

Performance Comparison of Breathing and Metabolic Simulators

Nicholas Kyriazi

National Institute for Occupational Safety and Health, National Personal Protective Technology Laboratory, 626 Cochran's Mill Road, P.O. Box 18070, Pittsburgh, PA 15236, USA

E-mail: nkyriazi@cdc.gov

ABSTRACT

A study was undertaken to compare the performance of the various types of breathing and metabolic simulators (BMSs) in current use by government agencies and breathing apparatus manufacturers around the world. BMSs are used for quantitative testing of closed-circuit breathing apparatus (CCBA). Different methods of achieving simulation of breathing and metabolism are used by the various BMSs. There have been no studies comparing the performance of apparatus tested by BMSs of different designs. In order to do so, two standardized CCBA were tested on the various BMSs at the same work load in the laboratories of the participating companies or agencies. The two major types of CCBA – compressed-oxygen and chemical-oxygen – were represented in this study by the CSE/Faser AU-9A1, a refillable compressed-oxygen apparatus, and the Dräger OXYBOKS K, a chemical-oxygen apparatus, a batch of which were made in a single production run by Dräger for this study. A metabolic work load able to be reproduced by all the BMSs was used. Identical breathing apparatus tested at the same work load on each BMS enabled side-by-side comparison of the BMSs.

The most notable differences between the simulators included in this study are 1) the lower average inhaled CO₂ concentrations measured by the simulators having uni-directional versus bi-directional internal flow paths; and 2) the lower DB inhalation temperatures measured on chemical-oxygen apparatus by the simulators having large water reservoirs. Users will experience higher average inhaled CO₂ concentrations and higher DB inhalation temperatures than predicted by testing on BMSs of the above-mentioned respective BMS designs.

Keywords: closed-circuit breathing apparatus (CCBA), breathing and metabolic simulators, compressed-oxygen and chemical-oxygen, PPE, CO₂ concentrations

INTRODUCTION

Because of their design which does not vent each breath to ambient like open-circuit breathing apparatus, lighter and smaller CCBA enable respiratory protection for long periods of time necessary for mine rescue; firefighting in subways and in high-rise buildings; and for chemical spill clean-up. CCBA are difficult to evaluate in a quantitative manner using human subjects. Human metabolic parameters change over time in both the short and the long term. In addition, although $\dot{V}O_2$ (oxygen consumption rate) and $\dot{V}CO_2$ (CO₂ production rate) are fairly stable at a constant work rate, tidal volume and respiratory frequency can vary from breath to breath and can be characterized only as averages over

longer periods. Further, although one metabolic parameter can be elicited from a human subject, the others cannot be forced to desired values.

The need for mechanical simulation of human respiration in the areas of oxygen consumption, CO₂ production, air movement, humidity, and temperature has been recognized for some time. Computer technology development in the early 1980s enabled this to be achieved to a significant degree. The U.S. Bureau of Mines funded the development of BMS technology from 1970 to 1985 (Kyriazi, 1986) resulting in the design presently used by NIOSH-NPPTL, the U.S. Navy, and manufacturers Ocenco and MSA. Other designs are used by manufacturers CSE and Dräger. The European Community uses the Auer 57 simulator design first described by Sauer (1940), found throughout Europe as well as in South Africa and Australia.

The objective of this investigation was to examine how the differences in BMS design affect the testing of identical apparatus. In addition, it is of interest to know how identical apparatus perform on a particular simulator as compared with a human subject at the same metabolic work rate. It is desirable for apparatus tested on a BMS to be as close as possible to those tested on human subjects in the important measured stressors: inhalation CO₂, O₂, temperature, and both inhalation and exhalation breathing pressures.

METHODS

Study Design

The goal was to evaluate the BMSs in two ways: compared with each other and compared with human subjects:

1) BMS vs. BMS - Using a standard set of metabolic parameters, the BMSs were compared with each other using three of each type of apparatus (compressed- and chemical-oxygen), a total of six at each site.

2) BMS vs. Human Subject – At each site, a human subject was metabolically monitored while walking on a treadmill while the speed was adjusted in order to match the target oxygen consumption rate. The other relevant metabolic parameters would be measured at this oxygen consumption rate. This

set of metabolic parameters, perhaps different from the standard values except for $\dot{V}O_2$, would be used to re-program the BMS to test the standard apparatus in order to achieve a side-by-side comparison of the BMS with the human subject. One apparatus of each type would be tested on the BMS and on the treadmill, a total of four at each site.

The human-subject protocol used in this study was approved by the NIOSH Human Subject Review Board, and informed-consent forms were signed by the human subjects who participated in this study.

Work rate

The standard work rate used at NIOSH for BMS testing of CCBA is the average work rate exhibited by a 50th-percentile miner weighing 87 kg while performing the one-hour man-test 4 as described in 42 CFR 84. This would have been the logical choice for the standard work rate; however, the tidal volume of the CSE simulator is fixed, using the Silverman 622 kg m/min work-rate cam (Silverman, 1945). Therefore, a work rate was chosen appropriate for its tidal volume of 1.64 L (absolute volume displacement). The exhalation breath exits the CSE simulator at core body temperature (37°C) and ambient barometric pressure, saturated (BTPS). To convert this to standard temperature and pressure, dry (STPD), in order to achieve molecular equivalency in different labs, from those conditions in Pittsburgh (735 mm Hg), a conversion factor of 0.797 was used. The 1.64 L/breath tidal volume converts to an STPD volume of 1.31 L/breath. The work rate created for this study was physiologically commensurate with this tidal volume, the other parameters of which were chosen by an internal BMS

program based on a desired oxygen-consumption rate. The parameters used for NIOSH standard CCBA testing and those used for this study are as follows:

NIOSH standard work rate used for BMS testing of CCBA
(All volumes in this paper are given at STPD unless noted)

Oxygen consumption rate	1.35 liter/minute
CO ₂ production rate	1.15 liter/minute
Ventilation rate	30.0 liters/minute
Respiratory frequency	17.9 breaths/minute
Breath volume	1.67 liters/breath
Peak flow rate	83 liters/minute (approximately)

BMS Comparison standard work rate (this study)

Oxygen consumption rate	1.00 liter/minute
CO ₂ production rate	0.94 liter/minute
Ventilation rate	22.3 liters/minute
Respiratory frequency	17 breaths/minute
Breath volume	1.31 liters/breath
Peak flow rate	67 liters/minute (approximately)

The waveform shape of the Silverman cam is somewhat of a blunted sine wave (Figure 1). This is not one that is easily communicated or reproduced, so a typical sine wave was chosen to be the standard as a compromise. Peak flow rates will be a little higher for a sine wave than those produced with the Silverman cam.

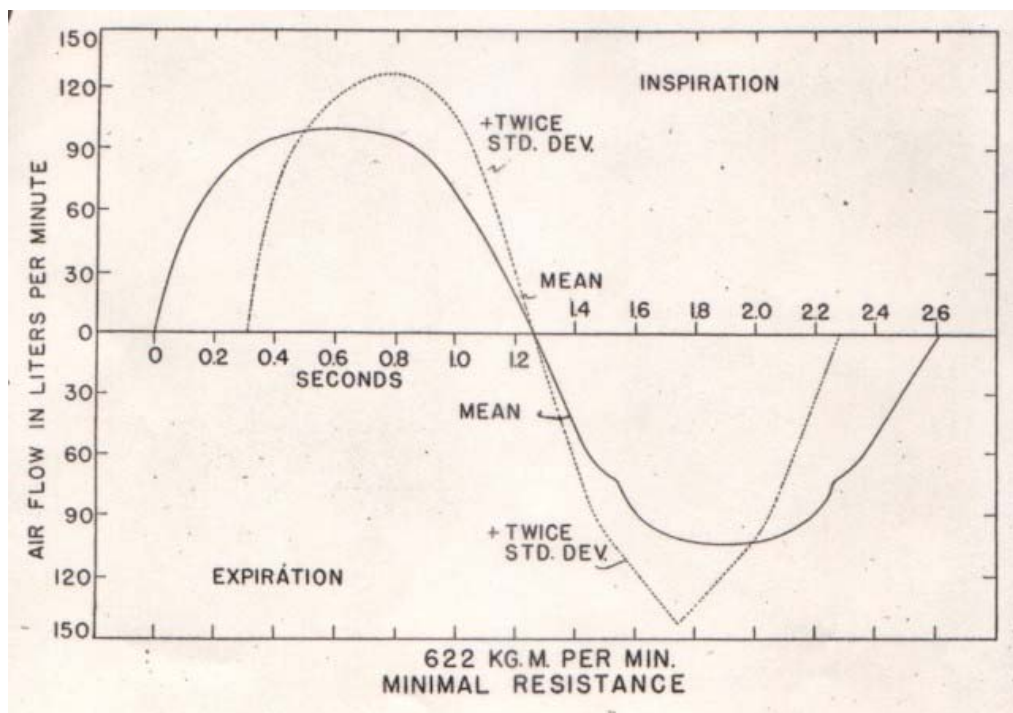


Figure 1. Silverman 622 kg*m/min wave form.

Breathing apparatus

CSE (Faser) AU-9A1 – This compressed-oxygen apparatus, built by Faser of Poland for CSE in the 1980s, has a demand valve and a constant flow of oxygen of approximately 1.71 L/min (ambient temperature and pressure, dry). It is able to be refilled with CO₂ absorbent and oxygen in measured quantities in order to assure identical performance. (See photo and schematic, Figures 2 and 3.) It was later learned that the apparatus cylinder may become stressed from pressure cycling since it was intended for one-time use. From that point on, the apparatus regulator was connected to a separate oxygen cylinder, terminating the tests at a set time instead of running them until empty since the oxygen cylinder was a larger volume than that used in the apparatus. The CO₂ absorbent was obtained from Molecular Products made from one batch of product (408-mesh Sofnolime, mostly calcium hydroxide). The quantities of CO₂ absorbent (500 g) and oxygen (157 g) were chosen to permit CO₂ breakthrough before the oxygen supply ran out. At 80 minutes, the minimum inhaled CO₂ (lowest concentration exiting the canister on inhalation) ranged from 2-4% CO₂. This enabled the BMSs to be compared more precisely in terms of CO₂ production and measurement.



Figure 2. CSE AU-9A1 photo (scale in inches).

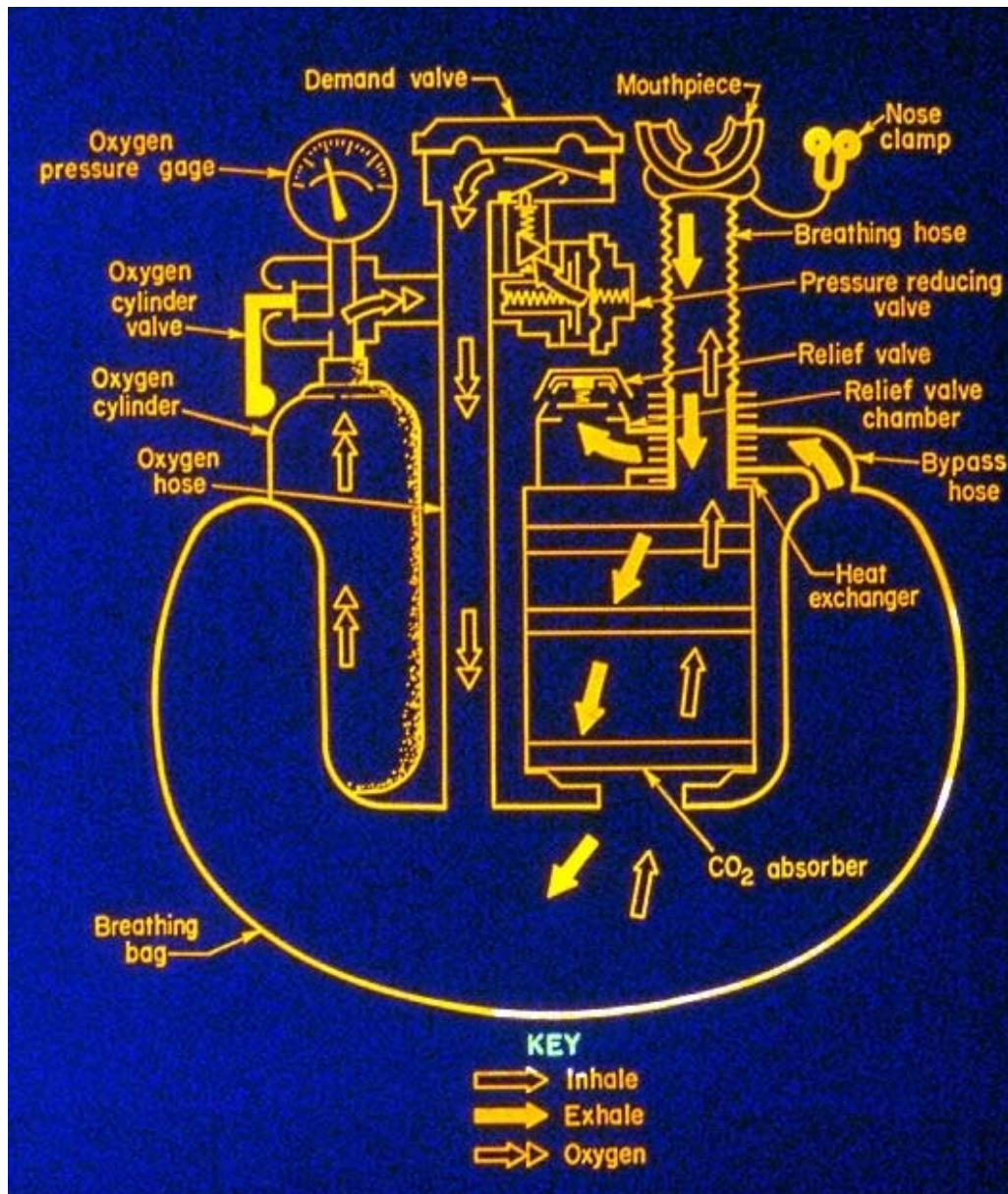


Figure 3. CSE AU-9A1 schematic.

Dräger OXYBOKS K – At our request, Drägerwerk produced a batch of 50 units for this study. (See photo and schematic, Figures 4 and 5) The OXYBOKS K was chosen because the apparatus showed little variation between units in past testing and it was of smaller capacity than the Dräger OXY K PLUS which has approximately 120 L of usable oxygen and would have lasted 120 minutes at our oxygen consumption rate. Other commercially produced KO₂ apparatus were either not as readily available, were of greater capacity, or exhibited variable performance among units.



Figure 4. Dräger OXYBOKS K photo.

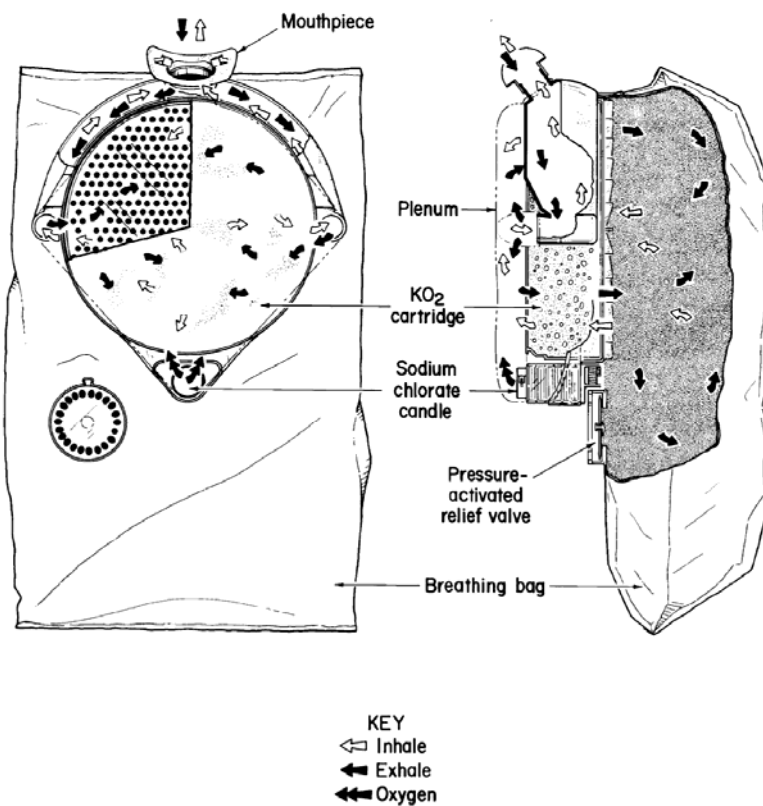


Figure 5. Dräger OXYBOKS K Schematic.

Participants

NIOSH – Pittsburgh, PA, USA: DEEC and Ocenco BMSs

CSE – Monroeville, PA, USA: CSE simulator

Ocenco – Pleasant Prairie, WI, USA: Ocenco BMS

Dräger – Lübeck, Germany: Dräger BMS adjusted to simulate Auer simulator

Mine Safety Technology Centre – Thornton, New South Wales, Australia: Auer simulator

Experimental Procedure

Although the target number of tests for the BMS-vs.-BMS testing was three of each type, testing on the NIOSH DEEC BMS expanded to 12 units of the compressed-oxygen type due to switching between components (base, hose, canister, and regulator) from two different units, type of filter material, and CO₂ absorbent from three different containers. The greatest variability was found in inhalation breathing pressures for various filter materials in the CO₂-absorbent canister, ranging from -24 to -38 mm H₂O. Deciding on one filter material reduced this variability.

Human-subject testing went as planned at NIOSH and CSE. It did not go as planned at Dräger, and neither Ocenco nor the Mine Safety Technology Centre (MSTC) were equipped to run human-subject tests. At Dräger, the method used for measuring human $\dot{V}O_2$ was later found to be incorrect, with the result that the two test subjects were run at speeds eliciting a $\dot{V}O_2$ lower than the target.

Measurements

The relevant human stressors for CCBA are inhaled levels of CO₂ and O₂, inhalation temperature, and inhalation and exhalation breathing pressures. Discussion of measurement considerations for each of these stressors follows.

CO₂ and O₂

Measurement of inhaled levels of CO₂ and O₂ is more complicated than simply sampling gas concentrations continuously at the mouth. Such monitoring shows only a cyclic rise and fall of the gas concentrations with inhalation and exhalation. All CCBA have dead space, defined as volume that contains exhaled breath uncleansed of CO₂ or augmented by O₂ that is inhaled back on inhalation. The actual inhaled concentrations of the gases will, therefore, not be merely the highest O₂ or lowest CO₂ values observed at the mouth. The average inhaled gas concentrations contain the dead-space contributions. On BMSs, this measurement can be made by splitting the inhalation and exhalation flows inside the BMS and measuring the concentrations of only the inhaled gases in an internal mixing chamber, as in the Auer 57 BMS. The average inhaled gas concentration can also be determined by electronically measuring the instantaneous gas concentrations at the mouth at a high sampling rate, weighting each value by multiplying it by the instantaneous flow rate, multiplying each product by the sampling interval, summing the volumes over inhalation, and dividing the volume of inhaled CO₂ by the breath volume (Kyriazi, 1986). Termed volume-weighted averaging, this is done in the DEEC and Ocenco BMSs. These average inhaled values add the high CO₂ (and low O₂) at the beginning of an inhalation with the lower CO₂ (and high O₂) value at the end of an inhalation. We do not, at present, have the capability for measurement of average inhaled gas concentrations on human subjects. However, since average inhaled gas concentrations are already calculated on the BMS, and since average inhaled values depend upon the ratio of the dead space to the full breath volume which varies widely in human subjects with each breath, this is not considered an important goal.

Inhalation temperature

Measuring inhalation temperature is also not as simple as might be imagined. What humans perceive as inhaled temperature is the wet-bulb (WB) temperature, not the dry-bulb (DB) temperature. This is due to the fact that the inhalation of dry gases causes moisture to be evaporated from the wet respiratory tract, cooling the tissues from the evaporation. Dry air will feel cooler than humid air at the same DB temperature. Measurement of WB temperature breath-by-breath, however, has not been possible until NIOSH's development of a fast-response WB thermocouple, not widely known or used (Kyriazi, 1988). While a valuable tool, however, it is not a robust instrument and is especially difficult to use in treadmill testing. Consequently, we continue to also measure DB temperature.

Both the DEEC and Ocenco BMSs measure the end-inspiratory WB and DB temperatures rather than simply the highest measured values. This is because, at the beginning of most tests, when the apparatus is still at room temperature, the highest temperatures measured during inhalation are of the exhalation breath in the apparatus dead space. The other BMSs in this study rely on human derivation of the inhalation temperatures from chart recordings, and manually distinguish inhalation from exhalation temperatures, or have programs that find the maximal peaks of temperature.

Breathing pressures

Inhalation and exhalation breathing pressures are given as peak values for all the simulators in this study.

Performance characterization

There are several ways to characterize a monitored stressor over a test short of simply presenting all of the data: noting the stressor level at a particular point in time for different tests or at the end of each test, or averaging the stressor over the entire test duration or over a common fixed portion of the duration. This study presents the average stressor values over the entire test duration for the chemical-oxygen apparatus since duration was determined predominantly by the BMS. For the compressed-oxygen apparatus using an external oxygen cylinder, however, the test was terminated at a pre-determined time – 80 minutes. The average value over a fixed time period is presented for each stressor as a consequence.

Some tables contain results consisting of the test-averages of only one test; some tables contain results consisting of test-averages of multiple tests. The latter also contain the standard deviation for the sample.

Considerations

If a compressed-oxygen apparatus with a regulator providing oxygen at a constant-flow rate is tested at an oxygen consumption rate lower than the constant-flow rate, as in this study, there is little opportunity for comparing BMSs with regard to apparatus duration. The greater oxygen supply rate fills the breathing bag and vents excess breathing circuit gas out the relief valve to ambient. The duration of the apparatus in this case is determined by the oxygen constant-flow rate; oxygen would run out in the same time even if not connected to a BMS. If the BMS oxygen consumption rate were errantly much higher than the target rate, such that the demand valve were called into operation, this would reduce the apparatus duration and would be an obvious indictment of the BMS.

The relation of the oxygen consumption rate to the oxygen flow rate – if, and how much, excess breathing circuit gas is vented - will have an effect on the oxygen concentration rise in the breathing circuit: the more rapidly that nitrogen in the breathing circuit gas is vented, the faster the rise in oxygen concentration. If the oxygen consumption simulation of a particular BMS withdraws breathing circuit gas instead of exclusively oxygen (volumetric-equivalent oxygen consumption), more oxygen is left in the

breathing circuit and the rise in oxygen concentration will be faster than in BMSs which simulate oxygen withdrawal exclusively.

An oxygen consumption rate equal to the oxygen constant flow rate should result in oxygen concentration neither rising nor falling in the breathing circuit; however, in volumetric-equivalent oxygen consumption BMSs, oxygen concentration would rise. This is because the volume of withdrawn breathing circuit gas, only partially composed of oxygen, is replaced with 100% oxygen. In this study, oxygen concentrations should always rise since the oxygen constant-flow rate is higher than the consumption rate for the compressed-oxygen apparatus.

Duration in chemical-oxygen apparatus is determined entirely by the quantities of exhaled water vapor and CO₂. Oxygen consumption does not affect the duration at all except that the breathing bag would never bottom, even when the chemical bed was expended, unless some volume, simulating oxygen consumption, is removed. Oxygen concentration should always rise until all nitrogen is (theoretically) purged from the system since chemical-oxygen apparatus produce about 50% more oxygen than is needed.

RESULTS AND DISCUSSION

The BMS at each site is first described. The numerical results are then given followed by a subjective assessment and comments.

NIOSH

The NIOSH BMSs are of a design shown in Figures 6 to 8, schematic and photo. A stepper motor controlled by a computer moves a piston in a cylinder to effect ventilation. Water circulated by a pump rains on top of the piston, is drained out the bottom into a heated reservoir, and is then circulated back to the lung. Three needle valves controlled by the computer continuously meter CO₂ and N₂ into the lung and extract system gas from the upper trachea to simulate oxygen consumption and CO₂ production. The quantity of gas extracted is determined by the desired oxygen consumption rate and the oxygen concentration measured at the mouth. N₂ in-flow replaces the N₂ unavoidably extracted in oxygen consumption simulation. The same applies to CO₂. The computer controls the needle valve flows based on flow-vs-valve step calibration tables, previously created during a calibration process for each valve. One modification made to the original system was the addition of a 10-L water reservoir through which the exhaust flow is drawn before it enters the exhaust flow needle valve. This is to ensure that exhaust gas temperature and humidity are the same during testing as during calibration. Nitrogen and CO₂ flow rates are firmly linked to the needle valve orifice size because the conditions inside the needle valves are the same during calibration and testing. The exhaust flow rate for a given needle valve orifice size, however, varies depending on gas conditions (temperature and humidity). The water reservoir anchors the exhaust flow gas to room temperature and saturated conditions before it enters the needle valve.

In addition to the gas concentrations monitored at the mouth, also monitored are WB and DB temperatures, and peak breathing pressures.

The DEEC BMS was built in 1984 by its inventor, Scott Deno, under contract to the Bureau of Mines. The Ocenco BMS was built in 2002 by Ocenco, Inc. under license from Scott Deno.

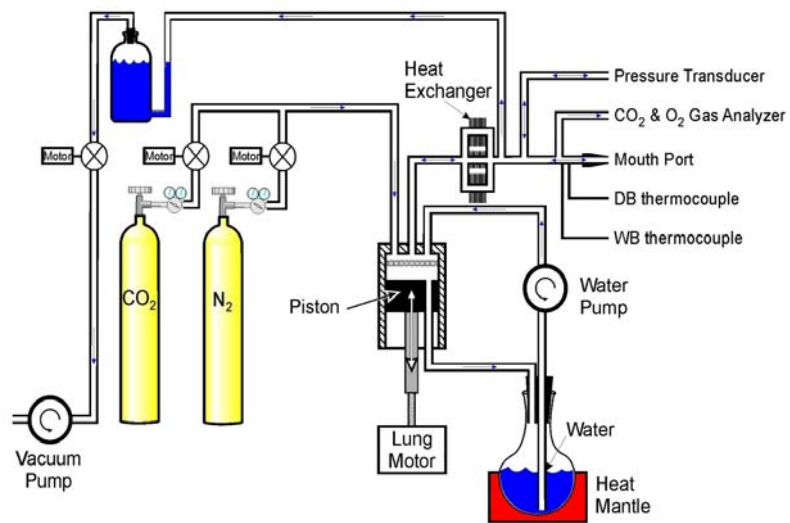


Figure 6. Schematic of DEEC BMS.



Figure 7. Photo of DEEC BMS.



Figure 8. Photo of NIOSH Ocenco BMS.

Table I. DEEC BMS versus NIOSH Ocenco BMS - Compressed-oxygen Apparatus

<i>Compressed-oxygen apparatus</i>	<i>DEEC BMS</i>	<i>Ocenco BMS</i>
<i>75-minute test averages + SD</i>	<i>n=12</i>	<i>n=4</i>
<i>Duration, minutes:</i>	<i>81 ± 2</i>	<i>80 ± 1</i>
<i>Average inhaled CO₂, %:</i>	<i>3.1 ± 0.2</i>	<i>2.8 ± 0.3</i>
<i>Minimum inhaled CO₂, %:</i>	<i>0.5 ± 0.1</i>	<i>0.5 ± 0.1</i>
<i>Average inhaled O₂, %:</i>	<i>76 ± 1</i>	<i>76 ± 2</i>
<i>Inhalation WB, °C:</i>	<i>47.1 ± 1.0</i>	<i>46.5 ± 1.7</i>
<i>Inhalation DB, °C:</i>	<i>47.6 ± 0.9</i>	<i>48.1 ± 1.0</i>
<i>Peak inhalation pressure, mm H₂O:</i>	<i>-30 ± 4</i>	<i>-36 ± 2</i>
<i>Peak exhalation pressure, mm H₂O:</i>	<i>30 ± 2</i>	<i>32 ± 1</i>

Table II. DEEC BMS versus NIOSH Ocenco BMS - Chemical-oxygen Apparatus

<i>Chemical-oxygen apparatus</i>	<i>DEEC BMS</i>	<i>Ocenco BMS</i>
<i>Full-duration test averages + SD</i>	<i>n=4</i>	<i>n=3</i>
<i>Duration, minutes:</i>	<i>47 ± 1</i>	<i>47 ± 2</i>
<i>Average inhaled CO₂, %:</i>	<i>1.3 ± 0</i>	<i>1.2 ± 0.1</i>
<i>Minimum inhaled CO₂, %:</i>	<i>0 ± 0</i>	<i>0 ± 0</i>
<i>Average inhaled O₂, %:</i>	<i>86 ± 0</i>	<i>81 ± 0</i>
<i>Inhalation WB, °C:</i>	<i>31.1 ± 0.9</i>	<i>32.7 ± 1.3</i>
<i>Inhalation DB, °C:</i>	<i>49.8 ± 0.8</i>	<i>52.6 ± 2.4</i>
<i>Peak inhalation pressure, mm H₂O:</i>	<i>-58 ± 2</i>	<i>-69 ± 6</i>
<i>Peak exhalation pressure, mm H₂O:</i>	<i>45 ± 2</i>	<i>55 ± 6</i>

Evaluation: The correlation between the two simulators was good in the areas of duration, average and minimum inhaled CO₂, and WB temperatures. The average inhaled O₂ in the compressed-O₂ apparatus for both BMSs were nearly identical but definitively lower for the chemical-O₂ apparatus on the Ocenco BMS for unknown reasons. Also unexplained was the variability of DB temperatures in the chemical-O₂ but not the compressed-O₂ apparatus on the Ocenco BMS. Breathing pressures were close in the compressed-O₂ apparatus although somewhat higher, with higher variability, for the chemical-O₂ apparatus on the Ocenco BMS. It could be that the chemical-O₂ apparatus are not as alike as had been assumed.

DEEC BMS versus Human Subject

Two human subjects were used in this comparison. Some of the human-subject work-rate parameters were different from those of the BMS work rate for the same $\dot{V}O_2$. Therefore, the BMS was reprogrammed to simulate each of the two human subjects for the comparison test. The metabolic parameters for each human subject are listed below with those of the study standard shown for comparison:

Table III. NIOSH Human Subject Work Rates

<i>Metabolic parameter</i>	<i>Subject 1</i>	<i>Subject 2</i>	<i>BMS</i>
<i>Oxygen consumption rate</i>	1.0	1.0	1.0 liter/minute
<i>CO₂ production rate</i>	0.94	.80	0.94 liter/minute
<i>Ventilation rate</i>	33.0	24.0	22.3 liters/minute
<i>Respiratory frequency</i>	19	19	17 breaths/minute

Table IV. DEEC BMS vs. Human Subject 1 - Compressed-oxygen Apparatus

	<i>DEEC BMS</i>	<i>Human Subject 1</i>
	<i>n=2; 75-min avg</i>	<i>n=1; 71-min test avg</i>
<i>Duration, minutes:</i>	80 $\pm$ 1	71
<i>Minimum inhaled CO₂, %:</i>	0.4 $\pm$ 0.1	1.1
<i>Maximum inhaled O₂, %:</i>	83 $\pm$ 1	77
<i>Inhalation WB, °C:</i>	44.6 $\pm$ 0	47.3
<i>Inhalation DB, °C:</i>	45.6 $\pm$ 0.2	47.3
<i>Peak inhalation pressure, mm H₂O:</i>	-52 $\pm$ 2	-44
<i>Peak exhalation pressure, mm H₂O:</i>	36 $\pm$ 1	58

Evaluation: The human-subject test was terminated for high CO₂ levels at 71 minutes (6%, minimum inhaled) at the request of the test subject due to non-specific discomfort. Given that the BMS was programmed to match the human subject's metabolic rate, different from the standard metabolic rate, it was expected that the monitored stressor levels on the BMS and the human subject would be closer. To speculate on the reasons for the differences:

The performance of a CO₂-absorption bed is dependent on the dwell time of the CO₂ inside the chemical bed. The dead-space inside the breathing hose may result in higher inhaled CO₂ causing higher ventilation rates on human subjects which then reduces the dwell time. This may have caused a positive feedback loop which resulted in the early CO₂ breakthrough. A short, post-test experiment adding the breathing hose to ambient-air breathing did not, however, increase the ventilation rate of the first human subject. It may be that there is a physiological CO₂ threshold for increased ventilation which is higher than that resulting from adding the dead-space volume CO₂ to low- CO₂ ambient air.

The lower oxygen level in the human-subject test may be due to leaks at the breathing hose taps from the bouncing motion of walking prying open the hose tap holes in the breathing hose.

No explanation for the higher inhalation breathing temperatures on the human-subject test is offered. The temperature probe used for the human-subject test is a needle which, due to the large diameter necessary to puncture thick breathing hoses, has a longer response time than that used in the BMS tests, sometimes preventing full response; i.e., resulting in lower temperature readings. In addition, less chemical reaction in the bed would have resulted in lower temperatures, not higher ones.

Peak breathing pressure differences may be caused by differences in breathing wave form and peak flow rates which are extremely variable in human subjects.

Because of the unsatisfying results with the first human subject, a second human subject was enlisted to re-test the apparatus. The results are given below.

Table V. DEEC BMS vs. Human Subject 2 - Compressed-oxygen Apparatus

<i>75-minute test averages</i>	<i>DEEC BMS</i>	<i>Human Subject 2</i>
	<i>n=1</i>	<i>n=1</i>
<i>Duration, minutes:</i>	80	80
<i>Minimum inhaled CO₂, %:</i>	.1	0.5
<i>Maximum inhaled O₂, %:</i>	68	64
<i>Inhalation WB, °C:</i>	43.4	Not available
<i>Inhalation DB, °C:</i>	43.9	40.8
<i>Peak inhalation pressure, mm H₂O:</i>	-32	-40
<i>Peak exhalation pressure, mm H₂O:</i>	31	41

Evaluation: Both tests were terminated empty at 80 minutes with no significant CO₂ breakthrough in either test. This is undoubtedly because the $\dot{V}CO_2$ was lower for human subject 2 than for human subject 1. Similar to that for human subject 1, however, the inhaled CO₂ level was higher in the treadmill test than the BMS test with no obvious explanation. The inhaled O₂ level was lower in the treadmill test as with the other treadmill test, with the same probable cause. Human Subject 2 accidentally pulled the WB thermocouple out of the breathing hose shortly after beginning the test. The inhaled DB temperature was lower for this human subject than that for the BMS, unlike the other treadmill test. Also differing from the other treadmill test were the breathing pressures, both inhalation and exhalation pressures being greater than those with the BMS. This, at least, shows no inherent BMS design bias.

Table VI. DEEC BMS vs. Human Subject 1 - Chemical-oxygen Apparatus

<i>Full-duration test averages + SD</i>	<i>DEEC BMS</i>	<i>Human Subject 1</i>
	<i>n=2</i>	<i>n=1</i>
<i>Duration, minutes:</i>	46 ± 0	40
<i>Minimum inhaled CO₂, %:</i>	0 ± 0	0
<i>Maximum inhaled O₂, %:</i>	81 ± 10	81
<i>Inhalation WB, °C:</i>	41.9 ± 4.9	32.1
<i>Inhalation DB, °C:</i>	56.4 ± 0.7	55.0
<i>Peak inhalation pressure, mm H₂O:</i>	-135 ± 10	-127
<i>Peak exhalation pressure, mm H₂O:</i>	106 ± 6	99

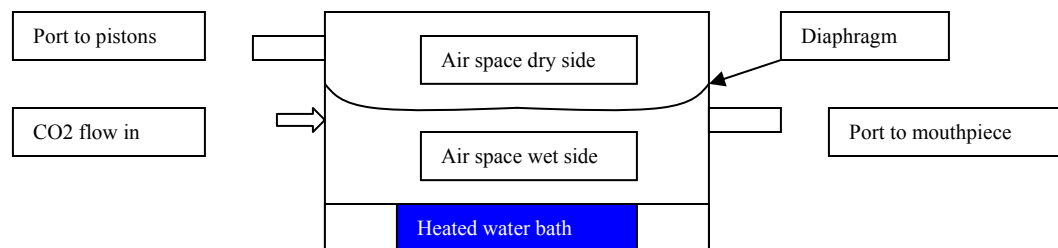
Table VII. DEEC BMS vs. Human Subject 2 - Chemical-oxygen Apparatus

<i>Full-duration test averages</i>	<i>DEEC BMS</i>	<i>Human Subject 2</i>
	<i>n=1</i>	<i>n=1</i>
<i>Duration, minutes:</i>	59	49
<i>Minimum inhaled CO₂, %:</i>	0	0
<i>Maximum inhaled O₂, %:</i>	83	84
<i>Inhalation WB, °C:</i>	35.9	Not available
<i>Inhalation DB, °C:</i>	48.7	41.9
<i>Peak inhalation pressure, mm H₂O:</i>	-104	-127
<i>Peak exhalation pressure, mm H₂O:</i>	95	78

Evaluation: The chemical-oxygen apparatus terminated empty in both human subject tests and BMS treadmill-equivalent tests but sooner in both treadmill tests. One of the BMS treadmill-equivalent tests for human-subject 1 had a low volume of starter oxygen which lowered the oxygen values from the beginning and resulted in the large standard deviation. The WB temperatures were extremely variable, possibly due to the sensitive nature of the probe itself (the thermocouple either drying out or being covered by a water droplet), especially problematic for human-subject tests. The DB temperatures were close for BMS and human-subject 1, but not for BMS and human-subject 2. The breathing pressures were different between BMS and both human subjects but with no clear bias.

CSE

The CSE BMS was built in-house utilizing a Silverman 622 (kg-m/min) cam driving a piston exchanging air with a breathing chamber sealed with a large rubber diaphragm. The air flow generated by this arrangement is transmitted by the diaphragm through a large water bath heated to 37°C, and then out through a mouth port. See Figure 9 for a partial diagram:

**Figure 9. CSE BMS.**

The water bath temperature in these tests was reduced to 32°C to better match that of human subjects and the NIOSH BMSs which are set to have exhalation WB and DB temperatures of between 31 and 33°C. The NIOSH BMS exhalation temperature setting is based on monitoring human subjects; in addition, Turner et al (1992) have shown that human exhalation WB and DB temperatures vary with inhalation WB and DB temperatures. The NIOSH BMSs replicate this behavior due to their thermal mass and heat exchange features. The greater quantity of water entrained in 37°C air would theoretically result in quicker reaction of chemical beds.

CO₂ in-flow is continuous to the wet side of the breathing chamber while gas volume removal, simulating oxygen consumption, is pulsatile, occurring during inhalation at the mouthpiece. The CSE

BMS has a bi-directional flow path and does not measure average inhaled gas concentrations. CSE estimates the average inhaled values by using the measured end-tidal gas concentrations, the known breath volume, and the volumetric dead space of the apparatus being tested. Only the minimum inhaled CO₂ and maximum inhaled O₂ are reported.

Three compressed-oxygen apparatus tests on the CSE simulator and one human-subject test on a treadmill were performed before a leak was found in the gas sampling line. In addition, a flawed method of analyzer calibration was being used which had different flow paths for analyzer calibration versus apparatus testing, and which pressurized the CO₂ and O₂ cells during calibration resulting in measurement errors. Only one compressed-oxygen apparatus test was run on the CSE simulator and one on CSE's treadmill after the corrections.

Table VIII. CSE BMS vs. DEEC BMS - Compressed-oxygen Apparatus

	DEEC BMS	CSE BMS
	<i>n</i> = 12; 75-min avg	<i>n</i> = 1; 74-min test avg
<i>Duration, minutes:</i>	81 ± 2	81
<i>Average inhaled CO₂, %:</i>	3.1 ± 0.2	NA
<i>Minimum inhaled CO₂, %:</i>	0.5 ± 0.1	.5
<i>Average inhaled O₂, %:</i>	76 ± 1	NA
<i>Maximum inhaled O₂, %:</i>	NA	88
<i>Inhalation DB, °C:</i>	47.6 ± 0.9	43.0
<i>Peak inhalation pressure, mm H₂O:</i>	-30 ± 4	-22
<i>Peak exhalation pressure, mm H₂O:</i>	30 ± 2	31

Evaluation: This limited data showed good correlation with the DEEC BMS in the areas of minimum inhaled CO₂ and peak pressures. Duration is determined, as discussed before, by the apparatus' oxygen flow rate, unrelated to BMS performance. Since CSE's simulation of oxygen consumption is not oxygen-selective, it was not surprising that oxygen concentrations were higher than those with the DEEC BMS. DB temperature was about 5° cooler on the CSE BMS. This is likely due to the large thermal mass of the water bath which serves as an anchor for exhalation temperature which, in turn, affects inhalation temperature.

Table IX. CSE BMS vs. DEEC BMS - Chemical-oxygen Apparatus

<i>Full-duration test averages + SD</i>	DEEC BMS	CSE BMS
	<i>n</i> =4	<i>n</i> =3
<i>Duration, minutes:</i>	47 ± 1	48 ± 1
<i>Average inhaled CO₂, %:</i>	1.3 ± 0	NA
<i>Minimum inhaled CO₂, %:</i>	0 ± 0	0 ± 0
<i>Average inhaled O₂, %:</i>	86 ± 0	NA
<i>Maximum inhaled O₂, %:</i>	NA	93 ± 5
<i>Inhalation DB, °C:</i>	49.8 ± 0.8	39.0 ± 6
<i>Peak inhalation pressure, mm H₂O:</i>	-58 ± 2	-54 ± 2
<i>Peak exhalation pressure, mm H₂O:</i>	45 ± 2	53 ± 2

Evaluation: This data showed good correlation with the DEEC BMS in the areas of duration, minimum inhaled CO₂, and breathing pressures. The higher maximum inhaled O₂ level in the CSE BMS test may be explained by the fact that, as previously mentioned, less oxygen is removed in the CSE volumetric oxygen consumption simulation, as well as by the fact that average inhaled O₂ level should be a little lower than the maximum value. The DB temperature averages on the CSE BMS were nearly 11° cooler than those on the DEEC BMS for presumably the same reason as speculated for the compressed-oxygen apparatus: the large thermal mass of the water bath on the CSE simulator.

CSE BMS vs. Human Subject

The human subject work rate at CSE was as follows:

<i>Metabolic parameter</i>	<i>CSE human subject</i>	<i>BMS</i>
<i>Oxygen consumption rate</i>	<i>1.0 liter/minute</i>	<i>1.0 liter/minute</i>
<i>CO₂ production rate</i>	<i>0.9 liter/minute</i>	<i>0.94 liter/minute</i>
<i>Ventilation rate</i>	<i>21.6 liters/minute</i>	<i>22.3 liters/minute</i>
<i>Respiratory frequency</i>	<i>22.8 breaths/minute</i>	<i>17 breaths/minute</i>

Since this was close to the BMS work rate, the results were compared directly to the BMS testing results using the standard work rate.

Table X. CSE BMS vs. Human Subject - Compressed-oxygen Apparatus

<i>Test averages</i>	<i>CSE BMS</i>	<i>Human Subject</i>
	<i>n=1; 70-min avg</i>	<i>n=1; 70-min avg</i>
<i>Duration, minutes:</i>	<i>81</i>	<i>70</i>
<i>Minimum inhaled CO₂, %:</i>	<i>0.4</i>	<i>0.3</i>
<i>Maximum inhaled O₂, %:</i>	<i>88</i>	<i>57</i>
<i>Inhalation DB, °C:</i>	<i>43.0</i>	<i>47.2</i>
<i>Peak inhalation pressure, mm H₂O:</i>	<i>-21</i>	<i>-70</i>
<i>Peak exhalation pressure, mm H₂O:</i>	<i>31</i>	<i>60</i>

Evaluation: Similar to the first NIOSH human-subject test, the CSE human-subject test was terminated during high CO₂ levels at 70 minutes (2.2%, minimum inhaled) at the request of the human subject for non-specific discomfort. The CO₂ level was higher than that of the CSE BMS at 70 minutes (1.3%) but with a slightly lower test-duration average than that of the CSE BMS. The lower O₂ in the human-subject test was due to a probable leak in the gas sampling hose tap, more obvious for O₂ than for CO₂ because of the higher O₂ concentration. The inhalation DB temperature on the human-subject test was higher than that of the CSE BMS, and nearly identical to that of the DEEC BMS (47.2 vs. 47.6°C). The breathing pressures were much higher than those of the CSE BMS, probably due to human reaction to rising CO₂ levels, since the pressures increased throughout the test, reflecting increasing ventilation rate.

Table XI. CSE BMS vs. Human Subject - Chemical-oxygen Apparatus

<i>Full-duration test averages + SD</i>	<i>CSE BMS</i>	<i>Human Subject</i>
	<i>n=3</i>	<i>n=1</i>
<i>Duration, minutes:</i>	<i>48 ± 1</i>	<i>48</i>
<i>Minimum inhaled CO₂, %:</i>	<i>0 ± 0</i>	<i>0</i>
<i>Maximum inhaled O₂, %:</i>	<i>93 ± 5</i>	<i>75</i>
<i>Inhalation DB, °C:</i>	<i>39.0 ± 0.6</i>	<i>52.8</i>
<i>Peak inhalation pressure, mm H₂O:</i>	<i>-54 ± 2</i>	<i>-59</i>
<i>Peak exhalation pressure, mm H₂O:</i>	<i>53 ± 2</i>	<i>37</i>

Evaluation: Test termination was an empty breathing bag on both the human-subject and BMS tests. There was good correlation between the CSE BMS and human subject in the areas of duration, CO₂ level, and inhalation breathing pressure. O₂ level was lower in the human-subject test, again likely due to a sample gas breathing hose tap leak, more obvious for O₂ than for CO₂ because of the higher O₂ concentration. DB temperature was much higher on the human-subject test than the CSE BMS, closer to both the NIOSH BMSs. As previously mentioned, this is probably due to the large thermal mass of the water bath in the CSE BMS.

Ocenco

Since the conceptual design of the BMS at Ocenco's headquarters in Pleasant Prairie, Wisconsin, is the same as those at NIOSH, including it in this study amounts to comparing the BMS peripherals, the various instrument and program settings, and the human operators of the BMS. After encountering technical problems during the Ocenco testing, it was decided that there was not enough reason to include the Ocenco BMS considering the expected effort and it was dropped from the study.

Dräger

The Dräger BMS (Figure 10) was built in-house using a Dräger motor bellow ventilator, as Dräger describes it. It has a uni-directional flow path from flow-splitting check valves on either side of the mouth. The lung is operated by a servo-motor. In the basic set-up, there is temperature and pressure monitoring at the mouth but no gas monitoring there. CO₂ and O₂ are monitored in the inhalation path from an auxiliary lung which extracts a sinusoidal portion of the inhaled breath stroke equal in volume to the desired $\dot{V}O_2$ /breathing frequency. Then the inhaled gas goes through a cooler before entering the main lung. CO₂ flows continually through a check valve to a point immediately before the main lung, with excess (during exhalation) diverted to an ancillary bellows. Exhalation gas flows through a heating/humidifying chamber in one of, or a combination of, three flow paths: 1) across the top surface of a heated water bath; 2) through a pipe under the water but having no contact with the water (heat without humidity); or 3) bypassing the heating/humidifying chamber (no heat or humidity). The flow path is adjusted automatically to ensure exhalation temperature and humidity attain the target values. Exhalation CO₂ is sampled on the exit side of the heating/humidifying chamber and returned to the exhalation gas path before the chamber.



Figure 10. Photo of Dräger BMS.

Dräger set their exhalation temperature to 32°C for this testing instead of their normal 37°C, the European standard. A separate large oxygen cylinder was used for testing the AU-9A1 instead of the original apparatus cylinder, and tests were all terminated at 80 minutes.

Table XII. Dräger BMS vs. DEEC BMS - Compressed-oxygen Apparatus

<i>75-minute test averages + SD</i>	<i>DEEC BMS</i>	<i>Dräger BMS</i>
	<i>n=12</i>	<i>n=3</i>
<i>Duration, minutes:</i>	81 ± 2	80
<i>Average inhaled CO₂, %:</i>	3.1 ± 0.2	2.0 ± 0.2
<i>Minimum inhaled CO₂, %:</i>	0.5 ± 0.1	NA
<i>Average inhaled O₂, %:</i>	76 ± 1	86 ± 0
<i>Inhalation DB, °C:</i>	47.6 ± 0.9	41.4 ± 0.6
<i>Peak inhalation pressure, mm H₂O:</i>	-30 ± 4	-28 ± 2
<i>Peak exhalation pressure, mm H₂O:</i>	30 ± 2	32 ± 2

Evaluation: Average inhaled CO₂ was about two-thirds that obtained with the DEEC BMS. This is believed to be because the end-tidal CO₂ was approximately 5.5% on the Dräger BMS versus over 9% on the DEEC BMS. The end-tidal CO₂ is what is contained in the apparatus dead space which causes the average inhaled CO₂ to be higher than the minimum inhaled CO₂. Uni-directional BMSs exhibit exhalation CO₂ waveforms resembling square waves, with CO₂ concentration being flat from the beginning of the breath to the end. The DEEC BMS design, however, exhibits CO₂ waveforms with CO₂ rising from beginning to end, more resembling human breathing.

Oxygen values are also higher on the Dräger BMS, presumably due to the volumetric-equivalent oxygen consumption simulation. DB inhalation temperature on the Dräger BMS was about 6°C lower than that obtained on the DEEC BMS. This is presumably due to the Dräger BMS holding exhalation temperature fast to the set exhalation temperature even as inhalation temperature from the apparatus

risers, while the DEEC BMS permits exhalation temperature to rise as the inhalation temperature from the apparatus rises.

The peak breathing pressures were very close to those obtained on the DEEC BMS.

Table XIII. Dräger BMS vs. DEEC BMS - Chemical-oxygen Apparatus

<i>Full-duration averages + SD</i>	<i>DEEC BMS</i>	<i>Dräger BMS</i>
	<i>n=4</i>	<i>n=3</i>
<i>Duration, minutes:</i>	47 ± 1	46 ± 0
<i>Average inhaled CO₂, %:</i>	1.3 ± 0	$.6 \pm 0$
<i>Minimum inhaled CO₂, %:</i>	0 ± 0	NA
<i>Average inhaled O₂, %:</i>	86 ± 0	86 ± 0
<i>Inhalation DB, °C:</i>	49.8 ± 0.8	50.3 ± 1.4
<i>Peak inhalation pressure, mm H₂O:</i>	-58 ± 2	-55 ± 8
<i>Peak exhalation pressure, mm H₂O:</i>	45 ± 2	49 ± 4

Evaluation: Average inhaled CO₂ was significantly lower on the Dräger BMS than that obtained on the DEEC BMS, for presumably the same reasons as those given for the compressed-oxygen apparatus. The test-averages for the average inhaled oxygen concentrations were identical for both BMSs, inexplicably. It is interesting to note that both types of apparatus had the same oxygen concentration on the Dräger BMS which may or may not be a coincidence. The DB temperatures obtained for both BMSs are essentially the same. Dräger adjusts the flow path through their heater/humidifier differently for chemical-oxygen and compressed-oxygen apparatus, biased towards less humidity for KO₂ apparatus. The peak breathing pressures were also very close to those obtained on the DEEC BMS. This is presumably due to the wave form shapes of both BMSs being a sine wave and, thus, having the same peak flow rates.

Dräger BMS versus Human Subject

In measuring the metabolic parameters for human-subject testing, Dräger used a Panorama Nova face mask to split the flow paths, measuring the inspired ventilation rate ($\dot{V}_i$) with a mass flow meter, and measuring the cycling gas concentrations in the mask, using the high CO₂ and low O₂ peaks to represent the exhalation gas. This aroused two areas of concern: since the face mask had substantial dead space resulting in non-zero inhalation CO₂ values, this possibly exaggerates the exhalation CO₂ values, and measuring inhalation flow instead of exhalation may bias the value depending upon the application of the conversion factor and the assumptions of temperature, pressure, and humidity. It was (months) later found that, using a small-dead-space 'T' valve to split the flow paths, and measuring ventilation rate and gas concentrations in an exhalation collection bag, the actual $\dot{V}O_2$ values were found to be approximately 0.64 of the values obtained with the previous method. Below are the original (errant) human-subject measurements:

Table XIV. Dräger Human Subject Work Rates

	<i>Subject 1</i>	<i>Subject 2</i>	<i>BMS</i>
<i>Oxygen consumption rate</i>	1.1	1.0	1.0 liter/minute
<i>CO₂ production rate</i>	0.87	.90	0.94 liter/minute
<i>Ventilation rate</i>	19.0	19.4	22.3 liters/minute
<i>Respiratory frequency</i>	17	15	17 breaths/minute

Table XV. Dräger BMS vs. Human Subject - Compressed-oxygen Apparatus

<i>75-minute test averages + SD</i>	<i>Dräger BMS</i>	<i>Human Subject 1</i>
	<i>n=3</i>	<i>n=1</i>
<i>Duration, minutes:</i>	80 ± 0	80
<i>Average inhaled CO₂, %:</i>	2.0 ± 0.2	NA
<i>Minimum inhaled CO₂, %:</i>	NA	0.1
<i>Average inhaled O₂, %:</i>	86 ± 0	NA
<i>Maximum inhaled O₂, %:</i>	NA	82
<i>Inhalation DB, °C:</i>	41.4 ± 0.6	45.5
<i>Peak inhalation pressure, mm H₂O:</i>	-28 ± 2	-35
<i>Peak exhalation pressure, mm H₂O:</i>	32 ± 2	39

Evaluation: Since the oxygen consumption and CO₂ production rates on the human subjects were only about two-thirds that of the BMS, comparisons are limited. They are further limited by the fact that average inhaled gas concentrations were measured on the BMS versus minimum CO₂ values and maximum O₂ values on the human subjects. Only the respiration rate on the human subject was comparable to that of the BMS. This is possibly evidenced by the similarity of the breathing pressures.

Table XVI. Dräger BMS vs. Human Subject - Chemical-oxygen Apparatus

<i>Full-duration averages + SD</i>	<i>Dräger BMS</i>	<i>Human Subject 2</i>
	<i>n=3</i>	<i>n=1</i>
<i>Duration, minutes:</i>	46 ± 0	54
<i>Average inhaled CO₂, %:</i>	.6 ± 0	NA
<i>Minimum inhaled CO₂, %:</i>	NA	0
<i>Average inhaled O₂, %:</i>	86 ± 0	NA
<i>Maximum inhaled O₂, %:</i>	NA	83
<i>Inhalation DB, °C:</i>	50.3 ± 1.4	49.3
<i>Peak inhalation pressure, mm H₂O:</i>	-55 ± 8	-85
<i>Peak exhalation pressure, mm H₂O:</i>	49 ± 4	55

Evaluation: The duration obtained on the human-subject test relative to that of the BMS was approximately inversely proportional to the relationship between the two ventilation rates. The water vapor exhaled into the chemical bed determines the reaction rate to a large extent. As with the other human-subject test, it is difficult to make comparison with most of the measured stressors.

New South Wales Mine Safety Technology Centre

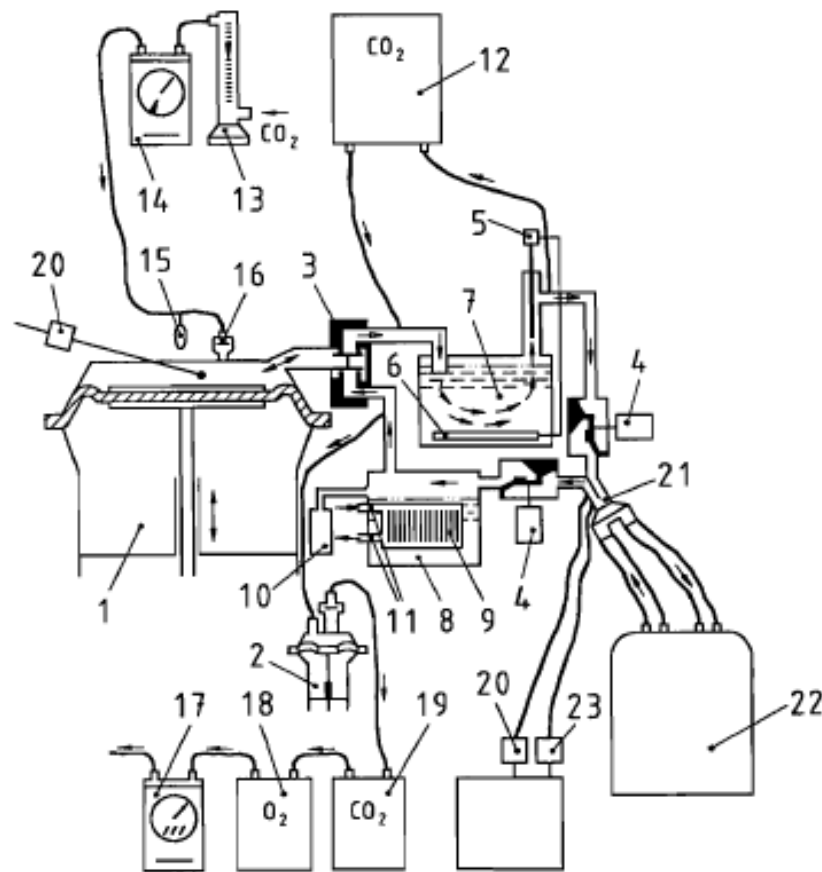
The Centre uses an Auer 57 simulator at its core with some modifications such as continually adding CO₂ directly to the main lung (bellows) instead of via the second auxiliary lung on a pulsatile basis (Figures 11-13). Two electric solenoid valves at the mouth, activated by the lung, open and close upon inhalation and exhalation, ensuring a uni-directional flow path through the simulator. Inhaled air passes through a condenser before it enters the main lung. During inhalation, the first auxiliary lung pulls gas from the line between the condenser and the main lung, effecting (volumetric-equivalent) oxygen removal and is dumped, during exhalation, to a small Plexiglas cylinder which vents to a beaker filled with water through a coiled hose under the water. Oxygen and CO₂ are sampled from the Plexiglas cylinder by a pump drawing gas continuously and pushing the sample through a flow meter and then to the O₂ and CO₂ analyzers, dumping to ambient. During exhalation of the first auxiliary lung, any gas not pulled by the pump is dumped to the beaker of water. Since the sample gas pump continually draws gas from the Plexiglas cylinder, this causes water to be pulled back into the coiled hose during inhalation.



Figure 11. New South Wales Mine Safety Technology Centre BMS.



Figure 12. New South Wales Mine Safety Technology Centre BMS, close-up.



- 1 Breathing machine
- 2 Auxiliary lung (controlled by the breathing machine)
- 3 Valve system
- 4 Control valve (controlled by the breathing machine)
- 5 Thermostat
- 6 Heating element (controlled by the thermostat)
- 7 Humidifier (see figure 3)
- 8 Conditioner (see figure 2)
- 9 Cooling ribs
- 10 Container for condensed water
- 11 Cooling water in- and out-put
- 12 Carbon dioxide analyser (exhaled air)
- 13 Control and measurement system for carbon dioxide
- 14 Gasmeter for carbon dioxide
- 15 Compensation bag for carbon dioxide dosage
- 16 Non-return valve
- 17 Gasmeter for the sampling air
- 18 Oxygen analyser
- 19 Carbon dioxide analyser and recorder (inhalation air)
- 20 Temperature measuring equipment with plotter
- 21 Connector (see figures 4, 5 and 6)
- 22 Breathing apparatus
- 23 Pressure meter with plotter

Figure 13. Schematic of Auer BMS from EN 145, March 2000.

NSW MSTC BMS versus DEEC BMS

Oxygen was supplied to the AU-9A1 by an external cylinder and all tests were terminated at 80 minutes. The first test run on the AU-9A1 had a leak around a temperature probe tap in a drain line after the condenser and the data was not used in the averages. After completion of the testing, it was found that the respiratory frequency was incorrectly set at 18.5 breaths/min instead of 17.0 breaths/min. Since

the $\dot{V}_e$, $\dot{V}O_2$, and $\dot{V}CO_2$ were all set on a flow-rate basis measured by dry gas meter independently of RF, this error resulted only in lower tidal volume and peak flow rates.

Table XVII. NSW MSTC BMS vs. DEEC BMS - Compressed-oxygen Apparatus

<i>75-minute averages + SD</i>	<i>DEEC BMS</i>	<i>NSW MSTC BMS</i>
	<i>n=12</i>	<i>n=2</i>
<i>Duration, minutes:</i>	81 ± 2	80
<i>Average inhaled CO₂, %:</i>	3.1 ± 0.2	2.4 ± 0.1
<i>Average inhaled O₂, %:</i>	76 ± 1	88 ± 1
<i>Inhalation DB, °C:</i>	47.6 ± 0.9	43.2 ± 0.1
<i>Peak inhalation pressure, mm H₂O:</i>	-30 ± 4	-20 ± 3
<i>Peak exhalation pressure, mm H₂O:</i>	30 ± 2	28 ± 1

Evaluation: The results obtained with the MSTC simulator differ from those of the DEEC simulator for largely the same reasons the Dräger simulator differs from the DEEC simulator.

Table XVIII. NSW MSTC BMS vs. DEEC BMS - Chemical-oxygen Apparatus

<i>Full-duration averages + SD</i>	<i>DEEC BMS</i>	<i>NSW MSTC BMS</i>
	<i>n=4</i>	<i>n=3</i>
<i>Duration, minutes:</i>	47 ± 1	46 ± 0
<i>Average inhaled CO₂, %:</i>	1.3 ± 0	0.9 ± 0
<i>Average inhaled O₂, %:</i>	86 ± 0	82 ± 4
<i>Inhalation DB, °C:</i>	49.8 ± 0.8	42.0 ± 1.0
<i>Peak inhalation pressure, mm H₂O:</i>	-58 ± 2	-46 ± 3
<i>Peak exhalation pressure, mm H₂O:</i>	45 ± 2	42 ± 1

Evaluation: The most notable difference in results between the simulators is that, like the CSE BMS, the DB temperature is much lower on the MSTC simulator than that of the DEEC for likely the same reason: the large thermal mass of the heater/humidifier. The only anomaly was the oxygen concentrations being lower than those of the DEEC and being lower than those obtained with the AU-9A1 on the same simulator; no explanation is obvious for this.

CONCLUSIONS

The most notable differences between the simulators included in this study are 1) the lower average inhaled CO₂ concentrations measured by the simulators having uni-directional versus bi-directional internal flow paths; and 2) the lower DB inhalation temperatures measured on chemical-oxygen apparatus by the simulators having large water baths forcing exhalation gas to be fully saturated at 37°C regardless of inhalation temperature. Artificially low end-tidal CO₂ is thought to be responsible for the first difference; unhumanlike thermal inertia is thought to be responsible for the second.

The faster CO₂ breakthrough in the human-subject tests compared with both NIOSH BMSs for both the compressed- and chemical-oxygen apparatus is unexplained and perplexing. This also occurred at CSE with the compressed-oxygen apparatus only. More thinking is needed to fully explain these findings. Of note for EN certification standards, volumes are not specified at STPD or any particular set of environmental conditions. This results in molecular inequivalency, varying mainly with ambient barometric pressure which is significantly lower in Johannesburg, South Africa than at sea level.

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