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**Demonstration of a Cylinder-fill System Based on Solid
Electrolyte Oxygen Separator (SEOS) Technology: One Year
Early Field Assessment at a USAF Maintenance Facility**

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Interim Report

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Executive Summary

The goal of the effort was to conduct an early field assessment of SEOS oxygen-generation technology and obtain user feedback and lessons learned. A SEOS breadboard for charging high pressure oxygen cylinders was installed at a maintenance facility at Oklahoma City-Air Logistics Center (OC-ALC), Tinker AFB OK. OC-ALC, Air Products and Chemicals, Inc., Ceramatec Inc., and the Air Force Research Laboratory (AFRL) worked collaboratively on this effort. Tinker AFB modified the facility to allow integration of the SEOS breadboard into its existing high pressure oxygen system.

The SEOS breadboard was capable of producing 99.9+% oxygen at pressures up to 2,200 psig. The breadboard used SEOS baseline electrochemical stacks and an external oxygen compressor. The oxygen was stored in high pressure cylinders and was used to fill aircraft oxygen bottles. The oxygen was tested several times per MIL-PRF-27210, Aviator's Breathing Oxygen (ABO), and it passed the ABO specification. On 20 November 2009 the first aircraft oxygen bottle was filled with SEOS oxygen. During the effort several electrical problems on the compressor and ancillary electrical equipment were addressed. The SEOS electrochemical stacks used to generate the high purity oxygen functioned as expected.

The SEOS cylinder fill system was installed at the Tinker AFB site from 20 November 2009 through 18 September 2010. The average up-time during that period was 51%. The unit was serviced twice during the test period.

The SEOS oxygen production unit initially worked well to fill aircraft oxygen bottles. The system successfully delivered oxygen at a flow rate, purity, and pressure meeting ABO requirements, and the Tinker AFB operating personnel found the system very easy to use. However, frequent building power interruptions with subsequent system shutdowns resulted in auxiliary equipment failures and stack leaks. The stack leak rates increased with time and eventually prevented the system from meeting the ABO specification for moisture content. The ABO specification for moisture was slightly exceeded.

Recently developed next generation SEOS oxygen production stacks require less auxiliary equipment and are more resilient to rapid shutdowns and start-ups. Future SEOS demonstration breadboards would include these newer stack designs and the possible elimination of mechanical compression equipment.

The program goal was to operate the breadboard for one (1) year at the user site. The design, installation, start-up and the first six (6) months of the early field assessment period were conducted under USAF R&D Contract FA8650-08-C-6824. The remainder of the one year was conducted under USAF R&D Contract F41624-00-C-6000. For continuity, this report includes the entire early field assessment period.

1.0 Introduction and Background

1.1 Introduction

This effort assessed the “real-life” performance of an advanced breadboard comprising oxygen-generation and cylinder-fill compression equipment developed under a research contract between Air Products and AFRL. The oxygen generation is accomplished using a planar ceramic, electrolytic membrane consisting of an advanced electrolyte. User feedback provided valuable information on the performance of the system and the technology, and will be beneficial in directing future development of this advanced oxygen-generation technology.

A six standard liter per minute Advanced SEOS Breadboard, previously built and demonstrated to the Air Force (under R&D contract F41624-00-C-6000), was modified and installed on a mobile cart. This breadboard was then integrated into the existing high pressure oxygen system at a maintenance facility at Tinker AFB OK. An important element of the integration was the breadboard could be easily disconnected and replaced by vendor supplied high pressure oxygen cylinders, if the breadboard malfunctioned.

1.2 Background: Design and Operation of SEOS Stacks

The ITM SEOS Oxygen Generator uses a stack of electrically-conductive ceramic membranes to separate and recover oxygen from air. At its most basic level, a solid electrolyte oxygen separator consists of an interconnect and an electrolyte plate with two electrodes, as illustrated in Figure 1. An oxygen-containing stream passes over the electrolyte plate; oxygen molecules are electrochemically reduced to oxygen ions on the cathode and are transported through the electrolyte as oxygen ions due to an applied electric potential. On the opposite side, the oxygen ions combine to produce oxygen molecules and free electrons. The interconnect serves to isolate the oxygen permeate stream from the air stream and to pass the electrons (current) to the next cell. In practice, additional components are required, including glass seals and structurally-supporting materials. Because these devices typically operate at elevated temperatures (600-750°C, 1100-1400°F), the interconnects are made from electrically-conductive ceramics.

The ITM SEOS stack (Figure 2) consists of several SEOS membranes arranged in a planar fashion, such that they are in series electrically and are in parallel with respect to the flow of the feed gas. Additional details on general SEOS technology are included as Appendix A.

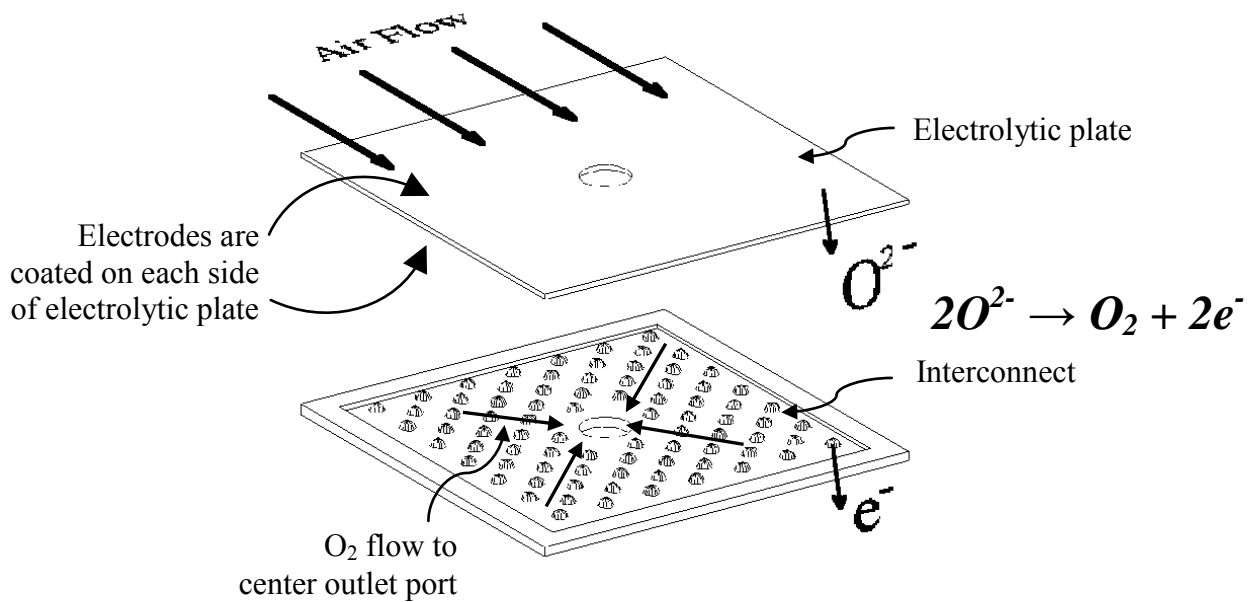


Figure 1. In this "exploded" view of a SEOS oxygen-generating couplet, air flows across the electrolyte. Oxygen is ionized on the cathode (not shown) and is transported through the electrolyte as oxygen ions due to an applied electric potential.

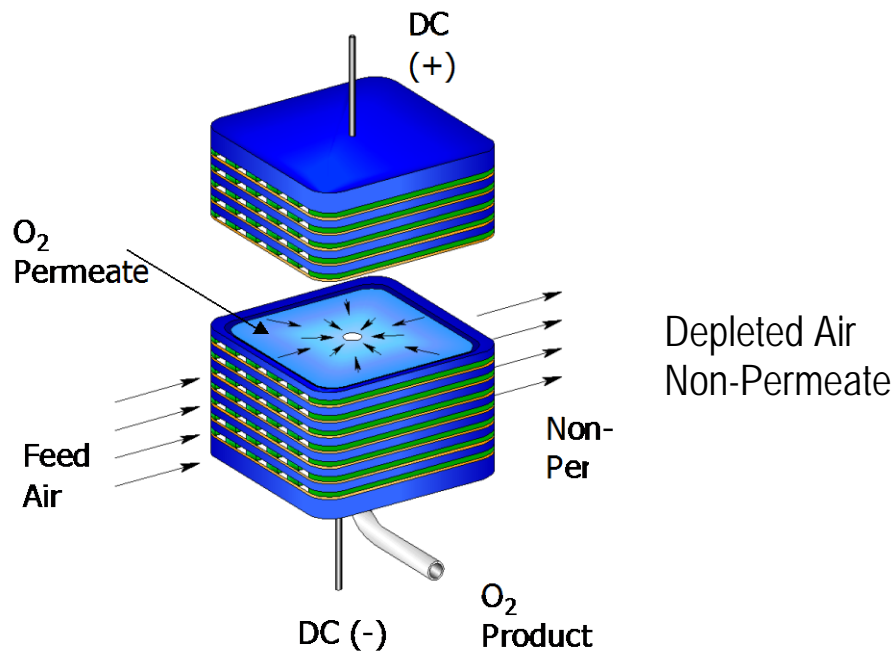


Figure 2. In this "exploded" view of an ITM SEOS stack, air flows in parallel through channels in the stack face and across the electrolyte. The oxygen product is isolated by a seal between the rim of the interconnecting plate and the electrolyte, collected in the central manifold, and exits from the stack through the centrally-positioned oxygen piping.

2.0 Discussion of Results

2.1 Design

A mobile Advanced SEOS Breadboard cylinder fill system was designed, assembled and tested. The design and assembly activities included development of the piping and instrumentation diagram (PI&D), safety hazard review, component pre-testing and assembly, air mover testing, TMS assembly, final unit assembly and system start-up. The configuration of the air manifold system that delivers fresh air to the SEOS stacks is shown in Photograph #1.



Photograph #1. SEOS 6 slpm cylinder fill breadboard air manifold system.

Facility demand for high pressure oxygen varied. In order to deliver high pressure oxygen at variable rates, the oxygen generators were designed to operate continuously and a Rix Microboost compressor compressed the low pressure oxygen from the generators to high pressure. The unit was designed to produce a steady flow of 6 slpm of SEOS oxygen at 2200 psig to two high pressure oxygen cylinders. The system was programmed to shut off the compressor when the pressure in the cylinders reached ~2200 psig and restart when the cylinder pressure fell to ~1800 psig. The cylinder fill system is shown in Photograph #2.



Photograph #2. SEOS 6 slpm cylinder fill breadboard as originally configured and tested at Air Products.

Previously, the breadboard was demonstrated in 2006. During the demonstration a small medical oxygen cylinder was filled to 2000 psig, and product oxygen demand was varied between zero and 11 slpm to demonstrate a typical operating installation (Figure 3). Oxygen purity during the demonstration was measured as 99.999% oxygen and continued to improve over time as impurities were purged from the delivery system. Oxygen purity increased to 99.9997% in four days after the start of the demonstration (Figure 4).

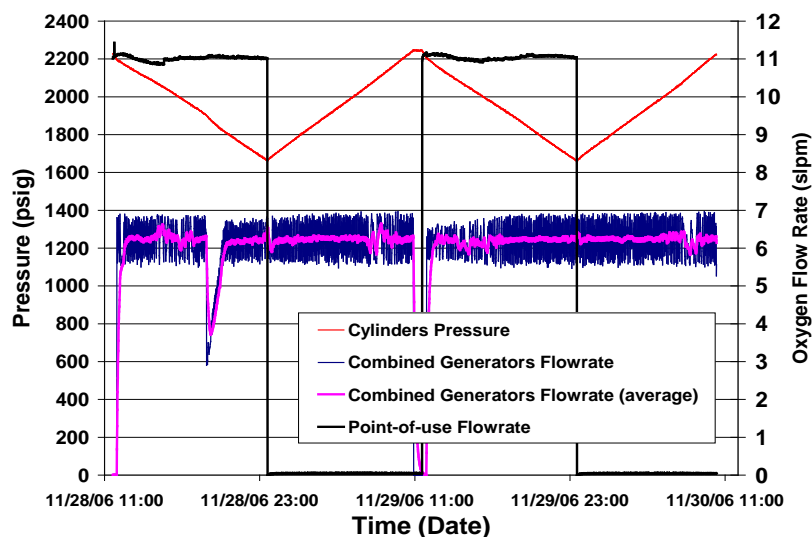


Figure 3. Laboratory testing of the cylinder filling system with varying oxygen demand rates.

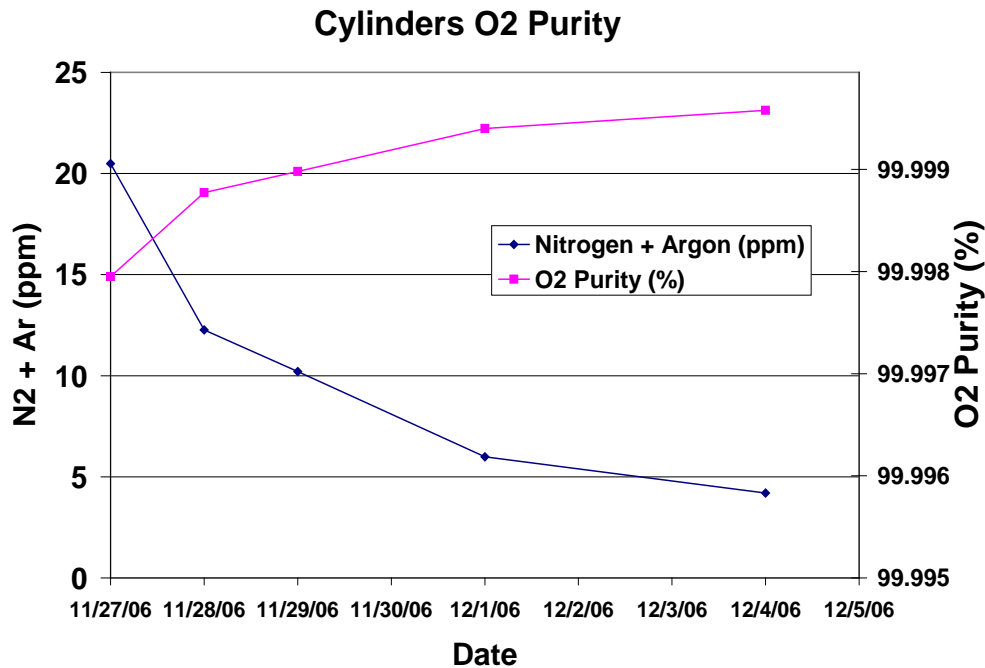


Figure 4. Laboratory demonstration of oxygen product purity of the cylinder filling system.

This 6 slpm Advanced SEOS Breadboard cylinder fill system was selected for the demonstration in an operating maintenance facility at Tinker AFB OK. The breadboard was integrated into the existing high pressure oxygen system to replace vendor supplied high pressure oxygen cylinders. The goal of this effort was to conduct an early field assessment of SEOS oxygen-generation technology and obtain user feedback and lessons learned.

Prior to beginning the effort, a SEOS oxygen sample was collected and analyzed at a Wright-Patterson AFB laboratory to ensure SEOS oxygen conformed to MIL-PRF-27210G, ABO. The results exceeded the military specification purity requirements. The analysis results are included in Appendix B.

Tinker AFB modified its facility to allow the integration of the SEOS breadboard into the facility's high pressure oxygen system. Tinker AFB also provided a piping and instrumentation drawing showing the modifications. An important element of the integration was that the breadboard could be easily disconnected and replaced by vendor supplied high pressure oxygen cylinders, if the breadboard malfunctioned. Air Products reviewed the drawings. Site modifications also included a new 30A/120V AC electrical service for the SEOS unit.

Air Products conducted a Hazard Analysis of the modified breadboard. The methodology identified and analyzed potential safety hazards and defined safeguards to mitigate or minimize the risk level. All of the corrective actions identified in the hazard review were completed prior to operation of the unit.

2.2 Equipment Modifications

The breadboard was modified to adapt it to the existing high pressure oxygen delivery system. The system changes included high/low pressure shutdowns, relocating compressor control switches, and

adding independent air manifolds for each of the two 3 slpm generators. Air Products also improved the general safety features of the breadboard installation, such as adding a locking mechanism on the cart to prevent rolling and securely mounting the generators to the cart. A simplified schematic of the modified breadboard is shown in Figure 5.

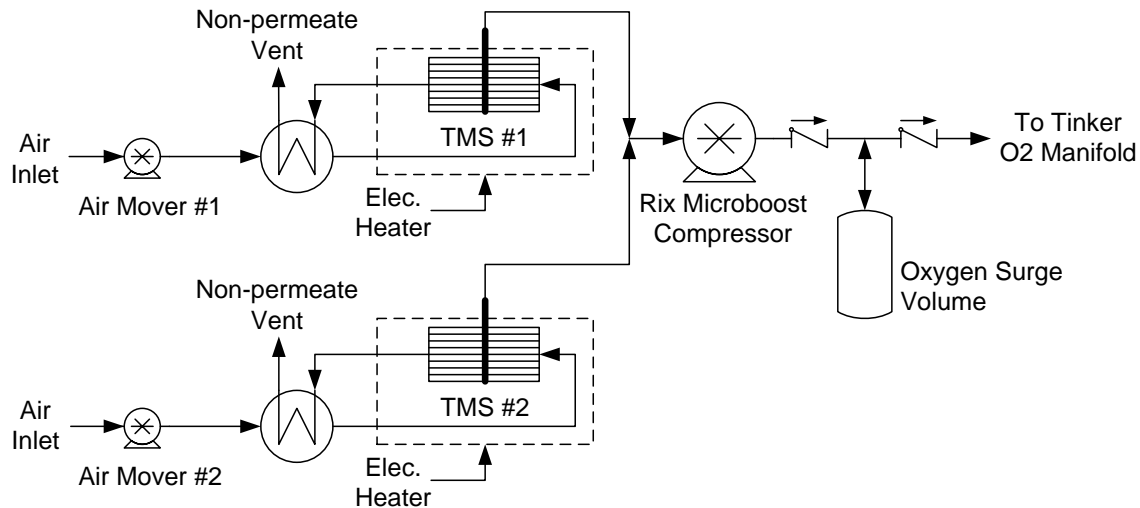


Figure 5. Simplified schematic of 6 slpm cylinder fill breadboard

Initial start-up tests showed the Rix Microboost Compressor did not properly restart when the discharge outlet line was pressurized. Modifications were implemented to depressurize the outlet discharge prior to a compressor restart. A solenoid valve was installed and interlocked to the compressor electronics, allowing it to open for one (1) minute to vent oxygen pressure prior to compressor start. A performance test of the entire breadboard system was successfully completed at the Air Products facility prior to shipment to Tinker AFB.

2.3 Installation

The SEOS cylinder-fill system was installed at OC-ALC, Tinker AFB on 15-20 November 2009. The Tinker AFB modifications allowed successful integration of the breadboard to the facility. The breadboard began producing oxygen within 72 hours of the Air Products start-up team's arrival on site, including unpacking, setup, installation, checkout, heat-up and start-up.

2.4 Start-up

The SEOS breadboard was started, tested and operating in the fully automatic mode at completion of the installation period. Tinker AFB personnel were trained in start-up, operation, shutdown, oxygen sampling and data logging of the system.

On 20 November 2009 Tinker personnel took two oxygen samples and submitted them to the Tinker AFB laboratory for analysis. The Tinker AFB laboratory confirmed that the oxygen samples met MIL-PRF-27210G, Aviators' Breathing Oxygen. In general, oxygen samples were collected and analyzed every forty-five (45) days.

Pictures below show the SEOS breadboard at Tinker AFB.



Photograph #3. SEOS breadboard installed at OC-ALC maintenance facility.



Photograph #4. SEOS breadboard shown with facility high pressure oxygen supply system.

2.5 Operation and Maintenance

The purpose of the early field assessment at a user site was to evaluate the performance of the breadboard in an actual operating environment. A Narrative Logbook of some events during the effort is provided in Appendix C, and the operating manual for the breadboard is in Appendix D.

The system was placed on-line and used to fill aircraft bottles on 20 November 2009. It operated until 1 December 2009, when the Rix oxygen compressor shut down. A loose power cable was discovered and then secured; and the unit returned to normal operation.

On 4 December 2009 the Rix compressor began to intermittently fail to restart after normal cyclical on/off operation. Tinker personnel observed the compressor would restart normally if the system was “re-booted” by powering down the control system. The oxygen generators were not affected. The root cause for the compressor control issue was a switch on the compressor suction interlock circuit. The interlock was designed to prevent the Rix compressor from operating without sufficient feed pressure; this feature prevents contamination of the oxygen product. However, the compressor feed circuit typically experienced low pressure conditions when the compressor was shut down for extended periods. This issue was corrected by adding a five second delay timer to the switch on the compressor suction interlock circuit.

The inlet air movers experienced mechanical and electrical problems on 13 January 2010, which resulted in some system downtime. It was discovered that both air movers and an air mover power supply malfunctioned. Both air movers showed significant wear on the diaphragm and inlet and exhaust flappers. Air Mover #1 (Oxygen Generator #1) was replaced with a spare unit, and an attempt was made to rebuild Air Mover #2 by installing a new head gasket, filter, inlet and exhaust flappers, diaphragm, and hold-down screws. The rebuild was unsuccessful, and Air Mover #2 required replacement on 8 March 2010. It is likely that electrical over-load caused the power supply to fail. The power supply was replaced during an Air Products maintenance trip on 16-18 February.

Oxygen Generator #1 and the compressor were returned to normal operation on 18 February. Oxygen Generator #2 was returned to normal operation on 8 March. The complete breadboard was placed on-line on 26 March 2010 following a successful oxygen purity analysis.

The system remained on-line until 23 April 2010, when the oxygen compressor began to experience control issues. The compressor was occasionally unable to automatically restart after a normal shutdown period. However, the compressor would start if the manual restart button was held for 90 seconds. A preliminary evaluation suggested this condition was caused by a timer sequencing upset. This issue was resolved by a system restart.

Tinker AFB experienced several prolonged power outages in May and June due to local construction activity. These events caused intermittent oxygen generator operation, stack leakage and problems with the electrical components. Oxygen Generator #1 failed on 4 June 2010 during the power outages. Air Mover #1 was operating, but the power supply on the thermal management system (TMS) failed. Oxygen Generator #2 was operating, but at a production rate of 80% capacity. The breadboard supplied oxygen at a reduced capacity of 2.4 slpm; however, this reduced rate was sufficient to meet the OC-ALC facility needs.

Oxygen Generator #2 stopped operating on 22 June due to a high stack current, but was restarted at a reduced oxygen production rate. Oxygen samples taken after the restart measured 9 ppm moisture, failing to meet the ABO moisture specification of 7 ppm maximum. Oxygen Generator #2 continued to be operated in a standby mode, but the SEOS system was taken off-line, and the Tinker facility was transferred to vendor cylinders while the cause of the contamination was investigated.

The SEOS oxygen delivery system was purged in early July to ensure that the moisture contamination in the oxygen samples was not due to a residual contamination in the oxygen storage cylinders. System purging was completed and the oxygen storage cylinders were repressurized from 1000 to 2000 psig.

Oxygen product samples were taken on 29 July after an extended 6 hour purge of the sample vessels, in order to minimize the potential for sample contamination. Moisture concentration results for these samples continued to be above 7 ppm, indicating that the product contamination was most likely occurring prior to the compressor discharge.

The system was serviced on 9-12 August. The work performed during the maintenance overhaul included the following:

- Preventative maintenance was performed on the Rix compressor seals. Both compressor check valves appeared to be leaking and were replaced.
- The Thomas Air Movers were wired with fully insulated male/female disconnect in-line type terminals. These connectors were specified to simplify the expected repair or replacement of components; however, these disconnect type terminals can develop significant resistance. Over six months of run time these terminals overheated the connectors and about 1/2" of wire insulation on either side of the terminals. The added resistance from the disconnect type terminals may have contributed to the failure of the power supplies and/or air movers. These disconnect type terminals were replaced with fully insulated, crimp, butt splice connectors which provide more metal contact and less resistance.
- The output voltage from the air mover power supplies slightly exceeded the rated voltage for air movers. This voltage mismatch could have been partially responsible for the reduced service life of the air movers. Both power supplies were replaced and the output voltage reduced to 12 volts, the rated voltage of the air movers.
- Both Thomas air movers were replaced.
- The power supply for TMS #1 had malfunctioned and was providing an inconsistent voltage. The power supplies for both TMS #1 and TMS #2 were replaced.
- TMS #1 had a large leak, as indicated by a very low measured Cold Pressure Decay (CPD). TMS #2 was also leaking significantly, and both units had a high measured resistance of ~20 mega ohms. Both required replacement; unfortunately spare TMSs with high quality, low leak rate stacks were not available. Both TMS #1 and TMS #2 were replaced with available lower quality spare units with low CPD measurements.

The unit was restarted on 12 August. An overall oxygen production rate of 5 slpm was achieved, with TMS #2 producing oxygen slightly below design flow due to low output from the new power supply. The compressor operation was verified, and the discharge pressure was cycled to 2,100 psig. In order to eliminate contaminated oxygen from the delivery system, the oxygen storage cylinders were vented down from 2000 to 100 psig, re-pressurized to 500 psig, vented down to 100 psig and then

repressurized to 1800 psig. The entire sample system was purged 5 times from 1000 to 0 psig. It was then flushed with oxygen flow from the Rix compressor for 30-45 minutes.

Product oxygen samples collected on 19 August measured 14 ppm moisture, failing to meet the ABO moisture specification of 7 ppm maximum.

TMS #1 shut down on 26 August due to a high stack current alarm. The TMS was restarted and operated until 30 August, when it shut down again due to high stack current. Attempts to restart the TMS on 13 and 14 September were unsuccessful due to high stack current. A final attempt to restart TMS#1 on 20 September was also unsuccessful.

An oxygen sample was taken at the outlet of the oxygen compressor, with the storage cylinders isolated on 31 August in an effort to locate the source of the product contamination. Additionally, the testing lab verified their analysis procedures by demonstrating that they were able to successfully measure the water content of other gas samples down to 1 ppm. The measured moisture content at the compressor discharge was 12 ppm, indicating that the contamination was originating in the TMS, the compressor, or the interconnecting piping.

TMS #2 shut down on ~18 September prior to any additional testing or system modifications. A restart attempt on 20 September was unsuccessful due to an air mover failure.

On 8 October Air Products and AFRL agreed to end the early assessment period and remove the SEOS breadboard from the Tinker facility. Additional testing and the cost of repairing the unit were not warranted because the lessons learned had been captured. In addition, the technology for SEOS stack design had progressed beyond what was being used in the unit at Tinker.

The SEOS Oxygen generator and related equipment were disassembled and packaged on 10 November. The oxygen in the high pressure cylinders was vented to 15-20 psig. The breadboard was shipped to Brooks City-Base TX on 9 December.

2.6 Operations and Contamination Summary

The SEOS cylinder fill system was installed at the Tinker AFB site from 20 November 2009 through 18 September 2010. The average up-time during that period was 51%. Generator #1, Generator #2 and the Rix Microboost Compressor up-times were 56%, 79% and 82%, respectively. All three units were serviced twice during the 303 day test period, with both TMS #1 and TMS #2 being replaced.

The most likely cause of the increased moisture, first observed on 22 June, was leaks in one or more of the SEOS ceramic stacks. The product oxygen stream is internal to the ceramic cells and typically operates at a higher pressure than the external air feed stream. Moisture in the lower pressure feed air is generally not a problem, since only oxygen ions can be transported across the solid electrolyte to the higher pressure product stream. The moisture in the air can become a problem if the cracks in the stacks are large enough to allow water vapor into the oxygen product by back diffusion. The probability of contamination by back diffusion will increase as the pressure differential between the internal oxygen and external feed air decreases. Contamination will be significantly worse if the external air pressure exceeds the oxygen pressure, since contamination by a larger convective flow will also occur.

The system was designed with both oxygen generators manifolded to the compressor suction without any means for isolation of an inoperative stack. In addition, the oxygen pressure within the stacks is set by the compressor suction pressure, which is lower when only one TMS is operating. Moisture contamination was absent or acceptable when both TMS #1 and TMS #2 were operating with high quality stacks with low leak rates. It is very likely that the thermal shocks that resulted from the frequent external power outages created significant leaks within the ceramic stack in TMS #1. When TMS #1 shut down on 4 June, the combined stack discharge pressure dropped from 10 to 8 psig. Leaks in TMS #1, combined with the lower pressure differential between the oxygen and the feed air, could have allowed a small amount of moisture to back diffuse into the oxygen line.

When the system was serviced on 9-12 August, TMS #1 and TMS#2 were replaced with spare units that had known high leak rates. Although not ideal, this calculated risk was accepted because it allowed the SEOS system to be brought back on-line with some level of oxygen generating capacity. Unfortunately, this attempt to restart the unit with lower quality stacks was unsuccessful because it did not address the fundamental contamination source, stack leaks.

2.7 Key Accomplishments

- A six (6) standard liter per minute Advanced SEOS Breadboard (built and demonstrated to the Air Force under Contract Number F41624-00-C-6000) was integrated into the existing high pressure oxygen system at the maintenance facility at OC-ALC, Tinker Air Force Base, OK. The subsequent operation demonstrated that a SEOS system is capable of supplying oxygen that complied with Aviators' Breathing Oxygen specification, MIL-PRF-27210G.
- Short start-up times were demonstrated. The breadboard began producing oxygen within 72 hours of the Air Products start-up team's arrival on site, including unpacking, setup, installation, checkout, heat-up and start-up.
- The SEOS cylinder fill system operated with a 51% up-time over a continuous 303 day test period. The longest continuous run time was 28 days.
- The Rix Microboost Compressor proved reliable, with an on-stream time was 82%.
- Operating experience and user feedback provided valuable insight into the performance of the system and the technology, which will be essential for directing future development of this advanced oxygen-generation technology.

3.0 Conclusions and Recommendations

Although reliability and servicing requirements of the current design need improvement, operation of this first of a kind unit has demonstrated that a SEOS system is capable of supplying the oxygen needs of a maintenance facility. We are very optimistic that the operational issues can be readily addressed with proper application of the latest SEOS technology, Next Generation SEOS electrochemical cells.

Feedback from the Tinker AFB facility personnel was very positive. They rated the controls of the unit as very easy to navigate and use. They also noted that it was significantly safer, smaller and quieter than the system that it replaced, with an associated man-hours reduction (see the user questionnaire in Appendix E).

SEOS oxygen production is a viable alternative to cylinder delivered oxygen. The system successfully delivered oxygen at a flow rate, purity, and pressure sufficient to meet the needs of the Tinker facility.

3.1 Recommendations

Although the Rix Microboost compressor was reliable, the periodic maintenance costs were significant. Future efforts should focus on extending the preventative maintenance interval for the Rix Microboost compressor. Regular compressor preventative maintenance is currently conducted quarterly. It is expected this maintenance interval can be extended while still maintaining reliable operation.

Intermittent power supply and frequent power interruptions were root causes for much of the system down time and equipment failures. Unfortunately, unreliable power systems may be a typical constraint for system environments. Future systems need to include a more robust Uninterruptable Power Supply (UPS) configuration and control system design to properly respond to power interruptions.

The potential for contamination by air back diffusion should be minimized. The changes might include:

- Minimizing the number fittings on the oxygen delivery system, and using welded joints and components wherever possible.
- Modifying the multiple-stack manifold with installed valves for isolation of individual TMSs. This change will allow positive isolation of non-operational stacks.
- Modifying control programs to shut down the air mover for a non-operating stack. This change will lower the external feed air pressure on the stack and minimize the potential for product contamination by back diffusion.

Reliability of the air movers was one of the most significant causes of system down time under otherwise normal operating conditions. The air movers appeared very sensitive to system voltage. Alternative air mover suppliers should be investigated.

Vibration from the Rix compressor was responsible for a bracket failure and may be partially responsible for early failure of the air movers, power supplies and SEOS stacks. The Rix compressor should be physically separated from the SEOS oxygen generators, and the vibration dampeners on the air movers should be upgraded.

3.2 Recommendations for Future Efforts

Recent SEOS technology developments have resulted in a more robust Next Generation (Next Gen) stack design. This Next Gen stack design has demonstrated better resilience to thermal shock, delivers electrochemically produced oxygen at pressures of 150-200 psig, and requires a lower pressure air feed. Future SEOS field tests and demonstrations should be based on the NextGen technology.

Non-mechanical compression options should be investigated. This could include full electrochemical compression using the ceramic stack.

The air circuit design should be modified to take advantage of the low pressure drop requirements of the NextGen stacks. The air movers could be replaced with simple, high reliability fans or blowers.

APPENDIX A – SEOS Technical Background Information

OXYGEN GENERATION USING SEOS ION TRANSPORT MEMBRANES

Joseph M. Abrardo
E. P. Ted Foster
Brian M. O'Neil

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7201 Hamilton Boulevard
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INTRODUCTION

Oxygen is used by the military in medical, breathing, and metal fabrication and cutting applications. Historically, this oxygen has been supplied as high purity, compressed gas in cylinders or bottles and as liquid in dewars. The distribution and handling requirements for these products necessitate a significant logistics infrastructure and associated cost. Point-of-use oxygen generation nearly eliminates the required logistics infrastructure and, for this reason, oxygen generators, based on adsorption technology, have made significant in-roads in oxygen supply for the military. Uses of these generators, however, have been limited to applications that will tolerate the lower oxygen purity provided by such systems. Applications, which demand high purity oxygen, have no alternative to distributed oxygen and its associated logistics infrastructure requirements. A new technology, employing ion transport membranes (ITM), has the potential to provide many of these applications with point-of-use generation of high purity oxygen ¹.

The ITM solid electrolyte oxygen separation (SEOS) technology is based on the principle of oxygen ion migration through a dense ceramic electrolyte membrane under the influence of an externally applied electrical potential, as illustrated in Fig. 1. The relationship between the equilibrium oxygen partial pressures on the anode and cathode side of the electrolyte is governed by the Nernst equation:

$$V_N = \frac{RT}{4F} \ln\left(\frac{P_{O_2,anode}}{P_{O_2,cathode}}\right) \quad (1)$$

Removal of the oxygen product from the anode side of the electrolyte membrane results in the continuous production of pure oxygen. The ITM SEOS process enables the production of high purity oxygen at elevated pressure from a feed stream of ambient pressure air.

STACK MATERIALS

The core of ITM SEOS technology is an electrochemical stack fabricated from high-temperature conductive ceramic materials ². The solid electrolyte is based on cerium oxide, with dopants added to enhance both ion transport and membrane processability. To achieve sufficient oxygen ion conductivity through the electrolyte, the device must be operated at a temperature above approximately 600 °C. At these temperatures, doped ceria exhibits a significant performance advantage over

zirconia-based materials. For example, the conductivity of Gd-doped ceria at 800 °C is about 0.1 S/cm, and is approximately one order of magnitude higher than that of YSZ³. The doped ceria electrolyte is combined with appropriate electrode materials to form an electrochemical cell. The electrode materials must be chosen to minimize or eliminate electrolyte-electrode interfacial resistances, to exhibit high ionic and electronic conductivity, and to be catalytically active for the electrochemical reduction and oxidation reactions. An SEM image of a porous electrode layer over the dense ceria-based electrolyte is shown in Fig. 2. Electrochemical test data have established cell performance over thousands of hours and have enabled optimization of electrolyte and electrode characteristics.

The principle of electrically driven ion migration provides the mechanistic basis for ITM SEOS technology. However, a device comprising several cells, in series or in parallel, is required for commercial use. An efficient means for accomplishing this goal involves a flat plate multi-cell stack. Each cell, comprising a dense electrolyte coated with porous anode and cathode layers, is in contact with a dense interconnect made from an electronically conductive perovskite material. A 32-cell ITM SEOS stack is shown in Fig. 3.

Each interconnect is featured to provide appropriate passages for the feed and product streams. In contrast to the electrolyte, the interconnect must be an ionic insulator and an electronic conductor. Because the interconnects provide the mechanical backbone of the planar ITM SEOS device, the materials used must provide the required strength, stability, degradation, and other properties and must be compatible with the electrolyte and electrode materials.

The repeat units of the ITM SEOS stack, connected electrically in series, also include biasing electrodes and offset glass-ceramic seals to maintain seal integrity under operating conditions. These measures are necessary to avoid delamination at the interface between the glass-ceramic sealant and the anode side of the doped ceria electrolyte during operation^{4,5}. In addition, all stack materials must be carefully selected to meet criteria for thermal expansion match, chemical compatibility, and mechanical robustness, as well as for ionic and electronic conductivity.

STACK PERFORMANCE

The two primary considerations for long term ITM SEOS stack operation are electrochemical performance and mechanical integrity. Electrochemical performance is characterized by the stack Area Specific Resistance (ASR) under operating conditions. Fig. 4 illustrates the electrochemical performance for a 3-cell test stack over more than 6500 hours. A relatively stable ASR of approximately 0.6 $\Omega\cdot\text{cm}^2$ is evident.

The mechanical integrity of the operating stack as a function of time was measured using flow efficiency measurements. These measurements are based on the general relationship between electrical current and oxygen produced in a multi-cell ITM SEOS stack. The flow efficiency is defined as the ratio of actual O₂ product flowrate to theoretical product flowrate.

In a flow efficiency experiment designed to detect leaks, the product O₂ pressure is raised incrementally to a test level of 5-10 psig. If a leak is present in the stack, the flow efficiency will decrease as some O₂ product is forced through the leak. The data may be characterized by the slope of

flow efficiency versus O₂ product pressure, which can be directly related to product loss. Flow efficiency data after 6500 hours of operation for the same stack are shown in Fig. 5. The slope of this flow efficiency plot was $m = -3.1 \times 10^{-4} \text{ psi}^{-1}$, indicating the absence of significant leaks. This flow efficiency slope was essentially unchanged from initial testing at the start of stack operation. Using such tests, the effect of thermal cycling, pressure cycling, current changes, and other operating parameters may be assessed.

Analytical techniques employing a high sensitivity discharge ionization detector have indicated a purity of greater than 99.99% for oxygen produced by a SEOS stack. Other tests indicate that feed stream contaminants, such as live chemical agents, are not found in the oxygen product⁶. In many important cases, the contaminants are also removed from the oxygen-depleted air stream. Similar results would obviously be expected for other carbonaceous contaminants, such as hydrocarbons and biological agents. Together with the electrochemical and mechanical performance data presented in Figs. 5 and 6, these results are extremely encouraging from the standpoint of long term operation and durability and are unprecedented in the literature.

BALANCE OF DEVICE

ITM SEOS technology offers the potential for producing a high purity oxygen product at elevated pressure via on-site generation. This compressed product can be generated electrochemically, without an external oxygen compressor. A typical generator, as illustrated in Fig. 6, comprises one or more electrochemical stacks, a thermal management system, an air mover, a power supply, and appropriate controls.

A low pressure feed air mover is the only moving part in an ITM SEOS oxygen generator. This is expected to result in lower maintenance and higher reliability compared with the commercially practiced options of pressure swing adsorption (PSA) or vacuum swing adsorption (VSA). This system would also be extremely quiet while operating. In applications where a pressurized air feed is available, zero moving parts would be required, and an ITM SEOS oxygen generator would be virtually silent.

The practical application of ITM SEOS technology requires applied voltages higher than the Nernst voltage, V_N . This overpotential increases the productivity per cell. However, the increased overpotential also increases the specific power. This effect is analogous to a pipeline, in which flow is proportional to velocity, but power is proportional to the square of the velocity. Because the cells in an ITM SEOS stack are configured in series, the total oxygen production is directly proportional to the applied DC current and the number of cells in the stack. Thus, a direct trade-off may be made between the cost of the stack (proportional to the number of cells) and the specific power (kWh per unit of oxygen) required for operation.

For the majority of applications, the recovery of heat from the non-permeate stream is essential in operating an ITM SEOS oxygen generator. An effective means to accomplish this objective is via gas-to-gas heat exchange, as shown in Fig. 7. Because oxygen is removed from the feed stream by the ITM SEOS stack, the feed air stream will require an additional input of energy. In many cases, this energy can be supplied by the resistive heating of the stack itself. Alternatively, the oxygen product can also be included in the gas-to-gas heat exchange.

Although simple in concept, the design of a high-temperature gas-to-gas heat exchanger is complicated by many factors, including significant thermal radiation, low heat transfer coefficients, and strong coupling with the surrounding insulation system. In addition, the design is typically constrained by the need to maintain the steady-state and transient metal temperatures below certain thresholds to minimize both the generation of chromia-containing species and the rate of corrosion.

The DC power required by the stack can either be supplied directly from an external source or from a DC power supply, which converts externally supplied AC power to DC. Most applications will employ a constant current power supply. The acceptable amount of output ripple and noise can be relaxed because of the capacitive nature and low-pass filtering effect of the SEOS stack. Various regulated or rectified strategies can be incorporated into the power supply.

Control systems may vary widely depending on the specific application. An important feature is the regulation of oxygen flow by current regulation. Current measurement is more reliable and accurate than typical flow measurement techniques. Oxygen pressure control is typically used to keep the stack at a constant operating pressure when the oxygen use pressure is varying or lower than the desired stack operating pressure. Start-up and stand-by modes of operation may also be incorporated into the control system.

CONCLUSION

ITM SEOS technology utilizes the principle of oxygen ion migration through a dense ceramic electrolyte membrane under the influence of an externally applied electrical potential. The key to this technology is the careful selection of materials for the electrolyte and other ceramic components to ensure electrochemical stability and mechanical integrity. A stack incorporating a rare earth-doped ceria electrolyte, with appropriate electrode materials and other compatible ceramic components, has demonstrated excellent electrochemical stability and mechanical integrity over a 6500-hour operating period. An oxygen generator based on this technology has been designed, including a thermal management system, feed gas supply, power supply, and appropriate controls. A self-contained generator, with an air mover as the only moving part, requires only standard power from an electrical outlet, battery, or other power source, such as a fuel cell. The ability of this compact device to produce high purity oxygen at elevated pressure, with minimal moving parts and very low noise, will make ITM SEOS an attractive supply mode for many military oxygen applications.

REFERENCES

- ¹ P.N. Dyer, R.E. Richards, S.L. Russek, and D.M. Taylor, *Solid State Ionics*, **134**, 21 (2000).
- ² M.F. Carolan, P.N. Dyer, E. Minford, S.L. Russek, M.A. Wilson, D.M. Taylor, and B.T. Henderson, U.S. Patent 5,750,279 (1998).
- ³ H. Inaba and H. Tagawa, *Solid State Ionics*, **83**, 1 (1996).
- ⁴ S.B. Adler, B.T. Henderson, M.A. Wilson, D.M. Taylor, and R.E. Richards, *Solid State Ionics*, **134**, 35 (2000).
- ⁵ S.B. Adler, B.T. Henderson, R.E. Richards, D.M. Taylor, and M.A. Wilson, U.S. Patent 5,868,918 (1999).
- ⁶ B.F. Roettger, "Oxygen Purification and Compression Capabilities of Ceramic Membranes", 29th Annual SAFE Symposium (November, 1991).

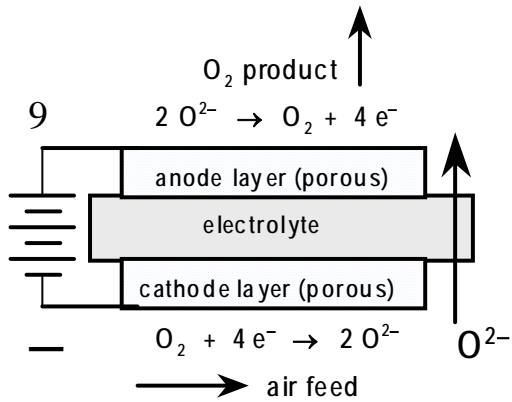


Figure 1

Operation of a SEOS electrochemical cell

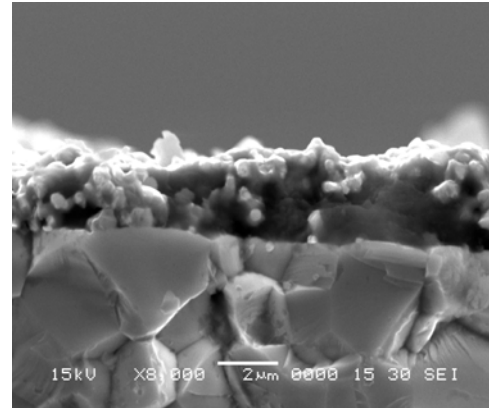


Figure 2

SEM image of porous electrode layer deposited on dense ceria-based electrolyte in an ITM SEOS electrochemical cell



Figure 3

A 32-cell ITM SEOS stack

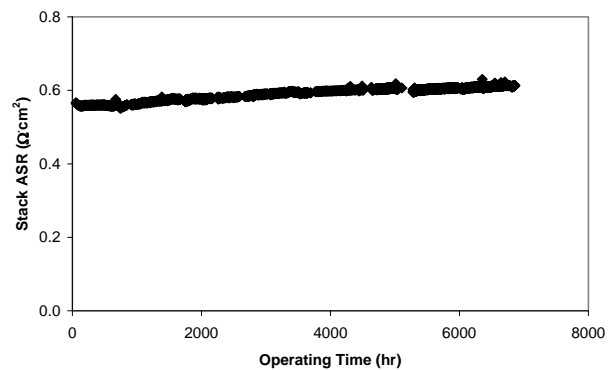


Figure 4

Area specific resistance (ASR) of a 3-cell test stack during operation

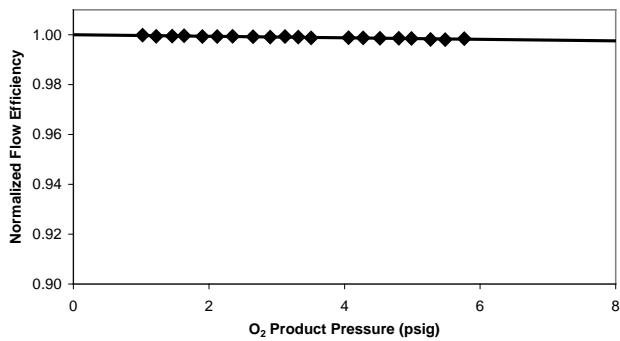


Figure 5
Flow efficiency data for the stack
represented in Figure 4

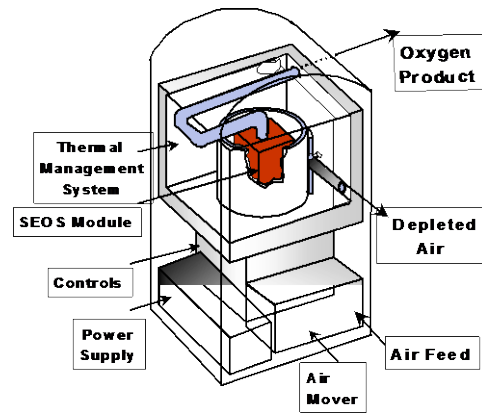


Figure 6
Schematic of a typical ITM
SEOS generator system

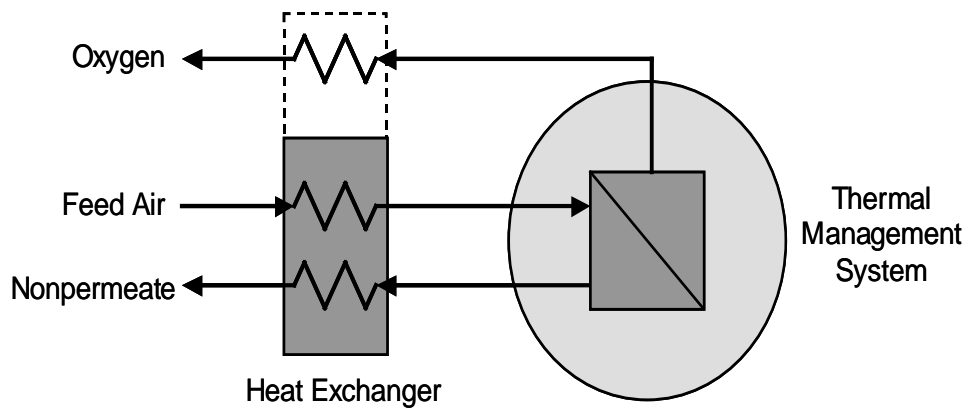


Figure 7
Schematic illustrating heating of the feed air stream via gas-to-gas heat exchange

APPENDIX B – Laboratory Oxygen Analysis Reports

AFPET LABORATORY REPORT
HQ AFPET/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No: 2008LA14694001	Protocol: GA-OXY-0003	Cust Sample No: 06046-011-B-1030 08
Date Sampled: 10/30/2008	Date Received: 11/05/2008	Date Reported: 11/06/2008
Contract No: NOT INDICATED		

Sample Submitter: HQ AFPET/PTPT 2430 C Street Building 70, Area B Wright-Patterson AFB, OH 45433-7632	Prime Contractor: Air Products & Chemicals 7201 Hamilton Boulevard Allentown, PA 18195-1501
---	--

Reason for Submission: Preproduction (Commercial)
Product: Oxygen, Aviator's Breathing, Gaseous
Specification: MIL-PRF-27210G(1) Type:I

Sample Eq Ser No: CG1080 Tank Pressure:1,200 psi

Method	Test	Min	Max	Result
CGA G-4.3-2000	Odor			None
CGA G-4.3-2000	Purity (% vol)	99.5		100.0
CGA G-4.3-2000	Moisture (ppmv)		7	1
MIL-STD-1564A	Minor Constituents (By IR)			
	Carbon Dioxide (ppmv)		10	0
	Methane (ppmv)		50	0
	Acetylene (ppmv)		0.1	0.0
	Ethylene (ppmv)		0.4	0.0
	Ethane + Ethane Equivalents (ppmv)		6	0
	Nitrous Oxide (ppmv)		4	0
	Refrigerants (Freons) (ppmv)		2	0
	Halogenated Solvents (ppmv)		0.2	0.0
	Others (ppmv)		0.2	0.0

Dispositions:

For information purposes only.

Approved By	Date
Miguel Acevedo, Chief	11/06/2008
\\SIGNED\\	

This report was electronically delivered to:
afpet.aftt@wpafb.af.mil, benet.curtis@wpafb.af.mil, dennis.swartz@wpafb.af.mil,
miguel.acevedo@wpafb.af.mil, steven.shaeffer@wpafb.af.mil

DEPARTMENT OF THE AIR FORCE
76 MXSS/MXDTAA/Analytical Chemistry Section
Tinker AFB, OK 73145-3038

LABORATORY TEST REPORT

Customer: 423 SCMS/GUEA/ C. Kissick

Report Date: 19 November 2009

Product: Oxygen (gas)

Specification: T.O. 42B6-1-1 Procurement

Base Sample No. : N6238

SAMPLE INFORMATION:

Lab Sample No. : N6238

Sample Origin: Oxygen Convert Shop
bldg 1055

Date Received: 18 Nov 09

Date Last Added: na

Sampler Pressure (psi): 1000

Date Last Purged: na

Sampler No. : 2

Manufacturer: bldg 1055

Date Sampled: 18 Nov 09

Reason For Analysis: Other(1)

LABORATORY TEST RESULTS

METHOD	TEST	MIN	MAX	RESULTS
T.O.\GC-TCD\ SOP-P-002	Oxygen, % vol	99.5		99.9
Mil-STD-1564\ SOP-P-001	Trace Contaminant Gases, IR			
	Carbon Dioxide, ppmv		5	0.4
	Refrigerants, ppmv		1	0
	Methane, ppmv		25	0
	Halogenated Solvents, ppmv		0.1	0
	Nitrous Oxide, ppmv		2	0
	C2+ Hydrocarbon as Ethane, ppmv		3	0
	Ethylene, ppmv		0.2	0
	Acetylene, ppmv		0.05	0
	Other, ppmv		0.1	None DET
T.O.	Odor		None	None
Mil-STD-1564\ SOP-P-001	Moisture, ppmv		7	6

REMARKS:

Sample complies with specified T.O. limits for tests performed.

Copy to: AFTT

Reported by:

Approved by:


D. Ponder/Chemist/MXDTAA /DSN 336-2135
Analytical Chemistry Section


J. Morris/Chemist/MXDTAA
Analytical Chemistry Section

DEPARTMENT OF THE AIR FORCE
76 MXSS/MXDTAA/Analytical Chemistry Section
Tinker AFB, OK 73145-3038

LABORATORY TEST REPORT

Customer: 423 SCMS/GUEA C. Kissick	Report Date: 23 December 2009
	Product: Liquid Oxygen
Base Sample No. : N6352	Specification: T.O. 42B6-1-1 Procurement

SAMPLE INFORMATION:

Lab Sample No. : N6352	Sample Origin: Bldg 1055
Date Received: 22 Dec 09	Date Last Added:
Sampler Pressure (psi):	Date Last Purged:
Sampler No. : B	Manufacturer: N/A
Date Sampled: 22 Dec 09	Reason For Analysis: other

LABORATORY TEST RESULTS


METHOD	TEST	MIN	MAX	RESULTS
T.O.\GC-TCD\ SOP-P-002	Oxygen, % vol	99.5		99.9
Mil-STD-1564\ SOP-P-001	Trace Contaminant Gases, IR			
	Carbon Dioxide, ppmv		5	0.2
	Refrigerants, ppmv		1	0
	Methane, ppmv		25	0
	Halogenated Solvents, ppmv		0.1	0
	Nitrous Oxide, ppmv		2	0
	C2+ Hydrocarbon as Ethane, ppmv		3	0
	Ethylene, ppmv		0.2	0
	Acetylene, ppmv		0.05	0
	Other, ppmv		0.1	None DET
T.O.	Odor		None	None
Mil-STD-1564\ SOP-P-001	Moisture, ppmv		7	5

REMARKS:

Sample complies with specified T.O. limits for tests performed.


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Reported by:


D. Ponder/ CHEMIST
Analytical Chemistry Section

/DSN 336-2135

Approved by:


J. Morris/ CHEMIST
Analytical Chemistry Section

DEPARTMENT OF THE AIR FORCE
76 MXSS/MXDTAA/Analytical Chemistry Section
Tinker AFB, OK 73145-3038

LABORATORY TEST REPORT

Customer: 423 SCMS/GUEA C. Kissick	Report Date: 8 March 2010
	Product: Compressed Oxygen
Base Sample No. : NA	Specification: T.O. 42B6-1-1 Procurement

SAMPLE INFORMATION:

Lab Sample No. : N6508	Sample Origin: Bldg 1055
Date Received: 4 Mar 10	Date Last Added:
Sampler Pressure (psi): NA	Date Last Purged:
Sampler No. : B	Manufacturer: NA
Date Sampled: 3 Mar 10	Reason For Analysis: Periodic

LABORATORY TEST RESULTS

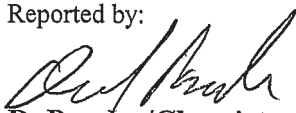
METHOD	TEST	MIN	MAX	RESULTS
T.O.\GC-TCD\ SOP-P-002	Oxygen, % vol	99.5		99.9
Mil-STD-1564\ SOP-P-001	Trace Contaminant Gases, IR			
	Carbon Dioxide, ppmv		5	0.53
	Refrigerants, ppmv		1	0
	Methane, ppmv		25	0
	Halogenated Solvents, ppmv		0.1	0
	Nitrous Oxide, ppmv		2	0
	C2+ Hydrocarbon as Ethane, ppmv		3	0
	Ethylene, ppmv		0.2	0
	Acetylene, ppmv		0.05	0
	Other, ppmv		0.2	None DET
T.O.	Odor		None	None
Mil-STD-1564\ SOP-P-001	Moisture, ppmv		7	6

REMARKS:

Sample does comply with specified T.O for tests performed.

Copy to: AFTT

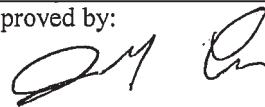
Reported by:



D. Ponder/Chemist
Analytical Chemistry Section

/DSN 336-2135

Approved by:



J. Childs/Chemist
Analytical Chemistry Section

DEPARTMENT OF THE AIR FORCE
76 MXSS/MXDTAA/Analytical Chemistry Section
Tinker AFB, OK 73145-3038

LABORATORY TEST REPORT

Customer:	423 SCMS/GUEA C. Kissick	Report Date:	22 March 2010
		Product:	Liquid Oxygen
		Specification:	T.O. 42B6-1-1 Procurement
Base Sample No. :	NA		

SAMPLE INFORMATION:

Lab Sample No. :	N6523	Sample Origin:	Bldg 1055
Date Received:	22 Mar 10	Date Last Added:	
Sampler Pressure (psi):	NA	Date Last Purged:	
Sampler No. :	B	Manufacturer:	NA
Date Sampled:	NA	Reason For Analysis:	Periodic

LABORATORY TEST RESULTS

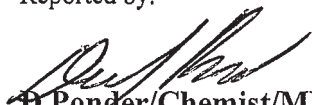
METHOD	TEST	MIN	MAX	RESULTS
T.O.\GC-TCD\ SOP-P-002	Oxygen, % vol	99.5		99.9
Mil-STD-1564\ SOP-P-001	Trace Contaminant Gases, IR			
	Carbon Dioxide, ppmv		5	0
	Refrigerants, ppmv		1	0
	Methane, ppmv		25	0
	Halogenated Solvents, ppmv		0.1	0
	Nitrous Oxide, ppmv		2	0
	C2+ Hydrocarbon as Ethane, ppmv		3	0
	Ethylene, ppmv		0.2	0
	Acetylene, ppmv		0.05	0
	Other, ppmv		0.1	None DET
T.O.	Odor		None	None
Mil-STD-1564\ SOP-P-001	Moisture, ppmv		7 MAX	7

REMARKS:

Sample does comply for tests performed.

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D. Ponder/Chemist/MXDTAA /DSN 336-2135
Analytical Chemistry Section

Approved by:



J. Morris/Chemist/MXDTAA
Analytical Chemistry Section

DEPARTMENT OF THE AIR FORCE
76 MXSS/MXDTAA/Analytical Chemistry Section
Tinker AFB, OK 73145-3038

LABORATORY TEST REPORT

Customer:	423 SCMS/GUEA C. Kissick	Report Date:	24 March 2010
		Product:	Liquid Oxygen
		Specification:	T.O. 42B6-1-1 Procurement
Base Sample No. :	NA		

SAMPLE INFORMATION:

Lab Sample No. :	N653 2	Sample Origin:	
Date Received:	24 Mar 10	Date Last Added:	NA
Sampler Pressure (psi):	NA	Date Last Purged:	NA
Sampler No. :	B	Manufacturer:	NA
Date Sampled:	23 Mar 10	Reason For Analysis:	Periodic

LABORATORY TEST RESULTS

METHOD	TEST	MIN	MAX	RESULTS
T.O.\GC-TCD\ SOP-P-002	Oxygen, % vol	99.5		99.9
Mil-STD-1564\ SOP-P-001	Trace Contaminant Gases, IR			
	Carbon Dioxide, ppmv		5	0.15
	Refrigerants, ppmv		1	0
	Methane, ppmv		25	0
	Halogenated Solvents, ppmv		0.1	0
	Nitrous Oxide, ppmv		2	0
	C2+ Hydrocarbon as Ethane, ppmv		3	0
	Ethylene, ppmv		0.2	0
	Acetylene, ppmv		0.05	0
	Other, ppmv		0.1	None DET
T.O.	Odor		None	None
Mil-STD-1564\ SOP-P-001	Moisture, ppmv		7 MAX	5

REMARKS:

Sample complies with specified T.O. limits for tests performed.

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Approved by:



D. Ponder/Chemist/MXDTAA /DSN 336-2135
Analytical Chemistry Section



P. Meredith/Chemist
Analytical Chemistry Section

DEPARTMENT OF THE AIR FORCE
76 MXSS/MXDTAA/Analytical Chemistry Section
Tinker AFB, OK 73145-3038

LABORATORY TEST REPORT

Customer: 423 SCMS/GUEA C. Kissick

Report Date: 29 June 2010

Product: Liquid Oxygen

Specification: T.O. 42B6-1-1 Procurement

Base Sample No. : N6662

SAMPLE INFORMATION:

Lab Sample No. : N6662

Sample Origin: bldg 1055

Date Received: na

Date Last Added:

Sampler Pressure (psi):

Date Last Purged:

Sampler No. : B

Manufacturer: na

Date Sampled: 28 Jun 10

Reason For Analysis: Other(1)

LABORATORY TEST RESULTS

METHOD	TEST	MIN	MAX	RESULTS
T.O.\GC-TCD\ SOP-P-002	Oxygen, % vol	Report		99.9
Mil-STD-1564\ SOP-P-001	Trace Contaminant Gases, IR			
	Carbon Dioxide, ppmv		5	0
	Refrigerants, ppmv		1	0
	Methane, ppmv		25	0
	Halogenated Solvents, ppmv		0.1	0
	Nitrous Oxide, ppmv		2	0
	C2+ Hydrocarbon as Ethane, ppmv		3	0
	Ethylene, ppmv		0.2	0
	Acetylene, ppmv		0.05	0
	Other, ppmv		0.1	None DET
T.O.	Odor		None	None
Mil-STD-1564\ SOP-P-001	Moisture, ppmv		7	9

REMARKS:

Sample does NOT comply with specified T.O. limits for tests performed.

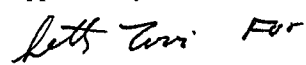
Moisture exceeds 7 ppm

Copy to: AFTT

Reported by:

Approved by:


D. Ponder/Chemist/MXDTAA /DSN 336-2135
Analytical Chemistry Section


J. Morris/Chemist/MXDTAA
Analytical Chemistry Section

DEPARTMENT OF THE AIR FORCE
76 MXSS/MXDTAA/Analytical Chemistry Section
Tinker AFB, OK 73145-3038

LABORATORY TEST REPORT

Customer: 423 SCMS/GUEA C. Kissick	Report Date: 29 June 2010
	Product: Liquid Oxygen
Base Sample No. : N6661	Specification: T.O. 42B6-1-1 Procurement

SAMPLE INFORMATION:

Lab Sample No. : N6661	Sample Origin: bldg 1055
Date Received: na	Date Last Added:
Sampler Pressure (psi):	Date Last Purged:
Sampler No. : A	Manufacturer: na
Date Sampled: 28 Jun 10	Reason For Analysis: Other(1)

LABORATORY TEST RESULTS

METHOD	TEST	MIN	MAX	RESULTS
T.O.\GC-TCD\ SOP-P-002	Oxygen, % vol	Report		99.9
Mil-STD-1564\ SOP-P-001	Trace Contaminant Gases, IR			
	Carbon Dioxide, ppmv		5	0
	Refrigerants, ppmv		1	0
	Methane, ppmv		25	0
	Halogenated Solvents, ppmv		0.1	0
	Nitrous Oxide, ppmv		2	0
	C2+ Hydrocarbon as Ethane, ppmv		3	0
	Ethylene, ppmv		0.2	0
	Acetylene, ppmv		0.05	0
	Other, ppmv		0.1	None DET
T.O.	Odor		None	None
Mil-STD-1564\ SOP-P-001	Moisture, ppmv		7	11

REMARKS:

Sample does NOT comply with specified T.O. limits for tests performed.

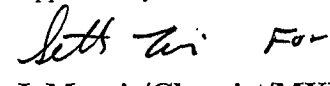
Moisture exceeds 7 ppm

Copy to: AFTT

Reported by:

Approved by:


D. Ponder/Chemist/MXDTAA /DSN 336-2135
Analytical Chemistry Section


J. Morris/Chemist/MXDTAA
Analytical Chemistry Section

DEPARTMENT OF THE AIR FORCE
76 MXSS/MXDTAA/Analytical Chemistry Section
Tinker AFB, OK 73145-3038

LABORATORY TEST REPORT

Customer: 423 SCMS/GUEA C. Kissick	Report Date: 25 August 2010
	Product: Liquid Oxygen
Base Sample No. :	Specification: T.O. 42B6-1-1 Procurement

SAMPLE INFORMATION:

Lab Sample No. : N6758	Sample Origin: Bldg 1055
Date Received: 8/19/10	Date Last Added: Na
Sampler Pressure (psi):	Date Last Purged: Na
Sampler No. : B	
Date Sampled: 8/19/10	Reason For Analysis: Other (1)

LABORATORY TEST RESULTS

METHOD	TEST	MIN	MAX	RESULTS
T.O.\GC-TCD\ SOP-P-002	Oxygen, % vol	Report		99.9
Mil-STD-1564\ SOP-P-001	Trace Contaminant Gases, IR			
	Carbon Dioxide, ppmv		5	0.14
	Refrigerants, ppmv		1	0
	Methane, ppmv		25	0
	Halogenated Solvents, ppmv		0.1	0
	Nitrous Oxide, ppmv		2	0
	C2+ Hydrocarbon as Ethane, ppmv		3	0
	Ethylene, ppmv		0.2	0
	Acetylene, ppmv		0.05	0
	Other, ppmv		0.1	None DET
T.O.	Odor		None	None
Mil-STD-1564\ SOP-P-001	Moisture, ppmv		7	14

REMARKS:

Sample Does Not comply with specified T.O. limits for tests performed.


Moisture exceeds 7 ppm

Copy to: AFTT

Reported by:


D. Ponder/Chemist/MXDTAA /DSN 336-2135
Analytical Chemistry Section

Approved by:


J. Morris/Chemist/MXDTAA
Analytical Chemistry Section

DEPARTMENT OF THE AIR FORCE
76 MXSS/MXDTAA/Analytical Chemistry Section
Tinker AFB, OK 73145-3038

LABORATORY TEST REPORT

Customer:	423 SCMS/GUEA C. Kissick	Report Date:	25 August 2010
		Product:	Liquid Oxygen
		Specification:	T.O. 42B6-1-1 Procurement
Base Sample No. :			

SAMPLE INFORMATION:

Lab Sample No. :	N6757	Sample Origin:	Bldg 1055
Date Received:	8/19/10	Date Last Added:	Na
Sampler Pressure (psi):		Date Last Purged:	Na
Sampler No. :	A		
Date Sampled:	8/19/10	Reason For Analysis:	Other (1)

LABORATORY TEST RESULTS

METHOD	TEST	MIN	MAX	RESULTS
T.O.\GC-TCD\ SOP-P-002	Oxygen, % vol	Report		99.9
Mil-STD-1564\ SOP-P-001	Trace Contaminant Gases, IR			
	Carbon Dioxide, ppmv		5	0.34
	Refrigerants, ppmv		1	0
	Methane, ppmv		25	0
	Halogenated Solvents, ppmv		0.1	0
	Nitrous Oxide, ppmv		2	0
	C2+ Hydrocarbon as Ethane, ppmv		3	0
	Ethylene, ppmv		0.2	0
	Acetylene, ppmv		0.05	0
	Other, ppmv		0.1	None DET
T.O.	Odor		None	None
Mil-STD-1564\ SOP-P-001	Moisture, ppmv		7	14

REMARKS:

Sample Does Not comply with specified T.O. limits for tests performed.

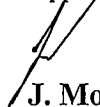
Moisture exceeds 7 ppm

Copy to: AFTT

Reported by:


D. Ponder/Chemist/MXDTAA /DSN 336-2135
Analytical Chemistry Section

Approved by:


J. Morris/Chemist/MXDTAA
Analytical Chemistry Section

APPENDIX C – Narrative Logbook

EARLY FIELD ASSESSMENT OF SOLID ELECTROLYTE OXYGEN SEPARATOR

AT OC-ALC, TINKER AFB OK

NARRATIVE LOGBOOK

08 Oct 10, Friday – Status: OFF-LINE

APCI and AFRL have determined the SEOS breadboard will be removed from the Tinker facility. The cost of repairing the unit is not warranted because the lessons learned from this early field assessment experience have been captured and the technology has progressed beyond what currently exists at Tinker. Sometime between now and 30 Nov 10 APCI will disconnect, package, and ship the unit.

24 Sep 10, Friday – Status: OFF-LINE

Tinker reported both oxygen generators are inoperative. One unit appears to have an inoperative air mover. Tinker may be able to provide more definitive information on the malfunctions later today. APCI and AFRL plan to determine if there are funding and resources available for a maintenance trip to Tinker.

10 Sep 10, Friday – Status: OFF-LINE

Telecon minutes: Tinker AFB reported right side oxygen generator running normally. Left side oxygen generator is not producing oxygen and has an OCA fault (stack current above limit). After discussion about the off-spec moisture issue APCI/Ceramtec recommended:

1. Isolate the non-operational left side oxygen generator by capping the outlet oxygen line. Attach oxygen sample cylinder to breadboard and allow it to purge. Take an oxygen sample and have it analyzed. Hypothesis: The left side TMS electrochemical stack may be leaking small amounts of moisture into the oxygen line due to the stack's non-operational state but continued air mover operation. Ceramtec will provide a list of procedures for this specialized sampling technique.

2. Tinker AFB will attempt re-starting the left side oxygen generator. TMS data and alarms will be recorded during the start-up to help troubleshoot the TMS issues. Ceramtec will provide a list of procedures for this start-up.

01 Sep 10, Wednesday – Status: OFF-LINE

Tinker AFB took an oxygen sample at the outlet of the oxygen compressor with the storage cylinders isolated. The sample had a moisture content of 12 ppm. Mil spec moisture content should not exceed 7 ppm. The moisture test was run on three lab setups. Further, the lab is able to test gases to a water content of 1 ppm. Tinker AFB suggested they have equipment that could

be used to purge the sample cylinders with heated, dry air. A telecon will be scheduled to discuss the way forward.

30 Aug 10, Monday – Status: OFF-LINE

Tinker AFB oxygen analysis reports (N6757 and N6758) noted moisture contents (14 ppm) which are outside MIL-PRF-27210. Mil standard moisture content should not exceed 7 ppm. Tinker AFB reported TMS #1 has an OCA error. OCA is stack current above maximum limit.

Telecon: APCI/Cerametec suggested as a diagnostic approach taking an oxygen sample just after the oxygen compressor and before the oxygen enters the storage cylinders. Tinker AFB plans to take this sample on 31 Aug 10.

26 Aug 10, Thursday – Status: OFF-LINE

Tinker AFB reported TMS #1 is showing FAL and CURR alarms and the TMS is not producing oxygen. FAL occurs when the unit is not producing oxygen and CURR occurs when a stack high current condition occurs. APCI recommended an alarm reset and a restart of the TMS. Tinker reported the TMS was restarted.

20 Aug 10, Friday – Status: OFF-LINE/ AWAITING OXYGEN SAMPLE ANALYSIS

Telecon minutes: The APCI maintenance work on the SEOS breadboard was successfully completed the week of 9 Aug 10. The air movers and power supplies were replaced. The wire connectors appeared slightly oxidized and had increased resistance. The connectors were replaced. The air movers had been operating at a voltage slightly over their rated voltage. The voltage was reduced to the rated voltage (approximately 12 V).

The thermal management systems (TMSs) were replaced. Past power outages may have caused TMS #1 to stop producing oxygen. Current system oxygen production is about 5 liters/minute. TMS #2 is producing oxygen slightly below is design flow rate. System design flow rate is 6 liters/minute.

The oxygen compressor preventive maintenance was accomplished. The compressor seal was replaced. Two compressor check valves were replaced because they appeared to be leaking. The compressor is operating properly and was cycled to 2,100 psig. The oxygen storage cylinders were vented to 100 psi and repressurized.

Tinker reported the cylinders achieved 1,800 psig and oxygen samples were collected. Oxygen sample results should be available the week of 30 Aug 10. Slightly increased moisture content in recent oxygen samples may have been due to leakage through the shutdown TMS.

Tinker noted the system bracket to support the sample cylinder is broken. Tinker plans to repair or replace the bracket. The system appears fully operational but will remain off-line until the oxygen sample results show compliance with MIL-PRF-27210.

30 Jul 10, Friday – Status: OFF-LINE

Telecon minutes: Tinker reported the right side oxygen generator is operating. The left side oxygen generator is off. An oxygen sample was taken using the 6 hour enhanced purge procedure. The oxygen sample is awaiting analysis at the laboratory. The APCI maintenance trip to Tinker AFB is scheduled for the week of 9 Aug 10. APCI will arrive at Tinker on the morning of 9 Aug. Parts needed for the maintenance work will be shipped next week.

09 Jul 10, Friday – Status: OFF-LINE

Telecon minutes: Tinker reported right-side oxygen generator displayed a ramp error and was at room temperature. Device was restarted and is in heating mode. Cylinders had about 1,000 psig of pressure. It was determined to fully charge the cylinders before collecting any oxygen samples. It is expected that oxygen samples will be collected the week of 19 Jul 10. APCI maintenance trip is planned for week of 16 Aug.

01 Jul 10, Thursday – Status: OFF-LINE

Telecon minutes: The SEOS breadboard is in stand-by mode and the vendor oxygen cylinder/s have been reconnected. Way forward is to take one additional oxygen sample using enhanced purging. Sample bottle will be purged for 4-6 hours. Tinker will ensure adequate room ventilation during the purging process. APCI maintenance trip is currently planned for the week of 16 Aug.

30 Jun 10, Wednesday – Status: ON-LINE BUT SUPPLING OXYGEN AT REDUCED CAPACITY

Tinker reported recent oxygen samples failed the moisture threshold. Device will be taken off-line and the vendor supplied oxygen bottle/s reconnected. A team telecom is planned for 01 Jul 10.

25 Jun 10, Friday – Status: ON-LINE BUT SUPPLING OXYGEN AT REDUCED CAPACITY

Telecon minutes: Right-side oxygen generator OK. Left-side oxygen generator off-line. Electrical current on generator shows zero. Air mover appears OK. APCI/Ceramtec suspect the generator thermal management system (TMS) has an electrical problem. Way-forward is to shut-down the left-side oxygen generator and keep right-side generator on-line. A maintenance trip to Tinker will be planned pending personnel availability.

Actions:

1. APCI – Determine date for a Tinker AFB maintenance trip.
2. APCI – Locate spare TMS.

3. Tinker – Shutdown left-side oxygen generator.
4. Tinker – Collect oxygen sample from SEOS breadboard.

22 Jun 10, Tuesday – Status: OFF-LINE

Tinker AFB reported both oxygen generators stopped running and are displaying error code “OCA.” Operating manual defines an “OCA” error as “Stack current went above the maximum limit.”

11 Jun 10, Friday - Status: ON-LINE BUT SUPPLING OXYGEN AT REDUCED CAPACITY

Telecon minutes: Oxygen generator #1 (left side) air mover is not working. APCI will ship a new air mover to Tinker. Tinker plans to install the air mover. Oxygen generator #2 is supplying oxygen at 2.4 LPM. Compressor is OK. Compressor auto-start function appears OK. APCI maintenance trip to Tinker is currently pre-planned for sometime during the month of July, pending contract modification to extend the SEOS Tinker effort to Nov 10 and personnel availability.

04 Jun 10, Friday - Status: ON-LINE BUT SUPPLYING OXYGEN AT REDUCED CAPACITY

Telecon minutes: Tinker reported construction in the area may be causing power outages. Presently, Oxygen Generator #1 is off-line. Its air mover will not start. Oxygen Generator #2 is working but at a slightly reduced capacity (2.5 LPM). Tinker plans to troubleshoot Generator #1. Compressor is ok. Supply cylinder pressure appears adequate. A pressure of 1800 psig was noted on 04 Jun 10. Tinker plans to take an oxygen sample next week.

02 Jun 10, Wednesday - Status: OFF-LINE.

Tinker AFB reported the shop lost power over the weekend. The breadboard was restarted and is in the heating cycle. Sometime today the DC ramp will be started.

07 May 10, Friday - Status: OFF-LINE.

Telecon minutes: Tinker AFB reported the facility had a prolonged power outage. The SEOS breadboard shutdown for an estimated three hours. Stack temperature dropped to an estimated 517°C. The device was restarted and is currently in the heat-up phase. Full startup should occur today. Also, the compressor auto start function will be checked.

29 Apr 10, Thursday - Status: OK.

Tinker AFB reported compressor is not starting automatically. Manual restart works but the start button must be held down for 90 seconds. APCI/Ceramatec are investigating possible causes for the problem.

23 Apr 10, Friday - Status: OK.

Tinker AFB had to manually start the compressor but it appeared to run OK. Start button had to be depressed 90 seconds.

23 Apr 10, Friday - Status: OFF-LINE

Telecon minutes: Based on review of the data set received on 22 Apr 10, the compressor isn't cycling on. The SEOS oxygen generators appear OK. Action: APCI/Ceramatec will contact Tinker AFB personnel on 26 Apr 10 and attempt to reset the compressor control circuit.

09 Apr 10, Friday - Status: OK.

Telecon minutes: Oxygen generators, air movers, and compressor functioning OK based on review of the latest data set.

02 Apr 10, Friday - Status: OK.

Tinker AFB reported a FAL alarm occurs when the compressor isn't pumping oxygen. The FAL alarm terminates when the compressor starts pumping oxygen. APCI/Ceramatec confirmed this occurrence is normal operation, however, it isn't noted in the O&M manual. A new O&M manual page 27 (Alarms) was prepared with an updated description of the FAL alarm.

26 Mar 10, Friday - Status: OK.

Telecon minutes:

- Lab analysis showed the oxygen samples were in compliance with the mil specs.
- SEOS breadboard is back on-line and connected to the high pressure oxygen manifold.
- Air movers are running at 2.7 to 2.8 liters/minute. Compressor is cycling normally.
- A replacement power supply arrived at APCI, Allentown PA. The item will be shipped to Tinker AFB.

24 Mar 10, Wednesday - Status: OFF-LINE/AWAITING OXYGEN SAMPLE LAB ANALYSIS REPORT

Tinker AFB reported the shop experienced a long term power outage over the weekend. Tinker AFB restarted the breadboard. Oxygen samples were taken and sent to the lab for analysis. If

the samples show the oxygen still in compliance with the mil specs, the breadboard will go back on-line.

08 Mar 10, Monday - Status: OFF-LINE/AWAITING OXYGEN SAMPLE LAB ANALYSIS REPORT

Tinker AFB replaced the right side air mover and powered-up the breadboard. Voltage at the right side air mover power supply was measured at 13.9 Volts. Oxygen samples will be collected. Breadboard will go back on-line after the oxygen samples show compliance with the mil specs.

05 Mar 10, Friday - Status: OFF-LINE/AWAITING OXYGEN SAMPLE LAB ANALYSIS REPORT

Telecon minutes:

-- Tinker AFB reported left side oxygen generator OK, right side air mover shutdown, and compressor OK. Oxygen samples were collected and sent to the lab. Results should be available next week.

-- Way forward: Tinker AFB will attempt to replace the right side air mover. A spare air mover is on-site at Tinker AFB. Tinker AFB will check the voltage supplied to the right side air mover. If needed, APCI and Ceramtec plan to support Tinker AFB in these actions via telephonic communication.

02 Mar 10, Tuesday - Status: OFF-LINE - Tinker AFB reported the breadboard malfunctioned on 22 Feb 10.

19 Feb 10, Friday - Status: OFF-LINE/AWAITING OXYGEN SAMPLE LAB ANALYSIS REPORT - APCI completed breadboard preventative maintenance and repair at Tinker AFB (17-19 Feb 10). The breadboard is operating normally. Air mover #1 was replaced. Air mover #2 was rebuilt. Power supply for air mover #2 was replaced and rewired. The oxygen generators and SEOS electrochemical stacks are functioning normally. The compressor wiring and timers were modified. The compressor modifications enable the compressor to restart after extended low pressure or zero pressure conditions. A small leak was detected in the compressor outlet piping but it should have negligible impact on breadboard operations. The compressor high pressure setting remains at 2100 psig and the low pressure setting was reset to 1700 psig. An oxygen sample must be taken to show continued compliance with the military specifications.

22 Jan 10, Friday - Status: OFF-LINE - APCI breadboard maintenance trip to Tinker AFB planned for 28 and 29 Jan 10. APCI plans to send two people.

13 Jan 10, Wednesday - Status: OFF-LINE - Tinker AFB reported the oxygen generator air movers are experiencing electrical problems. The air movers supply ambient air to the SEOS

electrochemical stacks. Tinker AFB isolated the SEOS breadboard and reconnected their oxygen supply manifold to the vendor oxygen bottles. The oxygen generator and compressor electrical problems will be resolved during the upcoming APCI maintenance trip. The trip is tentatively planned for the week of 25 Jan 10. Most likely APCI will need facility access for 2 days. Confirmation of the exact trip dates will be provided shortly.

12 Jan 10, Tuesday - Status: OFF-LINE

Telecon minutes:

-- Tinker AFB reported Oxygen Generator #1 is showing an alarm mode and Oxygen Generator #2 is not running. The electrochemical stack temperatures on both units are near the normal operational temperature; hence, APCI will assist Tinker AFB personnel in attempting to restart the generators.

-- Tinker AFB reported the compressor is running OK but disconnecting and reconnecting the compressor electrical connector may be causing excessive wear at the connector pins. The group noted compressor vibration might be causing the current issues. APCI will suggest an approach to mitigate compressor vibration.

-- 18 Dec 09 Action Item (Status: OPEN): Date for the APCI maintenance trip to Tinker AFB is TBD pending review of personnel availability.

23 Dec 09, Wednesday - Status: OK - Tinker AFB reported laboratory test reports for SEOS oxygen (samples N6350 and N6352) show compliance with the appropriate military standards.

18 Dec 09, Friday - Status: OK

Telecon minutes:

-- On 17 Dec 09 Tinker AFB noted the compressor was down but after reconnecting the compressor control box the problem resolved.

-- Action Item: APCI will determine if the planned February preventative maintenance trip can be scheduled earlier. Trip would be used to resolve the compressor intermittent electrical problem and conduct general preventative maintenance.

15 Dec 09, Tuesday - Status: OK - Compressor is working.

14 Dec 09, Monday - Status: OFF-LINE - Compressor is down. New control box should be installed today.

08 Dec 09, Tuesday - Status: OK - APCI shipped new compressor control box to Tinker AFB.

07 Dec 09, Monday - Status: OFF-LINE - Tinker AFB reported compressor is down. Disconnecting and reconnecting compressor control box resolved the problem.

04 Dec 09, Friday - Status: OK

Telecon minutes:

-- Tinker AFB reported when the compressor shutdown on 01 Dec 09 the troubleshooting guide was of limited value in helping to define the problem. Intermittent connections at the power cable connector most likely made troubleshooting more difficult. APCI suggested using duct tape on the power connector to help secure it.

-- Tinker AFB will retain the current oxygen manifold valves which have integral check valves. The check valves prevent SEOS from filling the manifold bottles. Presently, Tinker AFB believes the two SEOS breadboard oxygen bottles will meet their needs.

-- Tinker AFB will return the APCI tool kit. Also, Tinker AFB will ship the breadboard packaging foam to APCI.

02 Dec 09, Wednesday- Status: OK - Power cable from control box to compressor found loose. Cable retightened.

01 Dec 09, Tuesday - Status: OFF-LINE - Oxygen generators OK. Compressor shut down.

20 Nov 09, Friday - Status: OK - SEOS breadboard installed and operating properly at OC-ALC, Tinker AFB OK. Several facility personnel trained on start-up, operation, shutdown, oxygen sampling, and data logging. Tinker AFB laboratory confirmed SEOS oxygen complies with mil spec for aviator's breathing oxygen. Next oxygen sampling required in 45 days (04 Jan 10). First aircraft oxygen bottle filled with SEOS oxygen. User questionnaire and performance metrics are under development.

APPENDIX D – Operating Manual

**DEMONSTRATION OF A CYLINDER-FILL SYSTEM
BASED ON SOLID ELECTROLYTE OXYGEN SEPARATOR
(SEOS) TECHNOLOGY**

FA8650-08-2-6824

**Checklists and Operating Manuals
(CDRL A003)**

September, 2009

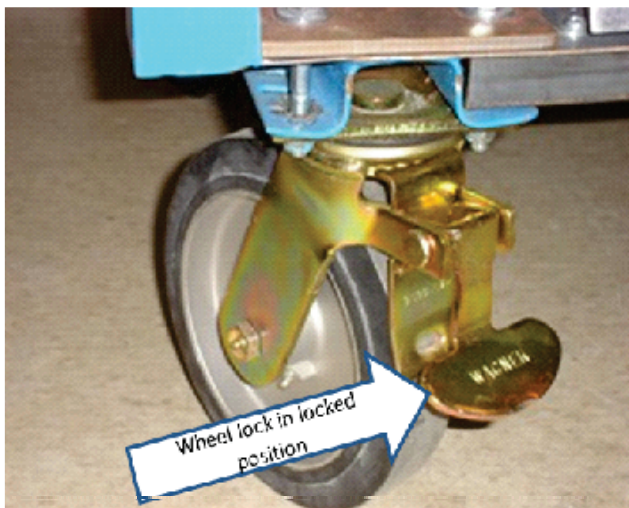
Air Products and Chemicals, Inc.
7201 Hamilton Blvd.
Allentown, PA 18195

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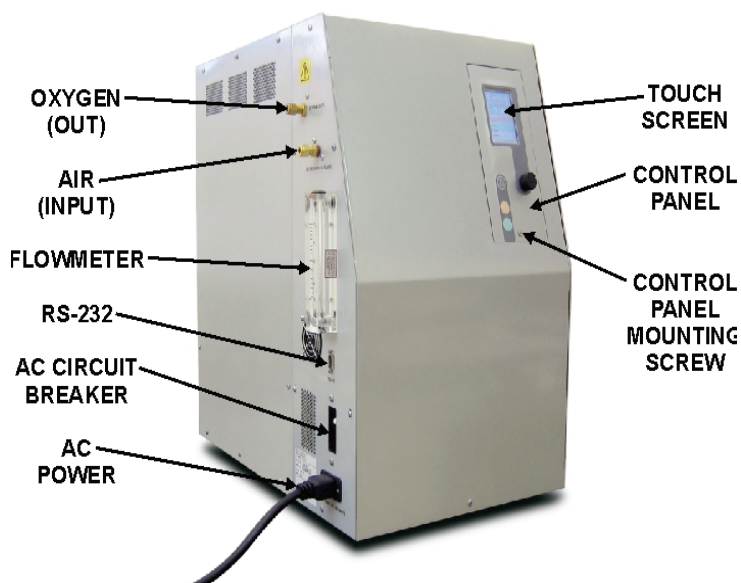
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6LPM Advanced Breadboard Pre-startup Checklist

- 1) Oxygen Cart is in position at the intended start-up location.
- 2) Rotatable/swivel wheels are locked for stability.



- 3) Front cart wheels (non-swivel under cylinder end of cart) are chocked.
- 4) The two (2) TMSs are in their operating positions on the cart top shelf and secured with respective "tie-down" ratcheting straps.
- 5) The two (2) TMSs have 120V AC electrical cords plugged in the bottom left side of their respective cabinets.



- 6) The 120V AC circuit breaker, bottom left side of their respective cabinets, is set to "off" (down) position.

- 7) The oxygen outlet lines, one line per TMS, (1/4" teflon) is connected to the "oxygen (out)" port on the top left sides of the TMS cabinets. The other ends should be connected to CV201 and CV203, respectively, the oxygen check valves penetrating the top decking of the cart.
- 8) The air inlet lines, one line per TMS, (3/8" Teflon) is connected to the "air (in)" port on the top left side of the TMS cabinets. The other ends should be connected to the bulkhead fitting penetrating the top decking of the cart.

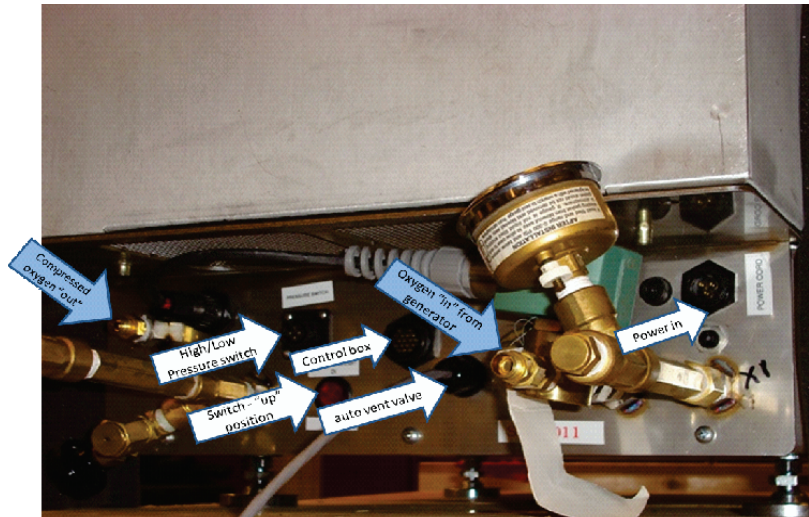


Rix Oxygen Compressor

- 9) The Rix Oxygen Compressor is positioned properly on the sliding compressor shelf (black, half moon markings on shelf indicate leg location for compressor).
- 10) The sliding shelf is secured by two (2) 1/4x20 x 2 inch screws to the cart base so that the shelf can't move.



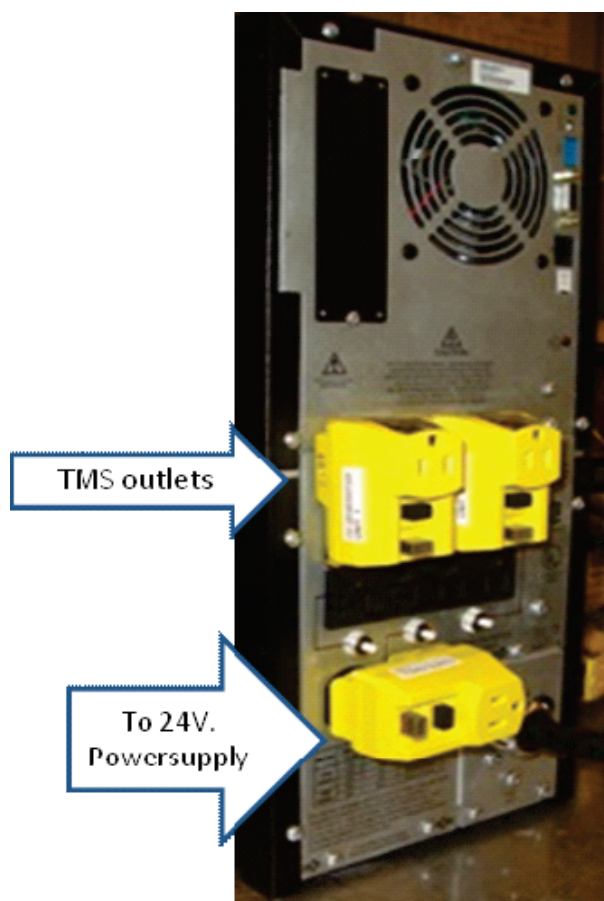
- 11) The oxygen inlet line is connected to the Rix and properly tightened.
- 12) The compressed oxygen outlet line is connected to the Rix and properly tightened.
- 13) All electrical connections to the compressor (1. Oxygen inlet solenoid, 2. Hp/Lp switch, 3. 120V. AC actuated compressor depressurization valve and 4. the 120V. AC power connector) are properly installed in their respective, keyed receptacles and secured.



- 14) Compressor 120V/20A AC power cord is plugged in to site power source.
- 15) The “power up auto start” switch, near the compressed oxygen outlet is in the up position not the “off” position.

Uninterrupted Power Source (UPS) Checklist

- 16 UPS mounted and secured to cart.
- 17) UPS plugged into 120V/30A AC wall receptacle.
- 18) TMSs plugged into respective labeled GFCI outlet of UPS .
- 19) Power cord supplying 12V power supply for air handlers plugged into labeled GFCI outlet of UPS.



Peripheral Checklist

20) Oxygen Sample manifold mounted securely on cart with associated plumbing connected and secure.



21) Oxygen surge Cylinders on cart and secured by straps and ramp mechanism.



22) Connect outlet of CV326 (rear of cart) to inlet of Tinker AFB Oxygen Supply Manifold via $\frac{1}{4}$ O.D. X .049 wall, copper tubing, supported every 18" with rubber insulated tube clamp anchored to site wall.

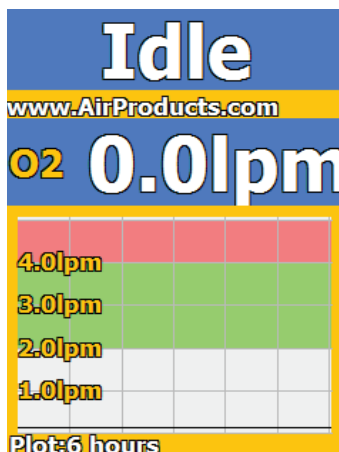
23) V-324, **CLOSED**

Rev Date: 17 Sept09

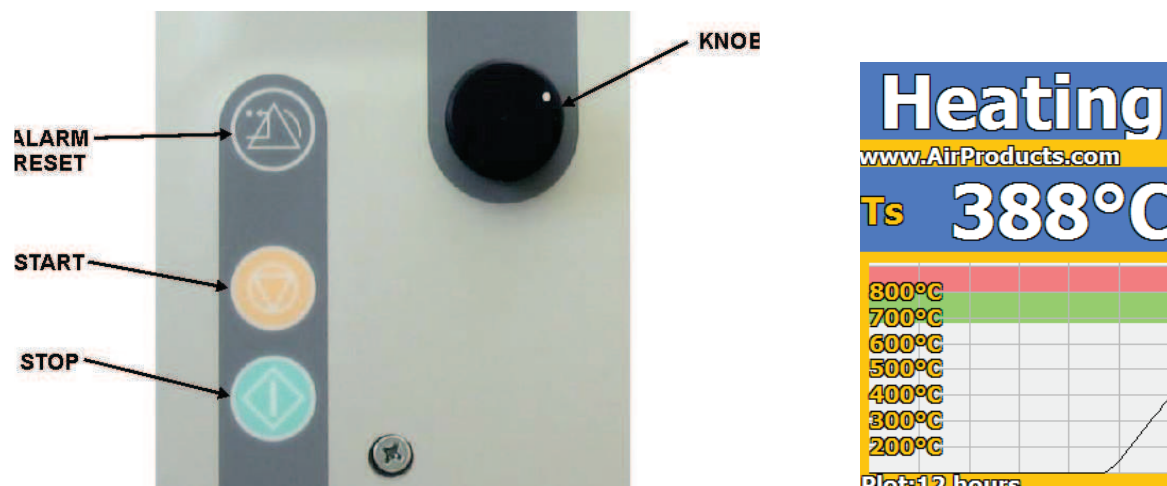
6lpm Advanced Breadboard System Start-up

Oxygen Generator Start-up Checklist

- The following procedure should be used for start-up of the oxygen generators . This procedure assumes that all items on the **6LPM Advanced Breadboard Pre-Startup Checklist** have been completed.
 - The following procedure can be used if there is a power outage that lasts for more than fifteen minutes (15 minutes is the amount of time that the Uninterrupted Power Supply, (UPS) will power up the generators and air movers when the UPS batteries are at full charge.
1. Turn on/Verify the AC power switch on the lower left side of the respective generator cabinets. The LCD screen will appear. In a short time the Main screen will appear with Idle displayed on the top line.

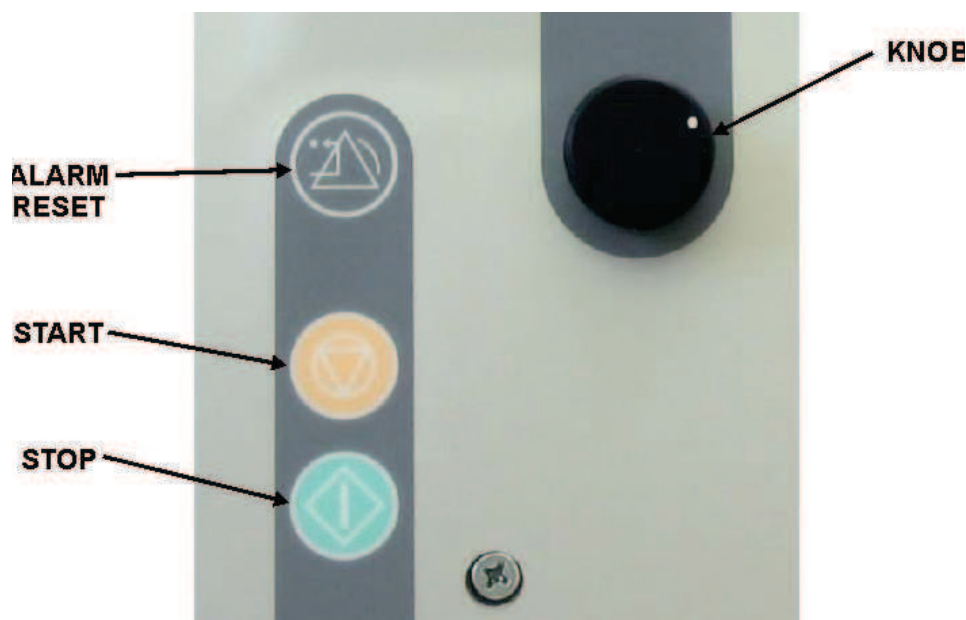


2. Press the **Start button** on the control panel. The touch-screen will display "Heating" and the oxygen generator will heat the stack to the stand-by temperature. This will take approximately 10 hours from room temperature and less time from an elevated generator temperature. (The generators heat-up at a rate of approximately 1°C/minute).

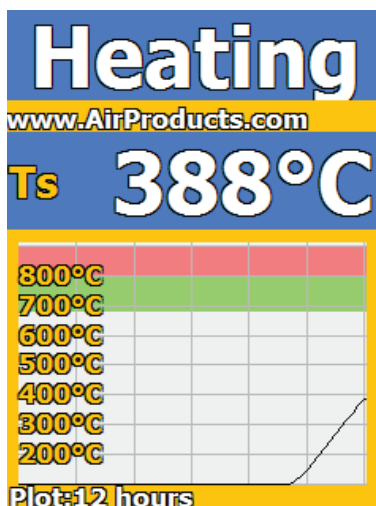


Upon reaching the stand-by temperature (e.g. 680C) the top most part of the screen will turn red and show a "PAL" alarm. (Incoming air pressure went below the minimum limit)

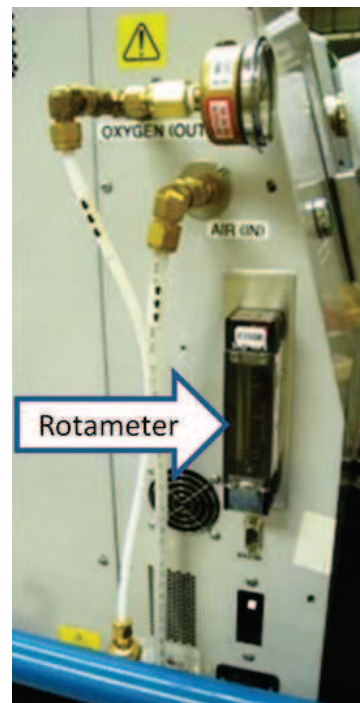
3. Push the "alarm reset" button on the control panel.



4. LCD screen should change to "Heating" and indicate the generator stack temperature (Ts).



5. Push and hold for 5 seconds, the "air mover startup", green button, on the face of the generator, TMS 1 cabinet. The air mover should start for TMS 1. Verify air flow by rotameter FI108 on left side of generator TMS1 cabinet.
6. Push and hold for 5 seconds, the "air mover startup", green button, on the face of the generator, TMS 2 cabinet. The air mover should start for TMS 2. Verify air flow by rotameter FI122 on left side of generator TMS2 cabinet



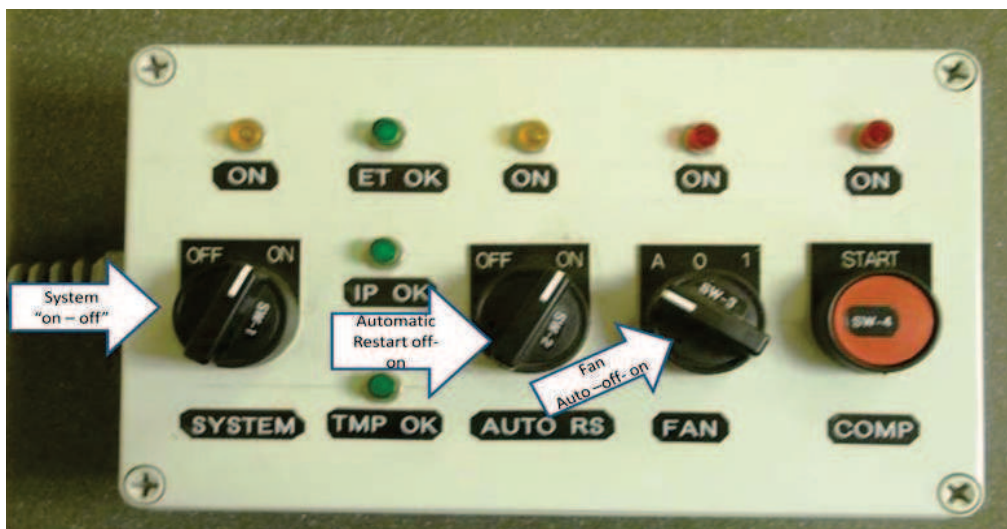
7. If the air movers don't start the LCD screen will display "Heating" on the top line. Wait 5 minutes and repeat steps 5-6 (above) until air movers start.
8. The generators will start ramping up the production of oxygen when the air movers are running. After approximately 90 minutes both generators should be producing 2.9-3.1lpm of oxygen. (**NOTE:** At this point the LCD will not show the proper oxygen flow rate. The Rix Compressor must be running to for the LCD to show the proper oxygen production).

Rix Compressor Start-up Checklist

- *This procedure assumes that all items on the **6LPM Advanced Breadboard Pre-startup Checklist** have been completed.*
- *This procedure assumes that all items on the **Oxygen Generator Start-up Checklist** have been completed and the air movers are running with respective generators producing 2.9 – 3.1 lpm oxygen product.*
- ***The Rix oxygen compressor is configured to run automatically after its initial manual start/ restart. If the compressor fails to restart or does not compress to 2200psig contact Air Products personnel.***
- *The following **Rix Compressor Start-up Checklist** is applicable in the instance of a power outage lasting more than fifteen minutes. The Uninterrupted Power Supply (UPS) will supply power to run the oxygen generators and their respective air handlers for fifteen (15) minutes when the UPS batteries are at full charge. In the event of a power outage of more than 15 minutes the Rix Compressor will have to be restarted manually after the oxygen generators have been restarted and are producing 2.9- 3.1lpm of oxygen.*

Valve Status:

9. **Verify** V314, V316, Surge cylinder #1 block valve, **OPEN**.
10. **Verify** V318, V320, Surge cylinder #2 block valve, **OPEN**.
11. **Verify** V324, valve to Tinker manifold, **OPEN**.
12. **Verify** V322 **CLOSED** .
13. **Verify** V410, **CLOSED**.
14. **Verify** V414, **CLOSED**.
15. **Verify** Rix Compressor control box on (SW-1). First switch "system- **ON**".
16. **Verify** Rix Compressor control box automatic restart switch (SW-2) to "**ON**".
17. **Verify** Rix Compressor control box fan switch (SW-3) to "**A**" automatic position.



18. Push and hold down Rix Compressor control box **"start"** button until compressor runs continuously.



Rev Date: 10Sept09 1505

Procedure for Sampling from the Oxygen Surge Cylinders

- *This procedure assumes both oxygen generators are producing 2.9- 3.1 lpm per unit*
- *The Rix compressor is operating and Surge Cylinders #1 and# 2 are pressurized above 1200psig (read pressure on PI308).*

- 1) Verify that surge cylinders #1 and #2 are pressurized above 1200 psig by ensuring cylinder valves are **OPEN**, V314 **OPEN**, V318 **OPEN**, and checking pressure at PI308
- 2) Verify that V322 is **CLOSED** (inlet valve to sampling manifold)
- 3) Install oxygen sample cylinder (pipe plug end down, V418) into sample cylinder rack until the pipe plug engages in the copper base stabilizer.
- 4) Hand tighten the oxygen sample cylinder ring clamp to secure the sample cylinder.
- 5) Check pressure of PI411. (should be 0 psig)
- 6) **SLOWLY OPEN** V414 to depressurize the manifold (downstream of V410) to reduce pressure in lines if it exists (line pressure PI411).
- 7) Remove ¼ “ Swagelok plug” from inlet of sample cylinder (V416).
- 8) Remove ¼ “ Swagelok cap” from outlet of sample line pigtail.
- 9) Connect outlet of sample line pigtail to inlet of (V416) of sample cylinder.
- 10) Status Check of oxygen sampling manifold valves -
CLOSED: V322, V410, V414,
- 11) PCV-402 backed out (turn counter-clockwise) allowing no flow of gas.
- 12) Valve status check of 1 L. sample cylinder
CLOSED: V416, V418
- 13) **SLOWLY OPEN** V322.
- 14) PI400 will read the surge cylinder pressure.
- 15) **SLOWLY OPEN** 410

PURGE SAMPLING MANIFOLD and Oxygen Sample Cylinder

- 15) Adjust PCV402 clockwise until PI404 reads 1200psi (oxygen is now filling sampling manifold to V416).
- 16) **CLOSE** V322
- 17) **SLOWLY OPEN** V414 (vent lines until PI411 reads 100psig).
- 18) **CLOSE** V414.
- 18) Repeat Step #12 –step #18 two more times

- 19) **OPEN** V322.
- 20) **SLOWLY OPEN V416** (inlet to oxygen sample cylinder).
- 21) Pressurize cylinder to 1200psig (PI411...will take 2-3 minutes)
- 22) **CLOSE** V410.
- 23) **SLOWLY OPEN** V414 to vent/purge oxygen sample cylinder until PI411 reads 100psig, **CLOSE** V414
- 24) **SLOWLY OPEN** V410
- 25) Pressurize cylinder to 1200psig (PI411...will take 2-3 minutes)
- 26) **CLOSE** V410.
- 27) **SLOWLY OPEN** V414 to vent/purge oxygen sample cylinder until PI411 reads 100psig, **CLOSE** V414
- 28) **REPEAT Steps #24 -#27** (to purge sample cylinder of residual air).

OXYGEN SAMPLE CAPTURE

- 29) **SLOWLY OPEN** V410
- 30) Pressurize cylinder to 1200psig (PI411...will take 2-3 minutes)
- 31) **CLOSE** V416
- 32) **CLOSE** V410.
- 33) **CLOSE** V322
- 34) **SLOWLY OPEN** V414 to depressurize manifold lines.
- 35) When PI411 is "0 psig" **CLOSE** V414
- 36) Unmake ¼ " Swagelok" fitting at inlet of V416.
- 37) Plug V416 inlet with ¼" Swagelok plug.
- 38) Loosen the oxygen sample cylinder ring clamp .
- 39) Lift and remove the oxygen sample cylinder from it's support.
- 40) **Replace ¼" Swagelok cap** on oxygen sample outlet pigtail.
- 41) Package sample cylinder per instructions for shipping.
- 42) **SLOWLY OPEN** V414.
- 43) **SLOWLY OPEN** V410.
- 44) Turn PCV402 counter clock until no regulator outlet pressure is on PI404.
- 45) **CLOSE** V410, V414

Rev Date: 17Sept09

Emergency Shutdown Procedure

Turn OFF both (2) oxygen generators main power switches on left side of generator cabinets.



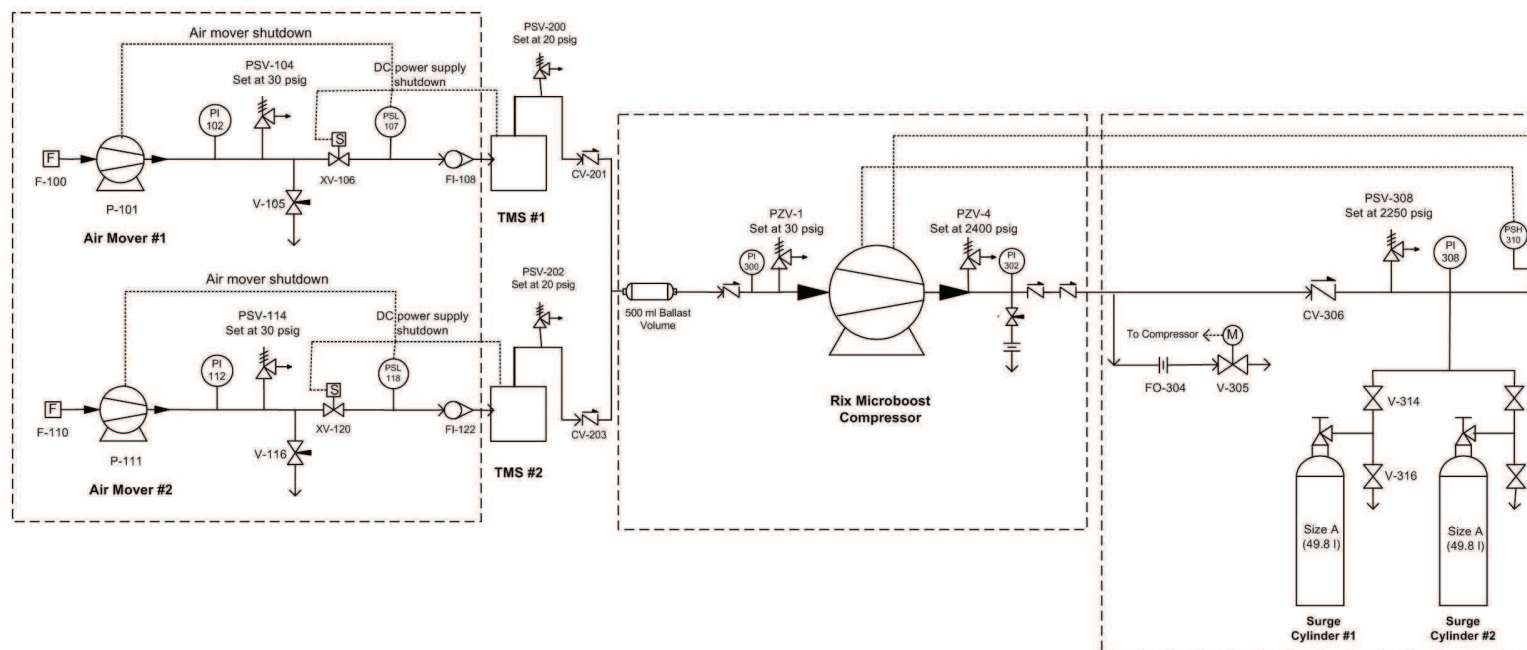
Turn the Rix Compressor System Switch to the OFF Position



CLOSE the Cylinders Shutoff Valve



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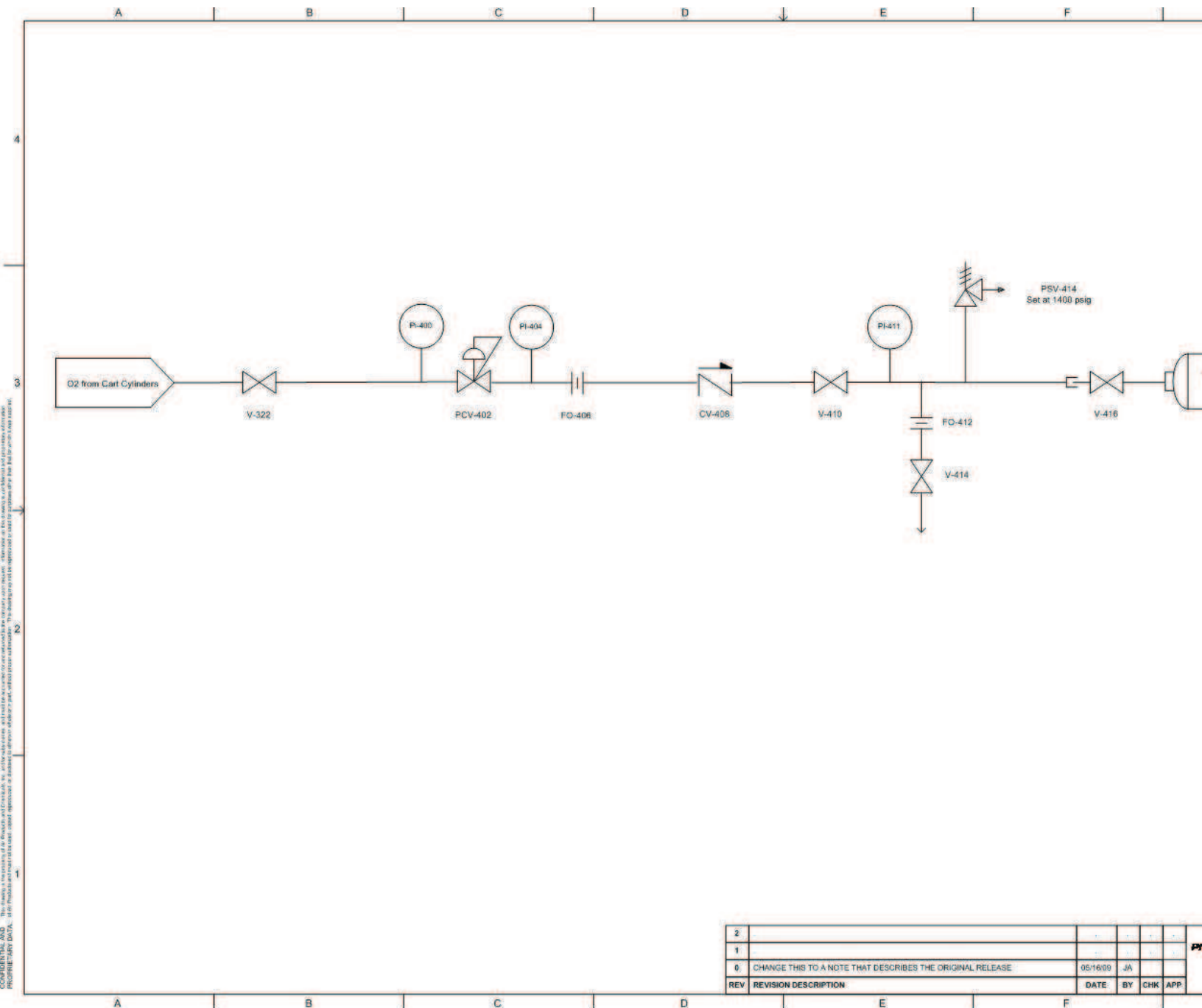
Air Manifold

Oxygen Generators

Oxygen Compressor

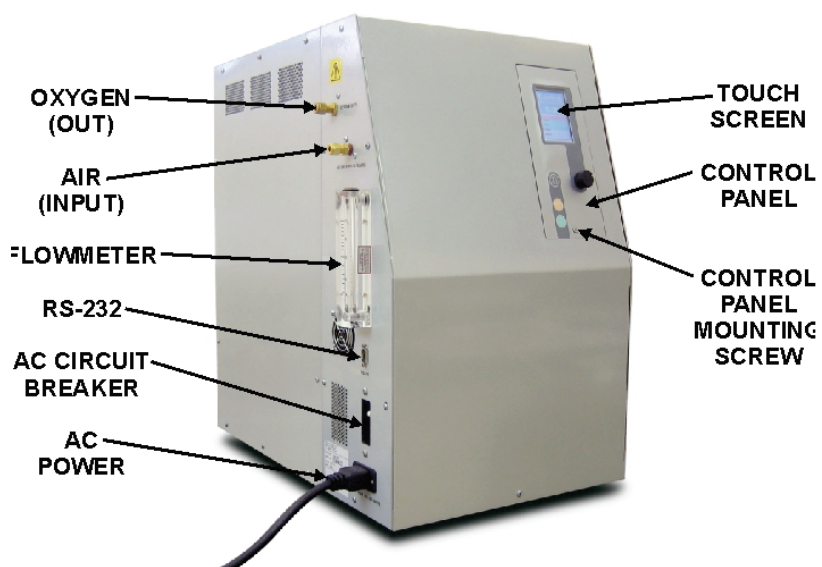
Oxygen Supply Manifold

2		-	-	-	-	
1		-	-	-	-	
0	CHANGE THIS TO A NOTE THAT DESCRIBES THE ORIGINAL RELEASE				07/27/08	JA
REV	REVISION DESCRIPTION	DATE	BY	CHK	APP	



Oxygen Generator Instruction Manual

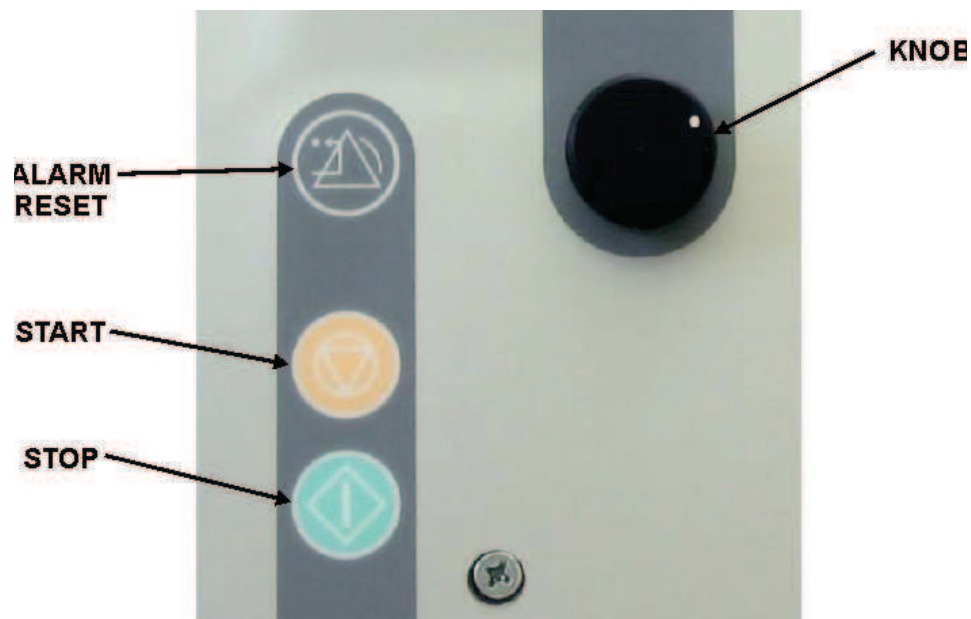
The following instruction manual provides the user with information and instruction to operate the oxygen generator.



Operation

Control Panel Functions

The Control Panel, on the right side of the front panel, consists of a Touch-Pad, three Push Buttons and a Knob.



Push Buttons below the Touch Screen

The Alarm Reset button is used to reset or clear an alarm. If an alarm occurs it will be displayed on the touch screen. Refer to the Alarms page for a list of alarms and possible causes.

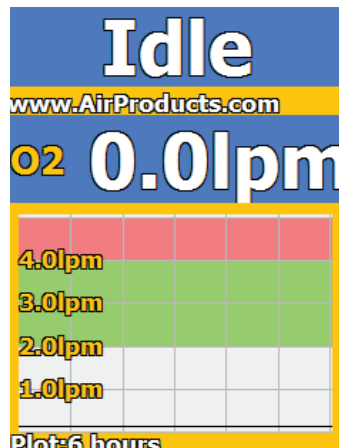
The Start button is used to start the oxygen generator and produce oxygen. "Heating" will appear on the top of the touch screen and the temperature displayed on the graph will increase. After the temperature stabilizes "Operate" will appear on the touch screen indicating the oxygen generator is producing oxygen.

The Stop button is used to stop the oxygen generator from producing oxygen. "Cooling" will appear on the touch screen and the temperature displayed on the graph will decrease. After the temperature stabilizes, "Idle" will appear on the touch screen indicating oxygen generation has stopped.

The Knob is used to zoom the chart and scroll through historical values. For a list of parameter abbreviations and their definitions refer to the Touch Screen Parameter Abbreviations page.

Touch Screen Operation

1. When the Oxygen Generator is first turned on (AC power switches on lower left side of respective TMS cabinets) the Splash screen will appear. In a short time the Main screen will appear with Idle displayed on the top line.



2. The operating parameter displayed on the graph is listed on the third line down. To select other operating parameters touch the parameter value.

3. Turn the Knob to zoom the chart. Selections are 10 minutes, 30 minutes, 1 hour, 2 hours, 6 hours, 12 hours, 24 hours and 48 hours.

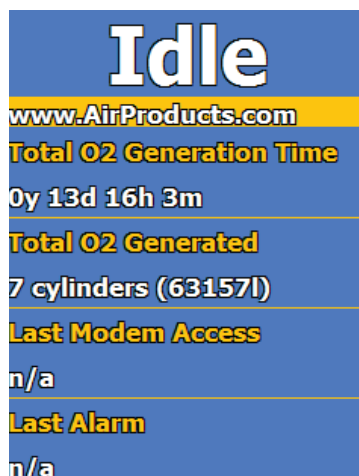
4. Touch the top line to display a table of all the operating parameters and their values.

Idle	
www.AirProducts.com	
Current reading	
O2 0.0lpm	Tc 23.6°C
Ts low	Is 0.0A
To low	Vs 0.1V
Th 24.3°C	Vp 4.30V
Version 1.28 1.28 A9	

5. The fourth line down displays the time the parameter values were recorded. By default the displayed values will be current values and the display will indicate current reading.

6. Turn the Knob counterclockwise to display a past list of operational parameter values. By turning the knob you can display past values for every minute for the past 48 hours. Touch the screen, while turning the knob, to advance in one-hour increments.

7. Touch the top line again to display the statistics.

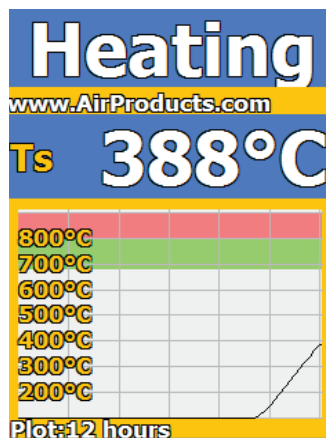


8. Touch the top line again to return to the Main screen.

Oxygen Generation

Start Oxygen Generation

1. Turn the oxygen generator on. The Main screen will appear.
2. Press the Start button on the control panel. The touch-screen will display Heating and the oxygen generator will heat the stack to the operating temperature. This will take approximately 6 hours.



3. The operating parameter displayed on the graph is listed on the third line down. To select other operating parameters touch the parameter value.
4. Turn the knob to zoom the chart. Selections are 10 minutes, 30 minutes, 1 hour, 2 hours, 6 hours, 12 hours, 24 hours and 48 hours.
5. As the generator is heating touch Heating to display a list of operating parameters and their values.

Heating	
www.AirProducts.com	
Current reading	
O2 0.1lpm	Tc 24.4°C
Ts 389°C	Is 0.0A
To 289°C	Vs 0.0V
Th 24.8°C	Vp 4.30V
Version 1.28 1.28 A9	

6. The fourth line down displays the time the parameter values were recorded. By default the displayed values will be the current values and the display will indicate Current Reading.

7. Turn the Knob counterclockwise to display a past list of operational parameter values. By turning the knob you can display past values for every minute for the past 48 hours. Touch the screen, while turning the knob, to advance in one-hour increments.

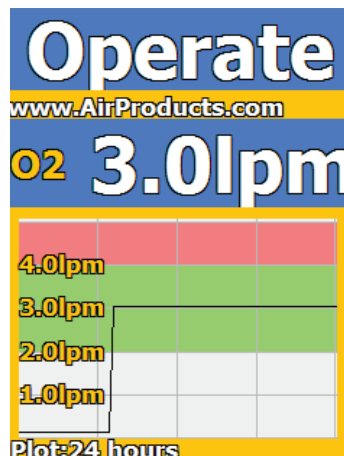
8. Touch the top line again to display the statistics.

Heating	
www.AirProducts.com	
Total O2 Generation Time	
0y 13d 16h 3m	
Total O2 Generated	
7 cylinders (63195l)	
Last Modem Access	
n/a	
Last Alarm	
n/a	

9. Touch the top line again to return to the Main screen.

Oxygen Generation

1. After reaching the operating temperature Operate will appear on the top of the screen and the generator will start producing oxygen.



2. As the generator is producing oxygen touch Operate to display a list of operating parameters and their values.

The screenshot shows the 'Operate' screen with the website 'www.AirProducts.com' at the top. Below the title, it displays 'Current reading'. The table below shows the following parameters and values:

O2 3.1lpm	Tc 25.3°C
Ts 745°C	Is 25.1A
To 645°C	Vs 8.5V
Th 41.1°C	Vp 9.65V

Version 1.28 1.28 A9

3. The fourth line down displays the time the parameter values were recorded. By default the displayed values will be the current values and the display will indicate Current Reading.

4. Turn the Knob counterclockwise to display a past list of operational parameter values. By turning the knob you can display past values for every minute for the past 48 hours. Touch the screen, while turning the knob, to advance in one-hour increments.

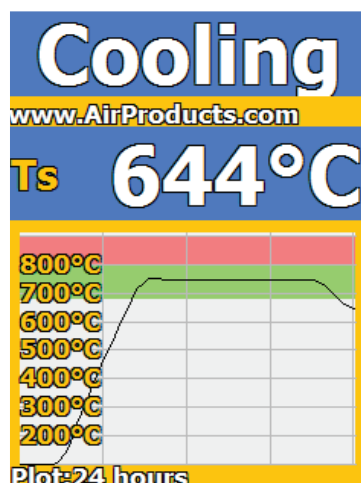
5. Touch the top line again to display the statistics.



6. Touch the top line again to return to the Main screen.

Stop Oxygen Generation

1. Press the Stop button on the control panel. The touch-screen will display Cooling and the oxygen generator will cool to ambient temperature. This will take a few hours.



2. The operating parameter displayed on the graph is listed on the third line down. To select other operating parameters touch the parameter value.

3. Turn the knob to zoom the chart. Selections are 10 minutes, 30 minutes, 1 hour, 2 hours, 6 hours, 12 hours, 24 hours and 48 hours.

4. As the generator is cooling touch Cool to display a list of operating parameters and their values.

Cooling	
www.AirProducts.com	
Current reading	
O2 0.1lpm	Tc 24.1°C
Ts 644°C	Is 0.0A
To 544°C	Vs 0.0V
Th 24.5°C	Vp 4.29V
Version 1.28 1.28 A9	

5. The fourth line down displays the time the parameter values were recorded. By default the displayed values will be the current values and the display will indicate Current Reading.
6. Turn the Knob counterclockwise to display a past list of operational parameter values. By turning the knob you can display past values for every minute for the past 48 hours. Touch the screen, while turning the knob, to advance in one-hour increments.
7. Touch the top line again to display the statistics.

Cooling	
www.AirProducts.com	
Total O2 Generation Time	
0y 14d 5h 20m	
Total O2 Generated	
7 cylinders (65703l)	
Last Modem Access	
n/a	
Last Alarm	
n/a	

8. Touch the top line again to return to the Main screen.

Touch Screen Parameter Abbreviations

The following is a list of parameter abbreviations with their definitions. These abbreviations will appear on the touch-screen during operation.

<u>Parameter</u>	<u>Definition</u>
O2	Oxygen Flow
Tc	Cold Junction Temperature
Ts	Stack Temperature
Is	Stack Current
To	Oxygen Pipe Temperature
Vs	Stack Voltage
Th	Heat sink Temperature
Vp	DCPS Voltage

Alarms

The following alarms will be displayed on the touch screen if they occur. Press Alarm Reset, on the front panel, to clear the alarm.

TAH	Stack temperature went above the maximum limit.
OCA	Stack current went above the maximum limit.
PAL	Incoming air pressure went below the minimum limit
FAL	Outgoing oxygen flow went below the minimum limit. Normal status for FAL light depends on the operating mode of the oxygen delivery system. The FAL (Flow Alarm Low) will not be illuminated when the compressor is operating and delivering oxygen to the user. The generators will indicate a FAL however when the compressor is shut down. During normal operation the FAL light indicates that the oxygen being continuously produced by the generators is being bled off through the relief valves inside the generator cabinets. The relief valves are located upstream of the oxygen flow meter and therefore the flow meter correctly registers the lack of oxygen flow to the compressor. When the compressor restarts, the relief valves close and the flow of oxygen through the flow meter is reestablished
RAMP	Stack temperature ramp rate went above the maximum limit.
SHORT	Stack voltage dropped below minimum while stack current was above threshold.
SNK	Heat sink temperature rose above maximum limit.
THRM	Stack or oxygen pipe thermocouples may be shorted or disconnected.
CURR	Stack current went above the maximum limit.
VROR	Reference voltage went out of range.
VPOR	Power supply voltage went out of range.
V24OR V+24V	power went out of range.
V5OR V+5V	power went out of range.
COR AC	line measurement circuit went out of range.
ACFLT	The AC line voltage went below the minimum limit.
OK	No alarms indicated.

AUTOMATIC SHUTDOWN GUIDE

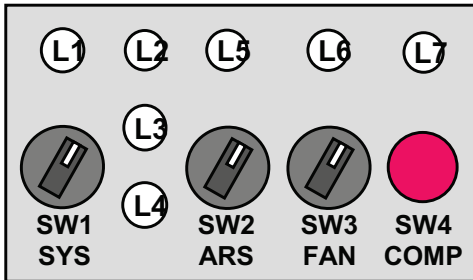
SEOS Oxygen Compressor

Upon recognizing the compressor as shutdown, before any control box switch adjustments are made, take note of the condition of the switches and lamps. Use this guide to find the matching control box face diagram. Comments in the adjacent dialog box list possible faults.

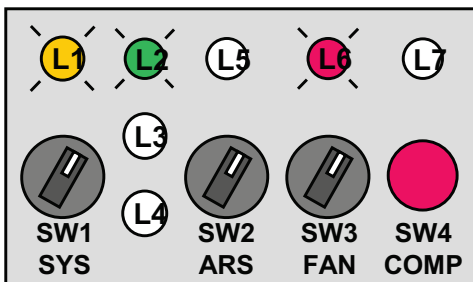
How to use this guide

First Note the position of the switches and turn to the pages that describe that set of positions. The switch positions are noted at the top of each page.

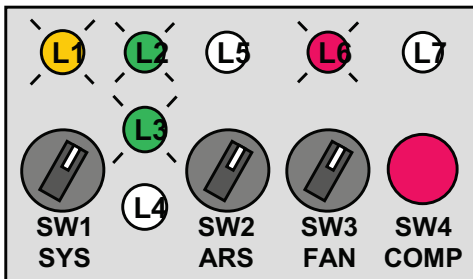
Second Note the status of all the lamps and find the corresponding diagram. Use the trouble shooting suggestions found to the right of the matching diagram



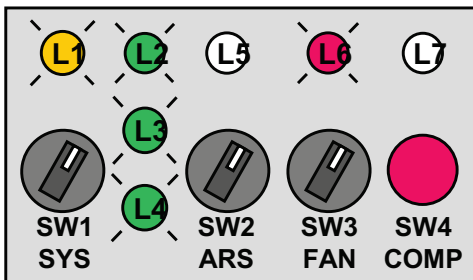
- Power unplugged
- Fuse blown
- CB-1 opened



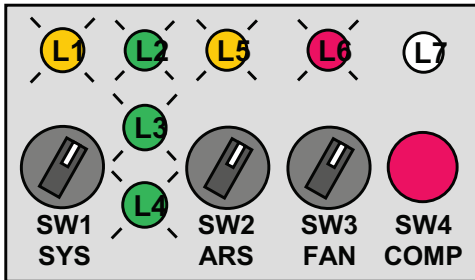
- Insufficient inlet pressure (supply)
- XV coil opened



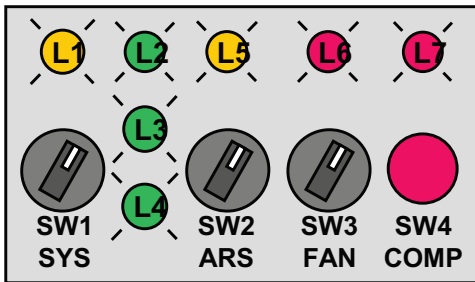
- High enclosure temp



- Low inlet pressure & reset
- High enclosure temp & reset

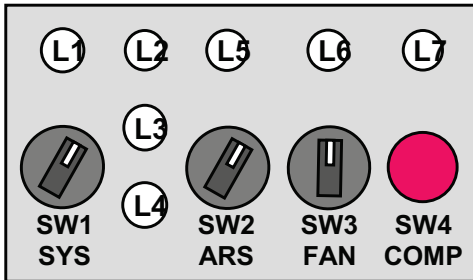


- Shutdown on high disch. press.

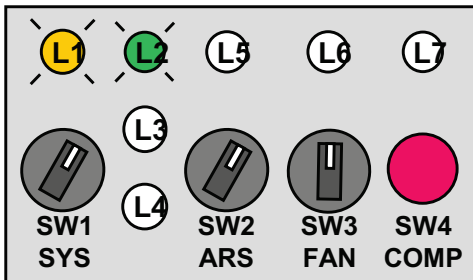


(Compressor audibly not running)

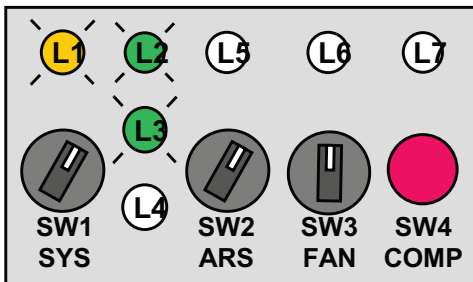
- CB-2 opened
- Rix motor contactor coil open
- Relay R1 coil open
- Rix motor thermal OL open



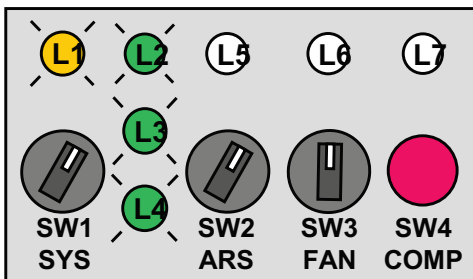
- Power unplugged
- Fuse blown
- CB-1 opened



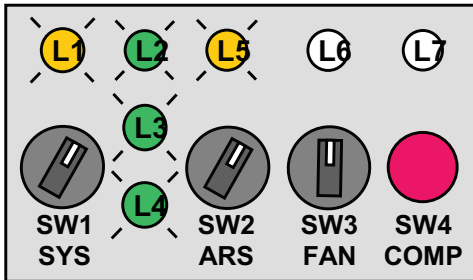
- Insufficient inlet pressure (supply)
- XV coil opened



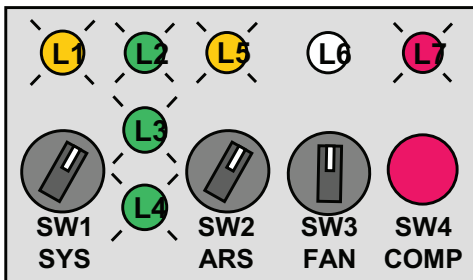
- High enclosure temp



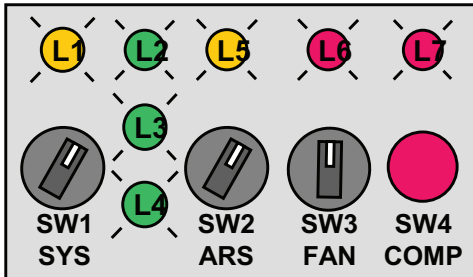
- Low inlet pressure & reset
- High enclosure temp & reset



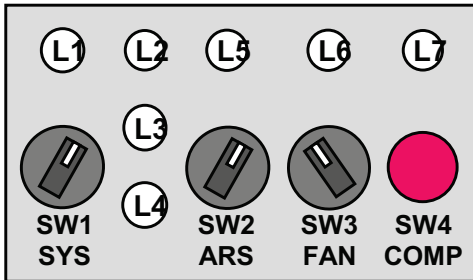
- Shutdown on high disch. press.



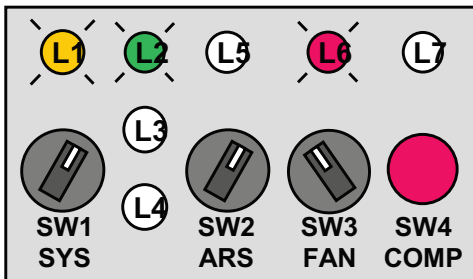
(Compressor audibly not running)
- CB-2 opened
- Relay R1 coil open
- Rix motor contactor coil open



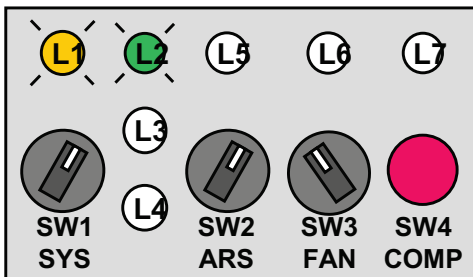
(Compressor audibly not running)
- Rix motor thermal OL open



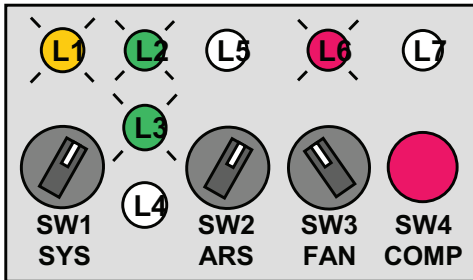
- Power unplugged
- Fuse blown
- CB-1 opened



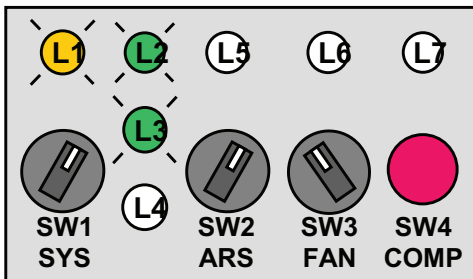
- Insufficient inlet pressure (supply)
- XV coil opened



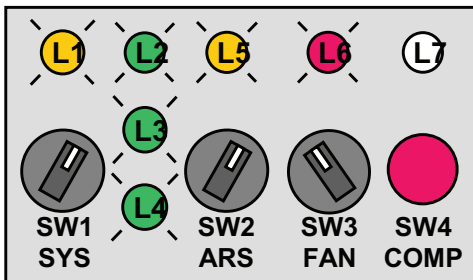
- Insufficient inlet pressure (supply)
- XV coil opened



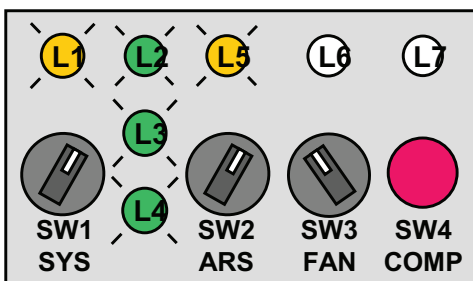
- High enclosure temp



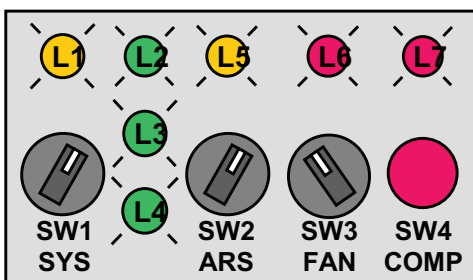
- High enclosure temp



- Shutdown on high disch. press.



- Shutdown on high disch. press.



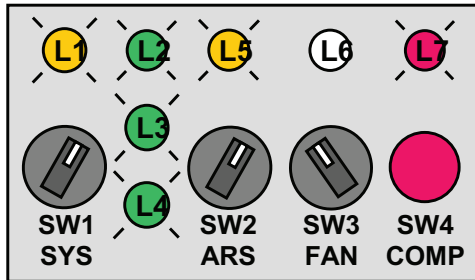
(Compressor audibly not running)

- CB-2 opened
- Relay R1 coil open
- Rix motor contactor coil open
- Rix motor thermal OL open

SYS = on ARS = on FAN = A

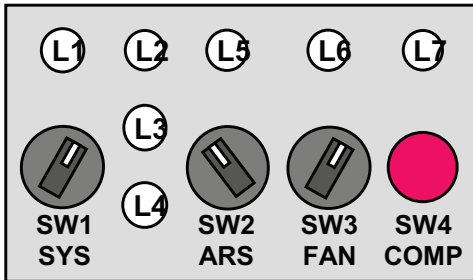
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of
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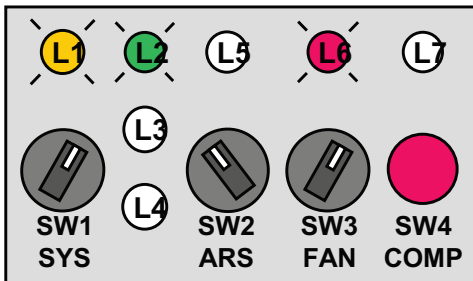


(Compressor audibly not running)

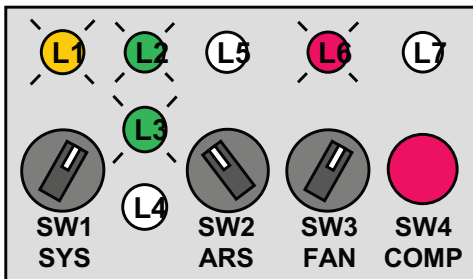
- CB-2 opened
- Relay R1 coil open
- Rix motor contactor coil open
- Rix motor thermal OL open



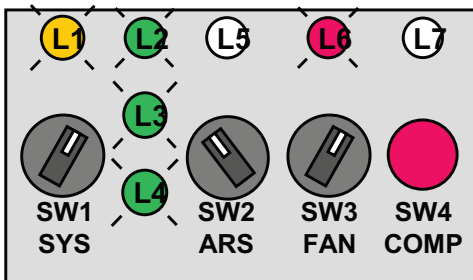
- Power unplugged
- Fuse blown
- CB-1 opened



- Insufficient inlet pressure (supply)
- XV coil opened



- High enclosure temp

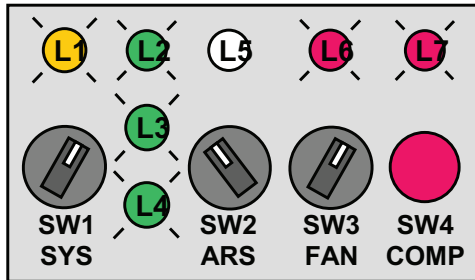


- Low inlet pressure & reset
- High enclosure temp & reset

SYS = on ARS = off FAN = 1

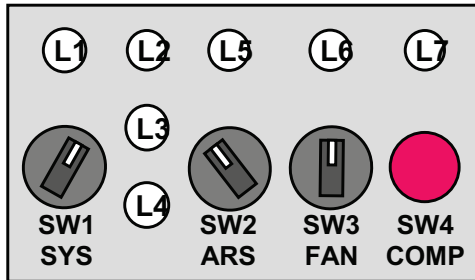
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of
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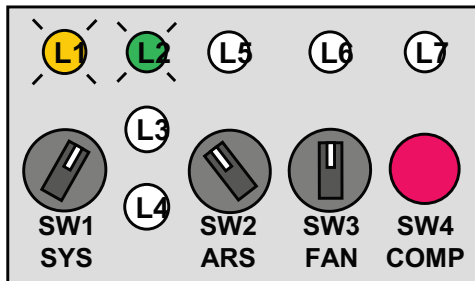


(Compressor audibly not running)

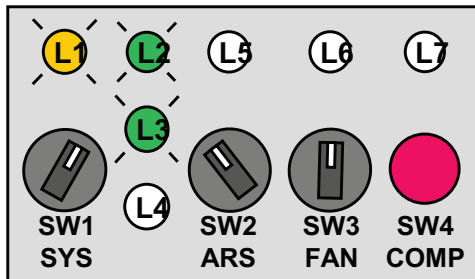
- CB-2 opened
- Relay R1 coil open
- Rix motor contactor coil open
- Rix motor thermal OL open



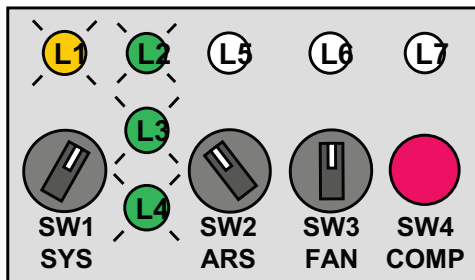
- Power unplugged
- Fuse blown
- CB-1 opened



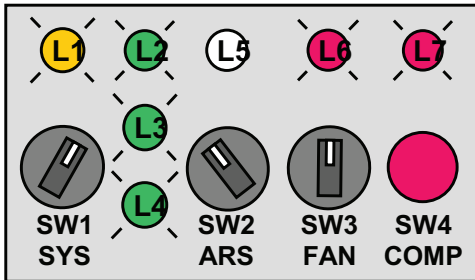
- Insufficient inlet pressure (supply)
- XV coil opened



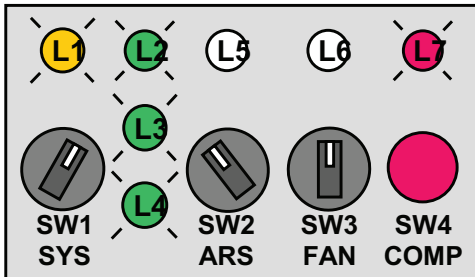
- High enclosure temp



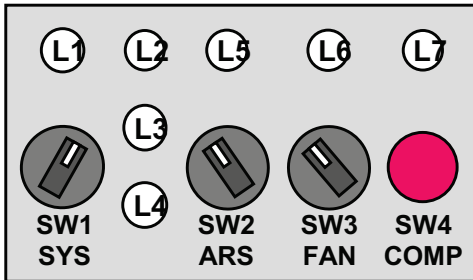
- Low inlet pressure & reset
- High enclosure temp & reset
- Shutdown on high disch. press.
- Relay R1 coil open
- Rix motor contactor coil open



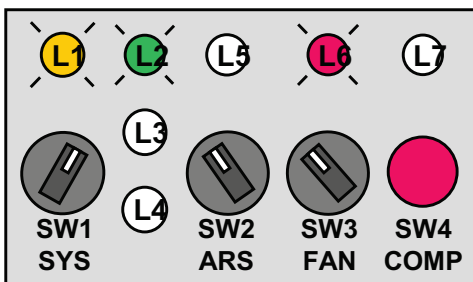
(Compressor audibly not running)
- Rix motor thermal OL open



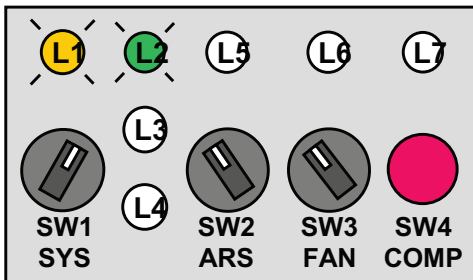
(Compressor audibly not running)
- Rix motor contactor coil open



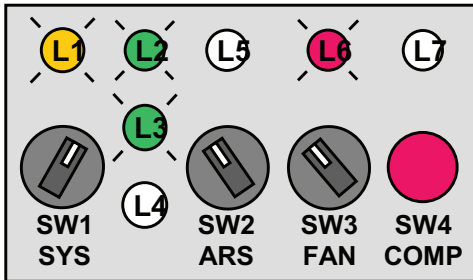
- Power unplugged
- Fuse blown
- CB-1 opened



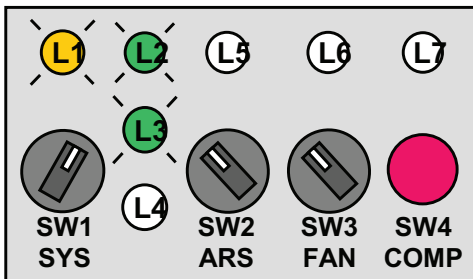
- Insufficient inlet pressure (supply)
- XV coil opened



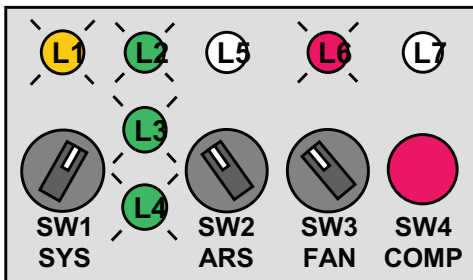
- Insufficient inlet pressure (supply)
- XV coil opened



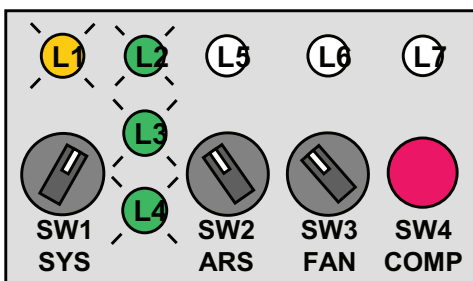
- High enclosure temp



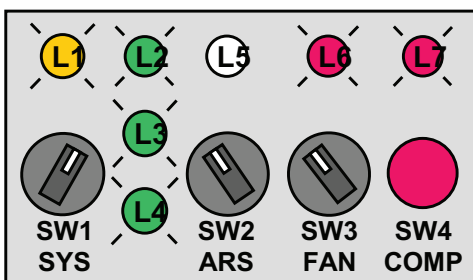
- High enclosure temp



- Low inlet pressure & reset
- High enclosure temp & reset
- Shutdown on high disch. press.
- Relay R1 coil open



- Low inlet pressure & reset
- High enclosure temp & reset
- Shutdown on high disch. press.
- Relay R1 coil open



(Compressor audibly not running)

- Rix motor thermal OL open
- Rix motor contactor coil open

APPENDIX E – Questionnaire

SEOS Questionnaire and Performance Metrics
(Frequency: On or About the 1st of Each Month)

Page 1 of 3

Name: Chris Kissick Organization: 423 SCMS/GUEA Date: 12 JAN 10

	N/A	Strongly Disagree	Disagree	Agree	Strongly Agree
1. SEOS is user friendly.	0	1	2	3	④

Comments: PDA interface is very easy to navigate, all valves clearly labeled, user instructions very thorough.

Shop comment: All info for data log easy to access.

	N/A	Strongly Disagree	Disagree	Agree	Strongly Agree
2. The controls are adequate to operate system.	0	1	2	3	④

Comments: Touch interface on PDA very easy to use.

	N/A	Strongly Disagree	Disagree	Agree	Strongly Agree
3. Displays are sufficient.	0	1	2	3	④

Comments: All necessary information for data sheet easy to find and read. Information on PDA all in one place.

	N/A	Strongly Disagree	Disagree	Agree	Strongly Agree
4. System checklists are sufficient.	0	1	2	3	④

Comments: Checklists are very thorough and easy to follow.

	N/A	Strongly Disagree	Disagree	Agree	Strongly Agree
5. System emergency shutdown procedures are adequate.	①	1	2	3	4

Comments: Have not had to shut down system. If shut down is necessary, it should be easy to accomplish.

SEOS Questionnaire (Page 2 of 3)

6. Markings and labels are adequate.	N/A 0	Strongly Disagree 1	Disagree 2	Agree 3	Strongly Agree 4
Comments:					
7. System noise level is acceptable.	N/A 0	Strongly Disagree 1	Disagree 2	Agree 3	Strongly Agree 4
Comments: System is more quiet than current equipment.					
8. System size is acceptable.	N/A 0	Strongly Disagree 1	Disagree 2	Agree 3	Strongly Agree 4
Comments: System requires less space than cylinder pallets.					
9.	N/A 0	Strongly Disagree 1	Disagree 2	Agree 3	Strongly Agree 4
Comments:					
10.	N/A 0	Strongly Disagree 1	Disagree 2	Agree 3	Strongly Agree 4
Comments:					
11.	N/A 0	Strongly Disagree 1	Disagree 2	Agree 3	Strongly Agree 4
Comments:					

SEOS Performance Metrics (3 of 3)

1. Estimated system up-time/on-line percentage/month.	<50%	50-79%	80-89%	90-95%	>95%
Comments:					
2. Estimated facility cost savings/month based on not using vendor supplied oxygen cylinders.	None	\$1-\$99	\$100-\$499	\$500-\$1,000	>\$1,000
Comments:					
3. Estimated man-hours saved/month based on not using vendor supplied oxygen cylinders.	None	1-9 hrs	10-19 hrs	20-50 hrs	>50 hrs
Comments:					
4. Estimated reduction in safety risk due to reduced handling of vendor supplied oxygen cylinders.	None	Somewhat	Moderate	Significant	
Comments:					
5.					
Comments:					