Calibration

3.3.1 Approach

A calibration for the orifice meter was required for accurate ventilation measurement. Since the emission rate equation uses ventilation rate as a variable, obtaining an accurate reading is required. But since flow rate inside the orifice meter cannot be directly measured, a formula to calculate the flow rate using differential pressure across the orifice plate must be derived through calibration. Following the ASHRAE Fundamentals Handbook and ASME Flow Measurement protocols, a reference Chamber-Nozzle Airflow System (CNAS) for calibrating orifice meters was custom designed and assembled using a performance standard from ANSI/AMCA Laboratory Methods of Testing Fans for Certified Aerodynamic Performance Rating (Ramirez et al., 2013).

3.3.2 Construction of calibration setup

The Chamber-Nozzle Airflow System (CNAS) consisted of two 610 mm x 610 mm (24" x 24") wood tunnels forming the entry and exit sections, with lengths of 1219 mm (48") and 914 mm (36"), respectively (Figure 3.3). The same centrifugal blower (Peerless Blowers, Hot Springs, NC, USA) used in the ventilation supply system to the REMS chambers was relocated for the test and placed at the opening of the CNAS to provide a constant air flow simulating actual operational conditions. An iris damper controlled flow rate through the CNAS by exhausting excess air from the CNAS to release pressure accumulated upstream of the nozzle. Three steel mesh flow conditioners (25 mm apart from one another) were placed 305 mm (12") inside the leading edge of the entry section to direct air flow and remove turbulence. A 19.05 mm (0.75") nozzle plate mounted in the center of a 610 mm x 610 mm x 12.7mm (24" x 24" x 0.5") plywood board was secured between the entry and exit sections using 16 clamps. Four pressure taps were

placed up and downstream of the nozzle. The differential pressure across the nozzle was measured using an inclined-vertical oil manometer (Series Mark II, Dwyer Instruments, Inc., Michigan City, Indiana, USA).

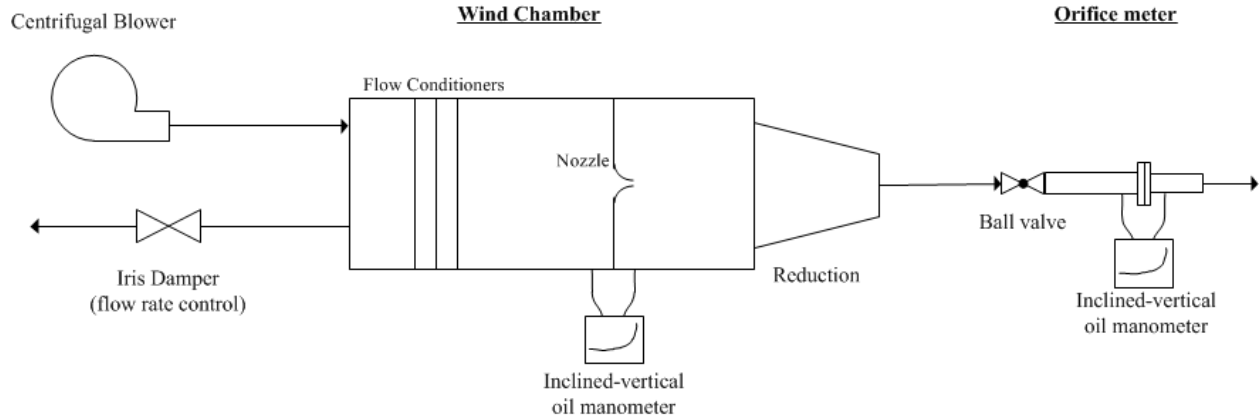


Figure 3.3: Schematic of Chamber-Nozzle Airflow System calibration arrangement showing relative location of blower, nozzle, and orifice meter.

3.3.3 Calibration of orifice using CNAS setup

Calibration was completed for an airflow range of 368 to 510 lpm (13 to 18 cfm), including 21 different flow rates, 10 increasing, 1 peak, and 10 decreasing. Temperature and relative humidity were monitored during the calibration using a calibrated handheld device (Hydropalm 23, Rotronic Instrument Corp., Hauppauge, NY). Reference flow rate for this calibration method was calculated following this equation (AMCA/ASHRAE 2007):

$$Q_{ref} = Y \sqrt{\frac{2\Delta P_n}{\rho_{ref}}} C A_n \quad (\text{Equation 3.1})$$

Where:

Q_{ref} = actual flow rate of the calibration reference at calibration conditions ($m^3_{ma} s^{-1}$)

Y = expansion factor

ΔP_n = static pressure drop across the nozzle (Pa)

ρ_{ref} = air density during calibration ($kg m^{-3}$)

$C = \text{discharge coefficient}$

$A_n = \text{area of the nozzle (m}^2\text{)}$

Using Equation 3.1, the theoretical flow rate through the orifice meter was calculated using the differential pressure, temperature, relative humidity and barometric pressure along with the specific design dimensions and parameters for each orifice meter. Differential pressure, temperature and relative humidity were measured in the experiment, while barometric pressure was calculated from a function of altitude (ASHRAE 2009). The following linear regression curve was fitted to the calculated results to model the relationship between reference flow rate and orifice meter flow rate:

$$Q_{OM}^{theoretical} = c \cdot Q_{ref} \quad (\text{Equation 3.2})$$

Where:

$c = \text{regression coefficient particular to one orifice}$

Reference flow rate provided by the CNAS was plotted on the x axis while actual orifice meter flow rate was plotted on the y axis. Using the inversion of Equation 3.2, shown as Equation 3.3, the actual flow rate corresponding to any theoretical orifice meter flow rate can be determined:

$$Q_{ref} = \frac{1}{c} \cdot Q_{OM}^{theoretical} \quad (\text{Equation 3.3})$$

Since each orifice meter is slightly different in dimensions, six unique calibration curves were generated. These curves can be used to calculate actual flow rates from differential pressure readings. Calibration was performed once for each of the six orifice meters, as calibration does not require replicates (AMCA/ASHRAE 2007).

3.3.4 Results

The following table (Table 3.1) shows a summary of results pertaining to the linear calibration curves for all orifices. Most importantly, the percent error at experiment conditions (481 lpm) is less than 0.04% for all chambers, demonstrating a very accurate calibration.

Table 3.1: Summary of calibration linear regressions for each orifice meter showed each one performed differently and thus each one required individual calibration. Relative error at 481 lpm was very small and an indicated of an accurate calibration. At the 0.05 confidence level, the slope is significantly different from 1.

Orifice Meter	Slope, c	Standard Error of c	Regression Standard Error (lpm)	Measurement Standard Error (lpm)	% error at 481 lpm
1	1.0199	0.00162	0.1068	0.1048	0.02%
2	0.9650	0.00159	0.1035	0.1073	0.02%
3	0.9735	0.00157	0.1024	0.1051	0.02%
4	0.9244	0.00248	0.1604	0.1735	0.04%
5	0.9865	0.00271	0.1730	0.1754	0.04%
6	1.0699	0.00250	0.1629	0.1523	0.03%

An example of a calibration curve is shown in Figure 3.4. A regression coefficient of one would indicate the instrument performed identical to the theoretical flow of an orifice (Equation 2.1).

Coefficients of determination from the linear regression were greater than 0.99 for each calibration curve. Regressing the flow rates instead of the calibration reference flow rate and the orifice meter differential pressure was advantageous because it accounts for the difference in air density when the orifice meter is used in conditions other than at calibration. The intercept of the calibration curve is forced through zero as no flow through the nozzle should result in zero flow through the orifice meter (Ramirez et al., 2013). Current relationships between manometer differential pressure and volumetric flow rate are shown in Table 3.2.

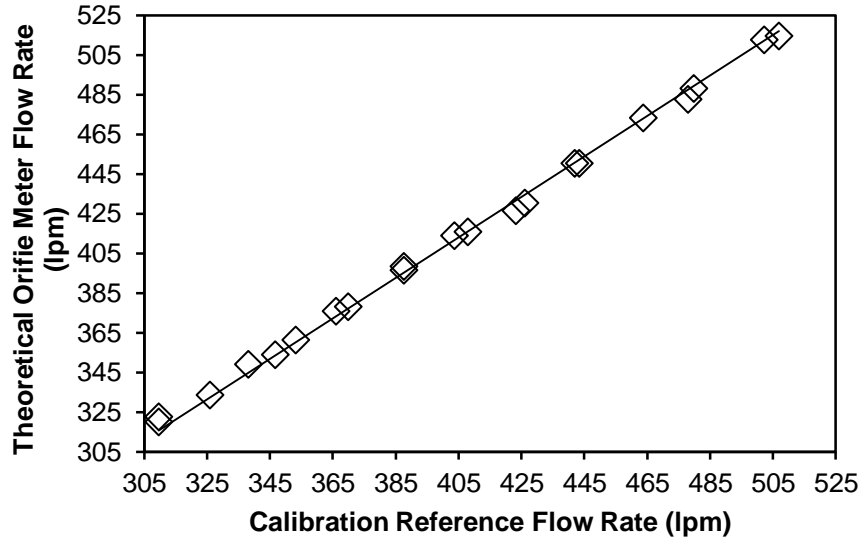


Figure 3.4: Example of one orifice meter calibration curve showing similar behavior between the theoretical orifice meter flow and actual flow (calibration reference). Linear regression was forced through zero as no flow at the calibration reference should result in no flow at the orifice meter.

Table 3.2: Volumetric flow rate (m^3/s) with respect to manometer differential pressure for each chamber, where dP is differential pressure read off the manometer (in. wg) and ρ_i is incoming air density calculated using dry bulb temperature, relative humidity and elevation (kg/m^3).

Orifice Meter	Volumetric Flow Rate (m^3/s)
1	$0.0074517 * (dP/\rho_i)^{0.5}$
2	$0.0078756 * (dP/\rho_i)^{0.5}$
3	$0.0078068 * (dP/\rho_i)^{0.5}$
4	$0.0082215 * (dP/\rho_i)^{0.5}$
5	$0.0077040 * (dP/\rho_i)^{0.5}$
6	$0.0071034 * (dP/\rho_i)^{0.5}$

3.4 Chamber Internal Pressure Map

3.4.1 Purpose

The design of the chamber required that all chambers maintain a positive internal pressure with reference to the background. The positive pressure system operates with intentional leakage occurring out of the chamber, eliminating infiltration. In order to confirm a constant positive pressure inside all chambers at all times, a chamber internal pressure validation test was conducted.

3.4.2 Approach

A total of 15 differential pressure readings (5 locations from 3 heights within the chamber, Figure 3.5) between inside and outside each chamber were taken to create a pressure chart. The orifice meters were completely open, the holes on the bottom of the chambers were sealed, the feed bin was inside the chamber, and the opening was maintained at an opening area similar to when animals are present. An electronic differential manometer (Model 260-MS4, SETRA, Boxborough, MA) was used for this test. The negative end of the pressure sensor remained open to the background air while the positive end was connected to a plastic tube with small bottle acting as a buffer attached at the other end. This buffer was included to reduce the readings from being affected by drafts inside the chamber. The buffer was affixed to a rigid pole for ease of measurement. A series of holes were poked into the sides of the bottle to prevent pressure build-up. This test was conducted once a day on 3 separate days to assess repeatability of results.

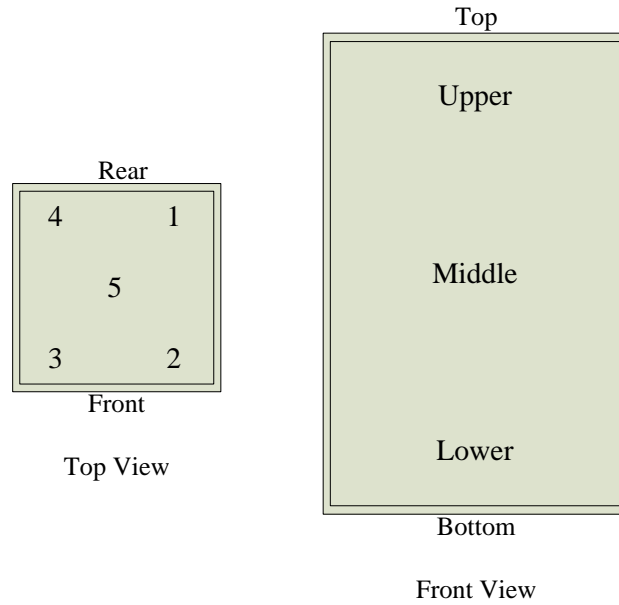


Figure 3.5: Location of pressure sample points inside chamber.

3.4.3 Results

Through analysis of the pressure test results, positive pressure inside the chamber was observed. Due to the loose nature of the hood, a small movement might induce a measurable pressure change, i.e. reducing the hood opening area will cause a more positive pressure while increasing the hood opening area will cause a near zero pressure. During normal test conditions, when the animal is immobile, the internal pressure should be positive for our test. Table 3.3 shows the average reading +/- standard deviation from three trials. The lowest observed pressure was 16.7 Pascals, which was still sufficiently positive. This shows that the chambers do not have openings that are sources of infiltration.

Table 3.3: Pressure mapping (unit: Pa) for chambers at five sample locations and three chamber heights; SD = standard deviation (unit: Pa); n = number of samples.

Chamber	Differential Pressure (Δ Pa) = (Average \pm SD)							
	Sample Location (n=3)					Region (n=5)		
	1	2	3	4	5	Upper	Middle	Lower
1	25 \pm 2.1	25 \pm 0.9	23 \pm 1.7	24 \pm 1.4	24 \pm 1.1	23 \pm 1.5	25 \pm 1.4	24 \pm 1.1
2	23 \pm 3.1	22 \pm 3.7	21 \pm 3.4	19 \pm 1.5	19 \pm 0.4	22 \pm 3.0	22 \pm 2.4	18 \pm 0.9
3	23 \pm 0.9	22 \pm 4.1	21 \pm 0.4	24 \pm 2.7	21 \pm 1.2	24 \pm 2.2	21 \pm 1.1	22 \pm 2.6
4	20 \pm 2.1	21 \pm 3.6	22 \pm 6.5	20 \pm 2.2	17 \pm 2.3	17 \pm 1.7	22 \pm 3.0	21 \pm 3.2
5	33 \pm 6.7	35 \pm 2.1	35 \pm 1.6	35 \pm 0.6	33 \pm 2.2	35 \pm 1.8	35 \pm 1.2	32 \pm 4.4
6	19 \pm 0.5	19 \pm 2.7	17 \pm 1.9	17 \pm 2.5	20 \pm 0.8	17 \pm 2.5	19 \pm 1.1	19 \pm 1.1

3.5 Chamber Uniform Air Distribution Test

3.5.1 Purpose

In order to verify how well the gas inside the chamber is mixing, a gas mixing test was conducted. This test serves as an important tool in verifying that the gas sample taken is representative of the entire chamber, that there is not additional ventilation air entering the chamber from a location other than the orifice, and that gases generated by the cattle are well-distributed throughout the chamber and not accumulating in a stagnant air pocket (and thus not being measured).

3.5.2 Approach

Air mixing was assessed using a smoke test. Since all chambers are identical, this test was only conducted on Chamber 1, though it might be advisable to test all chambers periodically as the system ages. First, the chamber was prepared for the test. In addition to supply and return ducts for the air recirculation unit, there is a ventilation port supplying fresh air, a sampling port and a sampling return port (Figure 3.6). Holes in the top of the chamber for gas sampling were blocked. One of the ports was left open to serve as the inlet for the ventilation air. The test was conducted without an animal in each chamber. The hood and panel normally used to create an enclosure around the animal (Figure 3.7) was partially sealed.

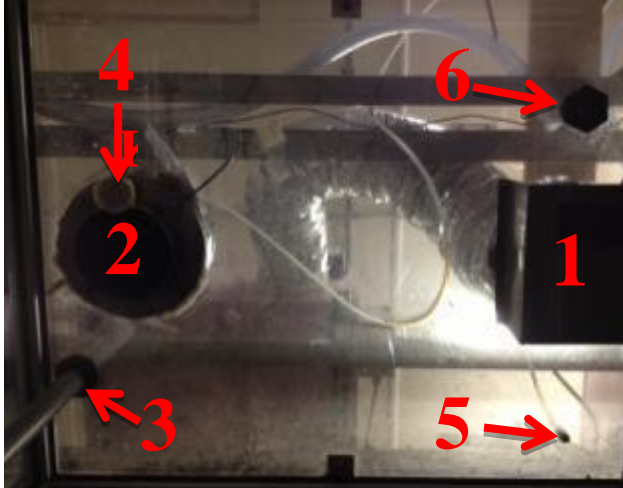


Figure 3.6: Bottom view of the top of the chamber showing supply (1) and return (2) air ducts, water line (3), sampling line (4), sampling return line (5) and ventilation port (6).



Figure 3.7: Styrofoam board within a section of 14" diameter plastic tube acts as an animal's head and sufficiently seals the hood.

A fog machine (Model 1700, Rosco Laboratories Inc., Stamford, CT) was placed in the feed bin inside the chamber. The smoke machine was turned on for 30 seconds. The general movement of smoke was observed. The test was only done on chamber 1, but repeated numerous times.

3.5.3 Results

Upon turning on the smoke machine, the chamber was filled with gray smoke within 10 seconds. Upon meeting the ventilation and supply air, the smoke mixed with chamber air and quickly dissipated, escaping through cracks left in the animal hood. Through visual observation of the behavior of the smoke inside the chamber, the gas inside the chamber should be observed to mix well and quickly. The location of the sampling port is not essential to accurate concentration readings as the air inside is well mixed and uniform, providing the same concentration throughout the chamber.

3.6 INNOVA 1412i Calibration

3.6.1 Purpose

The following section documents the approach and method of conducting the gas analyzer calibration. For step-by-step instructions, refer to Appendix C.

In order to maintain levels of high accuracy in gas concentration analysis, the INNOVA 1412i gas analyzer should be periodically calibrated, according to the discussion in the following section.

3.6.2 Approach

The INNOVA's accuracy should be checked weekly during daily operations. For each gas being monitored, a sample of gas with certified concentration should be directly injected into the INNOVA. The INNOVA 1412i should be calibrated when the difference between the manufacturer-specified concentration of the certified gas and the INNOVA reading is above an absolute value of 5%. Otherwise, it is recommended that it be calibrated every 3 months. For the calibration of the INNOVA a series of known concentration gases are required. The only upper and lower constraints for the concentrations are the INNOVA's detection limits. A Gas Dilution System (Model No. 4040, Environics, Tolland, CT) was used to provide a stable gas flow. A water bath capable of reaching between 10 and 30 °C was required to control the temperature and humidity of the gases, as psychrometric properties are crucial to the calibration sequence. A series of Teflon tubes and Swagelok connectors are required to provide leak-free gas connections between the calibration gas cylinders and the INNOVA. For N₂O, CO₂, and CH₄, their concentrations are affected by humidity, and thus to ensure the same level of humidity while calibrating, Nafion tubing was submerged in the water bath to reach similar to chamber operating

conditions. A zero-gas calibration using N_2 should be conducted first. A water vapor calibration should be next, followed by the other gases required in the experiment (N_2O , CO_2 , CH_4 , NH_3 and SF_6). Remember to reload the INNOVA's filter after each calibration for the new filter calibration settings to take effect. Immediately following the calibration, a post-calibration concentration check should be done to verify the accuracy of each gas and ensure a valid calibration was done.

3.7 System Evaluation (Concentration Recovery) Test

3.7.1 Purpose

The following section documents the approach and method of conducting the system component leakage test. For step-by-step instructions, refer to Appendix D.

A system component leakage test was conducted using a tracer-gas in order to identify problems with the gas sampling subsystem such as leakage in the lines or a gas analyzer fault. The gas sampling line is comprised of the multiplexer unit, 7 pumps, 100 ft of Teflon tubing to route and distribute samples and the INNOVA gas analyzer. This allows many potential sources of leakage that could dilute the sample analyzed and yield an erroneous emission calculation. This test should be performed before every recovery test.

3.7.2 Methods

For this test, SF₆ (6.293 ppm_v ±1%, primary certified) served as the tracer gas and was injected directly into the gas sampling port outside the chamber (Figure 3.8). Since the chamber leakage test identified no infiltration, the chamber may be regarded as contributing negligible leakage. For the sampling system of each chamber, one at a time, SF₆ was supplied through the vacuum pump, multiplexer, and into the gas analyzer (Figure 3.9). The Teflon coated pump was set at 17 lpm to mimic actual experiment conditions. Absolute leakage along the gas sampling line was quantified by the following formula:

$$C_{recovered} = C_{measured} / C_{target} * 100\% \quad (Equation 5)$$



Figure 3.8: Picture showing injection tube directed into sampling port.

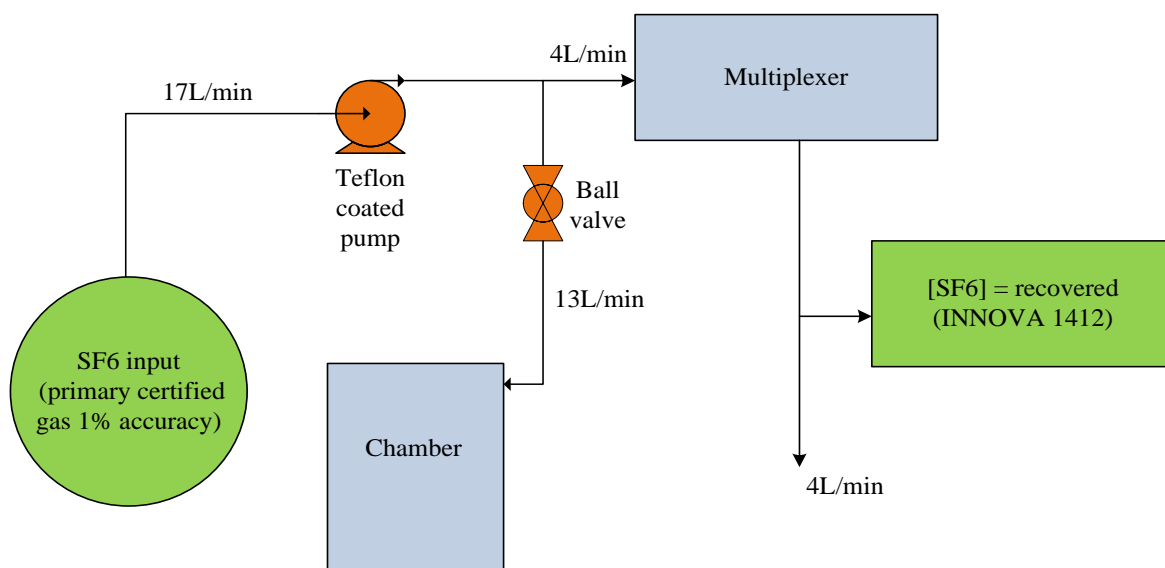


Figure 3.9: Leakage test setup showing gas injection location and direction. Ball valve shows location of orifice meter.

The INNOVA has a detection limit of 0.006 ppm for SF₆. For our injection rate, this accuracy equates to a 0.1% difference. Since the INNOVA can readily detect such minute changes, it is more than adequate for SF₆ concentration detection.

3.7.3 Results

The sampling line showed no significant leakage, with differences of within 0.1 ppmv between each chamber. Recoveries greater than 100% were within the measurement uncertainty of the INNOVA gas analyzer ($\leq \pm 5\%$). Results indicated that there was no gas dilution or leakage into the sampling lines from the chamber to the gas analyzer, ensuring no unexpected uncertainty due to differences in the INNOVA (Figure 3.10).

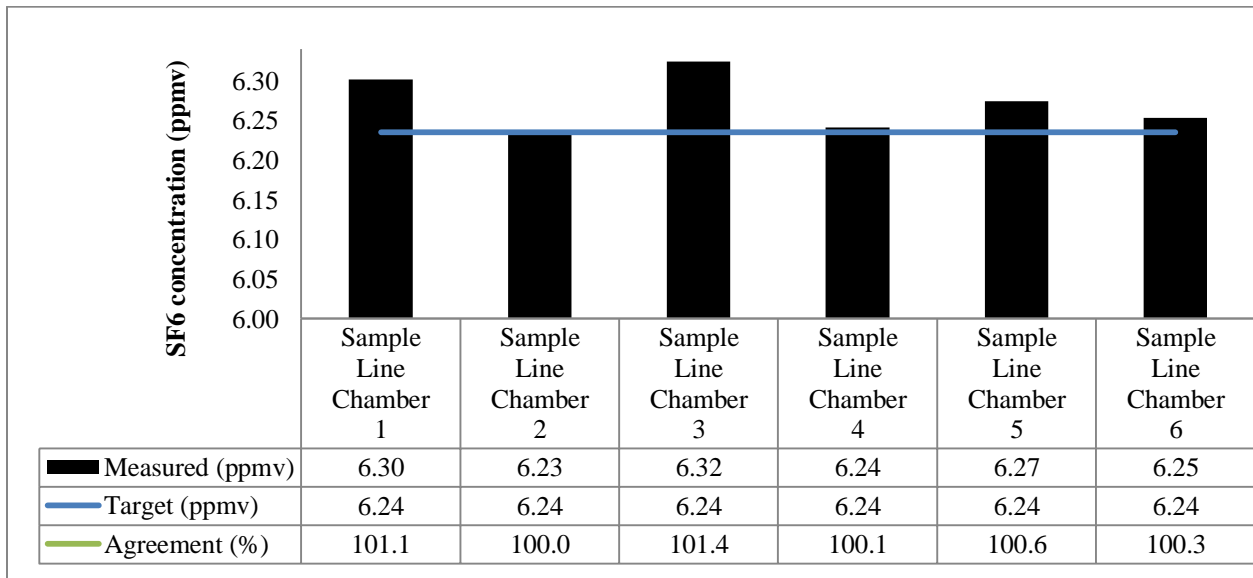


Figure 3.10: Concentration recovery results for all 6 chambers showing measured, target and concentration agreement.

3.8 System Performance (Mass Recovery) Test

3.8.1 Purpose

The following section documents the approach, an overview of the method, and sample results of a system recovery test. For step-by-step instructions, refer to Appendix E.

In order to validate emission calculations with animals, a system performance test was conducted to show the accuracy of our system. The integrity of the entire REMS system was quantified using a recovery test for system settings simulating those with animals present. SF₆ was selected for the tracer gas because animals do not produce it through ruminant activities, thus other animal activities in the background would not be expected to impact the results of this test. The recovery test should be done for all six chambers before and after every emission trial with animals.

3.8.2 Methods

Recovery tests were performed for one chamber at a time. The LabVIEW file “Project(3).vi” was used for this test. Tracer gas (6.293% ppm_v ±1%, primary certified SF₆) was introduced into only the chamber being tested, and the chamber and background concentrations were sampled during a test. A Gas Dilution System (GDS) (Model No. 4040, Environics, Tolland, CT) was used to provide a constant gas injection rate of 4.0 lpm (+/- 0.04 lpm). The GDS was used for the mass flow controller feature with no dilution because it can provide a very stable flow rate. A 30-minute warm-up period is required prior to use of the GDS. The gas was supplied directly into the chamber, with an injection point adjacent to the ventilation port to encourage complete mixing with the air inside the chamber (Figure 3.11). The rear hood was loosely blocked, also simulating the partial coverage when an animal is in the chamber (Figure 3.7).

At the start of the software for this test, 10 samples of background air were taken prior to any gas injection. The control software automatically switched to the user specified chamber after 10 samples of background air. After 5 samples of chamber air, sufficient data for a stable background concentration had been collected. At this time, the Gas Dilution System was turned on and the injection of SF_6 initiated. The system must be at steady state before assessing the final concentration, and approximately 20 minutes with constant gas injection were required to attain steady state. After attaining steady state, the injection of gas was stopped. The system continued to monitor as the concentration returned to background conditions, which took about 40 minutes (Figure 3.12). All gas concentration, temperature and relative humidity raw data were recorded and used for emission rate calculation.

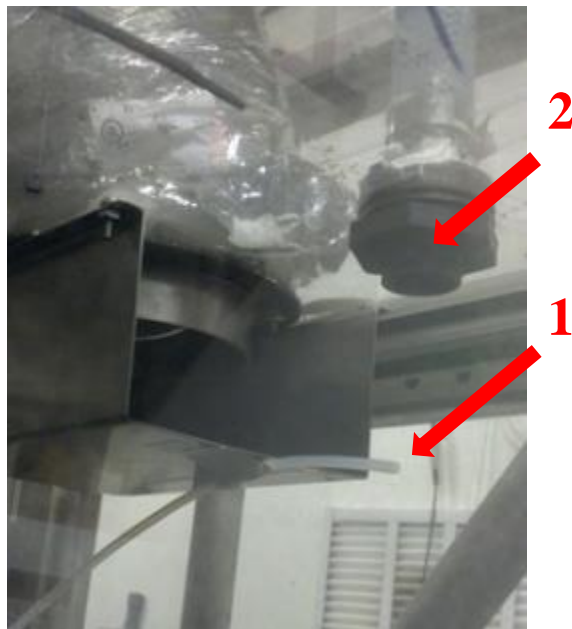


Figure 3.11: Internal picture of chamber showing injection point (1) next to ventilation port (2).

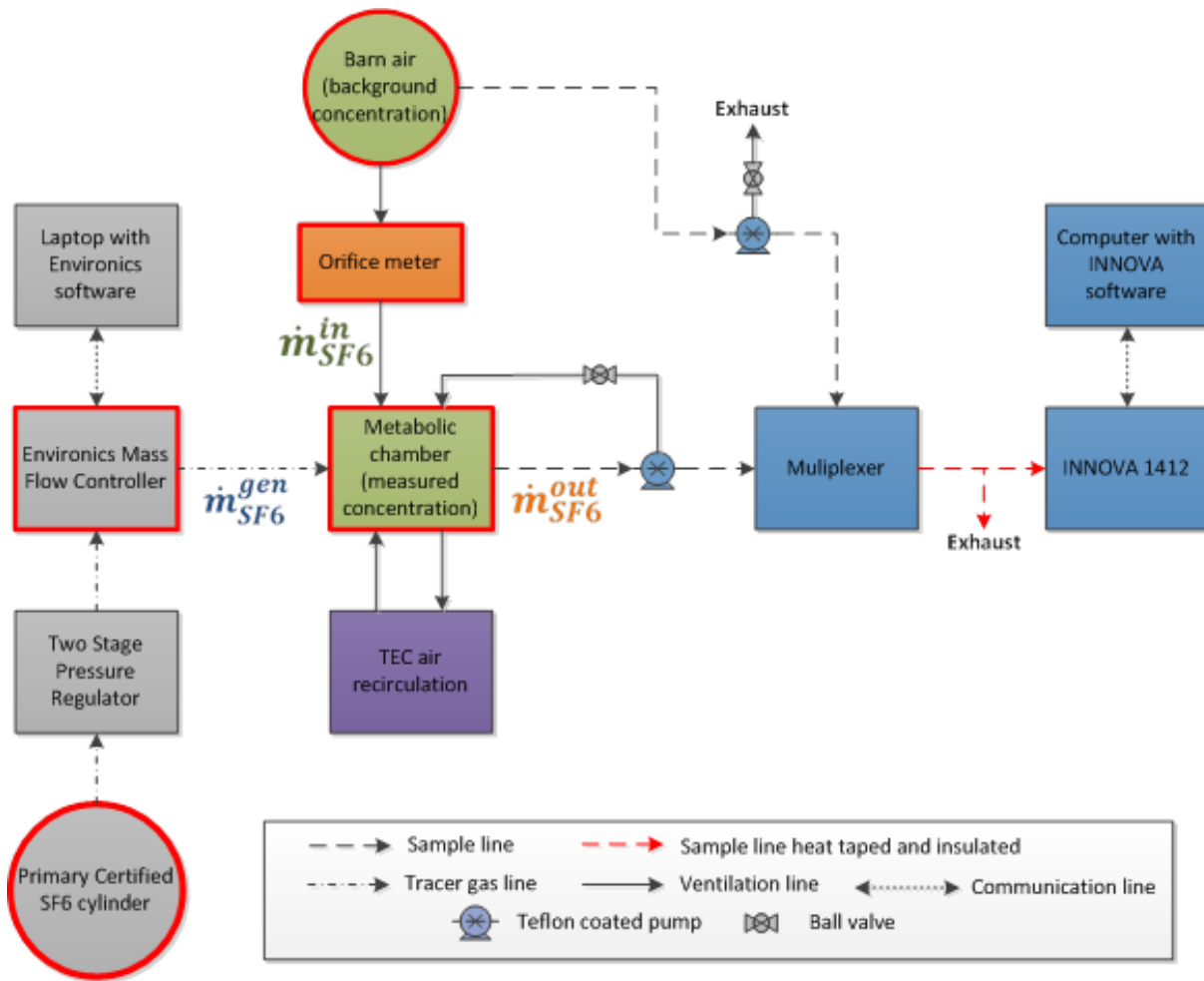


Figure 3.12: Schematic of tracer gas (SF₆) mass recovery experimental set-up including all sources of uncertainty.

The recovery test should be done for each chamber before and after each test or trial with animals. After averaging steady state concentrations to provide a background concentration, the mass flow rate of the gas being generated was calculated using Equation 3.4.

$$\dot{m}_g^{gen} = X_1 \times \dot{m}_{cyl} = X_1 \times \dot{V}_g^{gen} \times \rho_{cyl} \quad (\text{Equation 3.4})$$

Where:

X_1 = mole fraction of the gas component of interest

\dot{m}_{cyl} = mass flow rate of the cylinder $\left(\frac{kg}{h}\right)$

\dot{V}_g^{gen} = volumetric flow rate of the gas generated $\left(\frac{m^3}{h}\right)$

ρ_{cyl} = density of the cylinder $\left(\frac{kg}{m^3}\right)$

Volumetric flow rate can be converted to the correct unit according to the injected flow rate while density of cylinder is written on the cylinder. The emission rate calculated using measurements made with the REMS during the mass recovery test is found using Equation 3.5.

$$ER_{recovery} = T_g^{STD} \times \frac{P}{P_g^{STD}} \times \frac{M}{V_m^{STD}} \times 10^{-6} \left[\dot{V}_i \times \left(\frac{v_e c_g^e}{v_i T_g^e} - \frac{c_g^i}{T_g^i} \right) + \left(\dot{V}_{gen} \times v_e \times \rho_{gen} \times \frac{c_g^e}{T_g^e} \right) \right] \quad (\text{Equation 3.5})$$

Where:

T_g^{STD} = temperature of gas at STD conditons (K)

P_g^{STD} = barometric pressure of gas at STD conditions (atm)

M = molar mass of a gas $\left(\frac{kg_g}{mol}\right)$

V_m^{STD} = molar volume 0.022414 at STD conditions $\left(\frac{m^3}{mol}\right)$

\dot{V}_i = ventilation rate of inlet $\left(\frac{m_{ma}^3}{s}\right)$

v_e = specific volume of exhaust air $\left(\frac{m_{H2O}^3}{kg_{da}}\right)$

v_i = specific volume of inlet air $\left(\frac{m_{H2O}^3}{kg_{da}}\right)$

c_g = concentration of a gas (ppm_v)

Molar mass and specific volumes can be calculated with simple internet tools. The percent of mass recovered come from the mass balance is calculated by the following formula:

$$ER_{recovery\ test} = \dot{m}_g^{out} - \dot{m}_g^{in} = \dot{m}_g^{gen} \quad (\text{Equation 3.6})$$

For 100% recovered, i.e. the steady state mass of the tracer gas cylinder (\dot{m}_g^{gen}) equals steady state mass measured by the system ($\dot{m}_g^{out} - \dot{m}_g^{in}$).

$$\frac{\text{Mass measured by REMS}}{\text{Known amount of mass injected}} = \frac{\dot{m}_g^{out} - \dot{m}_g^{in}}{\dot{m}_g^{gen}} \times 100\% = 100\% \text{ for full mass recovery}$$

So, with a known ER (\dot{m}_g^{gen}) compared to the $ER_{recovery\ test}$ (measured by the system), the mass recovered can be evaluated by:

$$\frac{ER_{recovery\ test}}{\dot{m}_g^{gen}} \times 100\% = \text{recovery percent} \quad (\text{Equation 3.7})$$

3.8.3 Results

An example of recovery test results is shown in Figure 3.13. The plot displays the recovery rate for five tests for each chamber. Results show recovery percentages of between 90% and 100% for all chambers over the five tests. Table 3.4 shows the average recovery percentages for all six chambers. This is a good result, as a recovery rate of above 90% is deemed acceptable for animal emission recovery rates. If the recovery rate was below 90%, suggestions are to look for leaks in the sampling line, chamber, or air conditioning unit.

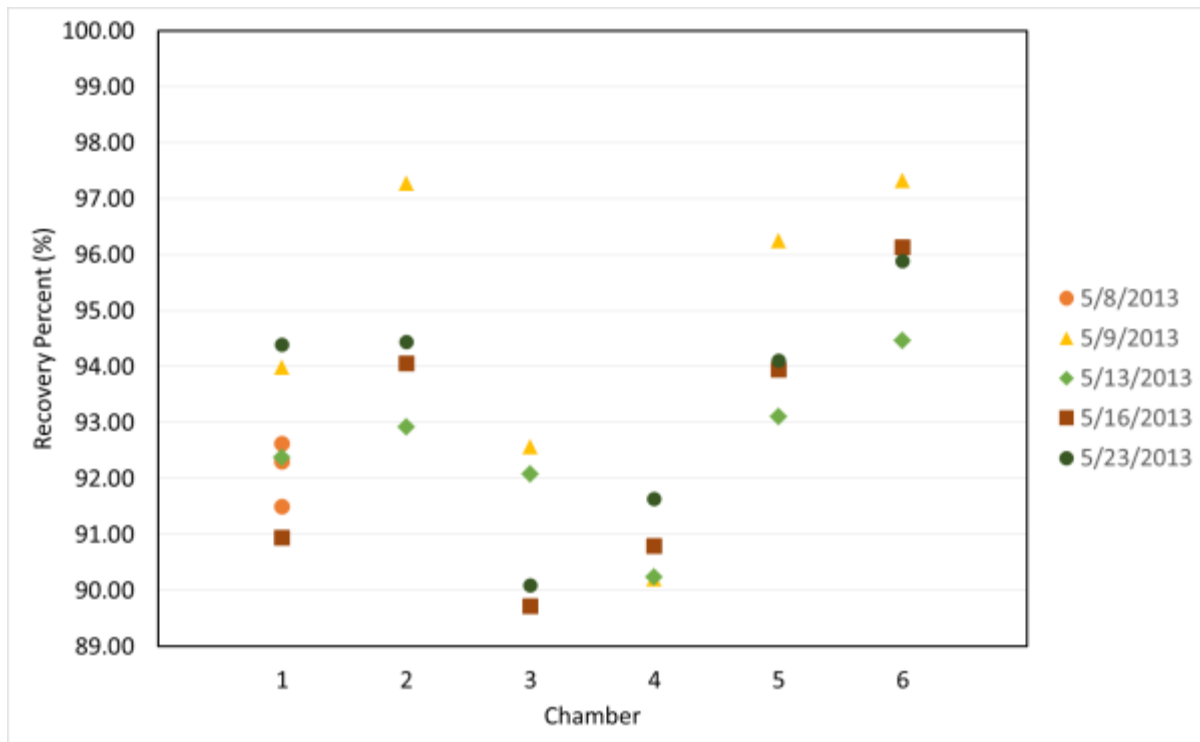


Figure 3.13: Recovery test results for 6 chambers from 5 separate tests. Percent recoveries were between 90% and 100%.

Table 3.4: Average recovery percentages in respect to chamber, including standard deviation.

Chamber	1	2	3	4	5	6	total
Average recovery percent	92.92	94.67	91.11	90.72	94.35	95.95	93.16
Standard Deviation	1.15	1.60	1.23	0.58	1.16	1.01	2.15

Chapter 4: System Implementation (Assessment of Beef Cattle Emissions)

4.1 General System Maintenance

4.1.1 REMS System Maintenance Checks

The following table (Table 4.1) is a comprehensive list of all maintenance checks and tests that should be conducted to maintain the integrity of the REMS. The “Check or Diagnostic Test” column indicates the check or test to be performed. The “Frequency/Timing” column indicates when or how often the check or test should be performed, if on a regular interval. The “Action Trigger” column indicates a parameter that signals the need to perform said check or test. Some items have both a frequency and a trigger for the check. The “Method Reference” column indicates the text and/or Appendix section that corresponds to the method for performing said check or test.

Table 4.1: Maintenance Checks/Tests, including frequency/timing, action trigger and method references.

Check/Diagnostic Test	Frequency/Timing	Action Trigger	Method Reference
Building Environmental Control System Check	Before each experiment	Animals in building	4.1.2
INNOVA Accuracy Test	Once every 2 weeks	Sampling for gas measurements	3.6; A.C
Chamber Air Conditioning Unit Seal Check	Once every month	CACU opened/filter changed	4.1.4
Filter Check	Variable	Animals in chamber; building environmental control system used	4.1.3
Filter Replacement	Variable	Filter is dirty	4.1.3
INNOVA Calibration	Variable	INNOVA Accuracy <95%	3.6; A.C
Mass Recovery Test	Before and after each experiment	Changes to system components	3.8; A.E
Multiplexer Leakage Test	Variable	Recovery percent <90%	3.2; A.B
Component Leakage Test	Variable	Recovery percent <90%	4.1.5
Concentration Recovery Test	Variable	Recovery percent <90%	3.7; A.D
Vaisala Accuracy Check	Variable	Recovery percent <90%	

4.1.2 Building Environmental Control System

Proper operation of the Building Environmental Control System (BECS) for the building that houses REMS is essential to maintain comfort and minimize gas concentrations within the building outside the chambers, as well as reduce fluctuations in concentrations to minimize the effects of building ventilation on emissions measurements. Before (during) and after (between) studies with animals, the settings for all of the building environmental control units should be adjusted to the appropriate settings.

The BECS within the building is provided by two sets of air conditioning units, supplemental heating and exhaust elements. One set serves the feed preparation room, computer room and bathroom. The other set serves the animal space. This section only discusses the set that serves the animal space. For this room, there is a large air handler that provides both heating and cooling for outdoor air supplied to the room through ceiling ducts opening near the front end of the animals. In cold situations, a supplemental heater provides the additional heat to keep the animals comfortable. A separate series of exhaust ducts located at the rear end of the animals with a fan in the equipment room facilitates steady ventilation and flow patterns, which result in more consistent and uniform air quality and steady background gas concentrations. This exhaust fan is only necessary when animals are in the barn. The switch for the exhaust fan is located on the east wall of the equipment room.

The large air handler and exhaust fans should be turned on during all experiments, with the appropriate settings selected. For further information on selecting the appropriate settings on the air handling units, when to turn on supplemental heater, and locations of thermostats and switches, refer to Appendix G.

4.1.3 Filters

Sampling line filters (4.7 cm diameter, CAT No. 1882-047, Whatman, Maidstone, Kent, United Kingdom) inside the chambers (Figure 4.1) should be changed every 24 hours if animals are present, otherwise once before every separate test.



Figure 4.1: Chamber ceiling showing sampling line filter.

Filters (295 mm x 448 mm x 19 mm, PerfectPleat, American Air Filter International, Louisville, KY) for the Chamber Air Conditioning Unit should be inspected for dust coverage every 2 months and replaced when necessary.

The filter for REMS ventilation air supply located on South wall (241 mm x 241 mm x 19 mm, PerfectPleat, American Air Filter International, Louisville, KY) for ventilation supply to the blower (Figure 4.2) should be inspected for dust coverage biweekly and replaced if necessary.

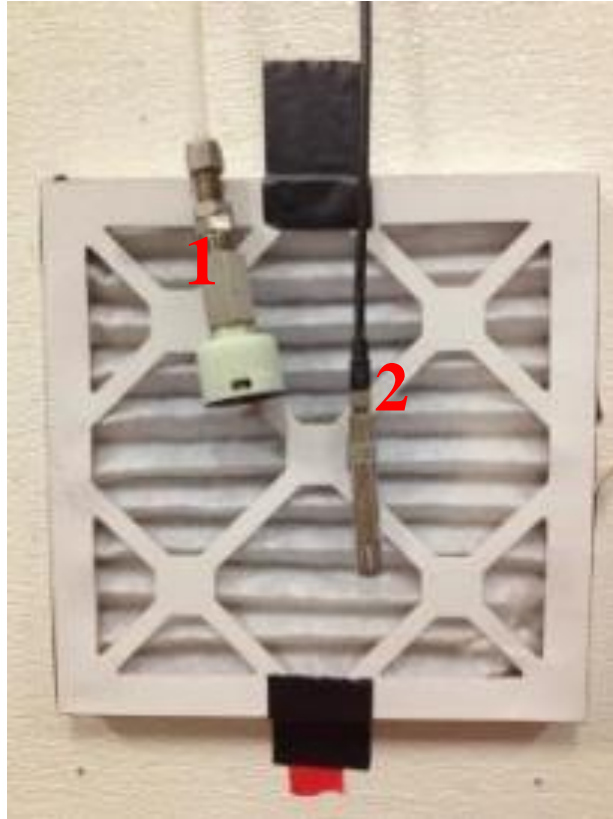


Figure 4.2: Filter to blower intake for chamber ventilation, with and background air sampling port (1) and temp/rh sensor (2) shown. Located on the south wall of the animal space.

AC and supplemental heater filters (495 mm x 448 mm x 44 mm and 495 mm x 622 mm x 44 mm, PerfectPleat, American Air Filter International, Louisville, KY) for the Building Environmental Control System (Figure 4.3, 4.4) inside the equipment room should be inspected every 2 weeks and replaced if necessary.

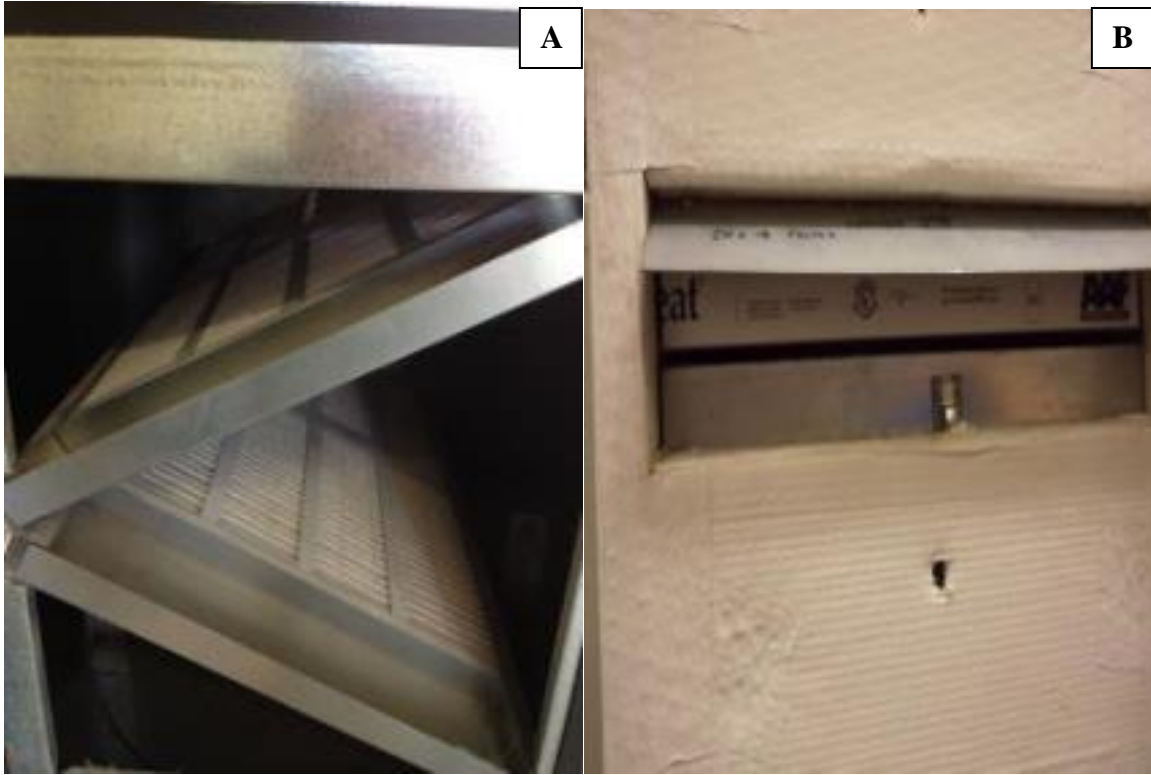


Figure 4.3: Filters inside Building Environmental Control units for the animal space. Main ventilation supply unit (A) and supplemental heating unit (B). Located in Equipment Room.

For filter locations refer to Figure 4.4.

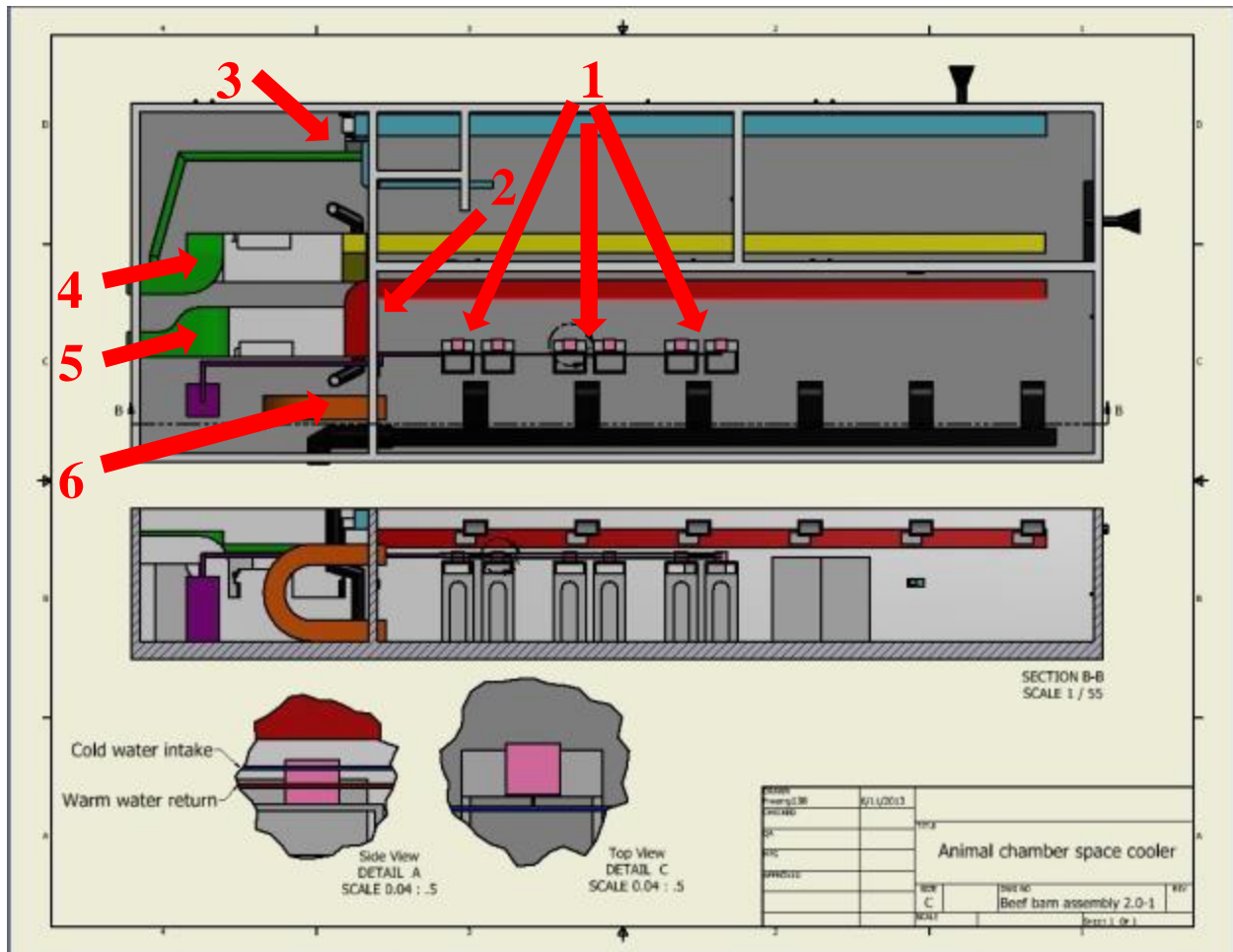


Figure 4.4: Schematic of building showing environmental control equipment and filter locations: (1) six sampling line filters inside chamber and six Chamber Air Conditioning Unit filters, (2) one filter for the inlet to the chamber ventilation supply, (3) one filter for environmental control unit for non-animal space, (4) one set of filters for air handling unit with supplemental heating to feed room, (5) one set of filters for environmental control unit for ventilation supply to the animal space, and (6) one filter for air handling unit with supplemental heating to the animal space.

4.1.4 Chamber Air Conditioning Unit

Since the Chamber Air Conditioning Unit maintains a substantial negative pressure, it the most significant source of potential leakage. The top cover is sealed with silicone along the edges and held tight by 4 butterfly nuts. Whenever the heat exchanger is opened or a low recovery rate

(<90%) is observed, the silicone should be replaced and used to seal all openings between cover and rest of unit, and duct tape should be applied over the silicone. Other openings around the unit may appear over time, and a visual inspection should be conducted every month. A small hatch (Figure 4.5) in the middle of the cover provides access to the filter. The edges of this hatch should also be taped to seal off leaks.



Figure 4.5: Top view of CACU with filter cover, sealed with tape. Please note location of screws for cover taped over (1) and butterfly nuts (2).

4.1.5 Gas Sampling Line Components

The pumps, connections and solenoids are a crucial part of the gas sampling system. A leak at any location under negative pressure or at the solenoids may dilute the sample, which would greatly affect the emission calculated. Leaks under positive pressure would not change the concentration of the sample, but it is important that a sufficient flow rate of sample reach the analyzer. The following check is another quick indicator that the leakage is within acceptable limits.

A rotameter (Figure 4.7) located next to the desktop computer in the sample preparation room should be used to verify the correct amount of air is being provided by the pumps and that the solenoids are opening properly.

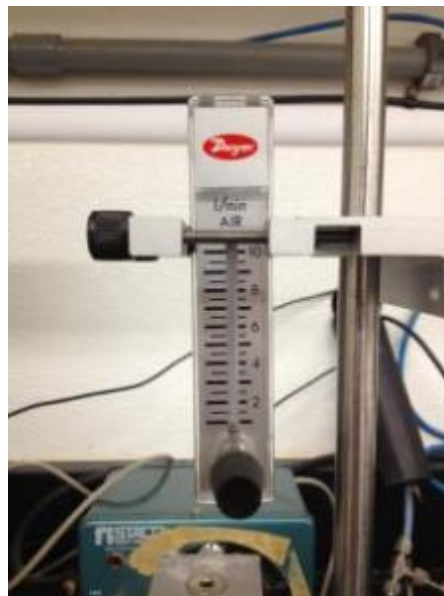


Figure 4.6: Rotameter used to check total airflow in the gas sampling line just prior to the analyzer.

Expected flow should be close to 4.0 lpm when the analyzer is not taking samples (all solenoids closed). When the analyzer is taking a sample (solenoid to chamber being sampled opened), the

flow rate should drop to approximately 2.0 lpm. Please note that this test only serves as an indication of a problem; if expected flow is not near 4.0 lpm, troubleshooting steps should be taken to identify if a leak occurs at any place within the sampling line, if a solenoid is failing, or if another problem has occurred. In this case, each individual component must be checked for leakage using a liquid leak detector.

4.2 Experimental Startup for Emissions Monitoring with Cattle

The following steps should be carefully followed when conducting experiments with animals in the chambers.

4.2.1 Prior to introducing cattle

Feed should be prepared in advance (coordinate with collaborating animal science team).

Animals should be prepped to be moved. All pumps above chambers should be turned on. A recovery test should be completed within one day in advance. All sample line filters should be replaced with clean ones. Make sure water drinkers dispense water. Line up the metal chain used to hold the cattle's neck for easy and quick connection. Feed bin should be inside chamber. Gas analyzer should be turned on at least one hour before experiment.

Adjust the settings for the Building Environmental Control System for the animal space, as described in Section 4.1.2 and Appendix G. The air handling unit should be on, the operating mode selected, and the setpoint temperature selected. The supplemental heating should be on, if needed, and the setpoint selected. The exhaust system should be on and in the automatic mode. If for any reason the exhaust fans do not start automatically, manually start the fans by pressing the green "Start" button on the main exhaust switch located in the equipment room.

4.2.2 Introducing cattle to chambers

The cattle staging area should be clear of all debris. Animal hoods should be unzipped and chamber doors should be unlocked. Use metal panels on east wall of the animal space to direct the cows into their stalls. All other doors should be closed. Once the animal enters its stall, one person should be waiting at chamber door to pull animal in using halter. Firmly hold halter after animal's head enters the chamber to allow chaining and hooding of animal. After animal is

chained and hooded, remove halter, then close and lock chamber door. For specific timing to introduce each animal, please refer Appendix F.

4.2.3 Adding feed to chamber

Feed should be added immediately after each respective chamber has completed the first round of sampling. Feed should be evenly distributed in the feed bin, but away from the drinker.

Remember to lock the chamber doors after feed has been introduced. Note: opening the doors while sampling will cause invalid measurements due to dilution. If door must be opened, it should be done immediately after the chamber in question has been sampled. Guarantee 20 minutes of undisturbed operation within each chamber before being sampled. If this timing cannot be granted, a note should be made and corresponding data points should be removed from further analysis.

4.2.4 Initiating software and gas monitoring

Open “Project (2)” from “C:/REMS”. Enter volumetric flow rates for each chamber (see Section 3.3.4 for details) on the second page immediately before animal is introduced. Click “Run” on the first page. Data will be automatically saved under “C:\REMS\Data”. For more information, refer to Appendix A.

Press “Monitor” on the INNOVA. Press “Proceed” then “Yes”. Make sure “Print Data Log” and “Print Error Log” are turned OFF. For more information, refer to Appendix A.

4.2.5 Periodic checks during data collection

Routine check-ups on the data collection program should be done every 30 minutes throughout the experiment, or as often as possible. A quick check of chamber concentrations could identify REMS problems, such as HVAC malfunction indicated by high CO₂ concentration. A quick

check of the program status could reveal any errors that could result in unsaved data. A quick check of the animals should also be done at this time via video cameras to identify other problematic situations early, such as animals out of the chamber or excessive condensation build-up on chamber door.

The computers at the farm are equipped with TeamViewer, a remote desktop program. Before leaving, open TeamViewer on the computer you are trying to access, record the ID number and password. These will be required to access the computers. For other people to gain access to remote desktop, the ID number and password must be shared. The TeamViewer program is required on all computers trying to gain access to the PC at the farm. For download info go to www.teamviewer.com. ID and password details should be agreed upon by the monitoring team before the experiment begins, and all team members and supervisors should be granted viewing access.

4.2.6 Removing cattle from chambers

At the conclusion of the data collection period, each animal should be removed following the final sample of the respective chamber. Leftover feed should be gathered and weighed separately from the feed bin. Buckets and scale are located in the feed preparation room. The feed is then dried and weighed again. Analysis of dry matter must be completed to account for water that is splashed out of the drinker. Each chamber must be internally cleaned before the next use. Walls and floor should be swept and vacuumed. Feed bins should be removed, hosed down, and allowed to dry before returning to chamber.

4.2.7 Shutting down System control software

After all gas samples are complete and animals are removed, wait for the system to conclude sampling the background air before closing the program. Click “Stop” to conclude sampling. For

more information about the program, refer to Appendix A. Press “Monitor” on the INNOVA. Press “Yes” when asked if sampling should be stopped.

4.2.8 Finalizing the system until next use

A recovery test (Section 3.8) should be done immediately after each sampling period to ensure nothing has been damaged or otherwise changed during the experiment. New filters should be installed before the recovery test.

4.3 Sampling and Analysis Strategies for 24-hour Emissions

4.3.1 Purpose

Sampling of animal emission measurements varies depending on the design and operation of the quantification system (Perez, 2001). Previous research using the REMS system has taken one sample approximately every 1.5 hours (refer to Section 2.6). One potential limitation of this approach is that peaks or dips between samples may be undetected and neglected from emissions calculations, which could result in over- or under-estimated daily emissions. Since our system cycles through all chambers before returning to the first chamber, over one hour passes between consecutive samples from each chamber. In order to determine if the emission rates calculated with REMS are representative of actual daily emissions, a more complete “fast-sampling” test was conducted in which a single chamber with a single animal was sampled once every 43.33 seconds for 24 hours, including short breaks to sample background. The results of this test were compared to a subsample from the full data set that would represent the typical sampling of REMS. Data were collected for six animals.

4.3.2 Approach

Chamber 1 was used for all fast-sampling tests. Six steers roughly 30 months of age and each weighing approximately 1900 pounds were tested over six consecutive days. Each steer was fed either a forage or grain-based diet, consistent with the diet each had been receiving for the prior two months. A companion animal was housed in the next stall to avoid social isolation effects for the test animal. On the morning of the start of each test for each animal, orifice meter flow rate and barometric pressure were recorded immediately before the sampling started.

The data collection began with the collection of 10 background (building) concentration measurements. The animal was placed into the chamber following the 10th sample from the background. This was to ensure that sampling occurred immediately following the introduction of the animal to the chamber to capture the dynamics of arriving at steady state. Data from the first 25 minutes of each chamber was not used in the calculation of emission rate, as the dynamic response of the chamber coming to steady state would not represent the actual emission rate. After one sampling cycle of 90 measures from the chamber followed by another 10 from the background, feed was introduced on the 10th sample of the background. Feed was only introduced once at the beginning of the experiment, and enough food was provided for 24 hours. Each animal was monitored for 24 hours.

The first 5 samples for each background and chamber sample were removed to avoid effects from transition between chamber and background and vice versa, and an estimated value was substituted for those samples in the calculations. The remaining 5 samples from the background were averaged to obtain a single background concentration. Linear interpolation was done between each background average to provide background concentrations for the full 24-hour period, used to calculate emissions rates. The remaining 85 gas concentrations from the chamber were used to calculate emission rate. For omitted background sample points, a value was generated by linearly interpolating between the previous and next 5-sample average background concentration. During the time of background sampling, the chamber concentration (25 samples = 5 from the previous chamber sample, 10 from the background, 5 that are omitted, and 5 more from the next chamber sample) was estimated by linearly interpolating between the average of the last 5 samples of the previous chamber measure and the average of the first 5 samples of the following chamber measure. Emission rate was calculated for each sample using Equation 4.1.

$$ER_{animal} = \dot{V}_i \times T_g^{STD} \times \frac{P}{P_g^{STD}} \times \frac{M}{V_m^{STD}} \times 10^{-6} \times \left(\frac{v_e c_g^e}{v_i T_g^e} - \frac{c_g^i}{T_g^i} \right) \quad (\text{Equation 4.1})$$

Where:

T_g^{STD} = temperature of gas at STD conditons (K)

P_g^{STD} = barometric pressure of gas at STD conditions (atm)

M = molar mass of a gas $\left(\frac{kg_g}{mol} \right)$

V_m^{STD} = molar volume 0.022414 at STD conditions $\left(\frac{m_g^3}{mol} \right)$

\dot{V}_i = ventilation rate of inlet $\left(\frac{m_{ma}^3}{s} \right)$

v_e = specific volume of exhaust air $\left(\frac{m_{H20}^3}{kg_{da}} \right)$

v_i = specific volume of inlet air $\left(\frac{m_{H20}^3}{kg_{da}} \right)$

c_g = concentration of a gas (ppm_v)

This formula provides an emission rate in grams/hour. In order to account for a whole day of emissions, that value was normalized for 24 hours. Since one sample was taken every 43.33 seconds, the normalization factor is 43.333 seconds/sample / 3600 seconds/hour to get 0.012 hours/sample. By multiplying our emission rate and the normalization factor, the result is observed in grams/sample. Finally, the results from a full day's worth of sampling (exactly 24 hours) are summed to get a final value in grams/24 hrs. This is effectively using the right rectangle integration method to calculate the area under the curve.

In the normal implementation of REMS with six animals, one complete REMS cycle is done every 86 minutes. Thus, only 10 samples of a particular chamber are taken in an 86-minute period. From the fast-sampling data, the samples corresponding to those taken at the same time as those in an 86-minute sampling frequency test are selected. If the samples happen to conflict

with the background being sampled, the selected data is shifted later in time until the 6th sample of the next chamber sample set because the first 5 chamber samples were discarded to avoid erroneous measurements during the transition period between background and chamber. This method allows us to mimic normal sampling frequencies using the data set collected for the fast-sampling test. These results also need to be normalized for 24 hours. Since one sample was taken every 86 minutes, the normalization factor is 86 minutes/sample / 60 minutes/hour to get 1.433 hours/sample. By multiplying our emission rate and the normalization factor, we observe a result in grams/sample. Again, the results from a full day's worth of sampling are summed to get a final value in grams/24 hrs.

In order to determine whether the results from the 86-minute sampling frequency of the REMS are representative of results obtained during the 43-second sampling test, the emission rates from each method were compared using a t-test. A two-tailed t-test was applied to compare the results of the two sampling methods. The null hypothesis for the t-test was $\mu_1 = \mu_2$ and the alternate hypothesis is $\mu_1 \neq \mu_2$, where μ_1 is total emission rate from the fast-sampling analysis and μ_2 is that from the 86-minute sampling frequency test. Visualization of the data to recognize any potential diurnal patterns was achieved by a time series plot for each steer's data set. For more robust analysis, two variations of the subsampling were completed: (1) selecting subsamples with different lag times from the first usable data point collected (15 minutes, 30 minutes and 45 minutes) from the placement of the cattle into the chambers; and (2) sampling frequencies with shorter gaps between each cycle than the 86-minute sampling frequency. Please note that the same method of estimating the chamber concentration during background sampling as the fast-sampling analysis was used. The first variation may help us capture any peaks or valleys in the

concentration. The second variation creates a smaller rectangle that can more accurately represent fluctuations in concentration.

4.3.3 Results

Table 4.2 shows the calculated total emission rates from one day of fast-sampling and the generated subset representing the same day with 86-minute sampling frequency for all six steers. No difference was observed between the emissions calculated using the two sampling frequencies (P=0.891). The right rectangle integration applied in this analysis has potential to over- or under-estimate the emission rates, depending if sample measures happen at peaks or valleys in the instantaneous emission.

Table 4.2: Total emission rates (g/d) from 24 hours of observations collected at 43-second and 86-minute intervals.

Steer	Sampling Frequency		
	43 seconds	86 minutes (5160 seconds)	Difference
325X	57.1	73.8	-16.7
104X	49.3	42.9	6.4
390X	54.5	51.3	3.2
475X	152.6	149.6	3.0
202X	107.9	125.4	-17.5
163X	134.2	117.4	16.8
Average	92.4	93.4	-1.0
Std Err			5.7
P-value			0.8910

From the time series plot (Figure 4.8) no apparent patterns were observed, though large fluctuations could be observed throughout the day. Further research is needed to determine the variables that affect the peaks and valleys, in order to assess whether or not diurnal patterns exist.

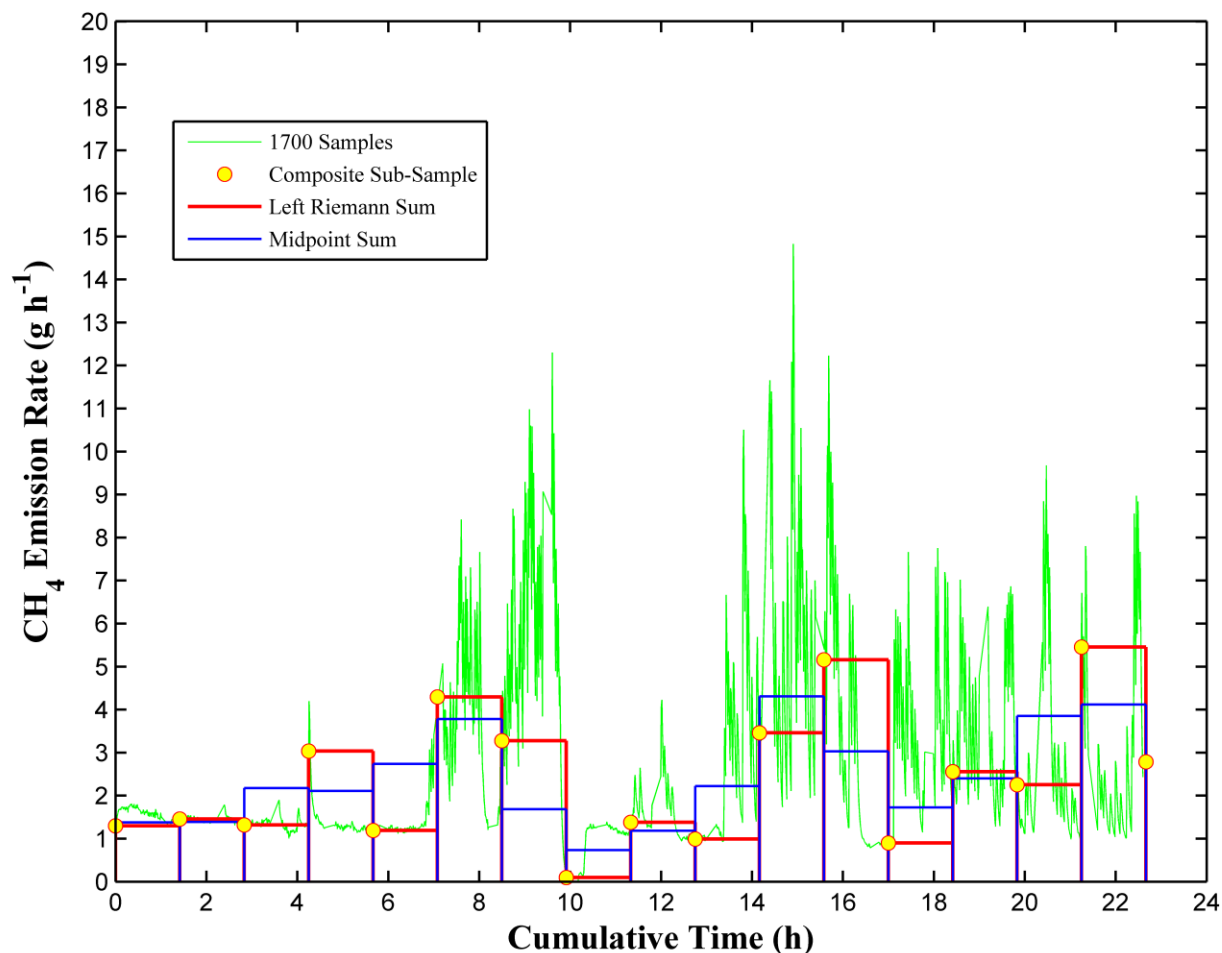


Figure 4.7: Time series plot of emission rate from one chamber with green rectangles showing fast-sampling emissions and red and blue rectangles showing 86-minute sampling frequency emissions integrated using different estimation methods.

When the subsample start times were shifted, the results showed trends for differences with longer lag times but were never statistically different (Table 4.3; $P=0.0543$ to 0.8910). The first sample point that was used for the analysis was at approximately 30 minutes after sampling started. Thus +30 minutes indicates typical experimental conditions, and +45, +60 and +75 corresponds to a lag time of 15, 30 and 45 minutes, respectively.

Table 4.3: Subsamples with different lag times for taking the first chamber sample. Values represent emission rate (gram/day) differences between samples collected at 43-second or 86-minute intervals.

Animal	+30 minutes	+45 minutes	+60 minutes	+75 minutes
325X	-16.7	4.6	1.3	8.0
104X	6.4	-1.1	0.5	-5.5
390X	3.2	10.8	2.0	-2.3
475X	3.0	2.9	25.8	-18.8
202X	-17.5	21.5	23.9	-12.1
163X	16.8	9.8	6.6	-13.1
Mean	-0.8	8.1	10.0	-7.3
Std Error	5.5	3.2	4.8	3.9
P-value	0.8910	0.0543	0.0905	0.1186

Taking subsamples with shorter gaps between each cycle also yielded no differences in emission rates (Table 4.4).

Table 4.4: Subsamples taken at different sampling frequencies. Values represent emission rate (grams/24 hrs) differences between samples collected using custom sampling frequency and 43-second sampling frequency.

Animal	15 minutes	30 minutes	45 minutes	60 minutes	86 minutes
325X	4.6	0	-1.2	-4.3	-16.7
104X	1.5	0.6	2.8	-1.9	6.4
390X	0.4	-0.3	2.4	0	3.2
475X	5.1	10.2	0.8	7.2	3
202X	0	7.8	0.4	-2.3	-17.5
163X	2	6.9	0.8	9.7	16.8
Mean	2.3	4.2	1	1.4	-0.8
Std Error	2.1	4.6	1.4	5.7	13.6
P-value	0.4236	0.1174	0.5802	0.0680	0.0026

The results of this study indicate that a sampling frequency of 86 minutes yields an estimated daily emission rate with no less accuracy than sampling as quickly as 43 seconds. More exploration is needed to strengthen the conclusiveness of this result and should be further explored to verify other scenarios, such as different diets and ages of animals. This test was limited to six animals, and more animals would strengthen the result. Additionally, different estimation methods such as trapezoid or Simpson’s method should be explored.

Appendix A: Using the LabVIEW System control software

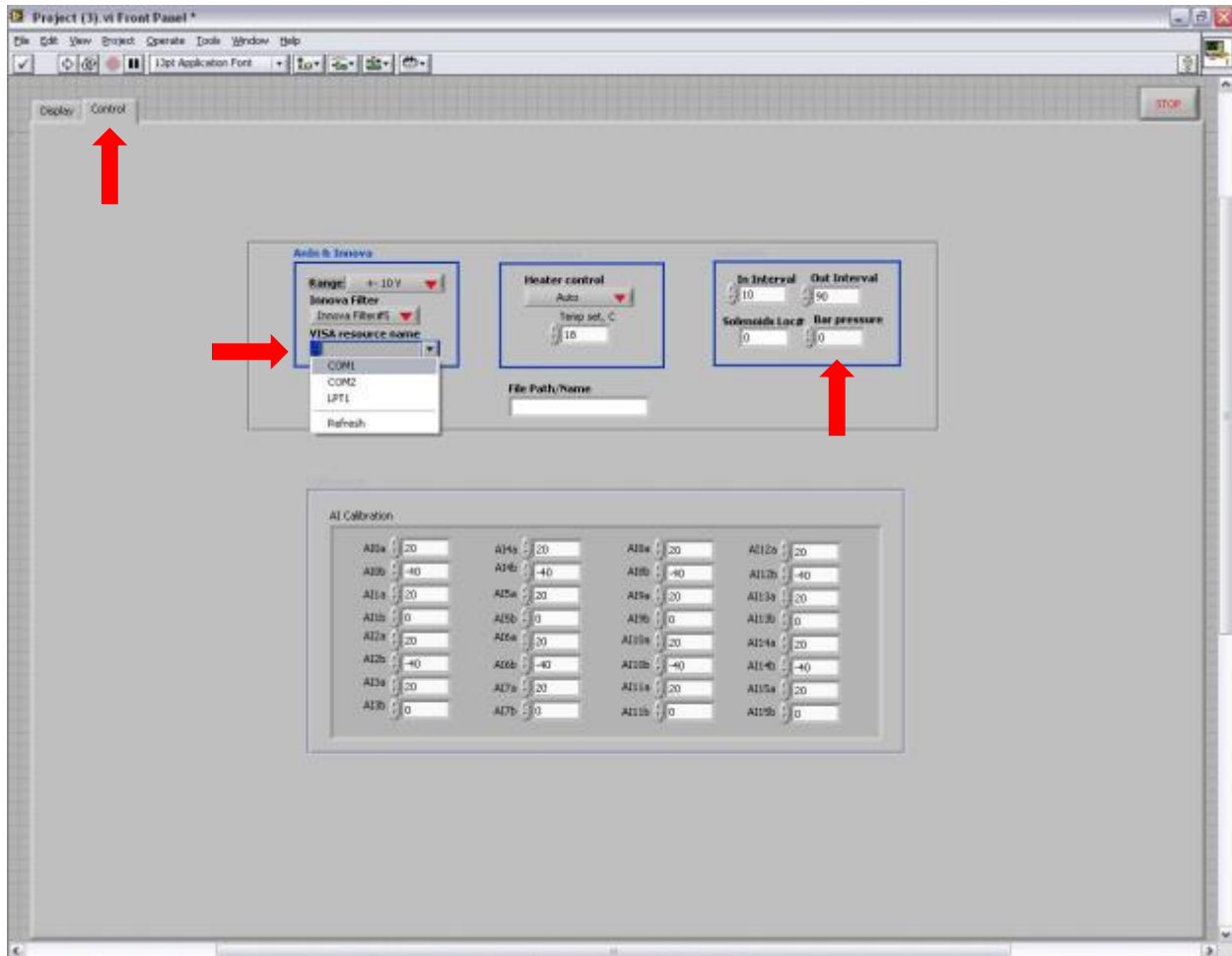
A-1 Starting a new task

To start a new task, choose the desired program from the correct folder. REMS related files are kept in “C:\REMS”. For an emission experiment with six animals, use “Project(2).vi”. For tests with one chamber at a time, such as recovery tests or sampling strategy test, use “Project(3).vi”.

To manually switch on and off each solenoid, use “XDOUT.vi”.

A-2 Program setup

Before starting the program, go to the “Control” page. “VISA resource name” should be “COM1”. Leave “Bar pressure” as “0”.



A-3 Starting a new sampling sequence

To start the program, go the “Display” page and click “Run” on the top left corner. The date and time should automatically be displayed, and environmental data and gas concentrations should be shown after each sample.

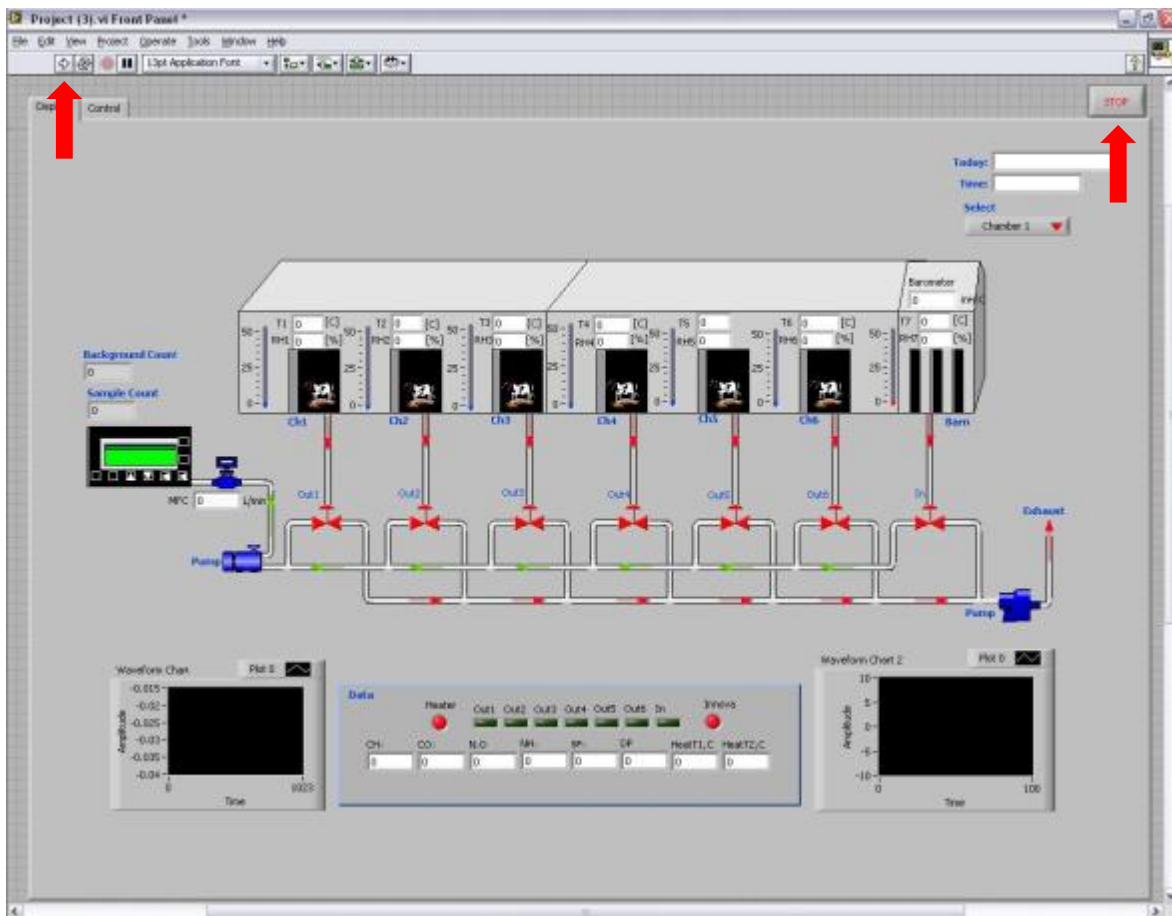
A-4 Stopping a sampling sequence

To stop the program, click the “STOP” button on the upper right corner of the “Display” page.

This will stop the program and allow it to be restarted instantaneously. Do not click “Abort Execution” on the top bar next to the “Run” icon. This will cause problems in the code execution.

A-5 During a sampling sequence

During the experiment, the sampling line in the Labview system schematic corresponding to the chamber being sampled will turn green and the number of samples done for this chamber in this iteration will be displayed under “Background Count” for background air and “Sample Count” for a chamber. Gas concentration measurements will be displayed on the bottom of the screen, under each gas. The “Waveform Chart” will produce a real-time amplitude graph of all gases being monitored.



A-6 Accessing saved data

Upon concluding the experiment it will be necessary to access the saved sampling data and do further analysis. Saved files are located under “C:\REMS\Data”. Microsoft Office Excel is used to analyze the data. Saved files are automatically named by the date the experiment was initiated. Each time the program is started, a new file will be created with a numbered suffix appended to the file name referring to the number of times the “Start” button is pressed.

Appendix B: Multiplexer Leakage Test

B-1 Experiment Setup

B-1.1 Purpose

Conduct a leakage test for the multiplexer using rotameters

B-1.2 Equipment required

1 vacuum pump, 2 rotameters with labels, gas sampling multiplexer unit, 3 m of Teflon tube, various Swagelog compression fittings and adjustable wrench.

B-2 Equipment setup

Note: All connections should be done using Teflon tube and compression fittings.

Connect pump to Rotameter 1.

Connect Rotameter 1 to inlet port of solenoid 1 in multiplexer.

Connect second Rotameter 2 to exhaust port of multiplexer.

Turn on pump for 5 minutes before initiating test.

B-3 Conducting the leakage test

B-3.1 Solenoid check

To test for leakage for each solenoid, move Rotameter 1 between the inlet ports of all 6 solenoids.

Figure B.1 shows the setup for checking solenoid 3.

Read, record and compare readings between Rotameter 1 and 2 for each position.

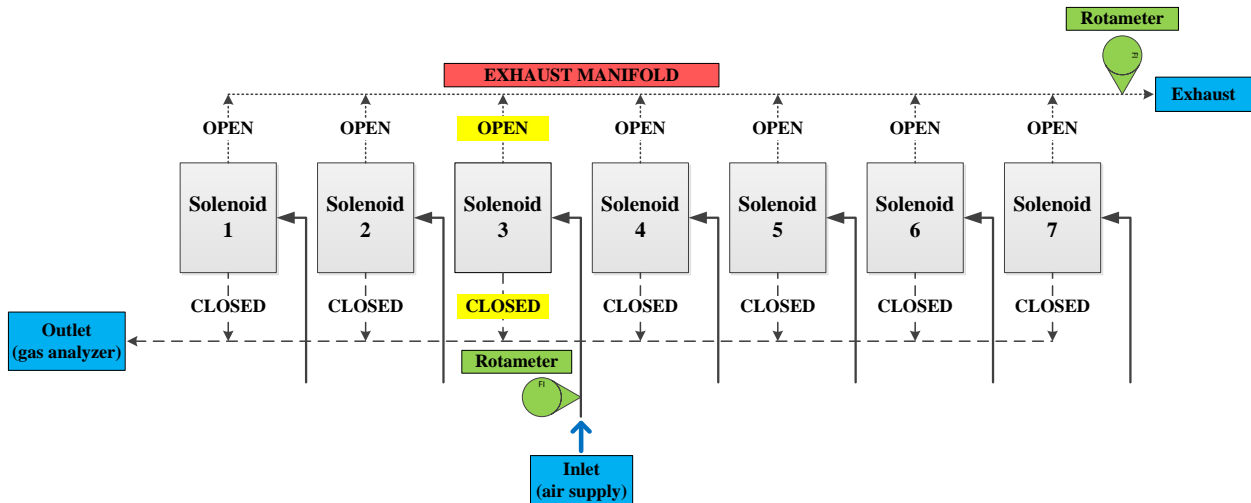


Figure B.1: Leakage test setup with Rotameter 1 at inlet of Solenoid 3 and Rotameter 2 at exhaust.

B-3.2 Sampling line check

To test for leakage in the sampling line, move Rotameter 2 to the sampling port (leading to the gas analyzer).

Move Rotameter 1 between the inlet ports of all 6 solenoids.

Figure B.2 shows the setup for checking the sampling line leading from solenoid 3.

Read, record and compare readings between Rotameter 1 and 2 for each position.

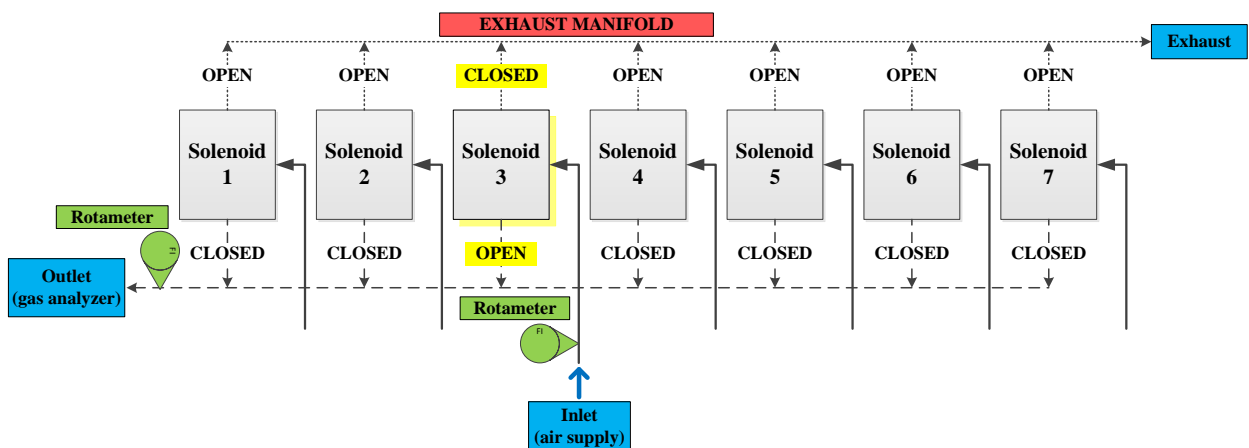


Figure B.2: Leakage test setup with Rotameter 1 at solenoid 3 and Rotameter 2 at gas analyzer outlet.

Appendix C: Gas Analyzer Calibration

C-1 Pre-calibration

C-1.1 Purpose

Calibrate INNOVA 1412i with zero gas (N_2), ammonia (NH_3), sulfur hexafluoride (SF_6), nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4).

C-1.2 Equipment required

PC with INNOVA Gas Monitoring Software 7034 - Calibration program and EnviroNics Series 4000 Instrument Control Software installed.

Gas Analyzer (INNOVA 1412i).

Gas Dilution System (EnviroNics 4040).

Water bath (Neslab RTE-221, Cole-Parmer, Inc., Vernon Hills, IL) capable of reaching between 10 degrees C and 30 degrees C.

Calibration gases for the gases to be monitored with precise concentrations: zero gas - pure nitrogen (N_2), ammonia (NH_3), sulfur hexafluoride (SF_6), nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4).

1 meter of Nafion tubing, 3 meters of 0.635 mm ($1/4$ ") flexible Teflon tubing, Swagelog connectors, Teflon tape.

Adjustable wrench for gas cylinder gasket and Swagelog connectors.

C-2 Calibration

C-2.1 PC setup and connections

Connect the PC (9-pin) to the INNOVA (25-pin) using a null modem RS-232 cable.

Connect the PC (9-pin) to the Environics (9-pin) using a null modem RS-232 cable.

Turn on the INNOVA 1412i at least one hour before calibration.

C-2.2 Communication parameters

The communication parameters necessary for the monitor to communicate with the Gas

Monitoring Software 7304 are shown below:

Baud rate	9600
Stop bits	1
Data bits	7
Parity	Even
Hardwire mode	Leased line
Handshake type	Hardwire

To prevent communication errors, the text line terminator, print data log and print error log must

be set as shown below:

Text Line Terminator	CR-LF
Print Data Log	YES
Print Error Log	YES

C-2.3 Gas Correction (K) Factors

Since all gases have different molecular weight, there is a correction (K) factor that the

Environics software automatically adjusts for. Individual K factors for our gases:

NH₃: 0.7189; SF₆: 0.2643; N₂O: 0.7089; CO₂: 0.7374; CH₄: 0.7192

C-2.4 Gas Dilution System port connections

Connect tubing from the calibration gas cylinder to Port 1 (Figure C.1) of the Environics 4040 Gas Dilution System.



Figure C.1: Rear view of Environics GDS showing gas sampling ports.

C-2.5 Equipment set-up for zero-point calibration with N₂ (zero set point for all gases); span-dry calibration for NH₃ and SF₆

For zero gas (N₂), ammonia (NH₃) and sulfur hexafluoride (SF₆), a tube is connected from the output port to a “T”, distributing the gas to the INNOVA and Rotronic HygroPalm. Compression fitting connections to the Rotronic HygroPalm should be secure enough to provide a constant and stable flow of gas. A mixing box (Figure C.2) should be affixed to the sensor tip for best



Figure C.2: Mixing box with electronic temperature and relative humidity sensor attached. results. The general equipment required to perform the calibration is shown in Figure C.3.

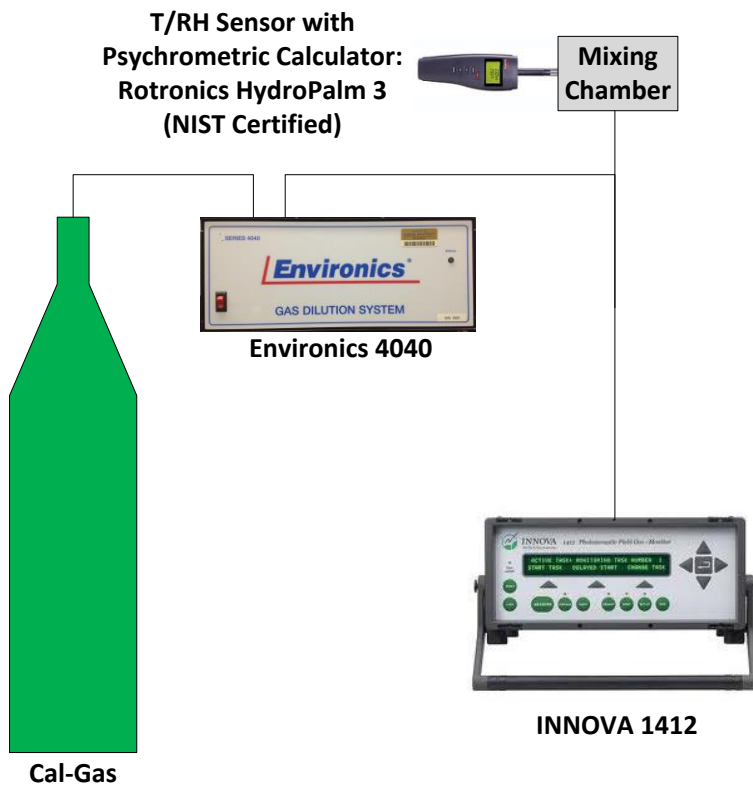


Figure C.3: Schematic of zero-gas and span-dry calibration set-up for NH₃ and SF₆.

C-2.6 Equipment set-up for humidity interference calibration (humidity corrections for all gases); span-wet calibration for N₂O, CO₂, and CH₄ using the Nafion water-bath system

For water vapor, nitrous oxide (N₂O), carbon dioxide (CO₂), and methane (CH₄), the calibration must include action to account for humidity interference in the measure of these gases. One meter of Nafion tubing immersed into a temperature controlled water-bath is required to provide stable and constant levels of humidity to the gases - the Nafion tubing should be fully submersed inside the water bath and should be connected between the diluter and “T”. Water bath should be set to the dew point temperature that simulated the humidity expected in the environment of the actual measurement, since humidity affects the accuracy of the calibration point. A length of flexible tubing extender might be required to reach inside the water bath.

The general equipment required to perform the calibration is shown in Figure C.4.

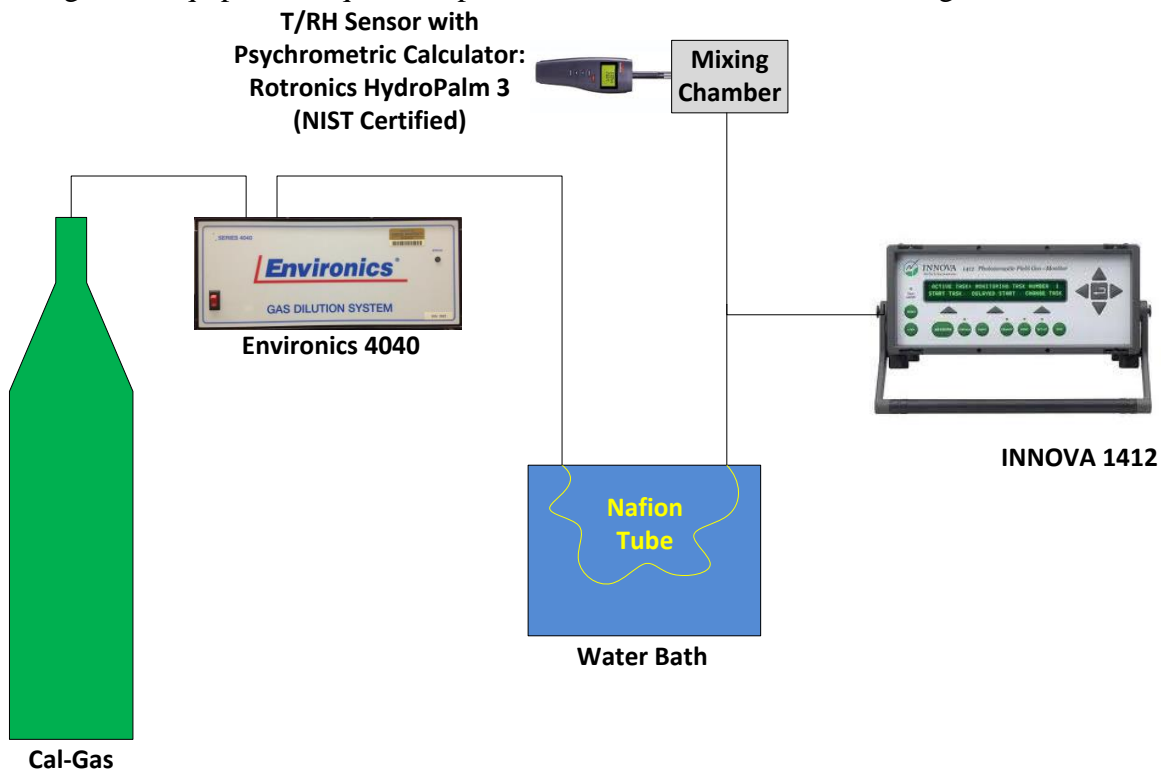
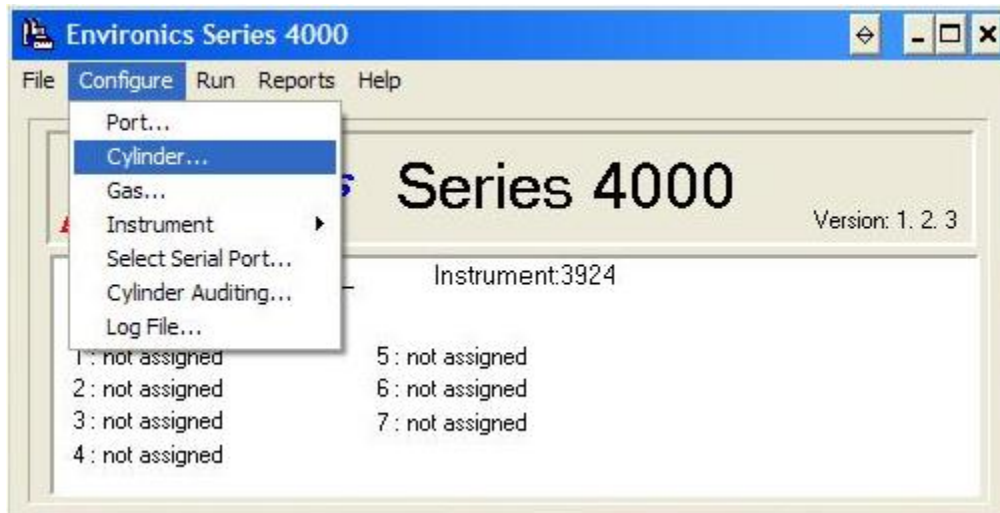


Figure C.4: Schematic of water vapor and span-wet calibration set-up for N₂O, CO₂ and CH₄.

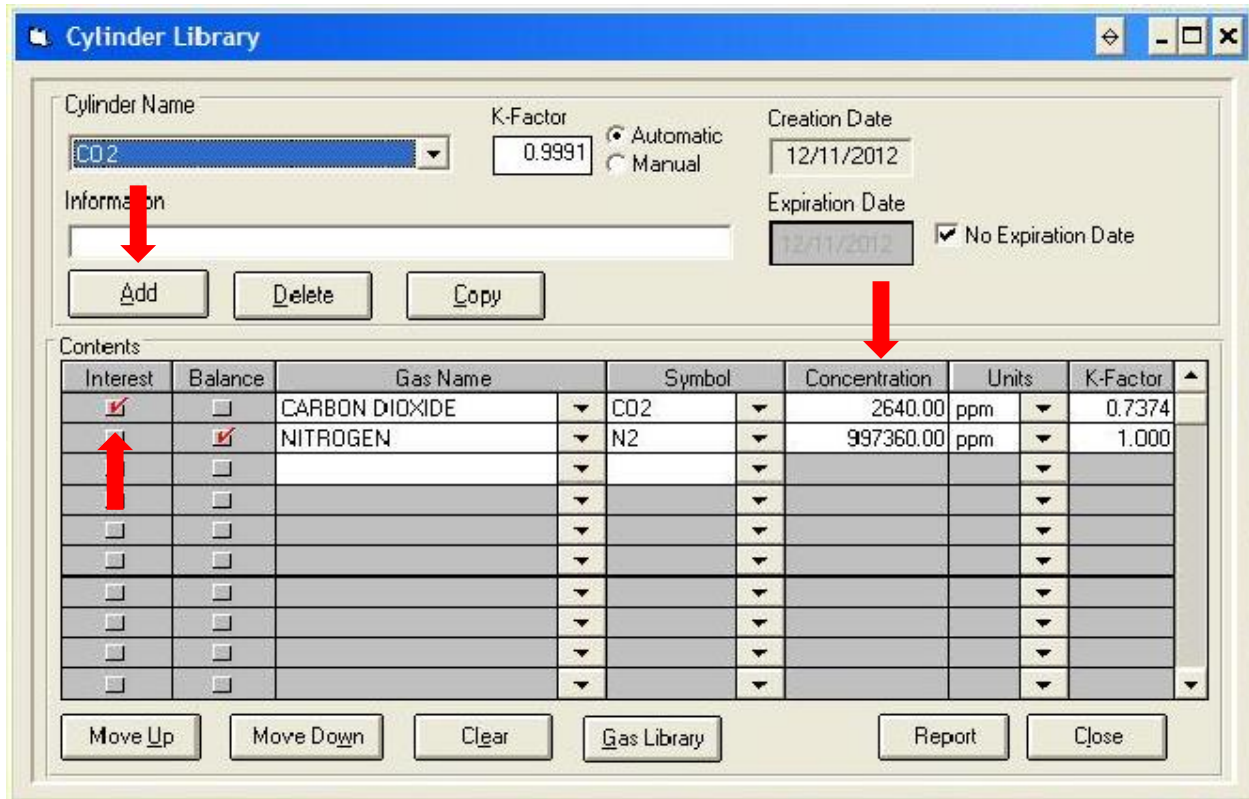
C-2.7 Using the Gas Dilution System

Open the Environics Series 4000 Instrument Control Software:

1. Pull down the **File** Menu. Click **New**.
2. Input file name for calibration attempt (Calibration_MMDDYYYY). Instrument is 3924. Click **OK**.
3. Pull down the **Configuration** menu. Click **Cylinder**.

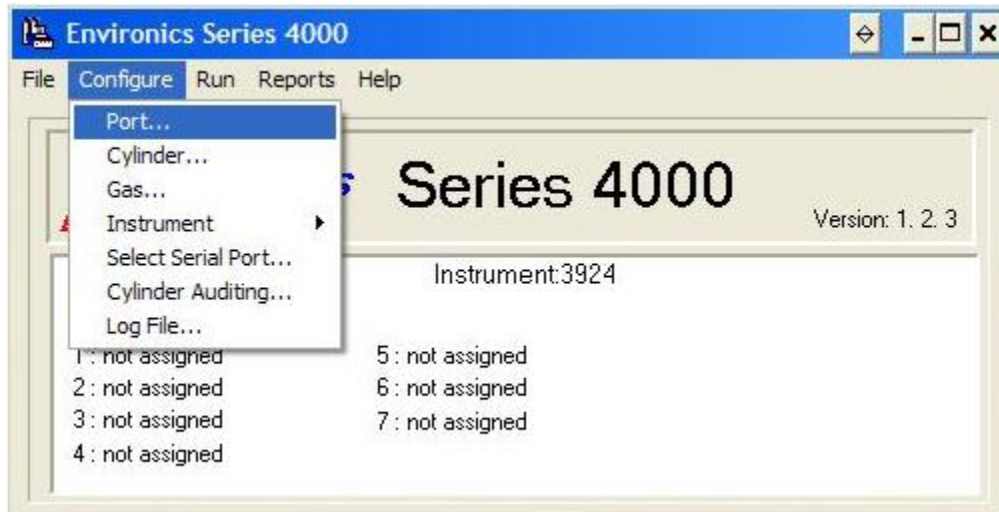


4. Click **Add** and input Cylinder name for each cal-gas.
5. Choose the zero gas (N₂) as Balance, and the cal-gas as Interest.
6. Input concentration according to concentration of cal-gas cylinder. K-factors should be automatically adjusted.

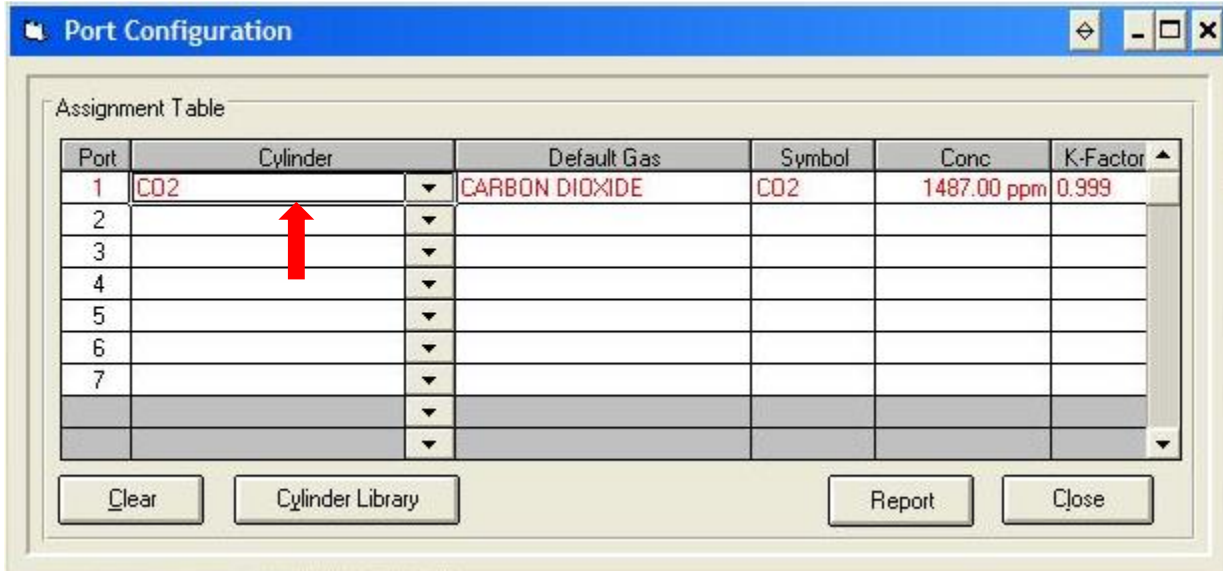


7. Click **Close** and save changes.

8. Pull down the **Configuration** menu. Click **Port**.

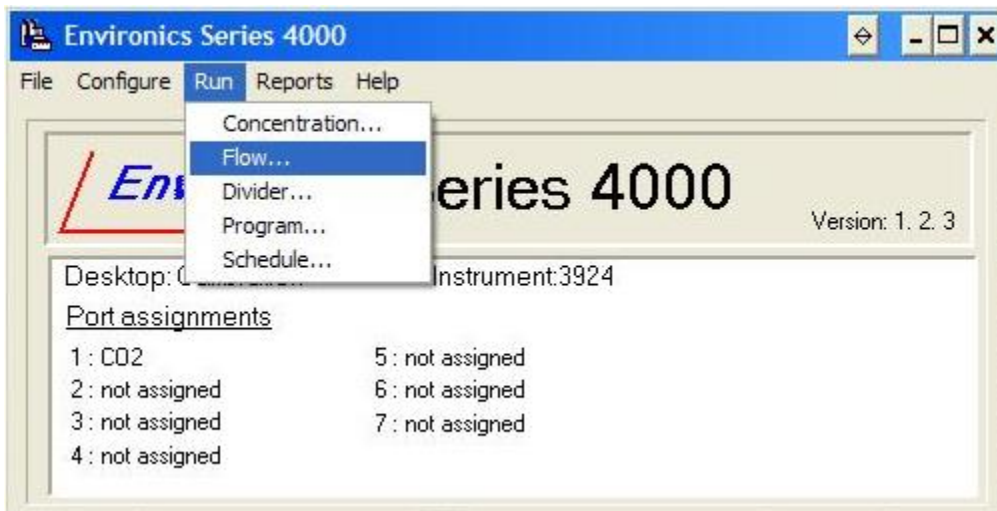


9. Choose Cylinder name under Port 1. Symbol, concentration and K-factor for chosen gas should show up automatically.



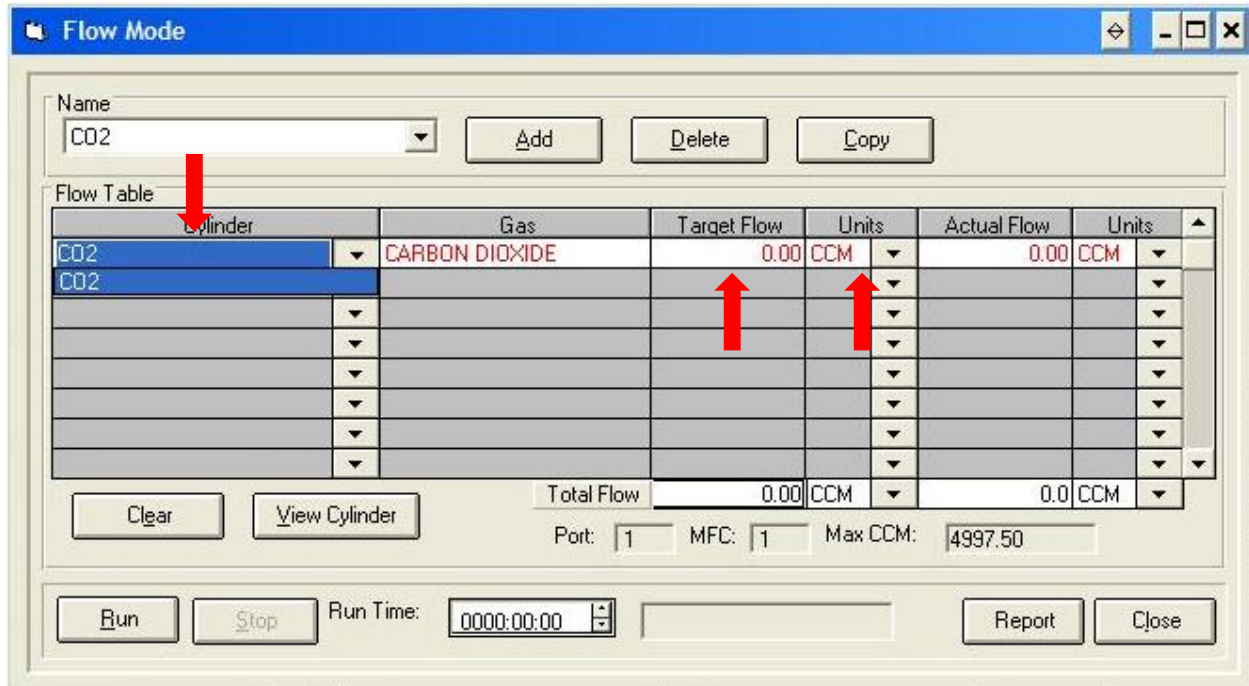
10. Click **Close** and save changes.

11. Pull down the **Run** menu. Click **Flow**.



12. Click **Add** to create a new cylinder for each cal-gas.

13. Under **Cylinder**, choose the cal-gas created in step 12.



14. Change the units to LPM in both target and actual flow rates.

15. Enter 4.025 under Target Flow rate.

16. Click **Run** when ready to inject gas.

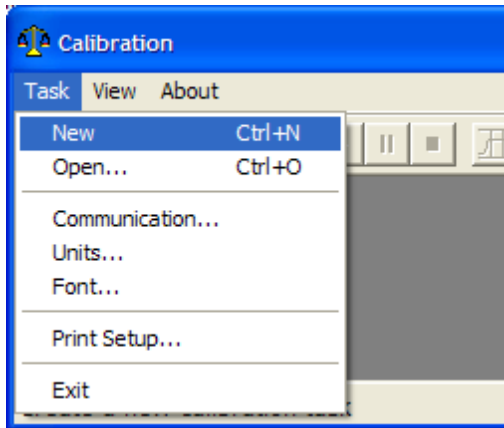
C-2.8 Using the INNOVA Calibration program

Detach the air inlet tube from the existing sampling manifold. Close the pipe adapter of the sampling manifold with a cap or plug.

Attach the 1412i to a calibration manifold.

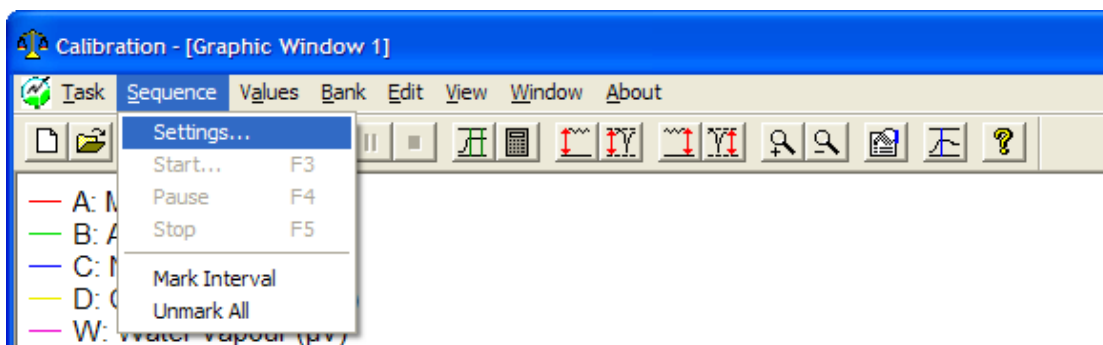
C-2.8.1 Zero (N2) Gas Calibration

1. Open the Calibration program and create a **New** task.

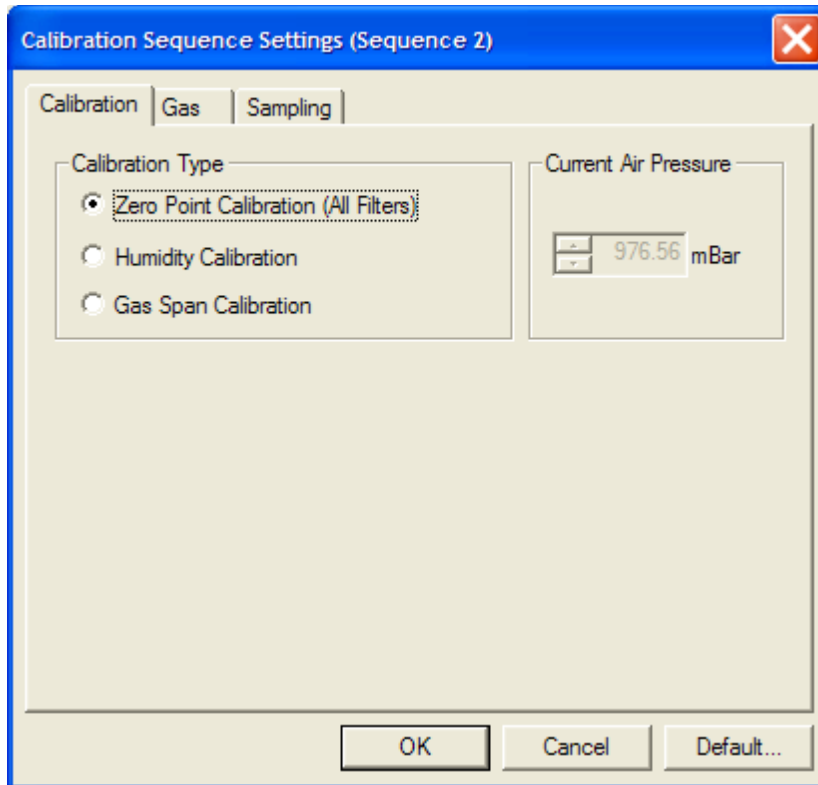


2. Type in the desired task name (CALIBRATION ##_MMDDYYYY) and click OK.

3. Pull down the **Sequence menu**. Click **Settings**.

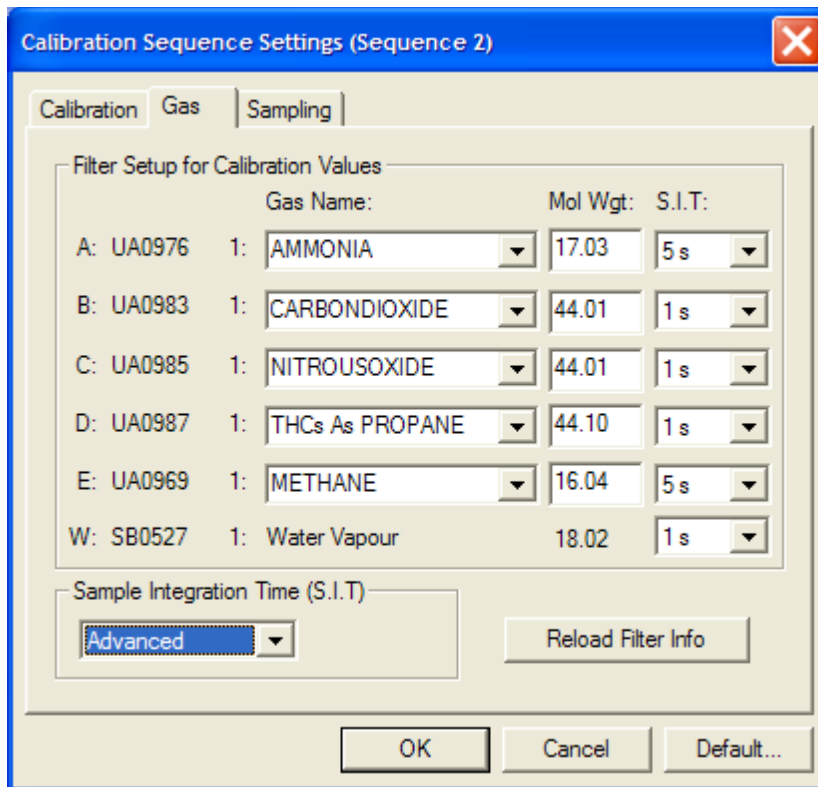


4. Click on the Calibration index-card, if it is not already at the front.

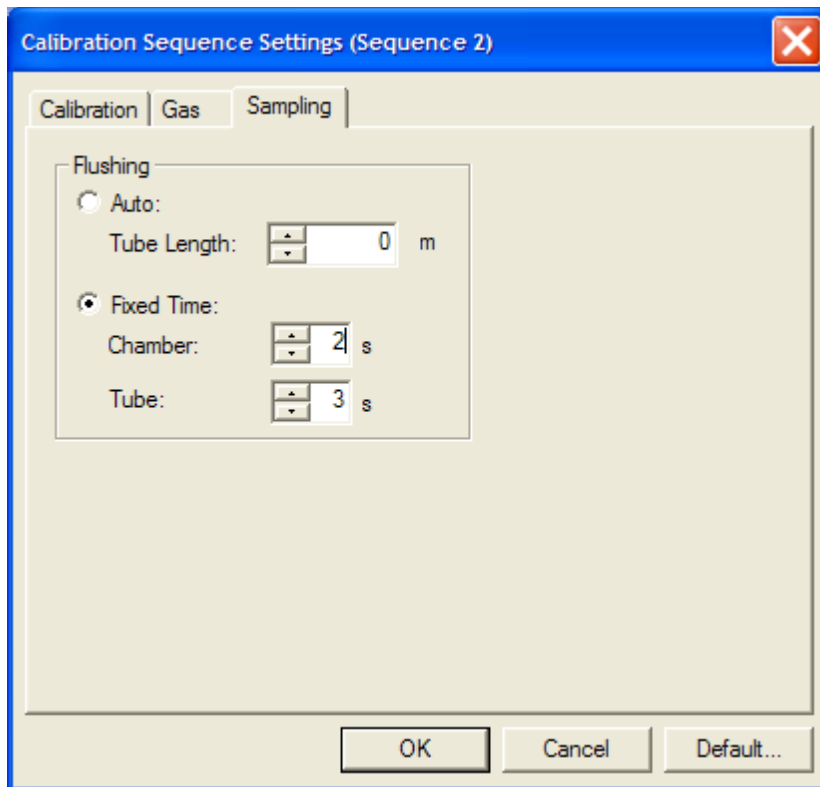


5. Click to select **Zero** point radio-button.

6. Click on the Gas index-card and click in the Sample Integration Time field, and select the desired time: 5 s for Ammonia, 1 s for CO₂, 1 s for Nitrous oxide (N₂O), 1 s for propane and 5 s for CH₄.

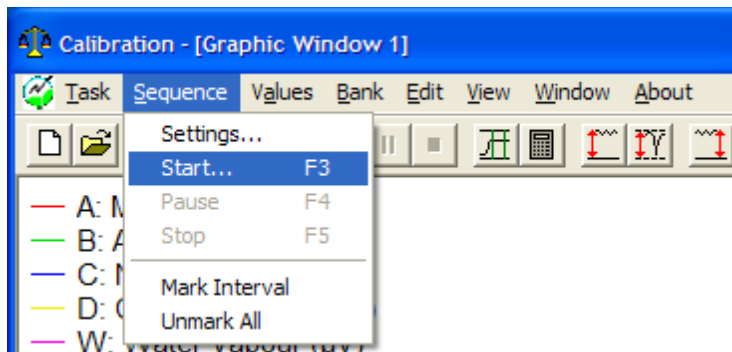


7. Click on the Sampling index-card and set the flushing time to desired time: Fixed time, 2 s for Chamber and 3 s for Tube.



8. When all the settings are correct, click on **OK**.

9. Pull down the **Sequence** menu and click on **Start**.

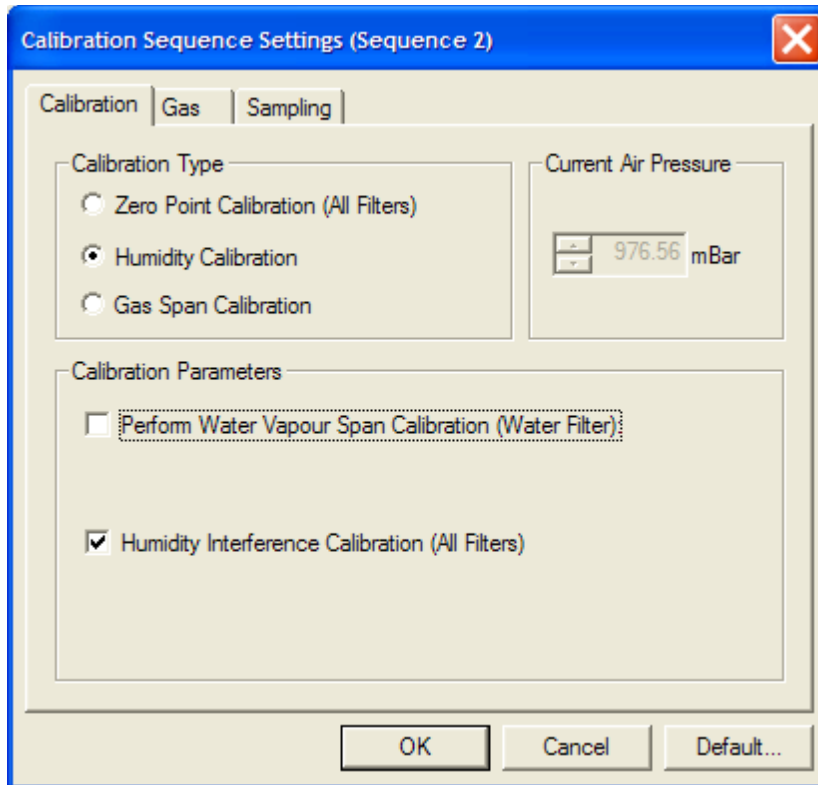


10. Insert the 1/4" ID tubing (from N2 gas regulator) to the flow meter mounted on the side of the instrument rack; then open the regulator valve to allow gas flow. Zero gas is now flowing from the cylinder to the 1412.

11. Adjust regulator valve until vent airflow is about 2.5 L/min (read from bottom of ball of the flow meter mentioned above). This provides a little extra zero air to the 1412 and keeps the pressure inside the manifold close to the atmospheric pressure.
12. Record time and analyzer display in lab notebook.
13. Continuously inject the gas for 15 min after display is stabilized.
14. Pull down the **Sequence** menu and click on **Stop**.
15. Close regulator and remove Zero gas tubing.

C-2.8.2 Humidity Calibration

1. Pull down the Sequence menu. Click Settings.
2. Click on the Calibration index-card, if it is not already at the front.
3. Click to select Humidity Calibration.

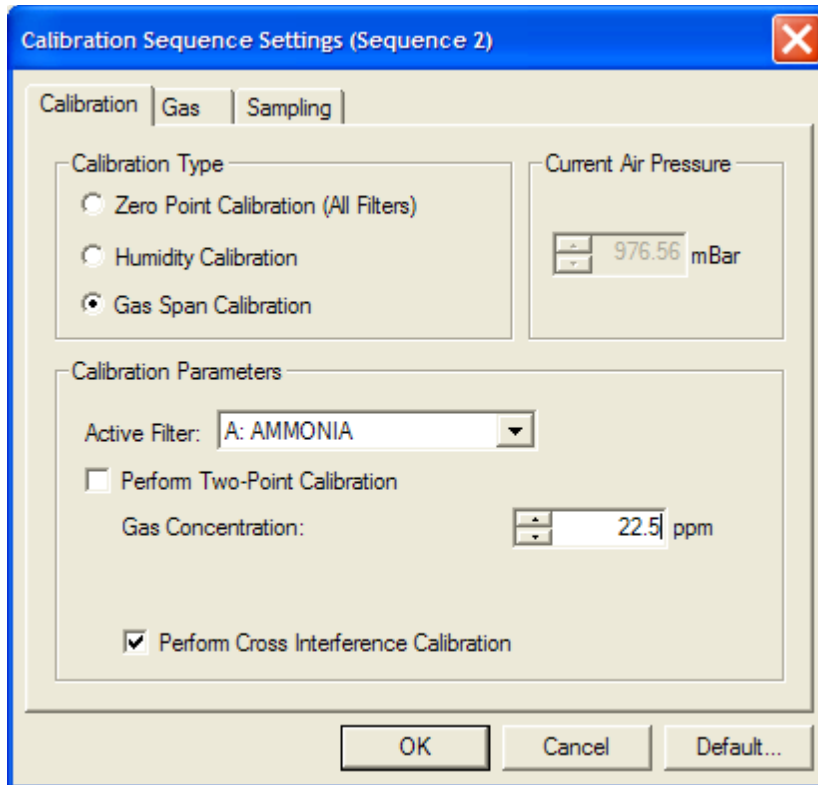


4. Only Select “Humidity Interference Calibration (All Filters)”. Do not select “Perform Water Vapor Span Calibration”.
5. Click on the Gas index-card and click in the Sample Integration Time field, and select the desired time as above.
6. When all the settings are correct, click on OK.
7. Pull down the Sequence menu and click on Start.
8. Connect a water bath device between the zero gas regulator and the flow meter mounted on the side of the instrument rack; then open the regulator valve to allow gas flow. Zero gas is now flowing from the cylinder to the 1412.

9. Adjust regulator valve until vent airflow is about 2.5 L/min (read from bottom of ball of the flow meter mentioned above). This provides a little extra zero air to the 1412 and keeps the pressure inside the manifold close to the atmospheric pressure.
10. Record time and analyzer display in lab notebook.
11. Continuously inject the gas for 15 min after display is stabilized.
12. Pull down the Sequence menu and click on Stop.
13. Close regulator and main valve and remove zero gas tubing.

C-2.8.3 Span Gas Calibration

1. Pull down the Sequence menu. Click Settings.
2. Click on the Calibration index-card, if it is not already at the front.
3. Click to select Gas Span Calibration radio-button.



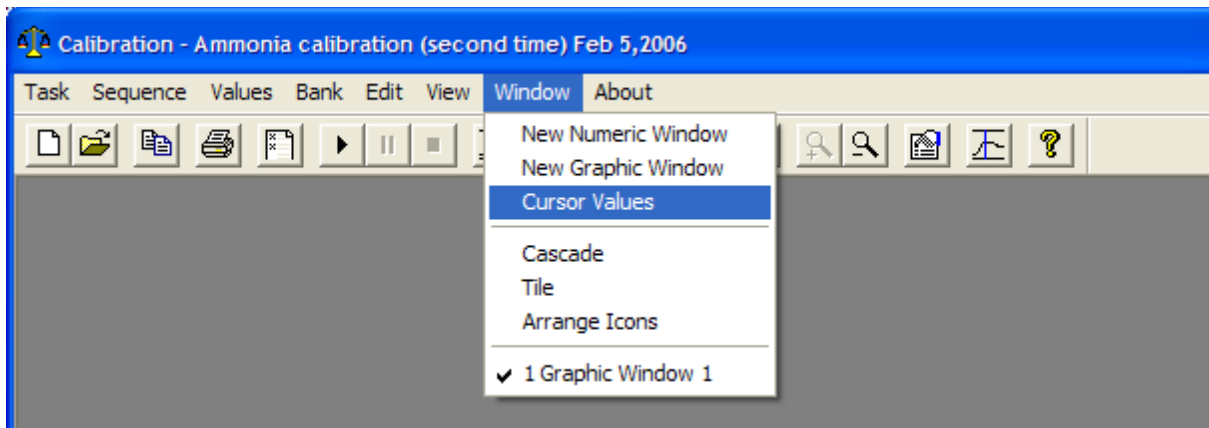
4. Click in the Active filter field “####” and select the gas you are calibrating, and check Perform Cross Interference Calibration and input the concentration of gas.
5. Click on the Gas index-card and click in the Sample Integration Time field, and select the desired time as above.
6. When all the settings are correct, click on OK.
7. Pull down the Sequence menu and click on Start.
8. Insert the 1/4” ID tubing (from the desired gas cylinder) to the flow meter mounted on the side of the instrument rack; then open the regulator valve to allow gas flow. Gas is now flowing from the cylinder to the 1412.

9. Adjust regulator valve until vent airflow is about 2.5 L/min (read from bottom of ball of the flow meter mentioned above). This provides a little extra gas to the 1412 and keeps the pressure inside the manifold close to the atmospheric pressure.
10. Record time and analyzer display in lab notebook.
11. Continuously inject the gas for 15 min after display is stabilized.
12. Pull down the Sequence menu and click on Stop.
13. Close regulator and main valve and remove tubing from the gas cylinder.

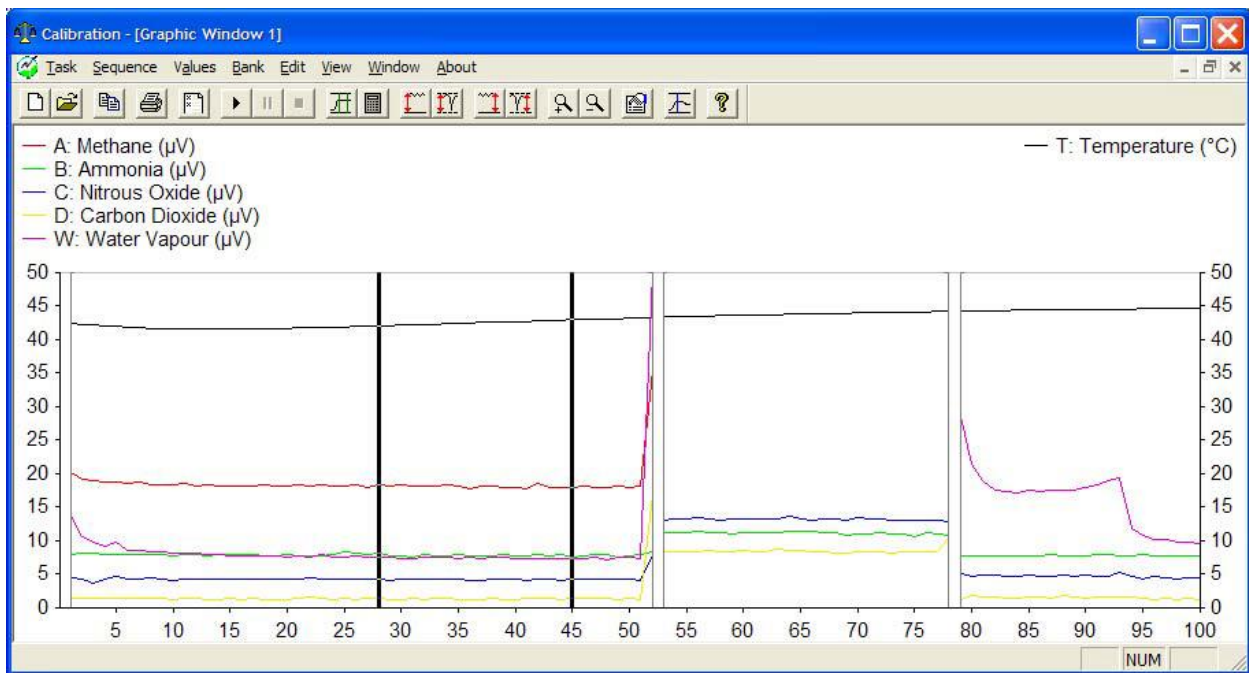
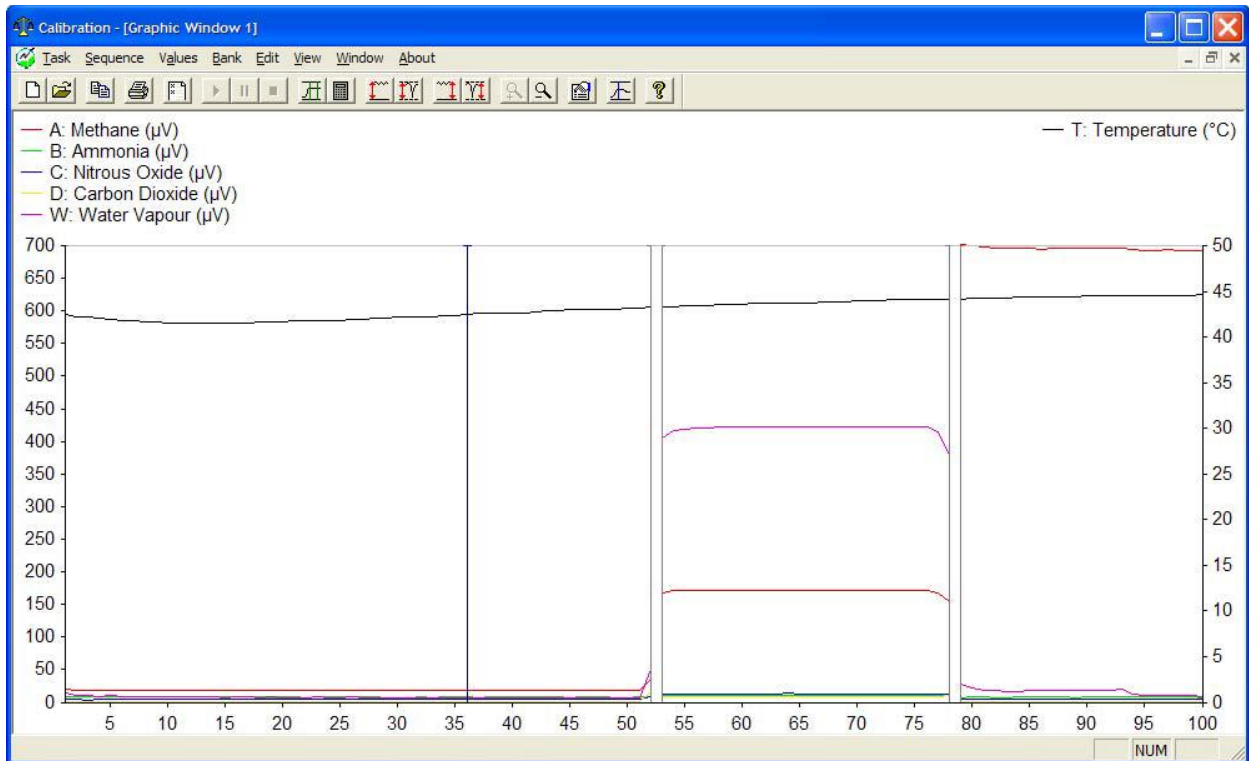
C-2.9 Calculating Calibration Factors

With the raw measurement data displayed on screen:

1. Open the **Cursor Values** dialogue.

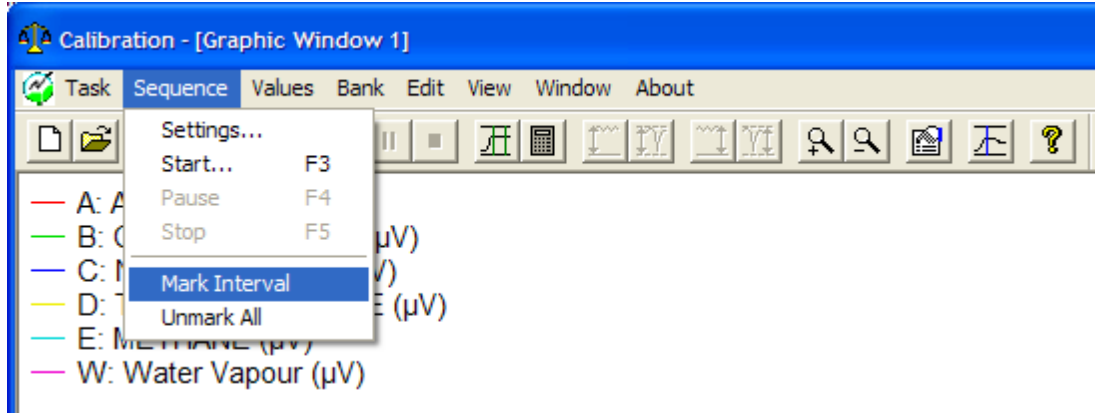


2. Use two cursors and the statistical data are displayed in the Cursor Values dialogue to locate a suitable range of data. All values in the select interval should be very stable and the temperature should be above 40 °C.



3. When you have the desired region between the cursors, pull down the **Sequence** menu

and click on **Mark Interval**.



The two cursors are replaced by a pair of green lines. These lines have markings at the end of them, which show the type of calibration data lying between the lines.

The markings are:

ZP: shows a zero point calibration

HI: shows a humidity interference calibration

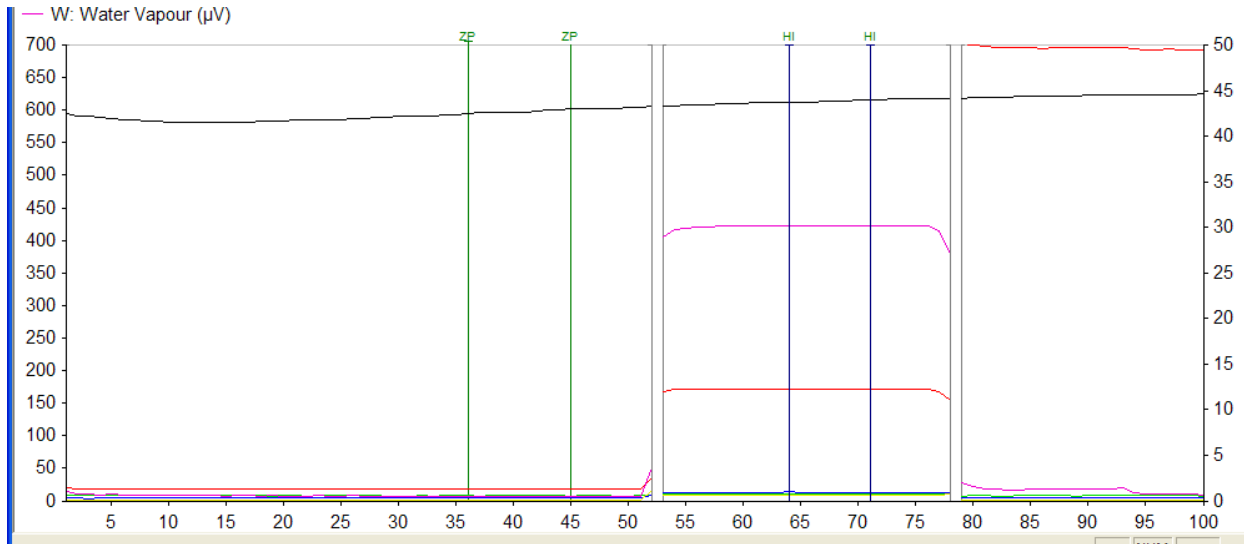
SHA: shows a span calibration (filter A)

SHB: shows a span calibration (filter B)

SHC: shows a span calibration (filter C)

SHD: shows a span calibration (filter D)

SHE: shows a span calibration (filter E)



4. Select 10 samples for which the calibrated gas is most stable and mark all the intervals for every calibrated gas.

5. Pull down the **Values** menu and click on **Calculate**.

6. When the calculation(s) is complete a Calculation Finished dialogue is displayed.

C-2.10 Downloading the calculated values

1. Pull down the **Values** menu. Click on **Download** and the Download dialogue is displayed.

2. Select the **Zero Point** index card

3. Set ticks in the NH₃, CO₂, Propane and Methane and Water Vapor check boxes.

4. Repeat steps 2 and 3 in the Humidity and Gas index cards.

5. Click on **OK**. The calibration factors are now downloaded to the monitor.

C-3 Post-calibration

C-3.1 Disconnecting the equipment

1. Check and close main valves on all cylinders
2. Calibration of the 1412 monitor is complete
3. Turn off the 1412 and disconnect 1412 with the PC.
4. Reconnect the 1412 with compact Fieldpoint and turn on the 1412.
5. Set the filter sampling integration time back to original setup: 1 s for each filter.
6. The communication parameters necessary for the monitor to communicate with the

compact Fieldpoint are shown below:

Baud rate	9600
Stop bits	2
Data bits	7
Parity	Even
Hardwire mode	Leased line
Handshake type	Hard wired

Print data log and print error log must be set as shown below:

Text line Terminator	CR-LF
Print Data Log	Yes
Print Error Log	Yes

C-3.2 Gas Concentration Check

In order to verify the calibration results, a concentration check is recommended after calibration.

1. Detach the air inlet tube from the existing sampling manifold. Close the pipe adapter of the sampling manifold with a cap or plug.

2. Attach the 1412 to a calibration manifold.
3. Insert the 1/4" ID tubing (from the NH₃ gas cylinder) into the manifold connected to the valve; then open the regulator valve to allow gas flow. Zero gas is now flowing from the cylinder to the 1412.
4. Adjust regulator valve until vent airflow is about 2.5 L/min (read from bottom of ball of the monitoring flow meter). This provides a little extra zero air to the 1412 and keeps the pressure inside the manifold close to the atmospheric pressure.
5. Wait for display to stabilize. Compare measured concentration to gas concentration provided by cylinder manufacturer.
6. Calibration is successful if error is within 1%. If not, recalibrate.
7. Close regulator and remove tubing from the zero gas cylinder.

Appendix D: System Evaluation (Concentration Recovery) Test

D-1 Experiment setup

D-1.1 Purpose

Using tracer-gas to locate any sources of leakage in the sampling line.

D-1.2 Equipment required

1PC with INNOVA Gas Monitoring Software 7034 – Online installed, 1PC with EnviroNics Series 4000 Instrument Control Software installed, INNOVA 1412i Gas Analyzer, EnviroNics 4040 Gas Dilution System, SF₆ (6.293 ppm_v ±1%, primary certified) cylinder with adjustable gasket, 10 m of Teflon tube, various Swagelok compression fittings, adjustable wrench.

D-2 Equipment setup

D-2.1 Sampling line connections

Note: All gas connection should be done using Teflon tub and compression fittings.

1. Connect SF₆ cylinder to Port 1 of GDS.
2. Direct injection tube directly into sampling port (Figure D.1).



Figure D.1: Picture showing injection tube directed into sampling port.

D-2.2 PC connections

PC with INNOVA Gas Monitoring Software 7034 – Online installed should be connected to INNOVA via null-modem RS-232 cable.

PC with with Environics Series 4000 Instrument Control Software installed should be connected to GDS via null-modem TS-232 cable.

D-3 Conducting the leakage test

D-3.1 Turning on the gas

1. Open Knob 1 completely (Refrain from using if Gauge 1 shows <500 psi).
2. Open Knob 2 slowly until pressure Gauge 1 reads 55 psi (Figure D.2).

3. Open Knob 3 completely (Further adjustments to Knob 2 might be required with initial loss of pressure).

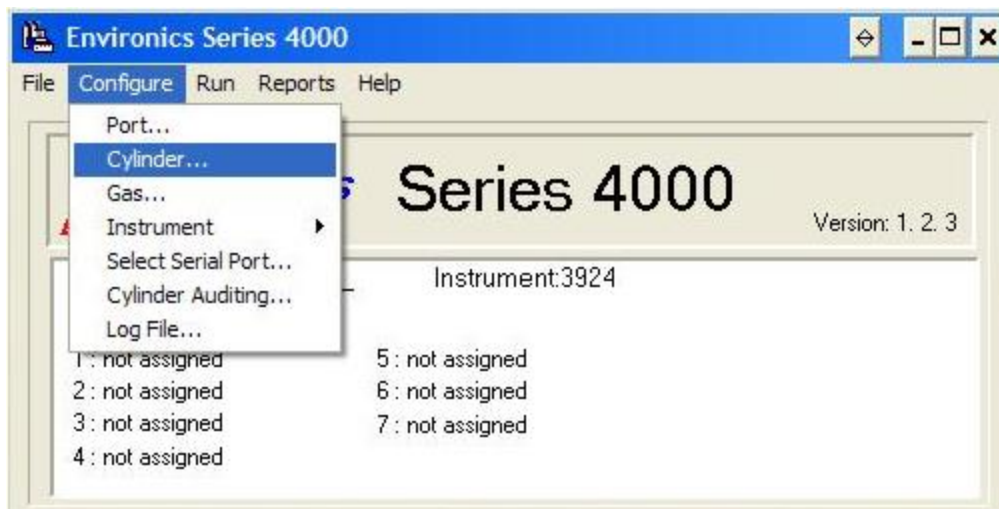


Figure D.2: Picture of cylinder gasket with knob and gauge labels.

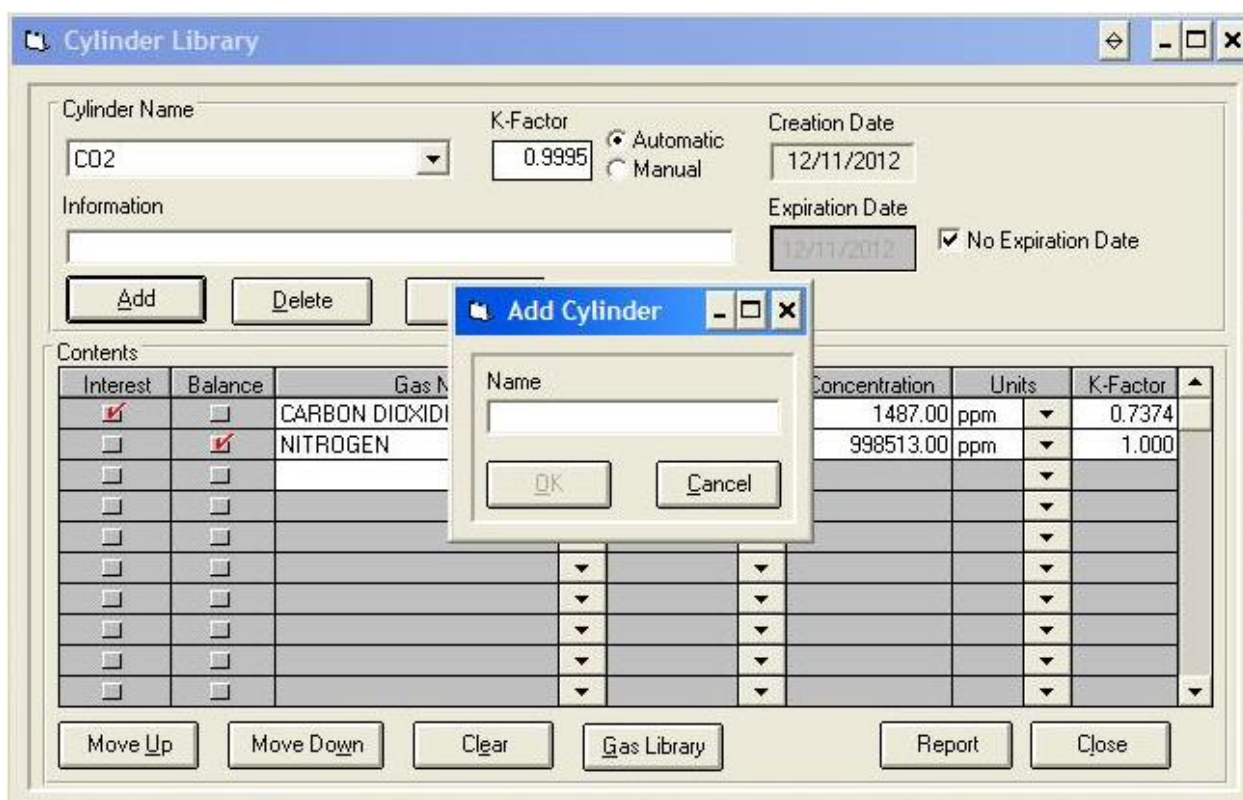
D-3.2 Using the Gas Dilution System

In the Environics Series 4000 Instrument Control Software:

1. Pull down the **File** Menu. Click **New**.
2. Input file name for test (Leakage_test_MMDDYYYY). Instrument should be 3924. Click **OK**.
3. Pull down the **Configuration** menu. Click **Cylinder**.



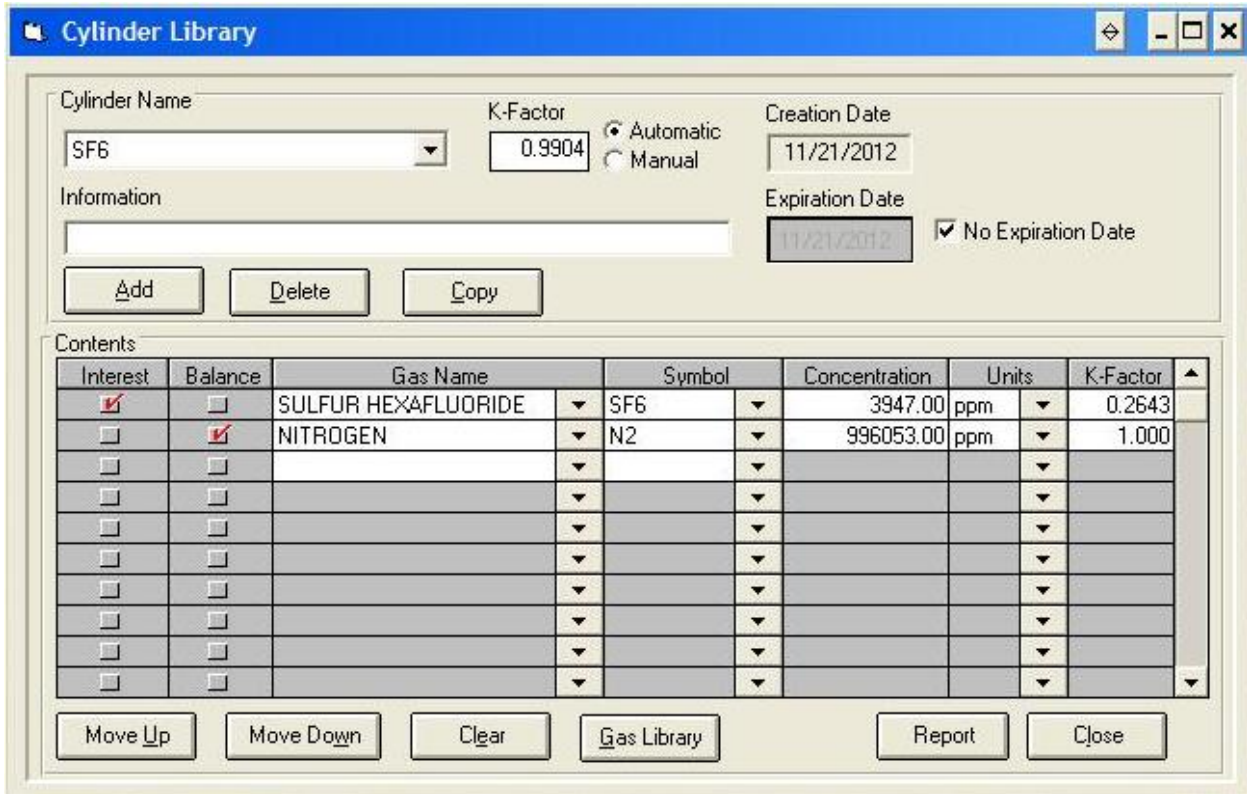
4. Click **Add** and input Cylinder name (SF₆).



5. Click **OK**.

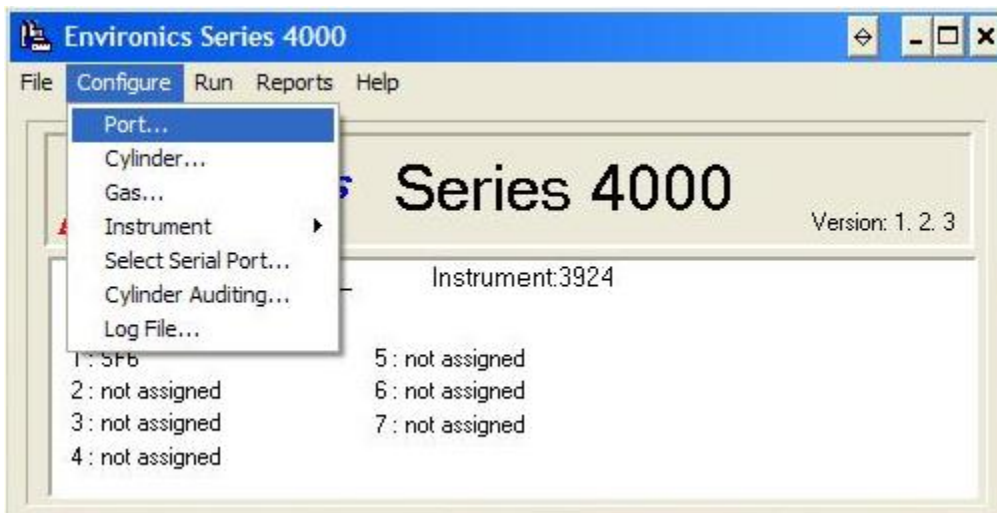
6. Choose the zero gas (N₂) as Balance, and SF₆ as Interest.

7. Input concentration according to concentration on SF₆ cylinder (3947 ppm).

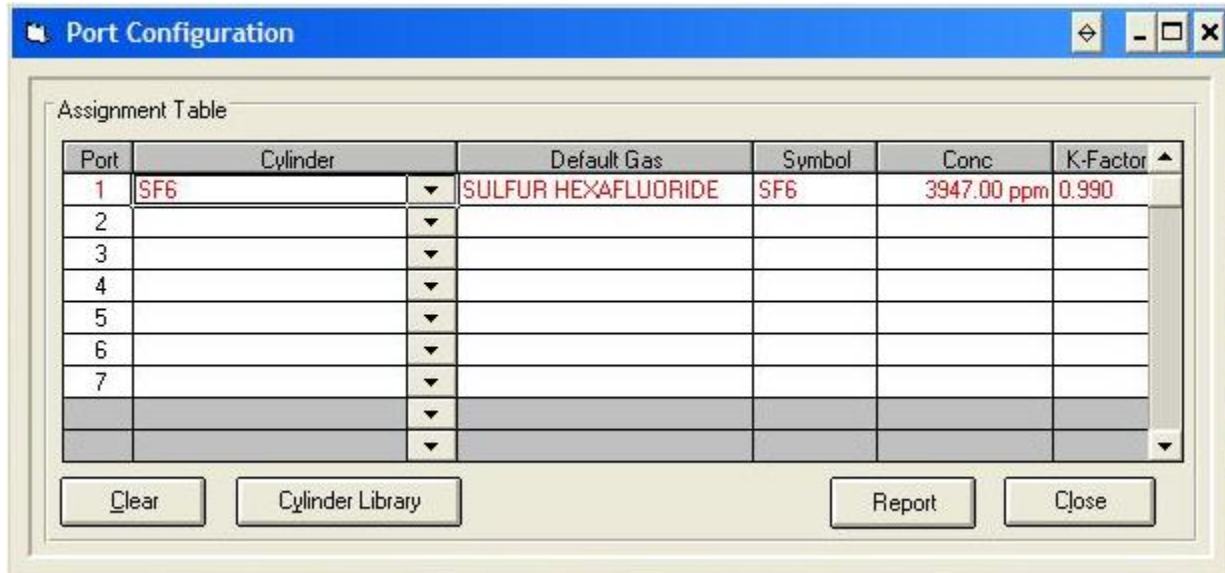


8. Click **Close** and save changes.

9. Pull down the **Configuration** menu. Click **Port**.

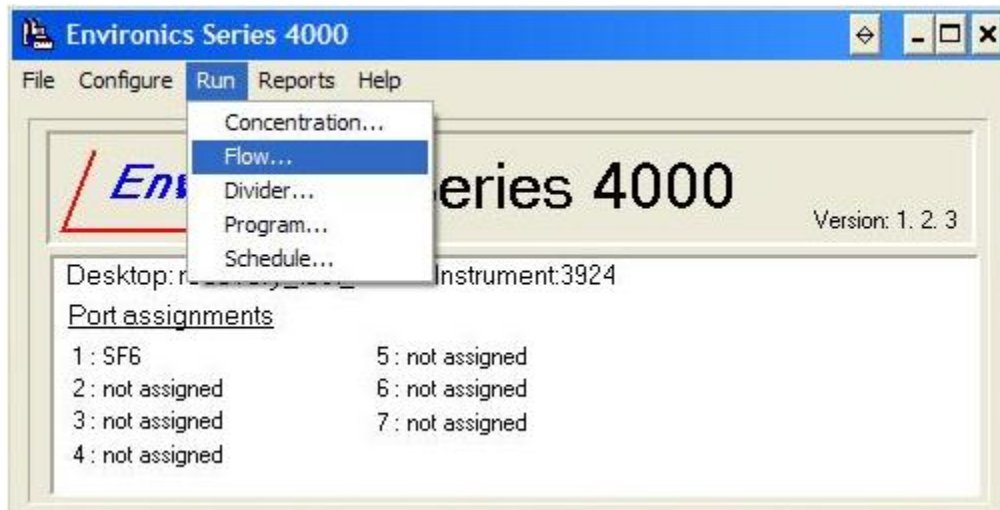


10. Choose Cylinder name (SF₆). Concentration for chosen gas should show up automatically.

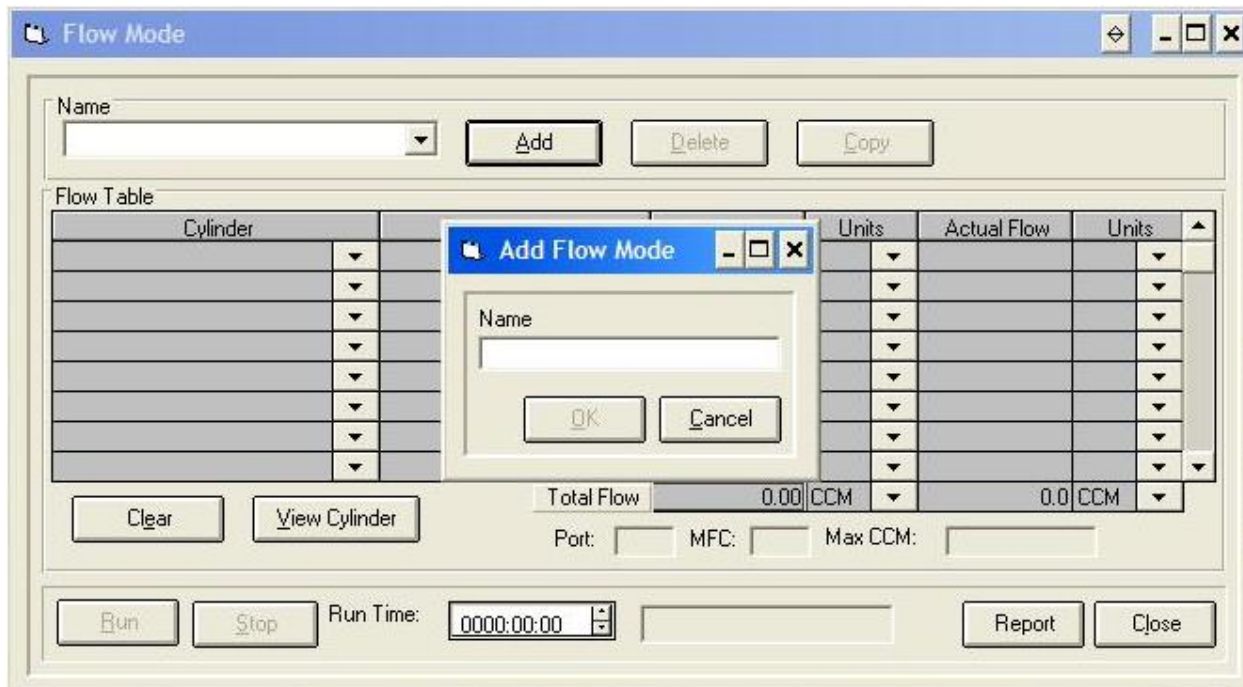


11. Click **Close** and save changes.

12. Pull down the **Run** menu. Click **Flow**.

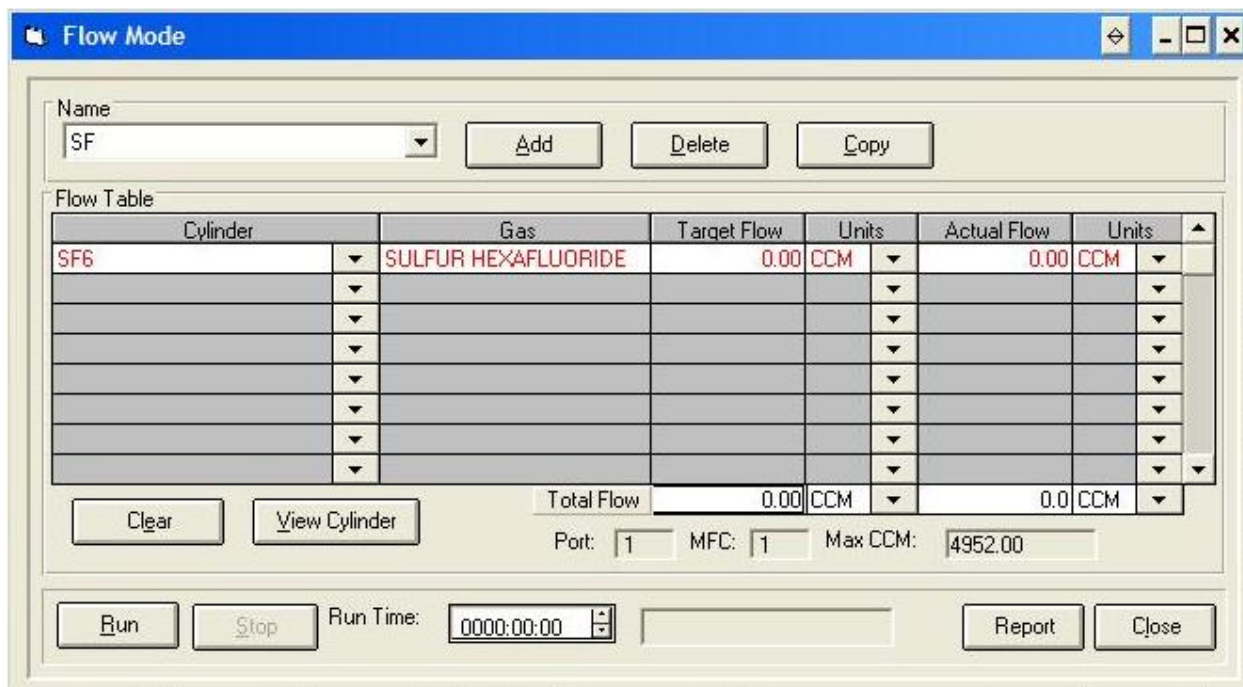


13. Click **Add** and input Flow Mode (SF₆).



14. Click **OK**.

15. Pull down **Cylinder** and choose SF6.



16. Change the units to LPM for both target and actual flow rates.

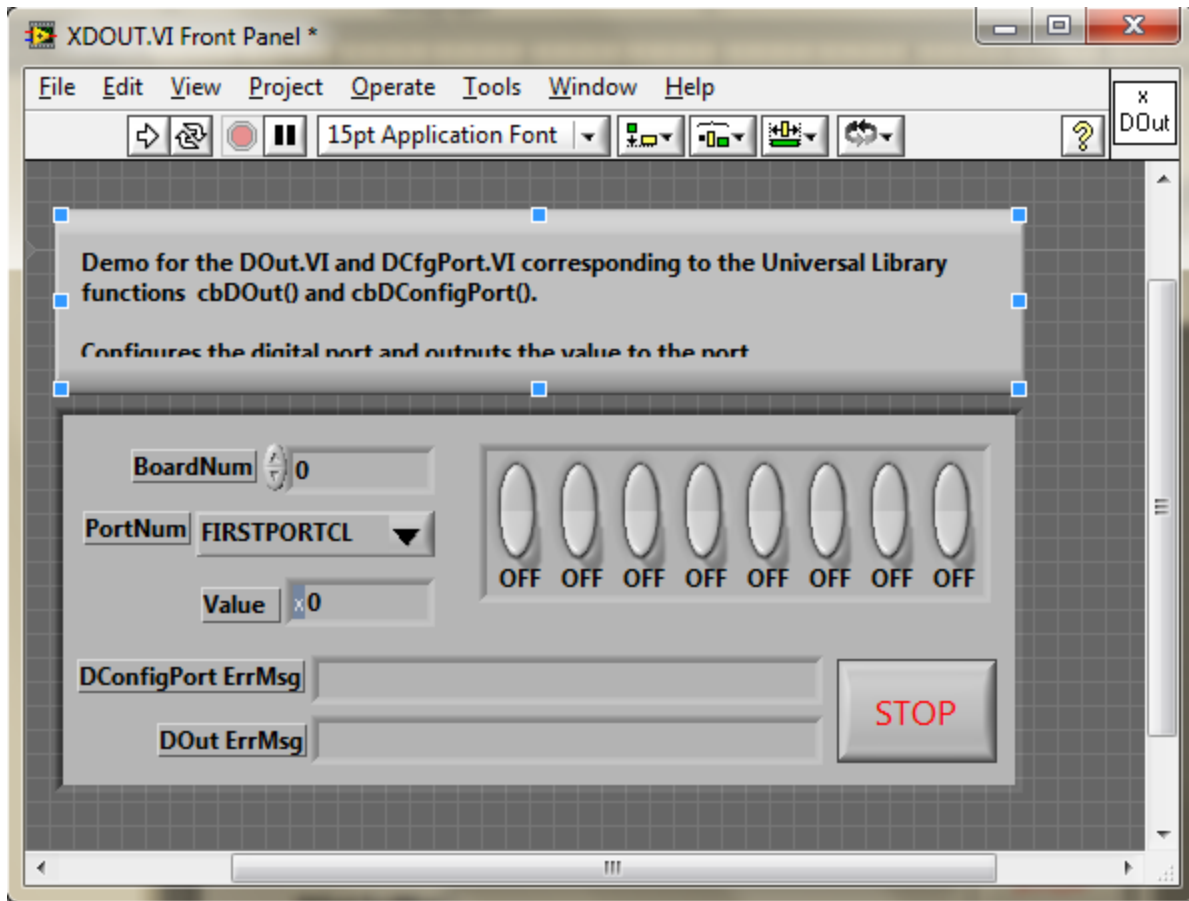
17. Enter 4.025 under target flow rate.

18. Click **Run** when ready to inject gas.

D-3.3 Using the LabVIEW program

1. Open “XDOUT.VI” under “C:\REMS”.

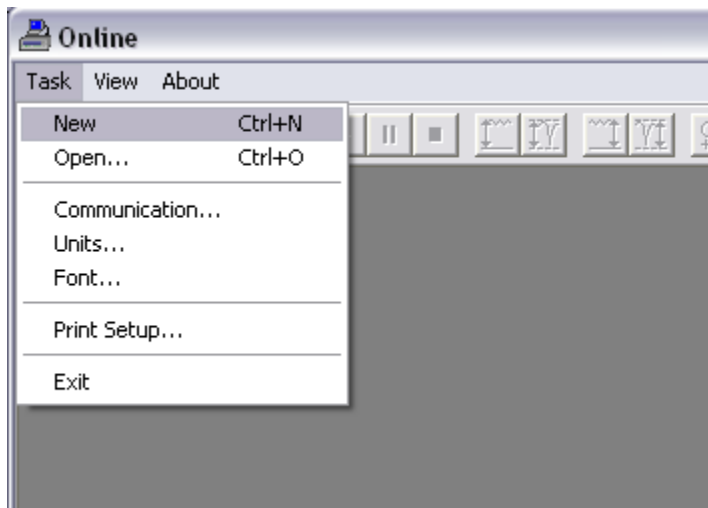
2. Under PortNum choose “FIRSTPORTCL” for solenoids 1-4, and “FIRSTPORTCH” for solenoids 5-7 (The buttons leading to each solenoid are lined up right to left, e.g. solenoid 1 would be the first button on the right in “FIRSTPORTCL” and solenoid 7 for the background would be the third button from the right in “FIRSTPORTCH”).



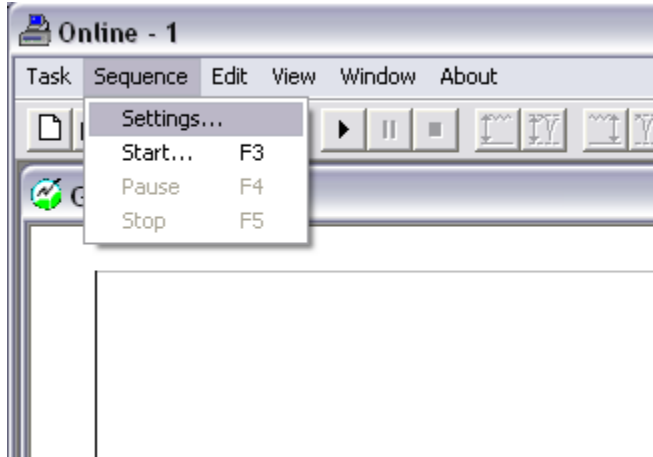
3. Turn off each solenoid after the experiment.

D-3.4 Using the Online program

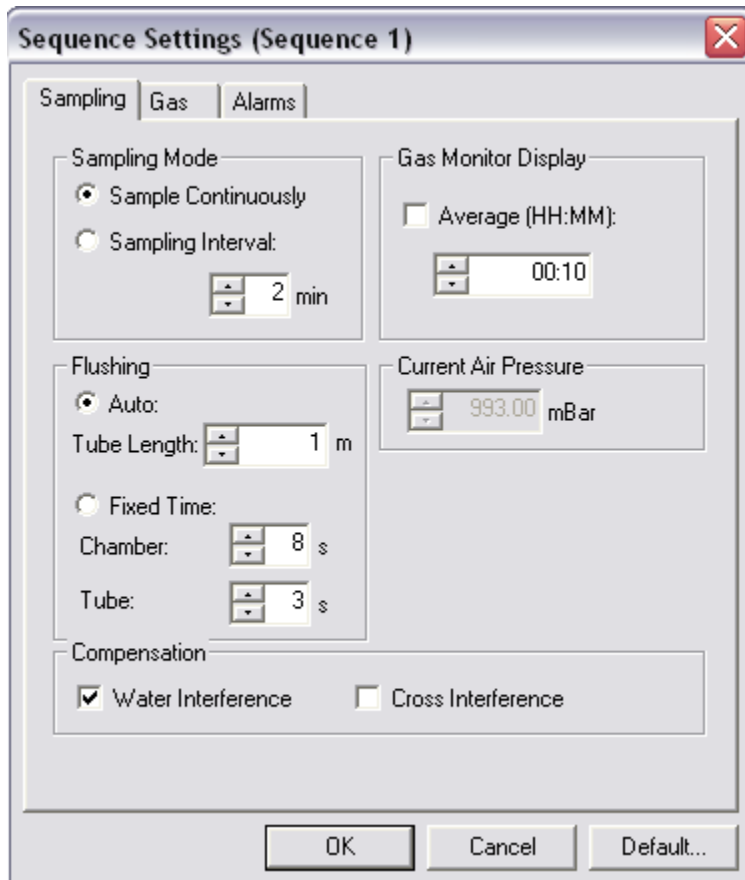
1. Open **Task** and click **New**.



2. Enter test name (Recovery_test_MMDDYYYY) under Enter Description
3. Open **Sequence** and click **Settings**.

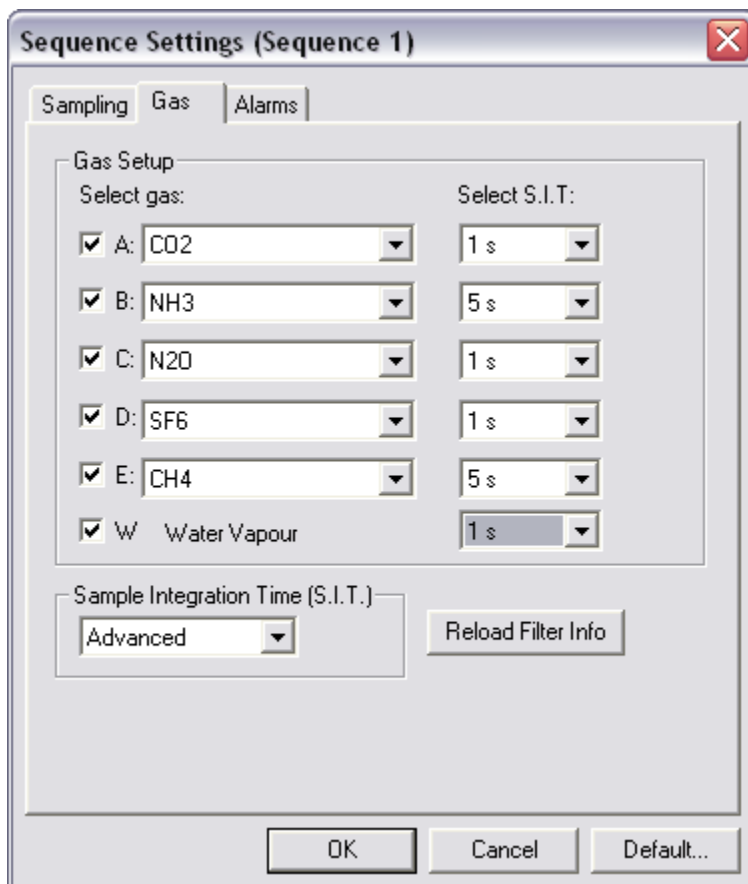


4. Under **Sampling**, change Tube Length to 1 m.



5. Under **Gas**, choose all gases (A-E) including water vapor (W), choose Advanced Sampling Integration Time, then select 1 s for CO₂, N₂O, SF₆ and Water Vapor, and 5 s for NH₃ and CH₄.

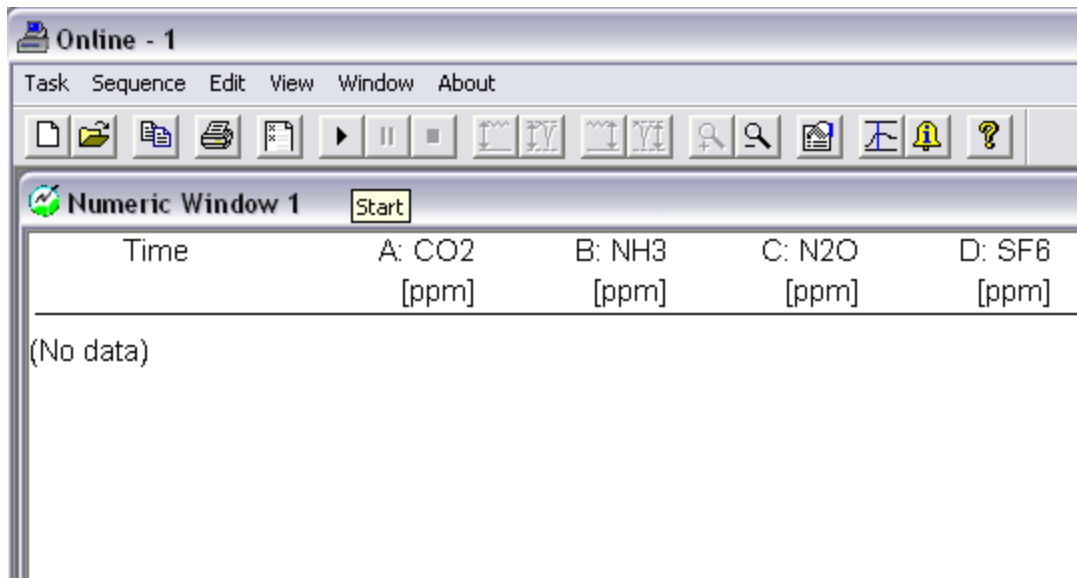
6. Click **Reload Filter Info** if this is the first use after a calibration attempt.



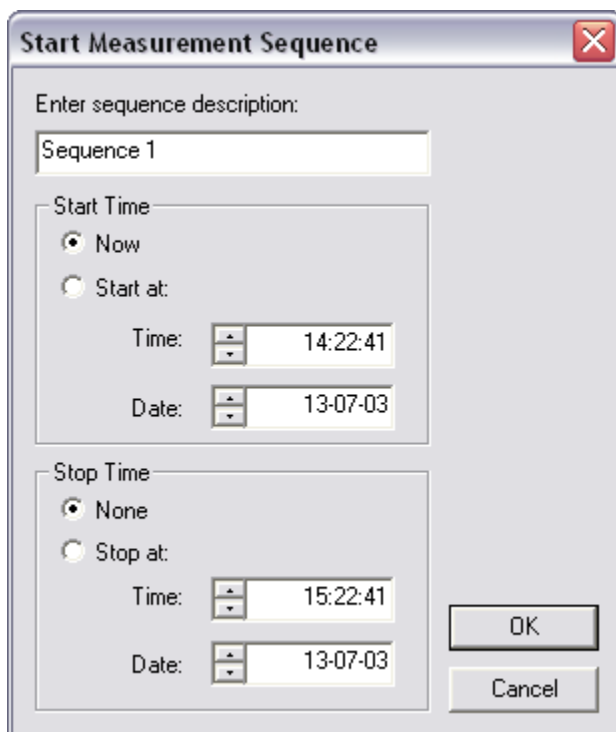
7. Click **OK**.

8. Open **Window** and click **New Graphic Window** then **Tile** to view graphic table and numeric table side by side.

9. Click **Run** on the second tab bar.



10. Change Sequence Description if necessary, date and time will be automatically recorded.



11. Click **OK** to start test.

Appendix E: System Performance (Mass Recovery) Test

E-1 Experiment setup

E-1.1 Purpose

Using tracer gas to detect a known amount of injected gas, in order to assess the integrity of REMS for monitoring emissions.

E-1.2 Equipment required

1PC with INNOVA Gas Monitoring Software 7034 – Online installed, 1PC with Environics Series 4000 Instrument Control Software installed, INNOVA 1412i Gas Analyzer, Environics 4040 Gas Dilution System, SF₆ (6.293 ppm_v ±1%, primary certified) cylinder with adjustable gasket, Styrofoam board cut-out within a length of plastic tube, 10 m of Teflon tube, various Swagelog compression fittings, adjustable wrench.

E-2 Equipment setup

E-2.1 Sampling line connections

Note: All gas connection should be done using Teflon tub and compression fittings.

1. Connect SF₆ cylinder to Port 1 of GDS.
2. Block hood of chamber 1 using Styrofoam board cut-out within plastic tube (Figure E.1).



Figure E.1: Hood blocked using Styrofoam board set within plastic tube.



Figure E.2: Injection point taped next to ventilation port.

3. Lead injection tube from Outlet port of GDS to chamber 1 through gaps in the hood. Tape injection point to metal enclosure next to ventilation port (Figure E.2).

E-2.2 PC connections

PC with INNOVA Gas Monitoring Software 7034 – Online installed should be connected to INNOVA via null-modem RS-232 cable.

PC with with Environics Series 4000 Instrument Control Software installed should be connected to GDS via null-modem TS-232 cable.

E-3 Conducting the recovery test

E-3.1 Turning on the gas

1. Open Knob 1 completely (Refrain from using if Gauge 1 shows <500 psi).
2. Open Knob 2 slowly until pressure Gauge 1 reads 55 psi (Figure E.3).
3. Open Knob 3 completely (Further adjustments to Knob 2 might be required with initial loss of pressure).

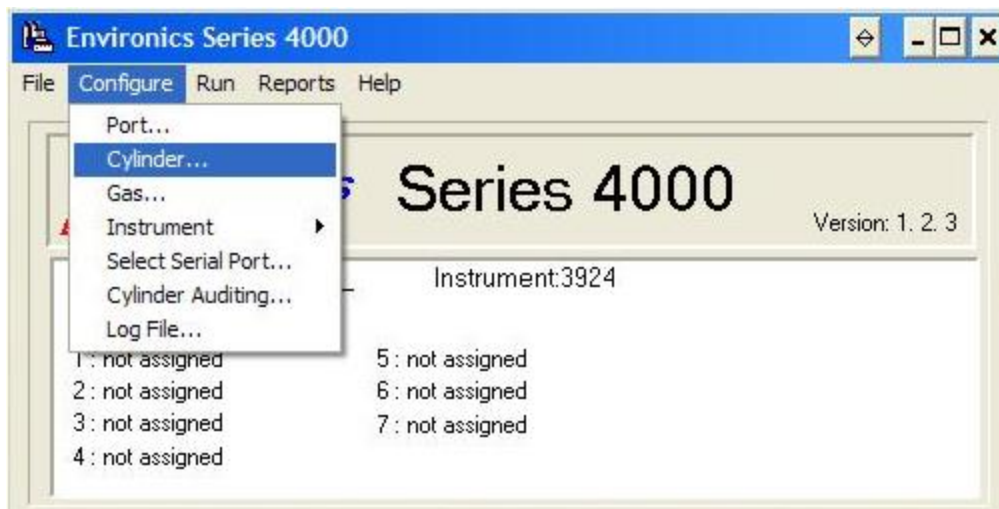


Figure E.3: Picture of cylinder gasket with knob and gauge labels.

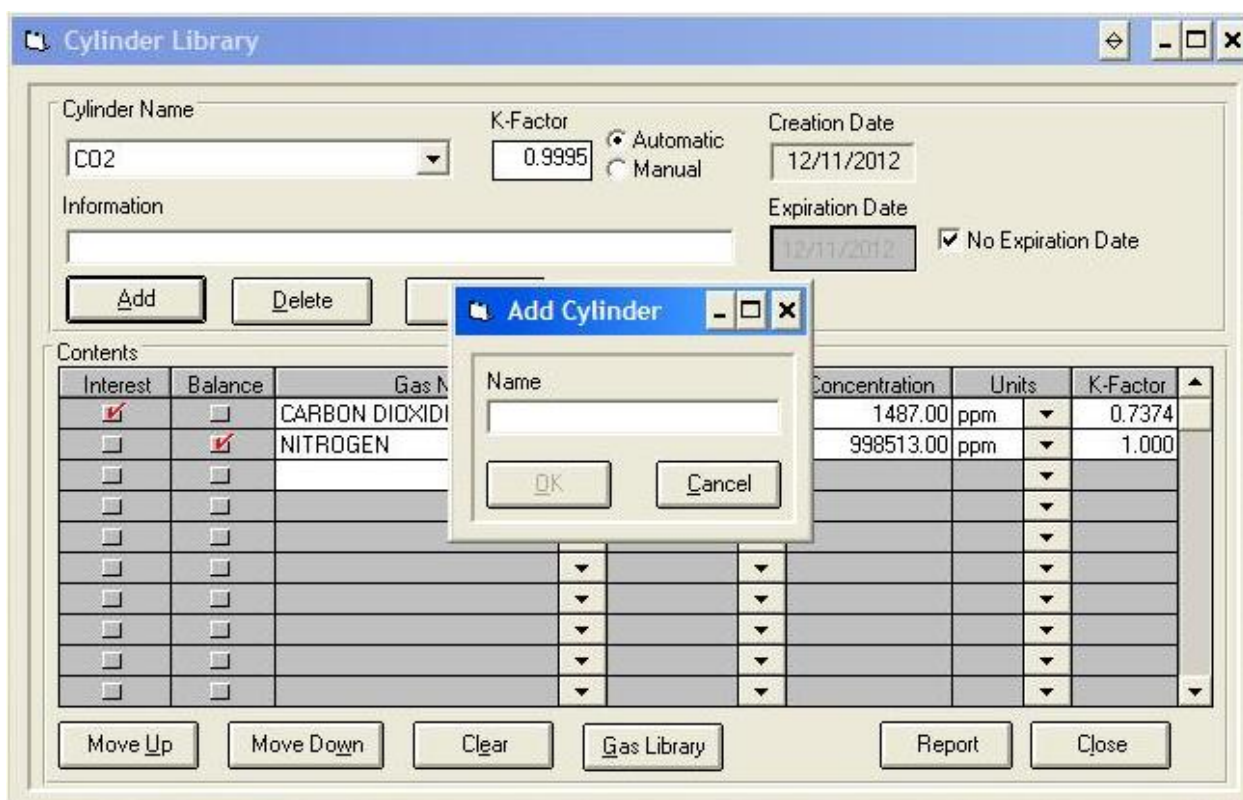
E-3.2 Using the Gas Dilution System

In the EnviroNics Series 4000 Instrument Control Software:

1. Pull down the **File** Menu. Click **New**.
2. Input file name for test (Recovery_test_MMDDYYYY). Instrument should be 3924. Click **OK**.
3. Pull down the **Configuration** menu. Click **Cylinder**.



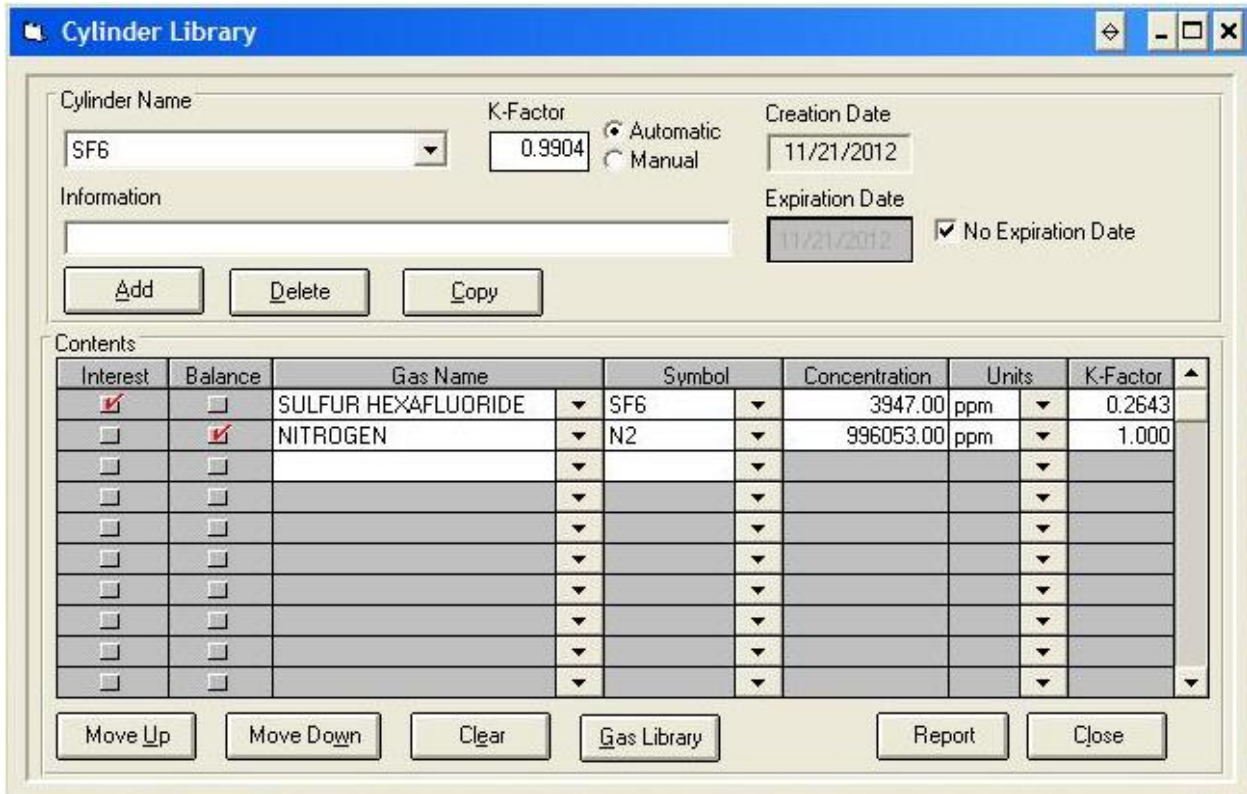
4. Click **Add** and input Cylinder name (SF₆).



5. Click **OK**.

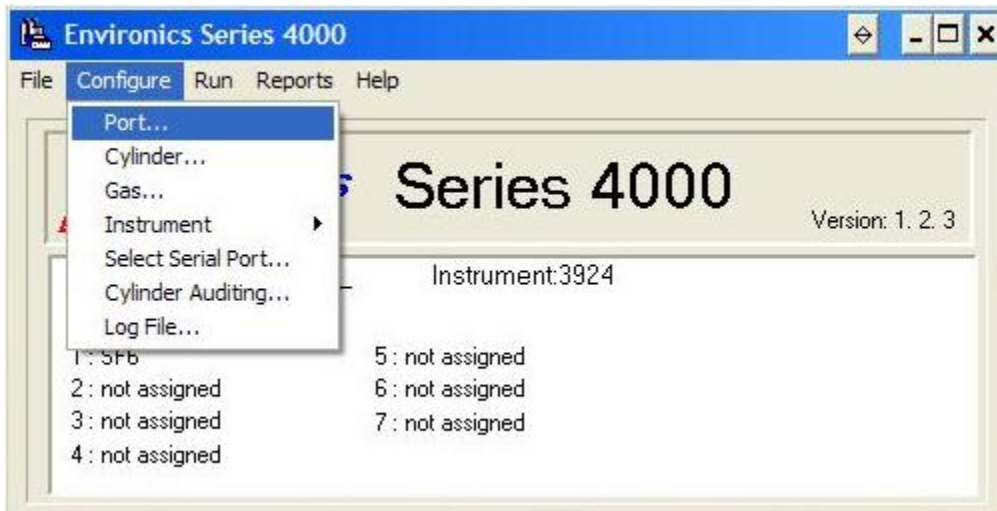
6. Choose the zero gas (N₂) as Balance, and SF₆ as Interest.

7. Input concentration according to concentration on SF₆ cylinder (3947 ppm).

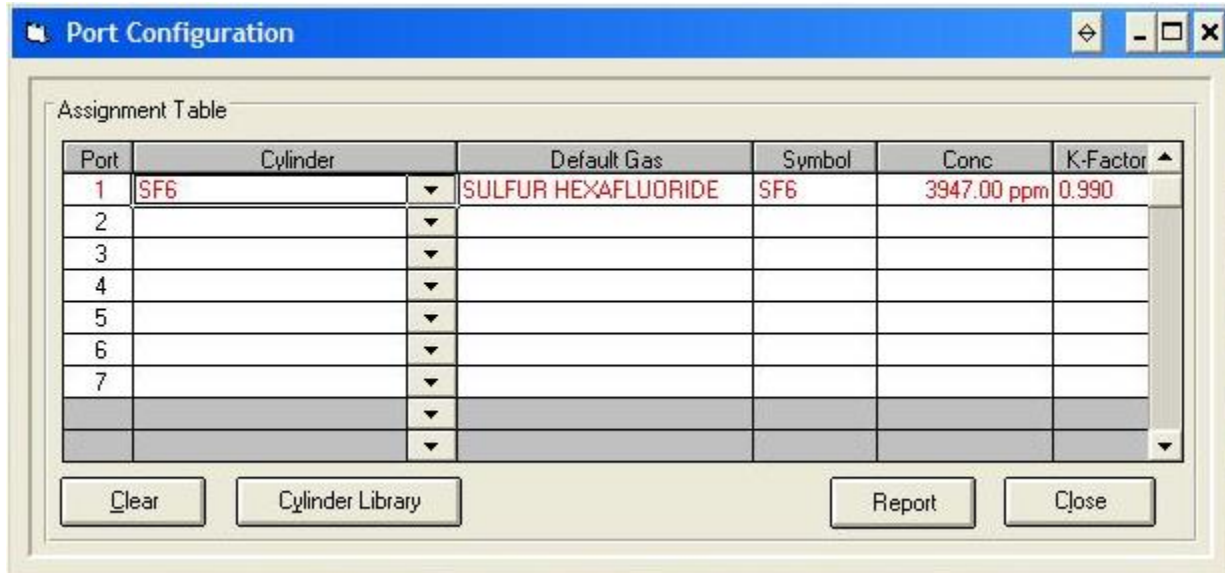


8. Click **Close** and save changes.

9. Pull down the **Configuration** menu. Click **Port**.

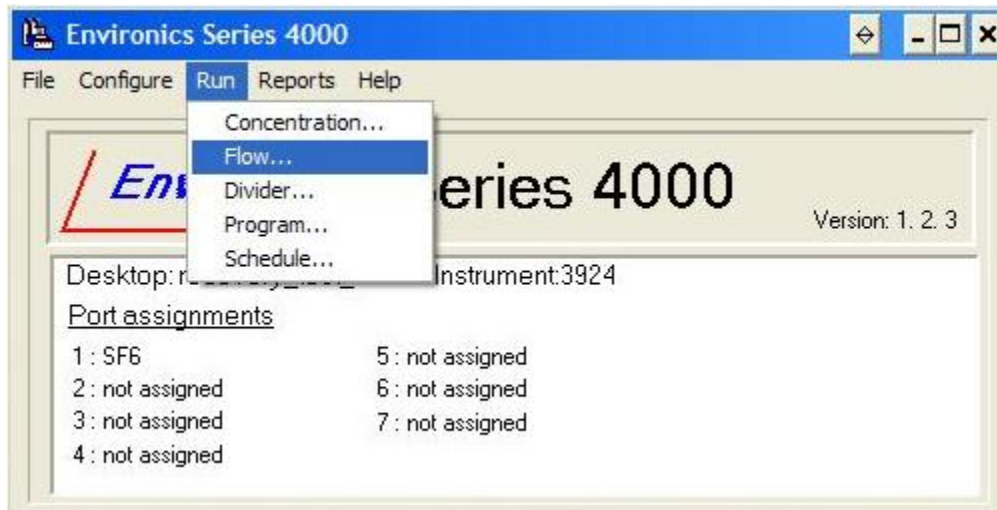


10. Choose Cylinder name (SF₆). Concentration for chosen gas should show up automatically.

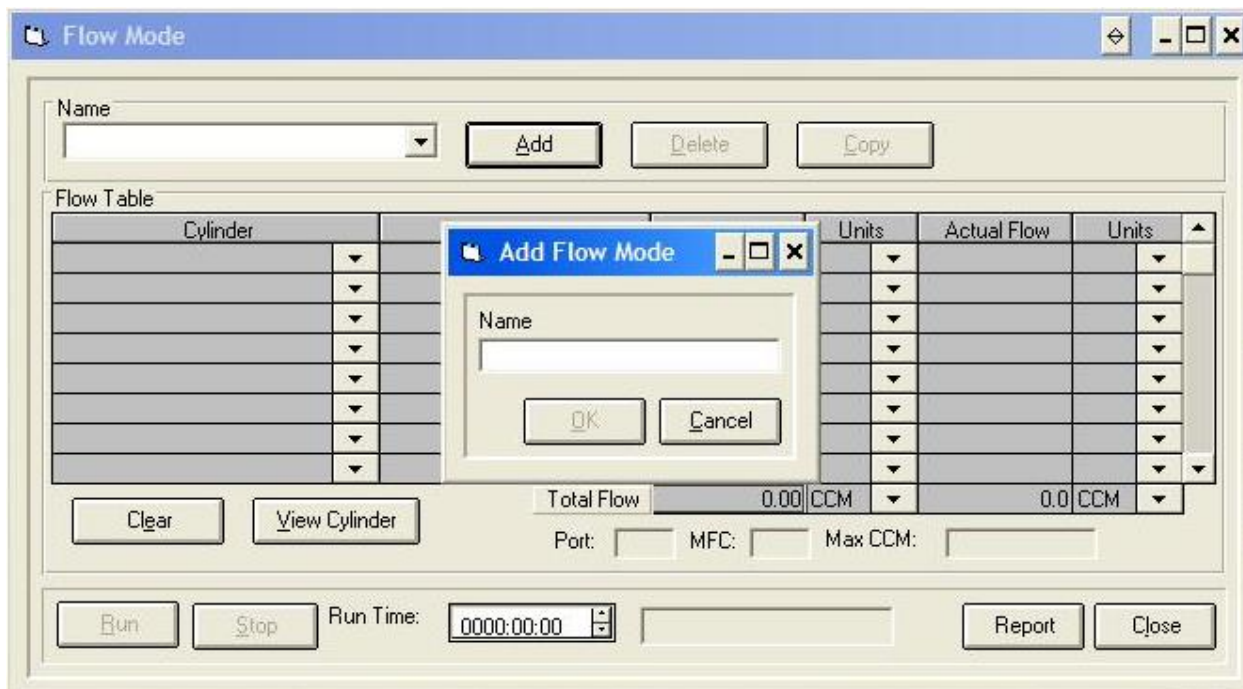


11. Click **Close** and save changes.

12. Pull down the **Run** menu. Click **Flow**.

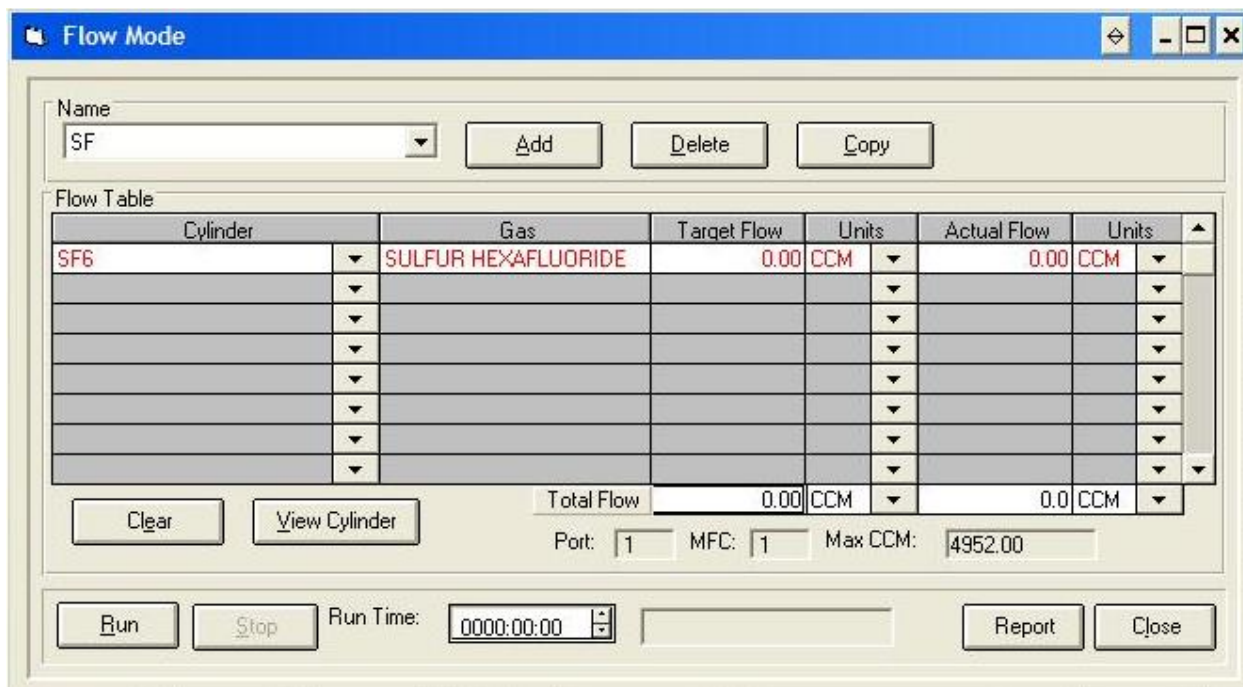


13. Click **Add** and input Flow Mode (SF₆).



14. Click **OK**.

15. Pull down **Cylinder** and choose SF6.



16. Change the units to LPM for both target and actual flow rates.

17. Enter 4.025 under target flow rate.

18. Click **Run** when ready to inject gas.

E-3.3 Using the LabVIEW program

For the recovery test, use “Project(3).vi” under “C:\REMS”. For more details on the software, refer to Appendix A.

Appendix F: Preparations for Experiments

The following series of checkups should be done immediately before a new experiment is conducted:

Replace filters on sample line inside each chamber

Check background air supply filter (replace or rotate if areas of air flow is dark gray in color)

Check duct tape sealing holes in the bottom of the chamber (retape if not creating seal)

Check silicone and tape sealing HVAC box (reseal if opened or low recovery rate)

Check TEC to chamber insulated duct connections

Fully open all orifice meters (blue/black ball valves)

Record pressure of each inclined-vertical red oil manometer

Ensure all 7 gas pumps are on and working (suction in sample port using Manometer)

Connect and turn on cameras, make sure they are pointed in right direction

Turn on TeamViewer on desktop computer, record ID No. and Password

Figure F.1 shows a typical timeline for the day of the experiment, including time to turn on INNOVA, introduce cow, introduce feed and collect rumen samples.

	A	B	C	D	E	F	G	H
1	Days of Experiment							
2	Notes:							
3	Notes:							
4	Notes:							
5	Notes:							
6	Elapsed Time (Day One)	Elapsed Time (Day Two)	Actual Time	Complete? (check-off)	Action	Required Status	REMS Gas Sample (sequence-chamber)	Notes
9	-1:00		7:00		Prepare Feed			
10	-1:00		7:00		Turn on INNOVA Analyzer			
11	-0:20		7:40		Begin placing steers into chambers			
12	0:00		8:00			Steer in Ch. 1		First steer in; each subsequent one in before 14 min 20 sec elapses
13	0:14		8:14			Steer in Ch. 2		
14	0:28		8:28		Start REMS Sampling for Day 1	Steer in Ch. 3	Sample 1-CH1	
15	0:43		8:43		Collect rumen gas from Steer 1 - pre-feed	Steer in Ch. 4	1-CH2	Actual time of rumen sample 1
16	0:57		8:57		Collect rumen gas from Steer 2	Steer in Ch. 5	1-CH3	Actual time of rumen sample 2
17	1:11		9:11		Collect rumen gas from Steer 3	Steer in Ch. 6	1-CH4	Actual time of rumen sample 3
18	1:26		9:26		Collect rumen gas from Steer 4		1-CH5	Actual time of rumen sample 4
19	1:40		9:40		Collect rumen gas from Steer 5		1-CH6	Actual time of rumen sample 5
20	1:54		9:54		Collect rumen gas from Steer 6		Sample 2-CH1	Actual time of rumen sample 6
21	2:09		10:09		Place feed in chamber and close door	Feed in Ch. 1	2-CH2	First feed bin in after second chamber 1 sample; Actual time of feed in chamber 1
22	2:23		10:23			Feed in Ch. 2	2-CH3	Each subsequent one following chamber sample; Actual time of feed in chamber 2
23	2:37		10:37			Feed in Ch. 3	2-CH4	Actual time of feed in chamber 3
24	2:52		10:52			Feed in Ch. 4	2-CH5	Actual time of feed in chamber 4
25	3:06		11:06			Feed in Ch. 5	2-CH6	Actual time of feed in chamber 5
26	3:20		11:20			Feed in Ch. 6	Sample 3-CH1	Actual time of feed in chamber 6
27	3:35		11:35				3-CH2	
28	3:49		11:49				3-CH3	
29	4:03		12:03				3-CH4	
30	4:18		12:18				3-CH5	
31	4:32		12:32				3-CH6	
32	4:46		12:46				Sample 4	

Figure F.1: Screenshot of experiment timeline, including time, action and notes.

Appendix G: HVAC System for Beef Metabolism Unit

This following section was adapted from the report generated by undergraduate students Ana Beatriz P. da Silva and Chris Hwang from their summer 2013 independent study.

G-1: System Description

The HVAC System in the Building was designed to maintain a setpoint temperature in each of its five rooms: Feed Room, Computer Laboratory, Bathroom, Equipment Room and Animal Space.

A depiction of the total area and its divisions can be seen in the following image:

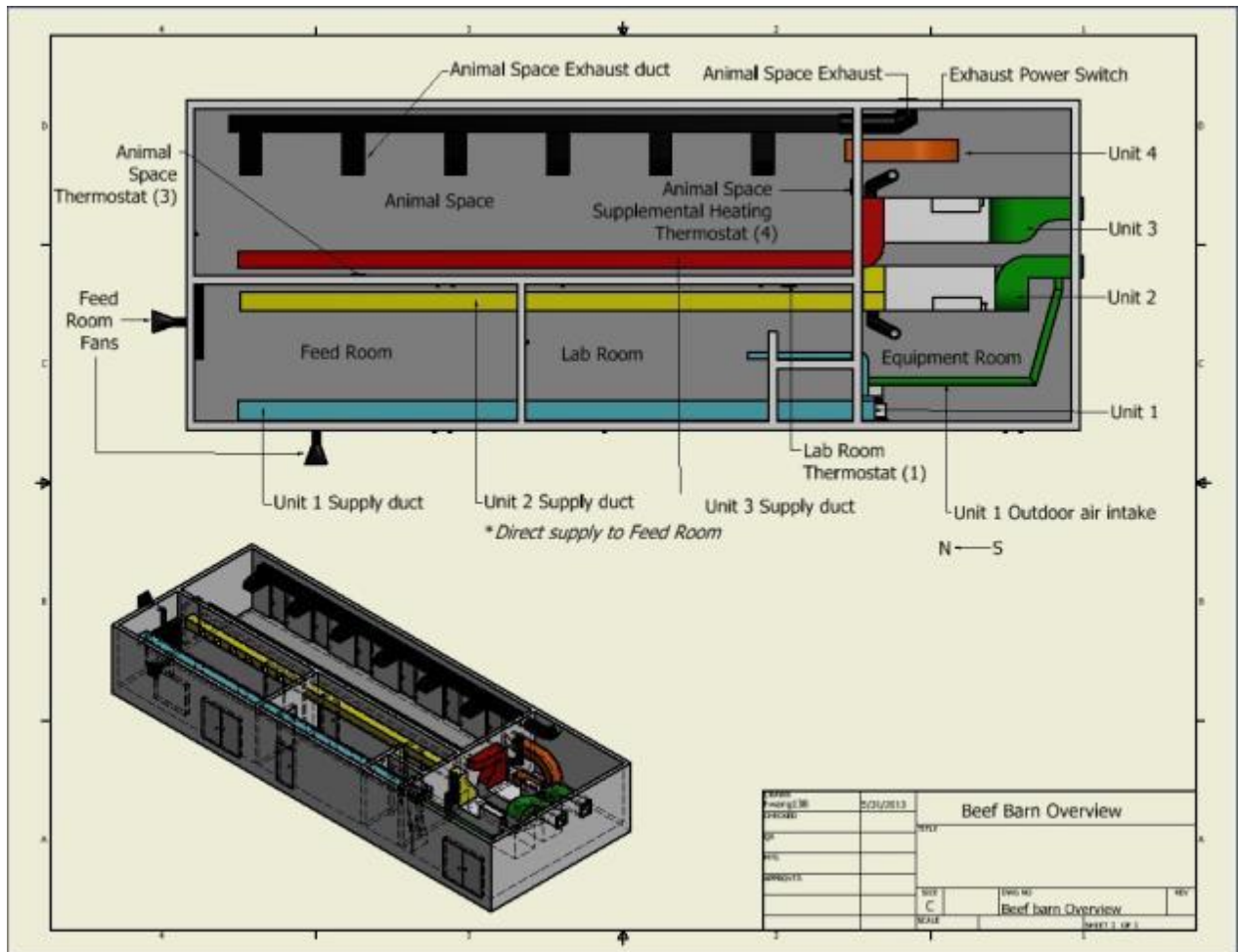


Figure G.1: Layout of the building.

G-2: HVAC Components

There are a total of five main HVAC components for the building.

Two HVAC units regulate temperature in the Feed Room and the Computer Laboratory (and consequently the Bathroom). These rooms will only be occupied by humans and feed, so the temperature is typically kept around 75° F. The HVAC system to maintain these rooms at this temperature consists of: one Small Handler (Unit 1) that conditions and supplies a mixture of return and outdoor air, one Supplemental Heater (Unit 2) that heats and supplies 100% outdoor air, and two exhaust Fans (just for the milling equipment in Feed Room). Unit 1 can heat or cool the three rooms and Unit 2 turns on automatically when the Feed Room fans are operating during feed milling. Both components have exhaust pipes for air supply. The Feed Room fans help clear out the dust created from the grinding process.

Three HVAC components are used to regulate temperature in The Animal Space. This room holds up to twelve animals simultaneously, including the REMS system for six animals. The ideal temperature for this room is 65/70°F, which is maintained with one Large Handler (Unit 3) that conditions and supplies 100% outdoor air, one Supplemental Heating Unit (Unit 4) that heats and supplies only return air, and one exhaust fan unit (Unit 5) that takes air from the animal space. Additionally, the REMS chambers each have their own small Cooling Unit. Unit 3 can provide heating or cooling as needed.

All of the units have individual thermostat or switch controls, except Unit 2. Thermostat 1 is on the wall near the Bathroom in the Laboratory; Thermostat 3 is in the Animal Space, near the door to the Feed Room and the unit has a mode switch on the side of the unit in the equipment room;

Thermostat 4 is on the back wall of the Animal Space. A switch for Unit 5 is located on the east wall of the equipment room.

G-3: System Operation

G-3.1: Unit 1 (Small Air Handler)

The most basic control of the HVAC components is provided by on/off power switches. The power switch for Unit 1 is located near the unit, and should remain on at all times except periodic maintenance of the unit. When the power switch is on, Thermostat 1 provides control to choose the operating mode (heating or cooling), fan state, and setpoint. Figure G.2 shows the power switch and Thermostat 1.

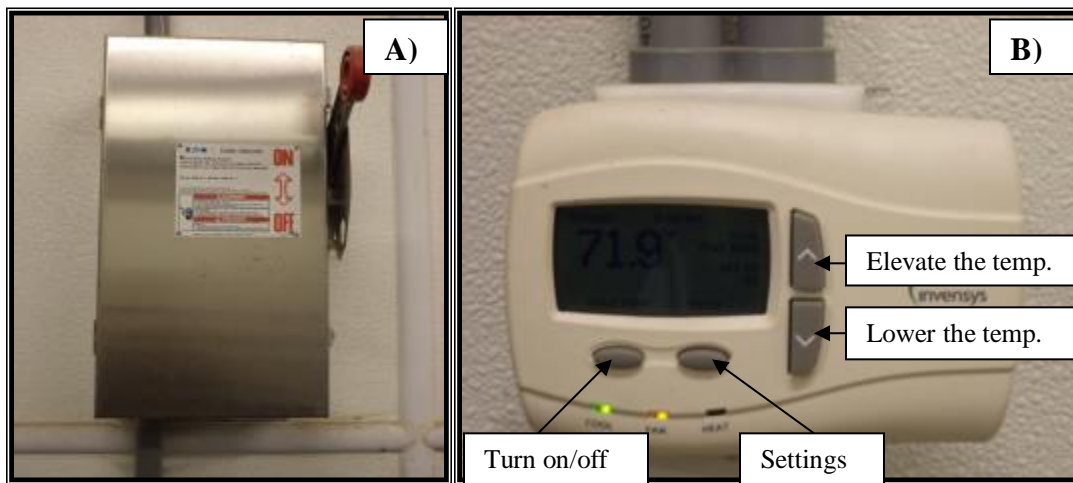


Figure G.2: Control Devices for Unit 1. A) Power Switch for Unit 1 (affixed to wall). B) Thermostat 1.

G-3.2: Unit 2 (Supplemental Heating)

The power switch for Unit 2 is located on the side of the unit. This is the only control for this unit; it doesn't have temperature regulation with a thermostat. When the power is on, this unit will turn on automatically when the fans in the feed room are active. Figure G.3 shows the only

control switch for this unit. This unit should be powered in cold weather, but may be switched off when the temperatures do not require supplemental heating.



Figure G.3: Power Switch for Unit 2 (affixed to Unit).

G-3.3: Unit 3 (Large Handler)

The power switch for Unit 3 is located on the side of the unit. Additionally, a mode switch located on the side of the unit selects the operating mode (heating or cooling). When the unit is on, Thermostat 3 allows the selection of a setpoint and controls the status of the unit within the bounds of the operating mode. Figure G.4 shows the power switch, control panel and Thermostat 3.

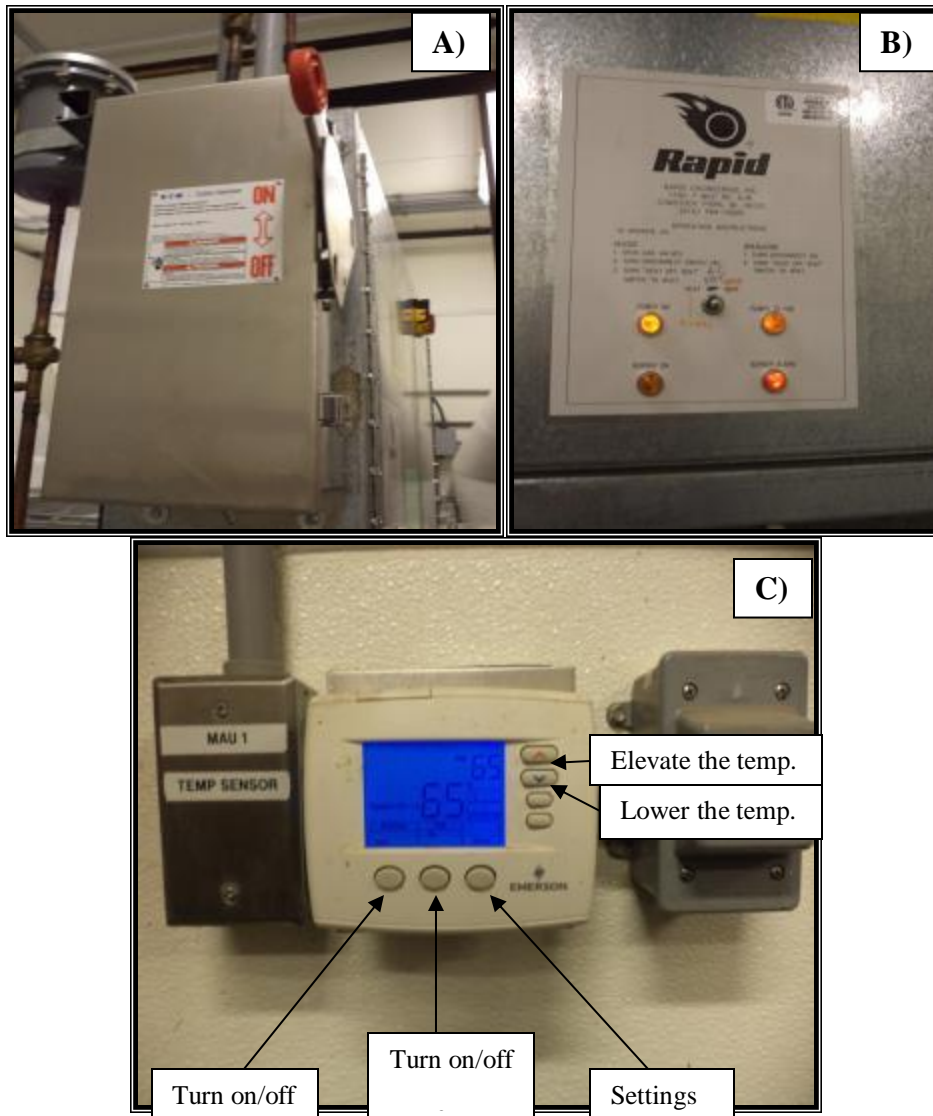


Figure G.4: Control Devices for Unit 3: (A) Power Switch for Unit 3 (affixed to Unit), (B) Operating Mode Selection (heat/cool), and (C) Thermostat 3.

G-3.4: Unit 4 (Animal Space Supplemental Heating)

The power switch for this unit is located to the right of the thermostat on the south was of the animal space. This component is only controlled by Thermostat 4 which can be used to turn the heater on or off and to change the setpoint temperature. Figure G.5 represents the control device for Unit 4.

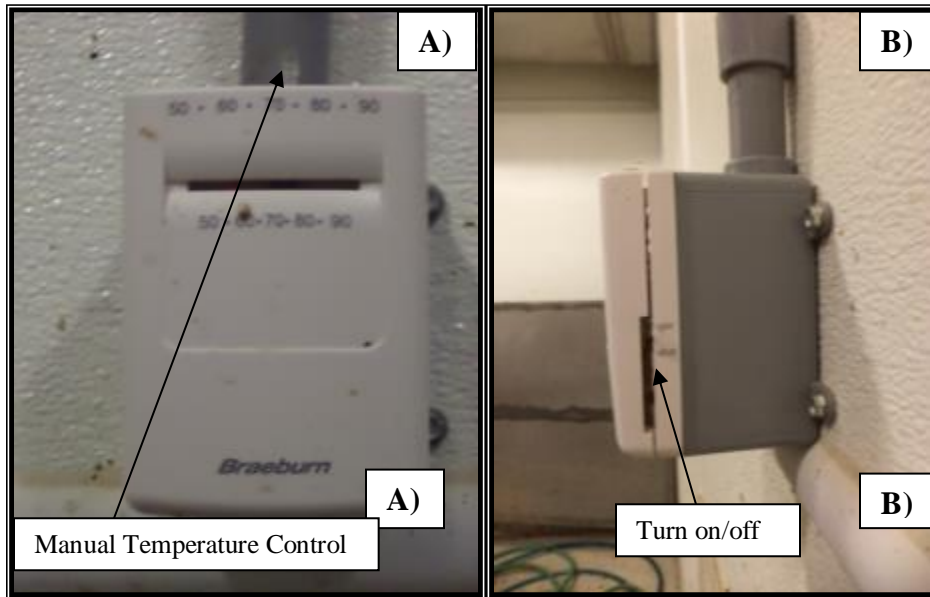


Figure G.5: Thermostat 4. (A) Front View. (B) Side View.

G-3.5: Unit 5 (Animal Space Exhaust)

This component should be turned on when there are animals inside the animal space. To control this unit, there is a power switch near the unit on the east wall of the equipment room to turn the equipment on or off. Additionally, there is an option to have the exhaust run automatically (to turn on and off with Unit 3) or to be manually controlled (on when the power is on and off when the power is off). Typically, this should be set to manual such that it runs continuously with animals in the barn, to prevent large fluctuations in the background gas concentrations. This unit should be turned off when no animals are in the barn to save on energy costs. Figure G.6 shows the control panel for the Animal Space Exhaust Unit.



Figure G.6: Power switch for Animal Space Exhaust Unit.

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