CHARACTERIZATION AND FEASIBILITY OF A PORTABLE OXYGEN CONCENTRATOR FOR USE WITH A MASS CASUALTY VENTILATOR

by

Paul Robert Williams

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Paul Robert Williams

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The following individuals read and discussed the thesis submitted by student Paul Robert Williams, and they evaluated his presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

Michelle Sabick, Ph.D.	Chair, Supervisory Committee
John Gardner, Ph.D.	Member, Supervisory Committee
Don Plumlee, Ph.D.	Member, Supervisory Committee
Trevor Lujan, Ph.D.	Member, Supervisory Committee
Lonny Ashworth, M.Ed.	Member, Supervisory Committee

The final reading approval of the thesis was granted by Michelle Sabick, Ph.D., Chair of the Supervisory Committee. The thesis was approved for the Graduate College by John R. Pelton, Ph.D., Dean of the Graduate College.

DEDICATION

To Alice and my parents, Mom and Dad.

ABSTRACT

The American Association for Respiratory Care has reported a need to stockpile 5,000-10,000 mass casualty ventilators with supplemental oxygen in preparation for pandemic emergencies (1). The American Medical Association specifies oxygen concentrators supply oxygen at 5 liters per minute at ≥90% purity (2). However, these design specifications may not be the most efficient use of system resources in portable oxygen concentrators using pressure swing adsorption. A testbed was developed to investigate the system performance of an oxygen concentrator while altering the system inlet and outlet pressures and flow rates. This investigation demonstrates that a more efficient portable oxygen concentrator, which provides oxygen at <90% purity, should be considered and developed for potential use with a mass casualty ventilator.

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LIST OF ABBREVIATIONS

AARC	American Association for Respiratory Care
AMA	American Medical Association
ARF	Acute Respiratory Failure
F_{IO2}	Percentage of Inspired Oxygen
LPM	Liters per Minute
MCV	Mass Casualty Ventilator
PaO_2	Arterial Partial Pressure
POC	Portable Oxygen Concentrator
PSA	Pressure Swing Adsorption
PSI	Pounds per Square Inch
SaO_2	Arterial Oxygen Saturation
SLPM	Standard Liters per Minute

CHAPTER ONE: INTRODUCTION

Chapter Introduction

- There is a demand for a portable oxygen concentrator (POC) device for use with a mass casualty ventilator (MCV) as described by the American Association of Respiratory Care (AARC).
- Current MCV devices do not provide their own oxygen supply.
- Current POC devices generate low volumes of highly concentrated oxygen gas. Similarly, oxygen tanks are used to provide varying flow rates of pure oxygen gas.
- Oxygen therapy is administered to a patient in order to increase their blood oxygen concentration to normal levels. This can be accomplished by providing low volumetric flow rates of highly concentrated oxygen gas mixed with ambient air or by providing higher flow rates of less concentrated oxygen gas.

Justification for a Portable Oxygen Concentrator System Designed for Use with a Mass Casualty Ventilator

American Association for Respiratory Care Guidelines

This research is intended to determine whether a unique POC design should exist that could be used with a MCV. Such a device is recommended by the AARC:

> Following the tragedy of September 11, 2001 and the anthrax mailings of the same year, the U.S. medical community has undertaken steps to deal with a potential event that could result in a large number of patients requiring mechanical ventilation. More recently, the threat from nature, in the form of the Avian Flu (H5N1), has accelerated preparations for a pandemic flu, which might result in thousands of patients requiring mechanical ventilation.
>
> In the United States, the treatment for acute respiratory failure (ARF) is supplemental oxygen and mechanical ventilation. Thus we can expect a surge in demand for ventilators if a pandemic of H5N1 were to occur. (1)

Current State of Mass Casualty Ventilators

There are commercially available MCV devices developed in response to the AARC guidelines. The AARC recommends stockpiling 5,000 to 10,000 ventilators that are easy to operate, require minimal training, have the "features and capabilities that can support patients with ARF," and can operate for 4-6 hours without electricity or gas supplies. (1)

As Allied Health Care Products Inc. describes their MCV's shown in Figures 1.1 and 1.2:

> With input from the medical community, disaster specialists, and first responders, Allied has developed the Mass Casualty Ventilator (MCV) 100, a 14-pound, battery powered, weather resistant ventilator featuring a simple user interface and the necessary ventilation parameter options to sustain patients during a mass casualty event. The MCV100 meets all requirements in the American Association for Respiratory Care's "Guidelines for Acquisition of Ventilators to Meet Demands for Pandemic Flu and Mass Casualty Incidents" report of May 25, 2006 and has received 510k approval from the Food and Drug Administration. (3)

Allied has developed additional mass casualty devices that include the MCV200, and the EPV 100 and 200. These ventilators use batteries, standard AC power, or pneumatic systems for operation. The MCV units, depending on usage, are expected to operate for 7 hours using the on-board lead acid battery. The EPV devices use D cell batteries and can operate for 48 hours. (4)

Figure 1.1 MCV200 from Allied Healthcare Products (4)

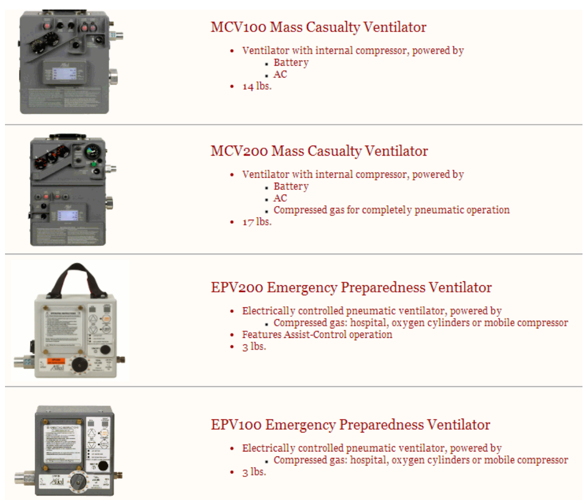


Figure 1.2 Allied Healthcare Mass Casualty Ventilators (4)

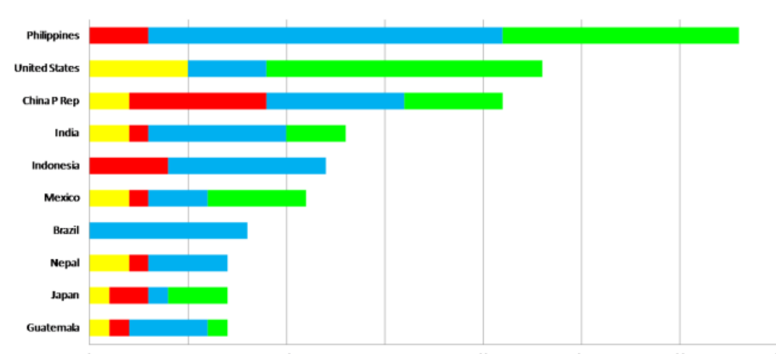
None of these products produce supplemental oxygen. Both the MCV 100 and 200 require continuous oxygen supplied at 40-87PSI while the EPV units suggest using D-sized oxygen cylinders, which are expected to last one hour each.

Mass Casualty Events

There are many examples in recent world history where a mass casualty ventilator with supplemental oxygen would have been beneficial. As Blakeman and Branson write, “Mass casualty events and disasters, both natural and human-generated, occur frequently around the world. Military conflicts, terrorist activities, epidemic and pandemic disease, floods, earthquakes, hurricanes/typhoons, and tsunamis have the potential to destroy infrastructure and strain resources while generating scores of injured or ill victims in need of these resources.” (5) They go on to describe oxygen as the “critical consumable resource in disaster management.” A portable device that could generate oxygen on-site without additional power sources or equipment would be valuable in most of the emergency situations listed by Blakeman and Branson.

In 2011, the United States reported the second highest number of natural disasters, 23 events of a reported 141, according to the Center for Research on the Epidemiology of Disasters as shown in Figure 1.3.

Figure 3 – Top 10 countries by number of reported events in 2011



	Philippines	United States	China P Rep	India	Indonesia	Mexico	Brazil	Guatemala	Japan	Nepal	Total
Climatological	0	5	2	2	0	2	0	1	1	2	14
Geophysical	3	0	7	1	4	1	0	1	2	1	20
Hydrological	18	4	7	7	8	3	8	4	1	4	64
Meteorological	12	14	5	3	0	5	0	1	3	0	43
Total	33	23	21	13	12	11	8	7	7	7	141

Figure 1.3 Top 10 Countries by Number of Reported Events in 2011 (6)

These natural disasters, as well as the H5N1flu, terrorist attacks, and anthrax mailings events provide ample reason to develop a POC for use in an emergency mass casualty event.

The Value of Oxygen Therapy with a Mass Casualty Ventilator

Supplemental oxygen therapy is required in both chronic and acute conditions when a patient has low blood oxygen concentration. As Tiep describes, “It is generally accepted that patients with $PaO_2 \leq 55$mm Hg (arterial partial pressure) or $SaO_2 \leq 88\%$ (arterial oxygen saturation) are hypoxemic and, thus, require oxygen.” (7)

There are many oxygen systems available for patients with chronic conditions such as chronic obstructive coronary disease. Oxygen can be stored in tanks and delivered and exchanged with gas companies for home use. Smaller tanks can be placed in carts, which provide patients some mobility. Some oxygen concentrators are designed for home use, which are powered using standard wall outlets. There are also POC’s designed to be small and lightweight so that patients can carry the device with them in small bags. All of these systems are designed for long term, frequent use.

There are no POC’s designed specifically for use with acute conditions. In an acute case, oxygen therapy can be administered in a hospital, ambulance, or other medical facility. In the case of a mass casualty event, emergency responders and available systems would be heavily taxed. The AARC report writes that “In the wake of a pandemic flu with a virulent flu strain like H5N1, patients with survivable illness will die from lack of resources unless more ventilators that have the capabilities to provide ventilatory support for patients with ARF are readily available.” (1)

Patients of a pandemic emergency could be suffering with acute conditions where:

> Some disease states may be accompanied by a sudden fall in PaO_2. In acute hypoxemia, the body has not yet had an opportunity to adapt by invoking its compensatory mechanisms. As a general rule, supplemental oxygen therapy is warranted when the $PaO_2 < 60$ mm Hg or the $SaO_2 < 90\%$...Supplemental oxygen therapy should be initiated and monitored in order to maintain arterial oxygen tensions substantially above 60 mm Hg (usually above 70 mm Hg). (7)

Within the context of existing POC’s, there is a market demand for a device capable of providing oxygen therapy during an emergency situation.

Existing POC’s

There are many POC’s commercially available for patients with chronic conditions. The primary design features for these POC’s are weight, size, ease-of-operation, cost, and oxygen response. A selection of available units is shown in Figure 1.4. “The medical oxygen concentrator typically produces a 90-93% O_2 enriched product gas from ambient air at a rate of ≤10 liters/minute (LPM) for individual use.” (8)

Figure 1.4 Sample of Commercial Portable Oxygen Concentrators (9)

Chatburn and Williams write while testing four POC systems:

> Because all oxygen concentrators operate from essentially the same engineering and design principles, some technical and performance trade-offs have to be made in the design of a POC to produce various specifications and features. The limitations of current battery and compressor technologies force a compromise between size, weight, and the amount of oxygen delivered per minute (oxygen minute volume), so POC performance specifications differ markedly among brands and models.

They go on to write that:

> The large differences among the tested POC's highlight the importance of understanding POCs' performance characteristics and titrating the POC setting to the patients requirements. Our results are consistent with previous studies of pulse-dose oxygen devices, and support the AARC recommendations. (10)

These comments are useful because much of this research is intended to better understand and define POC performance. It is important to recognize the balance between required system performance and the energy expense from system component selection.

Oxygen Tanks

Another common method of providing oxygen to patients involves using compressed oxygen stored in a gas cylinder. Oxygen cylinders are available in a selection of sizes to accommodate particular demands. H-sized cylinders are large tanks weighing more than 200 pounds and contain 6,900 liters of oxygen while D-sized cylinders weigh 9 pounds and contain around 250 liters of oxygen. (7) Operating with a continuous flow of 2 liters/minute, these cylinders are expected to last 2.5 days and 2 hours, respectively.

It should be noted that cylinders only provide a means of oxygen storage, not production. It is difficult to estimate the quantity or size of cylinders that would be required for mass casualty events due to the variability of demand. There is significant value in producing oxygen gas on demand due to the unpredictability of a mass casualty event. In addition, cylinders used to store oxygen for use in an emergency would need to be monitored and maintained. Without regular maintenance, cylinders' gaskets could fail, which would allow stored oxygen to leak. This would deplete the amount of oxygen available during an emergency situation and could be a significant fire hazard.

Considerations for a POC Designed for Use with an MCV

Existing POC's are used primarily to provide supplemental oxygen to a patient who is already breathing. Small volume pulses of highly concentrated oxygen are delivered to the patient through nasal cannulas. POC's typically use a battery and can operate between 3-5 hours at ≥90% oxygen at a flow rate up to 5 liters per minute. As Rao, Farooq, and Krantz describe, "An oxygen-concentrating device using atmospheric air as feed that is sufficiently small in size and lighter in weight (and at the same time delivers ≥90% pure oxygen at a rate of 5 LPM required by the American Medical Association, AMA) can significantly improve the quality of life for those people who need oxygen therapy to overcome lung insufficiency." (2) While similarly describing a POC device Fludger and Klein suggest, "Ideally, a portable ventilator, including oxygen and battery supplies, should be lightweight, robust, and able to function in demanding environments with little maintenance." (11)

Unique among current POC devices, in an MCV application it may be more beneficial to provide oxygen at a lower concentration and higher flow rate rather than the typical low flow rate of highly concentrated oxygen. Tiep describes the effect on patient F_{IO2} (percentage of inspired oxygen) treated with room air and increasing volumes of pure oxygen via nasal cannulas:

It is useful to remember that the patient does not receive anything resembling 100% oxygen. Low-flow nasal cannula delivery is supplementation, and is a small amount of pure oxygen that is entrained into a much larger volume of atmospheric gas, which is 20.9% oxygen. Each increase in liter-flow of 1.0 L/min adds approximately 3-4% to the fraction of inspired oxygen (F_{IO2}). Oxygen set at 1.0 L/min increases the F_{IO2} to 24%, and 2.0 L/min yields an F_{IO2} of 28%.These small increases in the F_{IO2} are adequate to reverse hypoxemia in most patients with chronic lung disease. (7)

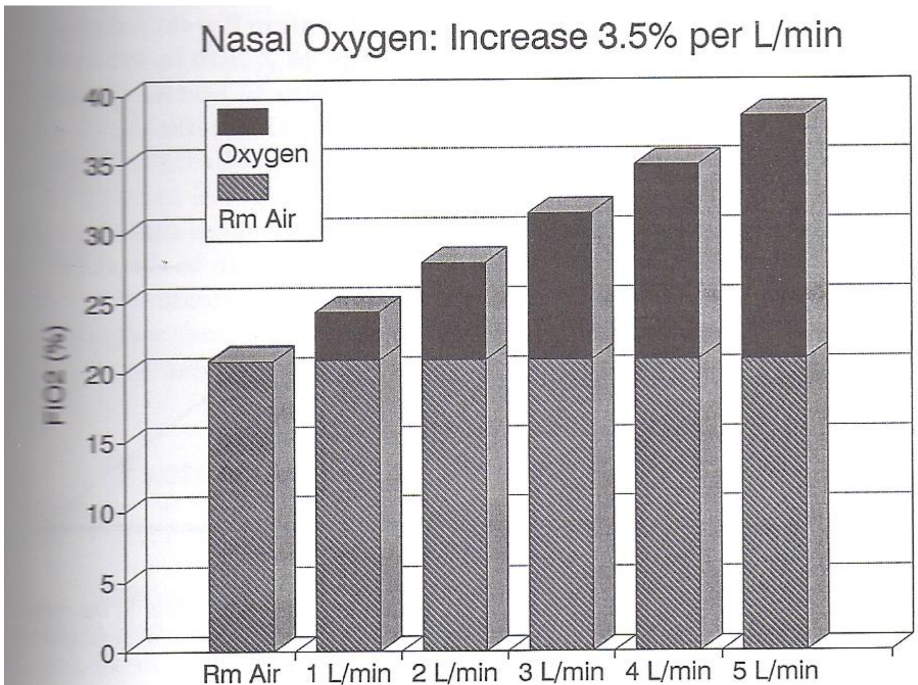


Figure 1. The FIO_2 measurements from breathing room air and supplemental oxygen at various liter-flows. Supplemental oxygen increases the FIO_2 by about 3.5% for each L/min.

Figure 1.5 Effects on F_{IO2} Regarding Oxygen Flow Rate (7)

This physiological response means that a patient being ventilated, and not mixing highly concentrated oxygen with ambient air, should have a similar F_{IO2} recovery receiving lower concentrated oxygen at an appropriate flow rate. As Fludger and Klein write, "The ability to control inspired oxygen concentration allows a balance to be struck between the patient's oxygen requirements and gas consumption, and the adverse effects of oxygen." (11)

Ideal Candidate for a Unique POC Device

Current POC devices generate high concentrations of oxygen while pure compressed oxygen can be stored in tanks and used on demand. In many cases, when a patient is prescribed oxygen therapy, this highly concentrated oxygen is mixed with ambient air to provide a lower concentration of oxygen gas. This research investigates the hypothesis that an existing POC system can operate more efficiently by using a less powerful compressor or with different system settings, which will generate more oxygen gas but at a lower concentration with a higher flow rate.

To test this hypothesis, a commercially available PSA system is characterized and tested in different configurations. A unique design should be considered for development if more oxygen can be produced while using less inlet air pressure, essentially a less-powerful compressor, or if more oxygen gas is produced while operating with system settings outside of the manufacturer specifications.

Chapter Summary

- The AARC has recommended stockpiling 5,000-10,000 MCV devices with supplemental oxygen.
- Currently, no MCV devices provide their own oxygen. Instead, they rely on alternate oxygen supplies.

- There are many examples in history where an MCV with supplemental oxygen would be beneficial, particularly in dealing with events like the H5N1 virus.
- Current available POC devices are designed for use with chronic conditions. Developing a POC device for use with acute conditions should be considered.
- A patient being ventilated will have a similar F_{IO2} recovery receiving lower concentrated oxygen when compared with a patient receiving supplemental pure oxygen via nasal cannulas.
- Oxygen tanks are also used for oxygen therapy but are only used as oxygen storage, not generation. Oxygen tanks must be refilled and maintained.
- A unique POC design may exist when operating outside of normal POC specification. This study investigated a system operating at a higher flow rate generating oxygen at <90% purity.

CHAPTER TWO: BACKGROUND

Chapter Introduction

- There are many techniques used to separate oxygen from atmospheric air.
- Pressure Swing Adsorption (PSA) is the most appropriate technique for separating oxygen in a POC.
- Zeolites are a crystalline material that can be used to adsorb component gases from atmospheric gas.
- The compressor used within a PSA system consumes the majority of power used in a POC. Any reduction in compressor size and power requirements greatly impacts the POC size, weight, cost, and efficiency.

Oxygen Separation Techniques

There are many ways to produce oxygen or separate it from atmospheric air. Joseph Priestly produced oxygen gas, for the first recorded time in history, using a lens to focus sunlight on mercuric oxide in 1774. (12)

Other techniques for producing or isolating oxygen include electrolysis where oxygen is separated from hydrogen in water, using an electrochemical cell to transport oxygen across a membrane (13), or using an oxygen "sieve" driven by pressure differentials to separate oxygen from ambient air. Ashcraft and Swenton write that, "Several methods exist for the process of separating air to produce purified oxygen. Membranes, cryogenic distillation, and pressure swing adsorption are the most common techniques.” (14) Meanwhile, Tiep suggests that there are two primary types of oxygen concentrators, one of which utilizes a molecular sieve while the other uses membranes. The molecular sieve uses zeolite materials to isolate oxygen from the nitrogen and argon components of atmospheric air and can reach oxygen concentrations of 99%, whereas oxygen membranes are only capable of generating 40% oxygen concentrations. (7)

It is important to consider all of the oxygen generation or isolation techniques when considering a portable oxygen concentrator. However, some techniques are too costly, too inefficient, too large, require too high or low temperatures or pressures, or require feed materials like water, which are not necessarily available in a mass casualty event. These considerations help determine which candidate system is most appropriate for a POC designed for use with an MCV.

Oxygen Membranes

Oxygen membranes act as filters, removing nitrogen and argon via “molecular barriers.” (14) The technique, although inexpensive, utilizes surface area to “screen” the passing air and is typically larger than what is considered portable as the modules can be a few feet in length. This technique generally produces oxygen at low concentrations around 40%. Most of the commercial versions of the membrane gas separation device are used to isolate nitrogen from ambient air rather than oxygen. Figure 2.1 describes the membrane technique used to isolate component gases from ambient air.

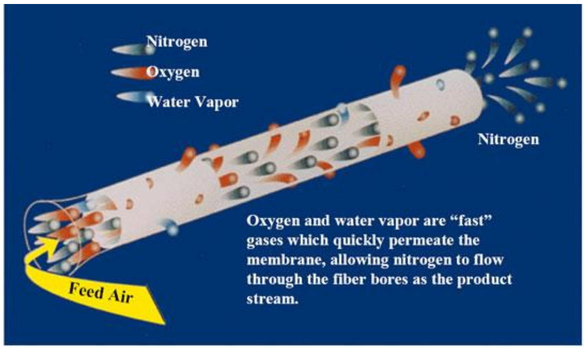


Figure 2.1 Oxygen Membrane Behavior (15)

Cryogenic Air Separation

"Cryogenic air separation processes are the leading process for producing 99% oxygen in bulk supply." (14) This process cools air to its liquid phase and then separates the various components. This is useful because the component gases are produced in a dense state and are therefore convenient for containment and transportation. However, the process requires large, expensive equipment and is only suitable for bulk production and distribution. Similar to the oxygen membranes, the size of this technology is not appropriate for a POC application.

Pressure Swing Adsorption

PSA is another technique used to separate oxygen from atmospheric air and is the method investigated with this research. This technique is used in most POC devices and is likely the most appropriate for an emergency response device. Rao, Farooq, and Krantz describe an oxygen concentrator using PSA as:

> An oxygen concentrator using PSA technology consists of one or more adsorption columns, a compressor and several valves to control the pressure cycling and flow sequence of atmospheric air fed to the system. The adsorption columns and the compressor are the two principal contributing factors to the size and weight of the device. **The main issues for size and weight reduction are miniaturization of the adsorption column and the compressor**. (2)

Within a PSA system, air is pressurized in a chamber filled with zeolite material. Component gases within the contained atmospheric air, primarily nitrogen and argon, are adsorbed on the surface of the zeolite. The chamber, now containing a gas primarily consisting of oxygen, is vented to a desired oxygen storage chamber or to an outlet hose. Then the zeolite chamber is depressurized, which purges the adsorbed gas back into the atmosphere. This system of pressurizing a chamber filled with zeolite, removing the oxygen enriched gas, and purging the depleted gas to atmosphere is considered PSA. This process is illustrated in Figure 2.2.

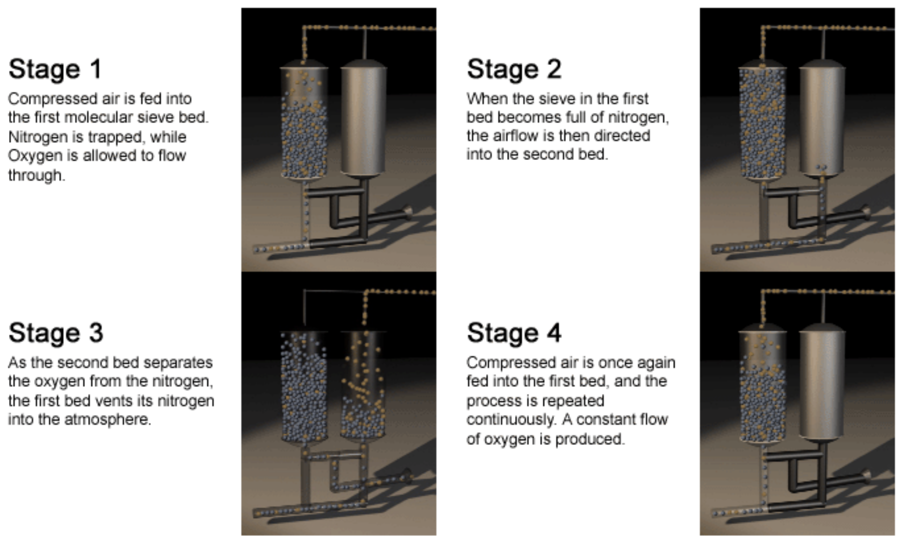


Figure 2.2 Pressure Swing Adsorption Process (16)

PSA is the primary technique used to produce oxygen for medical applications. Many large hospitals have their own PSA system on-site providing all needed oxygen for the facility. Even larger PSA systems are operated and used to provide oxygen for an entire community or region. This same PSA technique can be scaled from these large industrial settings to small portable units.

Zeolites

Zeolites are a crystalline material generally comprised of silicon and aluminum. (17) Example zeolites are shown in Figure 2.3. The zeolites used within PSA systems are usually bead shaped and vary in size depending on their function and role within the adsorption bed.

Figure 2.3 Sample Zeolite Materials (18)

Multiple zeolite types are used within a PSA system, each designed to more readily adsorb particular gas molecules. “The shape-selective properties of zeolites are also the basis for their use in molecular adsorption. The ability preferentially to adsorb certain molecules, while excluding others, has opened up a wide range of molecular sieving applications.” (17)

Peter Scott describes the ability of zeolite to adsorb nitrogen with two steps. The first step occurs when nitrogen is attracted to zeolite because of “the exposed cations of the zeolite crystal.” A dipole is formed and “the zeolite selectively adsorbs nitrogen,” because “nitrogen is more polarizable than oxygen.” After attracting the nitrogen to the zeolite, “the cage like structures of zeolite have been carefully designed to allow only nitrogen to pass to their inside and to exclude the larger oxygen molecules.” (19)

The selected zeolites are layered within a PSA column in order to make the most efficient use of volume. It is more effective to adsorb the component gases in a striated manner rather than in a mixed arrangement. Argon is more difficult to adsorb because nitrogen is less selective and will adsorb to sites within the zeolite intended to collect argon. For example, in their attempts to identify the most effective ratio of selective zeolite materials, Ashcroft and Swenton determined a PSA system was more effective using a layer of LiAgX zeolite, preferentially good at separating nitrogen, and then a layer of AgA zeolite, preferentially good at separating argon, than simply mixing the two zeolites in an adsorption bed. (14)

PSA System Components

In addition to zeolite chambers, the air compressor and power source are the primary components of a PSA system. A POC device typically uses batteries to store power for the compressor. Compressor selection is paramount within a POC device because any reduction in air compressing requirements reduces the required power to operate the entire system. In order to minimize power consumption, which sympathetically reduces the battery weight and cost, it is important to determine the most efficient pressure differential between the zeolite chamber and atmosphere.

Chapter Summary

- There are many techniques and technologies designed to separate oxygen from ambient air. Many of them are not appropriate for use with a POC application.
- Oxygen membranes filter component gases from atmospheric air. This technique is primarily used to isolate nitrogen and can only generate oxygen concentrations around 40%.
- Cryogenic air separation is used to produce 99% of the oxygen supply in the world. (14) However, this technique of isolating oxygen requires a large, industrial facility and does not scale to a portable device size.
- Pressure swing adsorption is the technique most commonly used in POC devices.
- Zeolites are alumina silicate materials with a precise crystalline structure that can be used as a molecular sieve. Zeolites can be designed to adsorb specific gases from atmospheric air when the air is pressurized.
- In addition to zeolites, the compressor and battery are the other primary components in a POC system. Compressing air requires the majority of the power consumed in a PSA system. If a smaller, more efficient compressor is used, less power will be required to operate the system.
- A unique POC design may exist by altering the operation of current POC devices featuring PSA technology. This design may provide more oxygen production and feature a more efficient system operation.

CHAPTER THREE: DESIGN AND FABRICATION OF THE TESTBED

Chapter Introduction

- The testbed consists of a Sequal Workhorse using an ATF PSA module and various sensors including an oxygen sensor, a temperature sensor, a flow rate sensor, pressure gauges, and a power gauge.
- Many of the sensor readings were incorporated into a Labview VI, which collected, compiled, and exported the data to Excel files.

Testbed Requirements

A testbed was developed and used to determine if an existing POC could be made more efficient by changing the design specifications for use with an MCV. Figure 3.1 shows the general air flow through the PSA testbed system. Sensors were incorporated throughout the system to monitor the system performance.

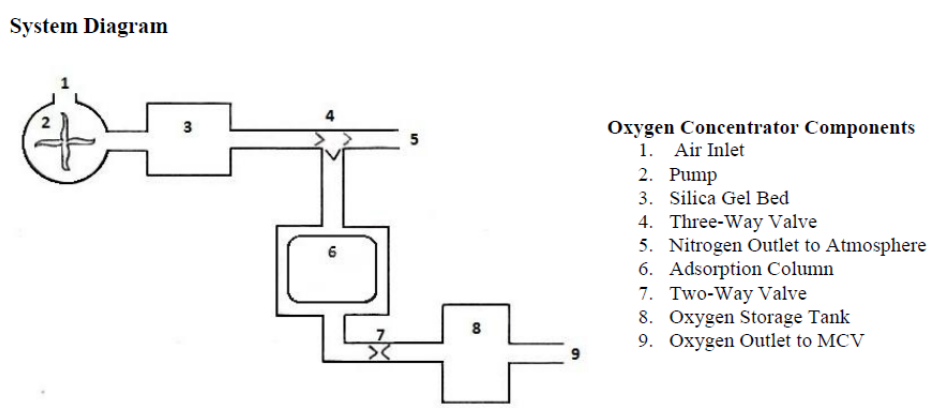


Figure 3.1 System Flow Diagram (20)

A Sequal Workhorse 8 Oxygen System was selected and purchased to use within the testbed system. Purchasing an existing PSA system and manipulating its inlet and outlet settings was more appropriate for this research rather than building an entire PSA system. The Workhorse included design specifications and an expected performance that could be verified and used as a baseline as the system was adapted.

The Workhorse device uses 12 cylindrical chambers filled with zeolite whose entrances are opened and closed by a rotating plate attached to motor. This off-the-shelf device is designed to produce oxygen at 90% purity with a flow rate of 3.8 standard liters per minute (SLPM).

The entire Workhorse system weighs 43 pounds, which includes the sheet metal, output flow gauge, system "hour meter," ATF module, and the compressor. This system's weight and size is not suitable as a POC designed for use with an MCV, but it does provide an appropriate and convenient system to investigate PSA performance. Also, the Workhorse system produces oxygen within the scale of many POC devices at 90% oxygen flowing at nearly 5 LPM.

In addition to the Workhorse device, sensors and controls were selected and incorporated into the testbed. The sensors were used in different locations throughout the testbed to monitor gas pressure, the volumetric flow rate, the temperature of the gas passing over the oxygen sensor, the oxygen concentration being produced by the POC, as well as the power consumed by the Workhorse system. A regulator, air filter, and many quick connect fittings and hoses were also added to the system.

Using the quick connectors, the sensors could be attached in-line to the inlet or outlet positions on the system. The sensors were selected to be accurate through the range of 0-30 PSI, with volumetric gas flows of 0-200 SLPM, in oxygen concentrations of 0-100%, and through all of the temperatures experienced at both the inlet and outlet during the testing.

Digital sensor readings were recorded using an NI-6008 DAQ board in conjunction with a Labview program. The program compiled the data along with matching timestamps and saved the data to an assigned Excel file. Analog sensor readings were collected and entered into a generic form that was incorporated with each digitally exported Excel file.

The Equipment Used for Testing

ATF Module and Sequal Workhorse

The ATF module is a device developed by Sequal illustrated in Figure 3.2. It incorporates 12 cylinders filled with select zeolites with a unique rotary plate system that simplifies the PSA process. As the plate slowly rotates, it "opens" and "closes" the zeolite cylinders. This eliminates the need for control electronics and pneumatics.

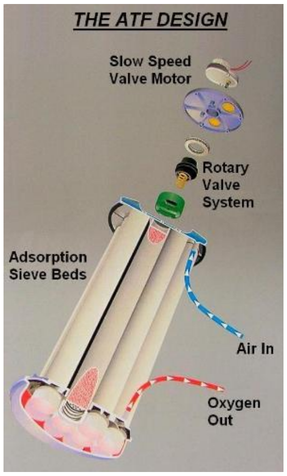


Figure 3.2 Sequal ATF Module (21)

The Workhorse system incorporates the Sequal ATF module with an air compressor, heat exchanger, output flow control, and power distribution components, which are shown in Figure 3.3. The assembly is simple to adapt, which is ideal for a testbed. Quick connectors were attached at the outlet of the compressor, before and after the heat exchanger, and at the air inlet and oxygen outlet locations. This allowed the test sensors to be moved throughout the system easily and quickly.

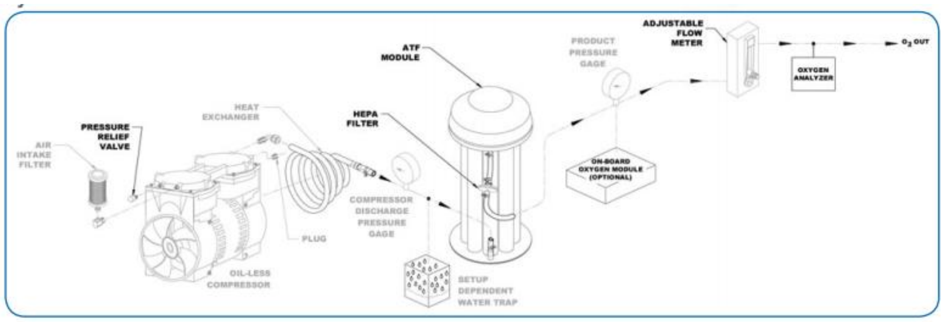


Figure 3.3 Sequal Workhorse System (22)

<u>Computer with Labview and Excel</u>

A computer containing the software Labview was used as a data acquisition station. A Labview VI was developed to collect sensor readings from the oxygen sensor, the temperature sensor, the flow sensor, a time stamp, as well as other electronic signals used to establish sensor readings. The data was compiled within Labview and exported to an assigned Excel document.

Data was collected at frequencies appropriate for each specific test. The sample rate varied between 1-200 Hz depending on the data resolution required and the specific goals for each test.

System Sensors

This system uses many sensors throughout the testbed. A 12 volt power supply, a 5 volt supply from the DAQ board, and various electronic components were used to supply the required voltages to the sensors, some of which are shown in Figure 3.4.

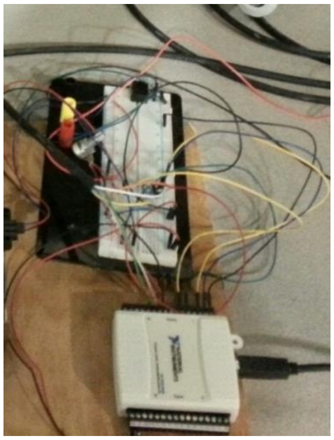


Figure 3.4 Breadboard and Electronics

Oxygen Sensor

An Apogee SO-210 fast response oxygen sensor and thermistor was purchased for this testing. A flow through head accessory was also purchased and used as shown in Figure 3.5. The sensor is accurate within 0-100% oxygen environments. It provides a 14 second response time, which is the time required to read 90% of a saturated response. Its operating range is -20 to 60 C, 0 to 100% humidity, and up to 20.3 PSI. Before use, the sensor was calibrated following instructions provided within the documentation materials. The digital oxygen concentration readings were compiled within the Labview VI. A reading of one millivolt provided by the sensor was equivalent to 4% of oxygen content in the tested gas, which provided relatively low resolution data. The readings were averaged through many samples to improve the accuracy of the reported values.

Figure 3.5 Apogee Oxygen Sensor

Pressure Sensor

Analog pressure gauges, such as the one shown in Figure 3.6, were used throughout the device. Digital pressure gauges could also have been used for more precise pressure readings. However, the inlet air pressure would vary +/- 2PSI as the ATF opened and closed the zeolite chambers. This large variance within the readings meant that sensor readings did not require the precision and expense of digital pressure gauges.

Pressure readings were collected at the locations within the in-line sensor structures such that the pressure readings would be most accurate. For example, the pressure gauge at the inlet of the ATF was the last sensor in place after all other sensors and connectors were attached. The analog sensor readings were manually recorded within the Excel data logs.

Figure 3.6 Analog Pressure Sensor

Flow Sensor

A Honeywell AWM720P1 Mass Airflow Sensor, shown in Figure 3.7, was selected for use with this project. The sensor provides a voltage proportional to the air flow as described in Figure 3.8. The digital flow sensor readings were compiled within the Labview VI. Linear interpolation was used to determine the flow rates. This sensor is calibrated such that the no-flow reading provides a nominal voltage of 1.00.

Figure 3.7 Flow Rate Sensor

FLOW SPECIFICATIONS

	Flow (SLPM)	Nominal (Vdc) Typical	±Tolerance (Vdc)
	0	1.00	0.05
	25	2.99	—
	50	3.82	0.18
	75	4.30	—
	100	4.58	—
	150	4.86	—
	200	5.00	0.36

Figure 3.8 Flow Sensor Specifications (23)

Temperature

Temperature readings were collected with the Apogee oxygen sensor. This sensor included a thermistor. The oxygen sensor electronics package also utilized the sensor reading to calibrate the oxygen concentration readings. The digital temperature readings were compiled within the Labview VI.

Power Meter

A Watts Up power meter was used to collect power readings of the Workhorse system. This device provided a gauge of power consumption primarily used by the oil-less air compressor. The digital power readings were manually recorded within the Excel data logs.

Figure 3.9 Watts Up Power Meter

Chapter Summary

- A Workhorse device was purchased for use with the testbed.
- A Labview VI was used to collect digital sensor readings. The readings were compiled and exported to an Excel file.
- Sensors used within the testbed included an oxygen concentration sensor, a temperature sensor, a volumetric air flow sensor, many pressure gauges, and a Watts Up power meter.

CHAPTER FOUR: TEST PLAN

Chapter Introduction

- A test plan was developed and updated through all of the testing.
- All of the sensors were proven to be accurate and functioned as expected.
- A plate was added to the Workhorse device to direct the oxygen-depleted gases and mix with the oxygen-enriched gases.
- It was determined that the system required a minimum of two minutes of operation before the sensor readings would be considered “steady state.”
- Each test is described including a hypothesis and test arrangements.

Test Plan

Initial Planning

An initial test plan was developed before any test equipment was purchased. The plan was updated after each step. A sample of this test plan is shown in Figure 4.1.

Overall Step	Specific Steps	Notes
Initial Startup	Identify current parts	concentrator, nylon tubing, pressure gauges, regulator, flow meter, oxygen sensor
	Identify needed parts	additional connectors? different tubing? compressed air tank?
	Verify system with Andy's (expert)	Met with Nick Copass (nick@alternativehose.com 344-3568) reviewed system.
	Met with Sun Source regarding sensors	Looked into parts. Nothing appropriate for our system.
	Email Justin	regarding money for tank and sensors
	Initial system turn on	planned for friday. Decided to wait until off gas design/safety settled
	Purge/O2 mix design	consider mixing out gases for safety. Draw quick plate for hose connectors for purge
	Operational yes/no	does it work? So far so good. Try to get working next week
Labview and other DAQ equipment	Connect flow meter sensor	Yes, able to get flow meter working with Labview. Likely both operation and working well
	Connect Pressure sensors	Sensors also work and provide analog signal
	Identify and purchase/collect O2 sensor	
	Integrate sensing into a VI	Does it work? What reporting technique? Dump readings into excel
	Pressure monitoring	Do we just read off gauges and record in data? Likely a combination of resources
	Ask to borrow power gauge from Dr. Gardner	
	Pick up Watts Up? meter	
	Power monitoring	Do we incorporate software and excel or similarly just read devices?
Rig Review, Functionality, Prelim. Results, Comparison to Literature	Does everything work so far	Does our test system operate as expected?
	Purge/O2 mix design	Plate, hose, and reservoir system design
	Purge/O2 mix design	Plate, hose, and reservoir system working?
	How do we want to test	Variables of interest? (power, flow rates, pressures, O2 conc., time, what do we change)
	How does testing look in literature	What do commercial units advertise, research show, how do we consider ventilation
	What should we expect/compare	advertised values, what do we expect will happen as we change
	Are we ready to begin testing	checkpoint
Initial Testing	Testbed Unaltered	Identify oxygen concentration degredation as flow rate increases
	Analyze Data	Compare with provided specifications

Figure 4.1 Image from the Initial Test Planning

In addition to the test plan, a list of available and needed parts was also generated and updated. A portion of this table is shown in Table 4.1.

Table 4.1 Sample From the Parts List

Parts That We Have Include:		
Supplier	Part Description	Part Number
Valworx	Air Regulator	M2R2NH
Valworx	Comm. Pressure Gauge	9747249
Valworx	Ind. Pressure Gauge	4270070
Valworx	Ind. Pressure Gauge	4270061
Valworx	Coalescing Air Filter	F35121-300
Ferguson Engineering	Workhorse O2 Concentrator	Workhorse-8 115V
Available Parts from other Projects-		
Honeywell	Mass Airflow Sensor	AWM720P1
Honeywell	ASDX Series Silicon Pressure Sensors	AV (axial port on top, vented cover on bottom)
Honeywell	ASDX Series Silicon Pressure Sensors	RR (radial port on top, radial port on bottom)
Labview DAQ	Analog/Digital Inputs and Outputs	
Parts We Need:		
	Oxygen Concentration Monitor	purchased
	Different Tubing/Connectors?	purchased/borrowing from HP
	Atmospheric Air Tank? How long will last? Connectors?	using available air from high bay

An expert at Andy's Supply reviewed the test system. (24) His only safety concern regarded the free flowing oxygen out of the concentrator and suggested remixing the concentrated oxygen with the purged atmospheric oxygen depleted air.

Labview and Other DAQ Equipment

While the testbed parts were being collected, a Labview VI was generated to use with the testbed. An NI-6008 DAQ board was used along with a breadboard and electronics to connect the flow sensors, the oxygen and temperature sensors, and the on-board heater for the oxygen sensor. Each of these components was integrated into the

Labview VI and each was verified as reading accurately and exporting to Excel. The front panel and block diagram of the VI program can be found in Appendix A.

A Watts Up power meter was used to monitor power consumption primarily by the compressor. The Workhorse system uses 120 volt 60 hertz electricity to power the provided compressor and ATF oxygen module. While advertised to use 450 watts of power, the system actually used as little as 174 watts when the compressor outlet was vented to atmospheric pressure and had a maximum power consumption of 320 watts when the compressor was providing air to the ATF module.

System Review, Functionality, Preliminary Results, and Comparison to Documentation

After verifying all the testing equipment worked properly, it was necessary to verify that the Workhorse oxygen concentrator also operated as expected. The sensors were attached and the system was turned on. The flow rate closely matched the settings on the outlet gauge. The oxygen concentration began to increase as the system began separating the oxygen gas from atmospheric air as shown in Figure 4.2.

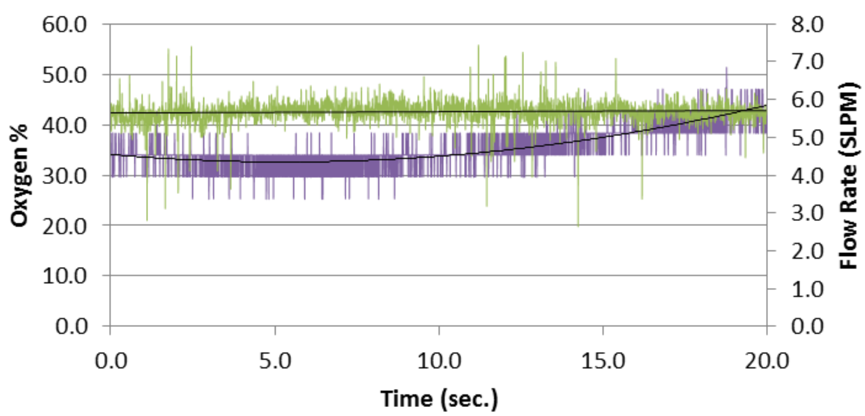


Figure 4.2 Workhorse System Verification

It was determined that the flow rate would equalize 20 seconds after the device was turned on. The oxygen concentration reached "steady state" after 2 minutes of operation. All subsequent testing utilized a 2 minute minimum operation before readings were used with any system calculations.

A plastic plate was designed to fit over the exhaust ports located at the bottom of the ATF device. This plate allowed the oxygen depleted gas to be exhausted through hosing and eventually mixed with the oxygen concentrated gas. Figure 4.3 shows the exhaust ports located on the base of the ADF while Figure 4.4 shows the plate that was machined and added to the assembly.

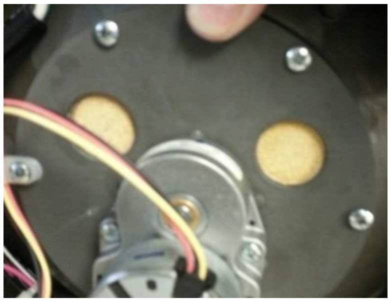


Figure 4.3 ATF Exhaust Ports

Figure 4.4 Added Exhaust Plate and Hosing

It was important to verify that the added plate and hosing system did not interfere with the overall system performance as it had the potential to increase pressure within the ATF. The test system was run with the plate and without the plate at various flow rates. The system performance was not impacted with the plate system as shown in Figure 4.5 and Figure 4.6.

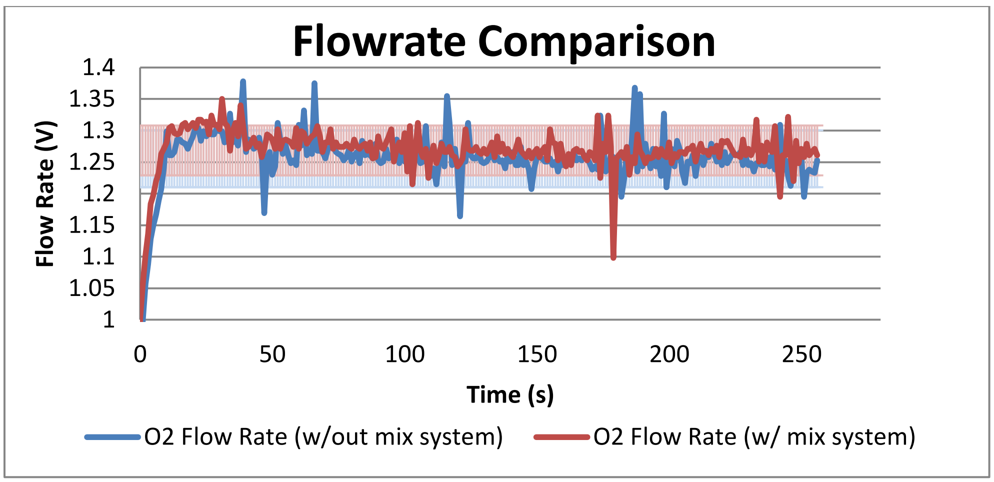


Figure 4.5 Flow Rate Comparison With and Without the Added Plate

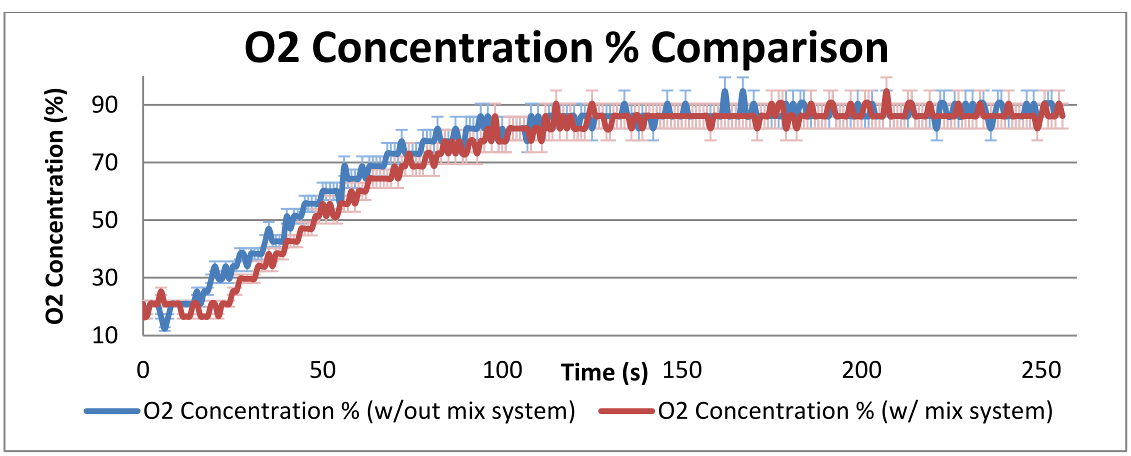


Figure 4.6 Oxygen % Comparison With and Without the Added Plate

After verifying the system was operating as expected and that the data collection system was also working correctly, a meeting was scheduled with the thesis committee to review the system and discuss the upcoming testing. The remaining testing was broken into three test phases as shown in Figure 4.7.

Committee Meeting	Meeting to review system and test plan	Review thesis to date and remaining plan/schedule
Phase 1 Testing	Vary input air pressure	In Process
	Vary output flow rate	Investigate system performance
	Analyze Data	Compare data with literature and use to adapt upcoming testing
Phase 2 Testing	Use provided air to vary inlet pressure and investigate performance	
Phase 3 Testing	Open system and investigate design	
Wrap Up Testing	Finalize data analysis	
	Conclusions regarding system functionality	
	Incorporate into Thesis	
	Thesis Review and Project next steps	

Figure 4.7 Test Phases

Phase One Testing

Test: Workstation Output Flow

Test Description

This test was developed to determine if the Workhorse system performance matches the specifications provided by the manufacturer. The testbed was operated without altering any of system components and the performance was quantified through a range of outlet flow rates.

Hypothesis

The system documentation describes that the oxygen concentration produced by the Workhorse device will quickly degrade to no oxygen concentration when the system is operated above 4 SLPM. The hypothesis for this test is that the system will continue to generate concentrated oxygen while operating above an outlet flow of 4 SLPM. However, the oxygen concentration will diminish at higher flow rates.

Testing Variables and System Arrangement

The system was unaltered from its designed arrangement. Oxygen concentration, temperature, and output flow readings were collected at the outlet of the system while the outlet flow gauge was adjusted in 1 SLPM increments in 3 minute intervals.

Test: Workstation Inlet Pressure

Test Description

This test was developed to compare the Workhorse system performance when operating at lower inlet pressures. A regulator was placed in-line between the compressor and the heat exchanger. The inlet pressure was reduced from 25 PSI, the normal inlet pressure, to 20 PSI and the system performance was measured over a range of outlet flow rates.

Hypothesis

The hypothesis for this test was that the system will continue to provide concentrated oxygen while operating with lower pressures. If the system functions appropriately at lower pressures, a smaller more efficient compressor can be considered for use with a PSA system.

Testing Variables and System Arrangement

The inlet pressure was adjusted by placing a regulator in-line between the compressor and the heat exchanger. Oxygen concentration, temperature, and output flow readings were collected at the outlet of the system and the inlet air pressure was recorded while the outlet flow gauge was adjusted in 2.5 SLPM increments in 3 minute intervals.

Test: Workstation Temperature Effects

Test Description

This test was developed to determine what, if any, effects air temperature had on the system performance because a heat exchanger was provided with the system. A temperature difference could be used to drive the system more effectively if there was a significant thermal effect on the system performance.

Hypothesis

The hypothesis for this test was that the system performance will not be significantly affected by the inlet air temperature.

Testing Variables and System Arrangement

This test was completed by operating the system in two states. Half of the testing ran the system from a "cold" state where the compressor had not been operated for many hours and was at thermal equilibrium with the room temperature. The other half of the testing was completed when the compressor had been operating for a long period of time and was quite warm to the touch. The inlet air hosing was also quite warm to the touch indicating the inlet air temperature was warmer than the ambient air temperature.

Oxygen concentration, temperature, and output flow readings were collected at the outlet of the system while the outlet flow gauge was adjusted in 2.5 SLPM increments in 3 minute intervals.

Phase Two Testing

Test: Alternate Air Inlet Pressure

Test Description

This test was developed to investigate the system performance of the testbed through a range of inlet air pressures.

Hypothesis

The hypothesis for this test was that the system will generate oxygen at varying inlet pressures and that more oxygen could be produced while operating beyond the system specifications.

Testing Variables and System Arrangement

An alternate air source was attached to the inlet of the ATF. A filter was used to remove any particulate, oil, or moisture from the pressurized air. A regulator was used to adjust the inlet air pressure. The system was operated with inlet pressures set at 5, 10, 15, 20, and 25 PSI.

At each inlet air pressure setting, oxygen concentration, temperature, and output flow readings were collected at the outlet of the system and the inlet air pressure was recorded while the outlet flow gauge was adjusted in 2.5 LPM increments in 3 minute intervals.

Test: Inlet Pressure Comparison

Test Description

This test was developed to compare the system performance operating with an inlet air pressure of 20 and 25 PSI using the Workhorse air compressor and the alternate air source. It was important to verify that the system performances at each inlet pressure setting match while operating with the two different air sources.

Hypothesis

The hypothesis for this test was that the system performance using the Workhorse air compressor and the alternate air source will match.

Testing Variables and System Arrangement

This test was a comparison of the system performance when operating with two different air sources. The system performances were graphed and visually compared.

Phase Three Testing

Test: System Disassembly

Test Description

This test was developed to determine if the Workhorse system could be disassembled for use in other testbed arrangements. Ideally, the ATF module could be isolated to a single zeolite chamber where the performance could be further investigated. However, the module is air tight and may not have a means to separate the columns from the inlet and outlet air chambers.

Hypothesis

The hypothesis for this test is that the system may be disassembled and used for further testing of zeolites and zeolite performance.

Testing Variables and System Arrangement

The Workhorse station was completely disassembled once all of the testing was completed.

Chapter Summary

- A test plan was developed and adapted as the testing occurred.
- All of the sensors were incorporated with the testbed device. All of the sensors were calibrated and their performances were verified.
- The system took two minutes of operation at each setting for the oxygen concentration readings to reach “steady state.” Therefore, each subsequent test required two minutes of operation at each setting before data was used to describe system performance at that setting.
- A plate was added to the base of the ATF device to collect oxygen depleted gases and feed that gas through hosing to mix with the concentrated oxygen gas. This addition was shown to have no effect on the overall system performance.
- The remaining testing was divided into three phases. All of the tests in each phase of testing were described.

CHAPTER FIVE: RESULTS

Chapter Introduction

- Testing shows that the PSA performance does not degrade rapidly as the output flow rate is increased beyond the system specifications.
- The PSA system performance remains the same while operating with a low outlet flow rate when the ATF is provided a lower inlet pressure. However, the performance degrades more quickly at higher flow rates.
- A PSA system can produce more oxygen when operated at a higher flow rate while providing a lower concentration of oxygen gas.
- A PSA system can operate at significantly lower inlet pressures, but the system performance degrades more quickly than higher inlet pressures.

Phase One Testing

Test: Workstation Output Flow

Analysis

The output flow rate was manually adjusted using the analog float gauge on the Workhorse station. The testing was incremented with 1 SLPM intervals operating for at least three minutes at each setting. The data was compiled and the average oxygen concentration was measured over 30 seconds after the system reached “steady state.” These values are recorded in the Table 5.1 and graphed in Figure 5.1. The expected system performance from the Workhorse documentation is shown in Figure 5.2 for the device “ATF-8.”

Table 5.1 Average Performance Varying Output Flow Rate

O2 Flow Rate SLPM	O2 Conc %
1.9	87.7
2.7	87.1
4.0	87.0
5.2	83.6
6.2	75.5
7.2	68.0
8.3	59.9
9.4	55.9
10.1	52.1

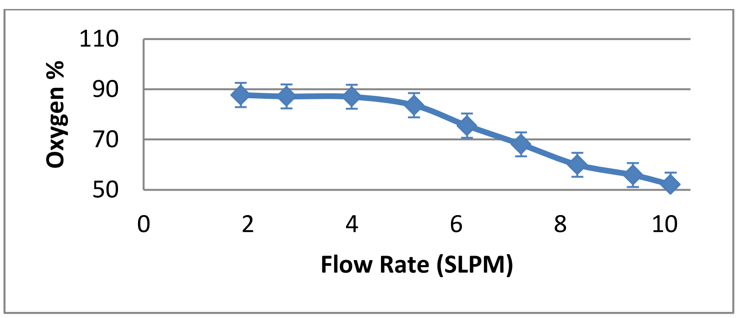


Figure 5.1 System Oxygen % Versus Output Flow Rate

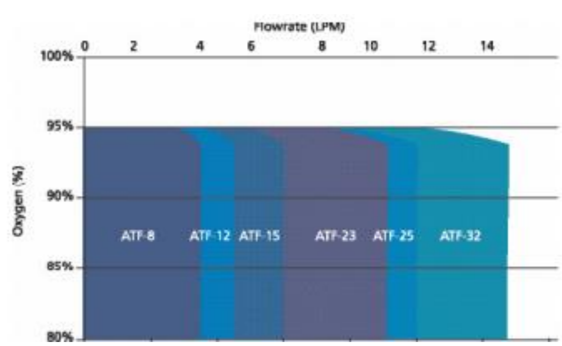


Figure 5.2 Documentation System Performance (22)

Discussion

As is shown in Figure 5.2, the expected performance for the ATF-8 is 95% oxygen from 0-3.8 SLPM output. Above a flow rate of 3.8 SLPM the performance was advertised to degrade sharply. Within other documentation, the device is expected to provide 90% oxygen (+3%/-5%) up to 3.8 SLPM. Testing shows that the oxygen concentration output does begin to degrade near 4 SLPM. However, it is important to note that the degradation is not immediate or severe. In fact, the ATF device generated >50% oxygen when operating at 10 SLPM which far exceeds expected oxygen production at that flow rate.

As has been described, “The productivity of a PSA generator is dependent on the oxygen purity required. A generator can produce significantly more oxygen at 90% purity than it can at 95.4%, with a relatively small increase in feed air.” (16)

This distinction is critical as it suggests that a PSA system can generate oxygen more efficiently when operating at a higher flow rate generating lower oxygen concentrations as shown in Table 5.2. More oxygen is produced while operating at a higher output flow rate while generating a lower concentration of oxygen gas.

Table 5.2 Varying Output Oxygen Provided

Flow Rate (SLPM)	Oxygen %	Liters of Oxygen/Minute
1.9	87.7	1.6
2.7	87.1	2.4
4.0	87.0	3.5
5.2	83.6	4.3
6.2	75.5	4.7
7.2	68.0	4.9
8.3	59.9	5.0
9.4	55.9	5.2
10.1	52.1	5.3

The Workhorse system is designed and advertised to produce 90% oxygen at a flow rate up to 3.8 SLPM, which generates 3.5 liters of oxygen per minute. If the system is set to run at 10.1 SLPM, the system will produce 5.3 liters of oxygen in a minute, which is a 50% improvement in oxygen production.

It is also important to note that the power consumption being monitored on the Watts Up gauge did not change when the system was set to run at lower or higher output flow rates. This again validates the suggestion that the overall system could be more efficient running at a higher output flow rate producing more oxygen.

Test: Workstation Inlet Pressure

Analysis

A regulator and pressure gauge were placed in-line between the on-board compressor and the inlet to the ATF. The pressure gauge validated the expected inlet air pressure of 25 as shown on the ATF module in Figure 5.3.

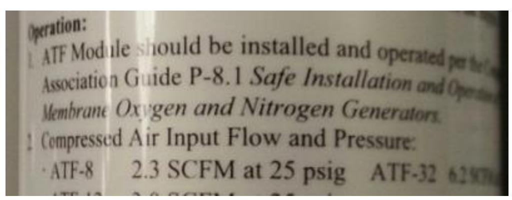


Figure 5.3 Sequal Column Pressure Recommendation

Using the regulator, the inlet pressure was reduced to 20 PSI to review the system performance. At that setting, the compressor utilized its on-board pressure release valve and sputtered intermittently. Because the pressure release sounded reasonably violent, the inlet pressure was not tested below 20 PSI. The outlet flow rate was adjusted through a range of settings and the system was allowed to reach steady state at each value. A comparison of performance between the designed 25 PSI and the 20 PSI performance is provided in Figure 5.4.

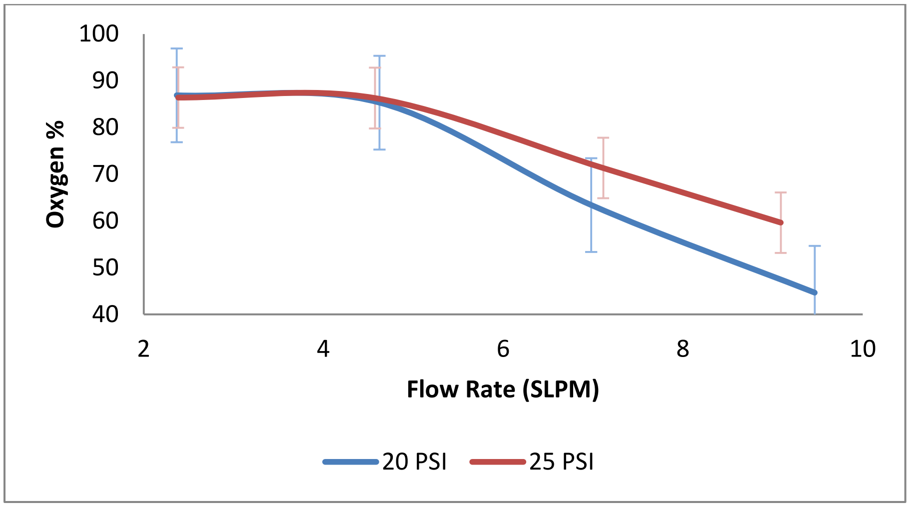


Figure 5.4 Oxygen % Versus Flow Rate at 20 and 25 PSI

Discussion

As expected, when the Workhorse system was operating at a low flow rate near 2 SLPM, the difference in inlet pressure did not impact the performance. As the output flow rate increased, however, the pressure difference did affect the outlet performance.

Similar to the findings using an inlet pressure of 25 PSI, the overall oxygen production was greater at a higher flow rate than the designed 3.8 SLPM while operating with 20 PSI of inlet pressure. However, the overall oxygen production was less at the highest flow rates using 20 PSI rather than 25 PSI as shown in Table 5.3. The maximum oxygen production occurred at a lower output flow rate setting of 7 SLPM rather than the 9.1 SLPM setting when operating with 25 PSI. This demonstrates that, as before, the overall system can be operated more efficiently at a higher output flow rate. However, there is a system performance ceiling that is based on the inlet pressure and was further considered within the phase two testing.

Table 5.3 Varying Inlet Pressure Oxygen Provided

20 PSI

Flow Rate SLPM	O2 %	Liters of Oxygen/Minute
2.4	86.9	2.1
4.6	85.3	3.9
7.0	63.4	4.4
9.5	44.7	4.2

25 PSI

Flow Rate SLPM	O2 %	Liters of Oxygen/Minute
2.4	86.4	2.1
4.6	86.3	3.9
7.1	71.3	5.1
9.1	59.6	5.4

Test: Workstation Temperature Effects

Analysis

Because the Workstation device included a heat exchanger, there were concerns that the system performance might be affected by the air inlet temperature. The product documentation specified that the operating temperature should be between 40^{o}F and 110^{o}F. The compressor heated up during operation. This provided a convenient way to test the system performance at a different temperature. The performance was studied while the compressor was cool, and again, while the compressor was quite warm. The results of this testing is shown in Figure 5.5.

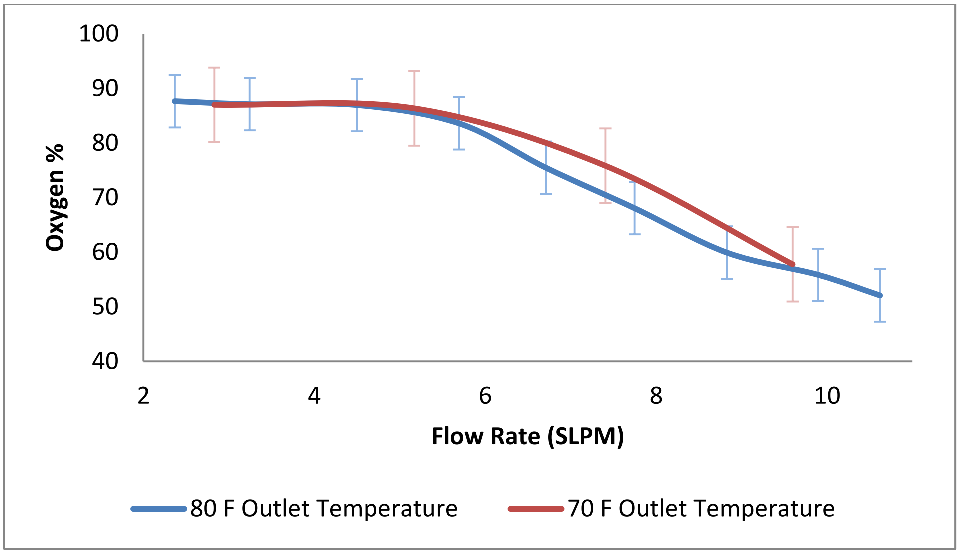


Figure 5.5 Oxygen % Versus Flow Rate at 70°F and 80°F

<u>Discussion</u>

The results, while not conclusive, do not suggest a significant performance effect with a ten degree Fahrenheit difference in output gas. It is important to note that while the temperature difference does not seem very large, the readings were collected at the outlet of the device and not the inlet. This means that the temperature difference between the two data sets was much greater at the inlet as the air travelled through the ATF module before the temperature readings were collected.

Because the installation and product documentation requires an operating temperature range between 40 and110°F and because there was no indication within the testing that temperature plays a meaningful role within the system performance, it is reasonable to conclude that the heat exchanger is used to keep the inlet air within the designed operating range and to protect the device hosing and zeolite from thermal and humidity damage.

Phase Two Testing

Test: Alternate Air Inlet Pressure

Analysis

The next step in investigating the Workhorse PSA system required disconnecting the provided compressor from the ATF and attaching an alternate pressurized air system as shown in Figure 5.6. The alternate air supply provided a much larger range of potential inlet pressures. A regulator and appropriate air filter, to remove particulate, oil, and moisture, were attached in-line to the ATF inlet. In addition, pressure gauges were added before and after the regulator to monitor the provided air pressure and to identify the inlet pressure intervals.

Figure 5.6 Alternate Air Supply In-Line Structure

The system was operated at 5, 10, 15, 20, and 25 PSI inlet pressures. Each inlet pressure was run through a selection of output flow rates. Figure 5.7 includes images of the inlet pressure gauge reading the appropriate inlet pressures during these tests and also shows that the pressure would vary +/-2 PSI as the system operated. The ATF module uses a motor that rotates a plate opening and closing the dozen cylinders of zeolite material. As the cylinders are opened and closed, the system experiences mild pressure swings.

Figure 5.7 Sample Inlet Pressure Gauge Readings

The average performances experienced by the system during operation at each of the pressure increments are listed in Table 5.4. With an inlet pressure of 5 and 10 PSI, the system did not have enough inlet pressure to provide an outlet flow exceeding 5 and 7.5 SLPM respectively.

Table 5.4 Varying Inlet Pressure System Performance

5 PSI Inlet		
O2 Flow Rate SLPM	**Oxygen %**	**Liters of Oxygen/Minute**
2.6	40.9	1.0
4.7	22.9	1.1
10 PSI Inlet		
O2 Flow Rate SLPM	**Oxygen %**	**Liters of Oxygen/Minute**
2.3	78.2	1.8
5.0	44.3	2.2
7.4	31.1	2.3
15 PSI Inlet		
O2 Flow Rate SLPM	**Oxygen %**	**Liters of Oxygen/Minute**
2.4	86.2	2.1
4.9	78.1	3.8
7.4	44.7	3.3
9.2	35.6	3.3
20 PSI Inlet		
O2 Flow Rate SLPM	**Oxygen %**	**Liters of Oxygen/Minute**
2.3	86.6	2.0
4.8	85.8	4.1
7.2	62.7	4.5
9.7	43.7	4.2
25 PSI Inlet		
O2 Flow Rate SLPM	**Oxygen %**	**Liters of Oxygen/Minute**
2.3	87.0	2.0
4.7	86.3	4.0
6.9	75.8	5.2
9.1	57.8	5.3

The oxygen concentration performance at the incremented inlet pressures are shown graphically in Figure 5.8.

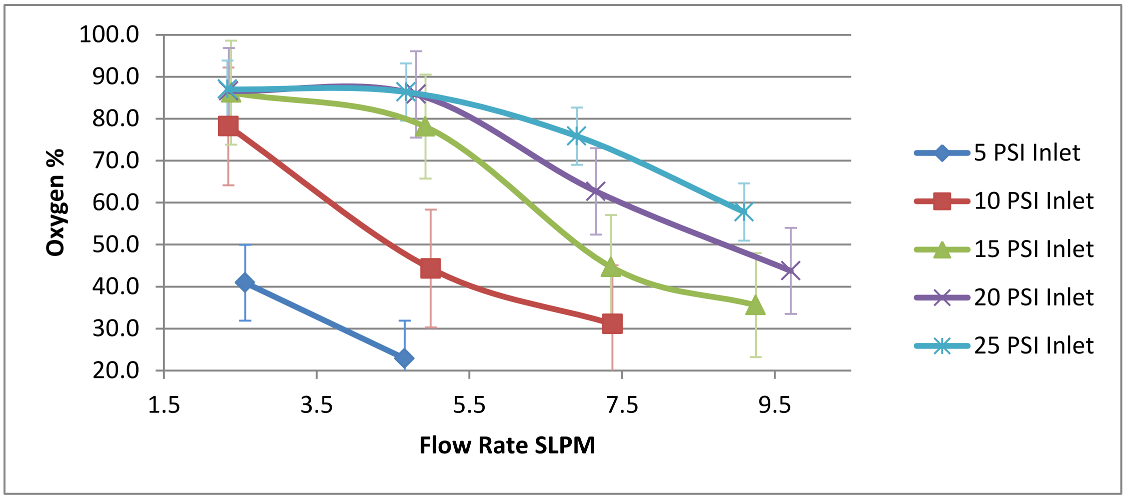


Figure 5.8 Variable Inlet Pressure Oxygen Concentrations

The oxygen flow rate performance at the incremented inlet pressures are shown in Figure 5.9.

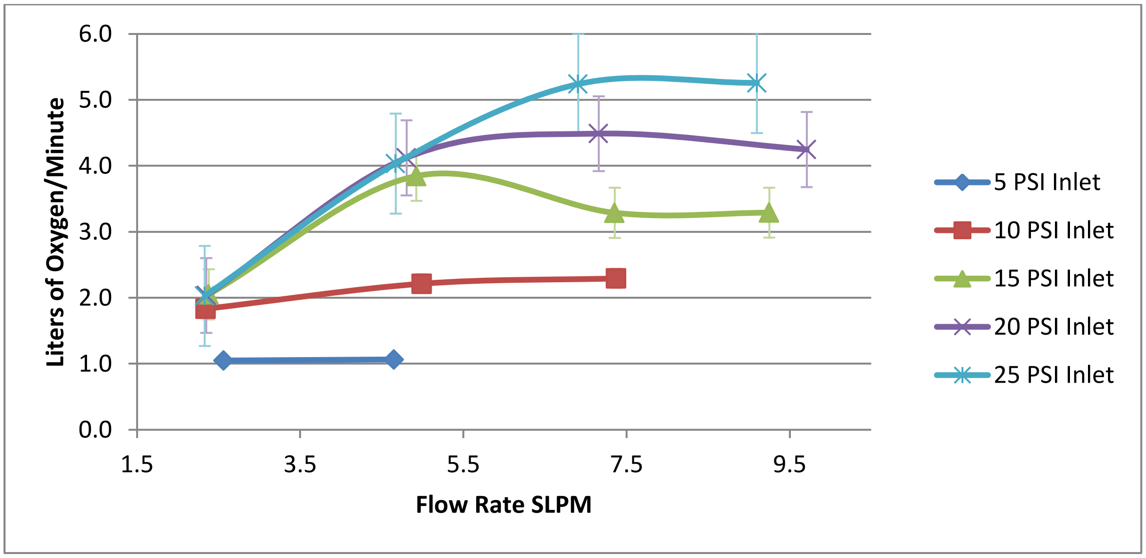


Figure 5.9 Variable Inlet Pressure Oxygen Flow Rate

Discussion

The system responded as expected generating lower oxygen concentrations as the output flow rate increased.

With an inlet pressure of 5 PSI and an outlet flow nearing 5 SLPM, the system concentrates oxygen at 22.9%, an additional 2% beyond ambient atmospheric air.

The overall oxygen production, in liters of oxygen per minute, was at its highest value at the largest flow rate possible for the 5 and 10 PSI inlet pressures, very near the middle setting flow rate for 15 PSI, and then again getting closer to the maximum flow rate for the inlet pressures of 20 and 25 PSI. This suggests that the PSA system can be optimized to generate the most oxygen at any concentration, rather than specifically at the >90% concentration assigned to all available POC's. In addition, this also means that weight and power consumption can be reduced with a design goal of maximum oxygen production rather than high concentrations of oxygen gas.

Test: Inlet Pressure Comparison

Analysis

It's important to compare the ATF system performance using the on-board air compressor versus the higher capacity alternate air source. The two performances are compared in Figure 5.10 while operating with 20 and 25 PSI inlet air pressure.

Discussion

The system performance is nearly identically between 2 and 4 SLPM using any of the supplied air techniques. Both the 20 and 25 PSI performances are similar between the Workhorse compressor and the alternate air supply.

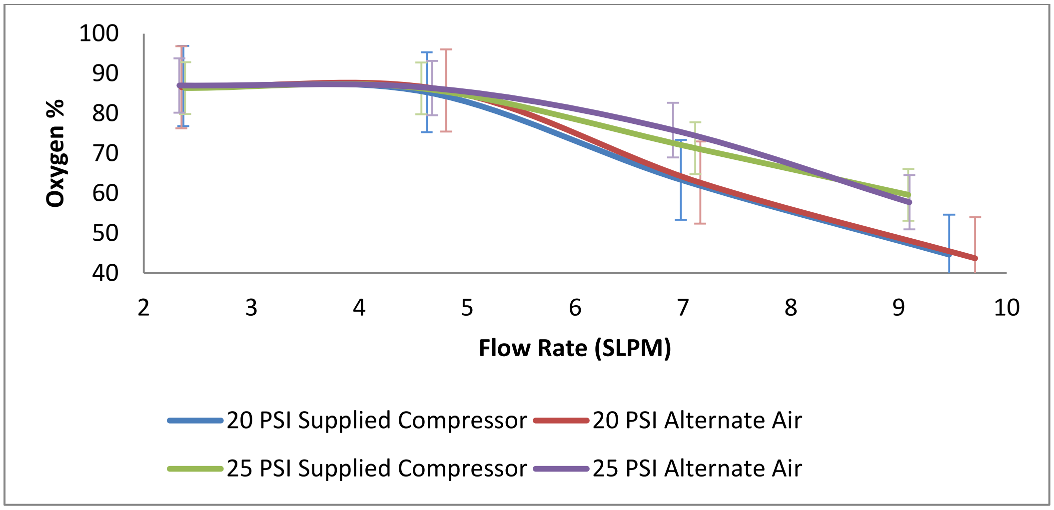


Figure 5.10 Performance Comparison Between Supplied Compressor and Alternate Air Supply

Phase Three Testing

<u>Test: System Disassembly</u>

<u>Analysis</u>

The ATF module was available for teardown once the testing was complete using the Workhorse system. Figures 5.11 through 5.16 are used to show the system and its components as the system was disassembled.

Figure 5.11 shows an exploded view of the Workhorse system. Ambient air is drawn through a filter and into a compressor which feeds the air through a heat exchanger into the ATF ½” reinforced silicon inlet tubing. The air circulates through one of a dozen cylinders filled with zeolite materials separating the oxygen gas from the other components in ambient air. The oxygen enriched air is expelled through an outlet hose that is attached to a flow control. The oxygen depleted gas is purged out of the base of the unit.

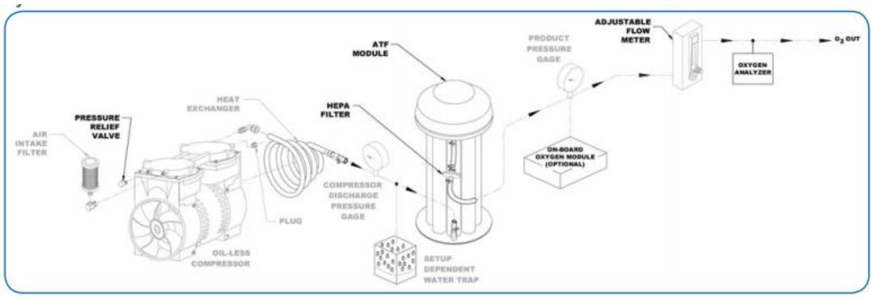


Figure 5.11 Exploded Diagram of the Sequal Workhorse System (22)

Figure 5.12 Picture of the Sequal Workhorse System

A Sequal website describes the ATF module shown in Figure 5.13 and 5.14:

> Sequal's 12-bed system uses a small geared motor to slowly turn a maintenance-free rotary distribution valve. This self-cleaning valve, built into each ATF unit, directs the flow of compressed air to one set of four molecular sieve beds at a time. Simultaneously, another four beds are purged to atmosphere through the valve. The final four beds are interconnected through the valve to equalize pressure as they transition between adsorbing and desorbing. This eliminates both electronic cycling controls and solenoid valves. (21)

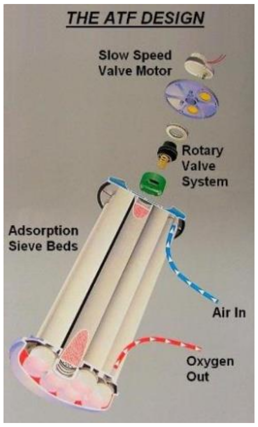


Figure 5.13 Exploded Diagram of the Sequal ATF System (21)

Figure 5.14 Picture of the Sequal ATF System

After removing the added mix plate and hosing, the motor valve assembly was removed from the bottom side of the ATF as shown in Figure 5.15. The assembly consists of a motor and rotating plate system. The contact surface between the rotating plate and the cylinder ports is smooth. The marrying surface of the plate shows the innovative system of pressurizing, purging, and transitioning the air supply through narrow troughs as shown in Figure 5.16.

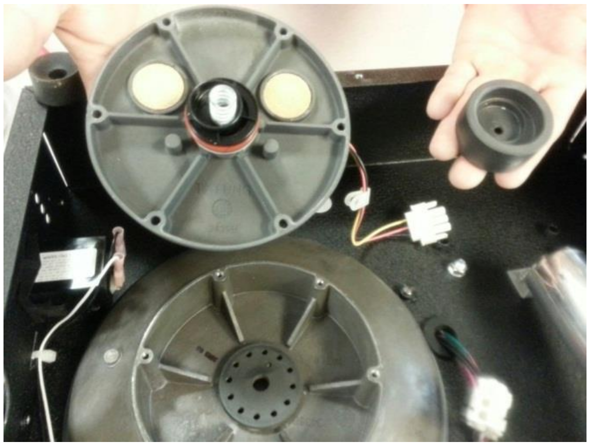


Figure 5.15 ATF Motor Disassembled

Figure 5.16 ATF Air Direction Rotating Plate

Discussion

While the system itself was very appropriate for testing the overall efficiency and determining whether a unique design should be considered for a POC for use with an MCV, the ATF module itself is likely not useful for breaking down into a singular test cylinder. All of the connections, beyond removing the motor/rotating plate assembly, are completely sealed. Additionally, the zeolite materials within each cylinder are striated in a particular order as shown in Figure 5.17.

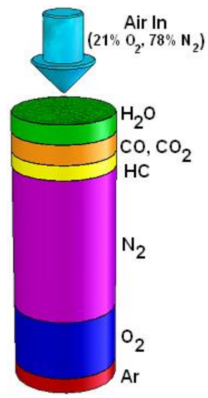


Figure 5.17 ATF Column Zeolite Structure (21)

PSA systems are most efficient using multiple types of zeolite. The columns are filled in order to adsorb particular molecules as is most effective for the system. Ashcraft and Swenton demonstrated that air component separation is most efficient in a stepwise manner because nitrogen preferentially adsorbs to zeolite surfaces in place of argon. (14) In an effort to remove both gases from ambient air, a zeolite system is best served removing the bulk of the nitrogen from the air before the air reaches zeolite designed to remove argon. It would be difficult to maintain the zeolite order and structure if the ATF module was opened and the materials were removed and replaced by alternative zeolites.

Chapter Summary

- Testing showed that the expected system performance provided with the documentation did not match the actual system performance. The system performance degradation was much less than expected at higher output flow rates.

- The maximum oxygen production from the unaltered Workhorse system occurred with the system operating at its maximum output flow rate. At nearly 10 SLPM, the system generates 5.3 liters of oxygen/minute.
- The heat exchanger included with the system is intended to reduce the inlet air temperature of the gas in order to maximize the zeolite performance.
- Using an alternate air source, it was shown that the PSA system can operate effectively at lower inlet air pressures than originally designed.
- The maximal oxygen output generally occurs at higher flow rates.
- This PSA system provides nearly the same amount of oxygen when operating at 4 SLPM using 25, 20, and 15 PSI for an inlet pressure. This means a significantly smaller compressor could be used if the oxygen output requirement is near 4 liters of oxygen/minute.
- The ATF module cannot be completely disassembled without irreversibly damaging the unit. It is not an appropriate candidate device for testing individual zeolite beds.

CHAPTER SIX: CONCLUSIONS AND FUTURE WORKS

Chapter Introduction

- Testing shows that a PSA system can be designed to operate more efficiently by providing a lower concentration of oxygen gas at a higher output flow rate.
- A thermodynamic analysis of the POC system could prove beneficial as the system wastes power as the compressor becomes hot and heats the pressurized air.
- More testing should be conducted by adapting an off-the-shelf POC device and altering its compressor characteristics.
- MCV specifications should be developed to determine if this altered POC design would be appropriate.

Thesis Overview

The purpose of this thesis was to develop and investigate a portable oxygen concentrator using a pressure swing adsorption system to determine system characteristics and the feasibility of developing a unique concentrator for use with a mass casualty ventilator.

This work began by reviewing the demand for such a system, its function and role with a mass casualty ventilator, and then investigating what techniques of oxygen concentration would be most suitable for this type of product. A pressure swing adsorption system was selected as the best candidate technology following a review of many commercially available portable oxygen concentrators systems. The Sequal Workhorse is a POC technology that was ideally suited for testing system performance characteristics because the system is accessible and easy to manipulate. It operates using simple mechanical devices and concentrates oxygen at the same output specifications of many POCs. Sensors and controls were incorporated into a testbed utilizing the Workhorse device in order to control and monitor the system performance.

A test plan was developed along with a Labview program to monitor and collect the system sensors and control readings. The data was compiled and reviewed within Excel. Testing was completed in three phases.

The first phase monitored the Workhorse system as designed and identified the system response in comparison with specifications provided by the manufacturer. The Workhorse inlet pressure was altered using an in-line regulator and the system performance was monitored and defined. The last testing in phase one investigated potential temperature effects on system performance. The unit came with a heat exchanger and it was important to verify the role of the exchanger and potential effects on system performance.

The second phase of testing removed the provided compressor from the Workhorse system and used an alternate air supply. This alteration allowed the system to be tested using varying inlet pressures. System performance was defined at 5, 10, 15, 20, and 25 PSI inlet pressures.

The third and final phase of testing was a system disassembly. It was important to fully understand how the Workhorse and ATF device operates and if it had the potential to be broken into a different testbed device.

Testing Conclusions

Phase one testing fully characterized the system performance of the Workhorse system as shown in the Table 6.1. While the system is designed to operate at 3.8 SLPM or less in order to generate the highest oxygen concentration, the system actually isolates and delivers more oxygen when operating at its maximum available flow rate of 10 SLPM. At this setting, the Workhorse station provides 5.3 liters of oxygen per minute compared with the maximum 3.5 liters of oxygen per minute when operating at its designed maximum flow rate near 4.0 SLPM.

Table 6.1 Varying Output Oxygen Provided

Flow Rate (SLPM)	Oxygen %	Liters of Oxygen/Minute
1.9	87.7	1.6
2.7	87.1	2.4
4.0	87.0	3.5
5.2	83.6	4.3
6.2	75.5	4.7
7.2	68.0	4.9
8.3	59.9	5.0
9.4	55.9	5.2
10.1	52.1	5.3

The Workhorse system generates concentrated oxygen at nearly the same performance at low flow settings, 4 SLPM or lower, when the provided inlet pressure is 20 or 25 PSI. However, once the flow rate is increased beyond that rate, the oxygen concentration performance degrades as shown in Figure 6.1.

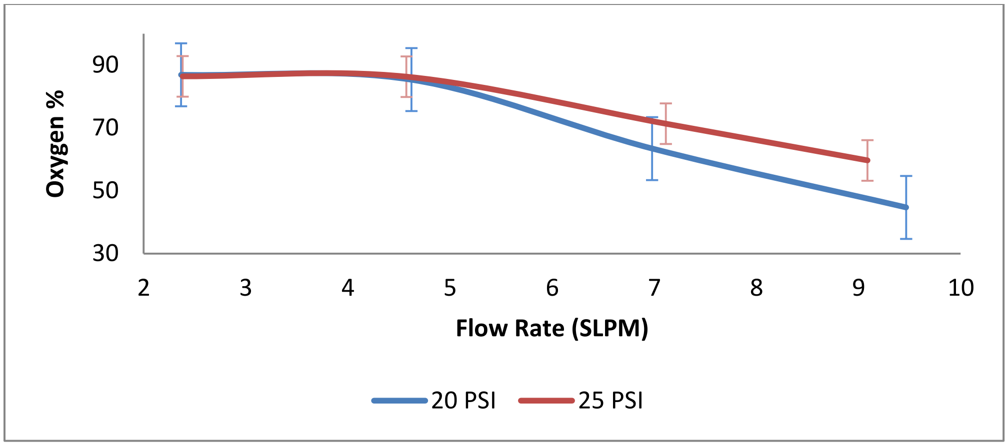


Figure 6.1 Oxygen % Versus Flow Rate at 20 and 25 PSI

As shown in Figure 6.2, the inlet air temperature had little to no effect on overall system performance when operating within the system specifications of 40-110°F. Therefore, the heat exchanger is in place to reduce inlet air temperature to this specified range as system performance is expected to degrade when operating in excess of these temperatures. Reducing the inlet air temperature also protects the system hosing and zeolite material from heat and humidity damage.

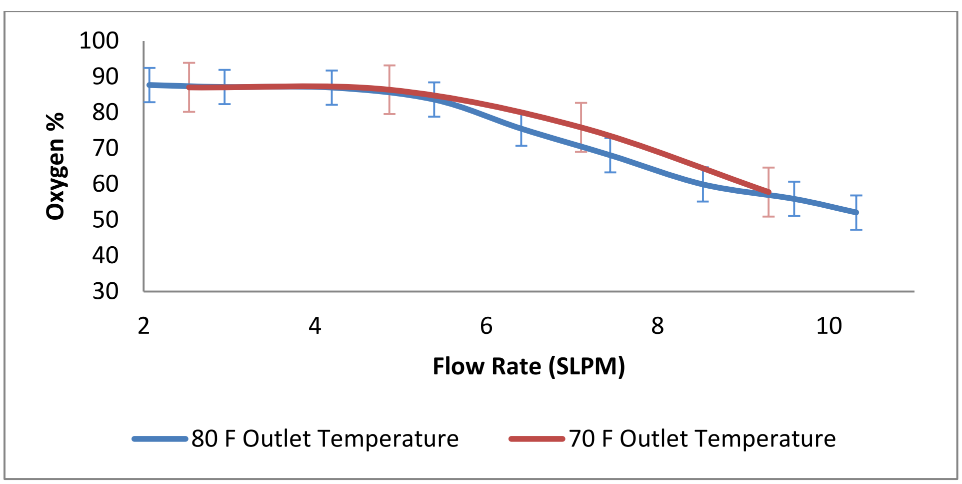


Figure 6.2 Oxygen % Versus Flow Rate at 70°F and 80°F

Operating the Workhorse system at varying inlet pressures demonstrates many important factors within a PSA POC design. At 5 PSI inlet pressure, which should be considered a low available pressure, the system is unable to generate high concentration oxygen and has a very low flow. At 10 PSI inlet pressure the oxygen concentration is significantly higher, approaching 80%, but again, the available flow rates are quite low and the performance degrades quickly as the outlet flow rate is increased. At 15 PSI inlet pressure, the system approaches the designed performance nearing 90% oxygen below 4 SLPM. At this setting, the maximum overall oxygen production occurs near 5 SLPM, which is unique to this inlet pressure setting. As the inlet pressure increases to 20 and 25 PSI, the overall oxygen production reaches a maximum at higher flow rates respectively as shown in Table 6.2.

Table 6.2 Varying Inlet Pressure System Performance

5 PSI Inlet		
O2 Flow Rate SLPM	**Oxygen %**	**Liters of Oxygen/Minute**
2.6	40.9	1.0
4.7	22.9	1.1
10 PSI Inlet		
O2 Flow Rate SLPM	**Oxygen %**	**Liters of Oxygen/Minute**
2.3	78.2	1.8
5.0	44.3	2.2
7.4	31.1	2.3
15 PSI Inlet		
O2 Flow Rate SLPM	**Oxygen %**	**Liters of Oxygen/Minute**
2.4	86.2	2.1
4.9	78.1	3.8
7.4	44.7	3.3
9.2	35.6	3.3

20 PSI Inlet		
O2 Flow Rate SLPM	**Oxygen %**	**Liters of Oxygen/Minute**
2.3	86.6	2.0
4.8	85.8	4.1
7.2	62.7	4.5
9.7	43.7	4.2
25 PSI Inlet		
O2 Flow Rate SLPM	**Oxygen %**	**Liters of Oxygen/Minute**
2.3	87.0	2.0
4.7	86.3	4.0
6.9	75.8	5.2
9.1	57.8	5.3

The oxygen concentration performance at the incremented inlet pressures are shown graphically in Figure 6.3.

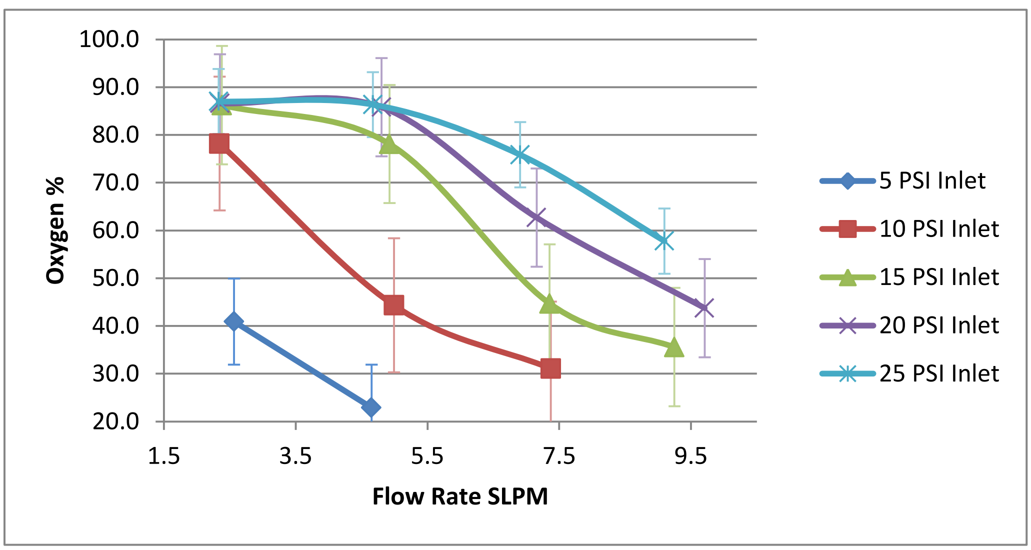


Figure 6.3 Variable Inlet Pressure Oxygen Concentrations

The oxygen flow rate performance at the incremented inlet pressures are shown in Figure 6.4.

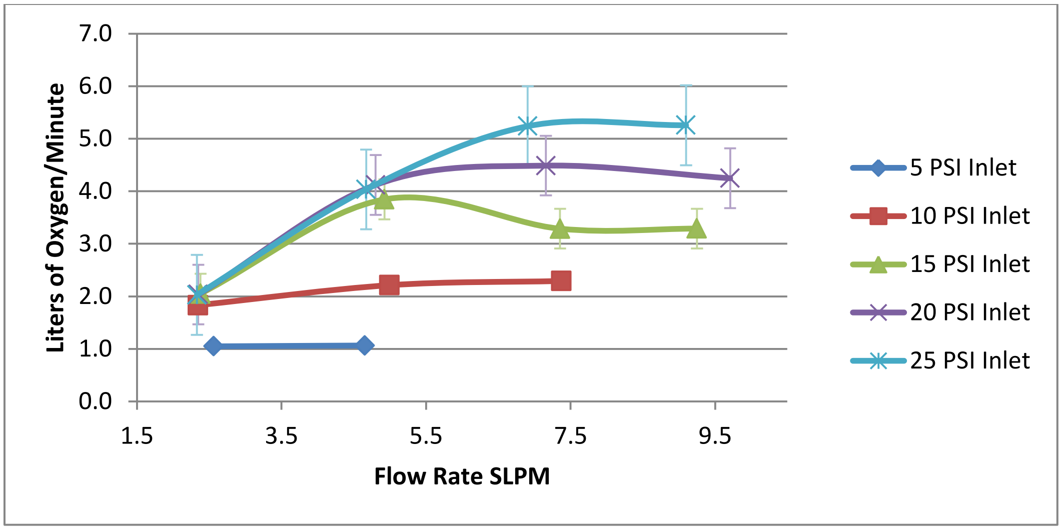


Figure 6.4 Variable Inlet Pressure Oxygen Flow Rate

These graphics demonstrate two key considerations when developing a POC for use with an MCV. One, the maximum oxygen production does not occur at >90% oxygen concentrations, which is the specification all commercially available POC's are designed to meet. And two, that the maximum oxygen production can be optimized by selecting an appropriate inlet pressure and outlet flow rate. This means that a PSA system can be developed with a lighter, less powerful compressor than is used in commercial POC's. This compressor exchange provides an opportunity to reduce system weight and extend battery life. These two considerations demonstrate the opportunity for a unique POC design for use with an MCV.

Future Work

This research was not focused on the thermodynamics of a POC. However, while testing, there were many questions that should be considered in upcoming research. Power availability and consumption is one of the largest factors that should be taken into account while designing a POC. The compressor uses the majority of the power and wastes some of this power as heat. The compressor and inlet hosing become hot to the touch during normal operation and this temperature differential could be used to harvest energy back to the system. It would beneficial to study this heat loss and determine if it can be captured or harnessed in some way.

As shown in Figure 6.3, there has been a significant amount of patents issued in the last 30 years regarding the separation of air via adsorption. The sizeable field of gas separation technology, particularly for use in isolating oxygen, must be recognized when considering development of a unique portable oxygen concentrator. There are many competing technologies and companies developing POC's for specific applications.

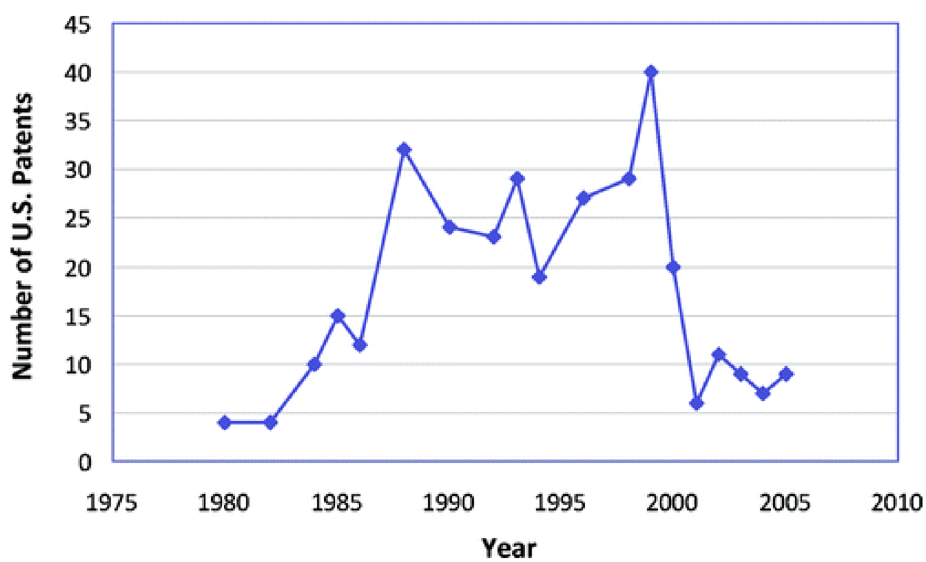


Figure 6.3 "Air Separation by Adsorption" Patent Search (8)

Because this technology is very well established, the next step should be adapting an existing POC that concentrates oxygen >90% and developing it to operate at the more efficient system performance with a lower oxygen concentration.

Two example POC’s that would be appropriate for this adaptation include the Airsep Focus and the Inova Labs Activox. Both of these units are small, around 100 cubic inches and 300 cubic inches respectively. The units weight 3 and 5 pounds, respectively. They both concentrate oxygen at 90% (+3%/-5%), which is typical of commercialized PSA systems. They both utilize a pulsed flow rather than a constant flow in order to maximize battery life, which varies between 2-6 hours for both units depending on usage, flow setting, environment, etc. The pulsed flow may be adapted to a constant flow system depending on which delivery mechanism is determined more useful with an MCV. Both of these candidate devices seem suited for use as a POC that could be adapted for use with an MCV. (25) (26)

Further testing would determine if these POC systems can produce more oxygen per minute generating lower concentrations of oxygen at a higher flow rate. It would be useful to test the systems with their compressor as well as other lighter, more efficient compressor. Lastly, it would be beneficial to identify or develop an MCV whose performance specifications could be considered while developing the specific POC device.

Figure 6.4 Airsep Focus and Inova Labs Activox (25) (26)

Chapter Summary

- Testing has shown that a PSA system used within a POC can be operated more efficiently by reducing the oxygen concentration requirements and increasing the output flow rate.
- A smaller compressor can be used to reduce power requirements for a POC thereby extending operational hours or reducing the battery size.
- An existing POC should be used in testing to determine if its peak oxygen production also increases at higher flow rates providing lower concentrations of oxygen.
- System requirements should be determined for a POC device used in conjunction with an MCV.

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APPENDIX A

Labview VI

Front Panel

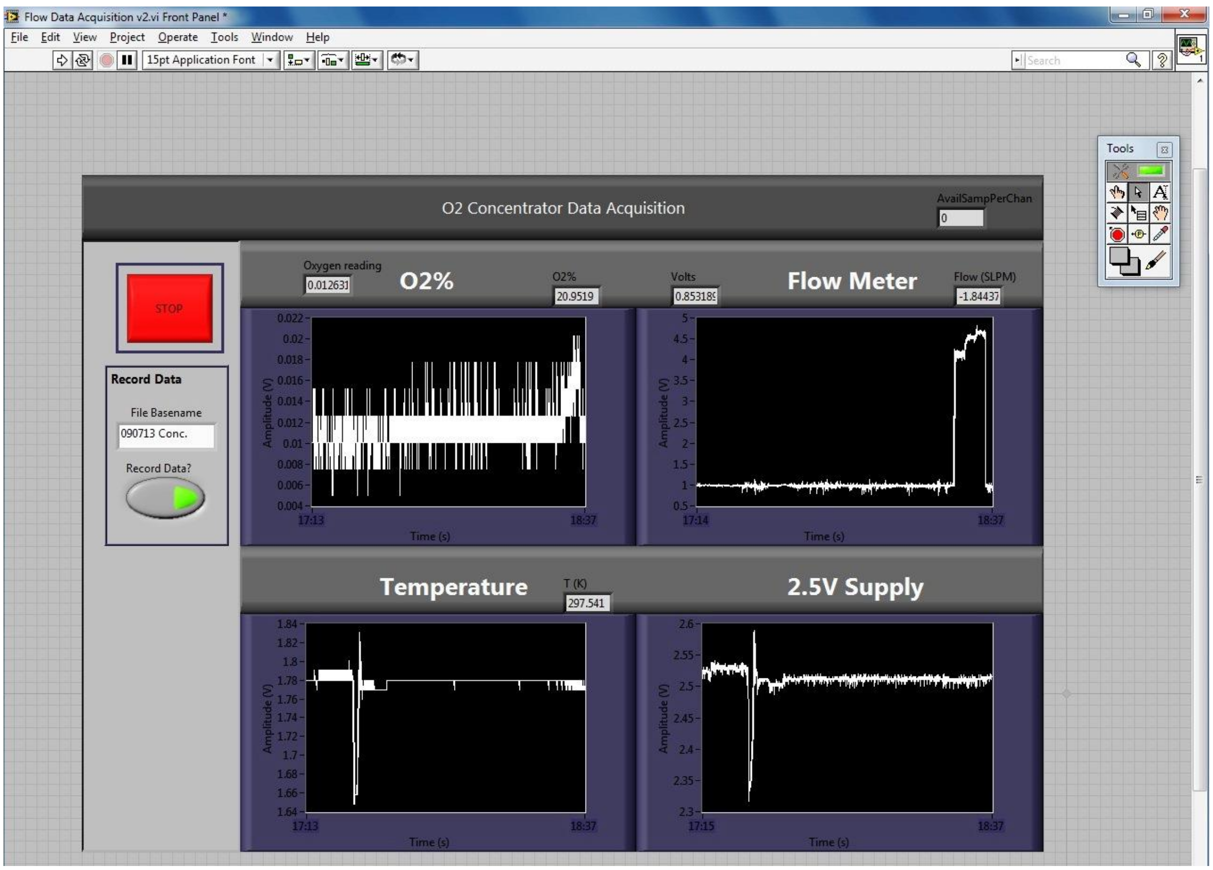

Figure A.1 Labview VI Front Panel

<u>Block Diagram</u>

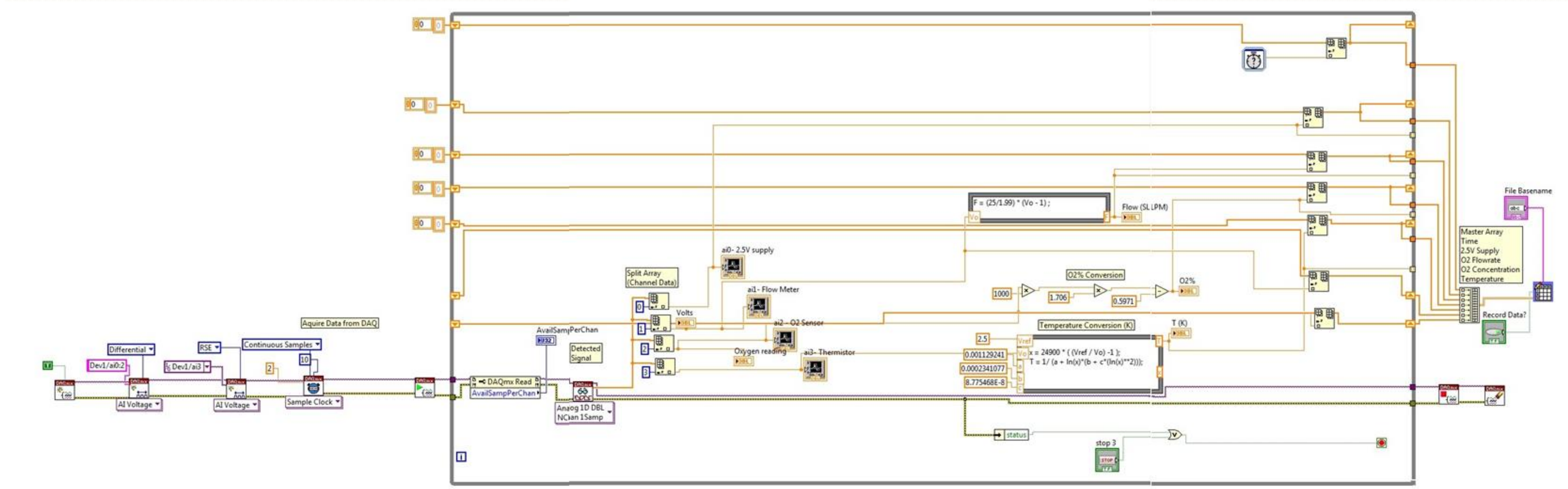

Figure A.2 Labview VI Block Diagram

APPENDIX B

Data Sets

Table B.1 System Verification Sample

Time (s)	2.5 V Supply	O2 Flow Rate	Flow (SLPM)	O2 Concentration %	Temperature
0.0	2.572	1.465	5.8	34.0	1.8
0.0	2.569	1.457	5.7	34.0	1.8
0.0	2.569	1.47	5.9	38.3	1.8
0.0	2.569	1.465	5.8	34.0	1.8
0.0	2.572	1.449	5.6	34.0	1.8
0.0	2.572	1.411	5.2	34.0	1.8
0.0	2.569	1.449	5.6	34.0	1.8
0.0	2.569	1.467	5.9	34.0	1.8
0.0	2.569	1.449	5.6	34.0	1.8
0.0	2.569	1.452	5.7	29.6	1.8
0.0	2.572	1.452	5.7	34.0	1.8
0.1	2.574	1.444	5.6	34.0	1.8
0.1	2.569	1.442	5.6	34.0	1.8
0.1	2.569	1.452	5.7	29.6	1.8
0.1	2.564	1.452	5.7	38.3	1.8
0.1	2.569	1.462	5.8	34.0	1.8
0.1	2.569	1.454	5.7	34.0	1.8
0.1	2.569	1.454	5.7	34.0	1.8
0.1	2.567	1.444	5.6	34.0	1.8
0.1	2.572	1.444	5.6	34.0	1.8
0.1	2.569	1.467	5.9	34.0	1.8
0.1	2.572	1.454	5.7	34.0	1.8
0.1	2.569	1.434	5.5	29.6	1.8
0.1	2.572	1.437	5.5	34.0	1.8
0.1	2.572	1.434	5.5	34.0	1.8
0.1	2.569	1.416	5.2	34.0	1.8
0.1	2.569	1.434	5.5	34.0	1.8
0.1	2.567	1.449	5.6	34.0	1.8
0.1	2.569	1.442	5.6	38.3	1.8
0.1	2.567	1.439	5.5	34.0	1.8
0.1	2.569	1.437	5.5	34.0	1.8
0.2	2.569	1.442	5.6	34.0	1.8
0.2	2.569	1.447	5.6	38.3	1.8
0.2	2.572	1.465	5.8	34.0	1.8
0.2	2.569	1.431	5.4	34.0	1.8
0.2	2.569	1.424	5.3	34.0	1.8
0.2	2.569	1.426	5.4	34.0	1.8
0.2	2.569	1.429	5.4	34.0	1.8
0.2	2.567	1.444	5.6	34.0	1.8
0.2	2.564	1.426	5.4	34.0	1.8
0.2	2.569	1.447	5.6	34.0	1.8
0.2	2.569	1.444	5.6	34.0	1.8
0.2	2.569	1.475	6.0	34.0	1.8
0.2	2.569	1.465	5.8	34.0	1.8
0.2	2.569	1.465	5.8	34.0	1.8
0.2	2.567	1.475	6.0	34.0	1.8
0.2	2.569	1.457	5.7	34.0	1.8
0.2	2.567	1.449	5.6	34.0	1.8

Barometric Press (in)	30.07
Humidity (%)	57
Ambient Temp (F)	
Test start Time	11:16
Pressure out of Compressor (psi)	25
Pressure of Concentrated O2 (psi)	N/A
Test stop time	11:16
Test duration (sec)	19.991
Sequal Flow Setting (SCFH)	10

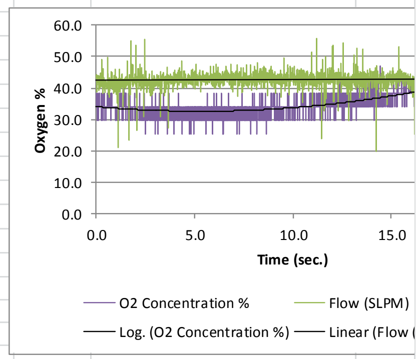

Table B.2 Plate Mixing Verification Sample

Time (s)	O2 Flow Rate (w/out mix system)	O2 Flow Rate (w/ mix system)
0.0	1.0	1.0
0.0	1.0	1.0
1.0	1.0	1.1
2.0	1.1	1.1
3.0	1.1	1.1
4.0	1.1	1.2
5.0	1.1	1.2
6.0	1.2	1.2
7.0	1.2	1.2
8.0	1.2	1.3
9.0	1.2	1.3
10.0	1.3	1.3
11.0	1.3	1.3
12.0	1.3	1.3
13.0	1.3	1.3
14.0	1.3	1.3
15.0	1.3	1.3
16.0	1.3	1.3
17.0	1.3	1.3
18.0	1.3	1.3
19.0	1.3	1.3
20.0	1.3	1.3
21.0	1.3	1.3
22.0	1.3	1.3
23.0	1.3	1.3
24.0	1.3	1.3
25.0	1.3	1.3
26.0	1.3	1.3
27.0	1.3	1.3
28.0	1.3	1.3
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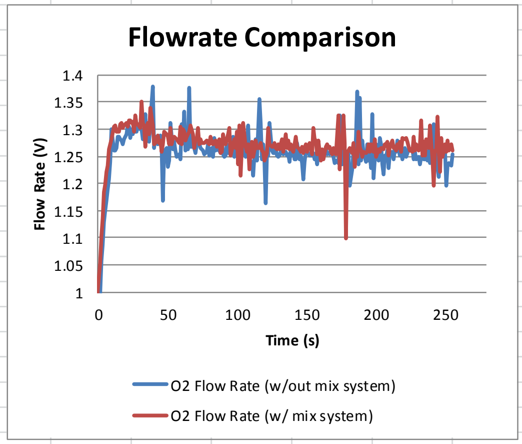
30.0	1.3	1.3
31.0	1.3	1.4
32.0	1.3	1.3



Time (s)	O2 Concentration % (w/out mix system)	O2 Concentration % (w/ mix system)
0.0	21.0	21.0
0.0	21.0	16.6
1.0	16.6	16.6
2.0	21.0	21.0
3.0	21.0	21.0
4.0	21.0	21.0
5.0	16.6	25.3
6.0	12.3	21.0
7.0	16.6	21.0
8.0	21.0	21.0
9.0	21.0	21.0
10.0	21.0	21.0
11.0	21.0	16.6
12.0	21.0	16.6
13.0	21.0	16.6
14.0	21.0	21.0
15.0	25.3	21.0
16.0	21.0	16.6
17.0	25.3	16.6
18.0	25.3	16.6
19.0	29.6	21.0
20.0	34.0	21.0
21.0	29.6	16.6
22.0	29.6	21.0
23.0	34.0	21.0
24.0	29.6	21.0
25.0	34.0	25.3

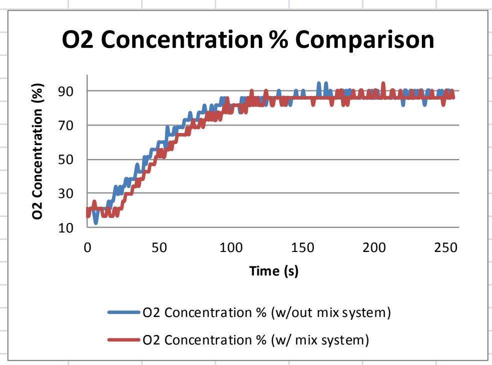


Table B.3 Varying Output 2 SLPM Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K)	Flow Reading (V)	Oxygen Reading (V)
0.0	2.544	1.8	81.8	298.9	1.144	0.048
0.0	2.544	1.9	86.1	298.9	1.149	0.051
1.0	2.541	1.9	90.5	298.9	1.149	0.053
2.0	2.544	1.9	86.1	298.9	1.149	0.051
3.0	2.539	1.9	86.1	299.4	1.149	0.051
4.0	2.544	1.8	90.5	299.4	1.146	0.053
5.0	2.536	1.9	90.5	298.9	1.149	0.053
6.0	2.544	1.9	86.1	298.9	1.149	0.051
7.0	2.541	1.9	86.1	298.9	1.149	0.051
8.0	2.544	1.9	86.1	298.9	1.154	0.051
9.0	2.544	1.9	90.5	298.9	1.149	0.053
10.0	2.539	1.9	86.1	298.9	1.151	0.051
11.0	2.533	1.8	90.5	299.4	1.146	0.053
12.0	2.546	1.8	86.1	298.9	1.146	0.051

Barometric Press (in)	29.95
Humidity (%)	22
Ambient Temp (F)	77
Pressure out of Compressor (psi)	Ranged from 22-24
Pressure of Concentrated O2 (psi)	N/A
Test Duration	
Sequal Flow Setting (SLPM)	2
Power Consumption (W)	306
O2 Calibration Factors	
Intial Voltage Reading (mV)	12.63
Multiplier (%O2 /mV)	1.706
Intercept (%O2)	0.5971
Concentration Formula	O2% = (mV * Multiplier) - Intercept

Table B.4 Varying Output 3 SLPM Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K)	Flow Reading (V)	Oxygen Reading (V)
0.0	2.536	2.8	86.1	299.4	1.144	0.048
0.0	2.536	2.8	86.1	299.4	1.149	0.051
1.0	2.533	2.7	90.5	299.4	1.149	0.053
2.0	2.539	2.8	86.1	299.4	1.149	0.051
3.0	2.541	2.6	86.1	299.4	1.149	0.051
4.0	2.536	2.9	86.1	299.4	1.146	0.053
5.0	2.531	2.6	86.1	299.4	1.149	0.053
6.0	2.536	2.9	86.1	299.4	1.149	0.051
7.0	2.536	2.8	86.1	299.4	1.149	0.051
8.0	2.539	2.9	86.1	299.4	1.154	0.051
9.0	2.541	2.9	81.8	299.4	1.149	0.053
10.0	2.536	2.8	86.1	299.4	1.151	0.051
11.0	2.533	2.9	86.1	299.4	1.146	0.053
12.0	2.539	2.8	90.5	299.4	1.146	0.051
13.0	2.539	2.9	86.1	299.4	1.149	0.051
14.0	2.533	2.9	86.1	299.4	1.149	0.051
15.0	2.539	3.0	86.1	299.4	1.161	0.053

Barometric Press (in)	29.95
Humidity (%)	22
Ambient Temp (F)	77
Pressure out of Compressor (psi)	Ranged from 22-24
Pressure of Concentrated O2 (psi)	N/A
Test Duration	
Sequal Flow Setting (SLPM)	3
Power Consumption (W)	306
O2 Calibration Factors	
Intial Voltage Reading (mV)	12.63
Multiplier (%O2 /mV)	1.706
Intercept (%O2)	0.5971
Concentration Formula	O2% = (mV * Multiplier) - Intercept

Table B.5 Varying Output 4 SLPM Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K)	Flow Reading (V)	Oxygen Reading (V)
0.0	2.549	3.8	86.1	299.4	1.144	0.048
0.0	2.544	3.8	81.8	299.4	1.149	0.051
1.0	2.544	3.7	86.1	299.4	1.149	0.053
2.0	2.541	3.8	86.1	298.9	1.149	0.051
3.0	2.541	3.9	86.1	299.4	1.149	0.051
4.0	2.544	3.9	86.1	299.4	1.146	0.053
5.0	2.541	3.6	90.5	299.4	1.149	0.053
6.0	2.541	3.9	86.1	299.4	1.149	0.051
7.0	2.541	3.5	86.1	299.4	1.149	0.051
8.0	2.541	3.9	86.1	299.4	1.154	0.051
9.0	2.541	4.1	86.1	298.9	1.149	0.053
10.0	2.544	3.8	90.5	299.4	1.151	0.051
11.0	2.541	4.5	90.5	299.4	1.146	0.053
12.0	2.541	3.7	90.5	299.4	1.146	0.051
13.0	2.539	3.6	90.5	299.4	1.149	0.051
14.0	2.541	4.1	86.1	299.4	1.149	0.051
15.0	2.546	4.1	86.1	299.4	1.161	0.053
16.0	2.544	3.8	90.5	298.9	1.146	0.053

Barometric Press (in)	29.95
Humidity (%)	22
Ambient Temp (F)	77
Pressure out of Compressor (psi)	Ranged from 22-24
Pressure of Concentrated O2 (psi)	N/A
Test Duration	
Sequal Flow Setting (SLPM)	4
Power Consumption (W)	306
O2 Calibration Factors	
Intial Voltage Reading (mV)	12.63
Multiplier (%O2 /mV)	1.706
Intercept (%O2)	0.5971
Concentration Formula	O2% = (mV * Multiplier) - Intercept

Table B.6 Varying Output 5 SLPM Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K)	Flow Reading (V)	Oxygen Reading (V)
0.0	2.539	5.0	86.1	299.4	1.144	0.048
0.0	2.539	5.1	90.5	299.4	1.149	0.051
1.0	2.539	5.0	86.1	299.4	1.149	0.053
2.0	2.541	5.0	90.5	299.4	1.149	0.051
3.0	2.541	5.3	86.1	299.4	1.149	0.051
4.0	2.531	5.0	86.1	299.4	1.146	0.053
5.0	2.541	5.1	86.1	299.4	1.149	0.053
6.0	2.541	5.3	81.8	299.4	1.149	0.051
7.0	2.539	5.5	81.8	299.4	1.149	0.051
8.0	2.533	5.0	86.1	299.4	1.154	0.051
9.0	2.541	5.5	86.1	299.4	1.149	0.053
10.0	2.539	5.0	86.1	299.4	1.151	0.051
11.0	2.544	5.3	86.1	299.4	1.146	0.053
12.0	2.541	5.3	86.1	299.4	1.146	0.051
13.0	2.539	5.3	86.1	299.4	1.149	0.051
14.0	2.539	5.0	86.1	299.4	1.149	0.051
15.0	2.539	5.2	90.5	299.4	1.161	0.053
16.0	2.544	5.3	86.1	299.4	1.146	0.053
17.0	2.539	5.2	86.1	299.4	1.149	0.051

Barometric Press (in)	29.95
Humidity (%)	22
Ambient Temp (F)	77
Pressure out of Compressor (psi)	Ranged from 22-24
Pressure of Concentrated O2 (psi)	N/A
Test Duration	
Sequal Flow Setting (SLPM)	5
Power Consumption (W)	306
O2 Calibration Factors	
Intial Voltage Reading (mV)	12.63
Multiplier (%O2 /mV)	1.706
Intercept (%O2)	0.5971
Concentration Formula	O2% = (mV * Multiplier) - Intercept

Table B.7 Varying Output 6 SLPM Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K)	Flow Reading (V)	Oxygen Reading (V)
0.0	2.536	6.1	81.8	299.4	1.144	0.048
0.0	2.536	6.2	81.8	299.4	1.149	0.051
1.0	2.536	6.5	81.8	299.4	1.149	0.053
2.0	2.533	6.2	81.8	299.4	1.149	0.051
3.0	2.533	6.4	81.8	299.4	1.149	0.051
4.0	2.531	6.0	81.8	299.4	1.146	0.053
5.0	2.539	6.4	81.8	299.4	1.149	0.053
6.0	2.533	6.3	86.1	299.4	1.149	0.051
7.0	2.544	6.2	81.8	299.4	1.149	0.051
8.0	2.533	6.2	81.8	299.4	1.154	0.051
9.0	2.539	6.3	81.8	299.4	1.149	0.053
10.0	2.539	6.4	81.8	299.4	1.151	0.051
11.0	2.531	6.3	81.8	299.4	1.146	0.053
12.0	2.539	6.5	77.4	299.8	1.146	0.051
13.0	2.544	6.2	81.8	299.4	1.149	0.051
14.0	2.533	6.2	81.8	299.4	1.149	0.051
15.0	2.536	6.3	81.8	299.4	1.161	0.053
16.0	2.539	6.4	77.4	299.4	1.146	0.053

Barometric Press (in)	29.95
Humidity (%)	22
Ambient Temp (F)	77
Pressure out of Compressor (psi)	Ranged from 22-24
Pressure of Concentrated O2 (psi)	N/A
Test Duration	
Sequal Flow Setting (SLPM)	6
Power Consumption (W)	306
O2 Calibration Factors	
Intial Voltage Reading (mV)	12.63
Multiplier (%O2 /mV)	1.706
Intercept (%O2)	0.5971
Concentration Formula	O2% = (mV * Multiplier) - Intercept

Table B.8 Varying Output 7 SLPM Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K)	Flow Reading (V)	Oxygen Reading (V)
0.0	2.536	6.9	77.4	299.4	1.144	0.048
0.0	2.536	7.3	77.4	299.4	1.149	0.051
1.0	2.539	7.1	73.1	299.4	1.149	0.053
2.0	2.536	7.1	73.1	299.4	1.149	0.051
3.0	2.539	7.1	73.1	299.4	1.149	0.051
4.0	2.539	7.4	73.1	299.4	1.146	0.053
5.0	2.539	7.4	73.1	299.4	1.149	0.053
6.0	2.536	7.4	73.1	299.4	1.149	0.051
7.0	2.533	7.0	73.1	299.4	1.149	0.051
8.0	2.536	7.3	73.1	299.4	1.154	0.051
9.0	2.536	7.2	68.7	299.8	1.149	0.053
10.0	2.536	7.0	73.1	299.4	1.151	0.051
11.0	2.539	7.4	68.7	299.4	1.146	0.053
12.0	2.539	7.4	73.1	299.4	1.146	0.051
13.0	2.536	7.1	68.7	299.4	1.149	0.051
14.0	2.536	7.1	73.1	299.4	1.149	0.051
15.0	2.541	7.5	73.1	299.4	1.161	0.053
16.0	2.541	7.7	73.1	299.4	1.146	0.053
17.0	2.541	7.3	73.1	299.4	1.149	0.051

Barometric Press (in)	29.95
Humidity (%)	22
Ambient Temp (F)	77
Pressure out of Compressor (psi)	Ranged from 22-24
Pressure of Concentrated O2 (psi)	N/A
Test Duration	
Sequal Flow Setting (SLPM)	7
Power Consumption (W)	306
O2 Calibration Factors	
Intial Voltage Reading (mV)	12.63
Multiplier (%O2 /mV)	1.706
Intercept (%O2)	0.5971
Concentration Formula	O2% = (mV * Multiplier) - Intercept

Table B.9 Varying Output 8 SLPM Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K)	Flow Reading (V)	Oxygen Reading (V)
0.0	2.544	8.3	64.4	299.4	1.144	0.048
0.0	2.539	8.2	64.4	299.4	1.149	0.051
1.0	2.544	8.1	64.4	299.8	1.149	0.053
2.0	2.539	8.1	64.4	299.4	1.149	0.051
3.0	2.539	8.5	64.4	299.4	1.149	0.051
4.0	2.539	8.2	64.4	299.4	1.146	0.053
5.0	2.539	8.5	64.4	299.4	1.149	0.053
6.0	2.536	8.5	68.7	299.4	1.149	0.051
7.0	2.536	8.5	64.4	299.4	1.149	0.051
8.0	2.533	8.4	64.4	299.4	1.154	0.051
9.0	2.539	8.2	64.4	299.4	1.149	0.053
10.0	2.536	8.2	64.4	299.4	1.151	0.051
11.0	2.533	8.6	64.4	299.4	1.146	0.053
12.0	2.536	8.3	64.4	299.4	1.146	0.051
13.0	2.539	8.3	64.4	299.4	1.149	0.051
14.0	2.536	8.4	68.7	299.4	1.149	0.051
15.0	2.536	8.9	64.4	299.8	1.161	0.053
16.0	2.539	8.0	64.4	299.4	1.146	0.053
17.0	2.536	8.3	64.4	299.4	1.149	0.051

Barometric Press (in)	29.95
Humidity (%)	22
Ambient Temp (F)	77
Pressure out of Compressor (psi)	Ranged from 22-24
Pressure of Concentrated O2 (psi)	N/A
Test Duration	
Sequal Flow Setting (SLPM)	8
Power Consumption (W)	306
O2 Calibration Factors	
Intial Voltage Reading (mV)	12.63
Multiplier (%O2 /mV)	1.706
Intercept (%O2)	0.5971
Concentration Formula	O2% = (mV * Multiplier) - Intercept

Table B.10 Varying Output 9 SLPM Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K)	Flow Reading (V)	Oxygen Reading (V)
0.0	2.539	9.3	64.4	299.4	1.144	0.048
0.0	2.536	9.5	64.4	299.4	1.149	0.051
1.0	2.539	9.3	60.1	299.4	1.149	0.053
2.0	2.541	9.8	60.1	299.4	1.149	0.051
3.0	2.536	8.9	60.1	299.4	1.149	0.051
4.0	2.533	9.3	60.1	299.4	1.146	0.053
5.0	2.539	9.6	55.7	299.4	1.149	0.053
6.0	2.541	9.2	60.1	299.4	1.149	0.051
7.0	2.544	8.9	55.7	299.4	1.149	0.051
8.0	2.536	9.3	60.1	299.4	1.154	0.051
9.0	2.536	9.1	60.1	299.4	1.149	0.053
10.0	2.533	9.4	60.1	299.4	1.151	0.051
11.0	2.536	9.3	55.7	299.4	1.146	0.053
12.0	2.539	9.1	55.7	299.4	1.146	0.051
13.0	2.541	9.3	60.1	299.4	1.149	0.051
14.0	2.539	9.2	55.7	299.4	1.149	0.051
15.0	2.541	9.2	60.1	299.4	1.161	0.053
16.0	2.539	9.2	55.7	299.4	1.146	0.053
17.0	2.531	9.0	60.1	299.4	1.149	0.051

Barometric Press (in)	29.95
Humidity (%)	22
Ambient Temp (F)	77
Pressure out of Compressor (psi)	Ranged from 22-24
Pressure of Concentrated O2 (psi)	N/A
Test Duration	
Sequal Flow Setting (SLPM)	N/A
Power Consumption (W)	306
O2 Calibration Factors	
Intial Voltage Reading (mV)	12.63
Multiplier (%O2 /mV)	1.706
Intercept (%O2)	0.5971
Concentration Formula	O2% = (mV * Multiplier) - Intercept

Table B.11 Varying Output 10 SLPM Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K)	Flow Reading (V)	Oxygen Reading (V)
0.0	2.531	9.9	51.4	299.8	1.144	0.048
0.0	2.533	10.4	55.7	299.8	1.149	0.051
1.0	2.531	10.3	51.4	299.4	1.149	0.053
2.0	2.533	10.3	55.7	299.8	1.149	0.051
3.0	2.531	9.8	55.7	299.8	1.149	0.051
4.0	2.533	9.9	55.7	299.8	1.146	0.053
5.0	2.531	9.9	51.4	299.4	1.149	0.053
6.0	2.533	9.8	55.7	299.8	1.149	0.051
7.0	2.533	10.4	51.4	299.8	1.149	0.051
8.0	2.533	10.0	51.4	299.8	1.154	0.051
9.0	2.531	10.3	51.4	299.4	1.149	0.053
10.0	2.531	10.1	55.7	299.8	1.151	0.051
11.0	2.533	10.6	51.4	299.8	1.146	0.053
12.0	2.531	9.9	55.7	299.8	1.146	0.051
13.0	2.536	9.7	55.7	299.4	1.149	0.051
14.0	2.531	10.4	55.7	299.8	1.149	0.051
15.0	2.531	10.0	51.4	299.8	1.161	0.053
16.0	2.531	10.1	51.4	299.8	1.146	0.053
17.0	2.531	9.9	55.7	299.8	1.149	0.051

Barometric Press (in)	29.95
Humidity (%)	22
Ambient Temp (F)	77
Pressure out of Compressor (psi)	Ranged from 22-24
Pressure of Concentrated O2 (psi)	N/A
Test Duration	
Sequal Flow Setting (SLPM)	N/A
Power Consumption (W)	306
O2 Calibration Factors	
Intial Voltage Reading (mV)	12.63
Multiplier (%O2 /mV)	1.706
Intercept (%O2)	0.5971
Concentration Formula	O2% = (mV * Multiplier) - Intercept

Table B.12 Varying Inlet Pressure 20 PSI Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K	Flow Reading (V	Oxygen Reading (V)		
0.0	2.508	0.3	55.7	294.9	1.026	0.033	20 PSI	
0.0	2.508	0.3	55.7	295.4	1.021	0.033	Flow Rate SLPM	O2 %
0.5	2.503	0.4	55.7	295.4	1.029	0.033	2.4	86.9
1.0	2.508	0.4	55.7	295.4	1.034	0.033	4.6	85.3
1.5	2.511	0.4	55.7	295.4	1.032	0.033	7.0	63.4
2.0	2.508	0.3	55.7	295.4	1.024	0.033	9.5	44.7
2.5	2.508	0.3	55.7	294.9	1.021	0.033		
3.0	2.503	0.4	55.7	295.4	1.034	0.033		
3.5	2.505	0.3	55.7	295.4	1.026	0.033		
4.0	2.511	0.3	55.7	294.9	1.026	0.033		
4.5	2.508	0.4	55.7	294.9	1.029	0.033		
5.0	2.508	0.4	55.7	294.9	1.032	0.033		
5.5	2.508	0.3	55.7	295.4	1.024	0.033		
6.0	2.505	0.3	55.7	295.4	1.021	0.033		
6.5	2.505	0.3	55.7	294.9	1.026	0.033		
7.0	2.508	0.3	64.4	294.9	1.026	0.038		
7.5	2.503	0.3	64.4	294.9	1.026	0.038		
8.0	2.505	0.3	55.7	294.9	1.021	0.033		
8.5	2.508	0.4	55.7	294.9	1.032	0.033		
9.0	2.508	0.4	55.7	295.4	1.034	0.033		
9.5	2.508	0.4	55.7	295.4	1.029	0.033		
10.0	2.508	0.2	55.7	295.4	1.016	0.033		
10.5	2.508	0.3	55.7	295.4	1.026	0.033		

Table B.13 Varying Inlet Pressure 25 PSI Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K	Flow Reading (V	Oxygen Reading (V)		
0.0	2.505	0.1	51.4	294.9	1.011	0.03	25 PSI	
0.0	2.505	0.2	55.7	294.9	1.016	0.033	Flow Rate SLPM	O2 %
0.5	2.505	0.2	55.7	294.9	1.016	0.033	2.4	86.4
1.0	2.508	0.0	55.7	294.9	1.003	0.033	4.6	86.3
1.5	2.505	0.1	55.7	294.9	1.009	0.033	7.1	71.3
2.0	2.505	0.3	55.7	294.9	1.024	0.033	9.1	59.6
2.5	2.508	0.3	55.7	295.4	1.026	0.033		
3.0	2.508	0.2	51.4	295.4	1.014	0.03		
3.5	2.503	0.1	55.7	295.4	1.009	0.033		
4.0	2.508	0.3	55.7	294.9	1.024	0.033		
4.5	2.511	0.1	55.7	294.9	1.011	0.033		
5.0	2.508	0.4	55.7	294.9	1.029	0.033		
5.5	2.513	0.2	55.7	294.9	1.019	0.033		
6.0	2.511	0.2	55.7	295.4	1.016	0.033		
6.5	2.508	0.1	55.7	294.9	1.011	0.033		
7.0	2.513	0.1	55.7	294.9	1.006	0.033		
7.5	2.508	-0.1	55.7	295.4	0.991	0.033		
8.0	2.508	0.3	60.1	294.9	1.021	0.036		
8.5	2.503	0.2	55.7	294.9	1.019	0.033		
9.0	2.508	0.1	55.7	294.9	1.009	0.033		
9.5	2.505	0.2	55.7	294.9	1.019	0.033		
10.0	2.508	0.3	55.7	294.9	1.021	0.033		
10.5	2.508	0.2	55.7	294.9	1.016	0.033		

Table B.14 Temperature Comparison Data

80 F Outlet Temperature		70 F Outlet Temperature		
Flow Rate (SLPM)	**Oxygen %**	**Flow Rate (SLPM)**	**Oxygen %**	
1.9	87.7	2.3	87.0	
2.7	87.1	4.7	86.3	
4.0	87.0	6.9	75.8	
5.2	83.6	9.1	57.8	
6.2	75.5			
7.2	68.0			
8.3	59.9			
9.4	55.9			
10.1	52.1			

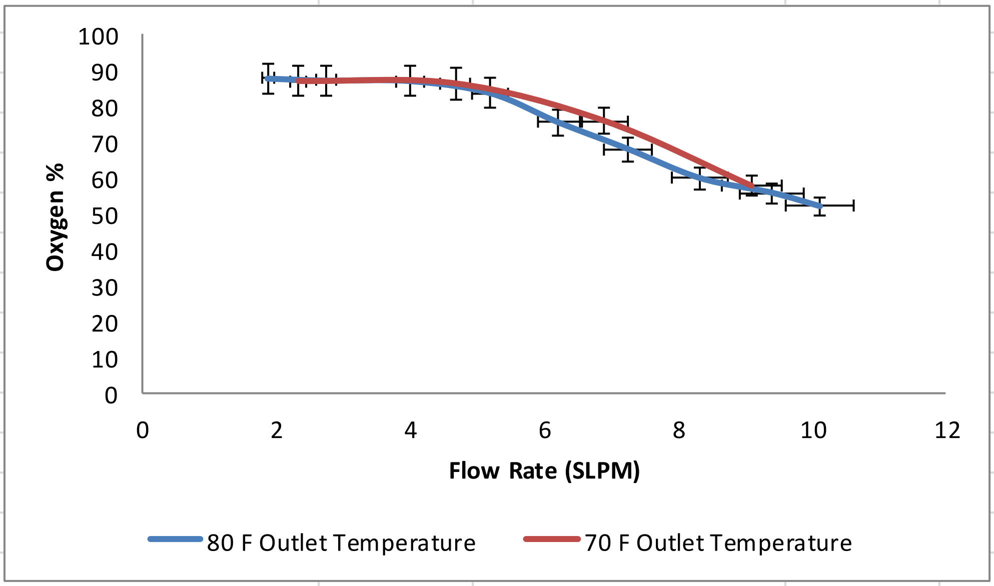


Table B.15 Varying Inlet Pressure 5 PSI Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K	Flow Reading (V	Oxygen Reading (V)		5 PSI Inlet	
0.0	2.511	0.2	21.0	294.9	1.014	0.013		O2 Flow Rate SLPM	Oxygen %
0.0	2.511	0.2	25.3	294.9	1.019	0.015		2.6	40.9
0.5	2.511	-0.1	21.0	294.9	0.993	0.013		4.7	22.9
1.0	2.508	0.1	25.3	294.9	1.006	0.015			
1.5	2.508	0.2	21.0	294.9	1.016	0.013			
2.0	2.511	0.2	21.0	294.9	1.019	0.013			
2.5	2.508	0.2	21.0	295.4	1.016	0.013			
3.0	2.508	0.3	21.0	294.9	1.024	0.013			
3.5	2.511	0.0	21.0	294.9	1.001	0.013			
4.0	2.511	0.2	21.0	294.9	1.016	0.013			
4.5	2.508	0.1	21.0	294.9	1.011	0.013			
5.0	2.508	0.1	25.3	294.9	1.006	0.015			
5.5	2.511	0.3	25.3	294.9	1.021	0.015			
6.0	2.505	0.4	21.0	294.9	1.032	0.013			
6.5	2.511	0.2	25.3	294.9	1.014	0.015			
7.0	2.511	0.2	21.0	294.9	1.014	0.013			
7.5	2.508	0.0	25.3	294.9	1.003	0.015			
8.0	2.508	0.2	25.3	295.4	1.019	0.015			
8.5	2.511	0.7	21.0	294.9	1.057	0.013			
9.0	2.5	0.0	25.3	294.9	1.003	0.015			
9.5	2.511	0.1	21.0	294.9	1.009	0.013			
10.0	2.508	0.3	21.0	294.9	1.021	0.013			
10.5	2.511	0.2	25.3	294.9	1.016	0.015			
11.0	2.508	0.1	25.3	294.9	1.011	0.015			

Table B.16 Varying Inlet Pressure 10 PSI Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K	Flow Reading (V	Oxygen Reading (V)		10 PSI Inlet	
0.0	2.505	0.2	21.0	294.9	1.014	0.013		O2 Flow Rate SLPM	Oxygen %
0.0	2.505	0.0	21.0	295.4	1.001	0.013		2.3	78.2
0.5	2.503	0.1	25.3	294.9	1.006	0.015		5.0	44.3
1.0	2.511	0.1	21.0	294.9	1.006	0.013		7.4	31.1
1.5	2.511	-0.2	21.0	294.9	0.983	0.013			
2.0	2.508	0.1	21.0	294.9	1.006	0.013			
2.5	2.508	0.2	21.0	294.9	1.014	0.013			
3.0	2.505	0.2	21.0	294.9	1.016	0.013			
3.5	2.511	0.1	16.6	294.9	1.006	0.01			
4.0	2.511	-0.2	25.3	294.9	0.981	0.015			
4.5	2.511	-0.1	21.0	294.9	0.991	0.013			
5.0	2.508	-2.0	25.3	294.9	0.84	0.015			
5.5	2.508	0.9	21.0	294.9	1.07	0.013			
6.0	2.511	-0.8	21.0	294.9	0.935	0.013			
6.5	2.508	-0.2	25.3	294.9	0.986	0.015			
7.0	2.505	-0.3	21.0	294.9	0.975	0.013			
7.5	2.508	-0.1	21.0	294.9	0.991	0.013			
8.0	2.508	-0.2	25.3	294.9	0.986	0.015			
8.5	2.511	-0.3	21.0	294.9	0.978	0.013			
9.0	2.508	-0.1	21.0	294.9	0.996	0.013			
9.5	2.508	-0.1	25.3	294.9	0.988	0.015			
10.0	2.511	-0.1	21.0	294.9	0.993	0.013			
10.5	2.511	-0.6	25.3	294.9	0.955	0.015			
11.0	2.508	-0.1	25.3	295.4	0.988	0.015			

Table B.17 Varying Inlet Pressure 15 PSI Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K	Flow Reading (V	Oxygen Reading (V)		15 PSI Inlet	
0.0	2.508	0.3	34.0	294.9	1.024	0.02		O2 Flow Rate SLPM	Oxygen %
0.0	2.508	0.3	34.0	294.9	1.026	0.02		2.4	86.2
0.5	2.508	0.5	34.0	295.4	1.037	0.02		4.9	78.1
1.0	2.513	0.3	34.0	294.9	1.024	0.02		7.4	44.7
1.5	2.513	0.2	34.0	295.4	1.016	0.02		9.2	35.6
2.0	2.511	0.4	34.0	294.9	1.029	0.02			
2.5	2.508	0.2	34.0	294.9	1.014	0.02			
3.0	2.511	0.2	29.6	294.9	1.014	0.018			
3.5	2.511	0.2	29.6	295.4	1.014	0.018			
4.0	2.508	0.3	34.0	294.9	1.021	0.02			
4.5	2.508	0.2	34.0	295.4	1.016	0.02			
5.0	2.508	0.2	29.6	294.9	1.014	0.018			
5.5	2.511	0.2	29.6	294.9	1.016	0.018			
6.0	2.513	0.2	34.0	295.4	1.014	0.02			
6.5	2.508	0.3	34.0	294.9	1.024	0.02			
7.0	2.508	0.2	29.6	294.9	1.014	0.018			
7.5	2.508	0.1	34.0	294.9	1.011	0.02			
8.0	2.508	0.2	34.0	294.9	1.014	0.02			
8.5	2.511	0.2	34.0	294.9	1.019	0.02			
9.0	2.513	0.2	34.0	295.4	1.016	0.02			
9.5	2.508	0.1	34.0	294.9	1.009	0.02			
10.0	2.511	0.2	34.0	294.9	1.019	0.02			
10.5	2.511	0.3	34.0	294.9	1.021	0.02			
11.0	2.508	0.3	34.0	294.9	1.021	0.02			

Table B.18 Varying Inlet Pressure 20 PSI Sample

Time (s)	2.5 V Supply	O2 Flow Rate SLPM	O2 Conc %	Temperature (K	Flow Reading (V	Oxygen Reading (V)		20 PSI Inlet	
0.0	2.511	-0.2	34.0	294.9	0.986	0.02		O2 Flow Rate SLPM	Oxygen %
0.0	2.508	-0.1	38.3	294.9	0.991	0.023		2.3	86.6
0.5	2.511	-0.1	34.0	294.9	0.988	0.02		4.8	85.8
1.0	2.511	-0.1	38.3	294.9	0.993	0.023		7.2	62.7
1.5	2.511	-0.2	34.0	294.9	0.981	0.02		9.7	43.7
2.0	2.508	1.0	34.0	295.4	1.077	0.02			
2.5	2.511	-0.3	34.0	295.4	0.978	0.02			
3.0	2.503	0.0	34.0	294.9	0.998	0.02			
3.5	2.508	0.7	38.3	295.4	1.06	0.023			
4.0	2.508	1.8	34.0	294.9	1.146	0.02			
4.5	2.505	-0.3	34.0	295.4	0.978	0.02			
5.0	2.508	0.0	34.0	294.9	1.001	0.02			
5.5	2.508	0.0	34.0	294.9	1.001	0.02			
6.0	2.511	-0.3	34.0	295.4	0.975	0.02			
6.5	2.511	1.2	34.0	294.9	1.093	0.02			
7.0	2.511	-0.3	34.0	295.4	0.975	0.02			
7.5	2.505	-0.2	34.0	295.4	0.983	0.02			
8.0	2.508	-0.8	34.0	294.9	0.94	0.02			
8.5	2.508	-0.4	38.3	294.9	0.97	0.023			
9.0	2.508	-0.1	38.3	294.9	0.996	0.023			
9.5	2.508	-1.2	34.0	294.9	0.904	0.02			
10.0	2.505	-0.7	34.0	295.4	0.945	0.02			
10.5	2.511	-0.5	34.0	294.9	0.963	0.02			
11.0	2.508	-0.1	34.0	294.9	0.988	0.02			

Table B.19 Varying Inlet Pressure 25 PSI Sample

Time (s)	2.5 V Suppl	O2 Flow Rate SLPN	O2 Conc %	Temperature (K	Flow Reading (V	Oxygen Reading (V)		25 PSI Inlet	
0.0	2.508	-1.7	42.7	295.4	0.868	0.025		O2 Flow Rate SLPM	Oxygen %
0.0	2.511	-0.2	42.7	294.9	0.983	0.025		2.3	87.0
0.5	2.505	0.0	42.7	294.9	1.003	0.025		4.7	86.3
1.0	2.503	-0.1	38.3	294.9	0.993	0.023		6.9	75.8
1.5	2.508	0.0	42.7	294.9	1.003	0.025		9.1	57.8
2.0	2.508	0.1	42.7	294.9	1.006	0.025			
2.5	2.508	-0.3	42.7	294.9	0.973	0.025			
3.0	2.508	-0.1	42.7	294.9	0.996	0.025			
3.5	2.5	0.2	42.7	295.4	1.016	0.025			
4.0	2.508	0.0	42.7	295.4	1.001	0.025			
4.5	2.511	0.1	51.4	295.4	1.006	0.03			
5.0	2.508	0.1	42.7	294.9	1.011	0.025			
5.5	2.505	0.1	42.7	294.9	1.009	0.025			
6.0	2.511	0.1	42.7	295.4	1.006	0.025			
6.5	2.503	0.2	42.7	295.4	1.014	0.025			
7.0	2.508	0.5	42.7	294.9	1.042	0.025			
7.5	2.508	0.2	42.7	294.9	1.016	0.025			
8.0	2.508	0.2	42.7	295.4	1.014	0.025			
8.5	2.511	0.3	42.7	295.4	1.021	0.025			
9.0	2.508	-0.1	42.7	294.9	0.988	0.025			
9.5	2.511	-0.2	42.7	294.9	0.981	0.025			
10.0	2.505	0.0	42.7	295.4	1.003	0.025			
10.5	2.508	0.0	42.7	295.4	1.003	0.025			
11.0	2.511	0.0	42.7	295.4	1.003	0.025			

Table B.20 Supplied Compressor v. Alternate Air

20 PSI Supplied Compressor			20 PSI Alternate Air		
Flow Rate SLPM	**O2 %**	**Liters of Oxygen/Minute**	**O2 Flow Rate SLPM**	**Oxygen %**	**Liters of Oxygen/Minute**
2.4	86.9	2.1	2.3	86.6	2.0
4.6	85.3	3.9	4.8	85.8	4.1
7.0	63.4	4.4	7.2	62.7	4.5
9.5	44.7	4.2	9.7	43.7	4.2
25 PSI Supplied Compressor			25 PSI Alternate Air		
Flow Rate SLPM	**O2 %**	**Liters of Oxygen/Minute**	**O2 Flow Rate SLPM**	**Oxygen %**	**Liters of Oxygen/Minute**
2.4	86.4	2.1	2.3	87.0	2.0
4.6	86.3	3.9	4.7	86.3	4.0
7.1	71.3	5.1	6.9	75.8	5.2
9.1	59.6	5.4	9.1	57.8	5.3