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OMSHR's EFFORT ON THE NEXT-GENERATION CLOSED-CIRCUIT MINE ESCAPE RESPIRATORS

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ABSTRACT

The Office of Mine Safety and Health Research (NIOSH-OMSHR) currently is leading an effort in the development of the next-generation self-escape apparatus as part of the research imperative directed by the MINER Act of 2006. A multifaceted contract program over the past 3 years delivered key components and base breathing modules to form the basis for developing backpack and vest-style versions of dockable self-contained (closed-circuit) self-escape respirators with hoods (CCMERs). This paper outlines the current status in developing the CCMER that incorporates a docking and switch-over valve (DSOV) for seamless transfer from one breathing device to another, and a hood with an inner mask and speech diaphragm (HMC) for ease of donning, ease of use, and communication ability. Three versions of the CCMER are being pursued, namely: the CCMER-B, which can be worn as a backpack and incorporates the features of a miner's belt; the CCMER-V, which is worn similar to a miner's vest and attaches to a miner's belt; and the CCMER-C, a breathing module cached along the escape route that can be docked to the -B and -V versions. Human factors considerations are a key element in the CCMER design, as it is to be continually worn by the miner while underground, and must be readily accessible for deployment when needed. The CCMERs are designed to be capable of being certified to 42 CFR part 84 standards, including sub-part O for mine use, and to meet MSHA permissibility regulations for use in underground mines. They are sized for sufficient oxygen capacities (Cap 2 and Cap 3 as defined in sub-part O) to yield a duration that is of practical use in a mine escape scenario.

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research (OMSHR) is leading the development of self-escape apparatuses to provide breathing gas to mining personnel operating in the event of an emergency in various capacities underground in environments containing hazardous gas components. The Mine Improvement and New Emergency Response Act of 2006 (also known as the MINER Act) and input from the mining community called for the need to move Self-Contained Self-Rescuer (SCSR) technology to a next-generation status. In response to this need, NIOSH's Office of Mine Safety and Health Research (OMSHR) established a strategic plan to develop key components and devices with help from external experts knowledgeable in breathing apparatus designs. The US Navy was identified as a key expert in this field through its extensive experience in diving apparatus and life support systems, and development work commenced through Inter-Agency Agreements with OMSHR. A contracts program was also launched with industry experts specializing in this field. This paper outlines the current status in developing the **Next-Generation Closed-Circuit Mine Escape Respirators (CCMERs)** that could be used for surviving and escaping from a mine following an emergency that renders the mine atmosphere irrespirable.

NEXT-GENERATION CCMER DESIGNS

CCMERs need to be designed so that they can be carried comfortably and worn continuously by miners during their daily work routine as well as function as an escape breathing apparatus in the event of an emergency. The CCMER should also be designed and manufactured as a closed-circuit oxygen rebreather, whereby the user breathes the same gas in a closed loop similarly to the current units in use in underground coal mines. This is the most efficient type of breathing apparatus and therefore lends itself to a small size which can be carried by a miner at all times underground. In this type of design, exhaled carbon dioxide (CO_2) is absorbed by a scrubber system and oxygen is added according to the user's metabolic needs. The oxygen addition may either be mechanically or electronically controlled and supplied from a gaseous or chemical source. Importantly, the CCMER must be certified to 42 CFR part 84 standards including sub-part O for mine use, and must meet MSHA 30 CFR Part 75 and 30 CFR Part 18 permissibility regulations. The design(s) must be jointly certified by both NIOSH and MSHA for use in underground mines in the US. The capacity of the units should be Cap 2 and Cap 3 as defined in sub-part O to meet mining requirements. The CCMER must incorporate docking and switch-over valves (DSOVs) for seamless transfer from one breathing device to another, and hoods with inner masks and speech diaphragms (HMCs) for ease of donning, ease of use, and communication ability.

In the design specifications, due consideration must be given to minimize size and weight of the device, resulting in a small package that can either be donned separately or integrated into a miner's ensemble. Due to the necessity of being continually carried by the miner while underground and being readily accessible for deployment when needed, the device must also be designed with ergonomic considerations in mind. Further, the -B & -V version CCMERs need to be designed with many of the tool-holders, pouches, and attachment points currently utilized by miners in their day-to-day work environment. Finally, features such as mini-gauges for determining oxygen cylinder pressure and indicators for the CO2 scrubber monitoring during routine maintenance/inspection should also be incorporated per NIOSH 42 CFR part 84.

With the above design specifications and constraints in mind, three versions of the CCMER are under development by OMSHR as described below.

CCMER-B (Backpack-Style Closed-Circuit Mine Escape Respirator)

The CCMER-B is worn like a backpack on a harness that has the same features (e.g. tool holders and pouches) as a miner's belt. The breathing module consists of the CO2 scrubber material, oxygen supply/delivery system, and the breathing loop. The entire system is attached to the harness assembly and positioned at the lower back. In the event of an emergency, the miner pulls on a release line that starts the oxygen flow and deploys the breathing hoses for a rapid donning of the apparatus. During the donning process, the miner does not need to remove the unit nor the miner's hat. The CCMER-B will incorporate a DSOV and HMC. It is envisioned that it will be sized for both a Cap 2 half-hour and Cap 3 one-hour duration. There will be at least three sizes of the harness assembly that fit the breathing module when the final version is produced.

CCMER-V (Vest-Style Closed-Circuit Mine Escape Respirator)

The CCMER-V is worn like a vest and attaches to the standard miner's belt. The CO_2 scrubber material is distributed within the vest's breathing loop to make the respirator more conforming to the body shape when worn. The vest is attached to the miner's belt and uses gaseous oxygen stored in a high-pressure cylinder in a fixture attached to the miner's belt. The breathing hoses are packed away in a pocket to be deployed easily by the miner in an emergency. The CCMER-V will incorporate a DSOV and HMC. It is envisaged that it will be sized for a Cap 3 one-hour duration and there will be at least three sizes of this vest style for the miners when the final version is produced.

CCMER-C (Cached Circuit Mine Escape Respirator)

The CCMER-C is a portable breathing module consisting of the CO_2 scrubber material, oxygen supply/ delivery system, and the breathing loop terminating at a connection to fit to a docking valve on the -V and -B versions. A carrying handle and a shoulder strap will be fitted to the CCMER-C to enable the user to carry it when in use. This module would be located along the escape route in caches so that miners can transfer to it when the donned unit is almost expended.

To deploy the CCMER-C, the miner opens a cover and extracts the breathing hoses, starting the oxygen flow in the process, and connects to the docking valve of the unit in use. The miner then switches over to the CCMER-C and disconnects the spent unit before resuming the escape. It is envisaged that only one size of the -C version will be needed for Cap 3 two-hour duty, as the module can be exchanged multiple times during the escape.

PROOF-OF-CONCEPTS

A proof-of-concept evaluation was conducted to identify potential solutions and then select the best options for future prototype designs. Components common between the different CCMER versions were lithium hydroxide (LiOH) polymer bonded sheets for the CO_2 absorbent and carbon composite high-pressure cylinders for the O_2 supply, as these were identified as the best options for this application through an initial study. Some key findings were that using LiOH sheets in the breathing loop offered less breathing resistance, weighed less, lowered peak-to-peak pressures and prevented absorption degradation due to vibration. Although LiOH typically produces higher breathing temperatures, further design of the sheets allowed for similar temperatures to using calcium hydroxide. Proof-of-concept models, also known as engineering development models (EDMs) were then constructed to undergo tests on a metabolic simulator. These EDMs did not have any DSOVs nor HMCs attached as the main objective was to optimize the breathing module of these devices. Also, oxygen was supplied from a facility storage source with the O_2 cylinder being used only to determine the form of the device.

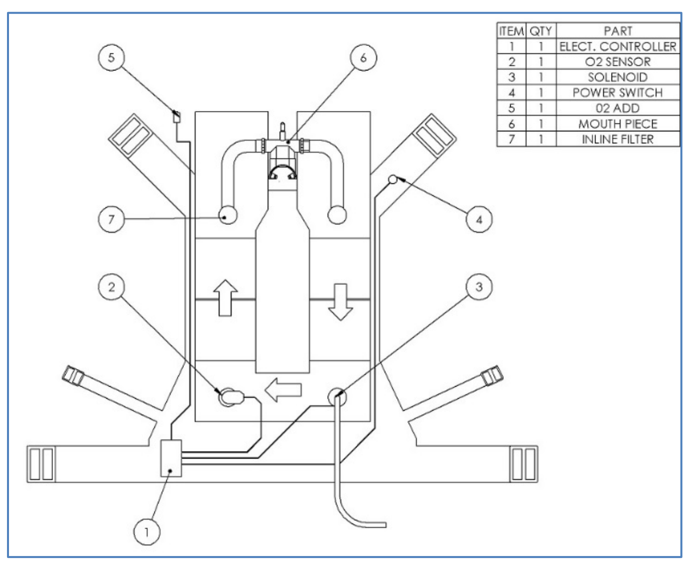
Twin breathing bags were used in all three designs to reduce the maximum gas velocities in the absorbent beds, therefore increasing the dwell time to allow for better CO_2 removal efficiency. Also, due to the increased surface area available, more heat was removed from the breathing loop. The breathing hoses formed an integral part of the bags in the -B and -C versions. These hoses were specially constructed as a series of attached discs that would pack tightly when collapsed and stretch a distance of approximately 15 times the collapsed length when extended for use. These hoses were averse to kinking when stored or deployed. The hoses for the -V version were rigid and attached to the breathing bags through connectors.

The CO_2 absorbent canisters for the -B and -C versions were in the form of a rectangular box with one (broad) side forming the baseplate that attached to the harness in the case of the -B version and handle/carry strap in the -C version. The thicknesses of these boxes were set by the diameter of the O_2 cylinder already developed and selected for these devices. In the -V version, CO_2 sheets are formed into blocks and distributed within a casing that is part of the breathing loop inside the vest cover.

All versions were fitted with T-Bit mouthpieces to attach to a metabolic breathing simulator for testing. The oxygen delivery system for the -B and -C designs added oxygen via a pressure activated mechanical demand regulator in the breathing loop mounted on to the canister. The -V design employs an electronic oxygen dosage system where the oxygen level in the breathing loop is maintained within allowable limits by monitoring the oxygen concentration with a sensor and dosing the required amount via a solenoid-operated valve triggered by an electronic control circuit. All versions are supplied from the external oxygen source mentioned above.

The housings for the -B and -C EDMs were rapid prototype printed out of plastic material and consisted of the baseplate with the integrated scrubber canister and a cover which closes over the baseplate similar to a clamshell. A quick release mechanism on the –B version operated by the user pulling on a line located in the shoulder strap releases the cover, deploys the breathing hoses, and starts the oxygen flow simultaneously in a single continuous motion. The housing (jacket) on the -V EDM encases the breathing loop and the oxygen delivery system except for the cylinder (which is attached to the belt) in a conformal vest form. A quick deploy method is yet to be developed for this version. The EDM of the backpack style and schematic of the vest style are shown in figs. 1 and 2.

Figure 1. EDM of backpack-style CCMER showing the breathing loop components and high-pressure cylinder.



ITEM	QTY	PART
1	1	ELECT. CONTROLLER
2	1	O2 SENSOR
3	1	SOLENOID
4	1	POWER SWITCH
5	1	02 ADD
6	1	MOUTH PIECE
7	1	INLINE FILTER

Figure 2. Schematic of the vest-style CCMER identifying the major components.

HUMAN FACTORS CONSIDERATIONS

In the design of a breathing apparatus, the form, fit, and function are the three main factors to be considered for a successful outcome. The "function" is driven by the design specification which in this case relates to the NIOSH standard 42 CFR part 84 and is proven by testing. The "fit" drives the "form" and directly impacts the user's interaction with the apparatus. Consideration of both these factors leads to an ergonomic and wearable device.

Human factors considerations were applied at the start for all of the designs with input from experts within OMSHR's Human Factors Branch. Starting from the 5 percentile female as the most challenging form, the sizes chosen were Small/Medium and Large/XLarge for developing the EDMs. In the course of refining the EDMs, ergonomic improvements impacted the weight distribution, vest shape, harness and belt designs, oxygen cylinder placement, and deployment of the devices. The EDMs were shown to experienced miners at key stages in the iterative development process to get their feedback on the designs for continuous improvement. Overall, the general fit of the EDMs was improved through to the final versions.

Figure 3. EDM of backpack-style CCMER showing the ergonomically designed harness assembly incorporating the miner's belt.

TEST RESULTS FROM EDMS

Many tests were conducted on the proof-of-concept EDMs, improving their design in a series of iterative steps to arrive at optimized models to lead into producing prototypes. The baseline for the tests was to subject the EDMs to work rates in the capacity and performance criteria while trying to meet the stressor limits in NIOSH 42 CFR part 84 subpart O (42CFR84-O). Further, some tests were conducted to criteria specified in US Navy standards for comparison with other breathing apparatus designs. Data was obtained for four stressors required for this type of apparatus, namely inspired O_2 and CO_2 levels, inspired temperature, and the maximum peak-to-peak breathing pressures given by the Work of Breathing (WoB) result, which is a more complete measurement of the resistive effort when testing closed-circuit apparatuses such as these designs.

EDM of CCMERs -B and -C

The breathing loop and oxygen delivery systems in both the -B and -C versions are essentially the same, with the differences being in the duration, size, and carrying method. The duration can be engineered by selecting the oxygen amount supplied from a cylinder coupled with carbon dioxide removed using absorber material.

After testing three formulations and geometries of LiOH absorber sheets, the most efficient was selected as the standard for all testing. For the oxygen supply, two high-pressure carbon composite cylinders containing nominally 70 and 100 liters of oxygen are available at a working pressure of 3,000 psi (and in the future to 5,000 psi) for designing the final CCMERs as Cap 2 and Cap 3 devices as defined in 42CFR84-O. The EDM duration was targeted at one hour and the CO_2 absorber block was calculated and sized for this duration.

Upon testing, 0.5 volume % CO_2 was reached in the breathing loop only after 60 minutes. This gave the data to initially size the scrubber to the required duration. The results from the breathing resistance and temperature requirements to meet the standard will also influence the final size and shape of the LiOH scrubber. The inspired temperature reached steady state value in about 15 minutes into the tests. The temperature remained at or above the maximum allowable limit of 109^0F for the entire duration. Heat exchanger material in the mouth T-bit area lowered the temperature below the limit to about 100^0F, indicating that some additional material is needed for these designs to help with heat removal.

The effort needed to circulate the gas through the breathing loop is given by Work of Breathing (WoB) measurements. The peak-to-peak pressure limits stated in the 42CFR84-O standard can be read off the WoB chart loop for complete inhalation and exhalation cycles. Design of all internal passages in the breathing loop (wetted areas) influences the WoB; therefore WoB tests are critical to the form and function of the device. It is expected that the WoB increases as the work rate increases. Overall the WoB was low with the peak-to-peak pressures approaching the maximum differential pressures of +/- 200 mmH_2O only at the peak work rate of 65 L/min RMV at 0°C and 760mmHg.

EDM of CCMER-V

The EDM duration was targeted at one hour and the same (most efficient) formulation of LiOH absorber sheets as above was used in the vest-style EDM. These were smaller blocks distributed inside the breathing loop in the vest as opposed to one single block for the -B and -C versions.

Different configurations of 2 and 4 blocks were tested to gauge the best arrangement for CO_2 absorption. Results showed that absorption capacity was greater than required at the Cap 3 capacity work rate according to 42CFR84-O for the targeted 60-min duration with four blocks placed symmetrically inside the vest. Further tests indicated that the design can be optimized to reach the required duration with two blocks by slightly increasing their weight. The average inspired temperature remained at or below the maximum allowable limit during the capacity tests, but exceeded the limits during the performance tests as specified by 42CFR84-O.

Heat exchanging material was added at different positions inside and outside the vest to remove or redirect the heat. The best results occurred when the material was placed inside the breathing loop casing adjacent to the scrubbers, but this also increased the WoB. The peak-to-peak pressures were within the limits of the NIOSH standard for the capacity tests at 30 L/min RMV and the performance tests, although they increased with heat exchanger material in the loop, as shown by the WoB results. To test its response to oxygen demand from the breathing loop, the electronic oxygen dosage controller was set to 25% and 30% set points for each of the minimum and maximum respiratory minute volumes (RMVs) i.e. 20 L/min (low) RMV for 5 mins, and 65 L/min (peak RMV) for 10 mins. The controller maintained the vest loop O_2 concentration, averaging about 31% at both work rates for set point 25%, and about 36% at both work rates for set point 30%. The oxygen capacity was calculated as 88 liters for a one-hour duration at an RMV of 30 L/min, 25% oxygen set point, and 1.35 L/min oxygen injection rate.

CONCLUSIONS

- The EDMs are capable of Cap 3 duty for a one-hour duration in a wearable form and are scalable for half-hour (Cap 2) and two-hour durations.
- Lithium hydroxide substrate in a sheet form, optimized for this application, was used for CO_2 absorption. The performance in controlling the CO_2 levels was proven and the tests gave valuable data for sizing the scrubber for the desired duration.

- Heat generation was the greatest concern with the inspired temperature at or above the allowed threshold during operation. Addition of heat exchanging material helped to reduce the temperature, but increased the WoB. Heat mitigation needs to be addressed in the prototype development.
- The peak-to peak pressures (using WoB data) was below the limits in all except one configuration. The highest work rate for the vest EDM with the heat exchanger exceeded this parameter.
- Both mechanical and electronic oxygen delivery systems were tested and functioned to maintain the breathing loop oxygen concentration above 19.5% by volume. Gaseous oxygen was supplied from high-pressure cylinders.
- All EDM versions of the CCMER have been optimized from a human factors standpoint with a few improvements remaining to be made at the prototype stage.

RELATED INTERNAL REPORTS

1. Toole, Brian and Cornman, Jacob (2014) “Mine Escape Breathing Apparatus (Task 1 Proof of Concept) report”, Inter-Agency Agreement Number 13FED1313301 with Naval Surface Warfare Center - Panama City Division

2. Juergensen, Kevin (2015) “Closed Circuit Escape Vest (CCEV) Milestone Report 9 and 10”, Contract # 200-2013-M-57270