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The Use of Cryogenic Air in Supplied Air Respiratory Protection

Matthew Doctor
Montana Tech of the University of Montana

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The Use of Cryogenic Air in Supplied Air Respiratory Protection

By

Matthew Doctor

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Abstract

The Mine Improvement and New Emergency Response (MINER) Act of 2006 implemented new regulations in the underground coal mining industry that allow for the certification of non-compressed gas equipment for respiratory protection in underground coal mines. NASA's Kennedy Space Center (KSC) Biomedical Research and Engineering Laboratory (BRL) is investigating the potential to expand cryogenic air supply systems into the mining and general industries. These investigations have, so far, resulted in four separate comparison and hardware development programs.

The Propellant Handlers Ensemble (PHE) and Level "A" Ensemble Comparison (LAE):

This study compared worker thermal stress while using the industry standard Level A hazardous material handling ensemble as opposed to using the similarly protective Propellant Handler's Ensemble (PHE) that utilizes a cryogenic air supply pack, known as an Environmental Control Unit (ECU) as opposed to the compressed air Self Contained Breathing Apparatus (SCBA) used in the LAE. The research found that, in a 102°F environment, test subjects experienced significantly decreased body temperature increases, significantly decreased heart rate increases, and decreased sweat loss while performing a standard work routine while using the PHE, compared to the same test subjects performing the same routine while using the LAE.

The Cryogenic Refuge Alternative Supply System (CryoRASS) project:

The MINER Act of 2006 requires the operators of underground coal mines to provide refuge alternatives that can provide a safe atmosphere for workers for up to 96 hours in the event of a mine emergency. The CryoRASS project retrofitted an existing refuge chamber with a liquid air supply instead of the standard compressed air supply system and performed a 96 hour test. The CryoRASS system demonstrated that it provided a larger air supply in a significantly smaller footprint area, provided humidity and temperature control, and maintained acceptable oxygen and carbon dioxide levels in the chamber for the required amount of time.

SCBA and Mine Rescue System (CryoBA/CryoASFS)

Another requirement of the MINER Act is that additional emergency breathing equipment must be staged along evacuation routes to supplement the Self Contained/Self Rescue (SCSR) devices that are now required. The BRL has developed an SCBA known as the Cryogenic Breathing Apparatus (CryoBA), that has the ability to provide 2 hours of breathing air, a refill capability, and some cooling for the user. Cryogenic Air Storage and Filling Stations (CryoASFS) would be positioned in critical areas to extend evacuation time. The CryoASFS stations have a significantly smaller footprint and larger air storage capacity to similar compressed air systems. The CryoBA pack is currently undergoing NIOSH certification testing.

Technical challenges associated with liquid breathing air systems:

Research done by the BRL has also addressed three major technical challenges involved with the widespread use of liquid breathing air. The BRL developed a storage Dewar fitted with a Cryorefrigerator that has stored liquid air for four months with no appreciable oxygen enrichment due to differential evaporation. Testing of liquid breathing air was material and time intensive. A BRL contract developed a system that only required 1 liter of air and five minutes of time compared to the 10 liters of air and 75 minutes of time required by the old method. The BRL also developed a simple and cost effective method of manufacturing liquid air that joins a liquid oxygen tanker with a liquid nitrogen tanker through an orifice controlled "Y" fitting, mixing the two components, and depositing the mixed breathing air in a separate tanker.

Keywords: Air, breathing, cryogenic, supplied, mine

Dedication

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List of Acronyms

Term	**Definition**
BRL	Kennedy Space Center Biomedical Research and Engineering Laboratory
COTS	Commercial Off-The-Shelf
CryoBA	Cryogenic Breathing Apparatus
CryoRASS	Cryogenic Refuge Alternative Supply System
ECU	Environmental Control Unit
EKG	Electrocardiogram
IDLH	Immediately Dangerous to Life or Health
KSC	Kennedy Space Center
LAE	Level A Ensemble
MINER Act	Mine Improvement and New Emergency Response Act of 2006
NASA	National Aeronautics and Space Administration
NIOSH	National Institute for Occupational Safety and Health
NMA	National Mining Association
OSHA	Occupational Safety and Health Administration/Act
PHE	Propellant Handler's Ensemble
SAR	Supplied Air Respirator
SCAPE	Self-contained Atmospheric Protection Ensemble
SCBA	Self-Contained Breathing Apparatus
SCSR	Self-Contained/Self-Rescue device
WBGT	Wet Bulb Globe Temperature

1. Introduction

Working in hazardous atmospheres is a challenge in industry. Today's workforce can be exposed to a wide range of acute toxicants. In addition to the acute toxicants, there are agents that displace the oxygen in the local atmosphere, and chronic poisons that can cause long term illness and injury. The most hazardous atmospheric conditions are referred to as ***immediately dangerous to life or health (IDLH).*** This term "means an atmosphere that poses an immediate threat to life, would cause irreversible adverse health effects, or would impair an individual's ability to escape from a dangerous atmosphere" should respiratory protection equipment fail (Occupational Safety and Health Administration, 2011). An IDLH atmosphere normally falls into three general categories; atmospheres of an unknown condition, atmospheres in to which exposure to contaminants is likely to cause death or permanent injury in 30 minutes or less, or atmospheres that contain less than 19.5% oxygen (Bollinger, 2004).

In IDLH conditions, the use of supplied air respiratory protection equipment is required (Bollinger, 2004). This equipment can either be continuously supplied by an airline (a supplied air respirator or SAR) or self-contained with the air source held in a cylinder carried by the user (a self-contained breathing apparatus or SCBA) (Occupational Safety and Health Administration, 2011). A SAR must also be equipped with an auxiliary self-contained air supply in case of air line failure (Occupational Safety and Health Administration, 2011). Typically, industry has relied on compressed breathing air that complies with Grade D standards as described in ANSI/Compressed Gas Association Commodity Specification for Air (Occupational Safety and Health Administration, 2011), to satisfy its requirements for supplied air operations. The air supply can either be produced on-site, or compressed off-site and delivered in cylinders.

The National Aeronautics and Space Administration (NASA) in general, and Kennedy Space Center (KSC) in particular, have unique issues with the use and handling of exotic chemicals including hypergolic propellants, such as hydrazines and di-nitrogen tetroxide. These materials present serious hazards but have been an essential part of the American space program since its inception. Due to the low exposure thresholds of these materials, KSC workers often have to perform complex tasks in IDLH conditions or conditions that could suddenly become IDLH. To work in these conditions safely, NASA developed the Self Contained Atmospheric Protection Ensemble; also known as the SCAPE suit. The SCAPE suit, and the next generation Propellant Handler's Ensemble (PHE), are constructed of a chlorobutyl coated nomex fabric that is impermeable to hazardous propellants (Doerr D. , 2001). Supplied air moves through the suit continuously via a tubing manifold, illustrated in Figure 1, creating a positive pressure environment. While these suits can function with an airline or a compressed breathing air tank, the uniqueness of the suit is the liquid breathing air pack known as the Environmental Control

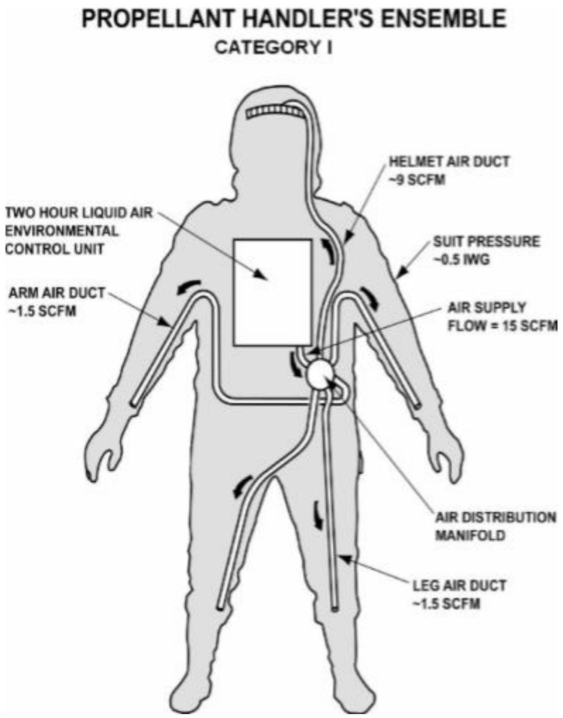

Figure 1: Propellant Handler's Ensemble (PHE) schematic (KD Cohen, 2011)

Unit (ECU). This pack allows a worker to function in a hazardous environment for up to two hours without any external air supply. An additional feature of the suit is the temperature of the air delivered. The air from the ECU is approximately 55° Fahrenheit, providing some heat stress protection and humidity control (KD Cohen, 2011). The first liquid air ECUs were developed in the mid-1960s to support the Apollo program. During the Space Shuttle Program, the ECU was adapted to be used as an advanced version of a Self-Contained Breathing Apparatus (SCBA) that could be used without the full PHE suit. These packs use a standard SCBA-type face mask and allow for up to one hour search and rescue operations in the event of a Space Shuttle launch pad emergency.

The NASA Kennedy Space Center Biomedical Engineering and Research Laboratory (BRL) is the center of NASA expertise in the field of cryogenic supplied air technology. The SCAPE suit, PHE, and ECU were all developed and tested by this organization. The BRL is currently partnering with the National Institute for Occupational Safety and Health (NIOSH) and other organizations to further certify and develop this technology for other fields including mine evacuation and rescue, supplied air for mine refuge chambers, and as an upgrade for a standard SCBA and level “A” hazardous materials ensemble (LAE). The BRL’s research also includes issues involving the storage and manufacture of liquid air. This paper will examine the benefits and challenges of using liquefied air as a source for activities that require supplied air respiratory protection and determine if this technology is a feasible upgrade to the current industry standard equipment.

2. Background

The use of cryogenic air has several potential advantages in the industrial and mining environment. Liquefied breathing air presents no additional fire hazard when compared to some systems that use pure oxygen, such as re-breathing systems. The liquid air systems operate at pressures of 100 psi or less whereas the current industry standard SCBA requires the use of 4500 psi compressed breathing air. Liquid air systems can store a much greater quantity of air in the same volume when compared to compressed air systems. Liquefied air supplies also have the ability to provide cooling to the user, minimizing the potential for heat stress.

Liquefied air use also presents several challenges that need to be addressed for the successful use of the technology. The primary issue with cryogenic air use is storage. Liquefied air that is stored for extended periods can become oxygen enriched due to the unequal evaporation rates of nitrogen and oxygen (Goetzfried & Madgett, 2012). Stored air must be periodically tested to verify the correct mixture of oxygen and nitrogen and this process is currently expensive, wasteful, and labor intensive (Blalock, 2014). Additionally, the production of cryogenic air is currently not widely available.

The NASA/KSC BRL is currently working to bring the advantages of cryogenic breathing air systems to mining and general industry by building on the proven technologies already developed by the lab. This work is broken up into four separate but related programs. A comparison was conducted between the PHE and the LAE to demonstrate the potential for heat stress mitigation provided by the PHE. The Cryogenic Refuge Alternative Supply System (CryoRASS) program tested a liquid air supply system for mine refuge chambers. The Cryogenic Breathing Apparatus (CryoBA) program is an advancement of the proven ECU technology that is designed to be a “change in the state of the art for SCBA” providing 2 hours of breathing air and heat stress relief specifically for mine evacuation and rescue operations (Doerr, Blalock, Bush, & and Fernando, 2013). Finally, the Cryogenic Air Storage and Filling Station (CryoASFS) has been developed to serve as fill stations for CryoBA units in an integrated mine evacuation and rescue system (Blalock, Doerr, Bush, & England, 2012). These programs will be described in sections three through six.

3. Comparison of PHE to LAE

Figure 2: Propellant Handlers Ensemble (PHE) (KD Cohen, 2011)

Figure 3: Environmental Control Unit (ECU) (KD Cohen, 2011)

One of the initial areas of BRL research into cryogenic supplied air systems was a comparison between the PHE and the LAE with respect to user heat stress. While providing similar levels of protection from hazardous environments, the LAE and PHE are very different systems. The LAE, shown in Figure 4, consists of a fully encapsulating chemical protective suit, a positive pressure SCBA, inner and outer chemical resistant gloves, and chemical resistant boots (National Institute of Health, 2013). Earlier research has indicated that full body protective ensembles similar to the LAE can "…impose a heat stress equivalent to adding 11° to 20° F to the ambient wet bulb globe temperature (WBGT) index (Rosenthal, 1987)." The Rosenthal tests were conducted using suits made of similar material to that of the LAE but utilizing air purifying respirators instead of the SCBAs used with the LAE. This additional heat stress can severely limit the amount of time a worker can spend in the suit. Additionally, the state-of-the-art for the

Figure 4: Level "A" Hazardous Material Handler's Ensemble (KD Cohen, 2011)

SCBA used as the air source for the LAE has a maximum 1 hour supply, further limiting a worker’s time on station. The PHE, described above in the introduction and shown in use in Figure 2, uses the liquid air ECU, shown in Figure 3, to supply up to two hours of continuous 425 liter/minute air flow through the suit’s distribution manifold including fresh air and venturi induced secondary air flow (Doerr D. , 2001). This continuous flow maintains a positive pressure in the suit and eliminates the need to use an SCBA type facemask. The air provided by the ECU, as mentioned above, flows out of the pack at 55°F; providing significant cooling to the user. The PHE however, is markedly heavier than the LAE. The PHE suit alone weighs 65 pounds, with the added weight of the ECU pack, the worker must bear a significant additional load (Doerr, 2001).

It was hypothesized that the PHE would provide a cooler environment for workers in similar atmospheric conditions when compared to the LAE. Testing consisted of a defined work/rest routine, illustrated in Figure 5, performed in an atmospherically controlled chamber set for 110° F. Work tasks consisted of walking on a treadmill, upper body exercises using an elastic strap, building a small wall with concrete blocks, walking stairs, and removing and installing the lid on a 55 gallon drum. Eight test subjects performed the routine twice; once in the LAE and once in the PHE (KD Cohen, 2011).

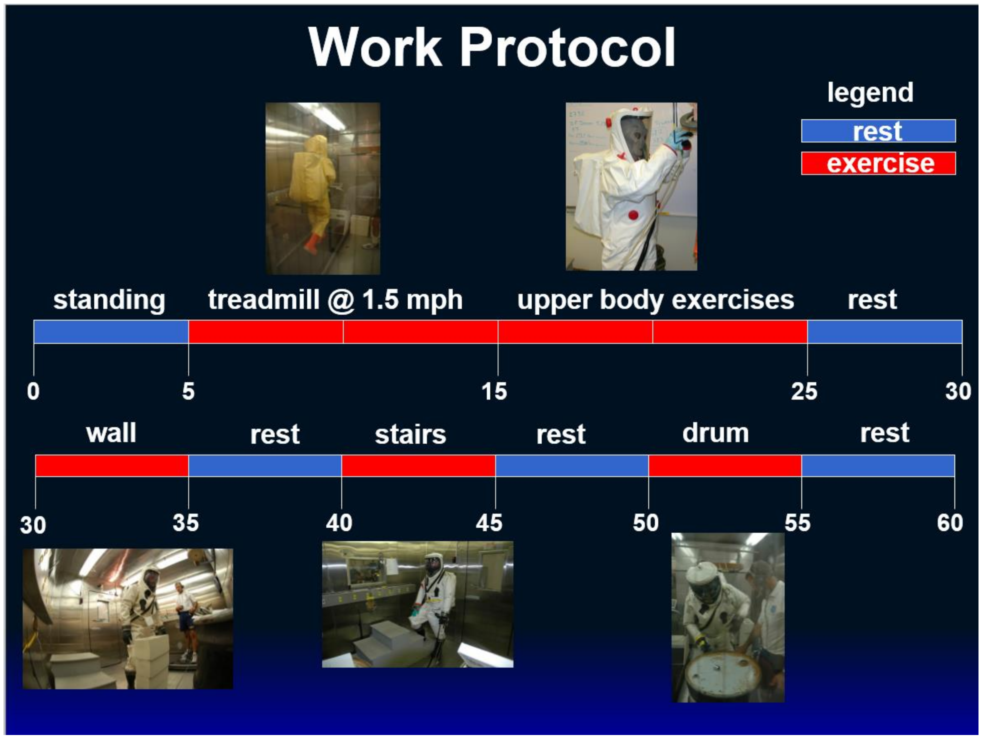

Figure 5: Work/Rest protocol for PHE/LAE comparison tests including pictures of work activities (KD Cohen, 2011)

The eight test subjects that performed the work/rest protocol were monitored for core body temperature, cardiac stress, and sweat loss during the test. Core temperature was measured using an ingestible telemetric pill that transmitted data to a cordless, handheld monitor. Cardiac function was monitored through the use of a basic 3 lead EKG system taped to the subject’s chest. Sweat loss was measured by weighing the subjects immediately before donning the suit and immediately after de-suiting. The test subjects were also closely watched for signs of stress by an observer in the environmental chamber. The protocol was terminated when a subject's core body temperature reached 102° F or if the subject reached 90% of their maximum heart rate. The test protocol with the LAE was paused at 40 minutes to change the SCBA compressed air cylinder (KD Cohen, 2011).

The testing concluded that, despite the additional weight of the PHE, the test subjects demonstrated significantly lower core body temperature and heart rate increases, and decreased sweat loss while using the PHE than when using the LAE. Six of the eight test subjects reached the maximum core body temperature and could not complete the work/rest protocol while using the LAE. All eight test subjects completed the protocol while using the PHE. Post-trial LAE heart rates were 78.0±7.0 beats/min above baseline, while in PHE, post-trial heart rates were 31.2±6.3 beats/minute above baseline (p=0.0078). Changes in core temperature, as illustrated in Figure 6, were also significantly different (p=0.0078) between the suits (core temperature increased 2.6±0.2°F in LAE vs. 1.2±0.1°F in PHE). These results indicate that the PHE provides significant protection from heat stress and allows the worker to spend more time on station with equivalent chemical protection when compared to the LAE (KD Cohen, 2011).

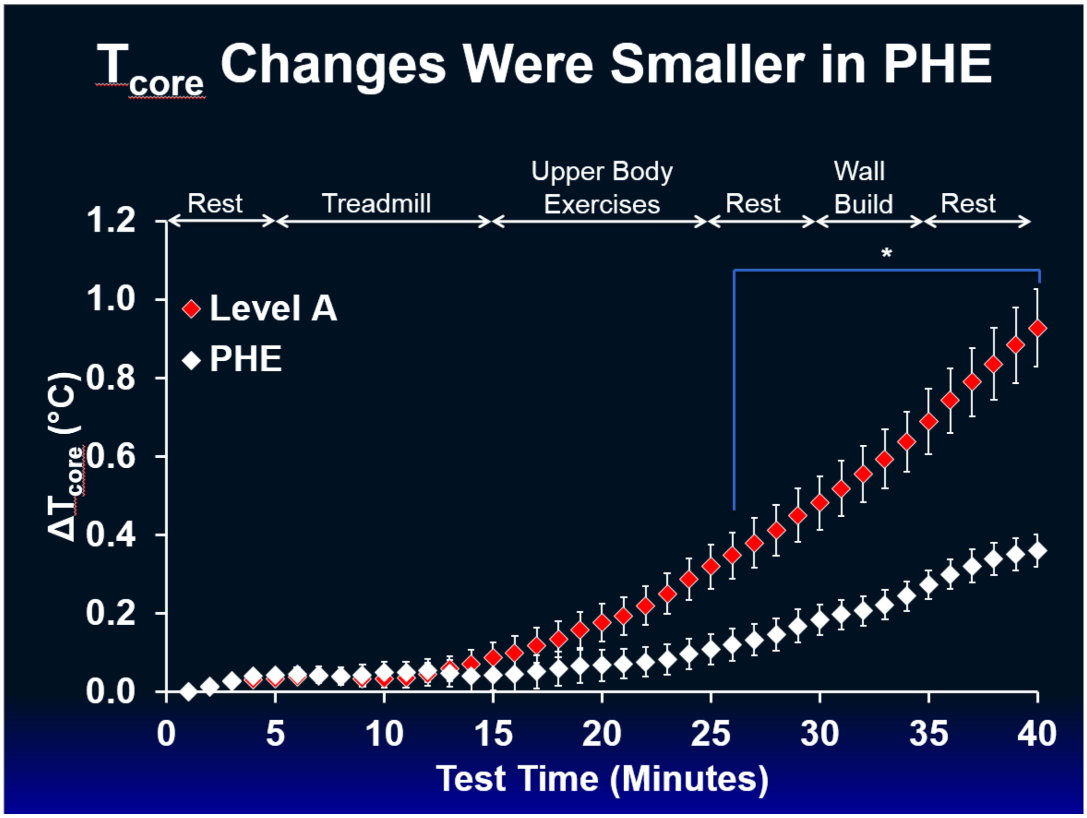

Figure 6: Core temperature increases; LAE in red, PHE in white (KD Cohen, 2011)

4. The CryoRASS Project

The Mine Improvement and New Emergency Response (MINER) Act of 2006 requires the operators of underground coal mines to provide refuge alternatives and to train mine workers on their use. These refuge alternatives must, among other requirements, provide breathable air and harmful gas removal for the occupants for up to 96 hours. Standard designs for these chambers use bottles of compressed oxygen for breathable air and chemical "scrubbers" for the removal of exhaled carbon dioxide (CO_2). In the United States, these chambers are normally portable and range in capacity from 12 to 36 occupants (Gillies et al; 2012).

Due to the limited space available in an underground coal mine, the size of the refuge chamber is minimal with respect to its occupant capacity. Internal conditions can quickly deteriorate if some sort of climate control is not incorporated into the refuge design. In a twelve person refuge chamber, mathematical modeling indicates that humidity saturation will occur in the first minute of full occupancy and temperature stabilizes at 76.8°F within the first hour in a 55-60°F ambient environment. This model ignores heat generated by exothermic CO_2 scrubbing processes that could contribute up to 11% of the total chamber heat. The only moisture removal method considered in the exercise was condensation formation on the interior chamber walls. These conditions (76.8°F and 100% relative humidity) result in an apparent temperature of approximately 88°F (Gillies et al; 2012). Although this apparent temperature is not inherently dangerous, the conditions listed above combined with very limited space to move or stretch could result in significant stress on the workers during prolonged refuge occupancy.

Figure 7: Cryogenic Refuge Alternative Supply System (CryoRASS) unit (Doerr D. , 2013)

The CryoRASS project is an attempt by the BRL to simplify and expand the capabilities of mine refuge alternatives by using liquid air as the air supply for these chambers instead of compressed air or oxygen. To this end, a 10 person Guardian Angel Refuge Alternative from Trinity Resources, illustrated in Figure 8, was retrofitted with a palletized liquid air system, shown in Figure 7, consisting of a 425 liter storage Dewar fitted with a 25 watt cryogenic cooler to maintain the liquid air temperature and minimize evaporative loss. Liquid air from the Dewar was routed into an air handler box that converted the liquid air to gas and collected the water that was condensed during the gasification process. Liquid air expands to the gaseous state in a ratio of 728:1 (gas: liquid) resulting in a supply of 309,400 liters of gaseous air from the Dewar in a package with exterior dimensions of 6’ x 4’ x 5’ (Doerr D. , 2013). This capacity is roughly equivalent to 37 k-bottles of compressed (3000 psi) air which would occupy more than twice the area used by the CryoRASS. The design of the air box also resulted in 220 liters/ minute of secondary air flow in addition to the air supplied from the Dewar. The passive secondary air

Figure 8: Trinity Resources 10 person mine refuge alternative modified with CryoRASS system (Doerr D. , 2013)

flow contributes to consistent atmospheric mixing in the chamber without the use of fans or other air handling equipment.

A test was conducted on the modified refuge chamber to measure conditions when a simulated 10 miners occupied the chamber for 96 hours. The conditions measured were temperature, relative humidity, chamber pressure, oxygen concentration, and CO_2 concentration. The chamber was housed in an air conditioned building with an ambient air temperature set at 75°F for the duration of the test. The chamber exterior was tented with plastic sheeting to prevent convective cooling of the surface from the airflow of the building's climate control system. The tent was constructed to provide approximately 3" of space around the exterior of the chamber (Doerr D. , 2013). It is noteworthy that these ambient conditions are significantly warmer than the assumed ambient temperatures of the Gillies et al. mathematical model (55°-60°F) (Gillies et al; 2012). Refuge occupants were simulated using a propane heater set at 4600 BTU/hr (Doerr D. , 2013).

Temperatures in the chamber varied throughout the test, ranging from 84°F to 87°F during the majority of the protocol. There was typically a 20°F temperature drop between the inlet and outlet of the heat exchange region of the air box. Relative humidity ranged from 43% to 64% keeping the apparent temperature within 2°-3°F of the actual temperature throughout the majority of the test. Due to concerns of incomplete mixing of "bad" and "good" air from the retrofitted air box, oxygen enriched liquid air was used to assure oxygen content in the chamber stayed between 21-23.5%. Oxygen concentration was typically 23.5% during the majority of the test. After a rapid increase in the initial hours of the test, CO_2 levels stabilized at 5.4% (Doerr D. , 2013).

Several technical issues were encountered during the test. The propane heater used to simulate the 10 chamber occupants used less oxygen (equivalent to 7.4 occupants), produced less CO_2 (equivalent to 5.5 occupants), and less water (equivalent to 2.6 occupants) than expected. This condition resulted in oxygen levels of 23.5% as opposed to the expected 21%. A primary flow meter failed about 70 hours into the test resulting in early exhaustion of the liquid air source and the utilization of a backup source to complete the test. The condensate removal system in the air box did not perform as expected and its function was seriously degraded by hour 70. This resulted in the higher humidity levels toward the end of the test (Doerr D. , 2013).

Despite the technical issues, the CryoRASS test demonstrated several major strengths of the cryogenic air supply system. The liquid air was able to supply substantial cooling capacity to the refuge chamber; water vapor condensation on the heat exchanger coils removed significant amounts of moisture from the chamber atmosphere; the system provided adequate oxygen to the refuge; and CO_2 was flushed from the chamber without the use of scrubbers. The CryoRASS system can also operate effectively without electrical power.

5. SCBA and Mine Rescue System (CryoBA/CryoASFS)

In addition to the requirement for the refuge alternatives, the MINER act also mandated that extra Self-Contained/Self-Rescue (SCSR) devices be made available to underground coal miners in addition to the SCSR already required to be carried by the miner (Mine Safety and Health Administration, 2013). SCSRs are closed circuit breathing devices that supply oxygen through a chemical or compressed oxygen source and chemically “scrub” CO_2 from exhaled air so that the user is not exposed to any toxic gasses in the ambient atmosphere. SCSRs provide one hour of oxygen and are used for escape purposes only; SCSRs are not designed for rescue or

Figure 9: Self-contained self-rescue device (SCSR) in use

firefighting operations and the user, as illustrated in figure 9, cannot speak while breathing on an SCSR (Kowalski-Trakofler et al, 2010). The additional SCSRs are required to give miners more time to reach a safe area with a non-hazardous atmosphere.

The National Mining Association (NMA) is currently encouraging a more proactive approach to mine safety and encouraging the use of more advanced systems that expand the evacuation and rescue capabilities of mines beyond SCSR dependent systems. An example of such a system has been developed by Draeger Safety Inc. and uses SCBA stations to satisfy the requirement for additional SCSRs. The concept of this system is that, in an emergency situation, a miner would immediately begin use of the belt-worn SCSR and then proceed to an SCBA station and change out the SCSR for an SCBA. The miner could then use the additional one hour air supply to evacuate or begin firefighting/ rescue operations. Additional breathing air charging stations would be positioned along egress routes so evacuating miners could refill their SCBAs if necessary. Draeger recommends that the SCBAs used in this system be refilled every 30 minutes to provide a safety margin. The charge stations are designed to service the SCBA while still in use by the miner. The SCBAs require 4500 psi air to provide one hour of breathing time. This system is promoted by the manufacturer to improve safety through better communication, since the miner can talk while wearing the SCBA, and the earlier commencement of firefighting and rescue operations (Gaggin, 2012).

Early in the Space Shuttle program, it was discovered that standard commercially available SCBA technology was inadequate for Shuttle pad fire and rescue operations. To accommodate variation in air consumption by rescue workers, time on station with a standard SCBA was limited to 30 minutes to assure adequate reserve air. The standard SCBA also did not provide any heat stress relief. A liquid air SCBA was developed from the ECU used with the PHE that provided a one hour time on station capability, and 55°F air for some heat stress relief. These liquid air SCBAs have been in use at Kennedy Space Center for over 27 years without any failures or mishaps. It became apparent to the NASA/ KSC BRL that this proven technology could have commercial applications, particularly in the mining industry (Doerr et al, 2013).

Figure 10: Cryogenic Breathing Apparatus (CryoBA) pack (Doerr et al, 2013)

The CryoBA program is an advancement of the current liquid air SCBA design that improves the capability and usability of the unit.   The new design, shown in Figure 10, is a dual tank system that has demonstrated up to 2.5 hours of air supply in preliminary testing. The earlier liquid air SCBA design revealed some liquid intake issues when user attitudes exceeded 70°-80° past vertical. CryoBA addresses the intake issue with an updated pick up system that has not been affected by attitudes of +/- 90° of vertical. Mask pressure machine testing per NIOSH protocols has been completed on this system and human testing that complies with 42CFR part 84 NIOSH certification test requirements is currently in progress (Doerr et al, 2013).

The CryoBA unit is part of a liquid air mine rescue and evacuation system that could advance the state-of-the-art beyond compressed air based systems similar to the Draeger system described above. In the event of a mine emergency, workers would use their SCSR until they could reach a CryoBA station. The worker would then service the CryoBA from the liquid air Dewar in the station. Servicing would take about 6 minutes and the worker could breathe from the CryoBA mask as soon as air began to flow into the unit (Bush interview, 2014). As mentioned earlier, the CryoBA will provide cool air to the user to reduce heat stress while still having the communication and flexibility advantages of a standard SCBA. The miner would then have 2 hours to evacuate the mine, begin firefighting and rescue operations, or locate a Cryogenic Air Storage and Filling Station (CryoASFS) that had been stationed along the evacuation route and re-fill his CryoBA (Blalock et al, 2012).

The CryoASFS, shown in Figure 11, is a liquid air servicing station designed to initially fill and refill CryoBA units and provide storage for liquid air at strategic locations throughout the mine. The prototype unit consists of a 425 liter Dewar equipped with a "Cryorefrigerator" to prevent unequal evaporation of the liquid air and the subsequent oxygen enrichment. The current iteration of the CryoASFS has the capacity to perform 4 simultaneous CryoBA fills 8 times, however the goal for an operational system is for 10 simultaneous fills 4 times. The CryoASFS will require electrical power for the Cryorefrigerator but the Dewar has enough passive insulation capacity to maintain the air supply for several days and the station can service CryoBA units without any external power (Blalock et al, 2012).

Figure 11: Cryogenic Air Servicing and Fill Station (CryoASFS) filling a CryoBA pack (Doerr et al, 2013)

The CryoBA/CryoASFS system has several significant advantages over similar compressed gas systems. Due to the compact nature of liquid air, the CryoASFS units have a substantially smaller footprint than equivalent compressed air stations. Cryogenic systems operate at pressures of less than 100 psi, compared to 4500 psi for compressed air systems. The lower pressure presents a much lower risk level in the event of damage to the unit. The 2 hour air supply of the CryoBA means that fewer refilling stations are required, resulting in an even smaller system footprint with no loss of capability. Finally, the cool air provided by the CryoBA will reduce the heat stress experienced by the worker in an already challenging environment.

6. Technical Challenges Associated with Liquid Breathing Air Systems

There are several technical challenges involved in the use of liquid air as a supplied air source. These issues must be addressed if cryogenic air sources are going to be a viable option in the respiratory protection market. The major challenges facing these systems are: differential evaporation of stored liquid air and subsequent oxygen enrichment; the efficient sampling and analysis of stored air; and the production of safe, liquefied breathing air. Fortunately, these issues have already been experienced at KSC and much of the testing of some viable solutions has been completed.

During the Space Shuttle program, liquid air was used in much larger quantities than are required by the current operational tempo. The liquid air is normally produced in 5000 gallon lots (Doerr et al, 2013) and during Shuttle operations this quantity was used before differential evaporation and oxygen enrichment became an issue. The decline in propellant handling activities led to large quantities of cryogenic breathing being discarded due to oxygen

Figure 12: Zero Loss Dewar prototype (Goetzfried & Madgett, 2012)

enrichment. To reduce waste, the BRL began testing of a 300 liter Dewar equipped with a Cryomech AL25 Cryorefrigerator; shown in Figure 12. This device is inserted into the modified Dewar and uses a high purity helium compressor to recondense the boiled off liquid air inside the tank; keeping the oxygen concentration in the Dewar between 19.5-23.5%. The system operates automatically based on the pressure inside the Dewar; when the high pressure setting is reached, the device activates and condenses the boil-off until the low pressure setting is achieved and then shuts off. The oxygen concentration levels documented in a three month test of this “Zero Loss” prototype illustrated that the system could maintain oxygen levels within 2% of the original value throughout the test period. This technology has been integrated successfully into the CryoRASS and CryoASFS prototypes (Goetzfried & Madgett, 2012).

In order to determine the correct mixture of nitrogen and oxygen in the liquefied breathing air that will be used by workers, the air must be sampled and tested. The current standard process involves the use of a “Cosmodyne Cryogenic Sampler”, requires 10 liters of liquid air to complete, and takes 75 minutes total to produce results. BCS Life Support, a commercial partner of the NASA/KSC BRL, developed a system that uses less than one liter of liquid air and required only five minutes to obtain results. Testing at the KSC Life Support Facility and subsequent linear analysis of the paired data demonstrated that results between the two techniques were “essentially similar” (Blalock, 2014). This new technique represents a potentially significant material and man hour savings.

The manufacturing of liquid air is not a common industrial process. The technique implemented at Kennedy Space Center uses liquid oxygen and liquid nitrogen tankers connected to a liquid air trailer using an orifice controlled "Y" fitting. This method, illustrated in Figure 13, is relatively simple and cost effective but it does depend on the availability of breathing quality cryogenic oxygen and nitrogen. The adaptation and use of an "commercial off-the-shelf" (COTS) system to manufacture and store cryogenic air at the site of use in a cost effective manner is one of the areas in cryogenic supplied air research that would benefit from further study.

Figure 13: The production of liquid breathing air from liquid oxygen and liquid nitrogen tankers (Doerr et all, 2013)

7. Future Research

There are two technical issues with cryogenic air systems that will need to be addressed in future research. Quantity indication systems for liquids that are carried by the user are challenging, especially in cryogenic conditions, and the current CryoBA prototypes have no means to show air supply quantity to the operator (Doerr D. , 2012). The ability to manufacture liquid breathing air on a worksite without the support of cryogenic oxygen and nitrogen tanker trucks would greatly contribute to the economic viability of liquid supplied air breathing systems. The BRL currently has plans to investigate the use of a Cryorefrigerator, similar to those used in the CryoRASS and CryoASFS systems but with a greater capacity, to actually produce liquid air on the worksite (Goetzfried & Madgett, 2012). These issues do not represent major challenges and will hopefully be solved quickly when resources permit.

8. Conclusion

Although some technical issues still need to be overcome before these liquid supplied air respiratory protection systems can be safely used in the general and mining industries, the concept represents a potentially major advance in the current state-of-the-art. Cryogenic supplied air systems are a proven technology that have been field tested in various configurations for over 30 years. These systems can improve worker safety through reduced working pressures, increased air supplies with no increase in supply footprint or pack size, and heat stress relief capabilities. Cryogenic air supply systems can also decrease the air supply footprint in work areas, particularly mines, with limited space without a loss of capacity or capability. The liquid air mine rescue and evacuation system uses smaller air refill stations with greater air supply capacity when compared to compressed air systems and fewer stations are required. Mine refuge alternatives with liquid air supplies can also provide more space for the occupants without increasing the refuge size. NIOSH has recognized the potential of cryogenic supplied air technology and the MINER Act of 2006 implemented new regulations that allow for the certification of non-compressed gas solutions to respiratory protection problems in mines (Bush, 2012). A large amount of the research and testing required to certify these systems to NIOSH standards has already been completed so the risk and expense to industry of pursuing this technology has been minimized. The changes in mining regulations, the existing NASA technology and experience, and the research funded and supported by NIOSH have come together to make cryogenic supplied breathing air a viable and feasible alternative to compressed breathing air.

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