

Enhanced Duration SCBA

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ABSTRACT

Background: The Open-Circuit Self Contained Breathing Apparatus (SCBA) has been used for almost a century in the fire service worldwide and contributed to keeping firefighters safe as well as enhancing their performance. Several improvements have been made over the years; however, the air flow pattern is still the same as it was one hundred years ago. All the exhaled air is vented to the surroundings, including the air that has not participated in the oxygen/carbon dioxide exchange in the lungs. It is the purpose of the presented concept to change the breathing pattern with the goal to make the SCBA more efficient.

Methods: With every breath we take, some of the exhaled air comes from the mouth and trachea and has not entered the lungs for the oxygen/carbon dioxide exchange and is consequently possible to re-breathe. If a breathing mask with valves is used, the amount of re-breathable air can be increased by the air contained in the nose cup and adjacent cavities in the end of the inhalation. In average, 0.4 -0.5 liter of air, which in current technology units is wasted, has full oxygen content and only insignificant amount of carbon dioxide and can be reused. By capturing the unused air in a reservoir in the beginning of the exhalation and re-using it for the next breath, the air consumption can be substantially reduced. By re-using the air as described and always keeping the gas concentrations within acceptable limits it is estimated that the Duration/Weight (D/W) ratio for a SCBA can be increased by 50-100%, compared to present technology, depending on the degree of electronics sophistication.

Results: A human pilot test with a laboratory prototype without any advanced electronics has been performed at Duke University, NC, USA, and an increase in D/W ratio of 30% was recorded, indicating that the concept has merits.

Conclusion: The actual working duration for current SCBA can vary enormously depending on the physiology of the wearer, the task being performed, and the operating environment. It is not uncommon for 30-minute rated sets to be exhausted in 15-20 minutes. The new technology can give the firefighter more duration and extra reserve in case of getting trapped or disorientated, without increased weight.

Keywords: SCBA, firefighter, duration, weight, air-saving, hybrid, reservoir, re-breathing.

Background

The Open-Circuit SCBA has been used for almost a century in the fire service worldwide and contributed to keeping firefighters safe and enhancing their performance. Several improvements have been made over the years: filling pressure has been increased to reduce the size of the SCBA, new cylinder materials have contributed to lower weight, positive pressure breathing has been introduced to improve the protection factor, electronics have been utilized to improve safety and efficiency, etc. However, the air flow pattern is still the same as one hundred years ago. All the exhaled air is vented to the surroundings, including the air that has not participated in the oxygen/carbon dioxide exchange in the lungs. It is the purpose of the presented concept to change the air flow pattern with the goal to make the SCBA more efficient.

SCBA are defined by National Institute for Occupational Safety & Health (NIOSH) as Closed-circuit apparatus or Open-circuit apparatus. In Closed-circuit apparatus, exhalation air is rebreathed after removal of carbon dioxide, while in Open-circuit apparatus the exhalation air is vented to the atmosphere and not rebreathed [42 Code of Federal Regulations (CFR) 84.70].

In the type of SCBA presented here, the first part of each exhalation is saved and when rebreathed in the subsequent inhalation without any removal of carbon dioxide and is consequently a mixture of current design SCBA. It is designated Hybrid SCBA and the proposed design modifications are outlined below.

History

The fire service is the predominant user of the SCBA. In the beginning of the last century, Closed-circuit SCBA, already used in mines, were tried by a few fire departments for longer rescue operations. With the development of lighter gas cylinders and higher-pressure cylinders, the Open-circuit SCBA with the advantage of easier maintenance was introduced and became the standard SCBA in the fire service. The mines with the need for duration of several hours kept the Closed-circuit SCBA as the standard SCBA.

With the standardization work that started in the 1970's and 1980's, first in Europe by the Comité Européen de Normalisation (CEN) organization and later in the USA by NIOSH and National Fire Protection Association (NFPA), the Open-circuit SCBA has become a high technological tool that has an enormous value for the fire service. Several millions are used daily worldwide and have contributed to firefighters' safety and their mission to protect lives and other valuables.

The Hybrid SCBA concept

With every breath we take, about 0.2 liter of the exhaled air comes from the mouth and trachea and has not been in the lungs for the oxygen/carbon dioxide exchange and is consequently possible to re-breathe. If a breathing mask with valves is used, the amount of re-breathable air can be increased by the content of the noes cup and adjacent cavities at the end of the inhalation. On average, 0.4 -0.5 liter of exhaled air that currently is wasted has full oxygen content and is relatively free from carbon dioxide. By capturing the unused air in a reservoir and re-using it for the next inhalation, the air consumption can be reduced.

The volume containing unused air in the end of the inhalation is the same volume that is filled with air with approximately 5% of carbon dioxide in the end of an exhalation and called "dead space" as it cannot contribute to more carbon dioxide take-up at the following breath.

Another factor with potential gas-savings is that the body according to NIOSH accepts up to 2% (2.5% for shorter durations) of carbon dioxide in the inhalation air without any adverse effect to the breathing [CFR 84.97]. The present concept is planned to control the average carbon dioxide content in the inhalation air

by always keeping it less than 1.5%, the generally accepted amount that doesn't trigger increase in ventilation significantly, and thereby contributing to an extra saving of air [International Organization for Standardization (ISO)/TS 16976-3]. The control is achieved by using small, reliable and affordable carbon dioxide electronic sensors that have become available in recent years.

The oxygen content in the inhaled air must according to NIOSH be a minimum of 19.5% [42 CFR 84.141 (a)]. To always keep the oxygen concentration over that limit, the concept involves using fresh air supply with an oxygen concentration of 23.5%, that still is atmospheric air by the Compressed Gas Association (CGA), and under the 30% stipulated by NIOSH for use in fires [CGA (2018)], [Federal Register (1985)].

By re-using the air as described and always keeping the gas concentrations within acceptable limits, it is estimated that the Duration/Weight (D/W) ratio for a SCBA can be increased by 50-100%, (depending on the degree of electronic sophistication), see Fig.1.

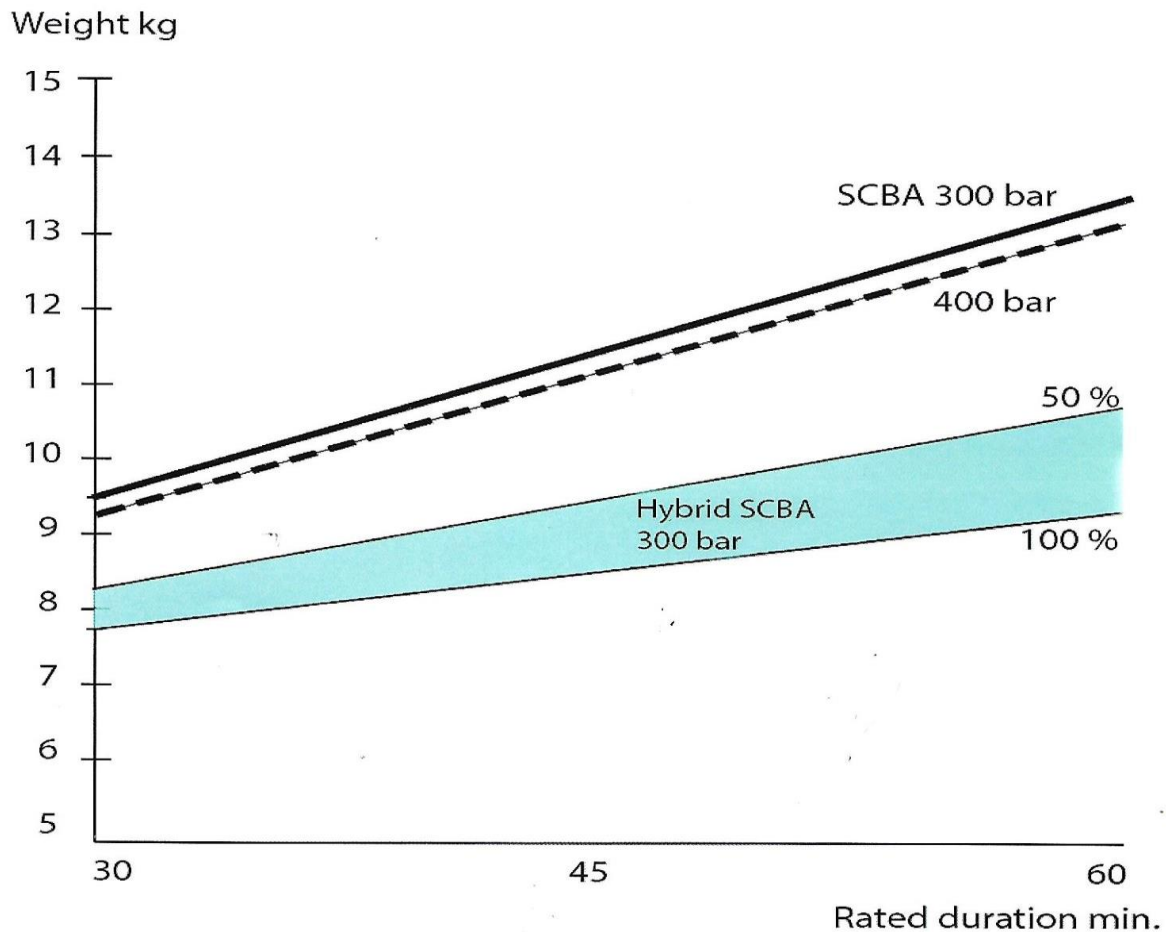


Fig. 1 Current SCBA and Hybrid SCBA weights for different rated durations

Design

Before going into the technical aspects of the Hybrid SCBA concept, let us look at the performance of the present design. In Fig. 2, a typical Pressure/Flow graph is shown [Almqvist H. et al. (1983)]. The values on the axis indicate the requirements in different standards; all breathing shall occur at positive pressure for peak flows up to around 300 l/min and the exhalation resistance must be less than 7 mbar. The same conditions will be valid for the Hybrid SCBA technology, further details on that subject will be addressed below.

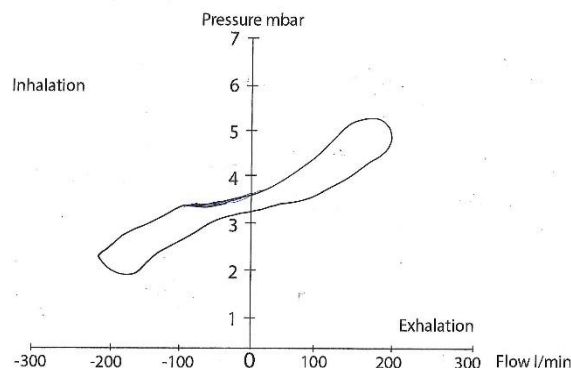


Fig. 2 Pressure/Flow graph for current SCBA

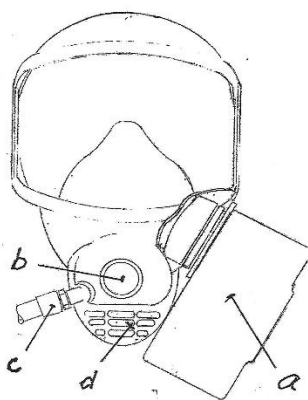


Fig.3 Facepiece with Reservoir

As mentioned above, the Hybrid SCBA technology is based on saving the first part of each exhalation in a reservoir and reusing that air as part of the subsequent breath. The reservoir must be placed in the proximity of the mouth. Fig. 3 shows an example of a preferred arrangement where (a) is the reservoir, (b) is a breathing regulator, (c) is a supply hose for fresh gas, and (d) is an exhalation valve.

An example of a reservoir is shown in Fig. 4. The air collecting part consists of a variable cylindric volume (a), a rolling diaphragm (b), whose position determine the actual filling volume of the reservoir, a spring (c) acting on a cylindric plate (d) and whereby determining the pressure in the reservoir, and a shut-off valve (e) that is controlled, open or closed, by an electronic control unit, not shown. A carbon dioxide sensor (f) is used to activate the shut-off valve and can have various positions, f1 or f2, depending on the mode of operation, discussed below.

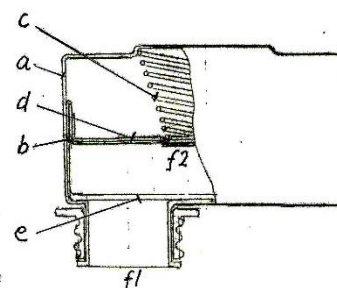


Fig.4 Reservoir

For the operation of the reservoir, reference is made to the requirements on breathing pressure shown in Fig. 2. For the Hybrid SCBA, the opening pressure of the breathing regulator is decreased and the opening pressure for the exhalation valve is increased compared to what is common for conventional Open-circuit SCBA. Thereby an operation area is created for the reservoir, see Fig. 5. Consequently, the reservoir is filled to a predetermined volume before the exhalation valve opens and the reservoir is emptied before the breathing regulator opens. Thus, the maximum utilization of the reservoir is obtained.

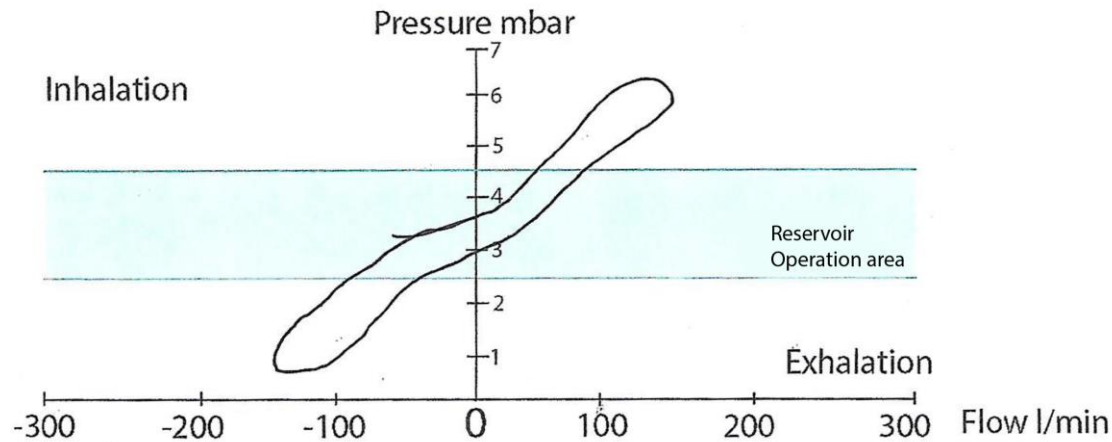


Fig 5 Pressure/Flow graph for Hybrid SCBA

Standard mode pf operation

To get maximum savings of fresh gas, the carbon dioxide content shall be measured during the exhalation by a fast sensor and the reservoir be shut off at a preselected value. The carbon dioxide concentration is shown in Fig. 6, where the trigger point indicates the shut-off of the valve. The inhalation breath will consist of a mixture of the amount of air in the reservoir with the preset carbon dioxide concentration, air from the dead space in the face piece with 5% carbon dioxide concentration, and fresh air from the breathing regulator with negligible carbon dioxide amount. The trigger point will be selected with the help of a microprocessor in a way that the average carbon dioxide concentration in the inhalation air is optimal from a gas savings point of view, but less than 1.5% to avoid increase in ventilation.

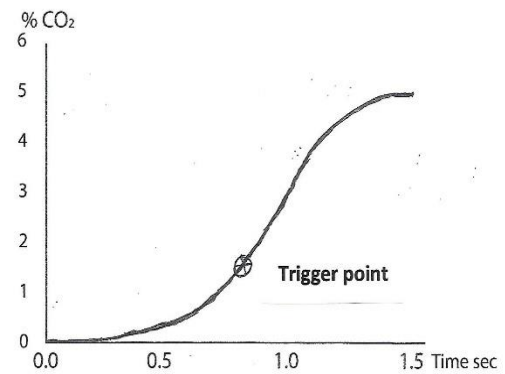


Fig. 6 CO₂% during exhalation

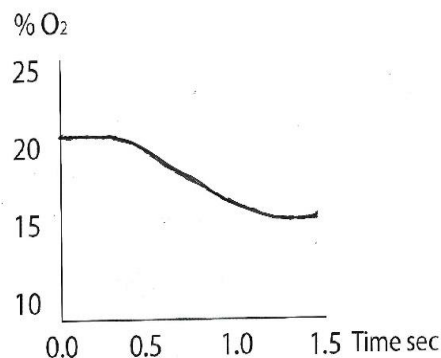


Fig. 7 O₂% during exhalation

When reusing exhalation air with relatively high concentrations of carbon dioxide, there is the risk that the air contains less than 19.5% oxygen, which is not allowed by NIOSH. The oxygen concentration in an exhalation is shown in Fig. 7. An inhalation breath consists of a mixture of air from the reservoir with reduced concentration of oxygen, air from the dead space with approximately 16% oxygen and fresh gas with 21% oxygen. To safeguard that the combination always exceeds 19.5%, the oxygen concentration in the fresh air cylinder should be elevated to 23.5% oxygen. Utilizing the system to its maximum, it is estimated to see an increase of D/W ratio close to 100% compared to the current technology, see Fig. 1.

Alternative mode of operation

The standard mode of operation includes adjusting the volume of reused air to the actual workload and ventilation. If instead a constant reservoir volume is selected, representing the user's predicted average workload and ventilation, the design can be made much simpler. In this case, the shut-off valve can be open most of the time and there is no need for fast carbon dioxide measurement. The only situation when the shut-off valve needs to be activated is when the carbon dioxide concentration reaches high levels, which can occur if the user is at rest and the volume of the breath is less than the preset volume of the reservoir. The remedy is to electronically close the shut-off valve for a number of breaths, temporarily converting the SCBA to an Open-circuit unit.

It is estimated that the alternative mode of operation can result in an increase of D/W ratio of 50% compared to current technology, see Fig. 1. This mode could probably be of interest for upgrading of old units.

Pilot test

A pilot test with a laboratory prototype (Fig. 8), without any advanced electronics, was performed at Duke University and an increase in D/W ratio of 30%, compared to currently use SCBA, was recorded [Freiberger J.J. et al. (2016)].

Certifications

The only deviations from the standardized test procedures would be that the NIOSH and CEN test to determine the rated duration by using an artificial lung must be exchanged for a metabolic simulator, already standard for testing closed circuit SCBA. Early, preliminary contact with NIOSH indicates that this exchange is possible.



Fig. 8 The Duke prototype

Purpose

The fire service is in charge when it comes to the choice of rated service time of the SCBA used and the work time selected for the firefighters. What manufacturers can do is to increase the options. The following is an extract from an Illinois Fire Service Institute (IFSI) report that represents a common opinion in the fire service [IFSI (2015)]:

Transitioning from the traditional 30-minute SCBA to extended duration SCBA should be done with a full evaluation of the consequences. While the 30-minute SCBA has been shown to be sufficient for use in many firefighting operations, extended duration SCBA may be better suited for high-rise or hazardous material (HAZMAT) operations. The additional weight and bulk does have some important impact on the biomechanics of movement and extended work time can further exacerbate these concerns. If extended duration SCBA are to be utilized, it is recommended that the work-rest cycles of a 30-minute SCBA still be followed (and the extra air be considered reserve) instead of relying on the End of Service Time Indicator to indicate time to exit the structure.

It is not uncommon that the present 30-minute SCBA lasts 15-20 minutes in firefighting, and the 45-minute SCBA lasts less than 45 minutes. The new technology can give the firefighter extra reserve in case of getting trapped or disorientated, without increased weight. As an example, it can offer a true 30-minute SCBA, with extra reserve in case of emergency, without increasing weight, when compared to current 30-minute SCBA.

Considerations

As with almost all new development, the new technology will come with a couple of changes in the SCBA design and the maintenance:

- Saving exhalation air for the next inhalation requires a reservoir close to the face piece or an integral part of the face piece. The size will be comparable to a military filter, but with a much lower weight. To increase comfort, the reservoir can be split into two units, one on each side.
- The cylinder charging of air with 23.5% oxygen will require a modified filling station, however, with a process that can be made fully automatic and requires a minor investment.

Only the fire service is in the position to decide what changes are acceptable for more efficient technology.

400 bar technology

The new high-pressure technology, 400 bar or 5500 psi, for the fresh air cylinders has resulted in smaller units for a given rated duration, that according to IFSI has some positive effect on balance and maybe also on heart rate [IFSI (2015)]. However, due to the negative influence of the compressibility factor for air, that reduces the volume increase of air in relation to the pressure, it has only a small positive impact on the D/W ratio and is in that respect very similar to the 300 bar and 4 500 psi technology, see Fig. 1. A combination of both the Hybrid SCBA technology and the elevated cylinder pressure technology is possible and would result in combined gain in D/W ratio.

Fire service support

The Hybrid SCBA technology is promising, but expensive to get to the market. The technology will need strong support from fire service organizations to become a reality.

Sponsoring institutions

Createc LLC

- Main sponsor

The Swedish Civil Contingencies Agency, Sweden

- Funding of background study performed by Royal Institute of Technology, Environmental Physiology, Sweden
- Funding of first prototype

Duke Center for Hyperbaric Medicine and Environmental Physiology, Duke University, Durham, NC, USA

- Funding of human pilot test

United States Patent and Trademark Office, USA

- Award of patent US 11,185,650 B2

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