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TECHNOLOGIES FOR THE NEXT GENERATION CLOSED-CIRCUIT ESCAPE RESPIRATORS

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Abstract

The National Institute for Occupational Safety and Health (NIOSH) National Personal Protective Technology Laboratory (NPPTL) is leading an effort to develop the next generation of self-escape breathing apparatus for egress from confined spaces in emergency scenarios. A backpack style closed-circuit mine escape respirator design was one configuration explored as part of the research imperative directed by the 2006 MINER Act. Stakeholder feedback from MSHA and at the NIOSH Breathing Air Supply Partnership Meeting indicated a smaller belt worn unit that does not sacrifice performance is desirable. This paper outlines some further technology advancements that may be investigated toward developing such a small-sized respirator. Technologies being considered are novel chemicals for improved carbon dioxide (CO_2) absorption and oxygen (O_2) production, eliminating a dedicated CO_2 scrubber by incorporating its function in the spaces of the respirator's breathing loop and storing O_2 in a liquid form with long standby capabilities. When these technologies are applied to a future design, there is the possibility of having an escape respirator that can be belt worn and capable of being certified to 42 Code of Federal Regulations (CFR) Part 84 standards, including sub-part O for escape purposes including mine escape.

BACKGROUND

NIOSH NPPTL has a Research and Development effort to provide mine workers with state-of-the-art breathing air technologies to comprehensively support initial and continued self-escape, refuge alternatives, and rescue needs, resulting from mine emergencies. As part of this R&D effort, NIOSH invested in the development of a next-generation closed-circuit mine escape respirator (CCMER) which would be compliant with NIOSH's respirator standard requirements, 42 Code of Federal Regulations Part 84, including sub-part O. The design features of the CCMER also address the MINER Act's requirements for transitioning between devices without the need for doffing the initially donned device. It would also allow for improved protection when using voice communications with a donned device [Ref.1.].

A breathing apparatus using the closed-circuit re-breathing principle offers the most efficient means of providing oxygen to a user. Using this principle, where the breathing gas is reconditioned and recirculated to the user in a closed loop allows for the design of a smaller breathing apparatus for a stated oxygen capacity than its open circuit counterpart, where the gas is exhausted to the ambient in every breathing cycle. The backpack CCMER is a closed circuit breathing apparatus whose breathing module was tested to conforming to the performance requirements of 42CFR Part 84 Subpart O for Cap 3 – 80L oxygen supply for one hour use at 1.35 L/min. oxygen consumption rate. It must be noted that the duration can change for different users due to the variability of oxygen consumption between users. This CCMER weighs approximately 10 lbs. with a harness/belt, docking/switchover valve and a Facepiece included. The breathing module dimensions are 10” wide × 7” tall × 3” thick excluding the harness/belt assembly and the space allocated to store the Facepiece and docking valve. The breathing module consists of the oxygen delivery system comprising an oxygen cylinder and multi-stage pressure reducing mechanisms. Oxygen is delivered according to the metabolic needs of the user into a breathing loop consisting of the breathing hoses, breathing bag and chemical CO_2 absorber. The user interface is through a Facepiece equipped mouth bit incorporating docking connections to the hoses. Prototypes of a backpack style CCMER with these features, having minimum impact on the underground mineworker when worn continuously, are under development [Ref. 2.]. This design was for initial escape from the working face and it is anticipated to be deployed quickly when needed, and worn comfortably in an un-deployed state at all times during their normal job functions. Feedback received from stakeholders indicated that it is desirable that the worn CCMER meet the requirements stated above, is more compact, belt wearable, and compliant with 42 CFR 84, subpart O. The initially worn CCMER is the first unit that the mineworker would use to isolate from the ambient in case of an irrespirable atmosphere. This unit needs to be worn by the mineworker or kept within 25ft according to the Mine Safety and Health Administration’s (MSHA) regulations.

TECHNOLOGY ADVANCEMENT

In a closed-circuit breathing apparatus design, the breathing module offers the best opportunity for size reduction through further technology advancement. Parts of a breathing apparatus that are more difficult to reduce in size are the harness/belt and Facepiece as the design of these are directed by the fit on the user and the carrying method. Currently approved CCERs do not use Facepieces, but use a mouthpiece, that prevents verbal communication after donning.

In the case of the CCMER prototype (Fig. 1), the harness and belt were already optimized by using proven lightweight and durable materials used in the industry for such purposes. The belt also doubles as a miner’s belt, eliminating the need for wearing a separate belt to carry tools and equipment needed for the job function. The Facepiece provided for ease of donning and communication ability, the docking valve to connect and switch to subsequent units during escape, and the breathing module are inside the backpack enclosure. The prototype backpack CCMER under development is ergonomically designed to be worn comfortably by mineworkers in an undeployed state when carrying out his/her normal job routines.

The breathing module (Figs. 2 & 3) consists of the Oxygen Delivery System (oxygen cylinder, pressure reducer, and demand valve) and the Breathing Loop (CO_2 absorber canister, breathing bags, and hoses). In order to reduce the size of the breathing module while retaining its capacity (operational duration), it will be necessary to examine each of its components and determine the potential for making these smaller, thereby contributing collectively to making the complete module smaller.

Size reduction can be achieved by improving the efficiency of components, incorporating the function of components within other components, replacing components with alternate designs or eliminating them altogether. There are a number of design challenges that must be solved in order to reduce the size of the breathing module with one of the initial tasks being to conduct basic research into some of the promising concepts that are identified. The size reductions to the breathing module can be applied not just for the CCMER, but to any Closed-Circuit Escape Respirator (CCER) or even in general to a Closed-Circuit Breathing Apparatus (CCBA), that is not used for escape purposes.

Novel Breathing Gas Chemicals

Novel chemicals for breathing apparatus are being researched at NIOSH by chemistry experts [Ref. 3.]. The objective is to investigate new materials and/or combinations of materials that increase the chemical absorbent capacity of either self-contained or filtering self-rescuers. The chemicals can also be used in Refuge Alternatives in mining and military applications. Currently closed-circuit devices use Soda Lime ($Ca(OH)_2$) with additives or Lithium Hydroxide (LiOH) with additives for carbon dioxide absorbents, Potassium Dioxide (KO_2) (aka. Potassium Superoxide) or Sodium Chlorate ($NaClO_3$) for oxygen generation, and Hopcalite (CuO/MnOx) or precious metal catalysts on supports for Carbon Monoxide (CO) oxidation. Chemical research in the past two decades has identified numerous novel materials, including nano-structured and high surface area catalysts which improve the chemical performance of device components. Chemical performance is measured and reported as molar capacity (moles of gas produced, absorbed or oxidized per kilogram material) and as volume capacity (liters of gas/kg). Candidates that show high capacities relative to the reference materials will be selected for further investigation. These candidates will also have superior measurable chemical properties which may include a greater affinity for reactants, higher concentrations of active sites, higher surface areas, differing chemical mechanisms with less toxic products, or greater absorbent capacity per unit mass. It is expected that novel chemicals for improving the efficiency of CCERs will be available in the near future, therefore contributing to their size reduction.

Replacing Components for size reduction of a CCER

The oxygen storage container is one component that could be replaced with a smaller more efficient unit. The oxygen is stored in a gaseous state in a high pressure cylinder or is chemically bonded to breathing gas chemicals to be released by the oxygen delivery system according to the metabolic needs of the user. Novel chemicals, as mentioned above, are being investigated for oxygen generation and may yield more efficient chemicals for use in a smaller space in the apparatus. Higher oxygen storage pressures are being used in the CCMER contained in lightweight aluminum lined carbon fiber wrapped, epoxy coated composite cylinders tested up to 5,000 psig [Ref. 4.] and 10,000 psig service pressure. Storing gas at very high pressures is not efficient due to the compressibility factor (Z-factor) effect. Therefore it is necessary to consider the trade-off between the expanded volume that dictates the size and capacity of the cylinder verses the weight to provide the required strength. It was determined that 10,000 psig was the maximum optimal pressure for the CCMER from a size/weight perspective. At this pressure, the Z-factor for oxygen is about 1.35 (@ 70°F, but still offers an appropriate free gas volume in a small sized cylinder.

To further reduce the size of the oxygen container a phase change from gas to liquid must be considered. Liquefied oxygen (LOX) maintained at cryogenic (extremely low) temperatures is commonly available and used in medical and industrial applications. A gas to liquid expansion ratio of 860:1 offers the means to store the liquid oxygen in a very small container, as less than 0.1 liters of LOX is needed to provide >80 Liters O_2 for a Cap 3 CCER. To prevent loss from evaporation, the LOX is maintained cryogenically at temperatures below 90K (or minus 297°F) usually in a vacuum jacketed double walled Dewars containing the liquid prior to expansion via heat exchangers into the gaseous state that is needed for use in the CCER. An improvement over a vacuum jacketed metal Dewar may be a carbon composite double walled Dewar with an inert cryogen as the insulator in between the walls. For this minute quantity (0.1L) of LOX, a better option than a regular Dewar is needed to minimize the size and weight. The solution would be to contain the liquid in a 'CryoCapacitor' which is a term developed for storing liquid commodities in a matrix of aerogel material analogous to a sponge. This technology has been explored at the Kennedy Space Center's Cryogenics Test Laboratory[Ref. 5.] by applying it to developing high performance insulating material. For this application, the oxygen molecules are stored within the high surface area matrix structure of the aerogel composite material i.e. the CryoCapacitor and released upon demand via thermal activation. These CryoCapacitors reduce heat loss from the matrix retaining the cryogen by nature of their construction, eliminating the need for a vacuum jacketed Dewar which is a great benefit towards reducing weight. With a simple built in heat exchanger, the LOX can be evaporated as a gas and metered into the breathing loop of the CCER. The CryoCapacitor is not constrained to be in a cylindrical form and can be adapted into the CCER in shapes that would make it more ergonomic and compact.

Eliminating Components for size reduction of a CCER

The CO_2 absorber (or Scrubber) canister occupies a substantial amount of space that forms the breathing loop in a CCER. The absorbent chemical, Soda Lime or Lithium Hydroxide with additives is available as granules that are placed in the canister, usually cylindrical, or bonded onto gas absorbent sheets that are then encased in the canister.

In the case of the CCMER, the absorber used is a LiOH coating on polymer sheets placed inside a rectangular canister measuring 6.5" × 6.5" × 2.75" deep (external dimensions) for the capacity required for a 80 Liter Cap 3 device.

A dedicated canister for the CO_2 absorber can potentially be eliminated if its function can be accomplished by other means such as in the breathing hoses, breathing bags, and interconnecting elements that are also part of the breathing loop. These parts of the loop have some flexible sections and provide the compliant volume or a counter lung (Fig. 3) for the user. They are connected directly to the user's airway and lungs. Incorporating a combined counter lung and chemical CO_2 absorber and/or chemical oxygen generator in a CCER design will negate the need for a dedicated CO_2 canister or, at a minimum, drastically reduce its size. This merger of the carbon dioxide removal and providing compliant volume in the same space within a CCER would greatly contribute to reducing the overall size of the closed-circuit breathing apparatus. Impregnating or lining the flexible material sections of the counter lung with existing or novel chemicals being researched should be investigated for this purpose. Properties of such a composite material must include good adhesion of the chemical to the material while maintaining reactivity and lack of permeation through the material walls while retaining flexibility to act as a usable counter lung.

SUMMARY

Mineworkers favor smaller self-escape devices that can be easily worn without encumbering to their normal job functions.

Closed-Circuit Escape Respirators can possibly be made smaller through research into technologies to improve the efficiency of components, incorporate the function of some components within other components, replace components with alternate designs or eliminate them altogether.

The following technologies for a CCER design offers the best opportunity for size reduction and should be targeted for research:

- Novel chemicals having improved efficiencies to replace that existing for CO_2 absorption and oxygen generation
- CryoCapacitor to replace the high pressure cylinder for oxygen storage
- Eliminate a dedicated CO_2 canister by incorporating its function in the counter-lung

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Figure 1.
Backpack-style CCMER complete.

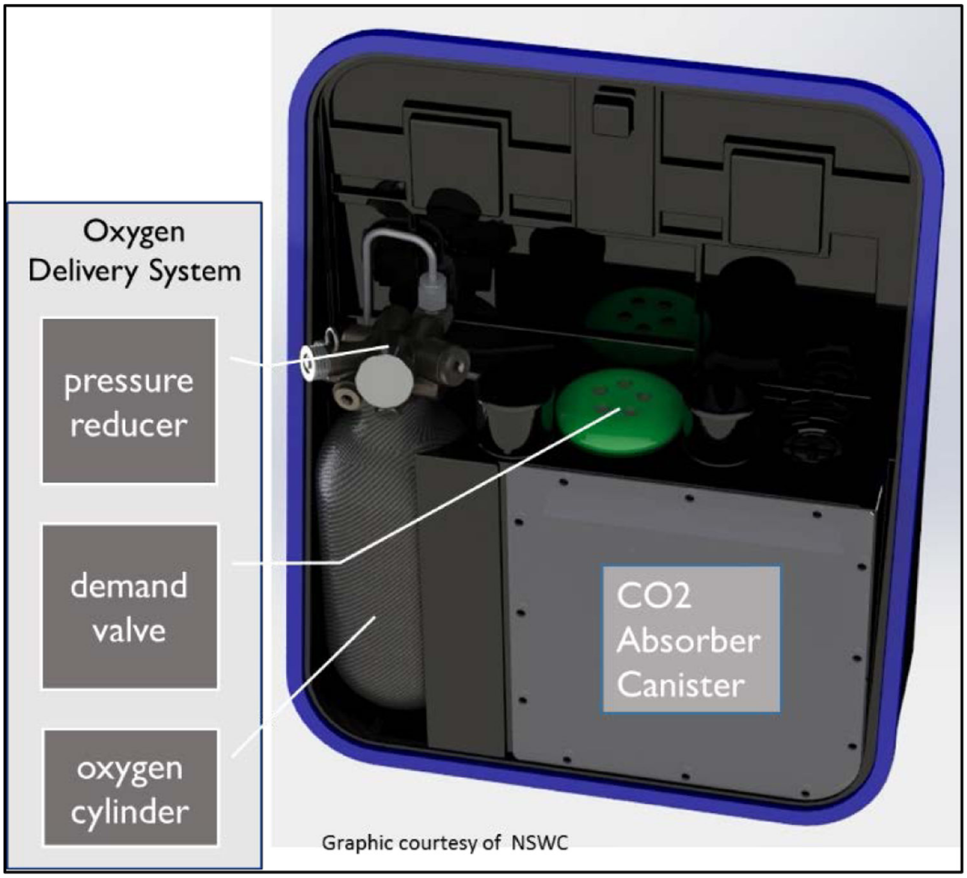

Figure 2.
Breathing Module of CCMER showing the Oxygen Delivery System and CO_2 Absorber canister of the Breathing Loop.

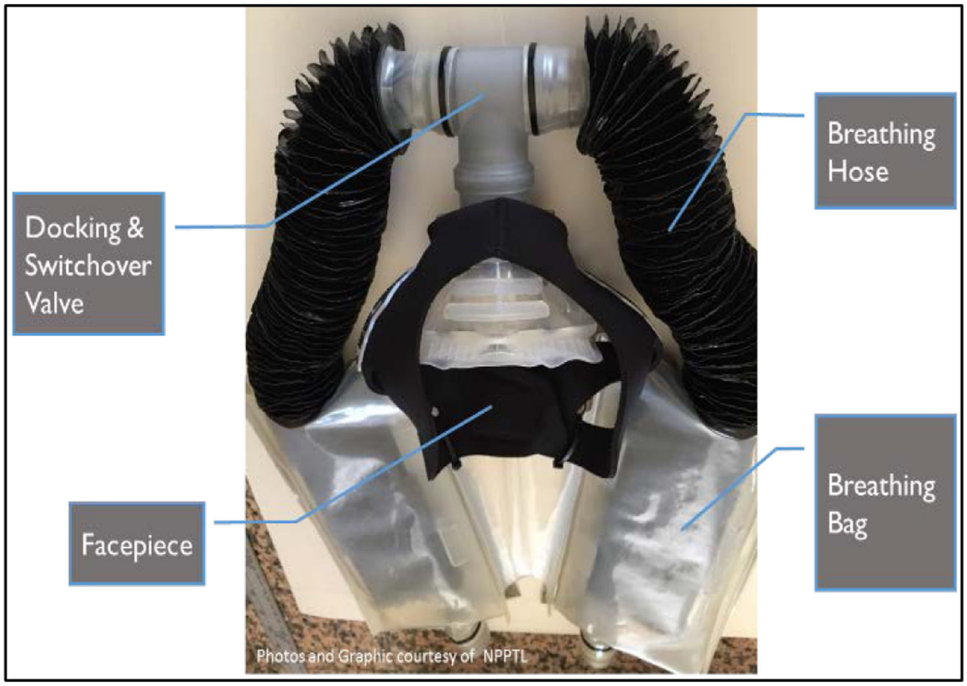

Figure 3.
Counterlung of the Breathing Loop connected to the docking valve and Facepiece.