DEVELOPMENT OF A CONTROL ALGORITHM FOR A DYNAMIC GAS MIXING SYSTEM

A Thesis

by

APRIL LOVELADY

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2005

Major Subject: Biological and Agricultural Engineering

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Approved as to style and content by:

Gerald Riskowski (Member)	Fred T. Davies, Jr. (Member)
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ABSTRACT

Development of a Control Algorithm for a Dynamic Gas Mixing System. (May 2005)

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Chair of Advisory Committee: Dr. Ronald E. Lacey

An algorithm was developed to control the partial pressures of N_2, O_2, and CO_2 in a gas mixing tank. The gases were premixed before being introduced into the low pressure Mars Dome. As an attempt to reduce the effects of pressure, the number of moles of the component gases was calculated and used to determine when gases needed to be added to the system or when gas concentrations needed to be diluted. There were two trial runs during each of the two experiments carried out. The total pressures in both the mixing tank and the Mars Dome remained within their limits of constraint during both trials. For the mixing tank, the pressure was maintained between 170kPa and 180kPa with a setpoint of 175kPa. Gas composition was evaluated at 67kPa and 33kPa in the Mars Dome. Again the pressure remained within its range of ±5kPa of its setpoint. Adequate control of the partial pressures of N_2, and O_2 were achieved in the mixing tank and the Mars Dome. With respect to the control of CO_2, the algorithm was unable to maintain the partial pressure within the operational limits specified. The tendency was for CO_2 to linger above its setpoint. Moreover, at 33kPa the CO_2 sensor in the Mars Dome began to reflect a lower concentration of CO_2 in the system than what was reported by the gas chromatograph or the CO_2 sensor in the mixing tank. While sufficient control of the partial pressures was achieved, there are modifications to be

made that should further tighten the control limits of the system. Such modifications include recalibrating the sensors in the system and adjusting gas flow rates.

DEDICATION

I dedicate this work to my family without whom I would have never made it this far. Thank you for nurturing me in my time of need and chastising me when necessary. I would especially like to thank Daniel who awakened in me a sense of endurance I never knew I possessed.

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I would like to acknowledge Dr. Ronald Lacey without whom I would never have attended graduate school. Thank you for being a wonderful advisor, mentor, and counselor.

I would also like to acknowledge Mr. Charles Quincy, Dr. John Sager, Dr. Philip Fowler and the host of other researchers and scientists at the Kennedy Space Center for seeing me through the trials of obtaining a graduate degree.

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CHAPTER I

INTRODUCTION

Extended manned space missions will require that atmospheric revitalization processes be carried out in atmospheres unlike that of Earth's. Specifically, NASA plans to land its first manned mission to Mars in the future, where the air pressure is approximately 1/100th that of Earth's and the atmosphere is 95% CO_2 (6). Because such a low pressure and high CO_2 concentration would be lethal to humans, any Martian base would have to be totally enclosed as a means of maintaining its own environment (7). Such an enclosed environment must have an atmosphere regeneration system.

Plants produce food, transpire water, and consume CO_2 and produce O_2 during photosynthesis. Currently, physical-chemical methods are used to produce O_2 and remove CO_2 from the atmosphere of International Space Station (ISS). However, NASA intends to use plants to supplement these methods. It would be impossible to grow and maintain plant life in Lunar or Martian conditions because of the atmospheric composition. An enclosed ecological subsystem in which the environmental parameters were controlled would be a creative solution for growing plants in environments that would otherwise be toxic. If such a subsystem were designed to operate at low pressure, the launch weight requirements for system hardware would be reduced, as would the leakage of gases (N_2, O_2, and CO_2) from the controlled ecosystem to the hypobaric

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This thesis follows the style of Habitation.

surroundings. Subambient conditions on Mars would require lower total levels of N_2, O_2, and CO_2, of which N_2 and O_2 would otherwise have to be transported from Earth or produced in space (12). A low pressure regenerative life support system would be an important component to NASA's ALS program because it would decrease the amount of re-supply needed from Earth.

Hypobaric studies on biological systems are important to the future of space exploration to quantify the effects of pressure on gas exchange and water evaporation rates in enclosed systems (3). In order to combat the effects of pressure, NASA has designed and built a gas mixing system that is capable of pre-mixing a variety of gases prior to introducing them into an enclosed environment; primarily of N_2, O_2, and CO_2. Specifically, this research focuses on developing the control algorithm necessary for a system to mix N_2, O_2, and CO_2 (at atmospheric pressure or above) before insertion into an enclosed, low pressure chamber. Operation of this gas mixing system necessitated the development of a control system capable of maintaining separate control of the individual partial pressures and molar volumes of N_2, O_2, and CO_2.

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CHAPTER II

LITERATURE REVIEW

Data Acquisition and Control Systems

A crop production unit is considered an important part of an Advanced Life Support system. The question of whether or not plants can grow under conditions of reduced gas pressure, reduced lighting, and reduced gravity, as might be encountered during a planetary exploration mission to the moon or Mars, has led to the development of environmental control systems that control and monitor such parameters as total pressure, CO_2 level, O_2 level, temperature, humidity, and lighting. Both gravity and gas composition in space (more specifically Mars) are very different from those on Earth.

Previous experiments conducted by Daunicht and Brinkjans (10) and Andre and Massimino (4) were carried out under various total pressures with no control of the individual partial pressures of N_2, O_2, and CO_2. With this in mind, Goto (22) set out to design a system that was expected to maintain total pressures as low as 40kPa and control the partial pressures of O_2, and CO_2. They developed a stainless steel cylindrical chamber that had an acrylic resin cover. N_2, O_2, and CO_2 were supplied from three separate lines with each line having its own gas bottle, pressure regulator, flow meter, and electromagnetic valve (23). On/off control of the valves was used to supply gases to the chamber. Environmental factors were controlled and monitored using a 16-bit microcontroller and relays. CO_2 was measured using an (Infrared Gas Analyzer) IRGA placed in the chamber, but a pressurized subsystem was designed for O_2 measurements because the O_2 galvanic cell could not operate at low pressure. The mean total pressure was maintained at approximately 50kPa, with pressures above 60kPa occurring when the vacuum pump was overloaded and stopped. This experimental setup was used to conduct short term experiments on spinach with 30 sample plants per experiment. Relative humidity, photosynthetic photon flux density (PPFD), and photosynthetic rates were also monitored.

At Ames Research Center (ARC), another four chamber low pressure system was developed (42) in which the effects of simultaneous changes in atmospheric pressure and composition on plant physiology and productivity could be studied. These chambers were also cylindrical and fabricated from stainless steel. The internal atmospheric composition was controlled by injecting N_2, O_2, and CO_2 as determined by an on-line gas composition analysis system. The control system itself was developed on an Apple Macintosh II CX, computer and outfitted with Opto22 interface hardware. This paper did not report on any plant studies conducted using the chamber as they were scheduled later in the year to determine the effects of different pressures and atmospheric compositions on wheat growth and yield.

The Variable Pressure Growth Chamber (VPGC) at Johnson Space Center (JSC) was used in a 34 day test to grow a wheat crop at 70kPa (9). The system performance was verified at the specified pressure by completing various leak tests. The VPGC was a large, enclosed, controlled environment chamber designed for testing human life support in combination with bioregenerative and physiochemical systems (5). With all of the systems off, the leak rate was approximately 10% chamber volume per day, otherwise when the fans were on, it was greater than 10% chamber volume per hour (41). The chamber leak rate was studied at 70kPa. Further details on the VPGC and the associated control system were not presented.

At Kennedy Space Center, a Mars Dome project was designed and constructed to grow plants under reduced pressures. The system included the dome enclosure, an environmental control and monitoring system, lighting and water delivery for a plant growth system, and an external vacuum pump unit. The dome itself was a polycarbonate enclosure with a stainless steel base. The case is fitted with ports to allow access for instrumentation and control lines for environmental control (18). It was initially designed to go inside a larger vacuum chamber that would maintain Martian pressure (~1kPa), but not temperature that can range from -72°C to 177°C (19). A set of printed circuit boards plugged into a base board were used to implement the microcontrollers and signal acquisition systems. The master microcontroller and the power supply were housed in the base board. Parameters were controlled by slave microcontrollers located on the adapter boards. Studies have concluded that the maximum vacuum the dome can sustain is 25kPa.

The Biomass Production Chamber (BPC) at Kennedy Space Center (KSC) was another large scale chamber but was not operated at reduced pressure. The Closed Ecology Life Support System (CELSS) program retrofitted a hypobaric test chamber from the Mercury Program thus creating the BPC. The BPC was a cylindrical chamber with two-levels of direct access. It enclosed a total of four vertically stacked, annular crop growing shelves. Air ducts and plumbing access points created system leaks that were approximately 5 – 10% of the chamber volume per day (50). The studies conducted within the BPC focused on features that were unique to the chamber such as the effects of high pressure sodium (HPS) lighting, variable CO_2 concentrations, and crop canopy growth and development using nutrient film technique (NFT) (50). Temperature, humidity, photoperiod, and CO_2 levels were continuously monitored. Ethylene and other volatile organic compounds (VOCs) were also measured. Criteria for selecting crops to be studied included crop yield, nutritional value, harvest index, and processing requirements (50). All of the crops chosen were C_3 plants because their CO_2 fixation rate was more efficient than C_4 plants at elevated CO_2 levels (50).

NASA-KSC developed a computer control system that provided control, monitoring, data storage, and configuration tracking capabilities for research hardware (35). The most recent control system is named the Control, Monitoring, and Data System (CMDS). CMDS has the ability to control up to 80 concurrent experiments with a centralized server to coordinate high level control. The primary controllers are manufactured by Opto22, while those controllers that were supplied with the controlled environment chambers were utilized as backup controllers. This setup requires a smooth transition between the primary and backup controllers or controlled environment chambers which was accomplished using a watch dog timer (P8-WDT24/PLC). As long as the timer received a signal from Opto22, the chambers were controlled with the primary controllers.

NASA's Advanced Life Support Project partially funded the development of the Generation III Low Pressure Plant Growth (LPPG) system at Texas A&M University. The system consists of six cylindrical chambers within which partial pressures of N_2, O_2, and CO_2 concentrations are controlled and monitored. The chambers themselves have a leak rate of 2 - 5% of total volume per day at a total pressure of 5kPa (40). Each chamber has its own independent control system based on the PIC16F877 microcontroller. The program for each microcontroller was written in the C language with LabVIEW directing information along the appropriate channels (7). First, the program checks to see that the pressure setpoint is being maintained. Then, it checks the concentrations of the component gases by reading the values returned from the gas sensors and adjusts them as needed. Gas concentrations are verified using a gas chromatograph.

Low Pressure Plant Growth Studies

Previous experiments have attempted to determine the effects of low pressure and varying gas concentrations on plant growth. Much of the earlier work done under low pressure conditions focused on seed germination. The experimental apparatus used to conduct these experiments often were not robust enough to provide the atmospheric control necessary to obtain reliable data. They often consisted of an enclosed glass jar with primitive control of parameters such as CO_2 and O_2 concentrations, ventilation rates and temperature.

An early study concluded that seeds cultivated in low O_2, low temperature environments demonstrated an enhanced resistance to freezing while the minimum temperature required for germination was decreased (45). Overall germination was inhibited. No experimental apparatus was described although environmental conditions were described. A modified Martian atmosphere was created using mostly CO_2 at a reduced but unspecified pressure.

Other experiments followed that attempted to germinate seedlings under low pressure (20 and 21). Gale (21) reported that at reduced pressures, the transpiration rates of plants increased as a result of the diffusion coefficient increasing. The model used consisted of a petri dish that was covered and sealed with filter paper. Bean and maize plants were used as subjects. The bean plants demonstrated low photosynthetic efficiency and relatively high mesophyll resistance to CO_2 uptake while the maize was chosen because of its high photosynthetic efficiency and low mesophyll resistance. Calculations were made using stomatal and mesophyll resistance values obtained under ambient conditions. These calculated values are questionable because these values are pressure dependent (47). While under subambient conditions, stomates tend to close as an attempt to reduce water loss, this is not necessarily the case at ambient pressures.

Tomato plants were grown at 40kPa and compared to those grown at 100kPa (10). There was a significant increase in the transpiration rates of those grown under low pressure. This was consistent with Gale's findings (21). Wheat grown at 20kPa also demonstrated an increase in transpiration (4). Photosynthesis increased under low pressure-low O_2 conditions, but photorespiration decreased (20). These experiments were conducted on young seedlings or sections of detached leaves.

Goto (22) began to study the effects of low total pressures on plant growth. They began by designing a system capable of controlling gas partial pressures, light intensity, relative humidity, and temperature. The relative growth rate of spinach was studied at 100kPa, 75kPa, and 50kPa. The O_2 partial pressure was held constant at 21kPa. This helped to distinguish between the effects of O_2 partial pressure and total pressure. While four treatments were carried out, two of them were done at 50kPa and the CO_2 partial pressure was changed from 0.05kPa to 0.10kPa. This particular study concluded that spinach grew faster in the CO_2 enriched environment (0.10kPa) than at 0.05kPa. The growth rate was reduced when total pressure was reduced from 100kPa to 50kPa with a constant CO_2 partial pressure of 0.05kPa. This particular grow out lasted 10 days with transplanted spinach grown hydroponically in a controlled environment room with fluorescent lamps from seeding.

Iwabuchi et al. (29) then decided to investigate the effects of O_2 partial pressures under low total pressures on the net photosynthetic rate of spinach. The same control system used in previous research efforts had to be modified to include measurement of O_2 partial pressure. The system was composed of an assimilation chamber, gas supply apparatus, humidity control equipment, a CO_2 gas analyzer, an O_2 gas analyzer, fluorescent lamps, and a PC with A/D converters and automatic relays (24). Previous research suggested that the photosynthetic rate was inhibited at atmospheric pressure by O_2 (16). Three trial were run with the O_2 partial pressure at 20kPa and three in which the O_2 partial pressure was 3kPa. CO_2 was fixed at 0.035kPa. The total pressures examined were 100kPa and 50kPa, with the balance being N_2 and 20kPa. The results concluded that the net photosynthetic rate was higher at 3kPa than 20kPa no matter the total pressure. The photosynthetic rates did not show significant change under any total pressure at 3kPa O_2, but increased dramatically at 20kPa O_2. The transpiration rate increased as the total pressure decreased for both O_2 partial pressures.

Spinach and maize plants were studied under hypobaric conditions and their net photosynthetic and transpiration rates measured (29). A new low pressure chamber was designed for these studies with the capability of maintaining pressures as low as 10kPa. Here again, the CO_2 partial pressure was held constant at 0.0355kPa. The O_2 partial pressure was allowed to decrease proportionately as the total pressure decreased with an initial partial pressure of 20.9kPa. Treatments were carried out at 100kPa, 70kPa, 40kPa, and 10kPa. The transpiration and net photosynthetic rates for both spinach and maize increased as the total pressure decreased, although the increase in transpiration was much less than that of photosynthesis. This study also examined the effects of vapor pressure deficit (VPD) on net photosynthetic and transpiration rates. Results showed that the net photosynthetic rate decreased with increasing VPD, but the transpiration rate increased. It would appear that healthy plant growth occurred under low total pressures ranging from 50kPa to 100kPa for short growth periods, with the growth rate increasing as the pressure decreased (29). Three treatments carried out varied the total pressure and the VPD. A continued effort to study the effects of VPD on spinach under hypobaric conditions at total pressures of 101kPa and 25kPa were coupled with VPDs of 0.95kPa and 0.48kPa and led to the conclusion that low pressure alone did not affect growth rate, but instead, it was the combination of low pressure with high humidity that significantly enhanced growth rate (29).

Schwartzkoff and Manicelli (43) conducted experiments to determine the germination and growth rates of wheat in simulated Martian atmospheres. The simulated Martian atmosphere was composed of 2.71% N_2, 0.13% O_2, 0.07% CO, 1.61% Ar, 0.0276% H_2O, and the balance CO_2. Initial experiments used the simulated Martian atmosphere at total pressures of 1kPa, 10.1kPa and 101.3kPa. After seven days, none of the wheat seeds had germinated under any pressure. The atmosphere in the experiments at 10.1kPa and 101.3kPa was repeated and replaced with atmospheric lab air at a total pressure of 101.3kPa and the experiments repeated, following which over 50% of the seeds germinated after five days. A second set of experimental trials were run to determine the O_2 concentration at which seed germination and seedling growth became evident. The simulated Martian atmosphere was enriched with O_2 partial pressures ranging from 0.3kPa to 5kPa. No germination occurred prior to an O_2 partial pressure of 3.3kPa and no significant growth was evident until 5kPa. This study concluded that germination was suppressed in low pressure atmospheres with high CO_2 concentrations, but this could be ameliorated by the addition of O_2 (43).

Other studies have shown the combined effects of ethylene and reduced pressure on the growth rates of plants. Ethylene is a plant hormone that increases when plants are stressed. Low atmospheric total pressure could cause such a response. Even small concentrations of ethylene significantly influence plant activity (46).

Ageev and Astafurova (1) investigated how dark respiration was affected by hypobaric conditions and resulted in increased C_2H_4 concentrations. Two trials were run to study the dynamic gas exchange activity of plants under low total pressures and increased ethylene concentration. At 101kPa, 54kPa, 29kPa, and 8kPa total pressure, CO_2 evolution increased as pressure decreased as did the alcohol dehydrogenase activity. The increase in alcohol dehydrogenase led to an O_2 deficiency. During the second trial, as the ethylene partial pressure was increased, so did the alcohol dehydrogenase activity. The C_2H_4 concentration in the control sample was not noted, but increasing the C_2H_4 concentration above that within the control experiment did not result in a significant increase in CO_2 evolution.

Research efforts using the low pressure plant growth (LPPG) system at Texas A&M University attempted to characterize the influence of low total pressures and ethylene evolution on lettuce and wheat (11). Higher levels of ethylene were expected under hypobaric conditions (15). With an atmospheric pressure of 101kPa used as the control, trials were run at 70kPa, 50kPa, and 30kPa. The partial pressures of N_2, O_2, and CO_2 were allowed to decrease proportionately as the total pressure decreased. Lettuce was germinated and grown for 28days at either 50kPa or 101kPa. The growth rate of lettuce increased as the pressure decreased. There was no difference between the germination rates of lettuce at 50kPa and 101kPa. For wheat, the increased growth rate caused by low pressure was less dramatic than what was observed for lettuce. The ethylene concentration in these experiments was 109.8 nmol mol^{-1} at 101kPa and 6.2 nmol mol^{-1} at 50kPa. Another experiment was run to determine the difference between the effects of purging under low and ambient pressure and hypoxia in the regulation of ethylene production (12). Purging the chambers reduced the ethylene concentration within the chambers. Ethylene production in lettuce was significantly reduced. The reduction in wheat was not so dramatic. This study concluded that the hypobaric effect on C_2H_4 reduction was due to more than just hypoxia.

Dynamic Gas Mixing Studies

High Pressure

Various mixtures of nitrox (N_2 and O_2), helios (He and O_2) and trimix (N_2, He, and O_2) are used in different diving depths. With respect to ambient air, these mixtures may have higher O_2 concentrations. They are used to facilitate decompression and reduce the probability of O_2 toxicity (49). Blenders and pumps can be used to obtain the required gas mixture at a specified pressure after N_2 and O_2 have been extracted from ambient air through the use of O_2 concentrators or air separation systems.

There are two basic methods used for mixing O_2 enriched air for diving, namely the gravimetric method and the partial pressure method. The gravimetric method weighs each gas component on an analytical balance and is the most accurate. The partial pressure method is based on the Ideal Gas Law and assumes that all gases behave as ideal gases. Because of this assumption, the error increases as the pressure increases (34). Mastro (34) discusses two techniques used to mix breathing air based on the partial pressure method. The cascade method is the most familiar and involves cascading pure O_2 through an O_2 clean mixing system into a clean high pressure cylinder. Oil-free N_2 or air is then cascaded until the desired endpoint mixture is reached. The constant mix method involves injecting pure O_2 into a mixing chamber that is attached to the intake of a compressor. The O_2 and air are mixed together and compressed into high pressure enriched air. An O_2 analyzer is used to measure the O_2 percentage in the mixture. The desired output percentage is obtained by adjusting the volume of O_2 flow into the mixing chamber. Tests have shown that once a mixture becomes homogeneous, it remains so (44). The difficulty lies in getting two or more gases to a homogeneous state.

Mixing breathing air is also prevalent in the medical field (14). Lin and Luo (30) developed a fuzzy logic control system that measured O_2 consumption and CO_2 production in premature infants. The control system reduced the overshoot of O_2 concentration during the adjustment period. A large overshoot could cause the risk of O_2 toxicity in the premature infants. Room air and O_2 were mixed to create an enriched O_2 mixture. A data acquisition card (DAC) and a personal computer (PC) were used to implement real-time fuzzy control of the system. O_2 and room air were supplied from the hospital room and regulated using flow meters. They were then mixed in a mixing chamber before passing through an O_2 analyzer to determine the O_2 concentration. The mixture was then humidified and warmed and the humidity and temperature determined before being inhaled by the preterm infant. With this control system O_2 overshoot was reduced from 45% to 1%, the rise-time shortened from 0.425sec to 0.1sec, and the settling time from 1.3sec to 0.7sec (30).

Low Concentration Gas Mixing

Early reports of gas mixing usually involved the vaporization of a liquid hydrocarbon that was to be diluted with clean air to form low concentration mixtures.

Methods of producing known and reproducible amounts of low concentration mixtures were typically based on the principle of diffusion as a means of studying air pollution, industrial hygiene, and other related areas (2). Eventually, studies began to concentrate on those gas mixtures (usually N_2 and O_2) that were important to the field of anesthesiology. Experimental setups involved tortuous channels that required many tubes of precisely known dimensions (37). Lundsgaard and Degn (31) were not simply concerned with mixing gas of particular concentrations, but began to explore the design of the mixing system itself. They developed a regulator unit that consisted of a set of on-off valves connected to parallel flow resistors. Finally, gas mixing had become an operation involving mechanical valves controlled by the electric output of a digital computer.

At the most basic level, dynamic gas mixing is needed to produce gas mixtures for the calibration of measuring instruments, the evaluation of analytical methodologies or for carrying out toxicity investigations (48). The present trend of automation has created a need for controlled gas mixers (13). The gas mixing assembly designed by NASA has four digital flow controllers that will control the flow rate of the three gases flowing into the mixing tank and into the receiving vessel as a way of maintaining the desired gas concentrations.

Previously, researchers focused on developing the instrumentation required to create low concentration gas mixtures. Fortuin (17) investigated several methods including diluting a small quantity of saturated air with a large quantity of pure air, saturating vapor air at low temperatures, vaporizing drops of a solution containing the agent to be studied, and diffusing the vapor through a porous wall. Each of these methods had their short comings. He eventually developed a new technique which satisfied the requirements of a gas flow containing low but constant vapor concentrations. The method was based on the diffusion of vapor through a cylindrical tube of known dimensions. They not only obtained reproducible low vapor concentrations at room temperature, but were also able to predict this concentration and rate of diffusion. The problem with this method and others like it is the experimental system in which test trials were run. The system involved the flow of gases in intricate channels to linear steady state diffusion through tubes of precisely known dimensions (37).

When preparing dilute gas mixtures, researchers often did so by first vaporizing a liquid and then diluting the vapor with pure air. Often times they were concerned with the vaporization of hydrocarbons specifically. McKelvey and Hoelscher (36) developed a cell based on the diffusion of a vapor into a gas stream. In this case, dilute mixtures of toluene in air were being prepared. They were able to continuously and accurately produce gas mixtures over a wide range of concentrations. The method seemed to work best when the low concentration component was a liquid at room temperature, but also worked for any substance that could first be liquefied under laboratory conditions. When preparing solutions in which the species of interest was present within the concentration range of 0.1 – 100ppm, this method was preferred to dilution. Here again, the focus was on the development of the experimental apparatus.

Lundsgaard and Degn (31) studied the digital regulation of gas flow rates and the composition of gas mixtures as they related to an anesthetic gas mixer. The regulator unit consisted of a set of on-off valves that were connected to parallel flow resistors with various conductivities. The resistors were made from single tubes of different lengths and combined so that they would control the flow rates of the gases. The digital regulation principle was employed as a means of constructing a unit capable of producing variable mixtures of O_2 and N_2 at a constant total flow rate of 50mL/min at atmospheric pressure. The resistors were connected to magnetic two-way valves and an analog to digital converter was used to allow electronic control of the gas mixture. Eventually, a pressure regulator was added for the proportional regulation of the two gas pressures (33). In order to verify performance, O_2 and N_2 are supplied at pressures whose ratio is equal to the ratio of their viscosities and independent of flow rates and total pressure. Lundsgaard et al. (32) continued to research the digital regulation of gas mixtures, but they adapted the same principles they used previously to construct a mixer for O_2 and N_2O in which the concentration regulation was independent of the flow regulation.

Heath et al. (27) also explored the performance of a digital gas mixer. The Quantiflex monitored dial mixer was designed to dispense mixtures of O_2 and N_2O as an alternative to the rotameter block of the conventional anesthetic apparatus.

Although gas mixing had evolved from the tediousness of flow through various tubes to digital regulation, the control system employed left much to be desired. These papers failed to mention the construction of a control algorithm. They only imply that valves could be open or closed, on or off as the digital principle would suggest.

While the environmental control system designed by Goto and Iwabuchi (25) utilized a gas mixing system prior to injecting gases into the low pressure chamber, there was no discussion as to why this was done. The previous control system injected N_2, O_2, and CO_2 directly into the low pressure chamber (23). No gas mixing was done prior to injection into the chamber and no explanation was provided as to why the gas injection method was modified. The capabilities of this gas mixing system were not specified. While the lack of air movement around the canopy leaves of lettuce plants was briefly mentioned (26) as a means of explaining tip burn, whether or not the gases within the chamber were thoroughly mixed, and whether or not this aided in this particular physiological disorder was not discussed.

A thoroughly mixed gaseous environment has the potential to increase growth rate and reduce physiological disorders (28). Both static and dynamic techniques exist for preparing gas mixtures at low pressure. When utilizing static techniques, the quantities of the different gases are measured gravimetrically, volumetrically, or manometrically, and then combined. With dynamic gas mixing, different gases with known mass flow rates are combined. In order to ensure accuracy, most dynamic gas mixers require constant input and output pressures. Degn and Lundsgaard (13) reported on the performance of various dynamic gas mixers such as those depending on flow meters and digital gas mixers, those using mechanical devices, and those based on diffusion. This research will focus on a gas mixer that utilizes flow meters that measure volumetric flow and improving the gaseous environmental composition created for low pressure studies. Premixing the gases at ambient pressures or higher before introducing them into a low pressure growth chamber will create a more uniform environment than directly injecting the gases into the chamber because of the lack of air flow under hypobaric conditions.

CHAPTER III

OBJECTIVES

The overall objective of this research is to design and develop a system to mix three gases, N_2, O_2, and CO_2 in an enclosed vessel in order to supply the necessary gases physiological plant growth experiments and equipment tests at reduced total pressures in a second vessel. In order to achieve this goal, two key objectives have been established.

Objective 1

Objective 1 was to design a control algorithm for the three gas mixing system that will monitor and control the partial pressures of N_2, O_2, and CO_2. The fundamental hypothesis of this objective is that the ideal gas law can be used to successfully prepare a three gas mixture to support plant growth in a hypobaric chamber continuously over a period lasting from germination to senescence of the plant. In order for this system to function properly it will need to possess the capability to create any gas mixture of arbitrary concentrations with N_2, O_2, and CO_2 by making adjustments to current atmospheric conditions. New setpoints can be established without shutting down the system and disrupting current experiments by using the interface created. Real-time concentration, pressure and temperature data will be recorded. This data will be analyzed to determine the limits of control the algorithm was capable of maintaining.

Objective 2

Objective 2 was to evaluate the performance of the control algorithm for each component gas. The working hypothesis of this objective is that the static and dynamic response of the control algorithm to changes in the setpoint and or concentration can be quantified. For Earth's ambient environment, a successful system will maintain partial pressure of the constituents to within ±1.05kPa O_2, ±0.0025kPa CO_2, and ±3.9475kPa N_2 of the set point and maintain the total pressure to within 5kPa. For the elevated CO_2 environment, a successful system will maintain partial pressure of the constituents to within ±1.05kPa O_2, ±0.005kPa CO_2, and ±3.945kPa N_2 of the set point and maintain the total pressure to within 5kPa.

The ultimate goal was to design a system capable of going from an arbitrary mixture A to any other arbitrary mixture B. With respect to this project the mixing system would go back and forth among Earth's ambient environment and an elevated CO_2 environment, but will possess the capability to do the same with any mixture. For example, gases were mixed within the tank with the same concentration that they are present in the Earth's atmosphere. This mixture was then introduced into the Mars dome which operated at low pressure. Enough time was allotted to allow the system to stabilize. Then, the setpoint concentrations in the mixing tank were changed to those represented by an optimum plant environment. This means that the gas mixture within the mixing tank had to be modified in order to maintain these new setpoints. The algorithm allowed for such modifications.

CHAPTER IV

EXPERIMENTAL METHODOLOGY

Experimental Apparatus

The experimental apparatus is comprised of two parts; a gas mixing chamber and a receiver, in this case a hypobaric plant growth chamber. The mixing chamber was the central apparatus for this research and had a volume of 0.1925m^3. There were three ports in the mixing tank that were used for injecting gases, recirculating the gases within the chamber, and evacuating the chamber. There were four digital flow controllers (DFCs) (model DFC2600, Aalborg Instruments and Controls, Inc, Orangeburg, NY) which were used for measuring the flowrates of the gases being injected and the exhaust stream. To ensure that the gases in the mixing tank were well mixed, there was a recirculation stream that pulled gases from the bottom of the chamber an injected them in to the top (at a rate of 4LPM) using a small pump manufactured by Thomas Compressors and Pumps (model 008CA13, Sheboygan, WI). In the event the mixing tank were to be evacuated, there was a vacuum pump manufactured by Gast Manufacturing (model DAA-V175-EB, Benton Harbor, MI) that was capable of 101kPa vacuum. The pressure was monitored using a Setra 370 (Setra SystemsInc., Boxborough, MA) pressure transducer. The total pressure was controlled by venting to the Mars Dome when too high and adding the necessary component gases when too low. The mixing tank is rated at a maximum pressure of 1020kPa. Relief valves were installed that ensure that the applied pressure never exceeds this rating. The temperature was monitored using a T-type thermocouple that was placed in the recirculation line.

The current hypobaric plant growth chamber is the low pressure Mars Dome, however, the mixing system will be designed to function with any plant growth chamber. The Mars Dome was designed to grow plants in an enclosed environment under reduced pressures and was a convenient receiver for system. The dome is a half-spherical polycarbonate enclosure approximately 1m in diameter that is mounted to a stainless steel base. The base is fitted with ports to allow access for instrumentation and to pass control lines in for environmental control (19).

The Mars Dome control and signal acquisition are implemented by a set of adapter boards that plug into a baseboard. The master microcontroller is mounted on the baseboard with most of the control work being carried out by various slave processors located on the different adapter boards.

The adapter boards contain smart chips with on-board data processing capabilities such as analog-to-digital converters (ADC) (model ADS1241, Texas Instruments, Attleboro, MA) with on-chip signal conditioning capabilities. Digital inputs and outputs were implemented by a microcontroller that contained all of the code, data memory, and input/output ports.

Local logic functions were carried out on the adapter boards with the processed data being passed on to the master microcontroller. The master microcontroller simply requests information related to the state for the Mars Dome and issues control commands. The base board which contains the master microcontroller has an RS-232 port that was wired into a SNAP-SCM-RS-232 module. The control algorithm would read the current state of the sensors in the dome via RS-232 serial communication. Figure 1 shows the piping diagram between the mixing tank and the Mars Dome.

Sensors

Temperature

<u>Mixing Tank Temperature Sensors</u>

A commercial T- type thermocouple (TC) was placed in the recirculation line to monitor the temperature of the gas mixture. A second T-type TC was used to monitor the

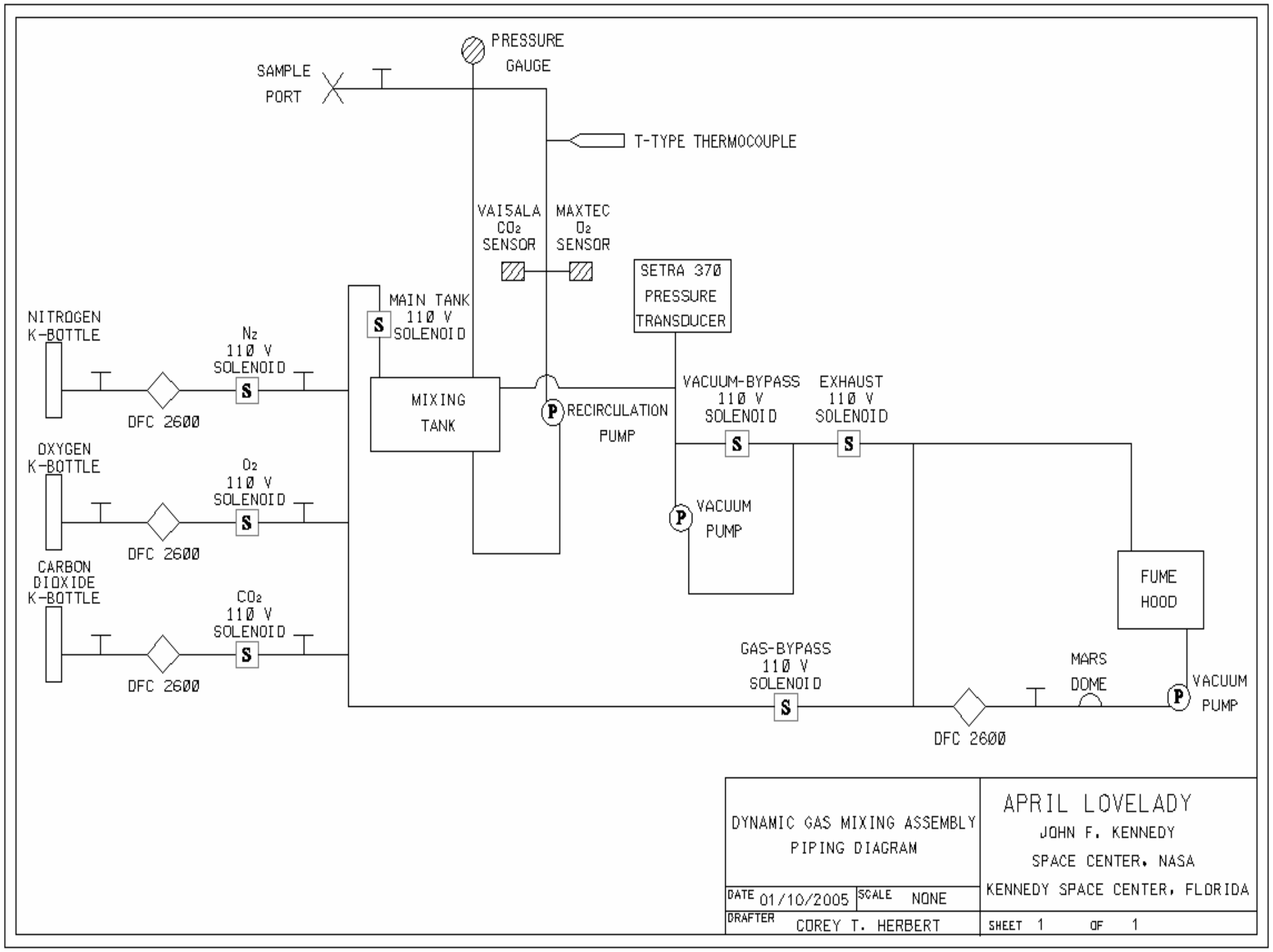

Figure 1 - Diagram of the piping system for the mixing tank and the Mars Dome. Gases enter the mixing tank from K-bottles containing either O_2, N_2, or CO_2. The pressure gradient between the mixing tank and the dome cause the mixture to flow into the dome.

temperature of the vacuum pump to ensure that it did not overheat. There was no need for a highly accurate sensor reading.

Mars Dome Temperature Sensor

The temperature sensor in the Mars Dome was wired into an analog to digital conversion (ADC) board. The number returned was 16-bit number from the sensor and thus it was divided by 16 to determine the temperature in degrees Celsius.

Carbon Dioxide

Mixing Tank Carbon Dioxide Sensor

The CO_2 sensor used on the mixing apparatus was manufactured by Vaisala (Model GMT221M0N0AN1A0B Boulder, CO). It is based on a silicon sensor that operates on non-dispersive infrared (NDIR) single-beam dual-wave principle. The GMT221M0N0AN1A0B model is capable of measuring 0 - 20% CO_2 with an accuracy of 0.02% [CO_2] + 2% of reading. This transmitter is designed to operate with a nominal 24 VDC power supply.

The CO_2 sensor was initially calibrated by plotting the expected concentrations obtained by using gas mixtures created in the GC against the actual concentration values returned from the sensor.

Calibration of the Mixing Tank CO_2 Sensor

The mixing tank CO_2 sensor was calibrated by first plotting predetermined CO_2 concentrations against the CO_2 sensor reading. The mixtures used for calibration were created by filling the mixing tank with N_2 until the total pressure in the mixing tank was approximately 165kPa. The mixing tank already contained some O_2 and CO_2. Then CO_2 was added until the CO_2 sensor read approximately 0.20%. Finally, O_2 was added until the se O2 sensor read approximately 21%. At this time, if the total pressure in the tank was below 175kPa, more N_2 was added until 175kPa was reached. This was to be the total pressure setpoint for the experiments run. The composition of the mixture was verified using GC analysis. The values returned from the GC were used as the standard values against which the sensor values were plotted. The final calibration equation was a function of both concentration and pressure. With each mixture created, the pressure in the tank was reduced from 175kPa to 102kPa with readings being taken at 175kPa, 150kPa, 125kPa and 102kPa. Two more mixtures were created in the manner described above. With each subsequent mixture, the CO_2 and O_2 concentrations were reduced. This was accomplished by simply refilling the mixing tank with N_2 until the pressure was 175kPa and yielded CO_2 concentrations of about 0.10% and O_2 concentrations of approximately 0.15%. The final mixture contained approximately 0.05% CO_2 and 0.10% O_2. Figure 19 is a graph of the mixing tank CO_2 expected concentrations versus the actual concentrations at different pressures. The slope and intercept from the different lines were plotted against the total pressure as shown in figure 20.

<u>Mars Dome Carbon Dioxide Sensor</u>

The CO_2 sensor mounted within the dome was also manufactured by Vaisala (Model GMP221HA0A3A2A1B, Boulder, CO). It operates on the NDIR principle like the sensor on the mixing assembly, but unlike the CO_2 sensor in the mixing tank, its range was 0 to 1% CO_2. The CO_2 module comes complete with a component board, cable, and probe. The probe within the dome is the GMP221 and measures 0 – 1% CO_2. The interface is a 5V TTL serial port. There is also a 0 – 2.5VDC output. The sensor is wired into an analog-to-digital converter ADC board that sends back a 16-bit number that is proportional to the sensors voltage. The sensor in the dome is read using an RS-232 communication module (SNAP-SCM-232, Opto22, Temecula, CA).

Calibration of Mars Dome CO_2 Sensor

The CO_2 sensor in the dome was calibrated so that the expected value would be a function of both pressure and concentration. Gases were mixed in the mixing tank and evacuated into the dome. This mixture was then verified with the GCs. The value obtained from the GC analysis was used to calibrate the sensors.

As a means of purging the dome, it was first evacuated to 25kPa. Then, the exhaust solenoid on the mixing tank was opened and the pressure in the dome was allowed to come up to ambient as a result of being filled with the mixture in the tank. The sensor was allowed to stabilize at the new pressure and then it was read. Five readings were taken and averaged at each pressure. The pressure calibration range was 30 – 101kPa. Readings were taken at 101kPa, 75kPa, 50kPa, and 30kPa.The 16-bit number was plotted against the actual concentration in percent for each pressure as shown in figure 21. Then, the slope and intercept of each line was plotted against the pressure as can be seen in figure 22.

Oxygen

Mixing Tank Oxygen Sensor

The O_2 sensor chosen was manufactured by Maxtec Inc. (MAX-250, Salt Lake City, UT). It is a galvanic cell that uses a weak acid electrolyte and is unaffected by acid gases including CO, CO_2, and NO_x. Its measurement range varies from 0 - 100% O_2 by volume and produces an output of 10 to 15.5 mV at ambient pressure. The sensor on the mixing assembly is connected directly to an Opto22 analog input module (SNAP-AITM2, Opto22, Temecula, CA).

Calibration of the Mixing Tank Oxygen Sensor

The O_2 sensor in the mixing tank was calibrated at the same time as the CO_2 sensor in the mixing tank. Here again, mixtures were created and their composition verified with GC analysis. Figure 23 shows the sensor readings plotted against the GC results. Readings were taken at 175kPa, 150kPa, 125kPa, and 102kPa. The slope and intercept associated with each pressure were plotted against pressure to obtain a final calibration equation as shown in figure 24.

Mars Dome Oxygen Sensor

The same sensor model is located on the mixing assembly and within the dome. The sensor in the dome is read using an RS-232 communication module (SCM-232, Opto22, Temecula, CA) and is wired to an ADC board that returns a 16-bit number that is proportional to the sensors output voltage. It was calibrated in the same manner as the O_2 sensor in the mixing tank.

Calibration of the Mars Dome Oxygen Sensor

The O_2 sensor in the dome was calibrated in the same manner as the CO_2 sensor in the dome. Mixtures created in the mixing tank were used to fill the Mars Dome. The composition of the mixture was verified using GC analysis. Figure 25 is a plot of the expected sensor readings versus the actual O_2 concentration. The results from the GC became the standard concentrations against which the sensor readings were plotted. Readings were taken at 101kPa, 75kPa, 50kPa, and 30kPa. The slope and intercept from

Pressure

Mixing Tank Pressure Measurements

The Setra (model 370, Setra Systems Inc., Boxborough, MA) pressure gauge was used to monitor the pressure of the tank. It is capable of displaying the pressure or altitude on a six digit LCD display and is accessible through a bidirectional RS232 serial port. This pressure transducer will operate at any voltage from 100 – 240VAC. The Setra 370 is rated for clean, dry gases. The maximum pressure which can be applied without distorting the calibration is 150%FS.The FS value is 687kPa (100psia). The Setra370 is accurate within ±0.02%FS at 21°C. This transducer was not calibrated because the accuracy of the total pressure was not as important as that of the individual partial pressures. The data format used by the pressure gauge is: 8 bits, 1 start bit, 1 stop bit, no parity. The serial interface is a standard DB25 female pin connector. The Setra370 would ordinarily be connected to the serial port of a computer. However, for the purpose of this research, it will be connected to an Opto22 RS232 serial module. This module is controlled by the SNAP-UP1-ADS Ultimate Brain (Opto22, Temecula, CA)

<u>Mars Dome Pressure Measurements</u>

The pressure inside the Mars dome is measured using a signal conditioned sensor manufactured by Honeywell (model ASCX15AN, Morristown, NJ). This particular model measures pressure from 0 – 100kPa but has a proof pressure of 210kPa. The sensor has an internal vacuum reference and an output voltage proportional to absolute pressure. It is wired into an ADC chip (model ADS1241, Texas Instruments, Allteboro, MA) that sends back a 16-bit number that is proportional to the sensors voltage. An Opto22 SNAP-SCM-232 (Opto22, Temecula, CA) module was used to read this 16-bit number which was converted into pressure. The pressure sensor was calibrated using the vacuum pump on the mixing tank as a base standard.

Digital Mass Flow Controllers

The digital flow controllers (DFCs) (model DFC2600, Aalborg Instruments and Controls, Inc, Orangeburg, NY) were used to measure the volumetric flow of the component gases entering the mixing tank and the flow rate of the exhaust stream. There were four DFCs, one each for the O_2, CO_2, and N_2 that were introduced into the mixing tank and the fourth to measure the flow from the mixing tank to the receiver (i.e. the Mars Dome). The DFCs were capable of analog or digital operation however, for this research the digital mode was used. The two DFCs used for N_2 and O_2 were low flow devices capable of flow ranges between 0 and 5SLPM (standard liters per minute). The third DFC used for CO_2 was capable of delivering 0 – 100SMLPM. With a volume of 0.192m^3, it would take approximately 20 minutes to fill the mixing tank at full flow. The final DFC used to measure the flow of the exhaust stream from the mixing assembly to the dome had a range of 0 – 15 SLPM. They have an accuracy of ±1%FS including linearity for gas temperatures in the range of 15 - 25°C and pressures if 68.9 – 413.7kPa. The DFCs communicate through an RS485 interface. Thus, they were connected to a four port multiplexer through an RS485 to RS232 converter (Model 233BSS4, B&B Electronics, Ottawa, IL).

Buffered Smart Switch

A buffered smart switch (model 232BSS4, B&B Electronics, Ottawa, IL) provided communication to all four DFCs through one master serial port. Each port was independently configured for data rate, data format, and protocol (Document # 233BSS43903 Manual). The master port was capable of sending and receiving data from one of the slave ports while the other slave ports continued to buffer data. Switching among the ports was accomplished through user-defined three or four character command strings. +10 – 15VDC is required for operation. The master port uses a DB25 female connector while the slave ports use DB9 male connectors. The switch was capable of handling data rates between 1200 and 115.2kbps (kilobytes per second).

One of the ports is connected to a master DFC which controls the flow of the combined gas stream into the Mars dome. The other three ports are connected to the DFCs that regulate each of the individual gases.

Mixing Tank Vacuum Pump

The vacuum pump on the gas mixing system was manufactured by Gast Manufacturing (model DAA-V175-EB, Benton Harbor, MI) and was used to maintain the total pressure within the tank. It is an oil-less diaphragm vacuum pump capable of a maximum vacuum of 100kPa.

Mars Dome Vacuum Pump

The vacuum pump controller on the Mars Dome was manufactured by KNF Neuberger, Inc. (Model PU842, Trenton, NJ). This vacuum pump contains a diaphragm pump controller that uses a 12-bit microprocessor. Because of this microcontroller, the pressure in the Mars Dome was controlled independently of the Opto22 software on the mixing tank. Both a pressure setpoint and a hysterisis value were set on the controller. Once these values had been specified, the controller operated the pump to maintain them.

Mixing Tank Recirculation Pump

The recirculation loop in the gas mixing system pulls gases from the bottom of the tank and pumps them into the top of the tank using a small pump manufactured by Thomas Compressors and Pumps (Model 008CA13, Sheboygan, WI). The maximum flow rate of the pump was 4LPM. With the volume of the mixing tank being 192L, this meant that it tool approximately 50 minutes to ensure one volume turnover and thus that the gas mixture had been sufficiently mixed.

Gas Chromatographs

The gas chromatographs (GCs) (Model 6890, Agilent Technologies, Palo Alto, CA) were used to measure the atmospheric gases (O_2 and CO_2) using thermal conductivity detectors. There were two GCs; one was used to measure O_2 concentration and the other CO_2 concentration. Each GC had two different columns. The thermal conductivity of the sample gas is compared to that of the carrier gas. The detector contains an electronically heated filament whose temperature is kept constant while alternating streams of the carrier gas and the gas which contains the sample. The power required to maintain a constant filament temperature changes upon sample injection. A software package (Chemstation, Agilent Technologies, Palo Alto, CA) was used to set system parameters. The samples were analyzed at atmospheric pressure because the GCs did not possess the ability to operate at low pressure. Table 1 describes parameters for both O_2 and CO_2 analysis.

Table 1. Setup Used for GC Parameters During Operation. Parameter settings must be specified prior to running a gas analysis. The specifications are provided for both GCs.

	Inlet	Column	Flow	Oven Temperature	Detector	Reference Flow
CO_2	150°C (Front)	HP-Plot Q Capillary 30mX530µmX40µm Constant Flow	4.2mL/min (He)	25°C	250°C	20mL/min
O_2	35°C (Back)	RT-Msieve-5A Capillary 30mX530µm	14.3mL/min	30°C	200°	20mL/min (N2)

Prior to the beginning of any GC analysis, a standard curve of the selected analyte is created. The curve encompasses the range of responses found within the sample. For an O_2, analysis the standard curve ranges from 0 – 21% O_2. Figure 2 is a graph of the O_2 standard. A standard curve for CO_2 was also derived. Figure 3 is the standard curve created for CO_2. For the CO_2 analysis, the samples ranged from 0 – 99.8% CO_2. Because the GC used to analyze O_2 also analyzed N_2, a N_2 standard curve was developed ranging from 0 – 78.9% N_2. Figure 4 is a graph of the N_2 standard curve.

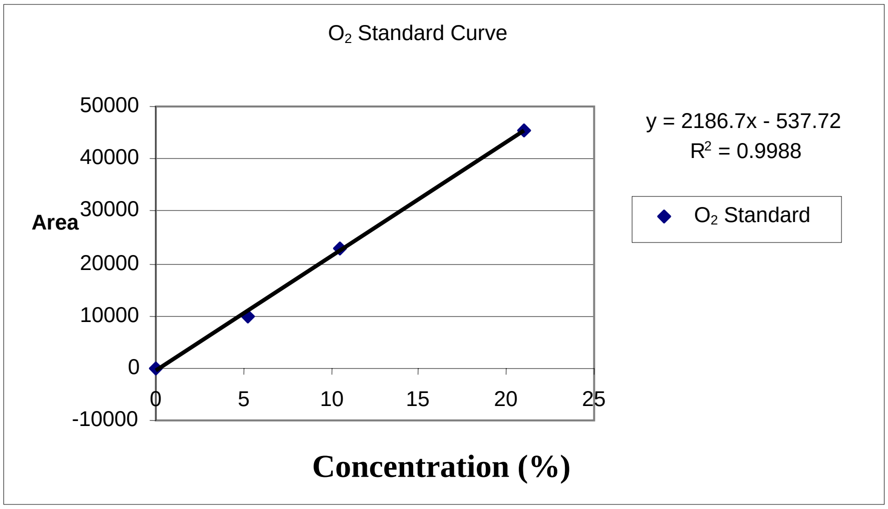

Figure 2 - Oxygen standard curve. The GC returns an area that is associated with the O_2 concentration. This area is plotted against the percent O_2 from various O_2 standards.

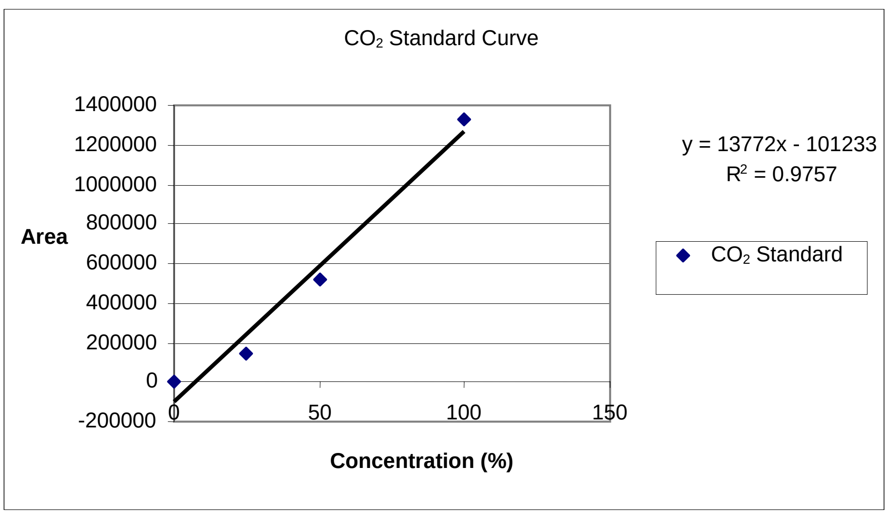

Figure 3 - Carbon dioxide standard curve. The GC returns an area that is associated with the CO_2 concentration. This area was plotted against the percent CO_2 from various CO_2 standards.

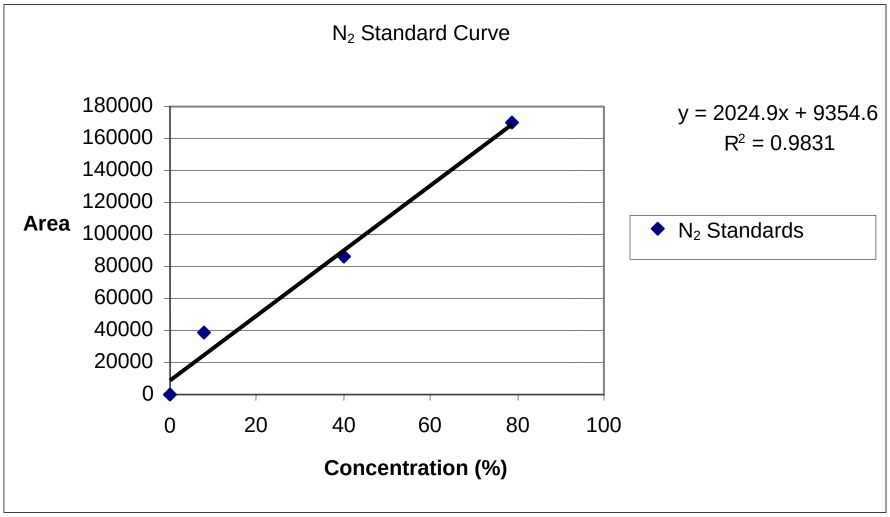

Figure 4 - Nitrogen standard curve. The GC returns an area that is scalable to the N_2 concentration. This area was plotted against the percent N_2 from various N_2 standards.

Sampling Bags

Gas sampling bags were manufactured by Calibrated Instruments, Inc. specifically for NASA. They were composed of a 0.1L pillow (model GSB-P/3X5) with a luer-fit valve (model V-L/F-1) and a Quik-mate™ connector. A 10 mL syringe was used to transfer a total of 30mL of the gas from the sampling port on the mixing tank to the sampling bags. Unlike the syringe used to inject the sample into the GC, this 10mL syringe was not gas tight. However, because the gases were only being transferred to the analytical chemistry lab, rather than being stored, any leakage that may have occurred was assumed to be negligible. The bags have a luer-lok fitting that connects directly to a valve, which when closed will protect the sample from contamination. One mL gas tight syringes were used to inject the sample into the CO_2 GC and 0.5mL syringes were used for O_2 analysis.

Computer and Data Acquisition Hardware

The SNAP Ultimate I/O brain (Opto22, model SNAP–UP1-ADS, Opto22, Temecula, CA) is a communications processor. It is capable of simultaneously communicating with multiple devices using various protocols (39). The brain stores data logs locally and has a real-time clock to time stamp the entries. Also included is an RS-232 serial connector which can be used for modem communication, programming, or direct connection to serial devices. The brain is programmed using the Opto22 software suite. They are connected to standard brain mounting racks that are available with 4, 8, 12, or 16 slots for I/O modules. For operation, the brain requires 5VDC and has a 32-bit coldfire processor. In terms of memory, it has 16MB of RAM total, with 512KB battery-backed RAM, and 8 MB flash EEPROM. A variety of I/O modules were used on the gas mixing system including: SNAP-SCM-232, SNAP-AITM2, SNAP-AIV4 and the SNAP-OAC5.

The SNAP-SCM-232 is a serial module with two channels for serial data. A serial communication module is interfaced with the Setra 370 pressure transducer and the 233BSS4 buffered smart switch. This module was also used to communicate with the sensors in the Mars dome. An Ethernet connection was established with each of the serial devices by using the IP address of the ultimate brain. Each of the module's serial ports had their own IP port number. The SNAP-SCM-232 can communicate over a range of baud rates from 300 to 115,200. 9600 was used for communicating with both the pressure transducer and the switch.

The SNAP-AITM2 is an analog input module designed for thermocouple or millivolt inputs. This module provides an input range of ±50mV, ±25mV, or type B, C, D, G, N, T, R or S thermocouples. There are two input channels for this specific module although other analog modules may have up to four inputs. The SNAP-AITM2 was used as a T-type thermocouple input module. The T-type thermocouple operates over a temperature range from -270°C - 400°C. The output voltage from the SNAP-AITM2 was proportional to the temperature.

Unlike the SNAP analog modules, the SNAP digital modules handle devices that can be in one of two states: on or off. The SNAP-OAC5 operates on 5VDC control logic. They are used to switch up to four separate AC or DC loads. The DC outputs are available in either a source or sink configuration while the AC outputs require zero voltage turn on and zero current turn off. There are three SNAP-OAC5 modules that are part of the gas mixing system that control relays. The diagram in appendix B shows how the modules are wired into the system.

Software

The Opto22 software allowed for monitoring, control, and data acquisition of the gas mixing system. The software is based on standard and commercially available technologies thus making it ideal for hardware and software integration (38). Opto22 is composed of three key components, namely ioControl, ioManager, and ioDisplay.

ioControl

ioControl is a flowchart based programming tool that was used to control the gas mixing hardware. The processors that are programmed to monitor and control various industrial processes are required for automation. In an ioControl system, the processor is referred to as a control engine and is built into the SNAP Ultimate Brain. ioControl is used to create a program that informs the control engine how a process should work. The program is downloaded to the SNAP Ultimate Brain and it carries out the process as a stand-alone application. The program will be stored in the SNAP Ultimate Brain's electronic memory. All components of the system communicate with the system via input/output (I/O) points.

The software program created is referred to as a strategy. The strategy provides instructions for controlling the processes. A strategy usually consists of a series of charts that work together. The total number of charts in a strategy depends on the amount of memory available in the control engine. Every strategy contains a powerup chart that is automatically started when the strategy begins running and as such, starts the other charts in the strategy. Up to seven charts can run simultaneously.

Each chart is composed of blocks that are connected by arrows forming a process flow diagram. Within each chart, each process begins with block 0. There are four types of blocks. Action blocks denote action within the process. Condition blocks indicate a decision point. OptoScript blocks contain OptoScript code which provides an alternative programming method and continue blocks point to another block in the chart as a means of continuing the process.

ioControl can be run in one of three modes including configure, debug, or online. The configure mode is used to create, modify, and compile strategies as well as to configure control engines and variables. Debug mode downloads, runs, and debugs strategies and is also capable of viewing the control engine status and errors. The online mode is a down graded version of the debug mode.

OptoScript is a scripting language that is part of ioControl and can be used to simplify certain strategy aspects. It was modeled after C and Pascal. It does not add any new functions but acts as a supplement to standard ioControl commands. OptoScript cannot be mixed with commands in action or condition blocks. This scripting language will be used to perform mathematical calculations throughout the gas mixing strategy.

ioManager

ioManager is used for configuring and maintaining I/O units. It can be used to assign IP addresses, configure points, and read or write to specific I/O units in real-time. While ioManager and ioControl serve two different purposes, some of their functionality overlaps. I/O units and points can be configured in ioManager and imported into ioControl, but can also be configured in ioControl.

ioDisplay

ioDisplay serves as the graphical human-machine interface (HMI) that allows for communication with the brain or controller. It monitors the system at hand providing operator's with information and transferring operator instructions to the control hardware. ioDisplay displays data trends, plots, logs data and handles alarms. ioDisplay is closely integrated with the controller in that when a strategy is created using ioControl, a tag database is created that is shared with ioDisplay. The operator interface that is created is referred to as a project. Graphical objects are created and linked to tags in the corresponding strategy. ioDisplay allows for the controlled access of the interface based on defined users and groups within the network. Access to the interface itself can be password protected.

Experimental Plan

A controlled atmosphere environment will always lose its desired gas concentrations with time because of the stored product respiration and leakage (8). For a system in which plant experiments are being conducted, photosynthesis during day and dark respiration must also be considered. This means that the component gases must be injected intermittently into the mixing tank to maintain the concentration at the setpoints. The experimental apparatus is such that the sensors in the receiving environment (i.e. the Mars Dome) were used to measure when concentration levels had deviated their setpoints and the algorithm determined when it was necessary to add more of the component gases. The partial pressures in the Mars Dome were lower than those in the mixing tank because of the reduced total pressure. In the Mars Dome, eight different scenarios for maintaining component gas setpoints were investigated as shown in table 2. The scenarios provide the basis for the control system algorithm to provide the three component gases in the desired concentrations.

Table 2. Potential Gas Mixing Concentration Scenarios Encountered as a Result of Mixing CO_2, O_2, and N_2. Each scenario describes whether the individual gas is above, below, or equal to its setpoint. It also tells which gases are to be added according to the scenario encountered.

Scenario	Above Setpoint	Below Setpoint	At setpoint	Injection Gases
1	CO_2			
	O_2			
2	O_2	CO_2		N_2 and CO_2
3	O_2		CO_2	N_2 and CO_2
4	CO_2	O_2		N_2 and O_2
5		O_2		O_2 and CO_2
		CO_2		
6		O_2	CO_2	O_2 and CO_2
7	CO_2		O_2	N_2 and O_2
8		CO_2	O_2	O_2 and CO_2

In scenario 1, while both the O_2 and CO_2 concentrations are above their setpoints, O_2 may be in excess more so than CO_2, CO_2 may be in excess more so than O_2, or they may be equally above their setpoints. N_2 and CO_2 will be injected if O_2 is in excess more so than CO_2. N_2 and O_2 will be injected if CO_2 is in excess more so than O_2, but where they are equally above their setpoints, only N_2 need be added. Table 2 describes the various scenarios related to component gas concentration that could have been encountered during experimental runs. It also describes which gases are to be added to the mixing tank to bring the concentrations to their setpoints. As an example, scenario 5 describes a situation where both CO_2 and O_2 were below their setpoints. In order to bring their concentrations to their setpoints, O_2 and CO_2 were added to the system. This table does not provide the status of the N_2 concentration because it was used only to maintain the total pressure. These cases provided the basis for the gas control algorithm. Using information from the sensors, the algorithm would determine the current status of the component gas concentrations and equate them with a scenario to determine which gases to add.

Three trials of each scenario were studied at two different total pressures of 67kPa and 33kPa. These pressures were chosen because of their historical significance. Apollo and Skylab were designed to operate at 33kPa and the shuttle operated at 67kPa for EVAs. The gas concentration setpoints will be the independent variables. Temperature will be measured and recorded and was considered an independent covariable. The actual gas concentrations for each gas, as achieved by the algorithm, are considered to be dependent variables. The injection of CO_2, O_2, and N_2 are controlled using on/off solenoid valves. Table 3 describes the variables that were measured in the mixing tank.

Table 3. Description of the Parameters Measured in the Mixing Tank. The table describes the measurement principles employed by each sensor or transducer and summarizes the variables that were measured. The mass flow was measured for CO_2, O_2, and N_2.

Parameter	Method	Instrument
Temperature	electrical potential	Thermocouple
Pressure	patented SETRACERAM sensor	Setra 370 pressure transducer
O_2 concentration	electrochemical cell	Maxtec250
CO_2 concentration	NDIR	Vaisala GMT221
Mass flow	thermal conductivity	Aalborg DFC 2600

This research focused on controlling and maintaining two different environments including Earth's ambient atmosphere, and an elevated CO_2 atmosphere. Table 3 provides the measured mixing parameters required to satisfy the specifications for the different atmospheres shown in table 4**.**

Table 4. Operation Specifications for Gas Mixtures Prepared in the Mixing. Describes the operational limits of control used when preparing either the mixture representative of atmospheric gaseous conditions or those associated with a slightly elevated CO_2 concentration. The range of the partial pressures of the component gases are specified along with the limits of operation of the total pressure. The total pressure is a function of the partial pressures.

Atmospheric Conditions		
	Variable	Range (kPa)
	Total Pressure	170 – 180
	N_2 partial pressure	134.2 – 142.1
	O_2 partial pressure	35.7 – 37.8
	CO_2 partial pressure	0.085 – 0.090
Elevated CO_2 Conditions		
	Total Pressure	170 – 180
	N_2 partial pressure	134.1 – 142.0
	O_2 partial pressure	35.7 – 37.8
	CO_2 partial pressure	0.170 – 0.180

The total pressure is a function of the individual partial pressures of the component gases and will therefore be maintained within ±5kPa of its setpoint. The only time that the pressure varied outside of these limits was during the time that the dome was being filled with the mixture from the tank. Then, the tank pressure was allowed to decrease to ambient.

The algorithm used to control and monitor gas concentration was based on the mass flow rates of N_2, O_2, and CO_2. As an attempt to reduce the effects of pressure on sensor measurements, concentrations were based on the number of moles of gas in the system. The total number of moles of gas will be calculated using the ideal gas law:

$$n_{\text{total gas pressure}} = \frac{PV}{RT} \qquad [1]$$

where:

P = pressure [kPa]
V = volume [m^3]
R = universal gas constant [kPa*m^3/mol*K]
T = absolute temperature [K]
n = moles.

Of these variables V and R are constant. The volume of the mixing tank is 0.19255m^3 and R is 8.314 kPa*m^3/mol*K.

The algorithm first calculates the total number of moles in the system based on the setpoint pressure:

$$\text{total\_n\_setpoint} = \frac{P_{set}V}{T_{abs}R} \qquad [2]$$

Then, it determines the total number of moles as a function of the actual system pressure:

$$\text{total\_n} = \frac{(\text{Pressure\_result})(V)}{(T_{abs})(R)} \qquad [3]$$

The difference between these values is found by subtracting total_n from total_n_setpoint:

$$\text{n\_diff} = (\text{total\_n\_setpoint}) - (\text{total\_n}) \qquad [4]$$

The number of moles (n_x) of each individual gas is calculated based on the measured concentration (x):

$$n_x = ([x])(\text{total\_n}) \qquad [5]$$

In this case, x can be equal to the proportional component of each gas; N_2, O_2, or CO_2. Then, the number of moles of each component gas based on the setpoint pressure (total_n_setpoint) is determined:

$$n_x\text{\_setpoint} = ([x])(\text{total\_n\_setpoint}) \qquad [6]$$

The number of moles that are to be added or diluted ($n_{x\ added/diluted}$) is found by taking the difference between n_x_setpoint and n_x:

$$n_{x\_added/diluted} = (n_x\text{\_setpoint}) - (n_x) \qquad [7]$$

The proper solenoid was opened for a predetermined amount of time. In order to dilute or decrease the concentration of O_2 or CO_2, N_2 was added.

During the statistical analysis of the system performance, instrument accuracy was taken into consideration. Table 5 summarizes the measurement instrument specifications according to the manufacturers.

Table 5. Measurement Instrument Specifications for the Sensors Used to Measure Environmental Parameters on the Mixing Tank and in the Mars Dome. Description of the sensors and transducers used to make various measurements located on the mixing tank or in the Mars Dome. The table lists the variable that was measured, the model number, the measurement range and the accuracy. Table 3 provides a description of the measurement principles employed by each sensor or transducer.

Variable	Sensor Model	Range	Accuracy
Tank Pressure	Setra 370	0 - 687kPa	± 0.02% FS
Dome Pressure	Honeywell ASCX15AN	0 - 103kPa	typically ±0.1% FS 0.044V/kPa
N_2 Flow	Aalborg DFC2600 mass flow controller	0 - 5 SLPM*	±1% FS between 68.7kPa and 412kPa.
O_2 Flow	Aalborg DFC2600 mass flow controller	0 - 5 SLPM	±1% FS between 68.7kPa and 412kPa.
CO_2 Flow	Aalborg DFC2600 mass flow controller	0 - 100 SMLPM**	±1% FS between 68.7kPa and 412kPa.
Exhaust Flow	Aalborg DFC2600 mass flow controller	0 - 15 SLPM	±1% FS between 68.7kPa and 412kPa.
O_2 Concentration	Maxtec 250	0 - 100 %	±2% FS
CO_2 Concentration	Vaisala GMT221	0 - 20 %	<±[0.02% CO2 + 2% of reading] and 0.15% of reading/kPa.
GC1	HP 6890	0 - 100% CO_2	±10mV of 0mV baseline
GC2	HP 6890	0 - 100% O_2 0 - 100% N_2	±10mV of 0mV baseline

* Standard Liters Per Minute
** Standard Milliliters Per Minute

CHAPTER V

RESULTS AND DISCUSSION

Objective 1

Program Logic

Control Algorithm

The control algorithm is composed of six charts. The algorithm itself can be found in appendix A. Below is a description of each. Figure 5 illustrates the hierarchy of the control flow diagram.

Powerup: This chart simply starts all of the other charts and turns on the recirculation pump.

Pressure Control: This chart monitors the total pressure in the mixing tank as reported by the Setra 370. It is a loop that either opens the exhaust solenoid valve when the pressure is too high, or starts the gas control chart if the pressure is below its setpoint. Figure 6 is a flow chart of the pressure control chart.

Gas Control: The gas control chart is responsible for a number of things. This chart calculates the number of moles for the component gases and decided which gases need to be added to the system to reach the individual setpoints. Gas enters the mixing tank as a result of various solenoids opening and closing. Figure 7 is the flow chart of the gas control chart.

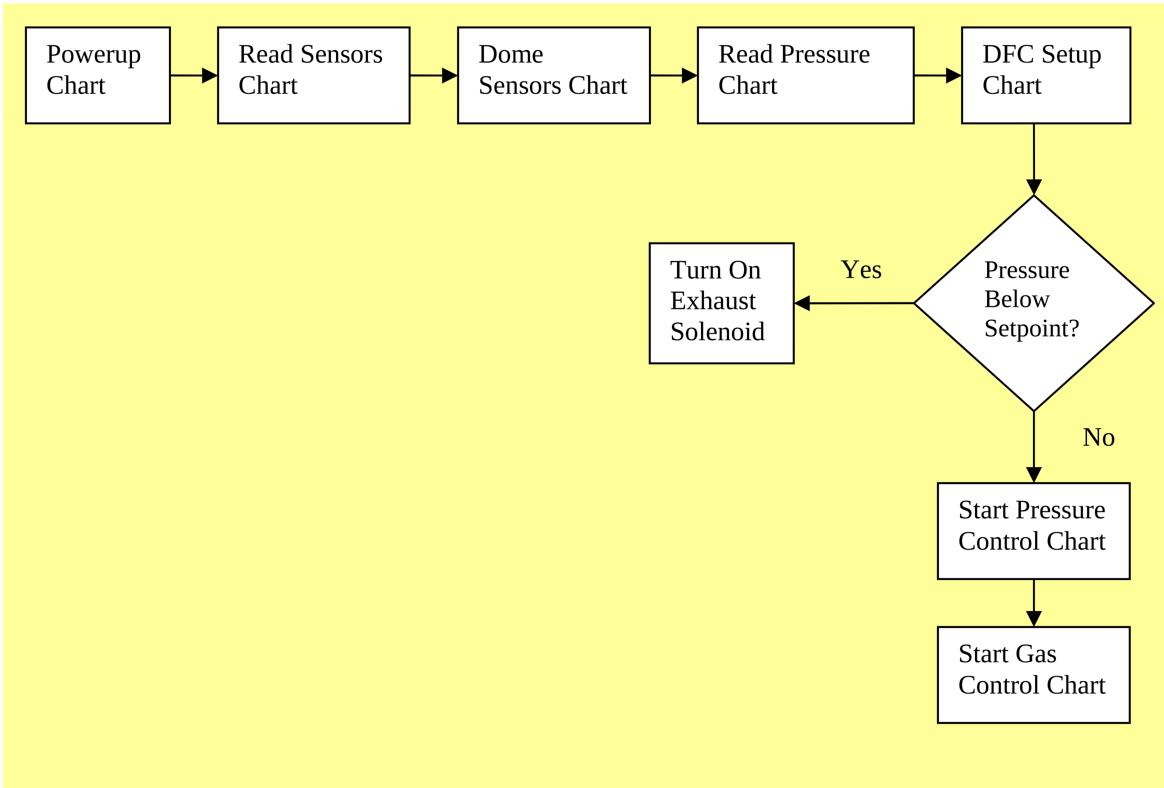

Figure 5 - Highest order of the program algorithm. It begins with the powerup chart where all other charts are managed.

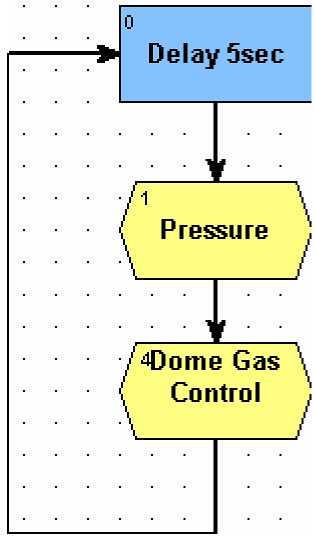

Figure 6 - Screen capture of the flow chart created in Opto22 that controls the pressure in the mixing tank and the gas concentrations in the Mars Dome.

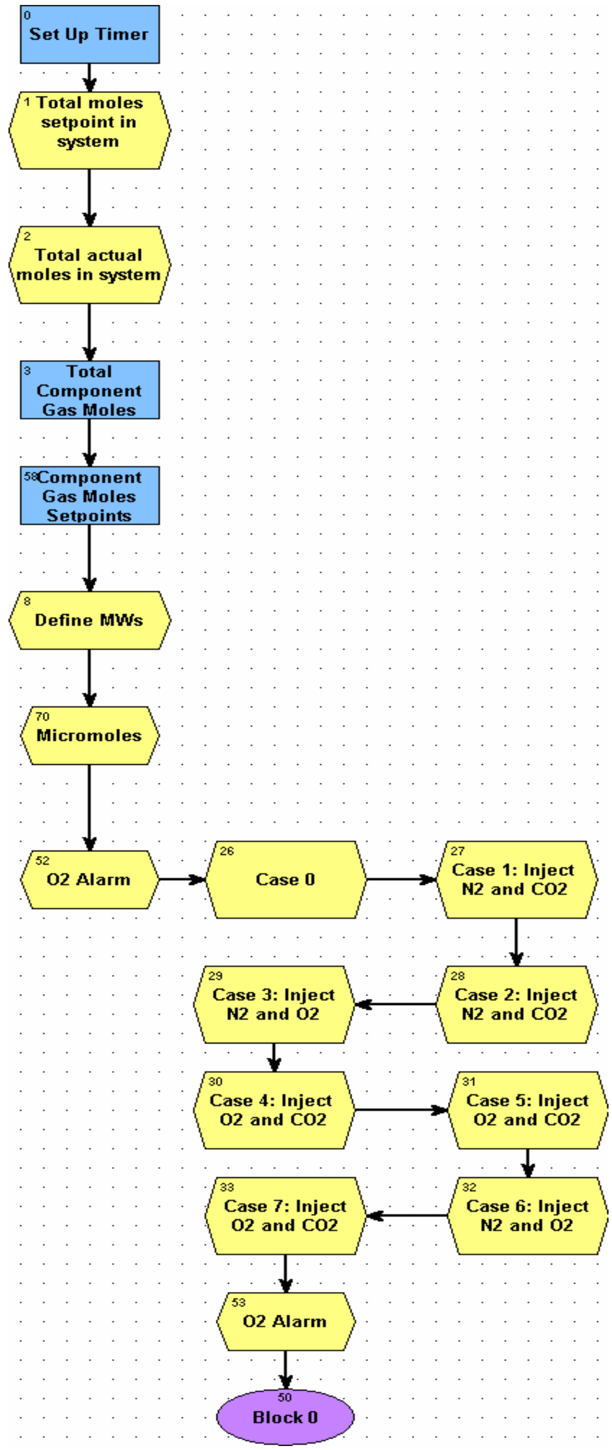

Figure 7 - The gas control flow chart calculates the current molar values and their setpoints. The setpoints are compared to the actual molar values and the algorithm decides which case presided in the mixing tank and thus which gases needed to be added to reach the desired setpoint.

DFC Setup: Within this flow chart, the setup conditions for the DFCs are established. Each slave port is individually selected and commands sent to define the status of the DFCs. All of the DFCs are set to operate in digital mode. The valve operation is set to automatic for all DFCs. The N_2 flow rate is 5SLPM, CO_2 is 5SMLPM and O_2 is 5SLPM. The exhaust DFCs flow rate is 15SLPM. The chart only executes these commands once.

Figure 8 is a picture of the first part of this chart. It depicts how these parameters are setup for the exhaust DFC and serves as an example for the other DCFs.

The second part of this chart polls the DFCs for the flow rate reading. It first checks to see which solenoid is open. If open, the program reads the DFC associated with that solenoid. Figure 9 is an illustration of this part of the chart. Again it is an example using the exhaust solenoid.

Read Sensors: This chart encompasses the calibration equations for the sensors on the mixing tank and in the dome. It also calculates the partial pressures of the gases. Figure 10 is a flow chart of the read sensors chart.

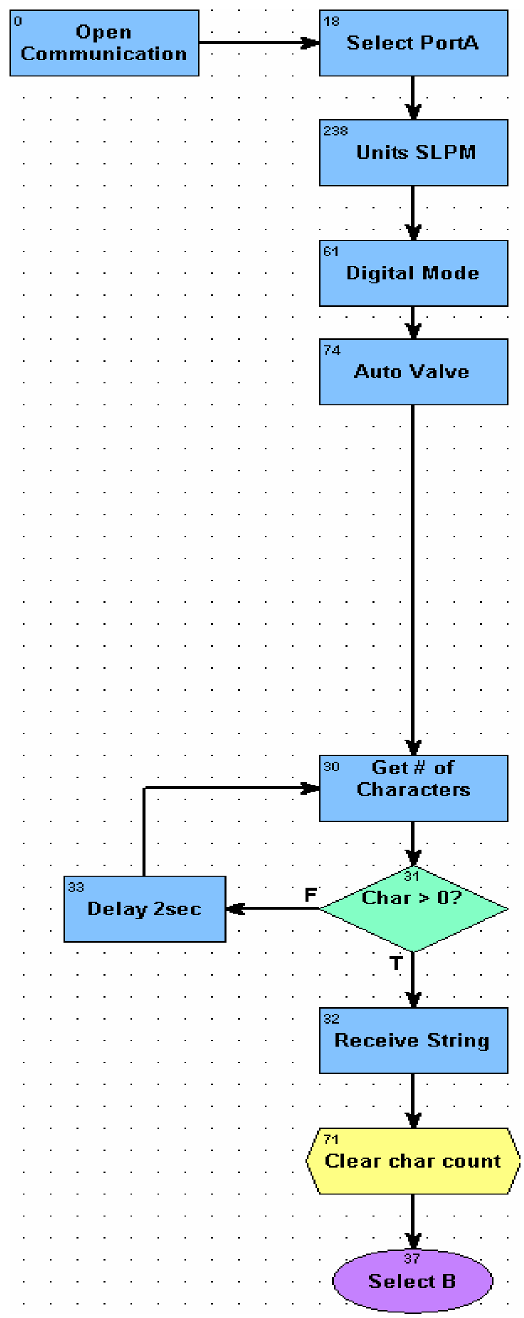

Figure 8 - Flow of instructions for the exhaust DFC found in the MFC setup chart. A command is sent that establishes the setpoints for the DFC. A string is returned that verifies those settings. The same instructions are used for the other three DFCs, but for the sake of brevity, they are not shown.

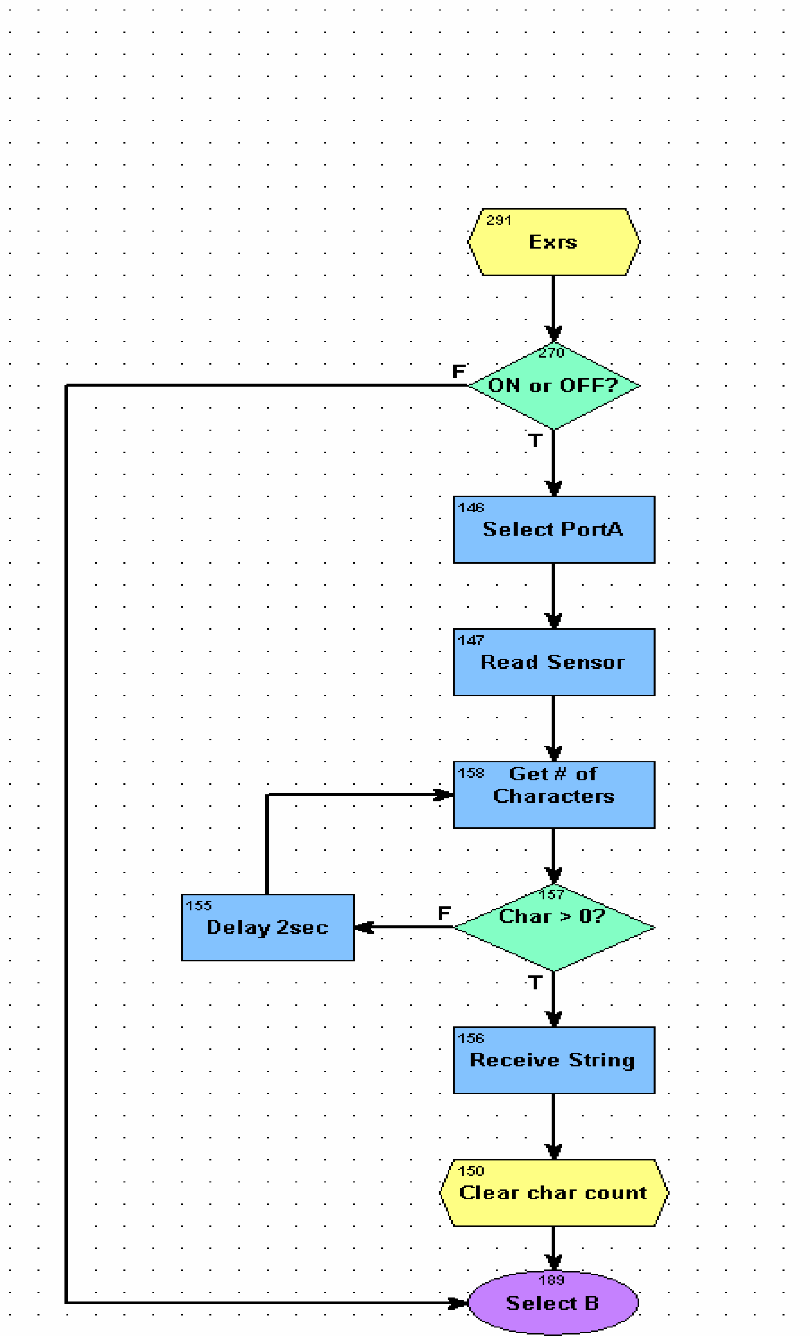

Figure 9 - Flow of instructions used to read the exhaust DFC sensor. The same instructions are used to read the other DFC sensors. A string is returned that contains the flow rate at the time the DFC sensor was read.

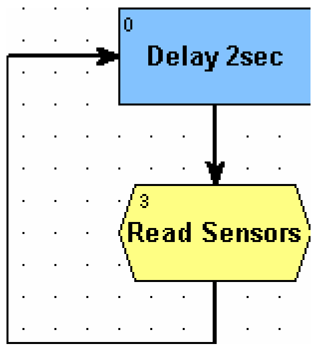

Figure 10 - Read sensors chart. This is a continuous loop that reads the sensors in the mixing tank every two seconds. It returns the current gas concentrations and temperature.

Dome Sensors: This chart reads the sensors in the dome. It receives a 16-bit number from the O_2, CO_2, pressure and temperature sensors. Figure 11 is a flow chart for the dome sensor chart.

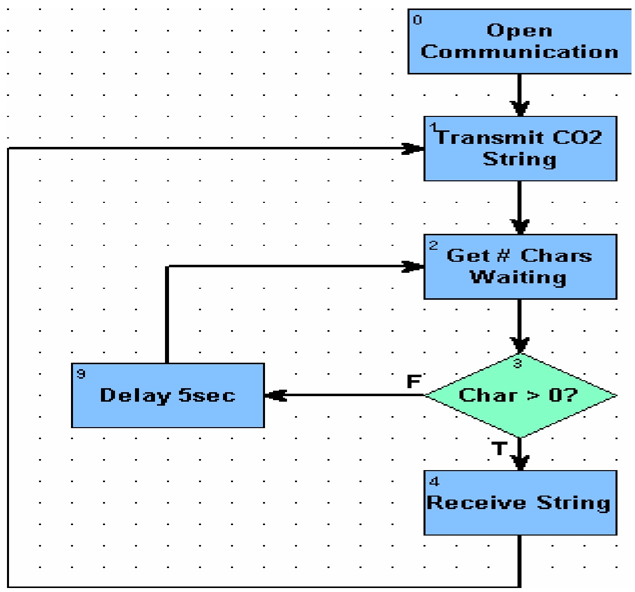

Figure 11 - Dome sensors flow chart. This is a continuous loop that reads the sensors in the Mars Dome. Commands are sent using RS-232 serial communication and a string is returned that contains the current state of the sensors in the Mars Dome.

Read Pressure: This chart uses RS-232 communication to read the pressure returned from the pressure transducer on the mixing tank. Figure 12 is the flow chart for the read pressure chart.

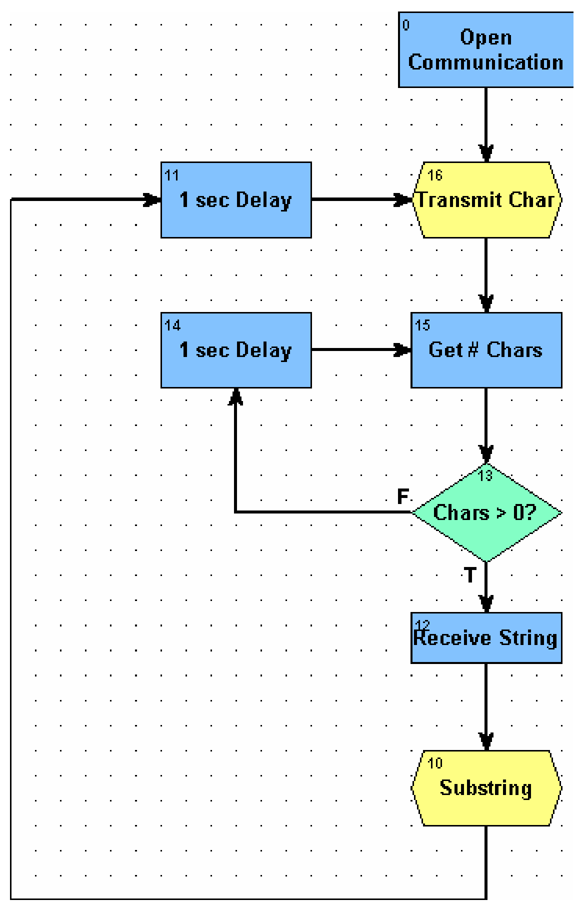

Figure 12 - Read pressure chart. This chart monitors the pressure in the mixing tank. It is a continuous loop that checks the total pressure using the Setra 370 transducer.

System Limitations

The O_2 sensor used limited the maximum mixing tank pressure. Because of the O_2 sensor used, the maximum tank pressure allowed was 180kPa. The system was tested and capable of maintaining a total pressure of 200kPa. The maximum pressure the tank maintained was 200kPa, but pressures above 175kPa were not evaluated.

Program Interface

During operation, the system was monitored using ioDisplay. Several windows were created to watch the system change. A brief description of each follows.

Main: This window displays on overall view of the system as seen in figure 13. In addition to monitoring environmental parameters of the tank and the dome, it shows which solenoid valves are open and for how long, which pumps are on, flow rates, etc. In the screen capture below, both the N_2 and exhaust solenoids are open as indicated by their green color. The O_2 and CO_2 solenoids are red and thus closed.

Temperature and Pressure: If the appropriate label is selected on the main window, a graph of the temperature and pressure associated with both the tank and the dome appear (Figure 14). The plot labeled tank pressure located at the top left side of the temperature and pressure window was a real-time plot of the mixing tank total pressure and its setpoint. The mixing tank setpoint is denoted in yellow and the current total pressure in blue. At the top right, the real-time total pressure in the Mars Dome is displayed. The window also showed the temperature of the gases in the recirculation line as well as the temperature of the vacuum pump on the mixing tank. There were no setpoints associated with these parameters.

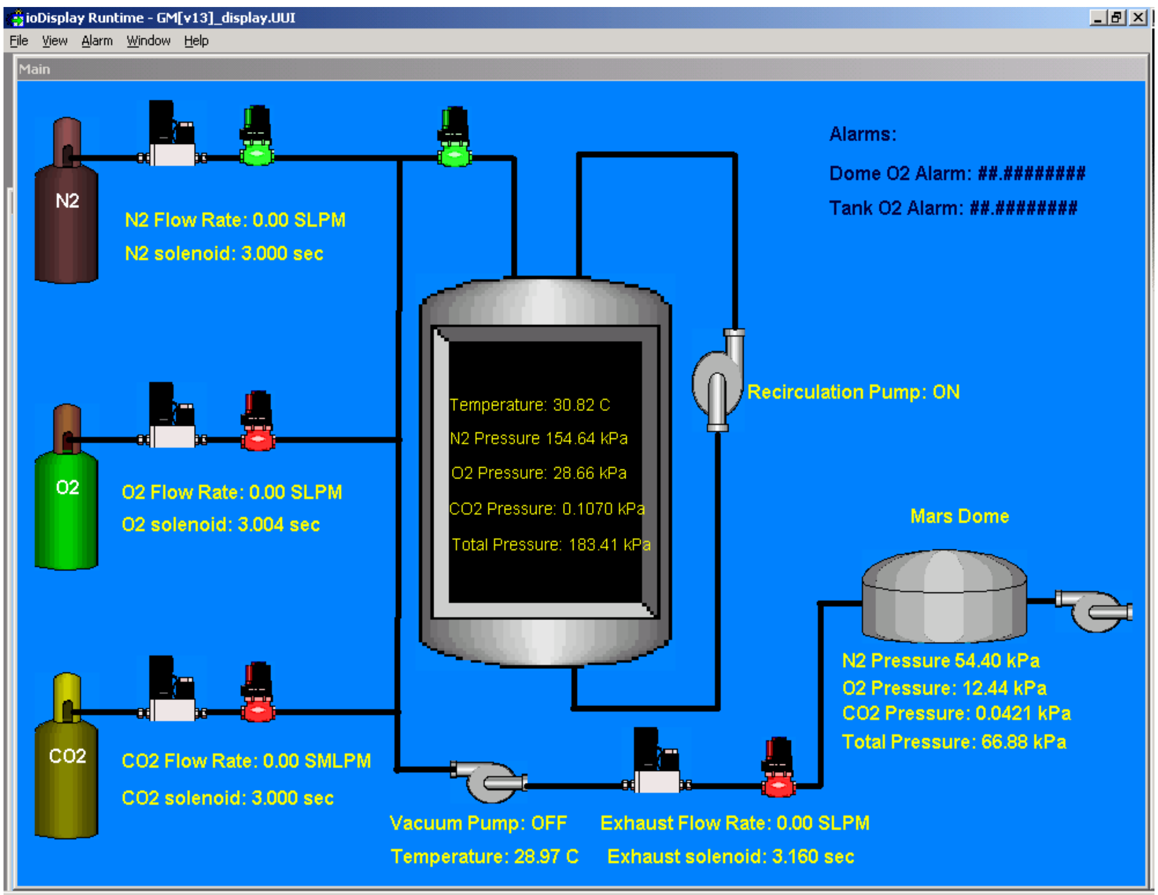

Figure 13 - Main window created in ioDisplay to monitor the system parameters. The green solenoids indicated that the N_2 and main tank solenoids were on and gas was flowing into the mixing tank. The red solenoids indicated that the O_2, CO_2 and exhaust solenoids were off.

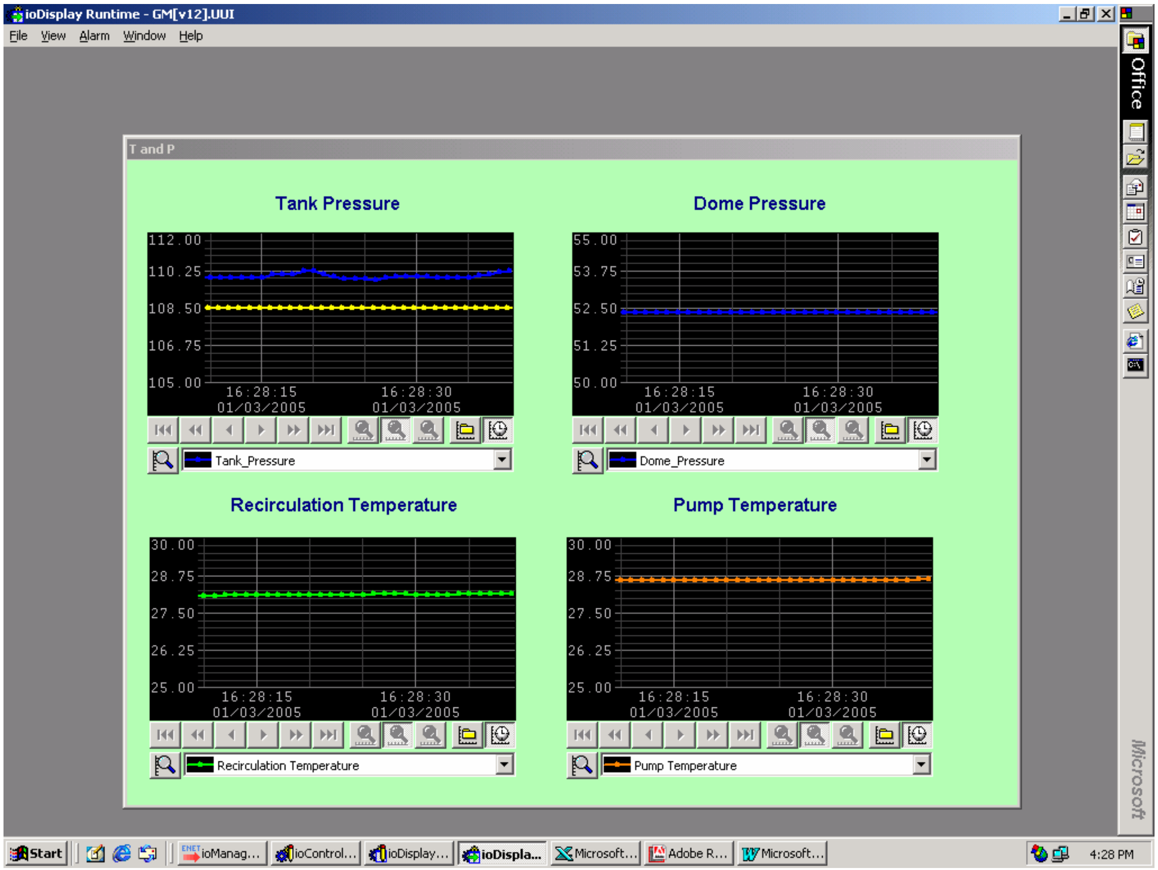

Figure 14 - Temperature and pressure window created in ioDisplay. It monitors the real-time temperature and total pressure in the both the mixing tank and the Mars Dome.

Dome Gas Concentration: This window was used to monitor the status of the partial pressures of CO_2, O_2, and N_2 in the Mars Dome at the time the experiments were run. Each plot tracked the real-time partial pressure of the component gases and their setpoints. The setpoints are shown in pink. At the time the screen capture was taken, both CO_2 and N_2 were above their setpoints and O_2 was below its setpoint. Figure 15 is a screen capture of this window.

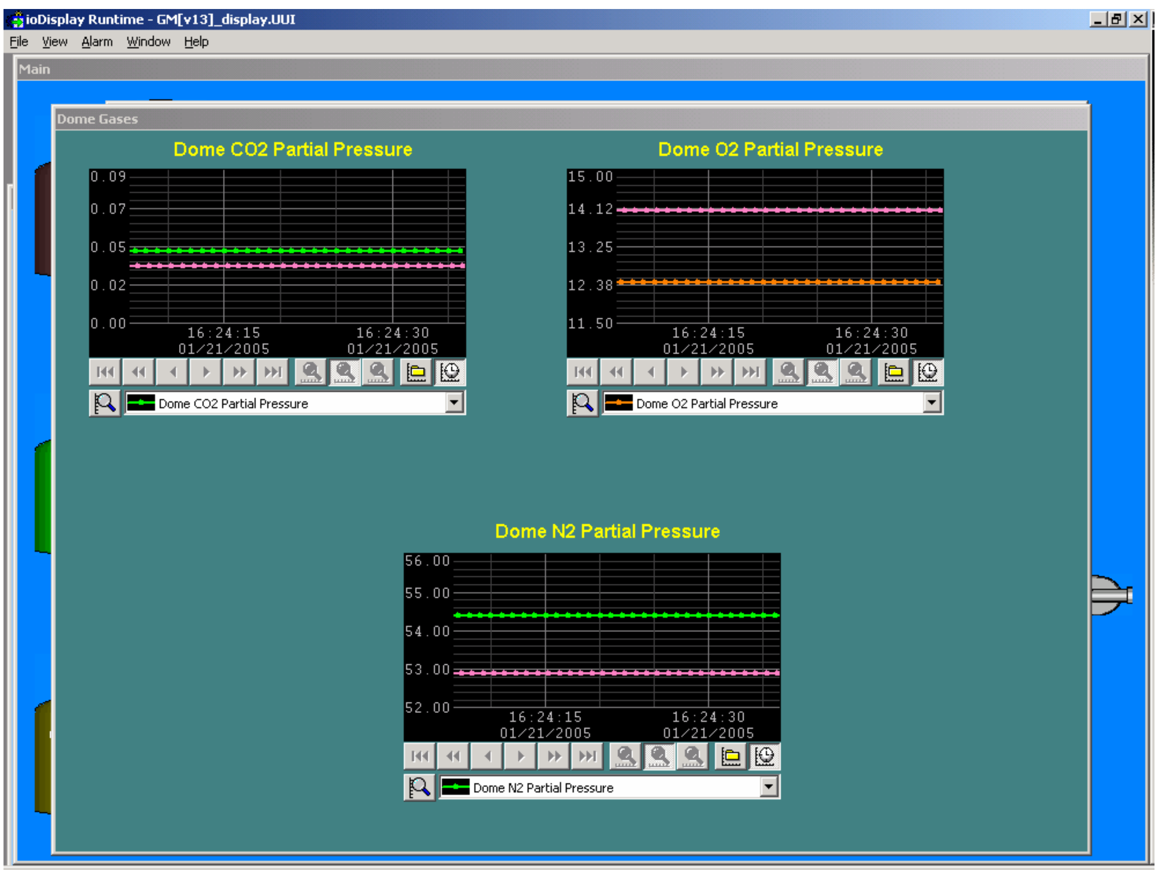

Figure 15 – Partial pressure window. This window monitors the partial pressure of CO_2, O_2, and N_2 in the Mars Dome. The component gas setpoints are displayed in pink.

Tank Concentrations: This window monitored the component gas concentrations (%) in the mixing tank. The CO_2, O_2, and N_2 setpoints were displayed in yellow. Figure 12 shows that at the time the screen capture was taken, CO_2 was above its setpoint, O_2 was below its setpoint, and N_2 was oscillating around its setpoint. Figure 16 is a screen capture of the tank concentrations window.

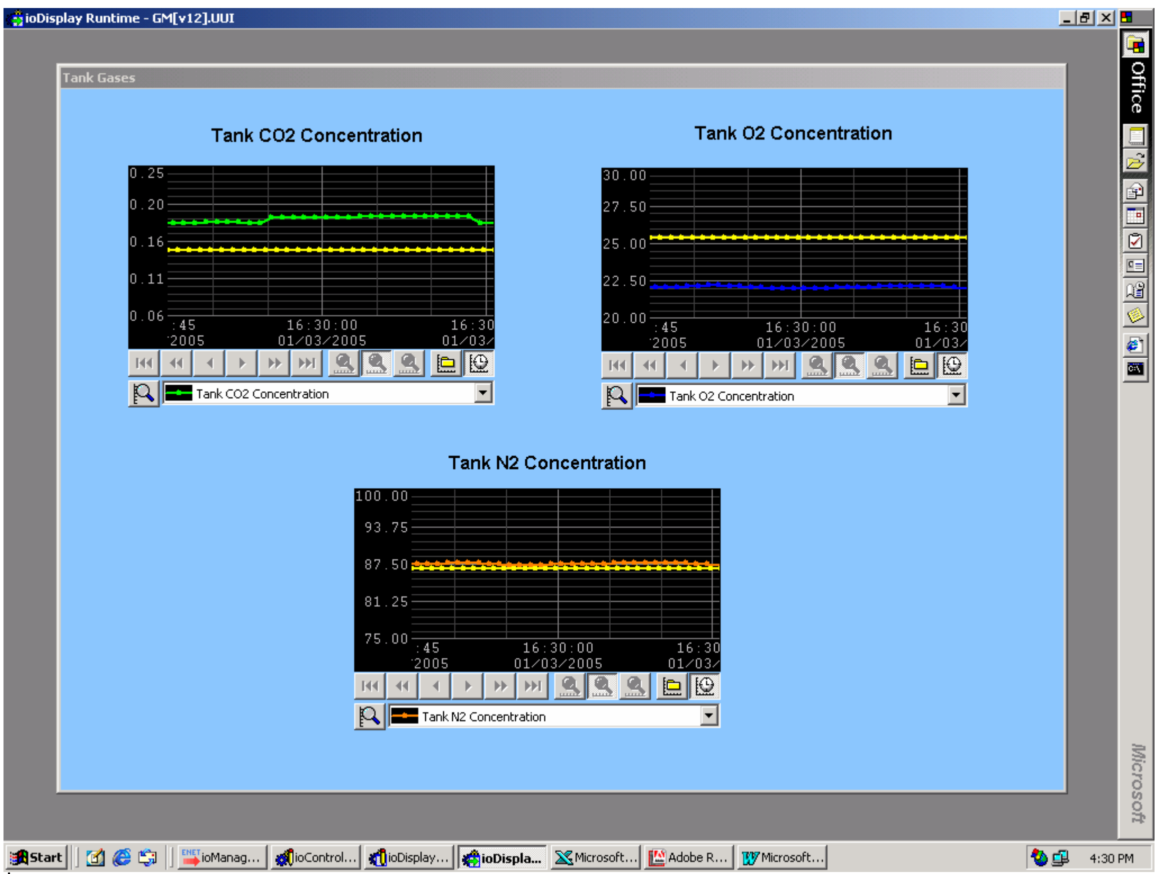

Figure 16 – Mixing Tank concentration window. This window displays both the real-time CO_2, O_2, and N_2 concentration changes and their setpoints in the mixing tank.

Molar Concentration: The molar concentrations of each of the component gases were monitored in both the mixing tank and the Mars Dome. The top left plot in figure 17 shows the number of millimoles of N_2 in the mixing tank and the Mars Dome and its setpoint. The same is illustrated for O_2 and CO_2. Figure 17 also displays the total number of millimoles in both systems.

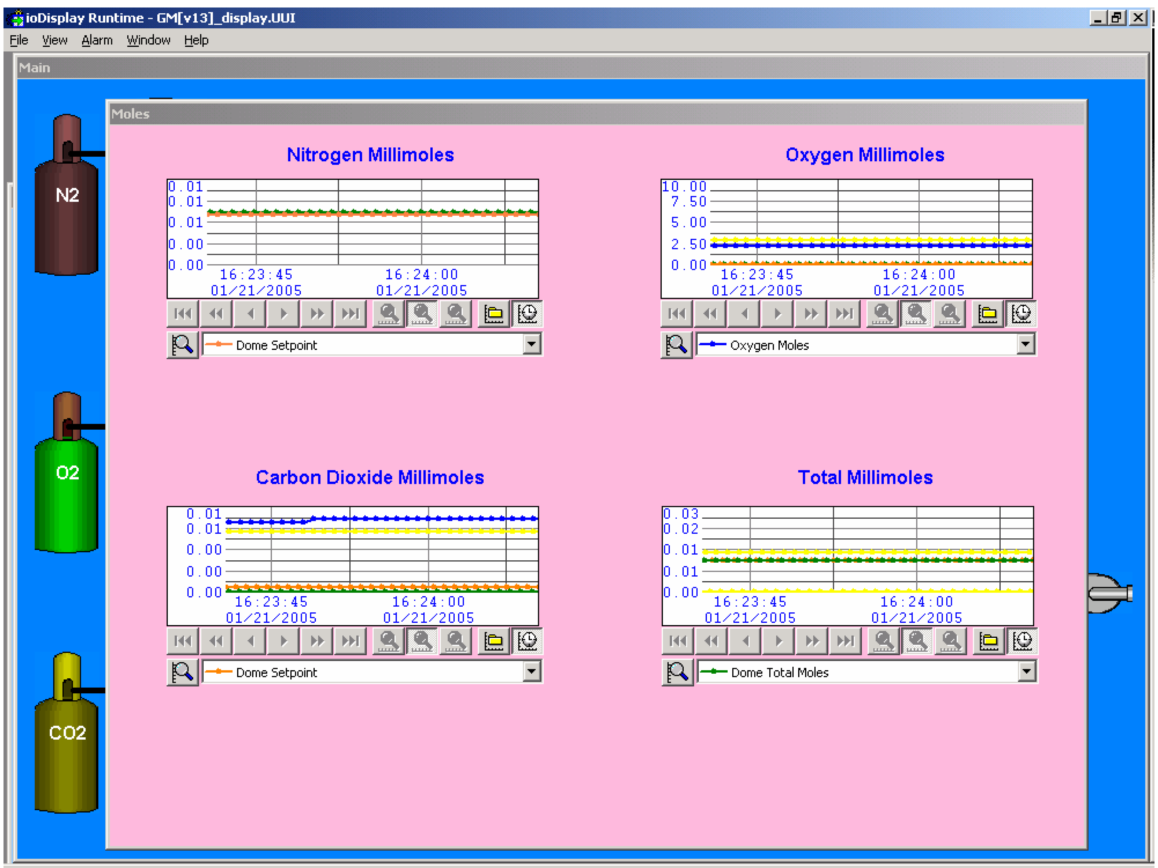

Figure 17 – Molar concentration window. This window displays the millimolar concentrations of the component gases in both the mixing tank and the Mars Dome are monitored in real-time. This window also displays a plot of the total molar concentration in both systems. N_2, O_2, and CO_2 setpoints were also plotted.

Flow Rate: The flow rates of the gases injected into the mixing tank and the exhaust stream were monitored during testing. All flow rates were measured in standard liters per minute (SLPM) except CO_2 which was measured in standard milliliters per minute (SMLPM). Figure 18 shows not only the flow rate, but how long the solenoids were open allowing gas flow. At the time of the screen capture, neither the CO_2 or exhaust solenoid were on, thus no gas was flowing and the flow rate was 0.

Figure 18 – Flow rate window. The flow rate for each of the DFCs was monitored when the solenoid associated with each component gas and the exhaust stream were opened. From the plot, it can be seen how long the solenoid was on and the flow rate according to the DFC.

Sensor Calibrations

All of the sensors in the system were calibrated prior to testing carried out during experiments 1 and 2.

Mixing Tank CO_2 Sensor Calibration

Figure 19 is a plot of the sensor reading versus the predetermined concentration at 175kPa, 150kPa, 125kPa and 102kPa. Then the slope and intercept from this graph was plotted against pressure to determine a calibration equation that was dependent on both pressure and concentration. Figure 20 is a plot of the slope and intercept versus the total pressure in the mixing tank.

The two equations obtained from plotting the slope against the pressure and the intercept against the pressure in figure 20 were added together to determine a calibrated sensor reading. The equation was solved for the percent CO_2.

$$CO_2\_reading = \frac{(CO_2B\_reading-(7X10^{-5}*PressureResult-0.0099))}{(0.006*PressureResult-0.2838)} \quad [8]$$

where: CO_2_reading = CO_2 concentration [%]

CO_2B_reading = CO_2 sensor output [V]

PressureResult = total pressure in the mixing tank [kPa]

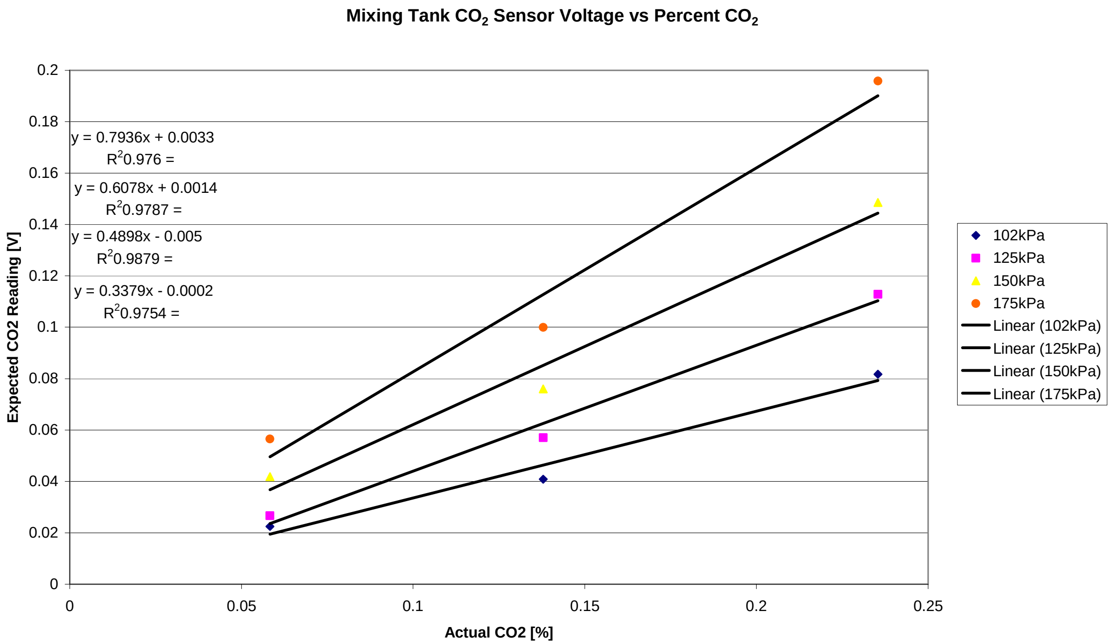

Figure 19 – Mixing tank CO_2 sensor voltage vs percent CO_2. Sensors readings were taken at 102kPa, 125kPa, 150kPa, and 175kPa in the mixing tank. The total pressure was measured using the Setra 370 pressure gauge.

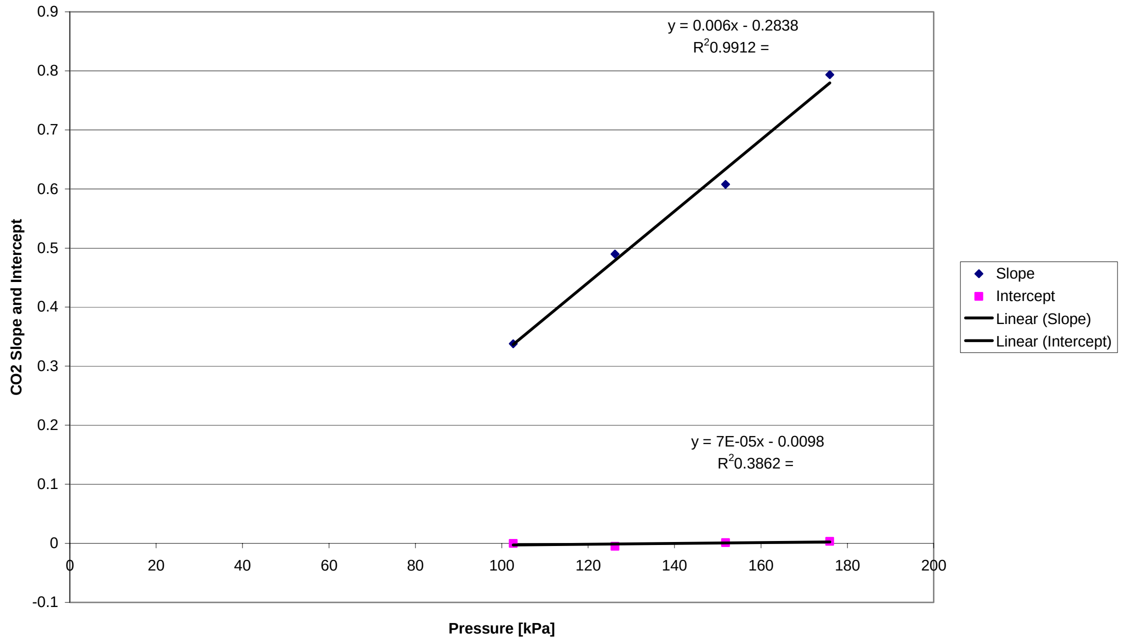

Figure 20 – Mixing tank slope and intercept vs total pressure. The CO_2 sensor voltage in the mixing tank was plotted against the percent CO_2 in the gas mixture. Sensors readings were taken at 102kPa, 125kPa, 150kPa, and 175kPa. The slope and intercept from each equation generated was plotted against the total pressure as seen in the plot above.

Calibration of the Mars Dome CO_2 Sensor

Figure 21 is a plot of the sensor reading versus the predetermined concentration at 101kPa, 75kPa, 50kPa and 30kPa. Then the slope and intercept from this graph was plotted against pressure to determine a calibration equation that was dependent on both pressure and concentration. Figure 22 is a plot of the slope and intercept versus the total pressure in the Mars Dome.

The equations from figure 22 were added together and rearranged to give the percent CO_2 in the Mars Dome.

$$dCO_2 = \frac{dCO_2\_reading + (0.9744 * DomePressure) - 2042.7}{-47.209 * DomePressure + 6056.7} \quad [9]$$

where: dCO_2 = CO_2 concentration [%]

DomePressure = total pressure in the Mars Dome [kPa]

dCO_2_reading = CO_2 sensor 16-bit number

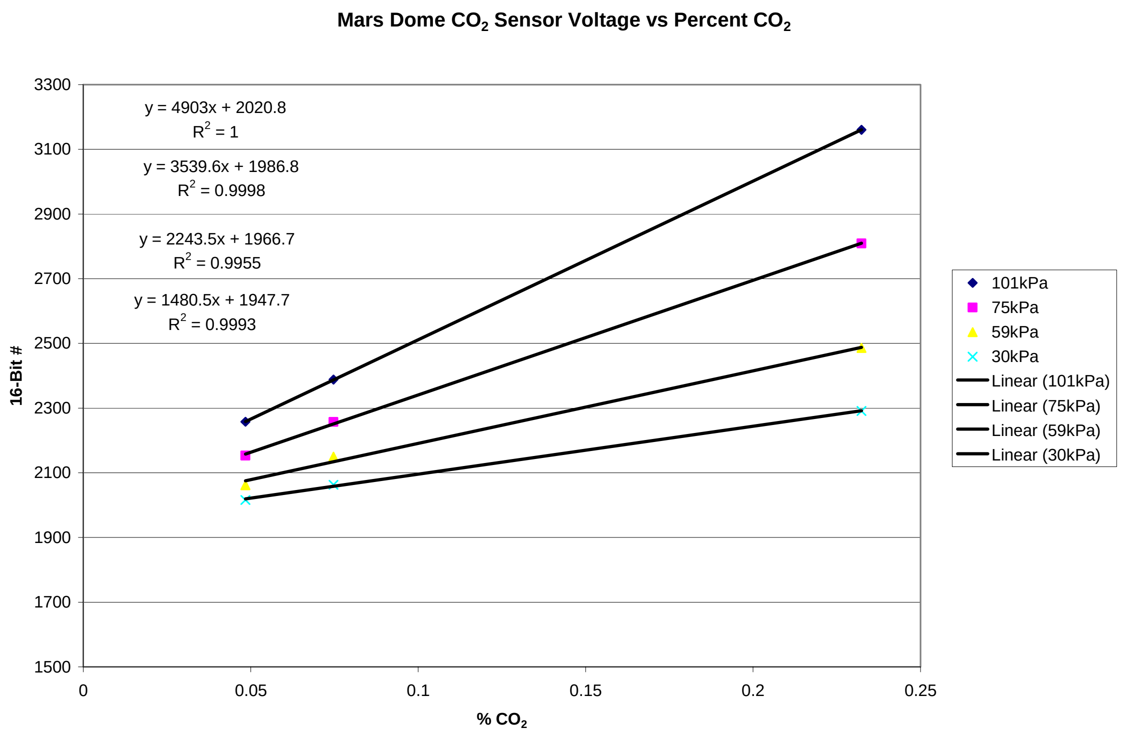

Figure 21 – Mars Dome CO_2 16-bit number vs percent CO_2. This graph depicts the curves associated with plotting the 16-bit number returned from the CO_2 sensor in the Mars Dome against the percent CO_2 in the mixture. Values were recorded at 101kPa, 75kPa, 50kPa, and 30kPa. The total pressure was monitored using theKNF vacuum controller.

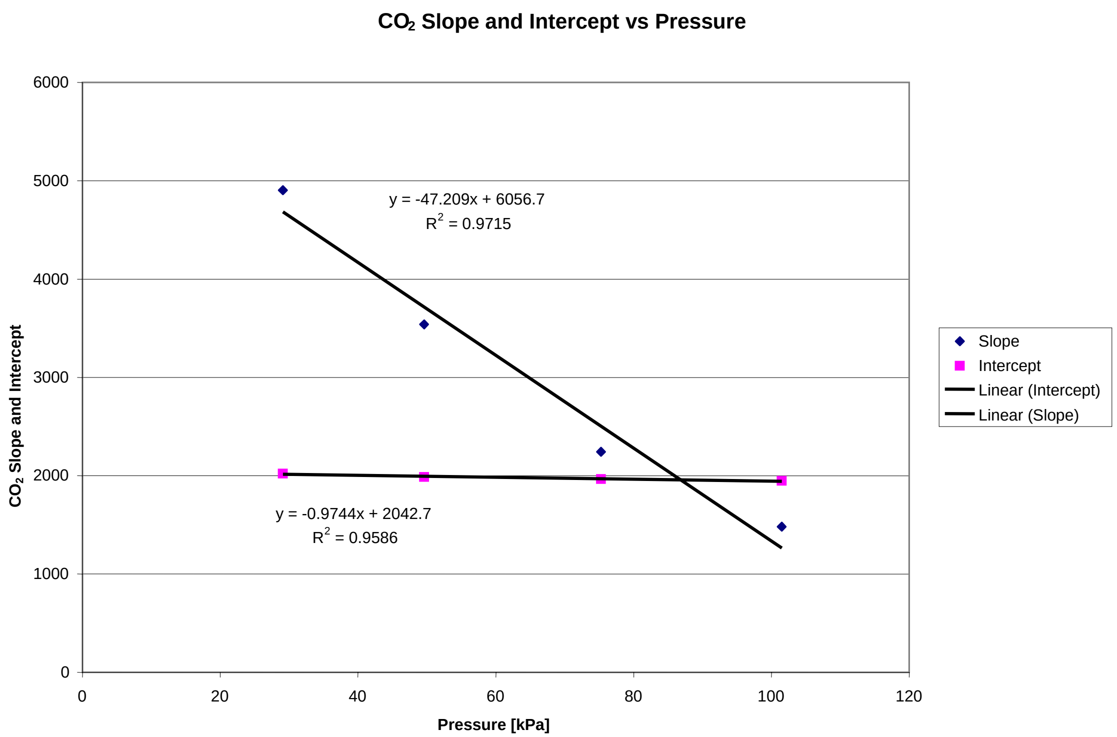

Figure 22 – Mars Dome CO_2 slope and intercept vs total pressure. The 16-bit number returned from the CO_2 sensor in the Mars Dome was plotted against the percent CO_2 in the gas mixture. Values were recorded at 101kPa, 75kPa, 50kPa, and 30kPa. The slope and intercept from this set of curves were plotted against the total pressure as seen in the graph above.

Calibration of the Mixing Tank O_2 Sensor

Figure 23 is a plot of the sensor reading versus the predetermined concentration at 175kPa, 150kPa, 125kPa and 102kPa. Then the slope and intercept from this graph was plotted against pressure to determine a calibration equation that was dependent on both pressure and concentration

The final equation used in the algorithm was determined by adding together the equations from figure 24 and rearranging.

$$O_2\_reading = \frac{O_2B\_reading - (-9\times10^{-6} * PressureResult + 0.0005)}{(8\times10^{-6} * PressureResult - 0.0002)} \qquad [10]$$

where: O_2_reading = O_2 concentration [%]

O_2B_reading = O_2 sensor voltage [mV]

PressureResult = total pressure in the mixing tank [kPa]

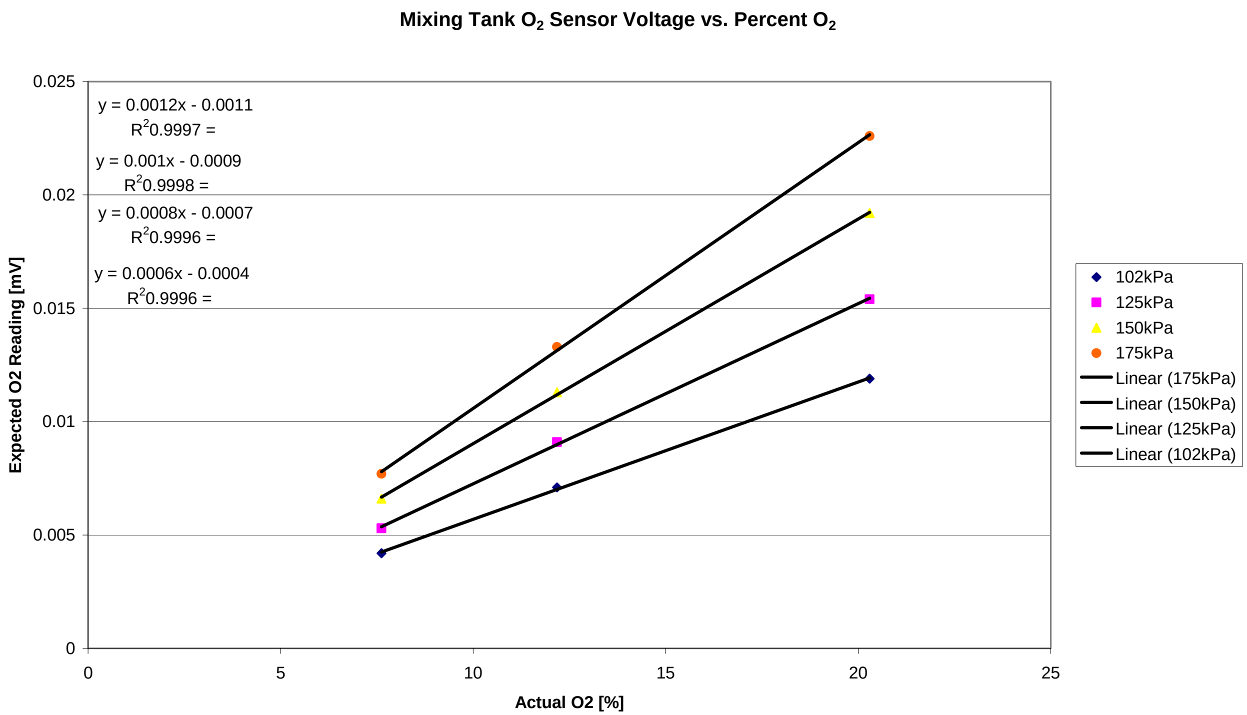

Figure 23 – Mixing tank O_2 sensor voltage vs percent O_2. The voltage returned from the O_2 sensor in the mixing tank was plotted against the actual percent O_2 in the mixture. Sensor readings were taken at 102kPa, 125kPa, 150kPa, and 175kPa. The total pressure was monitored using the Setra 370 pressure transducer.

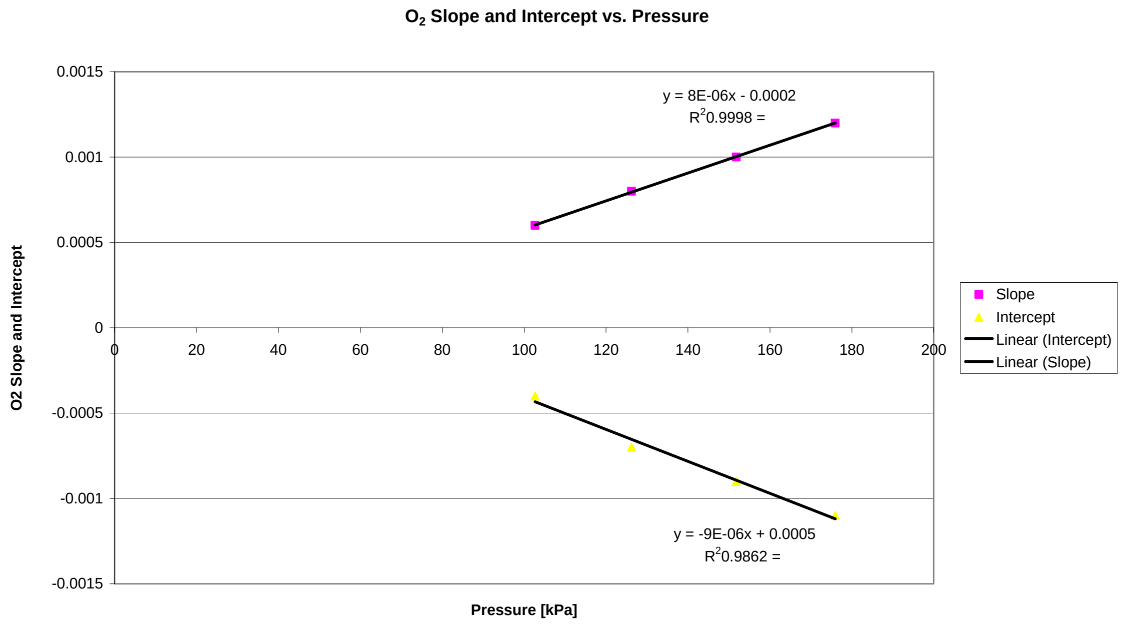

Figure 24 – Mixing tank O_2 slope and intercept vs total pressure. The voltage returned from the O_2 sensor in the mixing tank was plotted against the actual percent O_2 in the mixture. Sensor readings were taken at 102kPa, 125kPa, 150kPa, and 175kPa. The slope and intercept from this set of curves was plotted against the total pressure in the mixing tank as seen in the graph above.

Calibration of the Mars Dome O_2 Sensor

Figure 25 is a plot of the sensor reading versus the predetermined concentration at 101kPa, 75kPa, 50kPa and 30kPa. Then the slope and intercept from this graph was plotted against pressure to determine a calibration equation that was dependent on both pressure and concentration. Figure 26 is a plot of the slope and intercept versus the total pressure in the mixing tank.

The two equations generated as a result of plotting the slope and intercept against the total pressure were added together and rearranged to determine the O_2 concentration based on pressure and the sensor output.

$$dO_2 = \frac{dO_2\_reading + (1.7326*DomePressure + 60.822)}{(0.7193*DomePressure - 2.6653)} \qquad [11]$$

where: dO_2 = O_2 concentration [%]

dO_2_reading = O_2 sensor reading [16-bit number]

DomePressure = total pressure in Mars Dome [kPa]

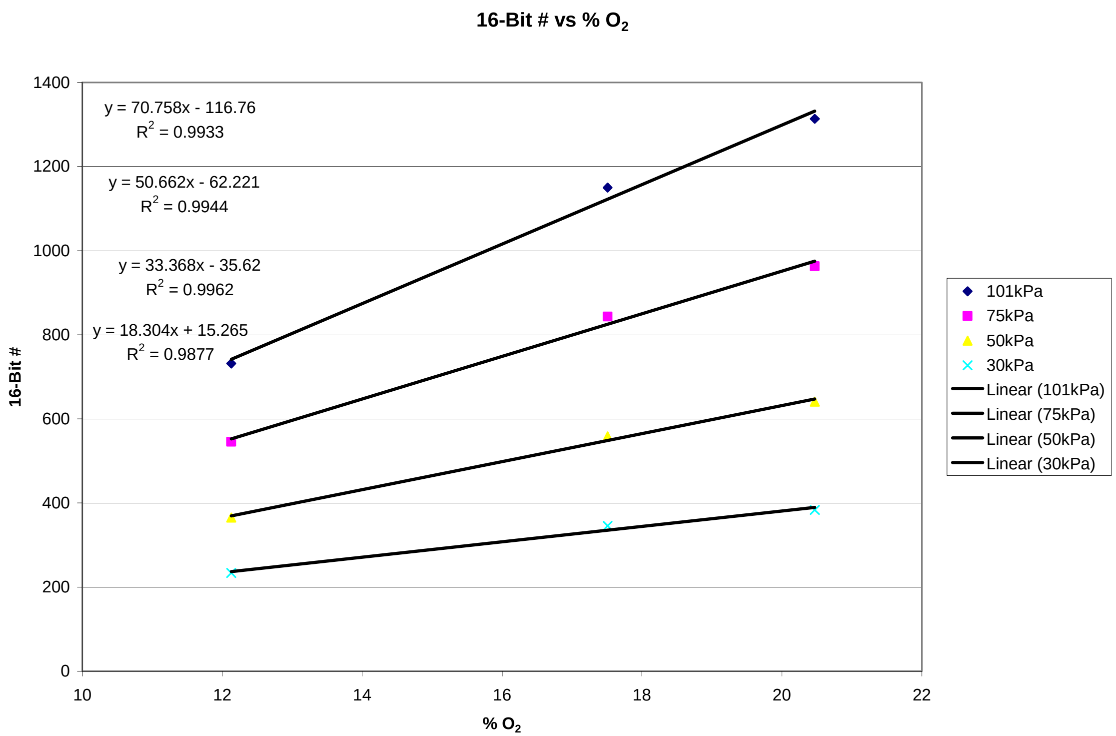

Figure 25 – Mars Dome O_2 16-bit number vs percent O_2. The 16-Bit number returned from the O_2 sensor in the Mars Dome versus the percent O_2. The sensor was calibrated at 101kPa, 75kPa, 50kPa, and 30kPa. The total pressure in the Mars Dome was controlled using the KNF vacuum controller.

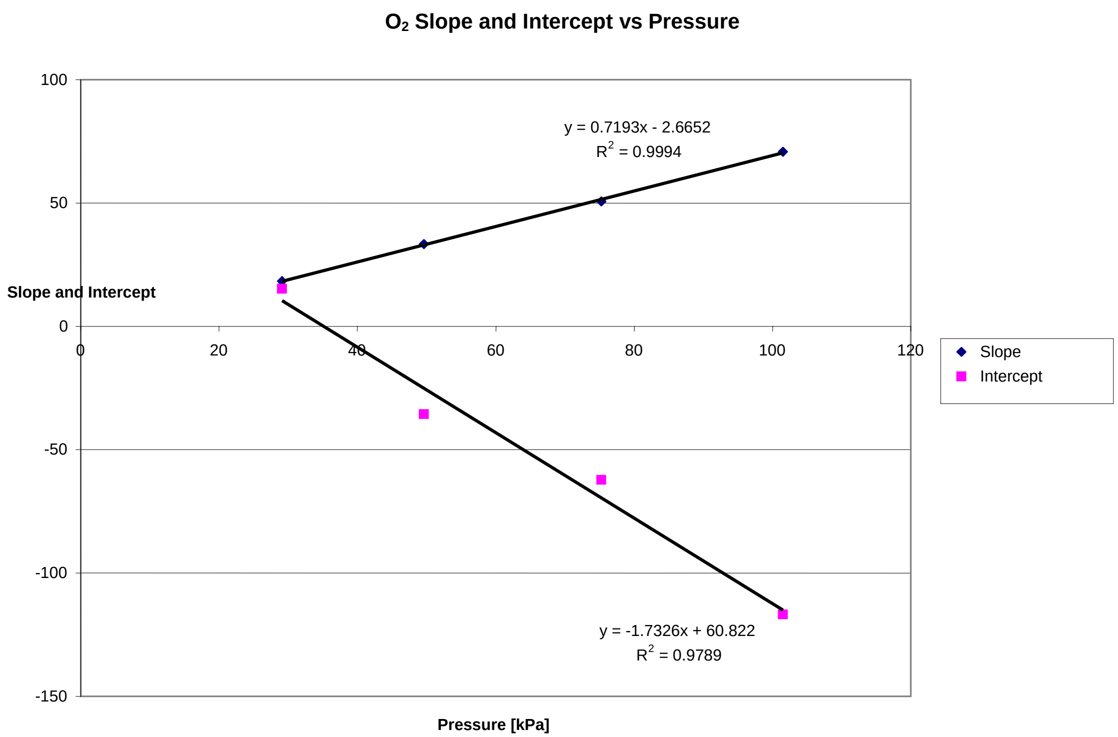

Figure 26 – Mars Dome O_2 slope and intercept vs total pressure. 16-Bit number returned from the O_2 sensor in the Mars Dome versus the percent O_2. The sensor was calibrated at 101kPa, 75kPa, 50kPa, and 30kPa. The slope and intercept from this set of curves was plotted against the total pressure n the Mars Dome as seen in the figure above.

Mars Dome Pressure Sensor Calibration

The pressure sensor (Model ASCX15AN, Morristown, NJ) in the Mars Dome was calibrated using the vacuum pump controller manufactured by KNF Neuberger, Inc. (Model PI842, Trenton, NJ). The vacuum pump controller was given a setpoint and the pressure in the Mars Dome was allowed to stabilize. Readings were taken at three different pressures including 100kPa, 75kPa, and 30kPa. The sensor returned a 16-bit number that was proportional to voltage. Figure 27 illustrates the pressure sensor calibration plot.

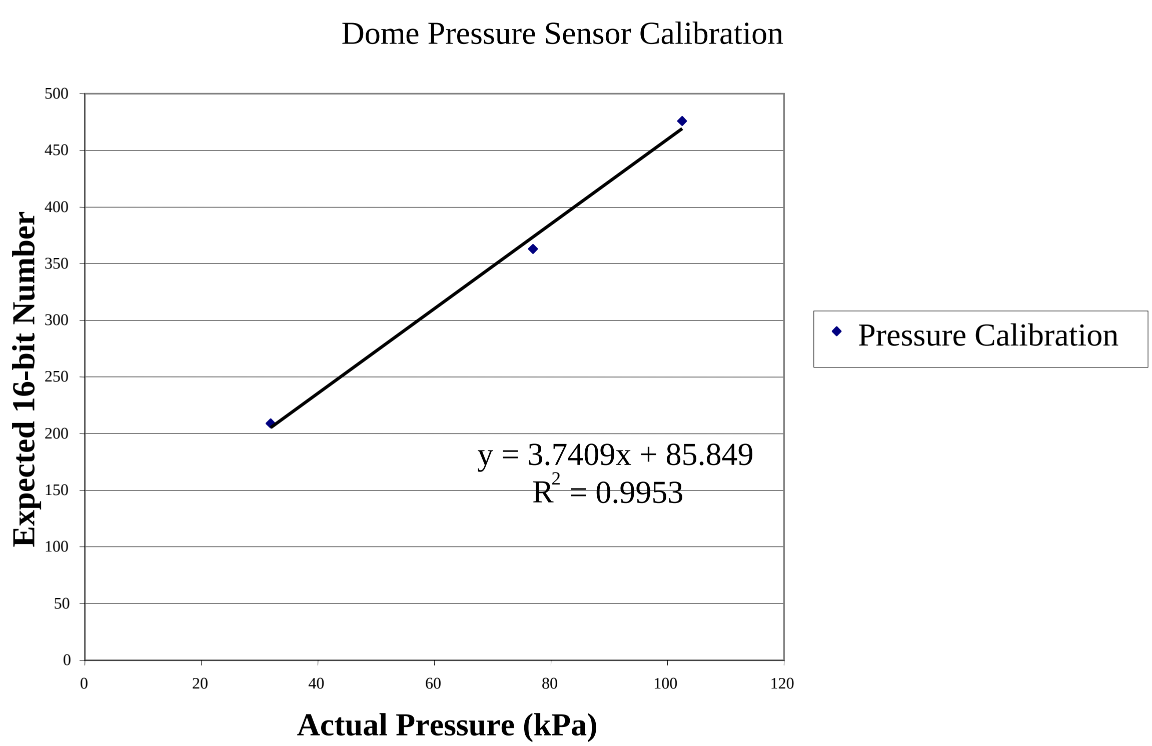

Figure 27 - Mars Dome pressure sensor calibration. The expected 16-bit number returned from the sensor was plotted against the actual pressure in kPa.

Objective 2

O_2 Analysis

Partial Pressure

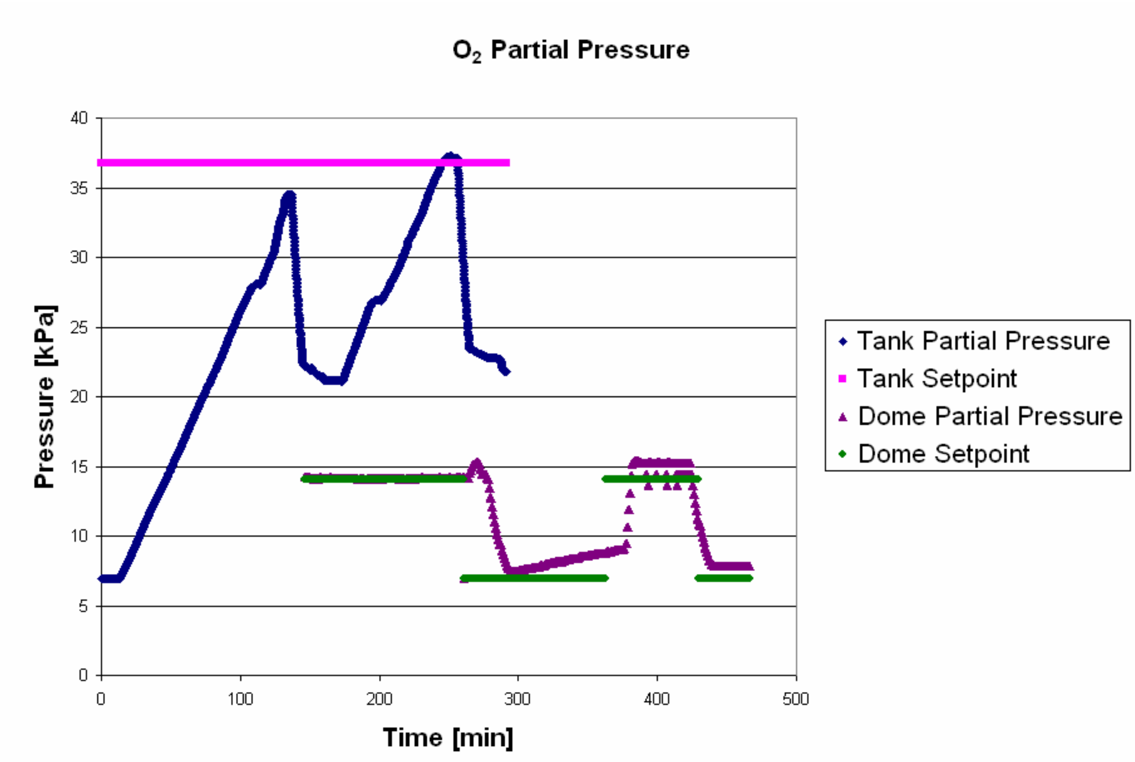

Figure 28 – O_2 partial pressure in the mixing tank and in the Mars Dome. The setpoints of the mixing tank and the Mars Dome for trials 1 and 2 of experiments 1 and 2 are also displayed.

Figure 28 shows the O_2 partial pressure in the mixing tank to its setpoint and the O_2 partial pressure in the dome to its setpoint. The percent of O_2 remained constant throughout both experiments 1 and 2 (21%). At the beginning of experiment 1, the O_2 partial pressure was well below its setpoint. This is illustrated by the sharp rise at the beginning of the graph as the O_2 partial pressure approaches its setpoint. The two sharp declines in pressure occur because the tank was being evacuated to fill the dome. The error associated with the partial pressure was calculated by subtracting the actual pressure from its setpoint.

Table 6. Statistical Description of the Error Associated With the Partial Pressure of O_2 During Experiments 1 and 2.

Statistical Error Summary for Mixing Tank O_2 Partial Pressure

	Experiment 1	Experiment 2
Mean	2.564	-0.312
Range	1.835	1.409
Minimum	2.244	-0.528
Maximum	4.079	0.881

.

During experiment 1, when the setpoint was 21kPa, the mean error value for the O_2 partial pressure was 2.564kPa. This implies that O_2 was below its setpoint considering that the error was calculated by subtracting the actual partial pressure from the setpoint. The mode was 2.267kPa which again supports the fact that the O_2 partial pressure was typically below its setpoint. The range calculated for the sample error population was 1.835kPa with a maximum and minimum error of 4.079kPa and 2.244kPa respectively.

Experiment 2 suggested different findings from those of experiment 1. The setpoint for experiment 2 was again 21kPa. The mean error value during experiment 2 was -0.312kPa which implied that the O_2 partial pressure tended to reside above its setpoint. The mode was -0.521kPa where the negative value again points to O_2 being above its setpoint. The range was 1.409kPa with a maximum error of 0.881kPa and a minimum error of -0.5281kPa.

The numbers from both experiments 1 and 2 suggest that the algorithm should be modified for improved O_2 control. O_2 partial pressure values lingered outside the predetermined range of 35.7 – 37.8kPa.

During experiment 1, the dome was operated at 67kPa before the pressure was drawn down to 33kPa. The decrease in O_2 partial pressure was proportional to the pressure change, but the percent O_2 remained at 21%. Table 7 describes the statistical error associated with the O_2 partial pressure in the Mars Dome during experiment 1 at 67kPa and 33kPa.

Table 7. Statistical Summary Error Obtained for the O_2 Partial Pressure in the Mars Dome During Trial 1 of Experiment 1.

Experiment 1 Statistical Error Summary for O_2 Partial Pressure		
	67kPa	33kPa
Mean	-0.071	-0.720
Range	0.223	0.498
Minimum	-0.171	-0.984
Maximum	0.051	-0.485

Trial 1 of experiment 1 was conducted at a total pressure of 67kPa in the Mars Dome. This would correspond to an O_2 partial pressure of 14.07kPa or 21% O_2. The mean error value for trial 1 was -0.071kPa. This implied that the O_2 partial pressure in the Mars Dome tended to reside above its setpoint. The range was 0.223kPa with maximum and minimum errors of 0.051kPa and -0.171kPa respectively. According to figure 28, the O_2 partial pressure was approximately equal to its setpoint during trial 1. Thus, the statistical summary of trial 1 supports the data used to generate the plot of the O_2 partial pressure in the Mars Dome of figure 28.

During trial 2 of experiment 1, the Mars Dome was at a total pressure of 33kPa. This corresponded to an O_2 partial pressure of 6.93kPa. The mean error value was -0.720kPa. This negative value would imply that the O_2 partial pressure was above its setpoint. Looking at figure 28, it can be seen that this was indeed the case. The O_2

partial pressure was above its setpoint with maximum and minimum errors of -0.485kPa and -0.984kPa respectively.

The results of trials 1 and 2 did not agree with the analysis of the O_2 partial pressure during experiment1 in the mixing tank. The results from experiment 1 in the mixing tank should agree with the results from trials 1 and 2 of the O_2 analysis performed on the partial pressure in the Mars Dome because the mixture created in the mixing tank was exhausted to the Mars Dome. Table 8 is a statistical summary of the error associated with the O_2 partial pressure in the Mars Dome during the two trials of experiment 2.

Like experiment 1, the statistical analysis conducted for experiment 2 suggested that the O_2 partial pressure in the Mars Dome was consistently above its setpoint. During trial 1, the mean error value was -0.725kPa. Here again, the negative value implied that the O_2 partial pressure was above its setpoint. The range was 2.353kPa with the maximum error being 1.107kPa and the minimum error being

Table 8. Statistical Summary Error Obtained for the O_2 Partial Pressure in the Mars Dome During Experiment 2.

Experiment 2 Statistical Error Summary for O_2 Partial Pressure		
	67kPa	33kPa
Mean	-0.725	-0.896
Range	2.353	0.093
Minimum	-1.246	-0.985
Maximum	1.107	-0.891

-1.246kPa. For trial 2, the mean error value was -0.896kPa. The range was 0.093kPa and the minimum and maximum values were -0.985kPa and -0.891kPa respectively. These findings support figure 28 which shows the O_2 partial pressure was above its setpoint during both trials 1 and 2 of experiment 2. The results here also agree with those of experiment 2 determined as a result of analyzing the error of the O_2 partial pressure in the mixing tank.

GC Data

The GC was used to verify the O_2 concentration during experiments 1 and 2. Figure 29 is a screen capture of the GC results from the first trial of the first experiment.

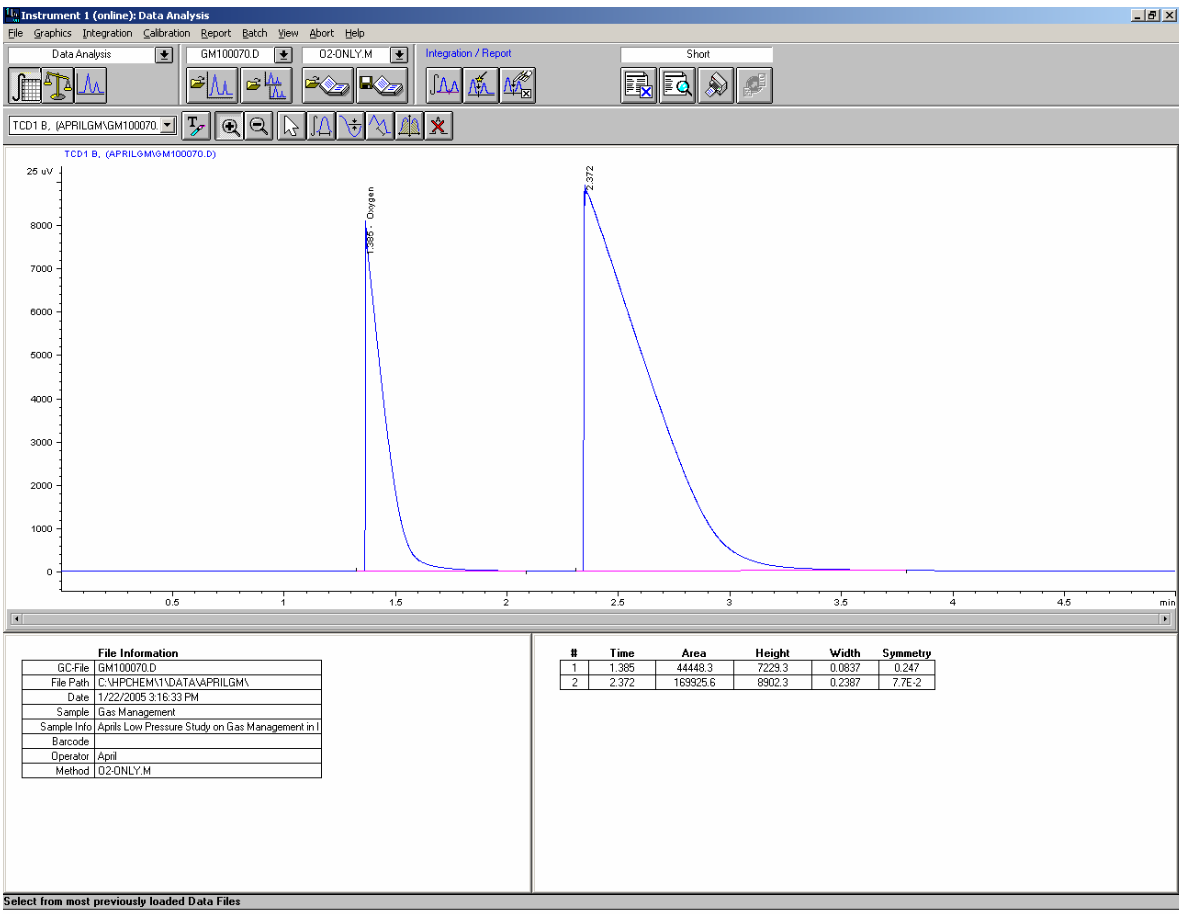

Figure 29 – Screen capture of the GC results obtained from the O_2 analysis during trial 1 of experiment 1. The first peak is O_2 (area = 44448.3) and the second peak is N_2 (area = 169925.6).

The GC reports concentration as an area. In this case, this GC was selective for O_2 and N_2. The O_2 concentration was obtained by dividing the O_2 area by the sum of the O_2 and N_2 areas. During trial 1 of experiment 1, the GC reported 20.73% O_2. Experimental conditions at the time the sample was drawn were such that the mixture contained 34.47kPa O_2 with a total pressure of 175.89kPa. If the percentage obtained from the GC is multiplied by the total pressure during the time of the experiment, the O_2 partial pressure is 36.46kPa. The goal was to maintain the partial pressure between 35.7kPa and 37.8kPa. The GC results are within these limits, but the experimental conditions within the mixing tank suggest that the partial pressure was slightly lower than the lowest tolerance limit. However, the analysis results of trial 1 of experiment 1 in the Mars Dome agreed with the GC findings with respect to the O_2 partial pressure being within the defined limits of control.

A second trial was run to verify the results of the first trial. Figure 30 refers to the O_2 concentration returned from the GC for this trial.

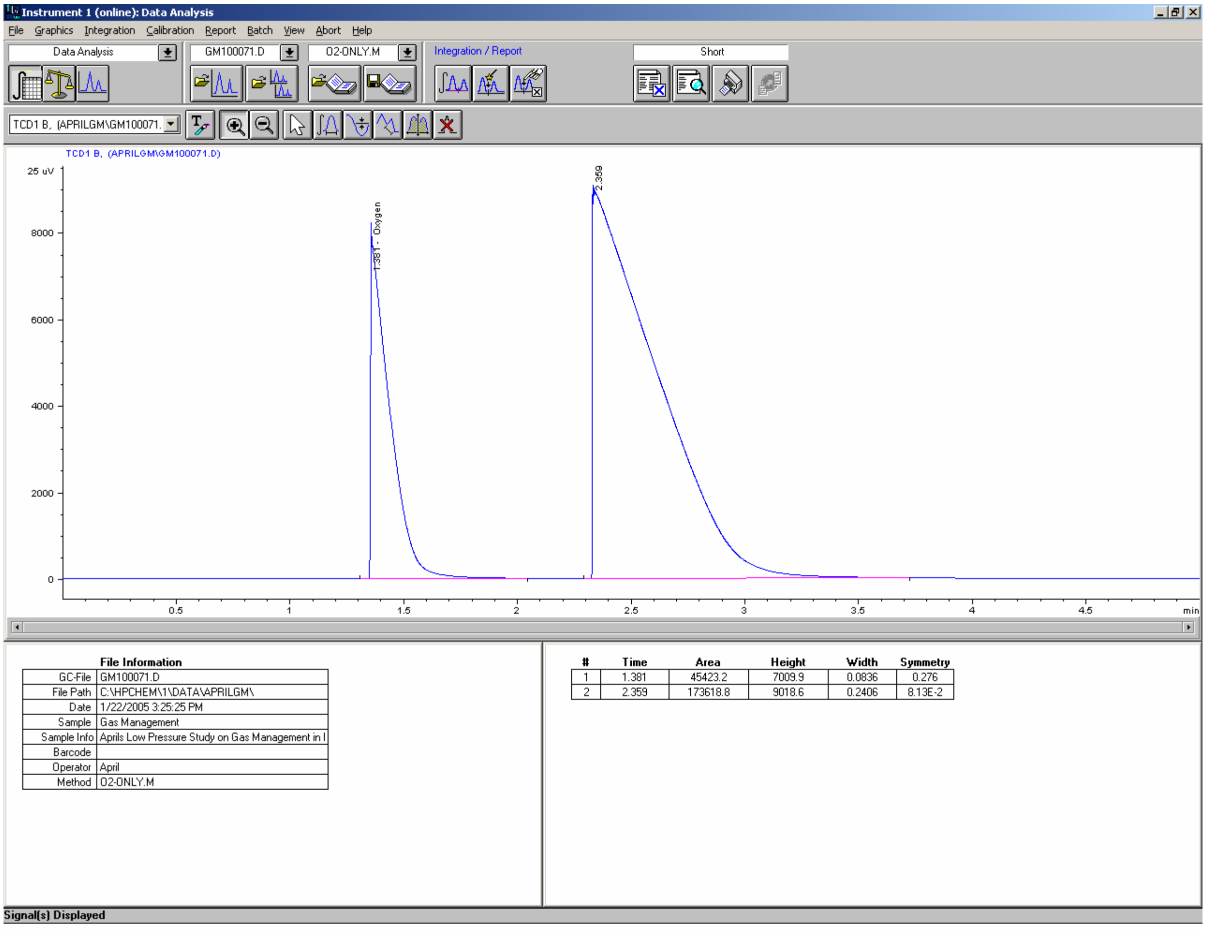

Figure 30 - GC results obtained from the O_2 analysis during trial 2 of experiment 1. The first peak in the figure is O_2 (area = 45423.2) while the second peak is N_2 (area = 173618.8).

Here again, the percent O_2 in the sample was obtained by dividing the O_2 area by the total area. The O_2 percent did not change from the results of the first trial which was 20.73%.

For experiment 2, the system reported an O_2 partial pressure of 37.11kPa and a total pressure of 175.63kPa. Figure 30 shows the results of the GC analysis during trial 1 of the second experiment.

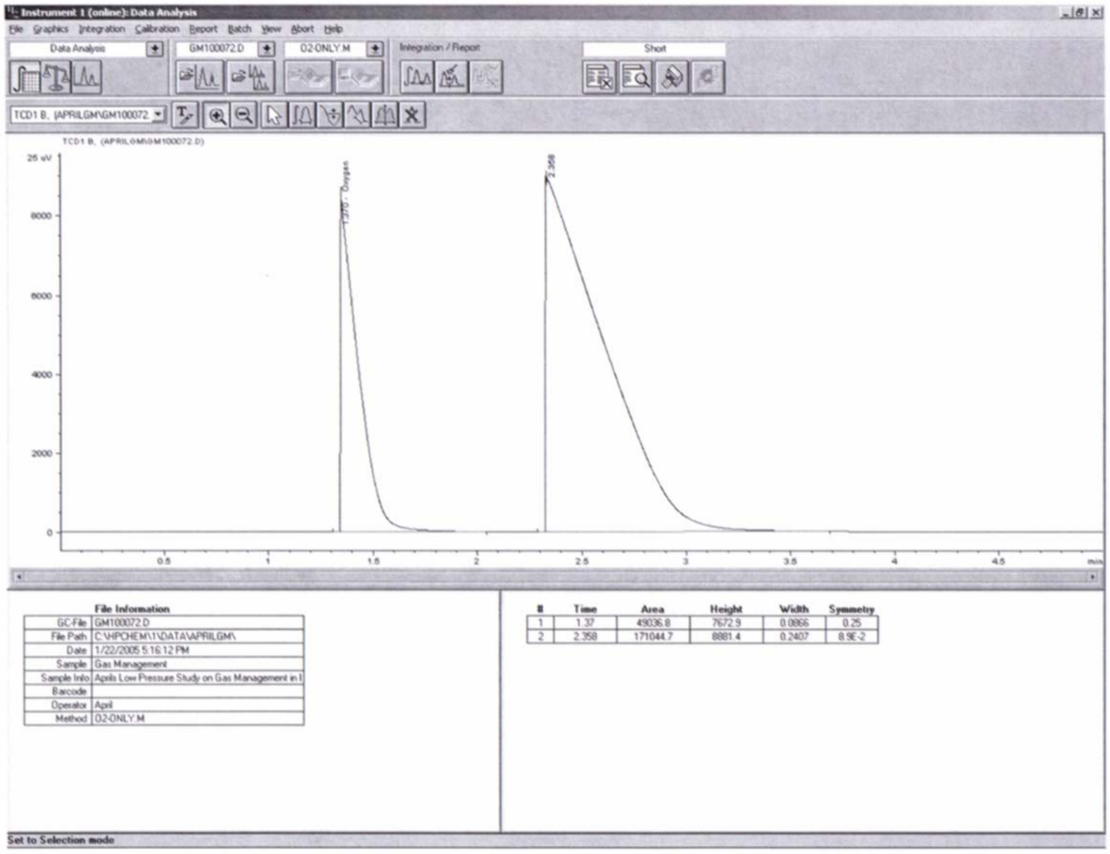

Figure 31 - GC results obtained from the O_2 analysis during trial 1 of experiment 2. The first peak is O_2 (area = 49036.8) and the second peak is N_2 (area = 171044.7).

The O_2 percent reported by the GC was 22.28%. When multiplied by the total pressure of the system, the O_2 partial pressure obtained was 39.13kPa. This is higher than the 37.11kPa reported by the system. While the system partial pressure falls within the O_2 tolerance limits, the partial pressure calculated using the GC results does not. The GC results substantiate those in figure 28 which suggest that the O_2 partial pressure was indeed above its setpoint in both the mixing tank and the Mars Dome.

Figure 32 is a screen capture of the GC results of the O_2 percentage during the second trial of the second experiment.

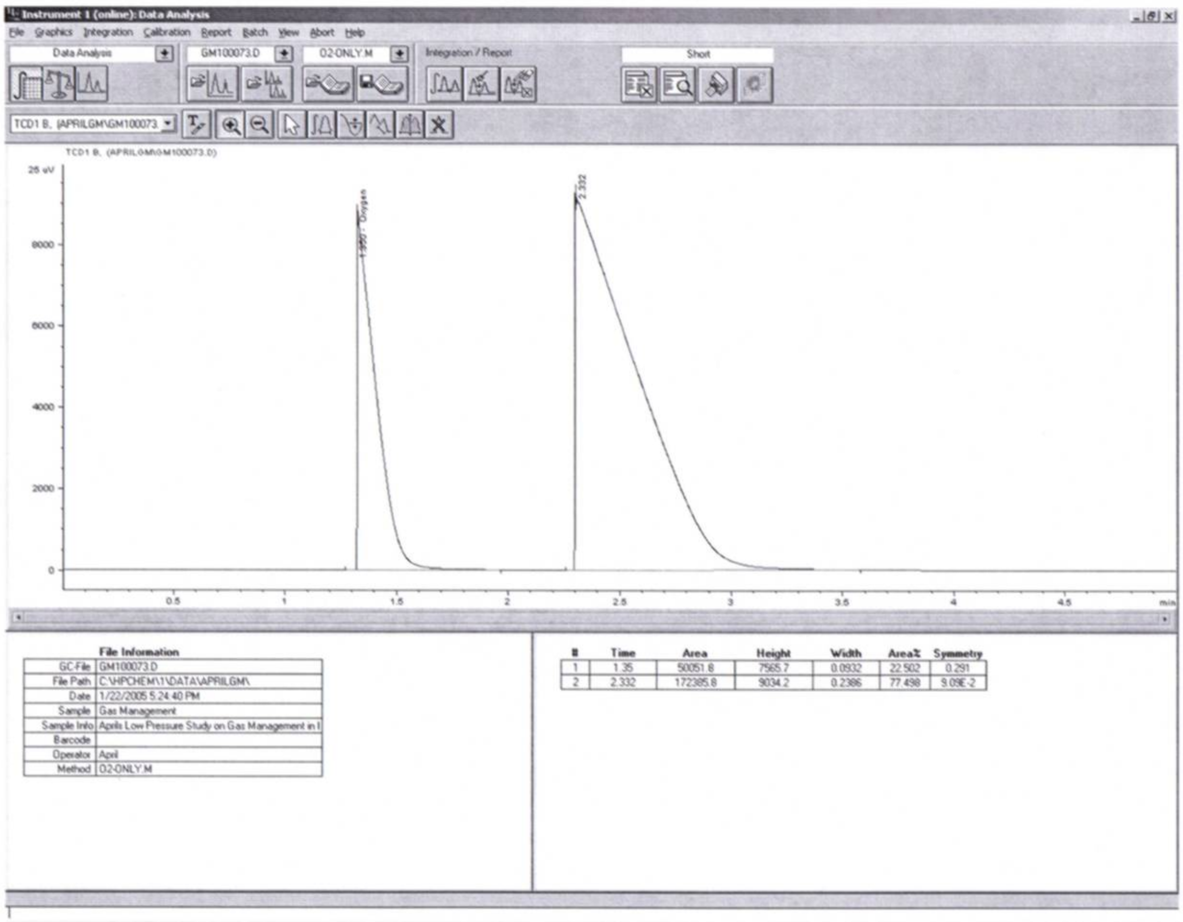

Figure 32 - GC results obtained from trial 2 of experiment 2 during the O_2 analysis. The first peak is O_2 (area = 50051.8) and the second peak is N_2 (area = 172305.8).

The GC results reported an O_2 percentage of 22.50%. The partial pressure in the system based on the percentage was 39.51kPa. The results are consistent with those obtained during trial 1 of the second experiment. Therefore, the analysis from this trial agreed with figure 28.

The error between the GC results and the system results could be due to the effects of pressure on the O_2 sensor. During testing, it was discovered that the O_2 sensor reported erroneous values at pressures above 185kPa. The analog Opto module would return a value of -37268 which signifies that there was an electrical disconnection. The pressure at the time of the reading was approximately 185kPa. That sensor was replaced with a different sensor of the same model. Again, when the pressure reached 185kPa, an error value was returned. The total pressure was decreased as a means of troubleshooting the sensor failure. Once the pressure was below 185kPa, the sensor returned normal values. Thus, the total pressure setpoint during all experiments was 175kPa. However, this is not to say that the values were not affected by pressure. Also, if the volume of the sample injected into the GC was not exactly the same during both trials, the concentration reported would vary proportionately to the injection volume.

The O_2 flow rate setpoint was 5SLPM. The time at which the flow rate was higher than its setpoint was most likely due to an increased pressure differential. This would have occurred at the beginning of experiment 2 when the total pressure in the mixing tank was well below its setpoint of 175kPa after having been evacuated to fill the Mars Dome. Figure 33 is a graph of the O_2 flow rate and its setpoint.

DFC Flow Rate

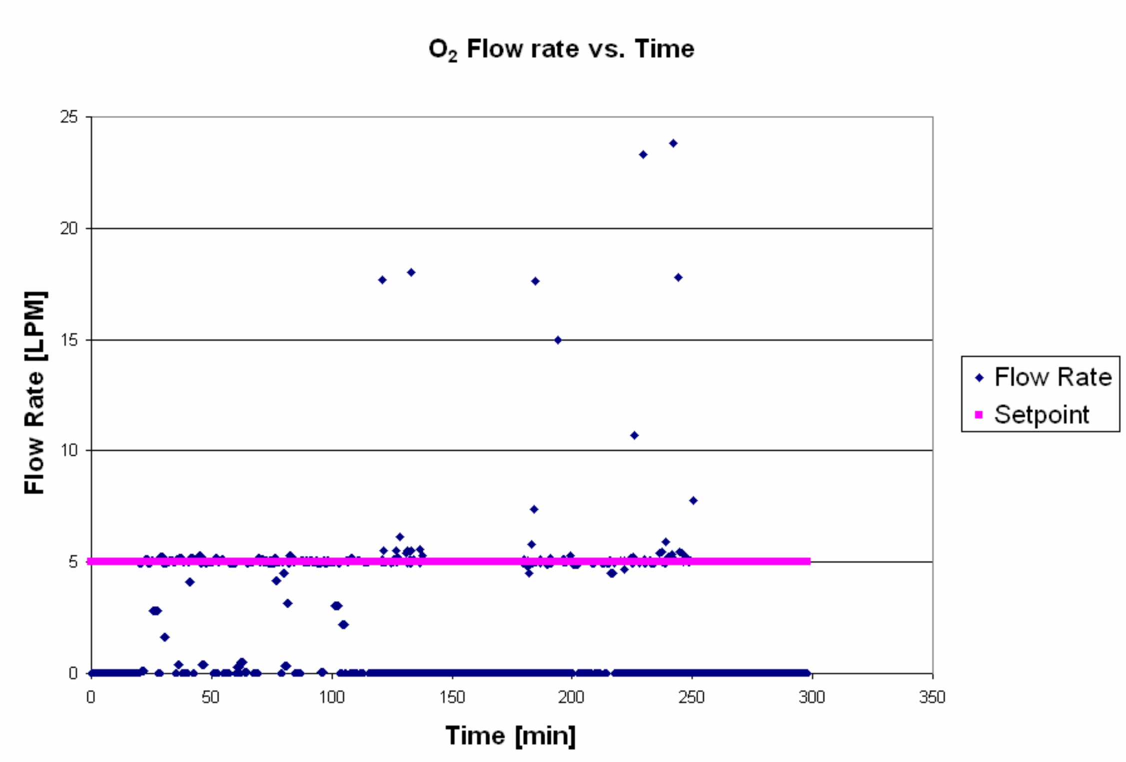

Figure 33 - O_2 flow rate vs time. The flow rate was measured when the O_2 solenoid was opened and gases flowed into the mixing tank. The pink data points were the O_2 flow rate setpoint and the blue points were the actual reading returned from the DFC sensor.

N_2 Analysis

<u>Partial Pressure</u>

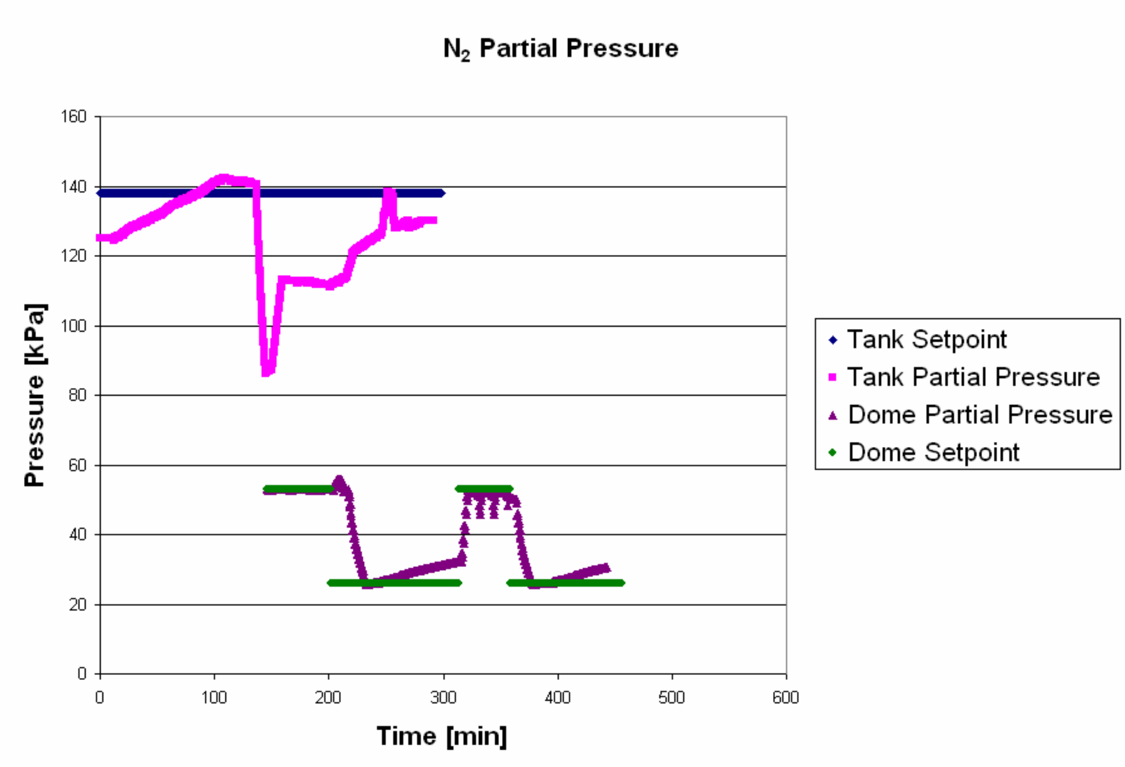

Figure 34 – Mixing tank N_2 partial pressure. The N_2 partial pressure in the mixing tank was plotted along with its setpoint against time during both experiments. The plot also shows the N_2 partial pressure in the Mars Dome during both trials of both experiments.

Figure 34 shows how the partial pressure of N_2 changes with respect to its setpoint in both the mixing tank and the dome. The sharp decreases in the mixing tank partial pressure correspond to the evacuation of the tank and the filling of the dome. The total pressure was allowed to decline until it was slightly above ambient to ensure that the mixture in the dome was the same as that in the tank. This was done twice, once for each experiment. The N_2 setpoint for experiment 1 was 138.16kPa and for experiment 2 it was 138.07kPa.Table 9 is a description of the statistical error computed by subtracting the actual partial pressure from its setpoint for experiment 1.

Table 9. Statistical Summary Error Associated With the Mixing Tank N_2 Partial Pressure During Both Experiments 1 and 2.

Statistical Error Summary for Mixing Tank N_2 Partial Pressure		
	Experiment 1	Experiment 2
Mean	0.546	0.099
Range	1.267	1.354
Minimum	2.0E-03	-0.267
Maximum	1.269	1.086

During experiment 1, the mean error value was 0.546kPa. Because this value is positive, it implied that N_2 was typically below its setpoint. Looking at figure 34, N_2 was slightly above its setpoint during experiment 1 in the mixing tank. The range was 1.267kPa and the maximum and minimum values were 1.269kPa and 0.002kPa respectively. The N_2 partial pressure was to remain between 134.21kPa and 142.11kPa which corresponds to ±3.95kPa of its setpoint. Although the N_2 partial pressure was above its setpoint during the first experiment, it remained between 134.21kPa and 142.11kPa and thus adequate control was achieved during experiment 1.

For experiment 2, the mean error was 0.099kPa. Here again, this would imply that N_2 was slightly above its setpoint. Looking at figure 34, this is quite possibly the case. The range was 1.354kPa and the maximum and minimum values were 1.086kPa and -0.267kPa respectively. The limits of operation were slightly different for experiment 2 than experiment 1 because the CO_2 partial pressure was increased. To compensate for this change, the N_2 partial pressure was decreased. The N_2 partial pressure was to remain between 134.13kPa and 142.02kPa. The setpoint was 138.07kPa. The plot of the N_2 partial pressure in the mixing tank in figure 33 suggests that N_2 was at or above its setpoint. The numbers from table 9 of experiment 2 support figure 34. During experiment 2, adequate control of N_2 was achieved because the partial pressure remained within ±3.95kPa of the setpoint.

While the tank operated at a total pressure of 185kPa, the dome was maintained at either 67kPa or 33kPa. This set of pressures was tested during each experiment. The graph shows that the dome started out at 67kPa. Then the pressure was decreased to 33kPa and the process repeated under the new experimental conditions. Table 10 refers to the error associated with the N_2 partial pressure in the dome during experiment 1 at 67kPa.

Table 10. Statistical Summary Error Associated With the Mars Dome N_2 Partial Pressure During Experiment 1. Two trials were run during experiment 1 with the total pressure during trial 1 being 67kPa and 33kPa during trial 2.

Experiment 1 Statistical Error Summary for N_2 Partial Pressure

	67kPa	33kPa
Mean	0.021	0.054
Range	0.726	0.940
Minimum	-0.278	-0.512
Maximum	0.447	0.428

During trial 1, the total pressure in the Mars Dome was maintained at 67kPa. The N_2 setpoint was 52.89±1.51kPa. The mean error value was 0.021kPa and the range was 0.726kPa. The maximum error was 0.447kPa and the minimum error was -0.278kPa. The data plotted in figure 34 of the N_2 partial pressure in the Mars Dome during trail 1 suggests that the N_2 partial pressure remained within the operational limits of control and thus the algorithm achieved adequate control of N_2.

For trial 2, the total pressure in the Mars Dome was reduced to 33kPa. This corresponded to a N_2 partial pressure of 26.05kPa. The N_2 partial pressure was to remain within ±0.744kPa. The mean error valued during trial 2 was 0.054kPa and the range was 0.940kPa. The maximum error was 0.428kPa and the minimum error was -0.512kPa. The positive error value would suggest that the N_2 partial pressure in the Mars Dome during the second trial was slightly above its setpoint. Figure 34 implies that instead there was some oscillation around the setpoint. In the figure, the N_2 partial pressure started out above its setpoint, fell slightly below the setpoint, and then ascended above the setpoint. Even with these variations, the N_2 partial pressure remained within ±0.744kPa of the setpoint. Here again, the algorithm maintained control of the N_2 partial pressure.

Table 11. Statistical Summary Error Associated With the Mars Dome N_2 Partial Pressure During Experiment 2.

Experiment 2 Statistical Error Summary for N_2 Partial Pressure

	67kPa	33kPa
Mean	0.260	0.129
Range	0.487	0.709
Minimum	0.052	-0.277
Maximum	0.540	0.431

During experiment 2, there were two trials run. Just as in experiment 1, they were run at total pressures of 67kPa and 33kPa respectively in the Mars Dome. The N_2 partial pressure changes slightly between the two experiments as it was decreased from 78.95%N_2 to 78.90%N_2 to compensate for the increase in the CO_2 partial pressure. During experiment 1, the N_2 setpoint partial pressure was 52.86±1.510kPa. The mean error value was 0.260kPa. The range was 0.487kPa with maximum and minimum error values of 0.540kPa and 0.052kPa, respectively. The fact that the mean error value was positive implied that the N_2 partial pressure was slightly above its setpoint during the first trial. Figure 34 shows that there was some oscillation around the setpoint. Taking these oscillations into consideration, the algorithm maintained adequate control because the N_2 partial pressure remained within ±1.510kPa of the setpoint. These findings were consistent with those of the N_2 partial pressure analysis carried out in the mixing tank during experiment 2.

For trial 2 of experiment 2, the mean error value was 0.129kPa and the range was 0.709kPa. The maximum and minimum error values were 0.431kPa and -0.277kPa respectively. Here again, these values suggest that the N_2 partial pressure in the Mars Dome was above its setpoint. The data seemed to fluctuate around the setpoint as in figure 34. The total pressure at the time of trial 2 was 33kPa. This corresponded to an N_2 partial pressure of 26.037kPa. The N_2 partial pressure was allowed to vary within ±0.743kPa of this setpoint. Figure 34 shows that the N_2 partial pressure in the Mars Dome remained within these limits of operation and thus sufficient control of N_2 was achieved. These findings were consistent with those of the N_2 partial pressure analysis carried out in the mixing tank during experiment 1.

<u>GC Data</u>

The GC used to analyze the N_2 content was also used to analyze O_2. Figures 29 – 32 report both the percent O_2 and N_2 in an injection sample. The percent N_2 in a sample was obtained by first calculating the O_2 percentage and subtracting if from 100.

During both trials 1 and 2 of experiment 1, the GC reported 79.26% N_2. The partial pressure of N_2 based on these results was calculated and found to be 139.42kPa. The system reported an N_2 partial pressure of 141.32kPa. Both of these numbers are within the N_2 tolerance limits of 134.25kPa and 142.11kPa. However, figure 34 suggests that the N_2 partial pressure was below its setpoint in the mixing tank. While the results of the GC analysis do not support the analysis of the N_2 partial pressure in the mixing tank, they do support those associated with the N_2 partial pressure in the Mars Dome. Those findings implied that the N_2 partial pressure remained within the operational limits.

The GC reported 77.72% N_2 during trial 1 of experiment 2. When multiplied by the total pressure during the second experiment, the partial pressure obtained was 136.50kPa. The system reported a N_2 partial pressure of 138.34kPa which was higher than the partial pressure calculated based on the GC analysis. Both of these values fall between the N_2 tolerance limits of 134.13kPa and 142.02kPa. These numbers substantiate figure 34. During the second trial, the N_2 percentage was 77.50%. This corresponded to a partial pressure of 136.11kPa. Here again, the system partial pressure is higher than that based on the GC results, but the numbers suggest that adequate control was achieved.

DFC Flow Rate

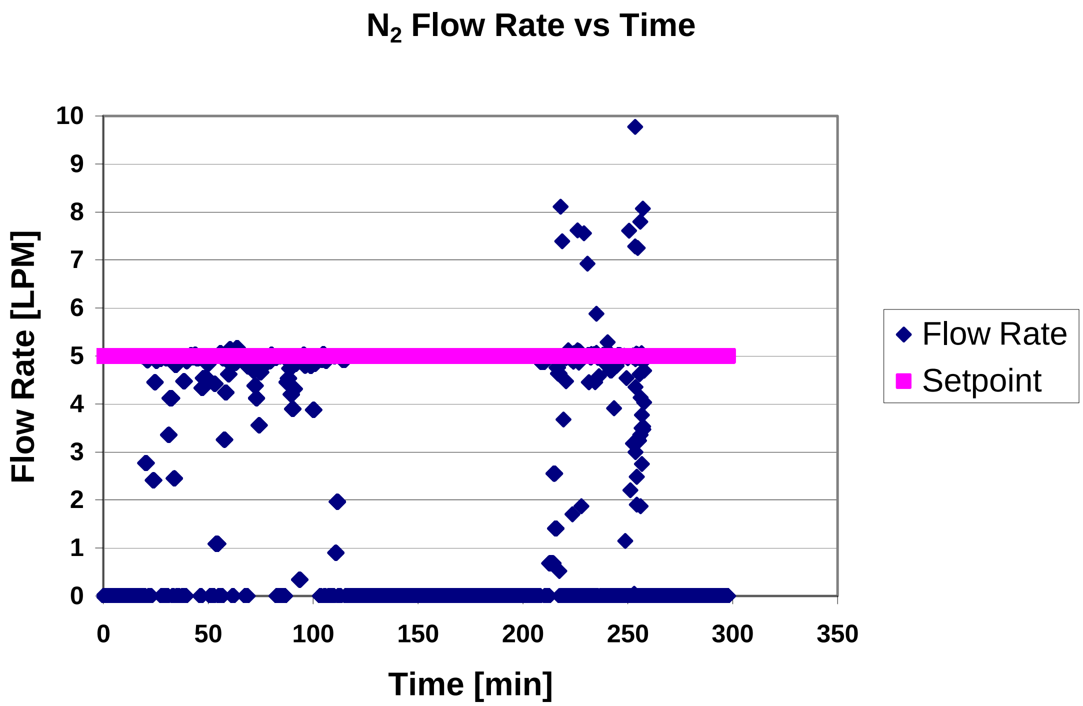

Figure 35 – N_2 flow rate vs time. The N_2 flow rate (SLPM) was plotted against time (min). The setpoint was 5 SLPM.

The N_2 flow rate setpoint was 5SLPM. The times at which the DFC reported values above the setpoint seems to have occurred at the beginning of experiment 2 when the mixing tank was well below its setpoint due to having been evacuated to fill the Mars Dome. Those times when the flow rate was below its setpoint probably occurred when the N_2 solenoid was closing and the algorithm happened to read the DFC sensor at this time.

CO_2 Analysis

<u>Partial Pressure</u>

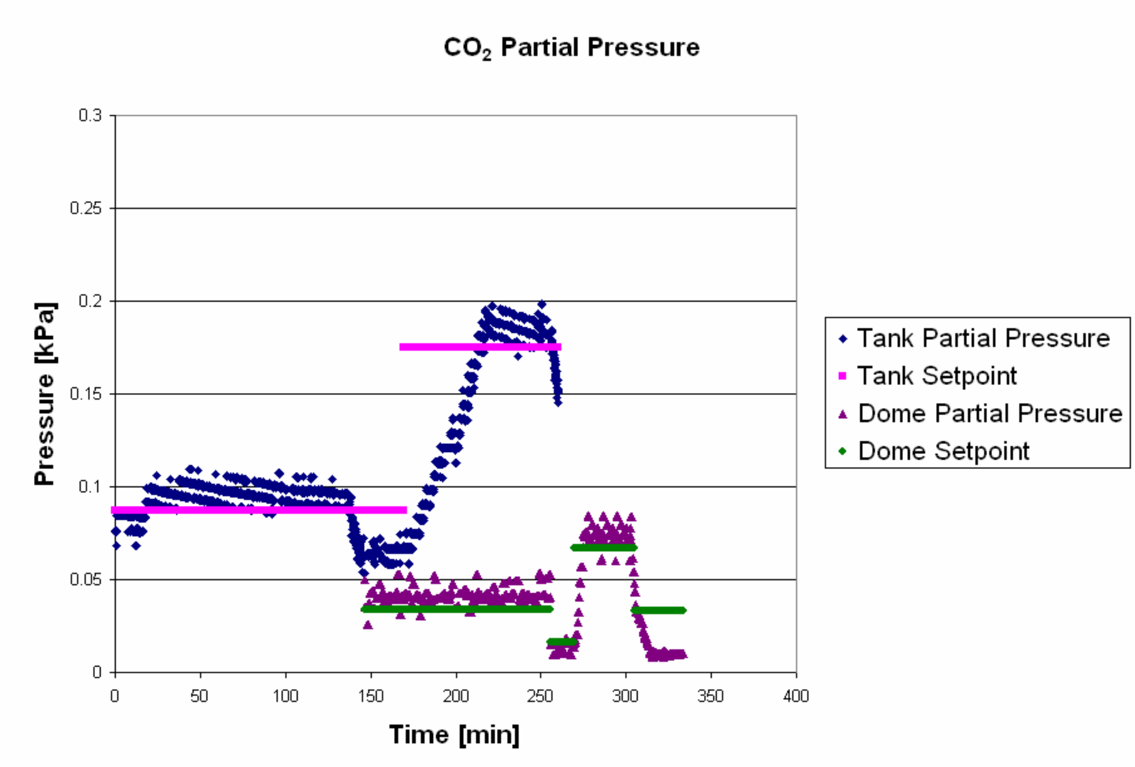

Figure 36 – Mixing tank CO_2 partial pressure. This figure plots the CO_2 partial pressure (kPa) in the mixing tank along with its setpoint against time during both experiments. It also shows the CO_2 partial pressure in the Mars Dome for both trials of both experiments.

Figure 36 depicts the CO_2 partial pressure in the mixing tank and in the dome during experiments 1 and 2. At the beginning of experiment 1, CO_2 was slightly below its setpoint, and eventually was maintained just above 0.05% which was the setpoint. During experiment 2, the percent of CO_2 was increased to 0.10%. The sharp increase in the graph shows the rise in CO_2 as the setpoint had been changed. The declines in the partial pressure of CO_2 in the tank were a result of the tank being evacuated to fill the dome. Table 12 describes the error associated with the CO_2 partial pressure in the mixing tank during experiment 1 and experiment 2.

Table 12. Statistical Summary Error Associated with the Mixing Tank CO_2 Partial Pressure During Experiment 1.

Statistical Error Summary for Mixing Tank CO_2 Partial Pressure

	Experiment 1	Experiment 2
Mean	-7.00E-03	-8.00E-03
Range	0.053	0.033
Minimum	-0.023	-0.022
Maximum	0.029	0.011

During the first experiment the total pressure setpoint in the mixing tank was 175kPa. At this time, the CO_2 setpoint in the gas mixture was 0.05% or 0.087kPa. The mean error value was -0.007kPa. This value being negative implied that the CO_2 partial pressure was above its setpoint during the first experiment. This supports figure 36 which shows that the CO_2 partial pressure was indeed above its setpoint. The range during experiment 1 was 0.053kPa with a corresponding maximum and minimum error of 0.029kPa and -0.023kPa, respectively. As long as the CO_2 partial pressure remained within ±0.002kPa of the setpoint, the algorithm would have achieved adequate control of CO_2. Looking at figure 36, adequate control was not achieved. The mean CO_2 partial pressure was 0.097kPa. This may be the result of the actual lag time of the sensor versus that reported by the manufacturer which was 20 seconds. From personal conversations with other researchers (Fowler, P.A. and Richards, J. 2005) the sensor response time was more like 30 seconds. The results of the CO_2 partial pressure analysis in table 12 agreed with the plot of the CO_2 partial pressure in the mixing tank during experiment 1.

For experiment 2, the mean error was -0.008kPa. The range reported in table 12 was 0.033kPa which would have been associated with a maximum and minimum error of 0.011kPa and -0.022kPa respectively. The CO_2 setpoint for experiment 2 was 0.01% which corresponded to 0.175kPa. As long as the CO_2 partial pressure remained within ±0.005kPa of the setpoint, adequate control of CO_2 would have been achieved. The negative value for the mean error implied that the CO_2 partial pressure was typically above its setpoint. These findings support those of figure 36 which show that CO_2 was indeed above its setpoint in the mixing tank during experiment 2. With respect to the operational limits defined, the algorithm did not achieve adequate control of CO_2. However, because this system is being designed for hypobaric plant growth chambers, the actual limits obtained are adequate.

Table 13. Statistical Summary Error Associated With the Mars Dome CO_2 Partial Pressure During Experiment 1. There were two trial run during experiment 1 with the total pressure being 67kPa during trial 1 and 33kPa during trial 2.

Experiment 1 Statistical Error Summary for CO_2 Partial Pressure

	67kPa	33kPa
Mean	-7.0E-03	4.0E-03
Range	0.027	8.0E-03
Minimum	-0.019	-1.0E-03
Maximum	8.0E-03	7.0E-03

During the first trial of experiment 1, the mean error associated with the CO_2 partial pressure in the Mars Dome was -0.007kPa and the range was 0.027kPa. The maximum and minimum error values were 0.008kPa and -0.019kPa, respectively. The CO_2 partial pressure setpoint was 0.033kPa. The fact that the mean error value was negative implied that the CO_2 partial pressure was above its setpoint during the first trial. Looking at figure 36, this was indeed the case. This finding also agreed with the analysis of the CO_2 partial pressure in the mixing tank, which pointed to the fact that the CO_2 was above its setpoint. With respect to the algorithm, adequate control was not achieved because the CO_2 partial pressure remained outside of the predefined operational limits of 0.033±0.0009kPa.

During trial 2, the percent CO_2 remained unchanged from the 0.05% of trial 1 and the mean error was 0.004kPa. The range was 0.008kPa with a maximum error of 0.007kPa and a minimum error of -0.001kPa. The fact that the mean error was positive suggests that the CO_2 partial pressure was below its setpoint. The total pressure for trial 2 was 33kPa and the corresponding CO_2 partial pressure setpoint was 0.016kPa. Sufficient control was not achieved according to the predetermined operational limits because the CO_2 partial pressure was often times outside of 0.016±4.0E-03kPa. These findings support the plot of the CO_2 partial pressure in the Mars Dome during trial 2 in figure 36 which show the CO_2 partial pressure being below its setpoint. They do not however agree with the results of the analysis of the CO_2 partial pressure in the mixing tank which pointed to the CO_2 partial pressure being above its setpoint. This discrepancy may be due to the effects of pressure on the CO_2 sensor.

Table 14. Statistical Summary Error Associated With the Mars Dome CO_2 Partial Pressure During Experiment 2. There were two trials run during experiment 2, during which the total pressure was 67kPa and 33kPa.

Experiment 2 Statistical Error Summary for CO_2 Partial Pressure		
	67kPa	33kPa
Mean	-7.0E-03	5.0E-04
Range	0.023	0.015
Minimum	-0.017	-0.010
Maximum	6.0E-03	4.0E-03

During the second experiment, the CO_2 concentration was increased from 0.05% CO_2 to 0.10% CO_2. The CO_2 partial pressure setpoint in the Mars Dome during the second experiment was 0.067±0.002kPa. The mean error was -0.007kPa and the range was 0.023kPa. The maximum error was 0.006kPa and the minimum error was -0.017kPa. The fact that the mean error value was negative suggested that the CO_2 partial pressure was above its setpoint. According to figure 36, this was indeed the case. The plot of the CO_2 partial pressure in the Mars Dome in figure 36 during the first trial of the second experiment shows that CO_2 was above its setpoint. This is consistent with the results obtained from experiment 2 in the mixing tank. Adequate control was not achieved. This may be because the lag time needs to be increased.

For trial 2, the mean error was 5.0E-03kPa and the range was 0.0150kPa. The maximum and minimum error values were 0.004kPa and -0.010kPa, respectively. The

CO_2 partial pressure setpoint was 0.033±0.001kPa. The positive mean error value implied that the CO_2 partial pressure was below its setpoint. This is substantiated by the plot of the CO_2 partial pressure in the Mars Dome during trial 2 of experiment 2 in figure 36. These findings are inconsistent with those from experiment 2 in the mixing tank which suggested that the CO_2 partial pressure was above its setpoint. This discrepancy may be caused by the effects of pressure on the CO_2 sensor, especially when it is considered that the same phenomenon was observed during the second trial of the first experiment. Adequate control of the CO_2 partial pressure was not achieved according to the predetermined operational limits.

<u>GC Data</u>

A GC was used to verify the CO_2 concentration during the experimental trials. There were two experiments conducted. The CO_2 setpoint during experiment 1 was 0.05%. During experiment 2, the percentage was increased to 0.10%CO_2. Figure 37 is a screen capture from the GC used to analyze the CO_2 content from the first trial of the first experiment.

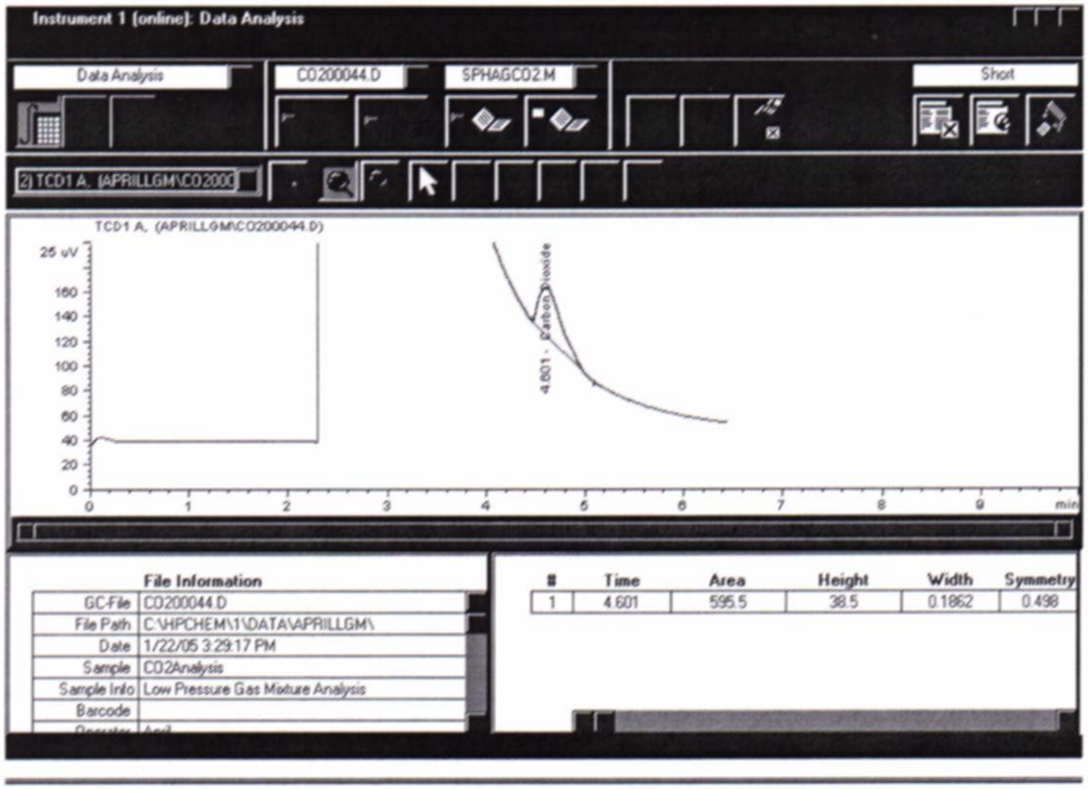

Figure 37 – GC CO_2 analysis during trial 1 of experiment 1. It shows the CO_2 peak (area = 595.5) on the side of a larger N_2 peak. It also provides the area of the peak which is associated with the CO_2 concentration.

The GC reports CO_2 concentration in parts per million (ppm). During this particular trial the CO_2 concentration was 595.5ppm or 0.059% CO_2. When this percentage is multiplied by the total pressure during the time of the experiment (175.895kPa) the CO_2 partial pressure is equal to 0.105kPa. Therefore, the CO_2 concentration was slightly higher than its setpoint. At the time the sample was taken, the CO_2 partial pressure was 0.093kPa which corresponds to 0.053%. Thus, the GC results agree with the conditions recorded with respect to the CO_2 concentration being slightly above its setpoint. These results also agree with the results of the CO_2 partial pressure analysis in the mixing tank presented in figure 36. The goal was to maintain CO_2 between 0.085kPa and 0.09kPa. The difference between the actual partial pressure and its maximum tolerance limit is negligible considering that plants are capable of normal growth at such a CO_2 concentration. However, with respect to the CO_2 setpoint, the algorithm did not obtained adequate control of CO_2 during trial 1 of experiment 1.

Figure 38 is a screen capture of the GC results for the second trial of the first experiment.

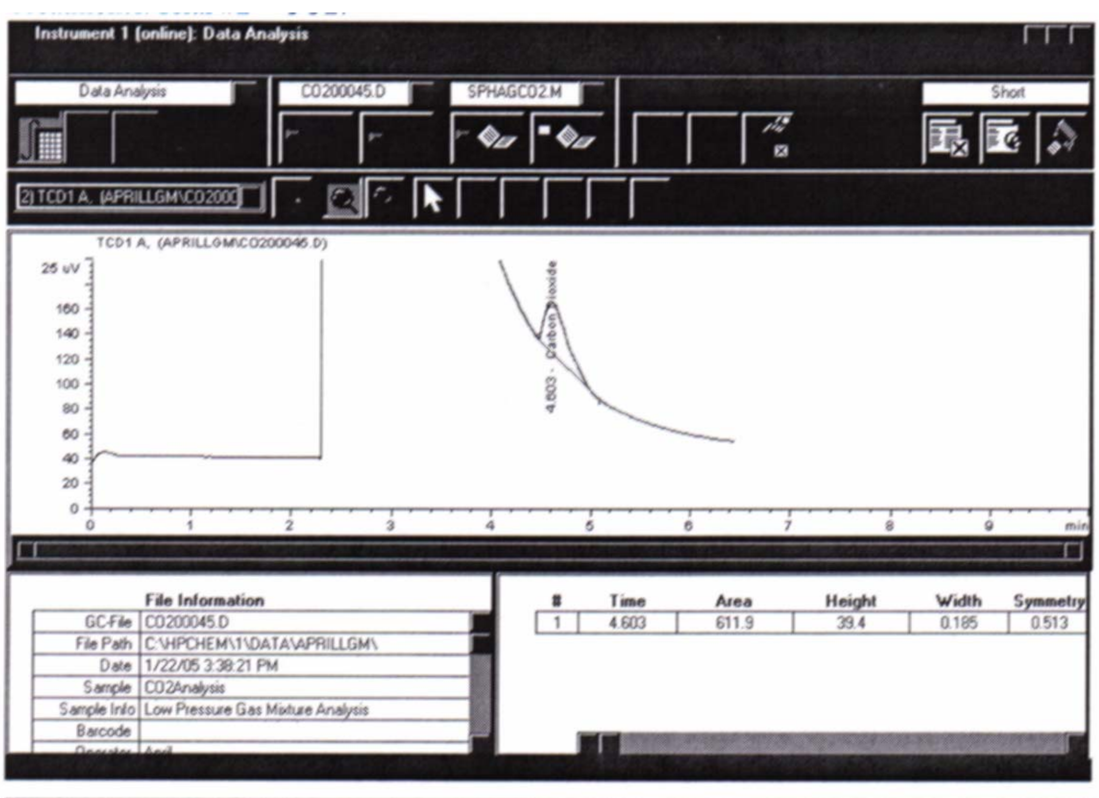

Figure 38 - GC CO_2 analysis from trial 2 of experiment 1. It shows the CO_2 peak (area = 611.9) as a part of a larger N_2 peak. The CO_2 concentration is provided in the form of an area that is related to the size of the peak.

During trial 2 of experiment 1 it was reported the GC reported the CO_2 concentration to be 611.9ppm or 0.061% CO_2. When this percentage is multiplied by the total pressure at the time the sample was taken, the CO_2 partial pressure is 0.107kPa. Here again, the goal was to maintain the CO_2 partial pressure between 0.085kPa and 0.09kPa The partial pressures obtained were outside of this range and thus adequate control was not obtained. These results were consistent with those from table 12 which suggested that the CO_2 partial pressure was above its setpoint in the mixing tank. However, they are not consistent with those of table 13 which implied that the CO_2 partial pressure was below its setpoint in the Mars Dome during the second trial of experiment 1.

Figure 39 refers to the CO_2 concentration reported by the GC during the first trial of the second experiment.

As with experiment 1, two trials were run for experiment 2. The conditions within the tank at the time sample was taken correspond to a total pressure of 175.63kPa and a CO_2 partial pressure of 0.186kPa. The results show a CO_2 concentration of 1102.5ppm or 0.11% CO_2. If multiplied by the total pressure in the tank during the time the sample was taken, a CO_2 partial pressure of 0.193kPa is obtained.

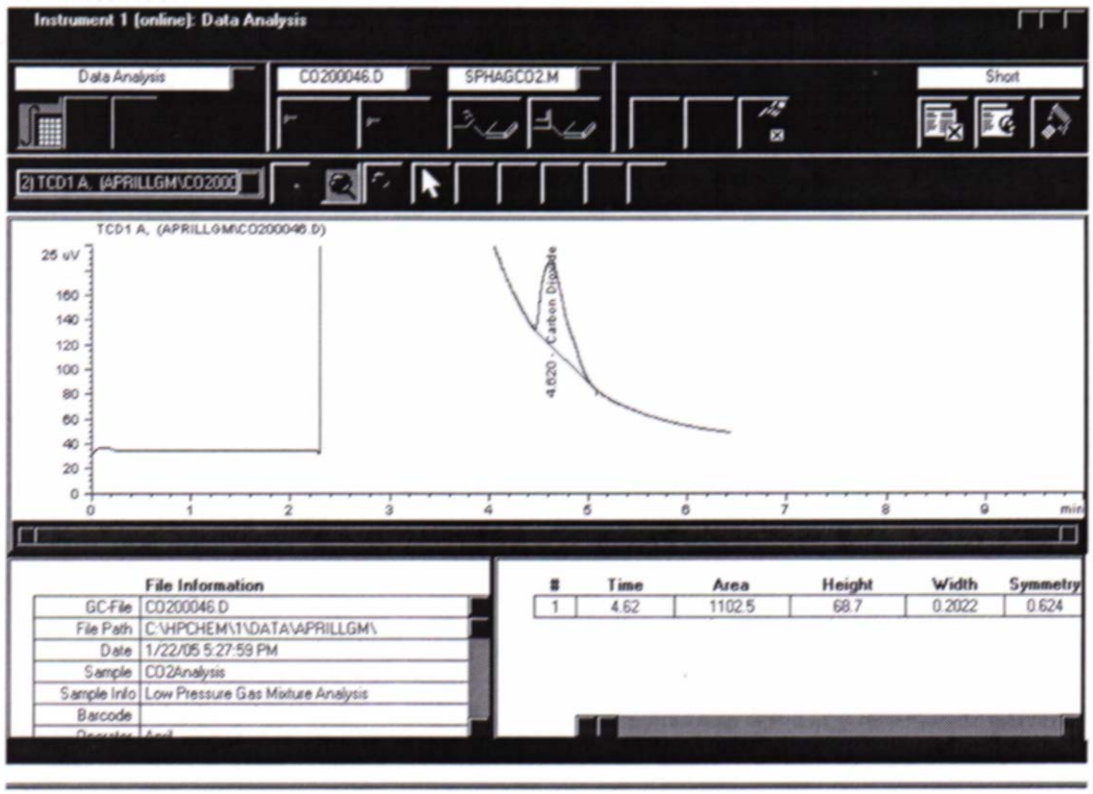

Figure 39 – GC CO_2 analysis from trial 1 of experiment 2. The CO_2 peak (area = 1102.5) is a part of a larger N_2 peak. The CO_2 concentration was provided as an area.

These results substantiate those of table 12 in which the CO_2 partial pressure in the mixing tank was above its setpoint. This was illustrated graphically in figure 36. The findings also agree with those of table 14 which implied that the CO_2 partial pressure in the Mars Dome was above its setpoint during trial 1 of experiment 2. The goal was to maintain the CO_2 partial pressure between 0.17kPa and 0.18kPa, but the partial pressures obtained were outside of these limits and thus sufficient control was not achieved.

Figure 40 refers to the concentration of CO_2 obtained during the second trial of the second experiment.

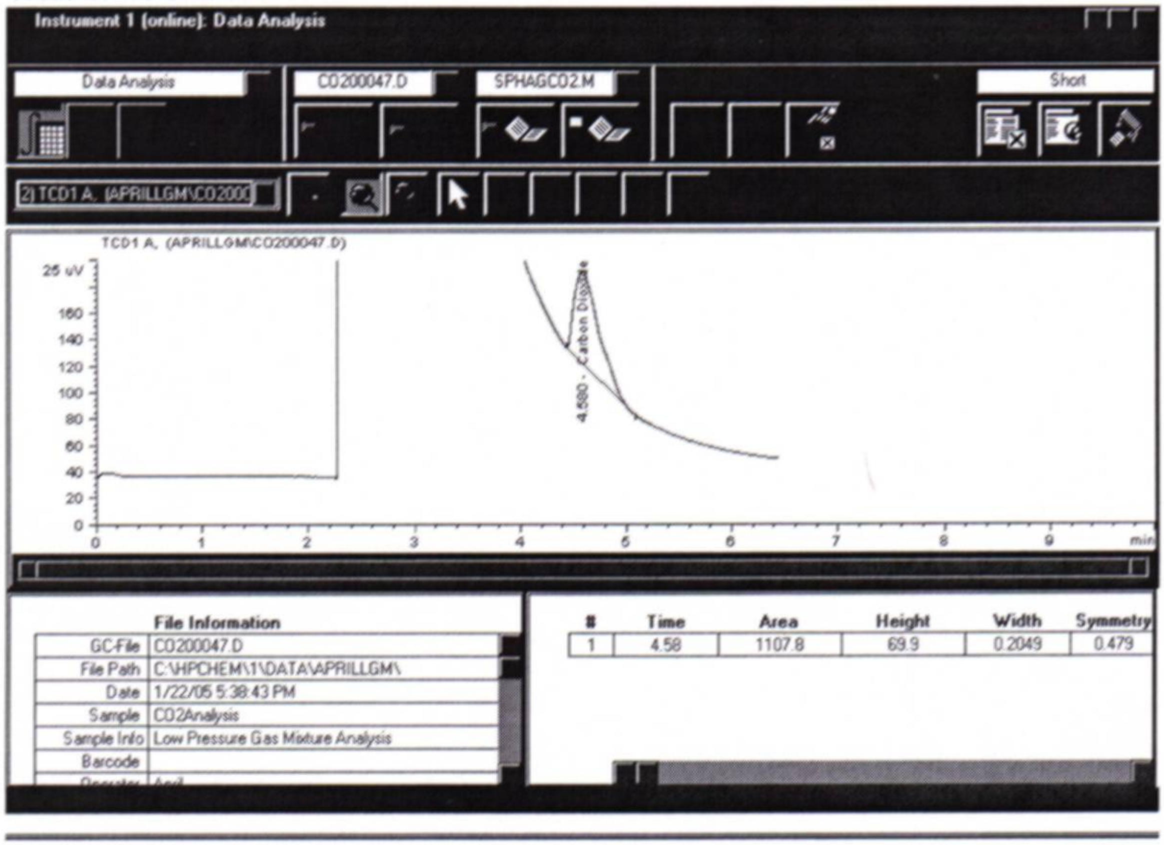

Figure 40 - GC CO_2 analysis from trial 2 of experiment 2. The CO_2 peak (area 1107.8) is on the side of a larger N_2 peak. The CO_2 concentration was related to the area of the CO_2 peak.

During the second trial of experiment 2, the concentration was 1107.8ppm or 0.11% CO_2. These results agree with those of the first trial of the second experiment. All of the conclusions drawn from the analysis of CO_2 during trial 1 of experiment 2 still hold with the exception of the partial pressure of CO_2 in the Mars Dome. According to table 14, the CO_2 partial pressure was below its setpoint. The same situation was observed for the CO_2 partial pressure in the Mars Dome during the second trial of experiment 1. Here again, such low pressures may have adversely affected the performance of the CO_2 sensor.

DFC Flow Rate

Figure 41 is a plot of the CO_2 flow rate against time. The setpoint was 5SMLPM. Each time a value greater than zero was returned, the CO_2 solenoid was open and CO_2 was allowed to flow into the mixing tank.

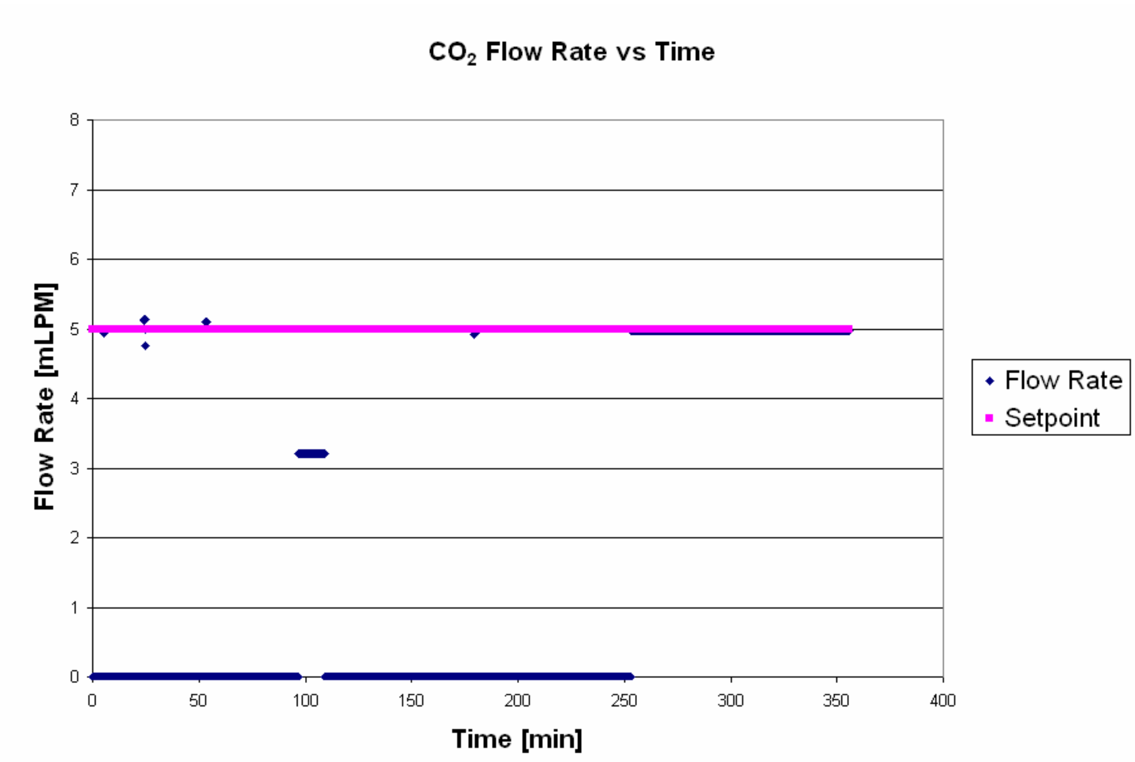

Figure 41 - CO_2 flow rate (standard milliliters per minute) vs. time (min). These are the values that were returned from the CO_2 DFC each time that it was read.

Exhaust Flow Rate

Figure 42 is a plot of the flow rate of the exhaust DFC against time. The setpoint was 15SLPM. The times that the flow rates were above their setpoint occurred when the mixing tank was being evacuated to fill the Mars Dome. The increased pressure differential caused a flow greater than that specified by the algorithm.

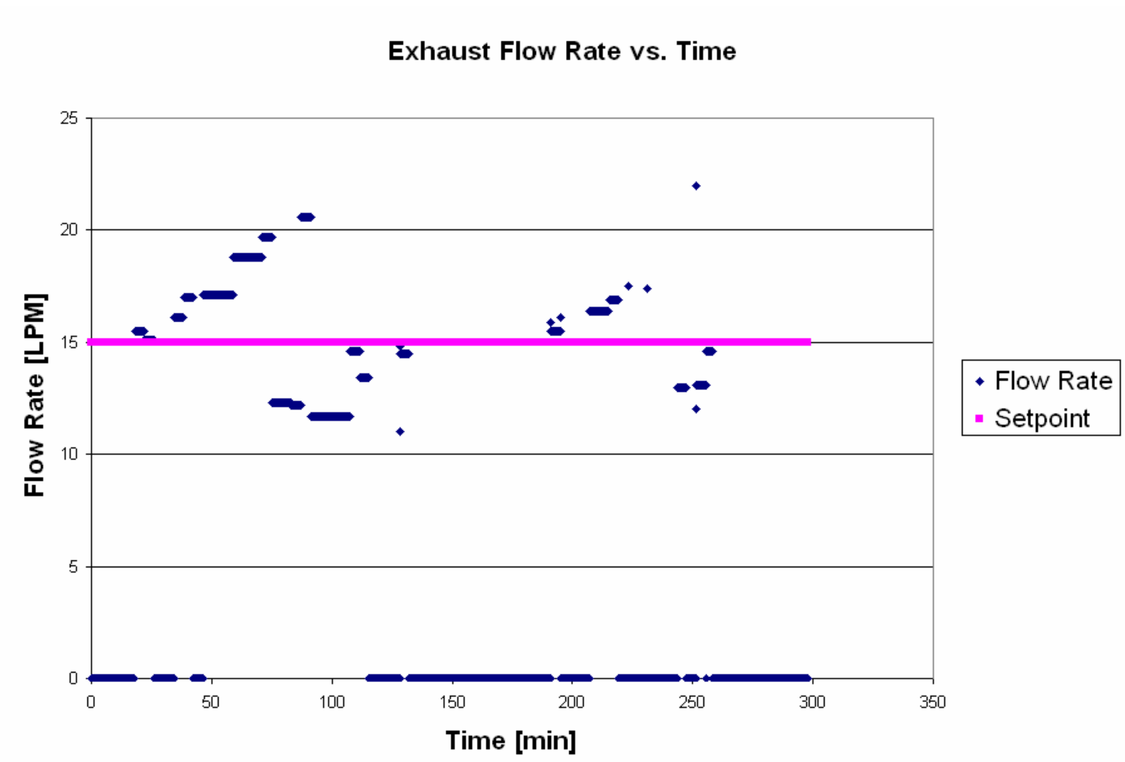

Figure 42 - Exhaust flow rate (SLPM) of the gas mixture vs. time (min). These were the values obtained as gases were allowed to flow from the mixing tank to the Mars Dome.

Temperature

The temperature in the tank and the dome were monitored as an independent covariable. There was no attempt to control them during either of the experiments. The increase in the mixing tank temperature is associated with the injection of compressed N_2. At the beginning of each experiment, the mixing tank was flooded with N_2 to bring it the total pressure close to its setpoint. As the gases expanded within the tank, they also cooled off which is evident by the decrease in temperature. By the time the gases were injected into the dome, they had reached thermal equilibrium. This explains why the temperature in the dome remained almost constant compared to the temperature in the mixing tank. Figure 43 is a graph of the temperature in the mixing tank and the temperature in the dome versus time.

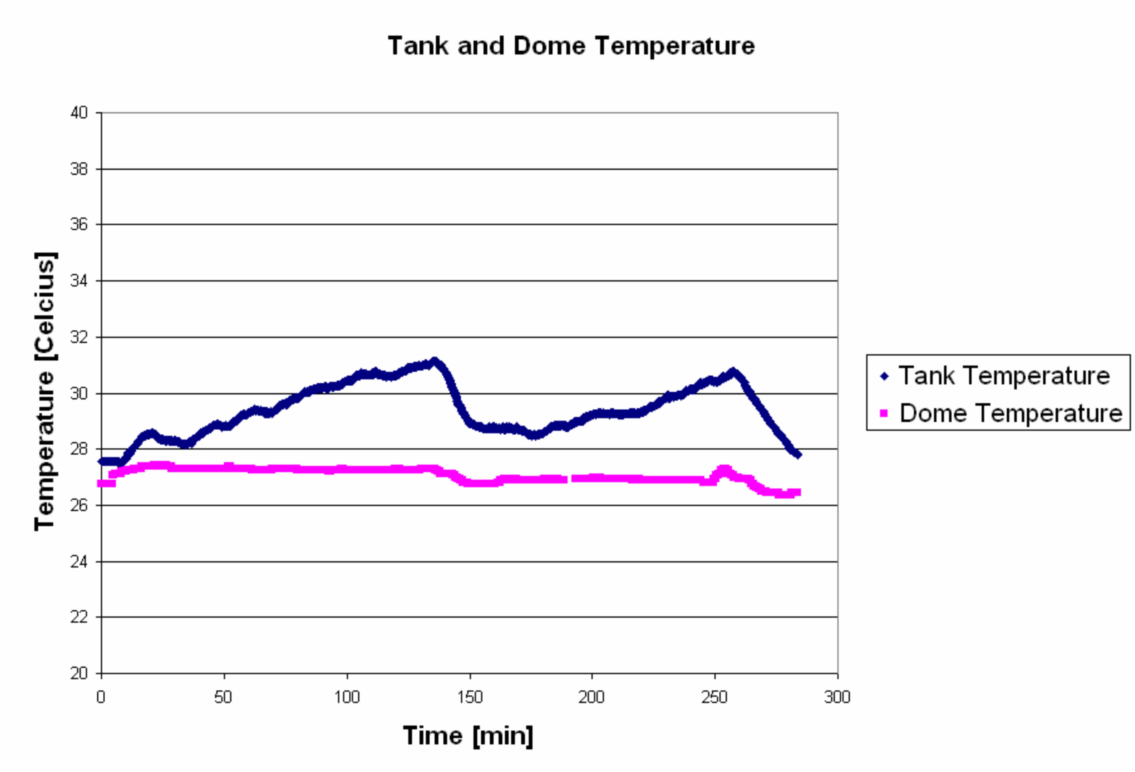

Figure 43 – Mixing tank and Mars Dome temperature. The temperature (°C) in the mixing tank and the Mars Dome were plotted against time (min). There was no temperature setpoint for either of the vessels.

Total Pressure

Figure 44 illustrates how the total pressure of both the tank and the dome varied with time.

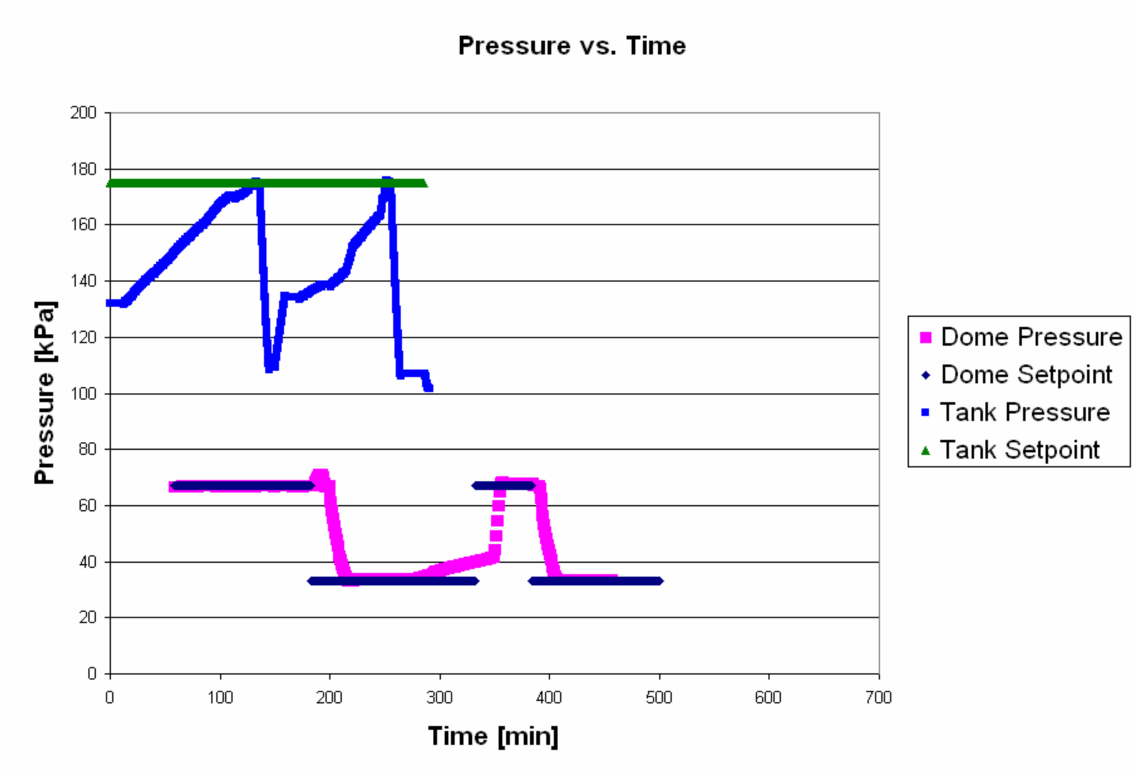

Figure 44 – Mixing tank and Mars Dome total pressure. The total pressure in the mixing tank (kPa) was plotted against time (sec) and compared to its setpoint during both experiments. The same was done for the total pressure (kPa) in the Mars Dome during both trials of experiments 1 and 2.

The total pressure setpoint for the mixing tank was 175kPa during both experiments 1 and 2. The sharp declines in pressure correspond to the evacuation of the tank when filling the dome. The total pressure setpoint for the Mars Dome was 67kPa for trial 1 of both experiments 1 and 2 and 33kPa for trial 2 of both experiments 1 and 2.

Table 15 describes the error between the total pressure in the tank and its setpoint during the first experiment.

Table 15. Statistical Summary Error Associated With the Mixing Tank Total Pressure During Experiments 1 and 2.

Statistical Error Summary for the Mixing Tank Total Pressure		
	Experiment 1	Experiment 2
Mean	-0.084	-0.128
Range	0.620	1.035
Minimum	-0.223	-0.210
Maximum	0.397	0.825

The setpoint in the mixing tank during both experiments 1 and 2 was 175kPa. The mean error value during experiment 1 was -0.084kPa and the range was 0.620kPa. The maximum and minimum error values were 0.397kPa and -0.223kPa respectively. The negative mean error valued implied that the total pressure in the mixing tank was above its setpoint during experiment 1. The plot of the total pressure against time in figure 44 suggests that the total pressure was at or below its setpoint. The algorithm achieved adequate control of the total pressure in the mixing tank because the total pressure remained within the operational limits of 175±5kPa. The mean error value for experiment 2 was -0.128kPa and the range was 1.035kPa. The maximum and minimum error values were 0.825kPa and -0.210kPa, respectively. According to figure 44, the total pressure oscillated around its setpoint. Even so, sufficient control of the total pressure in the mixing tank during experiment 2 was achieved because it remained within the operational limits of control.

Figure 44 also shows how the total pressure in the Mars Dome corresponded to its setpoints during both trials of experiments 1 and 2. Table 16 is a statistical summary of the total pressure error in the Mars Dome during the first experiment.

Table 16. Statistical Summary Error Associated With the Mars Dome Total Pressure During Experiment 1. The total pressure trial 1 was 67kPa and during trial 2 33kPa.

Experiment 1 Statistical Error Summary for the Mars Dome Total Pressure		
	67kPa	33kPa
Mean	-0.057	-0.702
Range	0.681	0.907
Minimum	-0.335	-0.968
Maximum	0.345	-0.060

During experiment 1, the total pressure in the Mars Dome was set at 67kPa during the first trial and 33kPa during the second trial. The mean error value during the first trial was -0.057kPa and the range was 0.681kPa. The maximum and minimum error values obtained were 0.345kPa and -0.335kPa, respectively. The fact that the mean error value was negative implied that the total pressure was typically above its setpoint during the first trial of experiment 1. According to figure 44, the total pressure oscillated around its setpoint. During the second trial of experiment 1, figure 44 shows that the total pressure was at times slightly above its setpoint. This is substantiated by the data in table 16. The mean error value for the second trial of experiment 1 was -0.702kPa and the range was 0.907kPa. The maximum and minimum values were -0.060kPa and -0.968kPa, respectively. The negative mean error value implied that the total pressure was typically above its setpoint.

Table 17 describes the error associated with the total pressure in the Mars Dome during the second experiment.

Table 17. Statistical Summary Error Associated With the Mars Dome Total Pressure During Experiment 2. During this experiment, two trials were run at different total pressures. The total pressure was 67kPa during trial 1 and 33kPa during trial 2.

Experiment 2 Statistical Error Summary for the Mars Dome Total Pressure

	67kPa	33kPa
Mean	-0.968	-0.968
Range	0.000	0.000
Minimum	-0.968	-0.968
Maximum	-0.968	-0.968

During the second experiment, two trials were run. The total pressure in the Mars Dome was 67kPa during the first trial and 33kPa during the second trial. The mean error value was -0.968kPa, which was the same as the minimum and maximum error values. The range was therefore 0kPa. The fact that the mean error value was negative implied that the total pressure was typically above its setpoint. This finding is substantiated by figure 44 which shows that during trial 1 of experiment 2, the total pressure was indeed above its setpoint. During the second trial, the mean error value was again -0.968kPa. The minimum and maximum error values were again -0.968kPa and the range was 0kPa. The conclusions drawn for trial 1 of experiment 2 remain valid for trial 2.

The total pressure in the Mars Dome was not controlled by the same algorithm that was written to control the partial pressures of the gases in the mixing tank. It was instead controlled by an independent controller on the vacuum pump.

CHAPTER VI

CONCLUSIONS AND FUTURE RESEARCH

Conclusions

The first objective of this experiment was to write an algorithm capable of maintaining the individual partial pressures of N_2, O_2, and CO_2 along with the total pressure. The final version of the algorithm used the mass, expressed as the number of moles in the mixture as the parameter by which the partial pressures of each of the constituent gases were controlled. This objective was accomplished using Opto22 software. The program controls the partial pressures while monitoring the partial pressure in addition to the temperature, total pressure, and DFC flow rates. DFCs were used to measure the volumetric flow rate of the gases injected into the mixing tank.

The second objective was to evaluate the limits of control for the dynamic gas mixing system. Plants do not use N_2 for any essential physiochemical functions. Therefore, the limits of control established by the control algorithm are sufficient for low pressure plant growth studies. It was more important to control and maintain the partial pressures of O_2 and CO_2. The O_2 percentage setpoint remained at 21% in both experiments 1 and 2. In experiment 1, the O_2 partial pressure was below its setpoint in the mixing tank and above its setpoint in experiment 2. Because O_2 can be lethal to plants at sufficiently high concentrations, the algorithm should be modified to achieve better control of the O_2 partial pressure. However, limits considered to be lethal were not reached during testing. CO_2 constantly remained outside of the operational limits of control established in the mixing tank. The same was true in the Mars Dome at 67kPa and 33kPa. However, unlike in the mixing tank and in the Mars Dome at 67kPa in which the CO_2 partial pressure was above its setpoint, at 33kPa, the CO_2 partial pressure was below its setpoint. The problem with the CO_2 partial pressure being above its setpoint can most likely be attributed to the need for an increased delay time between sensor readings. On the other hand, the issue of the sensor returning readings below its setpoint at 33kPa is probably due to the CO_2 sensor response being a function of density. While the sensor was calibrated as a function of concentration and pressure, these functions should be further explored at pressures below 67kPa.

The dynamic gas mixing assembly was capable of controlling the partial pressures of N_2, O_2, and CO_2 at pressures below 175kPa. Opto22 software was used to build the algorithm used to control and monitor the partial pressures of the component gases within the mixing tank. At the time the experiments were run, the Mars Dome was a convenient low pressure vessel used to receive the mixtures created in the mixing tank. Gas concentrations and temperature were only monitored in the Mars Dome but not controlled. It was expected the gas sensors in the Mars Dome would echo those in the mixing tank. The partial pressures were expected to decrease proportionately with the change in pressure as they were released from the high pressure environment in the mixing tank to the low pressure atmosphere of the Mars Dome. The O_2 sensor responded as expected at both 67kPa and 33kPa. However, the CO_2 sensor responded as expected at 67kPa, but not at 33kPa. At 33kPa, the CO_2 sensor returned a concentration less than expected according to the CO_2 concentration that was in the mixing tank at the time of testing. This scenario held true for both experiments 1 and 2.

Future Research

The Mars Dome has the capability to control various system parameters although they were only monitored for these experiments. In the future, experiments should be run that integrate the control system for the mixing tank and the system parameters in the receiving vessel (i.e. Mars Dome). Instead of using the sensors on the mixing tank to determine when gas concentrations should be adjusted in the Mars Dome, the sensors in the Mars Dome should be used to establish the environmental requirements. For this research, the sensors in the Mars Dome only monitored the gas concentrations. The DFCs adjusted the partial pressures of the gases according to the readings of the sensors on the mixing tank.

During testing, it was discovered that the O_2 sensors used were not suitable for pressures above 175kPa. As it turns out, the sensors were designed for use in the medical field. As an alternative, O_2 sensors used in the diving industry should be explored in an attempt to increase the pressure in the mixing tank allowing for larger volumes of gas to be mixed. This would vary the usage possibilities of the gas mixing assembly so that it could be used to control the atmosphere within a small room instead of just small chambers such as the Mars Dome.

A different CO_2 sensor should also be considered. During testing, the digital CO_2 gauge used to monitor the CO_2 concentration in the mixing tank was useless because as the pressure increased, the output of the sensor increased. This caused the gauge to read approximately twice the amount of CO_2 in the mixing tank as compared to the concentration returned by the calibrated equation and the GC. Here again, those sensors used in the diving industry should be considered. Other alternatives should be considered for the CO_2 sensor used in the Mars Dome also. Those sensors used in the diving industry are not likely to be an option here because they were designed for use in high pressure environments. At this time, not much data is available on sensor performance at such low pressures as are capable in the Mars Dome. The experimental setup used in this research can also be used to evaluate sensor performance at high and low pressures.

Also, the tests run for this project were short term tests that did not include plants in the Mars Dome. Long term studies should be conducted to validate the stability of the gas mixing assembly. This research was limited only to the development of the gas control algorithm and to establishing its limits of control.

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APPENDIX A

OPTO22 CODE

Read Sensors Chart:

Delay (Sec)
5.0

```
//Expected sensor reading in mV
//O2_reading = (0.0007 * O2_sensor) + 0.0003;
//The gain is 1/2 and 100 is to convert to decimal
O2B_reading = (O2_sensor - (-0.000006 * Pressure_Result + 0.0005))/(0.000008 *
Pressure_Result - 0.0002);
O2_reading = O2B_reading/100;

//Conversion from mV to %O2
//O2x = 181.157*(O2_reading - 0.01);
//O2x = 181.157 * ((O2_sensor + 0.4027)/1435.4);

//Calculate O2 partial pressure
Partial_O2 = O2_reading * Pressure_Result;

//calculate partial setpoint
spPartial_O2 = (spO2 * P_set)/100;

//Actual CO2 sensor reading
CO2B_reading = (CO2_sensor - (0.00007 * Pressure_Result - 0.0099))/(0.006 *
Pressure_Result - 0.2838);
CO2_reading = CO2B_reading/100;

//Expected CO2 sensor reading
//O2x = (CO2_reading *0.025);

//Calculate CO2 partial pressure
Partial_CO2 = (CO2_reading * Pressure_Result);

//calculate partial setpoint
spPartial_CO2 = (spCO2 * P_set)/100;

//Calculate nitrogen percentage
N2x = 1 - (CO2_reading) - O2_reading;

//Calculate N2 partial pressure
Partial_N2 = N2x * Pressure_Result;

//calculate Partial setpoint
spPartial_N2 = (spN2 * P_set)/100;
```

```
//Check sum of partial pressures
partial_sum = Partial_N2 + Partial_O2 + Partial_CO2;


//Calculate the temperature in the recirculation line
Temperature_Result = (Temperature-1.5111)/0.9337;

//Calculate the temperature of the pump
Pump_Temperature = (pump_temp - 1.9002)/0.8554;


//-----------------------------------------------------

//Expected value from Dome CO2 Sensor
DomeCO2 = (dCO2_reading + 0.9744 * DomePressure - 2042.7)/(100 * (-47.209 *
DomePressure + 6056.7));
//Convert to kPa
kDomeCO2 = (DomeCO2) * domepressure;

//Dome kPa setpoint
kspdomeCO2 = dspCO2_dec * dP_set;

//Expected value from Dome O2 Sensor
DomeO2 = (dO2_reading + 1.7386 * DomePressure - 60.822)/(100 * (0.7193 *
DomePressure - 2.6652));
//Convert to kPa
kDomeO2 = DomeO2 * domepressure ;

//Dome kPa setpoint
kspdomeO2 = dspO2_dec * dP_set;

//Expected Dome N2 value
DomeN2 = 1 - DomeCO2 - DomeO2;

//Convert to kPa
kDomeN2 = DomeN2 * domepressure;

//Dome kPa setpoint
kspdomeN2 = dspN2_dec * dP_set;

//calculate sum of dome partial pressures
sum_dpp = kDomeO2 + kDomeN2 + kDomeCO2;
```

//Expected Dome Pressure
DomePressure = (dpressure_reading - 24.348)/4.4056;

//---

Read Pressure Chart:
establishes communication with the setra 370
Open Outgoing Communication
  Communication Handle pressure_handle
  Put Result in pressure_comm_status

error_code1 = TransmitChar('P', pressure_handle);
error_code2 = TransmitNewLine(pressure_handle);

gets characters from comm handle
Get Number of Characters Waiting
  Communication Handle pressure_handle
  Put in pressure_char_count

Greater?
  Is pressure_char_count
  Than 0

1 sec delay
Delay (Sec)
  1.0

Receive String
  Put in pressure_recv_msg
  Communication Handle pressure_handle
  Put Status in pressure_recv_status

GetSubstring (pressure_recv_msg, 1,9, pressure_string);
Pressure_result = StringToFloat(pressure_string);

1 sec delay
Delay (Sec)
  1.0

Pressure Control Chart:

Delay (Sec)

```
            240.0
 //MT Pressure Control
if (Pressure_result >= 190) then
  StartTimer(timer_ex);
  TurnOn(exhaust_relay);
  DelaySec (3);
  TurnOff(exhaust_relay);
  PauseTimer(timer_ex);
  time_ex = timer_ex;
  endif

if (Pressure_result < P_set) then
StartChart (Gas_Control);
endif


//Add gases to the dome
if ((((Pressure_result <= P_set) and (Pressure_result >= 180)) and ((dnO2 <=(dnO2_sp -
(0.025 * dnO2_sp))) or (dnCO2 <= (dnCO2sp - (0.015 * dnCO2sp))) or (dnN2 <=
(dnN2sp - (0.01 * dnN2sp))))) and ((IsOn(N2_relay) == 0) and (IsOn(O2_relay) == 0)
and (IsOn(CO2_relay) == 0))) then
Starttimer (timer_ex);
TurnOn(exhaust_relay);
DelaySec (3);
TurnOff(exhaust_relay);
PauseTimer (Timer_ex);
time_ex = timer_ex;
endif


if ((((Pressure_Result <= P_set) and (Pressure_result >= 105)) and ((dnO2 <=(dnO2_sp
+ (0.025 * dnO2_sp))) or (dnCO2 <= (dnCO2sp + (0.015 * dnCO2sp))) or (dnN2 <=
(dnN2sp + (0.01 * dnN2sp))))) and ((IsOn(N2_relay) == 0) and (IsOn(O2_relay) == 0)
and (IsOn(CO2_relay) == 0))) then
Starttimer (timer_ex);
TurnOn(exhaust_relay);
DelaySec (3);
TurnOff(exhaust_relay);
PauseTimer (Timer_ex);
  time_ex = timer_ex;
endif
```

```
if ((Domepressure < dP_set) and ((Pressure_Result <= P_set) and (Pressure_result >=
180))) then
  Starttimer (timer_ex);
  TurnOn(exhaust_relay);
  DelaySec (3);
  TurnOff(exhaust_relay);
  PauseTimer (Timer_ex);
  time_ex = timer_ex;
endif
```

Gas Control Chart:

```
Delay (Sec)
        45.0

//Calculate absolute temperature
T_abs = Temperature_Result + 273;

//Define universal Gas Constant [kPa*m^3/mole*K]
R = 8.314;

//Define tank volume [m^3]
V = 0.19255;


//Calculate the total number of moles in the system
//based on the pressure setpoint

total_n_setpoint = (P_set * V)/(T_abs * R);

//Calculate setpoint partial pressures
sp_CO2pp = spCO2_dec * P_set;
sp_O2pp = spO2_dec * P_set;
sp_N2pp = spN2_dec * P_set;

n_diff = total_n_setpoint - total_n;

Divide
        spCO2
  By    100
  Put Result in spCO2_dec

Divide
```

```
        spO2
  By    100
  Put Result in spO2_dec

Divide
        spN2
  By    100
  Put Result in spN2_dec

calculate the CO2 mol setpoint
Multiply
        total_n_setpoint
  TimesspCO2_dec
  Put Result in nCO2_setpoint

calculate the CO2 mol setpoint
Multiply
        total_n_setpoint
  TimesspO2_dec
  Put Result in nO2_setpoint

calculate the CO2 mol setpoint
Multiply
        total_n_setpoint
  TimesspN2_dec
  Put Result in nN2_setpoint

Delay (Sec)
        1.0

Delay (Sec)
        1.0

calculate actual # of moles of O2 in the system
Multiply
        O2_reading
  Timestotal_n
  Put Result in nO2

calculate actual # of moles of CO2 in the system
Multiply
        CO2_reading
  Timestotal_n
  Put Result in nCO2
```

```
calculate actual # of moles of N2 in the system
Multiply
            N2x
  Timestotal_n
  Put Result in nN2

calculate the error for the moles of CO2
Subtract
            nCO2_setpoint
  Minus          nCO2
  Put Result in nCO2_diff

calculate the error for the moles of O2
Subtract
            nO2_setpoint
  Minus          nO2
  Put Result in nO2_diff

calculate the error for the N2 moles
Subtract
            nN2_setpoint
  Minus          nN2
  Put Result in nN2_diff



//Calculate absolute temperature
Temp1_abs = Temp1 + 273;

//Define universal Gas Constant [kPa*m^3/mole*K]
R = 8.314;

//Define tank volume [m^3]
dV = 0.417;


//Calculate the total number of moles in the system
//based on the pressure setpoint

dtnsp = (dP_set * dV)/(Temp1_abs * R);

//Calculate the total number of moles in the Mars Dome
dtn = (DomePressure * dV)/(R * Temp1_abs);
```

```
//Calculate the difference between the total setpoint moles
//and the actual moles in the Mars Dome
dn_diff = dtnsp - dtn;



Divide
        dspCO2
  By    100
  Put Result in dspCO2_dec

Divide
        dspO2
  By    100
  Put Result in dspO2_dec

Divide
        dspN2
  By    100
  Put Result in dspN2_dec

calculate the CO2 mol setpoint
Multiply
        dtnsp
  TimesdspCO2
  Put Result in dnCO2sp

calculate the O2 mol setpoint
Multiply
        dtnsp
  TimesdspO2_dec
  Put Result in dnO2sp

calculate the N2 mol setpoint
Multiply
        dtnsp
  TimesdspN2_dec
  Put Result in dnN2sp

Delay (Sec)
        1.0
```

```
Delay (Sec)
        1.0

calculate actual # of moles of O2 in the system
Multiply
        domeO2
  Timesdtn
  Put Result in dnO2

calculate actual # of moles of CO2 in the system
Multiply
        domeCO2
  Timesdtn
  Put Result in dnCO2

calculate actual # of moles of N2 in the system
Multiply
        DomeN2
  Timesdtn
  Put Result in dnN2

calculate the error for the moles of CO2
Subtract
        dnCO2sp
  Minus         dnCO2
  Put Result in dnCO2_diff

calculate the error for the moles of O2
Subtract
        dnO2sp
  Minus         dnO2
  Put Result in dnO2_diff

calculate the error for the N2 moles
Subtract
        dnN2sp
  Minus         dnN2
  Put Result in dnN2_diff


//Define the molecular weight for CO2 [g/mole]
mwCO2 = 44;

//Define the molecular weight for O2 [g/mole]
```

```
mwO2 = 32;

//Define the molecular weight for N2 [g/mole]
mwN2 = 28;
//Convert from moles to millimoles in the MT for ioDisplay
mO2 = nO2 * 1000;
mCO2 = nCO2 * 1000;
mN2 = nN2 * 1000;
mtotal = total_n * 1000;

spmO2 = nO2_setpoint * 1000;
spmCO2 = nCO2_setpoint * 1000;
spmN2 = nN2_setpoint * 1000;
spmtotal = total_n_setpoint * 1000;

//Convert from moles to millimoles in the dome for ioDisplay
dmO2 = dnO2 * 1000;
dmCO2 = dnCO2 * 1000;
dmN2 = dnN2 * 1000;
dmtn= dtn * 1000;

dspmO2 = dnO2sp * 1000;
dspmCO2 = dnCO2sp * 1000;
dspmN2 = dnN2sp * 1000;
dspmt = dtnsp * 1000;

//Determines how long the N2 solenoid was On/Off
if (IsOn(N2_relay) == 1) then
  Nvt = 1;
    elseif (IsOn(N2_relay) == 0) then
      Nvt = 0;
endif

//Determines how long the O2 solenoid was On/Off
if (IsOn(O2_relay) == 1) then
  Ovt = 1;
    elseif (IsOn(O2_relay) == 0)then
      Ovt = 0;
endif

//Determines how long the CO2 solenoid was On/Off
if (IsOn(CO2_relay) == 1) then
  COvt = 1;
    elseif (IsOn(CO2_relay) == 0) then
```

```
      COvt = 0;
endif

//Determines how long the Exhaust solenoid was On/Off
if (IsOn(exhaust_relay) == 1) then
  Exvt = 1;
    elseif (IsOn(exhaust_relay) == 0) then
      Exvt = 0;
Endif

//O2 Alarm for the MT and the Dome
O2_alarm = (0.25 * total_n) + total_n;
dO2_alarm = (0.25 * dtn) + dtn;

while ((nO2 > (O2_alarm)) or (dnO2 > (dO2_alarm)))
  TurnOff (O2_relay);
  TurnOn(main_tank_relay);
  TurnOn (N2_relay);

  TurnOn(exhaust_relay);
  DelaySec(5);
  TurnOff(N2_relay);
  TurnOff (exhaust_relay);

Wend
```

Case 0:

```
//Start fuzzy control of N2

if (nN2_diff >= 0.01134) then
StartTimer(timer_N2);

TurnOn(Main_tank_relay);
TurnOn (N2_relay);
Nvt = 1;
DelaySec (60);

TurnOff (N2_relay);
Nvt = 0;
PauseTimer(timer_N2);

time_N2 = timer_N2;
```

```
elseif ((nN2_diff < 0.01134) and (nN2_diff > 0.008508)) then
  StartTimer(timer_N2);

  TurnOn(Main_tank_relay);
  TurnOn (N2_relay);
  Nvt = 1;

  DelaySec (30);

  TurnOff (N2_relay);
  Nvt = 0;
  PauseTimer(timer_N2);

  time_N2 = timer_N2;


    elseif ((nN2_diff < 0.008508) and (nN2_diff > 0.005672)) then
      StartTimer(timer_N2);

      TurnOn(Main_tank_relay);
      TurnOn (N2_relay);
      Nvt = 1;

      DelaySec (20);

     TurnOff (N2_relay);
     Nvt = 0;
     PauseTimer(timer_N2);

     time_N2 = timer_N2;

     elseif ((nN2_diff < 0.005672) and (nN2_diff > 0.002836)) then
      StartTimer(timer_N2);

      TurnOn(Main_tank_relay);
      TurnOn (N2_relay);
      Nvt = 1;

      DelaySec (10);

     TurnOff (N2_relay);
     Nvt = 0;
     PauseTimer(timer_N2);
```

```
      time_N2 = timer_N2;


       elseif (nN2_diff <= 0.002836) then
           StartTimer(timer_N2);

           TurnOn(Main_tank_relay);
           TurnOn (N2_relay);
           Nvt = 1;

           DelaySec (3);

           TurnOff (N2_relay);
           Nvt = 0;
           PauseTimer(timer_N2);

           time_N2 = timer_N2;



endif
endif
//------------------------------------------------------------

if (nN2_diff >= 0.01134) then
StartTimer(timer_N2);

TurnOn(Main_tank_relay);
TurnOn (N2_relay);
Nvt = 1;
DelaySec (60);

TurnOff (N2_relay);
Nvt = 0;
PauseTimer(timer_N2);

time_N2 = timer_N2;

  elseif ((nN2_diff < 0.01134) and (nN2_diff > 0.008508)) then
    StartTimer(timer_N2);

    TurnOn(Main_tank_relay);
    TurnOn (N2_relay);
    Nvt = 1;
```

```
DelaySec (30);

TurnOff (N2_relay);
Nvt = 0;
PauseTimer(timer_N2);

time_N2 = timer_N2;


  elseif ((nN2_diff < 0.008508) and (nN2_diff > 0.005672)) then
   StartTimer(timer_N2);

   TurnOn(Main_tank_relay);
   TurnOn (N2_relay);
   Nvt = 1;

   DelaySec (20);

  TurnOff (N2_relay);
  Nvt = 0;
  PauseTimer(timer_N2);

  time_N2 = timer_N2;

  elseif ((nN2_diff < 0.005672) and (nN2_diff > 0.002836)) then
   StartTimer(timer_N2);

   TurnOn(Main_tank_relay);
   TurnOn (N2_relay);
   Nvt = 1;

   DelaySec (10);

  TurnOff (N2_relay);
  Nvt = 0;
  PauseTimer(timer_N2);

  time_N2 = timer_N2;


   elseif (nN2_diff <= 0.002836) then
     StartTimer(timer_N2);
```

```
            TurnOn(Main_tank_relay);
            TurnOn (N2_relay);
            Nvt = 1;

            DelaySec (3);

            TurnOff (N2_relay);
            Nvt = 0;
            PauseTimer(timer_N2);

            time_N2 = timer_N2;



endif
endif
//----------------------------------------------------------
if (((nO2 > nO2_setpoint) and (nCO2 > nCO2_setpoint)) and (nO2_diff == nCO2_diff))
then


if (nN2_diff >= 0.01134) then
StartTimer(timer_N2);

TurnOn(Main_tank_relay);
TurnOn (N2_relay);
Nvt = 1;
DelaySec (60);

TurnOff (N2_relay);
Nvt = 0;
PauseTimer(timer_N2);

time_N2 = timer_N2;

  elseif ((nN2_diff < 0.01134) and (nN2_diff > 0.008508)) then
    StartTimer(timer_N2);

    TurnOn(Main_tank_relay);
    TurnOn (N2_relay);
    Nvt = 1;

    DelaySec (30);
```

```
TurnOff (N2_relay);
Nvt = 0;
PauseTimer(timer_N2);

time_N2 = timer_N2;


  elseif ((nN2_diff < 0.008508) and (nN2_diff > 0.005672)) then
    StartTimer(timer_N2);

    TurnOn(Main_tank_relay);
    TurnOn (N2_relay);
    Nvt = 1;

    DelaySec (20);

   TurnOff (N2_relay);
   Nvt = 0;
   PauseTimer(timer_N2);

   time_N2 = timer_N2;

   elseif ((nN2_diff < 0.005672) and (nN2_diff > 0.002836)) then
    StartTimer(timer_N2);

    TurnOn(Main_tank_relay);
    TurnOn (N2_relay);
    Nvt = 1;

    DelaySec (10);

   TurnOff (N2_relay);
   Nvt = 0;
   PauseTimer(timer_N2);

   time_N2 = timer_N2;


    elseif (nN2_diff <= 0.002836) then
        StartTimer(timer_N2);

        TurnOn(Main_tank_relay);
        TurnOn (N2_relay);
        Nvt = 1;
```

```
        DelaySec (3);

        TurnOff (N2_relay);
        Nvt = 0;
        PauseTimer(timer_N2);

        time_N2 = timer_N2;



endif
endif
```

Case 1:

```
if ((nO2 > nO2_setpoint) and (nCO2 < (nCO2_setpoint))) then

  StartTimer (timer_CO2);

  TurnOn (Main_tank_relay);
  TurnOn (CO2_relay);
  Cvt = 1;

  DelaySec (3);

  TurnOff (CO2_relay);
  Cvt = 0;
  PauseTimer (timer_CO2);

  time_CO2 = timer_CO2;


//Start fuzzy control of N2


if (nN2_diff >= 0.01134) then
StartTimer(timer_N2);

TurnOn(Main_tank_relay);
TurnOn (N2_relay);
Nvt = 1;
DelaySec (60);
```

```
TurnOff (N2_relay);
Nvt = 0;
PauseTimer(timer_N2);

time_N2 = timer_N2;

  elseif ((nN2_diff < 0.01134) and (nN2_diff > 0.008508)) then
    StartTimer(timer_N2);

    TurnOn(Main_tank_relay);
    TurnOn (N2_relay);
    Nvt = 1;

    DelaySec (30);

    TurnOff (N2_relay);
    Nvt = 0;
    PauseTimer(timer_N2);

    time_N2 = timer_N2;


      elseif ((nN2_diff < 0.008508) and (nN2_diff > 0.005672)) then
        StartTimer(timer_N2);

        TurnOn(Main_tank_relay);
        TurnOn (N2_relay);
        Nvt = 1;

        DelaySec (20);

       TurnOff (N2_relay);
       Nvt = 0;
       PauseTimer(timer_N2);

       time_N2 = timer_N2;

       elseif ((nN2_diff < 0.005672) and (nN2_diff > 0.002836)) then
        StartTimer(timer_N2);

        TurnOn(Main_tank_relay);
        TurnOn (N2_relay);
        Nvt = 1;
```

```
 DelaySec (10);

TurnOff (N2_relay);
Nvt = 0;
PauseTimer(timer_N2);

time_N2 = timer_N2;


 elseif (nN2_diff <= 0.002836) then
     StartTimer(timer_N2);

     TurnOn(Main_tank_relay);
     TurnOn (N2_relay);
     Nvt = 1;

     DelaySec (3);

     TurnOff (N2_relay);
     Nvt = 0;
     PauseTimer(timer_N2);

     time_N2 = timer_N2;



endif
endif
```

Case 2:

```
if ((nO2 > nO2_setpoint) and (nCO2 == (nCO2_setpoint))) then


      StartTimer (timer_CO2);

      TurnOn (Main_tank_relay);
      TurnOn (CO2_relay);
      COvt = 1;

      DelaySec (3);

      TurnOff (CO2_relay);
```

```
      COvt = 0;
      PauseTimer (timer_CO2);

      time_CO2 = timer_CO2;

//Start fuzzy control of N2



if (nN2_diff >= 0.01134) then
StartTimer(timer_N2);

TurnOn(Main_tank_relay);
TurnOn (N2_relay);
Nvt = 1;
DelaySec (60);

TurnOff (N2_relay);
Nvt = 0;
PauseTimer(timer_N2);

time_N2 = timer_N2;

  elseif ((nN2_diff < 0.01134) and (nN2_diff > 0.008508)) then
    StartTimer(timer_N2);

    TurnOn(Main_tank_relay);
    TurnOn (N2_relay);
    Nvt = 1;

    DelaySec (30);

    TurnOff (N2_relay);
    Nvt = 0;
    PauseTimer(timer_N2);

    time_N2 = timer_N2;


      elseif ((nN2_diff < 0.008508) and (nN2_diff > 0.005672)) then
        StartTimer(timer_N2);

        TurnOn(Main_tank_relay);
        TurnOn (N2_relay);
```

```
 Nvt = 1;

 DelaySec (20);

TurnOff (N2_relay);
Nvt = 0;
PauseTimer(timer_N2);

time_N2 = timer_N2;

elseif ((nN2_diff < 0.005672) and (nN2_diff > 0.002836)) then
 StartTimer(timer_N2);

 TurnOn(Main_tank_relay);
 TurnOn (N2_relay);
 Nvt = 1;

 DelaySec (10);

TurnOff (N2_relay);
Nvt = 0;
PauseTimer(timer_N2);

time_N2 = timer_N2;


 elseif (nN2_diff <= 0.002836) then
    StartTimer(timer_N2);

    TurnOn(Main_tank_relay);
    TurnOn (N2_relay);
    Nvt = 1;

    DelaySec (3);

    TurnOff (N2_relay);
    Nvt = 0;
    PauseTimer(timer_N2);

    time_N2 = timer_N2;


endif
```

```
endif
```

Case 3:

```
if ((nO2 < nO2_setpoint) and (nCO2 > nCO2_setpoint)) then


  StartTimer (timer_O2);

  TurnOn(Main_tank_relay);
  TurnOn (O2_relay);

  DelaySec (3);

  TurnOff (O2_relay);
  PauseTimer (timer_O2);

  time_O2 = timer_O2;
endif


if (nN2_diff >= 0.01134) then
StartTimer(timer_N2);

TurnOn(Main_tank_relay);
TurnOn (N2_relay);
DelaySec (60);

TurnOff (N2_relay);
PauseTimer(timer_N2);
time_N2 = timer_N2;

elseif ((nN2_diff < 0.01134) and (nN2_diff > 0.008508)) then
StartTimer(timer_N2);

TurnOn(Main_tank_relay);
TurnOn (N2_relay);

DelaySec (30);

TurnOff (N2_relay);
PauseTimer(timer_N2);

time_N2 = timer_N2;
```

```
elseif ((nN2_diff < 0.008508) and (nN2_diff > 0.005672)) then
StartTimer(timer_N2);

TurnOn(Main_tank_relay);
TurnOn (N2_relay);

DelaySec (20);

TurnOff (N2_relay);
PauseTimer(timer_N2);

time_N2 = timer_N2;

elseif ((nN2_diff < 0.005672) and (nN2_diff > 0.002836)) then
StartTimer(timer_N2);

TurnOn(Main_tank_relay);
TurnOn (N2_relay);

DelaySec (10);

TurnOff (N2_relay);
PauseTimer(timer_N2);

time_N2 = timer_N2;


elseif (nN2_diff <= 0.002836) then
StartTimer(timer_N2);

TurnOn(Main_tank_relay);
TurnOn (N2_relay);

DelaySec (3);

TurnOff (N2_relay);
PauseTimer(timer_N2);

time_N2 = timer_N2;
```

```
endif
```

Case 4:

```
if ((nO2 < nO2_setpoint) and (nCO2 < (nCO2_setpoint))) then

  StartTimer (timer_O2);
  TurnOn(Main_tank_relay);
  TurnOn (O2_relay);

  DelaySec (3);

  TurnOff (O2_relay);
  PauseTimer (timer_O2);
  time_O2 = timer_O2;

  StartTimer (timer_CO2);
  TurnOn (CO2_relay);

  DelaySec (3);

  TurnOff (CO2_relay);
  PauseTimer (timer_CO2);

  time_CO2 = timer_CO2;

endif
```

Case 5:

```
if ((nO2 < nO2_setpoint) and (nCO2 == (nCO2_setpoint))) then

  StartTimer (timer_O2);
  TurnOn(Main_tank_relay);
  TurnOn (O2_relay);

  DelaySec (3);

  TurnOff (O2_relay);
  PauseTimer (timer_O2);
  time_O2 = timer_O2;

  StartTimer (timer_CO2);
```

```
  TurnOn (CO2_relay);

  DelaySec (3);

  TurnOff (CO2_relay);
  PauseTimer (timer_CO2);

  time_CO2 = timer_CO2;
endif
```

Case 6:

```
if ((nO2 == nO2_setpoint) and (nCO2 > nCO2_setpoint)) then

  StartTimer (timer_O2);

  TurnOn(Main_tank_relay);
  TurnOn (O2_relay);

  DelaySec (3);

  TurnOff (O2_relay);
  PauseTimer (timer_O2);

  time_O2 = timer_O2;


if (nN2_diff >= 0.01134) then
StartTimer(timer_N2);

TurnOn(Main_tank_relay);
TurnOn (N2_relay);
DelaySec (60);

TurnOff (N2_relay);
PauseTimer(timer_N2);

time_N2 = timer_N2;

  elseif ((nN2_diff < 0.01134) and (nN2_diff > 0.008508)) then
    StartTimer(timer_N2);
```

```
TurnOn(Main_tank_relay);
TurnOn (N2_relay);

DelaySec (30);

TurnOff (N2_relay);
PauseTimer(timer_N2);

time_N2 = timer_N2;


  elseif ((nN2_diff < 0.008508) and (nN2_diff > 0.005672)) then
    StartTimer(timer_N2);

    TurnOn(Main_tank_relay);
    TurnOn (N2_relay);

    DelaySec (20);

   TurnOff (N2_relay);
   PauseTimer(timer_N2);

   time_N2 = timer_N2;

   elseif ((nN2_diff < 0.005672) and (nN2_diff > 0.002836)) then
    StartTimer(timer_N2);

    TurnOn(Main_tank_relay);
    TurnOn (N2_relay);

    DelaySec (10);

   TurnOff (N2_relay);
   PauseTimer(timer_N2);

   time_N2 = timer_N2;


    elseif (nN2_diff <= 0.002836) then
        StartTimer(timer_N2);

        TurnOn(Main_tank_relay);
        TurnOn (N2_relay);
```

```
          DelaySec (3);

          TurnOff (N2_relay);
          PauseTimer(timer_N2);

          time_N2 = timer_N2;



endif
endif
```

Case 7:

```
if ((nO2 == nO2_setpoint) and (nCO2 < (nCO2_setpoint))) then

 StartTimer (timer_O2);
  TurnOn(Main_tank_relay);
  TurnOn (O2_relay);

  DelaySec (3);

  TurnOff (O2_relay);
  PauseTimer (timer_O2);
  time_O2 = timer_O2;

  StartTimer (timer_CO2);
  TurnOn (CO2_relay);

  DelaySec (3);

  TurnOff (CO2_relay);
  PauseTimer (timer_CO2);

  time_CO2 = timer_CO2;
endif

//O2 Alarm for the MT and the Dome
O2_alarm = (0.25 * total_n) + total_n;
dO2_alarm = (0.25 * dtn) + dtn;

while ((nO2 > (O2_alarm)) or (dnO2 > (dO2_alarm)))
 TurnOff (O2_relay);
```

```
  TurnOn(main_tank_relay);
  TurnOn (N2_relay);

  TurnOn(exhaust_relay);
  DelaySec(5);
  TurnOff(N2_relay);
  TurnOff (exhaust_relay);

Wend

Select Block 0
```

Dome Sensors Chart:

```
Open Outgoing Communication
  Communication Handle        dome_handle
  Put Result in  dome_handle_status

Set Up Timer Target Value
 Target Value  60.0
 Up Timer      timer_dome

Start Timer
  Timer timer_dome

Append Character to String
  Append       70
  To     sCO2

Append Character to String
  Append       49
  To     sCO2

Append Character to String
  Append       13
  To     sCO2

Transmit String
  From  sCO2
  Communication Handle        dome_handle
  Put Status in  sCO2_status

Delay (Sec)
         10.0
```

```
Append Character to String
  Append        68
  To      sO2

Append Character to String
  Append        48
  To      sO2

Append Character to String
  Append        13
  To      sO2

Transmit String
  From  sO2
  Communication Handle       dome_handle
  Put Status in  sO2_status

Delay (Sec)
        10.0

Append Character to String
  Append        86
  To      sdpressure

Append Character to String
  Append        49
  To      sdpressure

Append Character to String
  Append        50
  To      sdpressure

Append Character to String
  Append        13
  To      sdpressure

Transmit String
  From  sdpressure
  Communication Handle       dome_handle
  Put Status in  sdpressure_status

Delay (Sec)
        10.0
```

Append Character to String
 Append 84
 To dTemp

Append Character to String
 Append 49
 To dTemp

Append Character to String
 Append 50
 To dTemp

Append Character to String
 Append 13
 To dTemp

Transmit String
 From dTemp
 Communication Handle dome_handle
 Put Status in dTemp_status

Delay (Sec)
 10.0

Get Number of Characters Waiting
 Communication Handle dome_handle
 Put in dome_char_count

Greater?
 Is dome_char_count
 Than 0

Delay (Sec)
 1.0
 receives the reponses from the dome sensors
Receive N Characters
 Put in sCO2_recv_msg
 Num. Characters dome_char_count
 Communication Handle dome_handle
 Put Status in sCO2_recv_status

Delay (Sec)
10.0

gets the CO2 sensor response and puts it in a substring
Get Substring
From String sCO2_recv_msg
Start at Index 3
Num. Characters 4
Put Result in dCO2

converts the CO2 substring to a decimal value
Convert String to Float
Convert dCO2
Put Result in dCO2_reading

gets the O2 sensor response and puts it in a substring
Get Substring
From String sCO2_recv_msg
Start at Index 12
Num. Characters 4
Put Result in dO2

converts the O2 sensor response to a decimal value
Convert String to Float
Convert dO2
Put Result in dO2_reading

Get Substring
From String sCO2_recv_msg
Start at Index 22
Num. Characters 4
Put Result in dpressure

Convert String to Float
Convert dpressure
Put Result in dpressure_reading

Get Substring
From String sCO2_recv_msg
Start at Index 32
Num. Characters 4
Put Result in domeT

Convert String to Float

Convert domeT
Put Result in Temp2

Delay (Sec)
10.0

Move String
From
To sCO2_recv_msg

Move String
From
To sCO2

Move String
From
To sO2

Move String
From
To dCO2

Move String
From
To dO2

Move String
From
To dpressure

Move String
From
To sdpressure

Move String
From
To dTemp

Move String
From
To domeT

Move
From 0

To dome_char_count

Pause Timer
Timer timer_dome

Move
From timer_dome
To time_dome

//Temp2 = StringToFloat(domeT);
Temp1 = Temp2/16;

//Expected Dome Pressure
DomePressure = (dpressure_reading - 24.348)/4.4056;

DFC Setup Chart:

Open Outgoing Communication
Communication Handle comm_handle
Put Result in ch_status

appends switch control characters
Append Character to String
Append 27
To portA_string

Append Character to String
Append 2
To portA_string

Append Character to String
Append 65
To portA_string

Append Character to String
Append 13
To portA_string

Transmit String
From portA_string
Communication Handle comm_handle
Put Status in portA_string_error

Delay (Sec)
1.0

create master MFC string
Append Character to String
Append 33
To unit_stringA

Append Character to String
Append 49
To unit_stringA

Append Character to String
Append 49
To unit_stringA

Append Character to String
Append 44
To unit_stringA

Append Character to String
Append 85
To unit_stringA

Append Character to String
Append 44
To unit_stringA

Append Character to String
Append 83
To unit_stringA

Append Character to String
Append 76
To unit_stringA

Append Character to String
Append 80
To unit_stringA

Append Character to String
Append 77
To unit_stringA

Append Character to String
Append 13
To unit_stringA

Transmit String
From unit_stringA
Communication Handle comm_handle
Put Status in unitA_string_error

Delay (Sec)
1.0

create master MFC string
Append Character to String
Append 33
To Mmode_stringA

Append Character to String
Append 49
To Mmode_stringA

Append Character to String
Append 49
To Mmode_stringA

Append Character to String
Append 44
To Mmode_stringA

Append Character to String
Append 77
To Mmode_stringA

Append Character to String
Append 44
To Mmode_stringA

Append Character to String
Append 68
To Mmode_stringA

Append Character to String

```
  Append        13
  To     Mmode_stringA

Transmit String
  From Mmode_stringA
  Communication Handle        comm_handle
  Put Status in  Mmode_stringA_error

Delay (Sec)
         1.0


 create master MFC string
Append Character to String
  Append        33
  To     Vmode_stringA

Append Character to String
  Append        49
  To     Vmode_stringA

Append Character to String
  Append        49
  To     Vmode_stringA

Append Character to String
  Append        44
  To     Vmode_stringA

Append Character to String
  Append        86
  To     Vmode_stringA

Append Character to String
  Append        44
  To     Vmode_stringA

Append Character to String
  Append        65
  To     Vmode_stringA

Append Character to String
  Append        13
  To     Vmode_stringA
```

Transmit String
From Vmode_stringA
Communication Handle comm_handle
Put Status in Vmode_stringA_error

Delay (Sec)
1.0

create master MFC string
Append Character to String
Append 33
To flow_stringA

Append Character to String
Append 49
To flow_stringA

Append Character to String
Append 49
To flow_stringA

Append Character to String
Append 44
To flow_stringA

Append Character to String
Append 83
To flow_stringA

Append Character to String
Append 44
To flow_stringA

Append Character to String
Append 49
To flow_stringA

Append Character to String
Append 53
To flow_stringA

Append Character to String
Append 13

To flow_stringA

Transmit String
From flow_stringA
Communication Handle comm_handle
Put Status in flow_stringA_error

Delay (Sec)
1.0

gets the characters from the comm handle
Get Number of Characters Waiting
Communication Handle comm_handle
Put in portA_char_count

Greater?
Is portA_char_count
Than 0

Delay (Sec)
2.0

Receive N Characters
Put in unitA_recv_msg
Num. Characters portA_char_count
Communication Handle comm_handle
Put Status in unitA_recv_status

Get String Length
Of String unitA_recv_msg
Put Result in A1_length

Delay (Sec)
2.0

Move String
From
To portA_string

Move String
From
To unitA_recv_msg

Move String
 From
 To unit_stringD

Move String
 From
 To Mmode_stringA

Move String
 From
 To Vmode_stringA

Move String
 From
 To flow_stringA

Get String Length
 Of String unitA_recv_msg
 Put Result in A2_length

portA_char_count = 0;

Select portB

Port B:
appends switch control characters
Append Character to String
 Append 27
 To portB_string

Append Character to String
 Append 2
 To portB_string

Append Character to String
 Append 66
 To portB_string

Append Character to String
 Append 13
 To portB_string

Transmit String
 From portB_string

Communication Handle comm_handle
Put Status in portB_string_error

Delay (Sec)
1.0

create master MFC string
Append Character to String
Append 33
To unit_stringB

Append Character to String
Append 49
To unit_stringB

Append Character to String
Append 49
To unit_stringB

Append Character to String
Append 44
To unit_stringB

Append Character to String
Append 85
To unit_stringB

Append Character to String
Append 44
To unit_stringB

Append Character to String
Append 77
To unit_stringB

Append Character to String
Append 76
To unit_stringB

Append Character to String
Append 80
To unit_stringB

Append Character to String
Append 77
To unit_stringB

Append Character to String
Append 13
To unit_stringB

Transmit String
From unit_stringB
Communication Handle comm_handle
Put Status in unit_stringB_error

Delay (Sec)
1.0

create master MFC string
Append Character to String
Append 33
To Mmode_stringB

Append Character to String
Append 49
To Mmode_stringB

Append Character to String
Append 49
To Mmode_stringB

Append Character to String
Append 44
To Mmode_stringB

Append Character to String
Append 77
To Mmode_stringB

Append Character to String
Append 44
To Mmode_stringB

Append Character to String
Append 68

To Mmode_stringB

Append Character to String
Append 13
To Mmode_stringB

Transmit String
From Mmode_stringB
Communication Handle comm_handle
Put Status in Mmode_stringB_error

Delay (Sec)
1.0

create master MFC string
Append Character to String
Append 33
To Vmode_stringB

Append Character to String
Append 49
To Vmode_stringB

Append Character to String
Append 49
To Vmode_stringB

Append Character to String
Append 44
To Vmode_stringB

Append Character to String
Append 86
To Vmode_stringB

Append Character to String
Append 44
To Vmode_stringB

Append Character to String
Append 65
To Vmode_stringB

Append Character to String

Append 13
To Vmode_stringB

Transmit String
From Vmode_stringB
Communication Handle comm_handle
Put Status in Vmode_stringB_error

Delay (Sec)
1.0

create master MFC string
Append Character to String
Append 33
To flow_stringB

Append Character to String
Append 49
To flow_stringB

Append Character to String
Append 49
To flow_stringB

Append Character to String
Append 44
To flow_stringB

Append Character to String
Append 83
To flow_stringB

Append Character to String
Append 44
To flow_stringB

Append Character to String
Append 53
To flow_stringB

Append Character to String
Append 13
To flow_stringB

Transmit String
From flow_stringB
Communication Handle comm_handle
Put Status in flow_stringB_error

Delay (Sec)
1.0

gets the characters from the comm handle
Get Number of Characters Waiting
Communication Handle comm_handle
Put in portB_char_count

Greater?
Is portB_char_count
Than 0

Delay (Sec)
2.0

Receive N Characters
Put in unitB_recv_msg
Num. Characters portB_char_count
Communication Handle comm_handle
Put Status in unitB_recv_status

Get String Length
Of String unitB_recv_msg
Put Result in B1_length

Delay (Sec)
2.0

Move String
From
To portB_string

Move String
From
To unitB_recv_msg

Move String

From
To unit_stringB

Move String
From
To Mmode_stringB

Move String
From
To Vmode_stringB

Move String
From
To flow_stringB

Get String Length
Of String unitB_recv_msg
Put Result in B2_length

portB_char_count = 0;

Select PortC

Port C:

appends switch control characters
Append Character to String
Append 27
To portC_string

Append Character to String
Append 2
To portC_string

Append Character to String
Append 67
To portC_string

Append Character to String
Append 13
To portC_string

Transmit String

From portC_string
Communication Handle comm_handle
Put Status in portC_string_error

Delay (Sec)
1.0
create master MFC string
Append Character to String
Append 33
To unit_stringC

Append Character to String
Append 49
To unit_stringC

Append Character to String
Append 49
To unit_stringC

Append Character to String
Append 44
To unit_stringC

Append Character to String
Append 85
To unit_stringC

Append Character to String
Append 44
To unit_stringC

Append Character to String
Append 83
To unit_stringC

Append Character to String
Append 76
To unit_stringC

Append Character to String
Append 80
To unit_stringC

Append Character to String

Append 77
To unit_stringC

Append Character to String
Append 13
To unit_stringC

Transmit String
From unit_stringC
Communication Handle comm_handle
Put Status in unitC_string_error

Delay (Sec)
1.0

create master MFC string
Append Character to String
Append 33
To Mmode_stringC

Append Character to String
Append 49
To Mmode_stringC

Append Character to String
Append 49
To Mmode_stringC

Append Character to String
Append 44
To Mmode_stringC

Append Character to String
Append 77
To Mmode_stringC

Append Character to String
Append 44
To Mmode_stringC

Append Character to String
Append 68
To Mmode_stringC

Append Character to String
 Append 13
 To Mmode_stringC

Transmit String
 From Mmode_stringC
 Communication Handle comm_handle
 Put Status in Mmode_stringC_error

Delay (Sec)
 1.0

create master MFC string
Append Character to String
 Append 33
 To Vmode_stringC

Append Character to String
 Append 49
 To Vmode_stringC

Append Character to String
 Append 49
 To Vmode_stringC

Append Character to String
 Append 44
 To Vmode_stringC

Append Character to String
 Append 86
 To Vmode_stringC

Append Character to String
 Append 44
 To Vmode_stringC

Append Character to String
 Append 65
 To Vmode_stringC

Append Character to String

Append 13
To Vmode_stringC

Transmit String
From Vmode_stringC
Communication Handle comm_handle
Put Status in Vmode_stringC_error

Delay (Sec)
1.0

Append Character to String
Append 44
To flow_stringC

Append Character to String
Append 83
To flow_stringC

Append Character to String
Append 44
To flow_stringC

Append Character to String
Append 53
To flow_stringC

Append Character to String
Append 13
To flow_stringC

Transmit String
From flow_stringC
Communication Handle comm_handle
Put Status in flow_stringC_error

Delay (Sec)
1.0

gets the characters from the comm handle
Get Number of Characters Waiting
Communication Handle comm_handle
Put in portC_char_count

Greater?
 Is	portC_char_count
 Than	0

Delay (Sec)
	2.0

Receive N Characters
 Put in	unitC_recv_msg
 Num. Characters	portC_char_count
 Communication Handle	comm_handle
 Put Status in	unitC_recv_status

Get String Length
 Of String	unitC_recv_msg
 Put Result in	C1_length

Delay (Sec)
	2.0

Move String
 From
 To	portC_string

Move String
 From
 To	unitC_recv_msg

Move String
 From
 To	unit_stringC

Move String
 From
 To	Mmode_stringC

Move String
 From
 To	Vmode_stringC

Move String

From
To flow_stringC

Get String Length
Of String unitC_recv_msg
Put Result in C2_length

portC_char_count = 0;

Select PortD

Port D:
appends switch control characters
Append Character to String
Append 27
To portD_string

Append Character to String
Append 2
To portD_string

Append Character to String
Append 68
To portD_string

Append Character to String
Append 13
To portD_string

Transmit String
From portD_string
Communication Handle comm_handle
Put Status in portD_string_error

Delay (Sec)
1.0

create master MFC string
Append Character to String
Append 33
To unit_stringD

Append Character to String

Append 49
To unit_stringD

Append Character to String
Append 49
To unit_stringD

Append Character to String
Append 44
To unit_stringD

Append Character to String
Append 85
To unit_stringD

Append Character to String
Append 44
To unit_stringD

Append Character to String
Append 83
To unit_stringD

Append Character to String
Append 76
To unit_stringD

Append Character to String
Append 80
To unit_stringD

Append Character to String
Append 77
To unit_stringD

Append Character to String
Append 13
To unit_stringD

Transmit String
From unit_stringD
Communication Handle comm_handle
Put Status in unitD_string_error

Delay (Sec)
1.0
create master MFC string
Append Character to String
Append 33
To Mmode_stringD

Append Character to String
Append 49
To Mmode_stringD

Append Character to String
Append 49
To Mmode_stringD

Append Character to String
Append 44
To Mmode_stringD

Append Character to String
Append 77
To Mmode_stringD

Append Character to String
Append 44
To Mmode_stringD

Append Character to String
Append 68
To Mmode_stringD

Append Character to String
Append 13
To Mmode_stringD

Transmit String
From Mmode_stringD
Communication Handle comm_handle
Put Status in Mmode_stringD_error

Delay (Sec)
1.0

create master MFC string

Append Character to String
Append 33
To Vmode_stringD

Append Character to String
Append 49
To Vmode_stringD

Append Character to String
Append 49
To Vmode_stringD

Append Character to String
Append 44
To Vmode_stringD

Append Character to String
Append 86
To Vmode_stringD

Append Character to String
Append 44
To Vmode_stringD

Append Character to String
Append 65
To Vmode_stringD

Append Character to String
Append 13
To Vmode_stringD

Transmit String
From Vmode_stringD
Communication Handle comm_handle
Put Status in Vmode_stringD_error

Delay (Sec)
1.0

create master MFC string
Append Character to String
Append 33
To flow_stringD

Append Character to String
 Append 49
 To flow_stringD

Append Character to String
 Append 49
 To flow_stringD

Append Character to String
 Append 44
 To flow_stringD

Append Character to String
 Append 83
 To flow_stringD

Append Character to String
 Append 44
 To flow_stringD

Append Character to String
 Append 53
 To flow_stringD

Append Character to String
 Append 13
 To flow_stringD

Transmit String
 From flow_stringD
 Communication Handle comm_handle
 Put Status in flow_stringD_error

Delay (Sec)
 1.0

gets the characters from the comm handle
Get Number of Characters Waiting
 Communication Handle comm_handle
 Put in portD_char_count

Greater?

Is portD_char_count
Than 0

Delay (Sec)
2.0
Receive N Characters
Put in unitD_recv_msg
Num. Characters portD_char_count
Communication Handle comm_handle
Put Status in unitD_recv_status

Get String Length
Of String unitD_recv_msg
Put Result in D1_length

Delay (Sec)
2.0

Move String
From
To portD_string

Move String
From
To unitD_recv_msg

Move String
From
To unit_stringD

Move String
From
To Mmode_stringD

Move String
From
To Vmode_stringD

Move String
From
To flow_stringD

Get String Length
Of String unitD_recv_msg

Put Result in D2_length

portD_char_count = 0;

StartChart(Pressure_control);

Select EXRS

EXRS (Reads port A):

Exrs = IsOn(exhaust_relay);

Equal?
Is Exrs
To 1

Set Up Timer Target Value
Target Value 30.0
Up Timer timer_A

Start Timer
Timer timer_A

appends switch control characters
Append Character to String
Append 27
To portA_string

Append Character to String
Append 2
To portA_string

Append Character to String
Append 65
To portA_string

Append Character to String
Append 13
To portA_string

Transmit String
From portA_string
Communication Handle comm_handle

Put Status in portA_string_error

Delay (mSec)
30

create master MFC string
Append Character to String
Append 33
To sensor_stringA

Append Character to String
Append 49
To sensor_stringA

Append Character to String
Append 49
To sensor_stringA

Append Character to String
Append 44
To sensor_stringA

Append Character to String
Append 70
To sensor_stringA

Append Character to String
Append 13
To sensor_stringA

Transmit String
From sensor_stringA
Communication Handle comm_handle
Put Status in sensor_stringA_error

Delay (mSec)
30

gets the characters from the comm handle
Get Number of Characters Waiting
Communication Handle comm_handle
Put in portA_char_count

Greater?
Is portA_char_count
Than 0

Receive N Characters
Put in sensorA_recv_msg
Num. Characters portA_char_count
Communication Handle comm_handle
Put Status in sensorA_recv_status

Get Substring
From String sensorA_recv_msg
Start at Index 7
Num. Characters 4
Put Result in flowrateA_string

Convert String to Float
Convert flowrateA_string
Put Result in flowrateA

Get String Length
Of String sensorA_recv_msg
Put Result in SA1_length

Move String
From
To portA_string

Move String
From
To sensorA_recv_msg

Move String
From
To sensor_stringA

Move String
From
To flowrateA_string

Get String Length
Of String sensorA_recv_msg
Put Result in SA2_length

portA_char_count = 0;

PauseTimer(timer_A);
time_A = timer_A;

Select CO2RS

CO2RS (Reads Port B):

CO2rs = IsOn(CO2_relay);

Equal?
Is CO2rs
To 1

appends switch control characters
Append Character to String
Append 27
To portB_string

Append Character to String
Append 2
To portB_string

Append Character to String
Append 66
To portB_string

Append Character to String
Append 13
To portB_string

Transmit String
From portB_string
Communication Handle comm_handle
Put Status in portB_string_error

Delay (mSec)
30
create master MFC string
Append Character to String
Append 33
To sensor_stringB

Append Character to String
  Append 49
  To sensor_stringB

Append Character to String
  Append 49
  To sensor_stringB

Append Character to String
  Append 44
  To sensor_stringB

Append Character to String
  Append 70
  To sensor_stringB

Append Character to String
  Append 13
  To sensor_stringB

Transmit String
  From sensor_stringB
  Communication Handle comm_handle
  Put Status in sensor_stringB_error

Delay (mSec)
  30
 gets the characters from the comm handle
Get Number of Characters Waiting
  Communication Handle comm_handle
  Put in portB_char_count

Greater?
  Is portB_char_count
  Than 0

Delay (Sec)
  2.0

Receive N Characters
  Put in sensorB_recv_msg

Num. Characters portB_char_count
Communication Handle comm_handle
Put Status in sensorB_recv_status

Get Substring
From String sensorB_recv_msg
Start at Index 7
Num. Characters 4
Put Result in sflowrateB

Convert String to Float
Convert sflowrateB
Put Result in flowrateB

Get String Length
Of String sensorB_recv_msg
Put Result in SB1_length

Move String
From
To portB_string

Move String
From
To sensorB_recv_msg

Move String
From
To sensor_stringB

Move String
From
To sflowrateB

Get String Length
Of String sensorB_recv_msg
Put Result in SB2_length

portB_char_count = 0;

Select O2RS

O2RS (Reads Port C):

```
O2rs = IsOn(O2_relay);
Equal?
 Is      O2rs
 To      1

appends switch control characters
Append Character to String
 Append        27
 To      portC_string

Append Character to String
 Append        2
 To      portC_string

Append Character to String
 Append        67
 To      portC_string

Append Character to String
 Append        13
 To      portC_string

Transmit String
 From portC_string
 Communication Handle       comm_handle
 Put Status in  portC_string_error

Delay (mSec)
         30

create master MFC string
Append Character to String
 Append        33
 To      sensor_stringC

Append Character to String
 Append        49
 To      sensor_stringC

Append Character to String
 Append        49
 To      sensor_stringC

Append Character to String
```

Append 44
To sensor_stringC

Append Character to String
Append 70
To sensor_stringC

Append Character to String
Append 13
To sensor_stringC

Transmit String
From sensor_stringC
Communication Handle comm_handle
Put Status in sensor_stringC_error

Delay (mSec)
30

gets the characters from the comm handle
Get Number of Characters Waiting
Communication Handle comm_handle
Put in portC_char_count

Greater?
Is portC_char_count
Than 0

Delay (Sec)
2.0

Receive N Characters
Put in sensorC_recv_msg
Num. Characters portC_char_count
Communication Handle comm_handle
Put Status in sensorC_recv_status

Get Substring
From String sensorC_recv_msg
Start at Index 7
Num. Characters 4
Put Result in sflowrateC

Convert String to Float
 Convert sflowrateC
 Put Result in flowrateC

Get String Length
 Of String sensorC_recv_msg
 Put Result in SC1_length

Move String
 From
 To portC_string

Move String
 From
 To sensorC_recv_msg

Move String
 From
 To sensor_stringC

Move String
 From
 To sflowrateC

Get String Length
 Of String sensorC_recv_msg
 Put Result in SC2_length

portC_char_count = 0;

Select N2RS

N2RS (Reads Port D):

N2rs = IsOn(N2_relay);
Equal?
 Is N2rs
 To 1

Set Up Timer Target Value
 Target Value 30.0
 Up Timer timer_d

Start Timer
 Timertimer_d

appends switch control characters
Append Character to String
 Append 27
 To portD_string

Append Character to String
 Append 2
 To portD_string

Append Character to String
 Append 68
 To portD_string

Append Character to String
 Append 13
 To portD_string

Transmit String
 From portD_string
 Communication Handle comm_handle
 Put Status in portD_string_error

Delay (mSec)
 30

create master MFC string
Append Character to String
 Append 33
 To sensor_stringD

Append Character to String
 Append 49
 To sensor_stringD

Append Character to String
 Append 49
 To sensor_stringD

Append Character to String
 Append 44
 To sensor_stringD

Append Character to String
Append 70
To sensor_stringD

Append Character to String
Append 13
To sensor_stringD

Transmit String
From sensor_stringD
Communication Handle comm_handle
Put Status in sensor_stringD_error

Delay (mSec)
30

gets the characters from the comm handle
Get Number of Characters Waiting
Communication Handle comm_handle
Put in portD_char_count

Greater?
Is portD_char_count
Than 0

Delay (Sec)
2.0

Receive N Characters
Put in sensorD_recv_msg
Num. Characters portD_char_count
Communication Handle comm_handle
Put Status in sensorD_recv_status

Get Substring
From String sensorD_recv_msg
Start at Index 7
Num. Characters 4
Put Result in sflowrateD

Convert String to Float

Convert sflowrateD
Put Result in flowrateD

Get String Length
Of String sensorD_recv_msg
Put Result in SD1_length

Move String
From
To portD_string

Move String
From
To sensorD_recv_msg

Move String
From
To sensor_stringD

Get String Length
Of String sensorD_recv_msg
Put Result in SD2_length

portD_char_count = 0;

PauseTimer(timer_d);
time_d = timer_d;

Select EXRS

Powerup Chart:

Start Chart
Chart Dome_sensors
Put Status In dome_sensor_chart

Start Chart
Chart Read_Pressure
Put Status In read_pressure_chart

Start Chart
Chart Read_Sensors
Put Status In read_sensors_chart

```
Turn On
        Mixing_pump

Start Chart
  Chart MFC_Setup
  Put Status In  mfc_setup_chart
```

APPENDIX B

ELECTRICAL SCHEMATIC

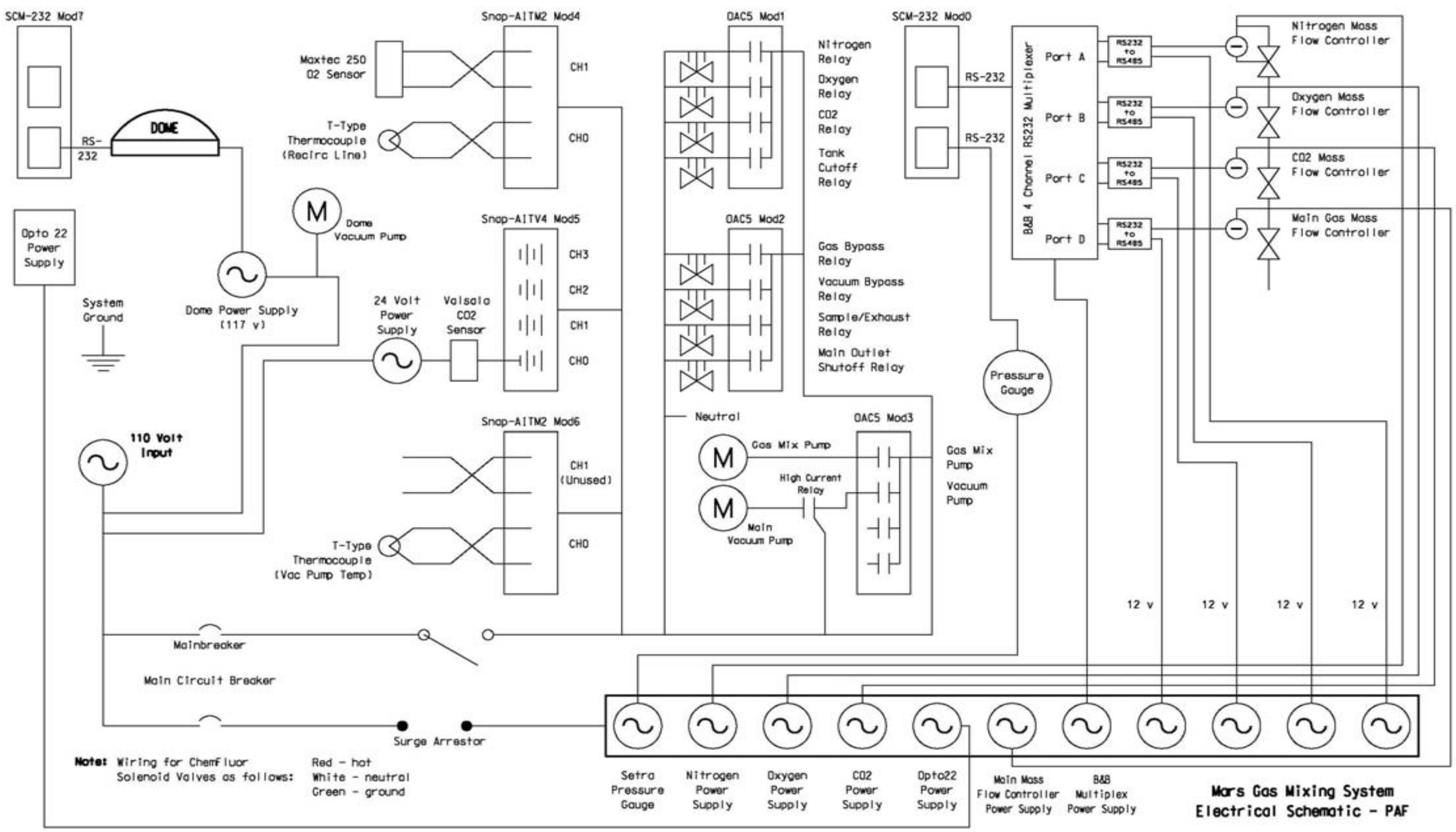

Figure B1 - Electrical wiring diagram for the gas mixing assembly.

VITA

April Lovelady

105 Sunset

Crockett, TX 75835

April Lovelady was born December 4, 1978 to Henry and Dorothy Lovelady. She spent the first five years of her life growing up in Crockett, TX. Her family then relocated to Odessa, TX where she lived for the next 13 years. She graduated from Odessa High School in 1997 and went on to attend Texas A&M University. In December 2002, she graduated with a degree in biological systems engineering. She chose then to continue her education at A&M and pursue a Master of Science in biological and agricultural engineering.

During her graduate career at A&M, she was selected by NASA to participate in the graduate co-op program at Kennedy Space Center. It was here that she conducted the research for her thesis. Eventually, she was hired by Kennedy Space Center as a bioengineer. She works in the area of low pressure controlled environments and atmospheric regeneration.