[1]U.S. Army Oxygen Generation System Development

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ABSTRACT

Oxygen is a huge logistical burden for the military in the deployed (field) medical environment. A single patient using only 3 litters of oxygen per minute will use the contents of a 150 pound oxygen cylinder each day. The oxygen cylinder is 145 pounds of steel and just 5 pounds of oxygen. It has been shown that 17% of combat casualties will require oxygen. This means that a 100 bed field hospital could theoretically need 2500 pounds of oxygen cylinders per day.

Recognizing the enormous impact oxygen has on its logistical tail, the U.S. Army started a developmental project in 1985 to develop the capability to generate oxygen at the point of use. Since 2001 the U.S. Army, in partnership with several vendors from industry, has been heavily involved in the development of POC gaseous oxygen systems.

1.0 HISTORY OF OXYGEN USE

The oxygen of planet earth was forged billions of years ago in the heart of an exploding star. The concentration of oxygen in the atmosphere has varied from 0% to 35% to the current 21%. It was discovered by Carl Wilhelm Scheele in 1773 and Joseph Priestly 1774. Priestly is commonly credited with the discovery because he was the first to publish his research. In 1895 Carl von Linde made large scale liquid oxygen production economical, beginning the widespread use of oxygen.

The use of oxygen by the U.S. Army can be traced to WWII where it was delivered to cyanotic patients at the rate of 4 to 5 litres per minute. Typically 4 to 5 patients were supplied from a single cylinder. Oxygen was generally administered in cycles; 100% for 12 hours with the flow reduced to 60% for 12 hours and then the flow was returned to 100%. The logistics of supplying oxygen must have been tremendously difficult. At 4 litres per minute each patient would use a 150 pound (70 kg) oxygen cylinder per day. Each cylinder only held 5 pounds of oxygen. I have not been able to find logistical details of supplying oxygen however; the use of medical oxygen was, no doubt, small compared to the requirements for aviator's breathing oxygen. All of the aviators in Europe flew long missions where they were using oxygen at high altitudes. The availability of oxygen for medical supplies was probably the result of the oxygen being produced for aviators.

The next major advance was during the Vietnam War. That advance was the local production of liquid oxygen for use by aviators. Since the mid 1950s military aircraft were using liquid oxygen to save weight and volume. The availability of liquid oxygen at air bases greatly reduced the logistical burden of supplying oxygen.

The arrival of the "Fourth Generation" jet fighter in the 1980s dramatically reduced the need for liquid oxygen. These aircraft used on-board oxygen generation systems. These systems used engine bleed air to feed a zeolite pressure swing adsorption molecular sieve to separate the nitrogen from the oxygen. This meant that there would be a decreasing need for liquid oxygen by the Air Force; therefore the Army needed a source of medical oxygen.

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14. ABSTRACT

Oxygen is a huge logistical burden for the military in the deployed (field) medical environment. A single patient using only 3 litters of oxygen per minute will use the contents of a 150 pound oxygen cylinder each day. The oxygen cylinder is 145 pounds of steel and just 5 pounds of oxygen. It has been shown that 17% of combat casualties will require oxygen. This means that a 100 bed field hospital could theoretically need 2500 pounds of oxygen cylinders per day. Recognizing the enormous impact oxygen has on its logistical tail, the U.S. Army started a developmental project in 1985 to develop the capability to generate oxygen at the point of use. Since 2001 the U.S. Army, in partnership with several vendors from industry, has been heavily involved in the development of POC gaseous oxygen systems.

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2.0 OXYGEN GENERATION TECHNOLOGIES

In 1983, the U.S. Army began to investigate the generation of oxygen at the field hospital where it was required. The technologies that were investigated were in several broad categories:

2.1 Cryogenic Separation

Air is liquefied, and then fractionally distilled, separating the air into its constituents -- primarily nitrogen, oxygen and argon. This is a complex process that is the most common and efficient method of large scale oxygen production. It is also the most efficient method of storing oxygen. Liquid oxygen or LOX storage is six to eight times more efficient than high pressure cylinders. The complexities and cool down requirements highly favor continuously operating production plants; this is not usually the mode of operation for field medical facilities. Liquid oxygen can be stored, but there is a loss rate that is dependent on the size of the container, the amount of LOX in the container, and the ambient temperature. LOX cannot be stored for long term use. It is a simple matter to safely fill high pressure oxygen cylinders using LOX.

A contract was awarded in 1989 to procure a portable liquid oxygen plant. This was to be a commercial off the shelf system. A system built by Pacific Consolidated Industries was selected. This system was already being used by the Air Force to provide LOX for their expeditionary requirements.

The LOX system was sent to Saudi Arabia at the outbreak of the Gulf War. With a great effort, the system was set up at a field hospital and was able to produce oxygen. The vast majority of the oxygen used was either imported from the U.S or Europe or filled from local sources.

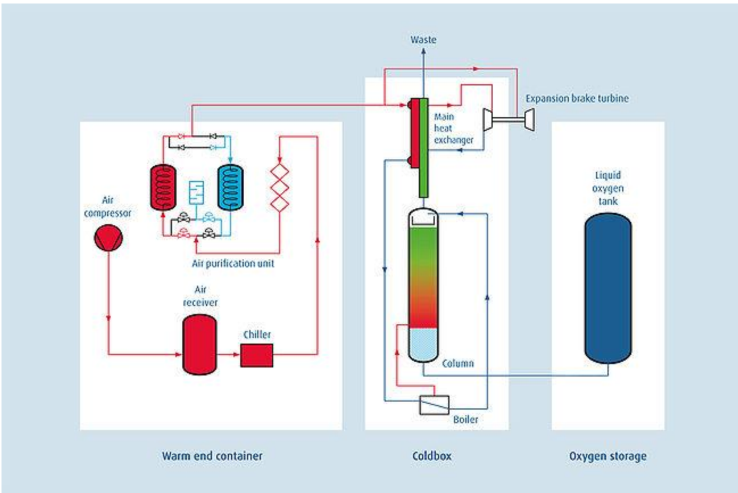

Figure 1: Typical oxygen liquefaction plant (courtesy of Linde Cryoplants Ltd.).

2.2 Molecular Sieves

Molecular sieves use containers of a granular aluminosilicate material called zeolite. When zeolite is exposed to pressurized air, nitrogen is absorbed into the structure of the material leaving the oxygen in the empty space. More air is introduced, sweeping the oxygen ahead of it. The pressure is reduced in the container, releasing the nitrogen from the zeolite and the process is started over. This process produces oxygen that is from 90% to 96% pure; the remaining gas is argon. This process requires at least 5 times as much air as product oxygen being produced under ideal conditions. Practical systems require at least 9 times as much feed air as oxygen is produced. This process is known as pressure swing adsorption (PSA). PSA is a mechanically simple process that is widely used to separate a variety of gasses; it is also the process used to produce oxygen in home oxygen concentrators that are used for long term oxygen therapy.

Because this process occurs at modest temperatures and pressures, it begins to produce oxygen rapidly and is relatively simple to operate and maintain. The PSA process is sensitive to moisture. The zeolite will turn into mud if it is exposed to water. A guard bed of silica gel is used to protect the bed from moisture. A variation of the process ends the cycle using a vacuum phase. With the vacuum assist the total change of pressure is the same as the PSA process, but the maximum pressure is lower. Not only does the vacuum assist process save energy, the air pressure is below the dew point of the moisture in the air, thus avoiding the moisture problem.

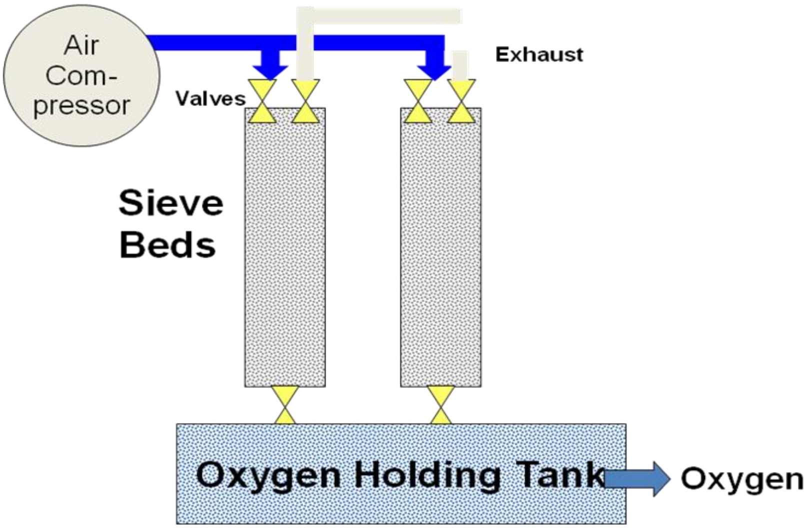

Figure 2: Typical PSA cycle (courtesy PCI).

A decision was made to develop PSA systems sized to supply oxygen for field hospital use. Two systems producing 120 litres per minute would provide the oxygen for a 160-bed hospital and be able to refill oxygen cylinders for portable and back-up use. This was named FMODGS for Field Medical Oxygen Generation and Distribution System.

Three contracts were awarded to develop systems meeting the requirements for 120 litres per minute of 93% oxygen, 8 hours of back-up oxygen, the capability to refill oxygen cylinders, and the ability to operate in desert temperatures of 50 degrees Celsius.

The PSA systems were tested and the system built by Guild Associates was selected for full development. The oxygen generation system was developed and tested for performance in a wide variety of conditions. By 1995 it was ready for operational testing.

During operational testing there was a high pressure oxygen fire. The fire started in a solenoid valve manifold when the system was filling oxygen cylinders. The fire consumed approximately 2 pounds of aluminium in less than 30 seconds. An exhaustive analysis was performed by NASA’s oxygen compatibility specialists from the White Sands Test Facility in New Mexico. The conclusion was that rust particles from the oxygen cylinders hit solenoid valve parts and ignited the aluminium valve manifold.

An oxygen hazard analysis was performed and the system was redesigned to eliminate sources of ignition and the aluminium that was fuel for fire.
The redesigned system was tested and the test was perfect with no machine faults or any other problems in a full month of testing. The fire so damaged the program that even though a decision was made approving it for full scale production, no systems were ever procured.

PSA systems are used for small oxygen concentrators that are used in the home healthcare setting an for both portable and large scale military oxygen concentrators.

The first of the large oxygen concentrators used by the U.S. Army was built by PCI. The first plant was a 120 litre per minute system deployed to Afghanistan in late 2001.

2.3 Electrochemical Oxygen Generation

Oxygen can be produced electrochemically. Simple electrolysis of water produces oxygen at the anode and hydrogen at the cathode. This method is used to produce breathing oxygen onboard nuclear submarines. The other electrochemical method uses a hot ceramic membrane that transports oxide ions or a floropolymer proton exchange membrane. These methods are essentially fuel cell processes being run in reverse. The challenge of this process is the same as those of fuel cells. The environment in electrochemical oxygen generators is extremely aggressive; the ceramic membrane operates at 700 degrees Celsius and the proton exchange membrane is sensitive to common contaminates such as calcium.

There are programs by the Army and Air Force for the development of ceramic oxygen generators. The contractor for the Army has been IGR Enterprises of Cleveland Ohio.

There are several major problems with ceramic membranes. It has very low tensile strength. This property makes it subject to catastrophic brittle failure just as familiar ceramic items such as flower pots or dinner plates. An additional challenge is the very hostile environment. The oxygen generation cells are in an intense electrochemical environment that exists to move ions, nearly the definition of corrosion. The high temperatures magnify the differences it thermal expansion resulting in large physical stresses.

3.0 CURRENTLY FIELDED EQUIPMENT

Figure 3: Oxygen cylinders for a field hospital, this is what we want to eliminate.

3.1 Large Oxygen Generators

Oxygen is currently supplied to combat support hospitals using the EDOCS 120 litre per minute oxygen concentrators build by Pacific Consolidated Industries of Riverside, California. These concentrators use a vacuum assisted pressure swing adsorption concentration cycle using a single sieve bed. Included in these systems is a high pressure compressor that is used to refill oxygen cylinders. It uses a scroll compressor to drive oxygen to the patient ward, operating room, and emergency department, or where ever oxygen is needed. These systems weigh 2800 pounds, are 8 ft long and 4 ft square in cross section. Two of these oxygen concentrators are used for 160-bed hospitals.

The cylinder refilling capability is used to fill oxygen cylinders used for patient transport and to keep the high pressure back up supply full. The backup supply is able to supply oxygen to the hospital for several hours, in the event of a loss of electrical power or an oxygen generator failure.

3.2 Portable Oxygen Concentrators

Forward surgical teams use oxygen concentrators that supply 5 litres per minute. These oxygen concentrators are used to supply low pressure oxygen to electrically driven ventilators. The clinicians use high pressure oxygen cylinders when patients are being transported.

Oxygen concentrators are used in the ambulance version of the Mine Resistant Ambush Protected (MRAP) vehicles. These are modified home healthcare oxygen concentrators made by SeQual in San Diego California. An Eclipse model was the basic device. The modifications included software changes to increase the maximum operating temperature and strengthened battery connectors. These concentrators can operate for 45 minutes on their internal batteries, supplying 93% oxygen at a rate of 3 litres per minute continuously or the equivalent of 6 litres per minute in a breath triggered, pulse mode. These oxygen concentrators are used in place of cylinders to eliminate the hazard of compressed oxygen in these vehicles. An additional benefit is that an oxygen concentrator will not run out of oxygen.

Figure 4a: MRAP vehicle under test.

Figure 4b: Oxygen concentrator in an MWRAP.

To date nearly 2000 oxygen concentrators have been installed in MRAP ambulances.

4.0 MILITARY OXYGEN GENERATOR DESIGN CONSIDERATIONS

Oxygen generators designed for the military have design considerations that are very different from civilian equipment. They operate in a much more difficult environment. They are exposed to extremes of temperature, humidity, shock, vibration, altitude and electro-magnetic interference. Additionally weight, size and power consumption must be minimized.

4.1 Temperature

Military equipment has to be able to function at temperatures up to 130 degrees F. Operation at high temperatures is difficult for PSA equipment because of the increase of the density altitude and the loss of efficiency of the adsorption process with increasing temperature. FMOGDS used a built in refrigeration system to maintain the cycle efficiency and to remove the heat generated during the cylinder filling process. The use of simple thermal controls, such as a sun shade is a significant help in improving the performance of systems such as EDOCS.

4.2 Dust

Dust and dirt are a major problem; equipment gets highly abrasive dust into every part of machinery. Maintenance is extremely difficult oxygen systems must be kept very clean to prevent fires. The desert environment is unimaginably dusty. The laws on the use of fluorocarbons have taken what was a useful tool for cleaning items undergoing maintenance; there has been no effective substitute.

Figure 5: A sand storm rolling toward a field hospital in Iraq.

4.3 Humidity

Humidity is a problem for the PSA process because the zeolite material is sensitive to moisture. As the air for the zeolite beds is compressed, moisture in the air reaches the dew point and begins to turn to liquid water. If the zeolite is exposed to water it will turn to mud. There are two approaches to controlling moisture. A guard bed of silica gel traps the moisture and releases it when the adsorption bed is purged. Guard beds work effectively, but take up space in the bed that would be otherwise used by zeolite. Vacuum assisted PSA systems use a different approach that avoids the problem. The PSA process uses an increase in pressure to drive nitrogen into the zeolite and a pressure drop to release it. The process typically is from atmospheric pressure up to 30 psig the vacuum assisted process operates from a vacuum up to 15 psig. The pressure does not become high enough to cause condensation. An added benefit is the lack of condensation which can freeze in cold weather.

4.4 Electromagnetic Compatibility

The electromagnetic environment can be difficult. The equipment must not interfere with other electronic systems and be resistant to very powerful electromagnetic interference. An example of this would be a portable oxygen concentrator used on a helicopter. It must not interfere with the helicopter’s electronic control systems or the aircraft radios. It must also work when the patient is carried in front of an aircraft with its radar on; this electromagnetic field can reach 200 volts per meter. The U.S. Army tests medical equipment for airworthiness and certifies it as safe to fly. This testing is conducted at Ft. Rucker in Alabama.

4.5 Regulatory Requirements

All U.S. Army medical equipment must also be cleared by the U.S. Food and Drug Administration before it can be used on patients. In addition there are requirements for CE mark, FAA, and even the U.N. which regulates lithium batteries on passenger aircraft.

4.6 What Size of Oxygen Concentrator?

The standard size of a U.S. Army field hospital is 84 beds. It is estimated that 17% of these patients will need oxygen at an average of 3 litres per minute. These 14 patients will use 42 litres per minute. This flow rate will use a 150- pound “H” cylinder per day per patient. This oxygen requirement would weigh a total of 2100 pounds, not including the oxygen used in the operating rooms, emergency departments, and small oxygen cylinders used for patient transport. This is the daily need of oxygen cylinders. This is almost exactly the weight of a large oxygen generator such as Pacific Consolidated Industries’ EDOCS which produces 120 litres per minute, which is nearly 3 times the oxygen required. This investment in weight and volume is a onetime investment that never runs out of oxygen. An alternative is a 3 litre per minute portable oxygen concentrators that weigh about 20 pounds sold for the home health care market. There are currently several manufacturers that make this size of oxygen concentrator. To meet the 120 litre per minute flow it would take 40 units which would weigh only 800 pounds. These devices are limited to low pressure and cannot refill cylinders.

5.0 CURRENT U.S. ARMY OXYGEN GENERATOR DEVELOPMENT PROGRAMS

5.1 Rotary Valve Pressure Swing Oxygen Generator (RVPSAOG)

A point of use portable oxygen concentrator that uses a vacuum assisted PSA process is being developed that is the size of a “D” cylinder. Using 5 small zeolite beds, it minimizes the amount of zeolite used by cycling the beds rapidly. Rapidly cycling the beds also increases the process efficiency, improving both the amount of oxygen recovered and minimizing the feed air needed. The feed air, purge air, and oxygen flow through the bed is controlled by a continuously rotating valve at each end of the bed assembly.

Figure 6: SeQual Omni II oxygen Concentrator next to a "D" cylinder.

Figure 7: Zeolite sieve bed assembly.

This oxygen concentrator was designed to be the same size and weight as a 360 litre "D" size high pressure oxygen cylinder. It is intended that it be used in the same way as a compressed gas cylinder. The oxygen concentrator produces 3 litres per minute it can also operate in a pulse conserved mode that is equivalent to a 6 litre per minute continuous flow rate. It can operate from the power mains, 120/240 volts, 12 or 24 volt DC, or its battery. Each battery will power the device for 1 hour at a 3 litre per minute flow rate; 2 batteries each weighing 2 pounds is the equivalent of a 14 pound oxygen cylinder. The battery is recharged when an external power source is used. One hour is needed to recharge the battery. If a greater flow rate is needed multiple units will work in parallel.

5.2 Ceramic Oxygen Generator

The ceramic oxygen generator is a portable oxygen generator that uses a ceramic solid electrolyte between two porous electrodes to produce oxygen. To make the oxide ions mobile, the ceramic is heated to approximately 700 degrees Celsius. Ceramic oxygen generators produce high purity oxygen and are impervious to chemical or biological warfare materials. They are also able to produce oxygen at above their rated design points by increasing the operating temperature and the electrical power. Because of the large amount of thermal energy present, good thermal management is crucial. The ceramic oxygen generator must be insulated from its environment to keep the cell temperature up without using large amounts of electrical heater power. It is also critical to use very high efficiency heat exchangers to recover the heat from the depleted exhaust air and from the oxygen. By recovering the heat energy, electrical power consumption can be approximately the same as other oxygen concentrators.

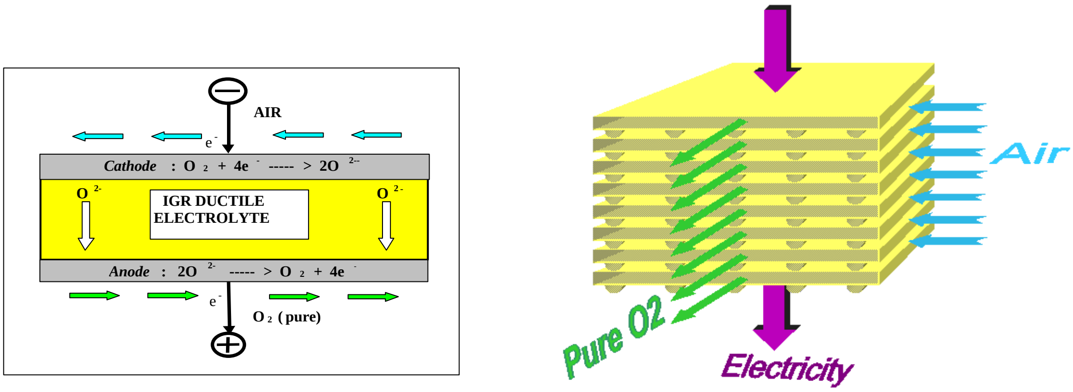

Figure 8: Ceramic oxygen generator.

The challenges for the development of a ceramic oxygen generator are many. The high operating temperature and powerful electrical field can cause the materials to do very "creative" chemistry with materials attacking one another and other materials migrating from their intended place and causing troublesome short circuits. As the ceramic heats and cools the forces of expansion and contractions are enormous, this will cause cracking unless the materials are matched for their coefficient of thermal expansion. This program uses a ceramic membrane supported by a nickel superalloy matrix, making the oxygen generator cells much less prone to cracking. The solid electrolyte is still an electrolyte and is very corrosive to metals at its operating temperature so the metal must be very corrosion resistant. These alloys are typically found in jet engines. This device can be operated form A.C. mains, vehicle power, or by battery. Once the correct materials, processing cycles and thermal designs have been developed, the ceramic oxygen concentrator is very reliable because there are no complex moving parts.

5.3 Turbo Compressor

The Pressure Swing Adsorption process requires pressurized air as a feedstock for the process. One of the difficult design problems is generating the air pressure and possibly the vacuum required in some systems. There have been various designs used to do this, these have included: piston pumps, lobed blowers (similar to super chargers used on engines), scroll pumps, and rotary vane pumps. The turbo compressor is a design that trades the size and weight of the low speed compressors for a very high speed centrifugal compressor. These designs are similar to the design of an automotive turbo supercharger, and are attractive because of their small size and light weight. The very high speeds that are required make the design of the electric motor complex. The reliability of bearings and seals are an engineering challenge. The turbo compressor and motor weigh less than 40 pounds, the equivalent blower and motor weigh nearly 200 pounds.

5.4 Oxygen Conservation

Part of the effort to reduce weight and volume has to go into oxygen conservation. This might mean pulse conservation schemes, the use of soda lime carbon dioxide scrubbers, the monitoring of patient oxygenation levels using pulse oximetery, and reducing the oxygen flow to meet the patient’s needs.

The establishment of how much oxygen a patient actually needs is an area that needs to be studied. In the civilian hospital setting, oxygen is not very expensive. When it is used in a military field hospital and must be made or brought in, it is very expensive.

Oxygen delivered to a patient at a constant flow rate wastes at least half the oxygen being delivered. Oxygen can be conserved by releasing oxygen at the beginning of the patient’s inhalation. This means that oxygen is going deep into the patients lungs and that the airway is filled with just room air. The patient is actually oxygenated to a higher level because the oxygen is delivered in a large bolus as opposed to delivering it throughout the breath cycle, including exhalation.

It is also possible to deliver oxygen in doses to patients on ventilators. This requires sensing the initial rise in pressure in the mechanical breathing cycle and rapidly delivering oxygen to the patient’s oxygen system near the patient end of the ventilator tubing.

By conserving oxygen the patient can actually get a higher percentage of inspired oxygen. The logistical benefit is that oxygen doesn’t have to be transported, stored or manufactured. Using conserving techniques extends the battery duration of portable oxygen concentrators.

These conserving techniques requires sensitive pressure sensors to detect the changes in the pressure in the oxygen tubing as the patients breath begins or the ventilator starts it’s cycle. There is also a need for safety measures in the software to detect missed breaths and revert to full flow and sound an alarm.

5.4.1 Closed Circuit Systems

Scrubbing the CO2 from the patients breath and re-breathing the oxygen has not been used as much as it should. One pound of absorbent will double the life of a 14 pound “D” cylinder or double the life of a battery. It may be possible to use a ceramic oxygen generator or a molecular sieve oxygen concentrator as the CO2 scrubber and use the depleted air as the feed gas dramatically increasing the generation efficiency. With molecular sieve oxygen concentrators at least 5% of the circulating gas is argon, which is not removed. The build-up of argon requires that at least 1 litre per minute is added to the circuit to prevent the concentration of argon.

5.5 Oxygen Storage

Oxygen concentrators perform better if they run at a near constant flow rate. Sizing oxygen generators for the maximum flow requirements results in equipment that is cycling on and off, this is very hard on the equipment.

Sizing the oxygen concentrator for the average flow rate and storing oxygen for use is a much more efficient tactic. Machines that are running constantly operate much more efficiently and have fewer failures. Oxygen concentrators sized for the average flow rate must be able to store oxygen during times of low demand for use during high demand periods.

Oxygen cylinders, are a typical storage device, they require a high pressure compressor and a supply of empty cylinders. Large steel oxygen cylinders weigh 150 pounds and store only 5 pounds of oxygen. To reduce the weight carbon fibre is being used as a reinforcing overwrap on thin brass liner cylinders. The commercial practice is to use a thin aluminium liner with a carbon fibre or fibre glass overwrap. The aluminium liner can contribute to a fire if the cylinder is hit by a bullet; the brass liner is non flammable.

Liquid oxygen is about six times more efficient to store than high pressure gaseous oxygen. It does have the disadvantage that it is always boiling to vapor. Classic liquefaction techniques are very complex, maintenance intensive and are best operated continuously. An acoustic cryocoolers is being investigated to liquefy oxygen using sound waves. This design is very compact and is transparent to the user and rapidly begins producing LOX. This concept is in its early stages of development.

6.0 RESEARCH AND DEVELOPMENT OPPORTUNITIES

6.1 Oxygen Generation

There may be novel processes or process improvements that increase the separation efficiency, oxygen purity, reduce the energy required to separate oxygen from air or reduce the size and weight of oxygen concentration equipment.

6.2 Oxygen Conservation

Oxygen conservation reduces the size of the oxygen concentrator the patient needs, it also reduces the power needed to make oxygen and extends the battery life for portable devices. Improvements are needed to sense patient breathing and oxygen delivery sequencing.

6.3 Batteries

Batteries are an area of research that portable oxygen concentrators will benefit from. The primary source of this research will be from the laptop computer and the electric automobile industries.

6.4 Oxygen Use Guidelines

The biggest unanswered question is how much oxygen does a patient need? The standard medical model delivers large quantities of oxygen to the patient, because it is essentially free, in the military environment oxygen is very expensive. Oxygen beyond the patients needs is a waste of resources.

7.0 CONCLUSION

The U.S. Army has made a large investment in oxygen generation on the battlefield. This is because of the very large logistical cost of importing oxygen. Oxygen is expensive and dangerous to transport, and is being consumed constantly -- always seeming to run out at the worst time. By generating oxygen near the point of use, the supply of oxygen will not be interrupted. A single days worth of oxygen cylinders weighs as much as the equivalent oxygen generator, the difference is that the oxygen concentrator only has to be shipped once, the oxygen has to be shipped every day. It is much better to make oxygen than it is to take oxygen with you.