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Cryogenic Air Supply Feasibility for a Confined Space: Underground Refuge Alternative Case Study

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Abstract

A breathable air source is required for a confined space such as an underground refuge alternative (RA) when it is occupied. To minimize the risk of suffocation, federal regulations require that mechanisms be provided and procedures be included so that, within the refuge alternative, the oxygen concentration is maintained at levels between 18.5% and 23% for 96 h. The regulation also requires that, during use of the RA, the concentration of carbon dioxide should not exceed 1%, and the concentration of carbon monoxide should not exceed 25 ppm. The National Institute for Occupational Safety and Health (NIOSH) evaluated the cryogenic air supply's ability to provide breathable air for a refuge alternative. A propane smoker was used to simulate human breathing by burning propane gas which will consume O_2 and generate CO_2 and H_2O. The rate of propane burned at the smoker was controlled to represent the O_2 consumption rate for the breathing of a certain number of people. Two 96-h tests were conducted in a sealed shipping container, which was used as a surrogate for a refuge alternative. While burning propane gas to simulate human oxygen consumption, cryogenic air was provided to the shipping container to determine if the cryogenic air supply would keep the O_2 level above 18.5% and CO_2 level below 1% inside the shipping container as required by the federal regulations pertaining to refuge alternatives. Both of

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the 96-h tests simulated the breathing of 21 persons. The first test used the oxygen consumption rate (1.32 cu ft of pure oxygen per hour per person) specified in federal regulations, while the second test used the oxygen consumption rate specified by (Bernard et al. 2018, “Estimation of Metabolic Heat Input for Refuge Alternative Thermal Testing and Simulation,” Min. Eng., **70**(8), pp. 50–54) (0.67 cu ft of pure oxygen per hour per person). The test data shows that during both 96-h tests, the oxygen level was maintained within a 21–23% range, and the CO_2 level was maintained below 1% (0.2–0.45%). The information in this paper could be useful when applying a cryogenic air supply as a breathable air source for an underground refuge alternative or other confined space. [DOI: 10.1115/1.4064062]

Keywords

confined space; gas concentration; breathable air; cryogenic air supply

1 Introduction

Human breathing consumes oxygen (air) and generates a significant amount of carbon dioxide. Air quality control is required to sustain the survivable environment in a confined space such as a submarine or RA. In considering the breathing activities of the occupants of such confined spaces, the oxygen and carbon dioxide levels are the major concerns. Numerous research studies have been conducted to address that concern in the past decades [1–8]. The federal regulations require that the oxygen concentration be maintained at levels between 18.5% and 23% for 96 h in an occupied RA, and the concentration of carbon dioxide should not exceed 1% [9,10]. The breathing activities by occupants will deplete the oxygen and generate carbon dioxide within the confined space. Without a breathable air supply and CO_2 mitigation, the oxygen level will drop below the safety limit, and the CO_2 level will also quickly increase beyond the safety limit [11].

Cryogenic air supplies are a developing technology that may be able to serve as a breathable air source as well as a heat mitigation strategy for RAs that are used in underground mines. Before cryogenic air is supplied to an occupied RA, the temperature of the cryogenic air is kept refrigerated at −195 °C (−318 °F) temperature inside a large dewar using a cryocooler. System pressure in the dewar is kept below 207 kPa (30 psi), which is considerably less than the storage pressure in the oxygen cylinders currently used to supply breathable air. The stability of the system in the event of an electrical power failure or during moving of the RA is not a concern. Research has shown that even without refrigeration, when the cryocooler is not in operation, the liquid air remains in a stable condition within the dewar for an extended period of up to 7 days [12].

CO_2 mitigation will be needed to maintain the CO_2 level below the 1% limit in an RA. Without mitigation, the CO_2 concentration can exceed the 1% limit even when the oxygen level is within the 18.5–23% range [10].

In this paper, researchers evaluate the cryogenic air supply as a breathable air source in a sealed shipping container (the confined space) to simulate an RA. A human breathing simulator (HBS) was developed and used in the tests to simulate human breathing.

2 Concept and Methodology

Human breathing can be simulated by burning propane. The burning process will consume oxygen and generate carbon dioxide and water like human breathing. The combustion equation for propane is given by Eq. (1) shown below. The process will also generate heat, but this paper focuses on the gas concentration only. To simulate the breathing activity by a certain number of people, the propane mass flowrate will be adjusted so that it consumes oxygen at the same rate as human breathing based on the mass ratio specified in Table 1. For example, to simulate the breathing of ten (10) people, the propane mass flowrate can be determined as follows. Assume the oxygen consumption rate is 1.32 ft^3/h/person (or 0.623 L/min/person) [9]. The oxygen density at room temperature is 1.291 g/L, so the oxygen consumption rate (mass) for ten (10) people is 0.623 L/min/person × 1.291 g/L × 10 persons = 8.043 g/min. Based on the mass ratio specified in Table 1, the amount of propane required to simulate the breathings of 10 people is $\frac{8.043\,\mathrm{g/min}}{3.63} = 2.216\,\mathrm{g/min}$

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \tag{1}$$

A cryogenic air supply evaluation (CASE) Lab was built to perform the tests. The CASE Lab comprises a shipping container (the confined space), a HBS, and a cryogenic air system (air storage and delivery). Various sensors/instruments were installed to monitor the gas concentration and other parameters at various locations. As a safety consideration, the propane tank was located outside of the building.

2.1 The Shipping Container (The Confined Space).

A 20-ft-long by 8-ft-wide by 8-ft-high shipping container was used to represent a refuge alternative or other confined space (Fig. 1). It was modified so that the cryogenic air system can deliver cryogenic air to the heat exchanger inside. Based on the floor area of the shipping container, all tests were set to simulate the breathing of 21 people.

2.2 The Human Breathing Simulator.

A HBS was developed to simulate human breathing by using a double-burner propane smoker (Fig. 2(a)). The propane flowrate can be adjusted to simulate breathings of the desired number of people by using a propane mass flow controller (Fig. 2(b)). The propane mass flow controller was located outside of the shipping container so that it could be adjusted during the test if needed. A solenoid valve was installed next to the mass flow controller and was controlled by a flame detector located near the smoker burners. In case the flame went out, the flame detector sent a voltage signal to shut off the solenoid valve in a few seconds.

2.3 The Cryogenic Air System.

The cryogenic air system has a 2000-liter horizontal-oriented dewar (Fig. 3). It has a spring-loaded pressure relief valve set at 517.1 kPa (75 psi). Two digital scales—one under each end—were used to monitor the weight of the liquid air remaining in the dewar. An Omega PX309–100GI-OX pressure transducer was installed at the dewar to monitor the pressure of the gases in the ullage space above the liquid air (Fig. 3). The transducer was oxygen cleaned due to its contact with oxygen-rich liquid or gas. The pressure transducer was connected to a data acquisition system to record the pressure during testing.

The dewar was connected to the heat exchanger (also referred to as an air handler) that was placed within the shipping container with a vacuum-jacketed hose (Fig. 4). To start the test, the cryocooler was turned off and the internal pressure built up. The liquid air inside the dewar expanded due to the increased pressure and delivered to the heat exchanger through the vacuum-jacketed hose. As the liquid courses through the heat exchanger, the heated air from the surroundings warmed and expanded the liquid air to gas, which was the primary supply of breathable air to the shipping container. The vaporization process and the introduction of cool breathable air not only reduced the temperature within the shipping container but also dehumidified the shipping container as the warm ambient air was drawn through the heat exchanger. Frost and ice formed on the heat exchanger fins, subsequently melting and draining into the collection tank below (the white tank in Fig. 4). This collected water could be an added or emergency supply of drinking water if necessary. More information about the dewar operates and the construction of the CASE Lab can be found in [12] and [13], respectively.

3 Test Setup

Multiple gas sensors were used to measure the $\%CO_2$ and $\%O_2$ at various locations inside the CASE lab (Fig. 5). To measure the $\%CO_2$, two CTI GG-CO_2 carbon dioxide sensors were positioned within the shipping container. The two sensors were located approximately 6 inches and 3 inches from the floor and positioned around 6.5 feet and 13 feet from the end-wall of the laboratory,, respectively. To measure the $\%O_2$, two Macurco OX-6 oxygen sensors were positioned approximately 6 inches and 3 inches from the floor and positioned around 6.5 feet and 13 feet from the end-wall of the laboratory, respectively. One additional O_2 monitor was positioned near the air pump to document the $\%O_2$ in the combustion air.

The sensor data were recorded using a Data Translation DT-9874 data acquisition system. All data were recorded at a sample rate of 2 samples per second with 24-bit resolution.

Procedures were taken to ensure safety during the tests. A Beacon 800 gas monitoring system with multiple CO_2 sensors, an O_2 sensor, a carbon monoxide sensor, and percentage lower explosive limit (% lower explosive limit (LEL)) sensor were used to ensure all gases within the test lab were at safe levels. If the gas levels exceeded predetermined levels, the Beacon 800 would activate an audible alarm to alert researchers. The presence of a flame in the HBS was monitored using a flame detector and a video camera. If the flame went out, the flame detector would activate an audible alarm and automatically turn off the propane flow via a solenoid valve. Gas monitors at the data acquisition table were used to ensure the O_2, CO_2, CO, and propane levels were at safe levels.

A group of CO_2 scrubbing curtains (Calcium Hydroxide or soda lime) were used to absorb and maintain the $\%CO_2$ level during the test (Fig. 6). As mentioned earlier, the CO_2 concentration can exceed the 1% limit due to breathing even when the oxygen level is within the 18.5–23% range if there is no CO_2 mitigation. Each curtain weighs 10 lbs and has a dimension of 3.3-ft long × 1.8-ft wide × 0.5-inch thick. According to the manufacturer, one (1) curtain is required per person/day. To absorb the CO_2 generated by 21 people, 105 pieces of curtain (21 people × 5 days × 1 piece/person/day) were used for each 96-h test.

4 Test Results

Four tests were performed at the CASE Lab to investigate the feasibility of cryogenic air supply as a breathable air source in a confined space. Two 96-h tests were conducted using two oxygen consumption rates. The federal regulations specify the O_2 consumption rate to be 1.32 ft^3/h/person and the CO_2 generation rate to be 1.08 ft^3/h/person (Test #1) [9]. The research conducted by the University of South Florida specifies the O_2 consumption rate to be 0.67 ft^3/h/person and the CO_2 generation rate to be 0.60 ft^3/h/person (Test #2) [14]. Two additional tests were performed (Test #3 and Test #4) for a shorter time (<96 h). The purpose of those two tests was to investigate how fast the CO_2 level will exceed the safety limit (1%) if no CO_2 scrubbing curtain was presented, and how fast the O_2 level will drop below the safety limit (18.5%) if no breathable air source is available.

4.1 Test #1 (96-h Test, 1.32 ft^3/h/Person O_2 Consumption Rate).

The cryo dewar was filled with approximately 2000 liters of cryogenic air before the test by mixing the liquid nitrogen (N_2) and liquid oxygen (O_2). The $\%O_2$ level was monitored during and after the filling process to make sure that the O_2/N_2 mass ratio is the same of the air. For safety purpose, the dewar was always filled with liquid nitrogen first, so the dewar internal content was not oxygen rich during the filling process. The cryogenic air was kept in a liquid stage by the cryocooler. To start the test, the cryocooler was turned off. The pressure build-up valve was then opened, and the internal pressure increased. The increased pressure then forced the liquid air into the heat exchanger located inside the shipping container. A 1.32 ft^3/h/person O_2 consumption rate was used in this test. The propane flowrate was set to be 21 × 1.32 = 27.72 ft^3/h to simulate the breathing of 21 persons with the O_2 consumption rate specified above. Figure 7 shows the weight change of the cryogenic tank during the test. As shown in Fig. 7, the cryogenic system delivered cryogenic air to the shipping container at a rate of 25.5 lb/h (11.56 kg/h) during the 96-h test period.

The internal $\%O_2$ level changing with time is plotted in Fig. 8. The test showed that, while the HBS simulated the breathing of 21 persons at 1.32 ft^3/h/person O_2 consumption rate, the cryogenic air supply maintained the $\%O_2$ level in the 20.5–23% range during the 96 test hours. The red line in Fig. 8 refers to the measurement within the combustion duct in which the $\%O_2$ was significantly low. However, the $\%O_2$ levels at other locations were within the safety limit (18.5–23%) during the test.

Figure 9 shows the internal $\%CO_2$ level changing with time during the test. With a rate of 25.5 lb/h (11.56 kg/h) of cryogenic air supply, the shipping container internal $\%CO_2$ level maintained at 0.3–0.5% during the 96 test hours, which is below the 1% limit. Note that a spike exists at around hour 50. It was caused by a frozen needle valve that controls the cryogenic air flow to the heat exchanger from the dewar.

4.2 Test #2 (96-h Test, 0.67 ft^3/h/Person O_2 Consumption Rate).

Test #2 basically duplicated Test #1 except the O_2 consumption rate. The cryo tank was refilled with cryogenic air under full storage capacity (2000 liters). A 0.67 ft^3/h/person O_2 consumption rate was used in this test. The propane flowrate was set to be 21 × 0.67 = 14.07 ft^3/h to simulate the breathing of 21 persons with the O_2 consumption rate specified above. Figure 10 shows the weight changes of the cryogenic air during the test. As shown in Fig. 10, the cryogenic system delivered cryogenic air to the shipping container at a rate of 25.1 lb/h (11.38 kg/h).

The internal $\%O_2$ level changing with time is plotted in Fig. 11. The test showed that while the HBS simulated the breathing of 21 persons at 0.67 ft^3/h/person O_2 consumption rate, the cryogenic air supply maintained the $\%O_2$ level in the 20–23% range during the 96 test hours. The red line in Fig. 11 refers to the measurement within the combustion duct in which the $\%O_2$ was significantly low. However, the $\%O_2$ levels at other locations were very uniform and within the safety limit (18.5–23%) during the test.

Figure 12 shows the internal $\%CO_2$ level changing with time during the test. With a rate of 25.1 lb/h (11.38 kg/h) of cryogenic air supply, the shipping container internal $\%CO_2$ level was maintained in the 0.2–0.4% range during the 96 test hours, which is below the 1% limit. Note that the bumps in Fig. 11 and the spikes in Fig. 12 at around hour 80. They were caused by a frozen needle valve that controls the cryogenic air flow to the heat exchanger from the dewar.

4.3 Test #3 (2-h Test, Same Setting as in Test #1, But No CO_2 Scrubbing Curtain).

To investigate how fast the CO_2 level will exceed the safety limit (1%) if no CO_2 mitigation, this test used the same setting as in Test #1 (1.32 ft^3/h/person O_2 consumption rate, HBS to simulate the breathing of 21 people, ~25.5 lb/h (11.56 kg/h) rate of cryogenic air supply), but all the CO_2 scrubbing curtains (the soda lime curtains) were removed from the shipping container. As shown in Figs. 13 and 14, the CO_2 concentration exceeded the 1% limit in 1 h when there was no CO_2 mitigation, and even the oxygen level was kept within the 18.5–23% range. This contrasted to the data in Test #1 and Test #2 in which the $\%CO_2$ level was maintained well below the 1% limit during the entire 96-h test period if CO_2 mitigation was used. The test was terminated at 2 h.

4.4 Test #4 (2-h Test, Same Setting as in Test #1, But No Cryo Air Supply, No CO_2 Scrubbing Curtain).

In this test, the same setting was used as in Test #1 (1.32 ft^3/h/person O_2 consumption rate, HBS to simulate the breathing of 21 people), but the cryogenic air supply to the shipping container was shut off (no cryogenic air supply), and all the CO_2 scrubbing curtains were removed from the shipping container. Without a breathable air supply, the interior oxygen will be depleted due to the breathing (propane burning), and the $\%O_2$ level will drop below the safety limit quickly (Fig. 15). The plot shows that the $\%O_2$ level dropped below 17% and the $\%CO_2$ level exceeded 2% in 2 h after the test started. The test was terminated at approximately 2 h because the gas concentration already exceeded the safety range. Figure 15 also shows the test data compared with a mathematical model. The confined space (the shipping container) is equipped with a pressure relief valve which allows air to release to outside of the space when the internal pressure reaches the set point of the relief valve. There are two sources that bring CO_2 into the confined space: the fresh air flow and the breathing by the occupants. There is one outward flow that allows CO_2 to exit the confined space through the exhaust pipe. It is reasonable to assume that the amount of the air exiting the space equals the amount of air entering the space, i.e., the outward air flowrate and inward air flowrate are the same. By tracing the CO_2 mass change within the confined space within an infinite time-step and applying appropriate initial conditions, a mathematical model that accurately descripts the event is then developed. The model will give the analytical solution of the $\%CO_2$ level at any time after testing starts. The model predicted well the gas concentration as shown in the plot. More details about the model can be found in [15].

5 Discussion

A temperature/humidity sensor was used to monitor interior temperature and relative humidity during all the tests. A test would be terminated if the temperature exceeded a certain level for safety reasons. However, due to the cooling capacity of the cryogenic air supply, the interior temperature was maintained and stabilized at below 95°F during both 96-h tests. The temperature and humidity data are not presented here because the data are not related to the topic of this paper.

Table 2 lists the desired propane burning rate for 21 people at two different O_2 consumption rates—1.32 ft^3/h/person and 0.67 ft^3/h/person. The CO_2 generation rates are also listed in the table. Because burning propane generates less CO_2 than human breathing for a set oxygen consumption rate, supplemental CO_2 was added to match both oxygen consumption and CO_2 generation.

Test #1 and Test #2 show that the cryogenic air supply can maintain the oxygen level within the 18.5–23% range during the entire 96-h period. During both tests, the cryogenic air supply fed the shipping container with cryogenic air at a rate of approximately 25 lb/h (11.34 kg/h), which was the minimum flowrate of the cryogenic air system. This cryogenic air supply rate could be reduced further in order to maintain the oxygen level within the safety range if the cryogenic air system had the capacity to decrease the flowrate more. An improvement for the cryogenic air system is to have the capacity of adjusting the cryogenic airflow rate from inside. Currently, the CASE Lab can only adjust the cryogenic air flowrate from outside of the shipping container during the test or occupancy. For application purposes, it would be desirable to have the capability of adjusting the air flow from inside by adding an adjustable valve at the heat exchanger.

Test #3 demonstrated the efficiency of the CO_2 scrubbing curtain on maintaining the CO_2 level. The CO_2 level will increase dramatically if there is no CO_2 mitigation used, and even the oxygen concentration is kept in the safety range. For occupied confined spaces, a suitable CO_2 mitigation strategy is needed to absorb the CO_2 generated by breathing and to maintain the CO_2 level below the safety limit.

Test #4 shows that without the cryogenic air supply, the %O_2 level will drop down quickly below the safety limit in less than 2 h. Without adding fresh air into the confined space, the breathing activities will eventually deplete all the oxygen inside it.

All the gas concentrations were measured by %volume on the sensors. However, it would be more convenient to use the gas concentration by %mass in modeling or mass calculation. More details on the conversion between gas %volume and %mass can be found in [15].

6 Limitations

In this research, a modified shipping container was used to simulate the RA or other confined space. However, confined spaces often have unique characteristics such as specific gas concentrations, temperature, humidity, or hazardous substances. A shipping container may not provide an accurate representation of these environmental factors, and these results should not be extrapolated beyond the context of underground U.S. coal mine environments.

An average oxygen consumption rate was used to calculate the desired propane flowrate to represent human breathing. However, the oxygen consumption rate can vary from person to person. The age, body size, physical activity level, health and fitness, underlying medical conditions among the population may also influence the differences in individual oxygen consumption rate. To account for these differences, further research would need to be performed to assess the performance of the cryogenic air supply with the full range of potential occupant groups that could take shelter in an RA.

Adjusting the cryogenic airflow from the system was difficult because the system uses a simple needle valve on the air box. An easily adjustable airflow control is needed so that the flow can be accurately adjusted to maximize duration of air delivery or cooling performance as needed. In practice, that airflow valve should be located inside the confined space, so it is accessible during occupancy.

7 Conclusion

A series of tests was performed at the CASE Lab to evaluate the cryogenic air supply as a breathable air source in a confined space. Our tests show the cryogenic air supply could be an option for providing breathable air to such confined spaces. The test data show that a cryogenic air supply can maintain the %O_2 and %CO_2 level within the safety range specified in [8,9] during the entire 96 h based on different oxygen consumption rates. The CO_2 mitigation is critical to keep the %CO_2 level from exceeding the safety limit. The tests also demonstrate that the 2000-liter cryogenic air system has the capacity of providing breathable air for 21 people for at least 96 h. For the point of application, the cryogenic air system would need the capacity of adjusting the cryogenic airflow rate from inside the confined space.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

Nomenclature

CASE Lab	cryogenic air supply evaluation lab
CO	carbon monoxide
CO_2	carbon dioxide
C_3O_8	propane
HBS	human breathing simulator
H_2O	water
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
O_2	oxygen
RA	refuge alternative

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Fig. 1.

The tests were conducted in the shipping container. The shipping container was modified to represent a refuge alterative or other confined space.

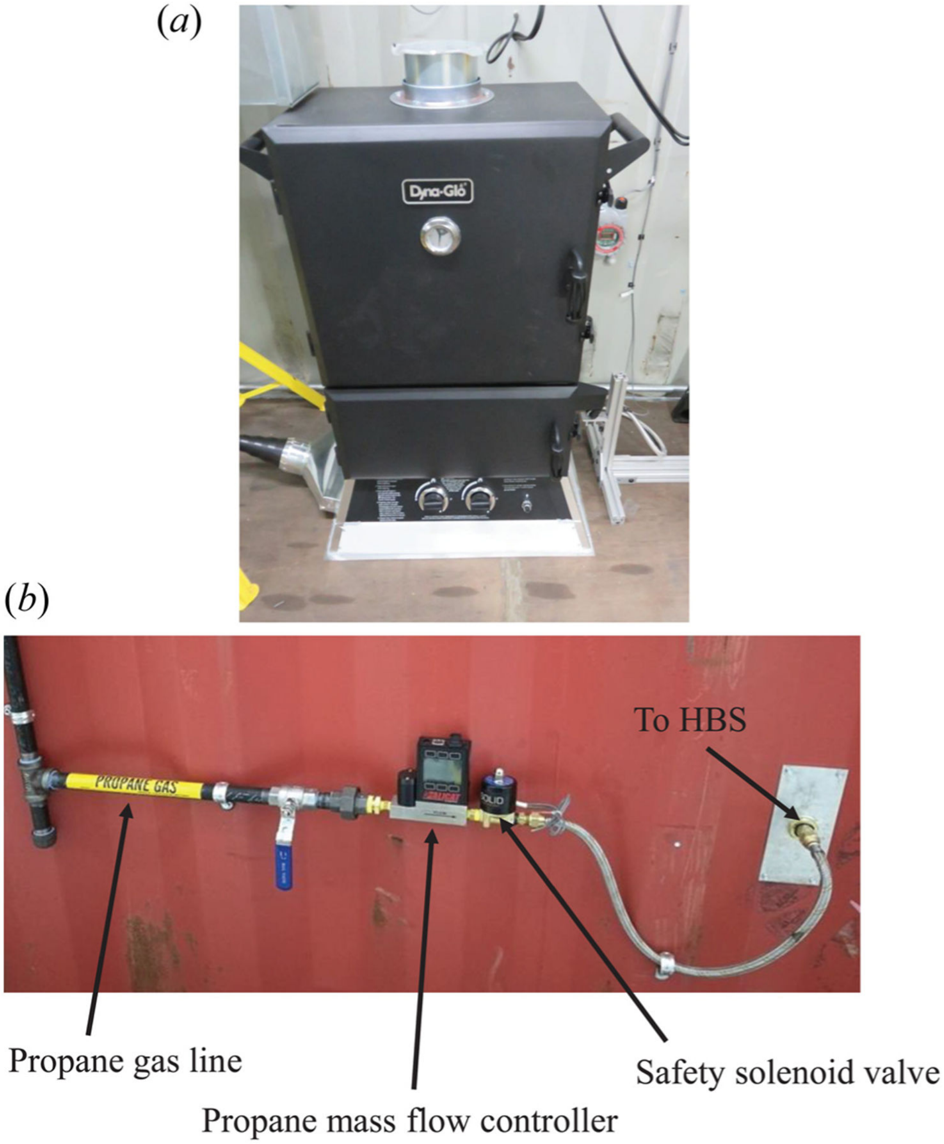

Fig. 2.

The human breathing simulator (HBS) (*a*) and the propane mass flow controller and the gas line to which it was connected (*b*)

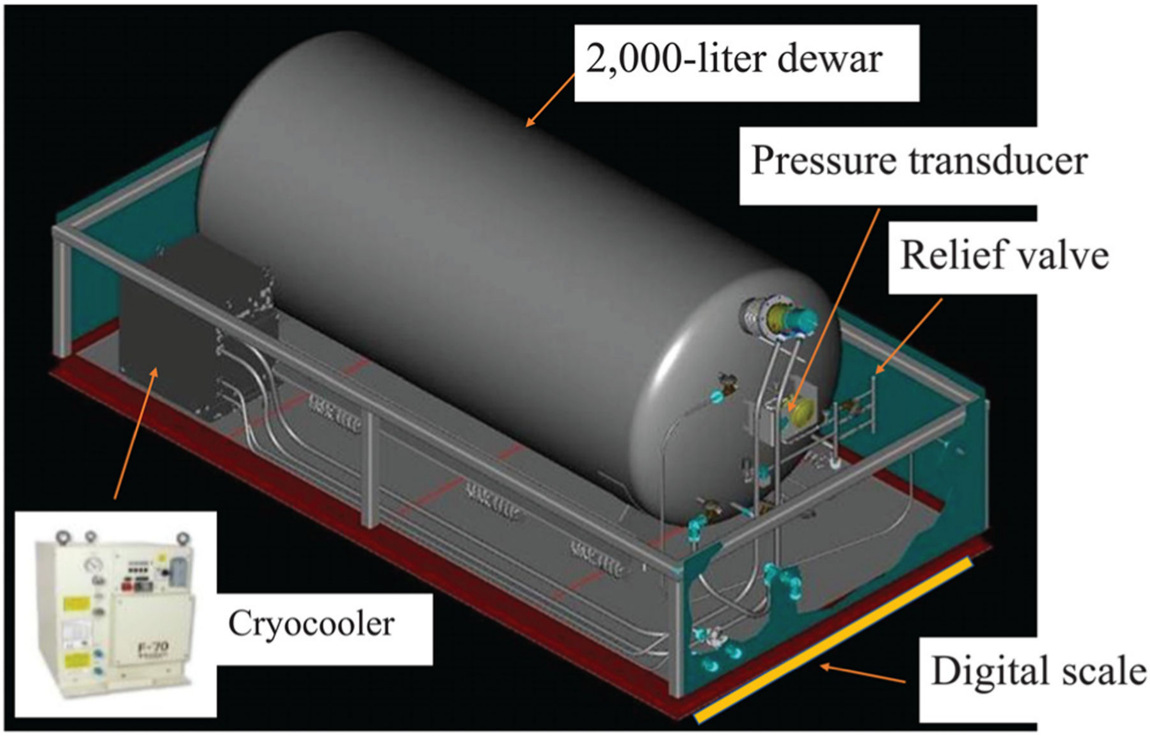

Fig. 3.

The cryogenic air system had a 2000-liter dewar and an electrical cryocooler. The gross weight was monitored using the digital scales located underneath.

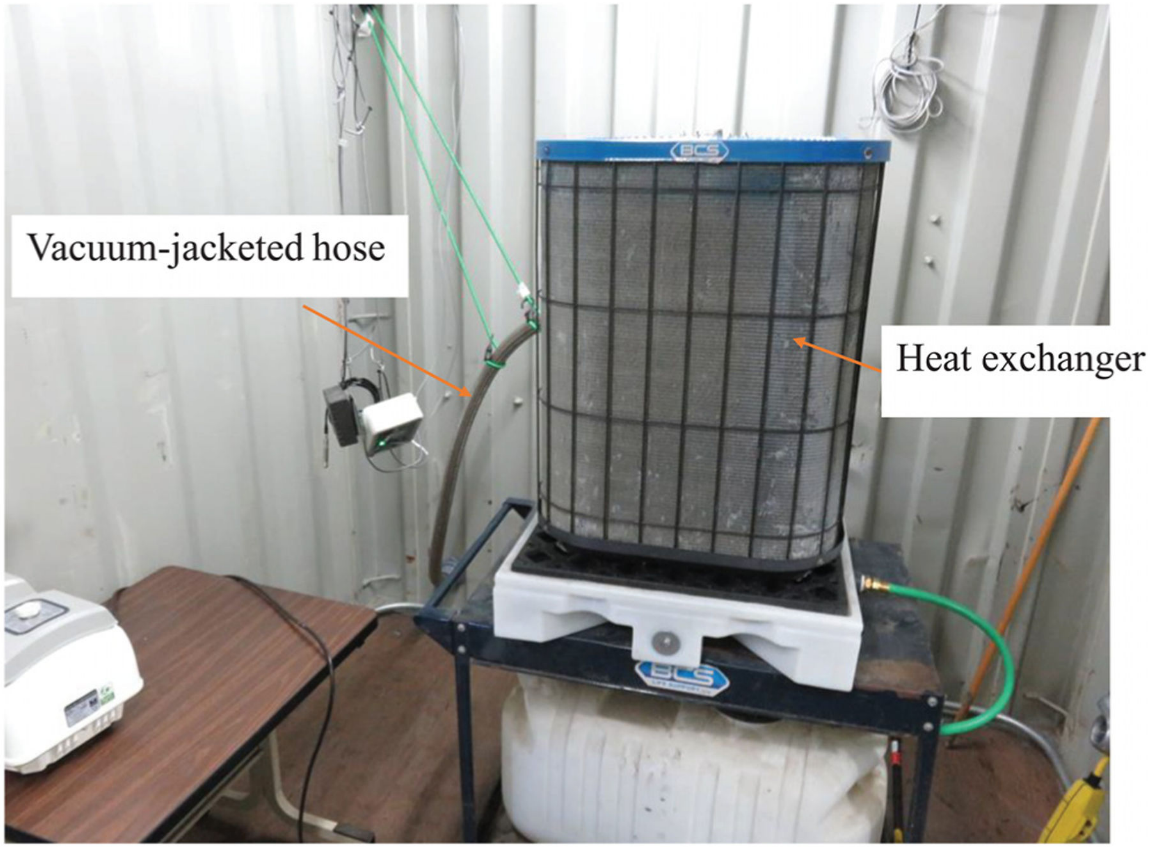

Fig. 4.

The heat exchanger located inside of the shipping container. The cryogenic air was delivered to the heat exchanger through a vacuum-jacketed hose from the dewar. The liquid air vaporized at the heat exchanger and turned into gaseous air. The collected water was drained to the storage tank underneath.

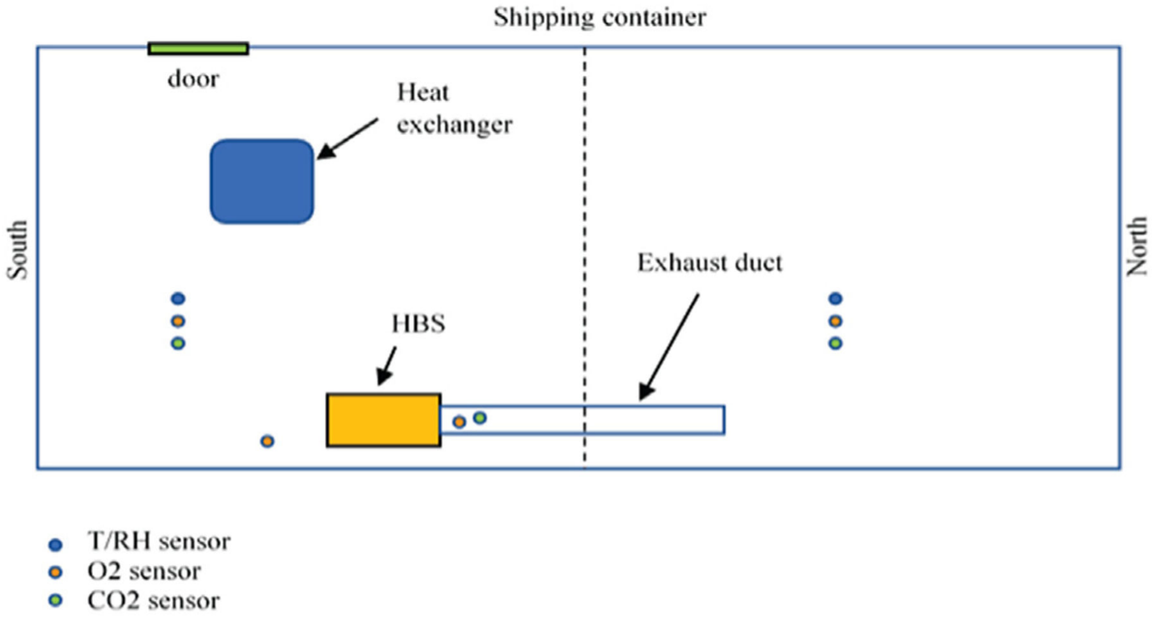

Fig. 5.
Sensor locations inside the shipping container

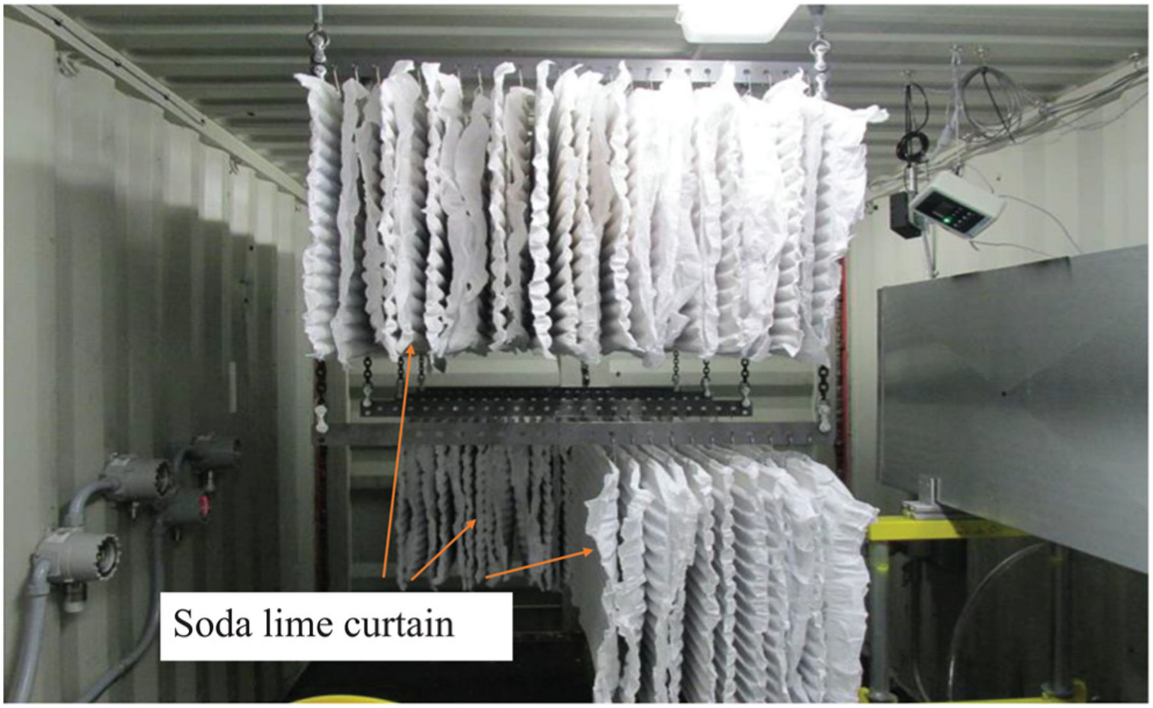

Fig. 6.
The CO_2 scrubbing curtain, or soda lime curtain, was used as CO_2 mitigation to absorb the CO_2 generated during the test

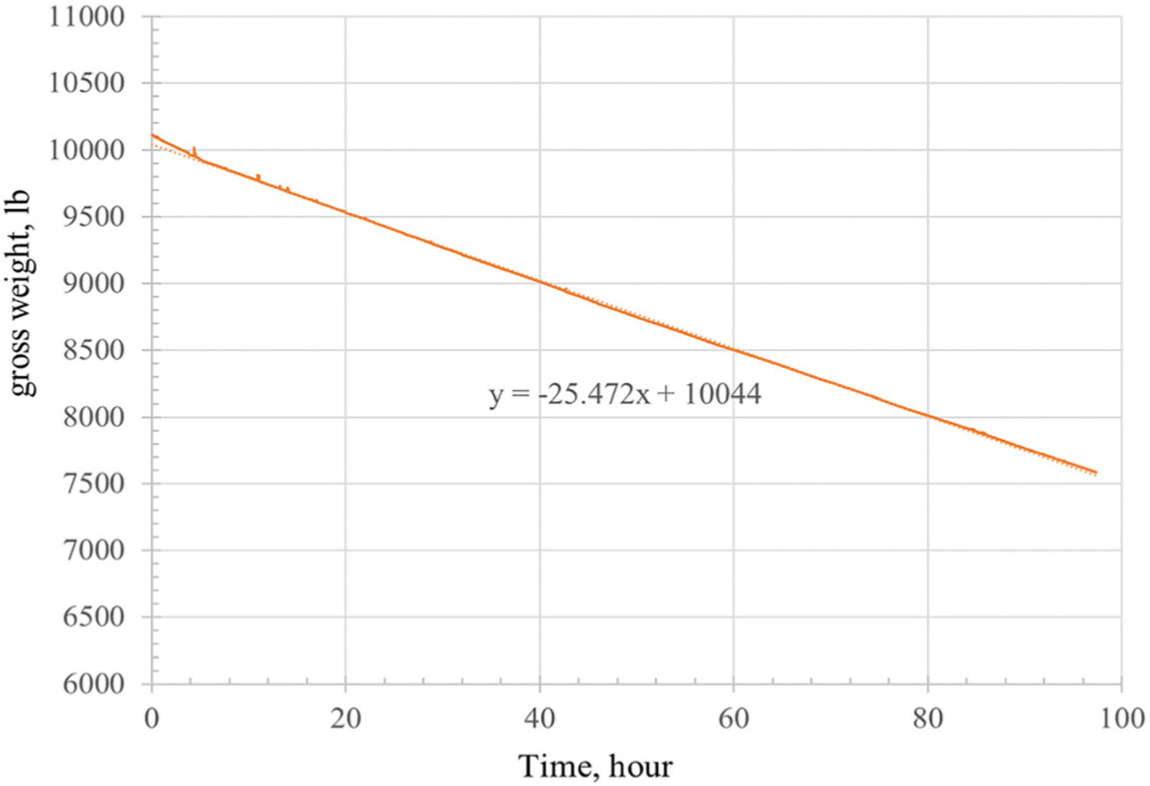

Fig. 7.

The recorded gross dewar weight during the test. The slope of the line showed the dewar lost 25.5 lb of cryogenic air loss per hour, i.e., the system supplied the shipping container with cryogenic air at a rate of 25.5 lb/h.

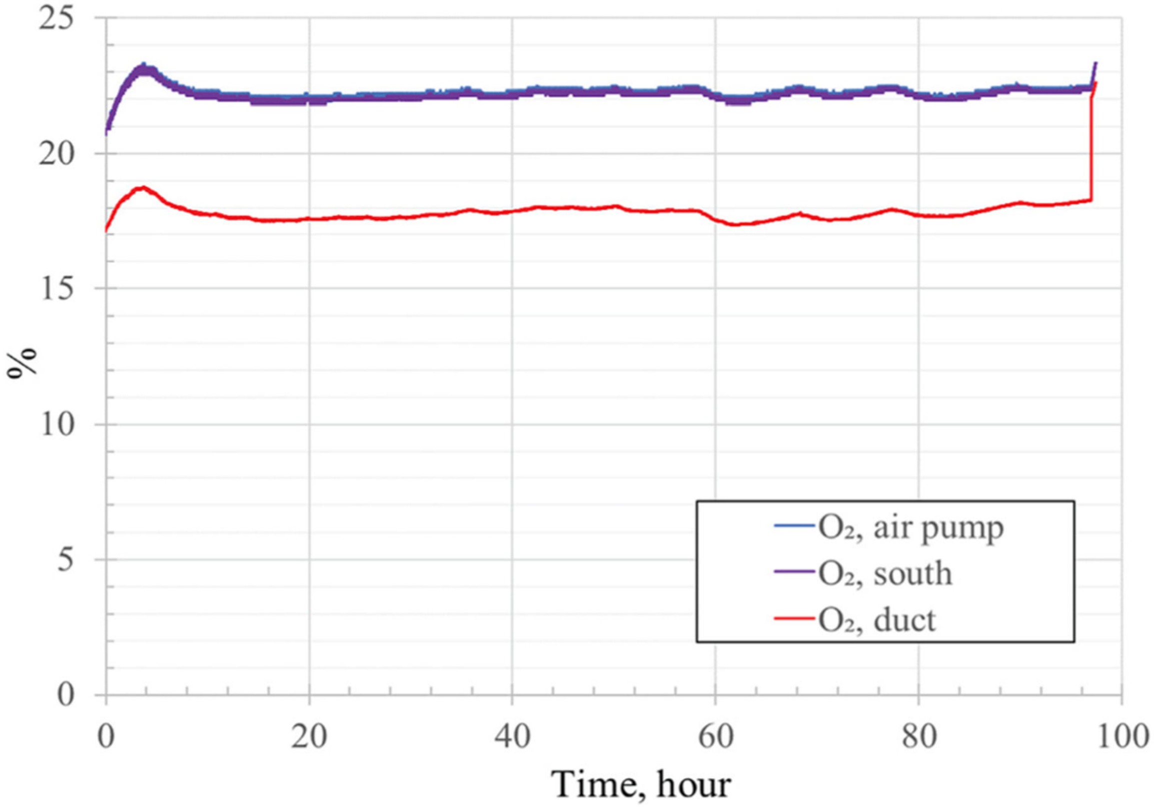

Fig. 8.

The %O_2 measured at various locations during Test #1

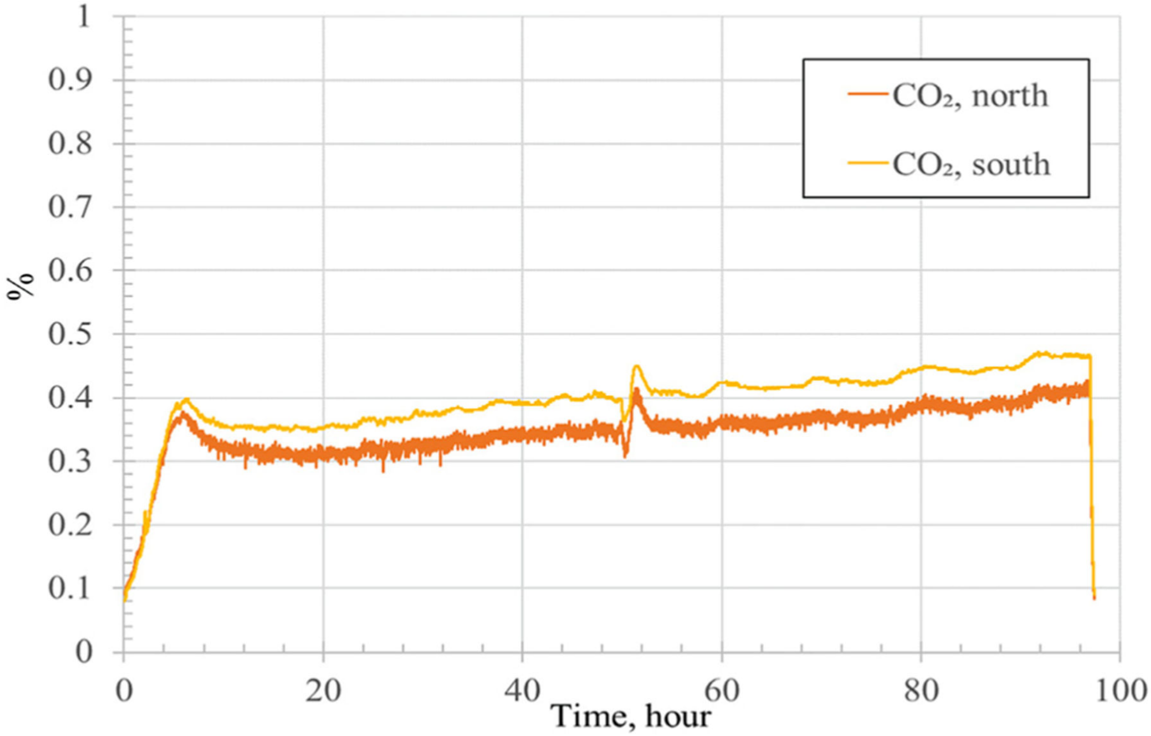

Fig. 9.

The %CO_2 measured at various locations during Test #1

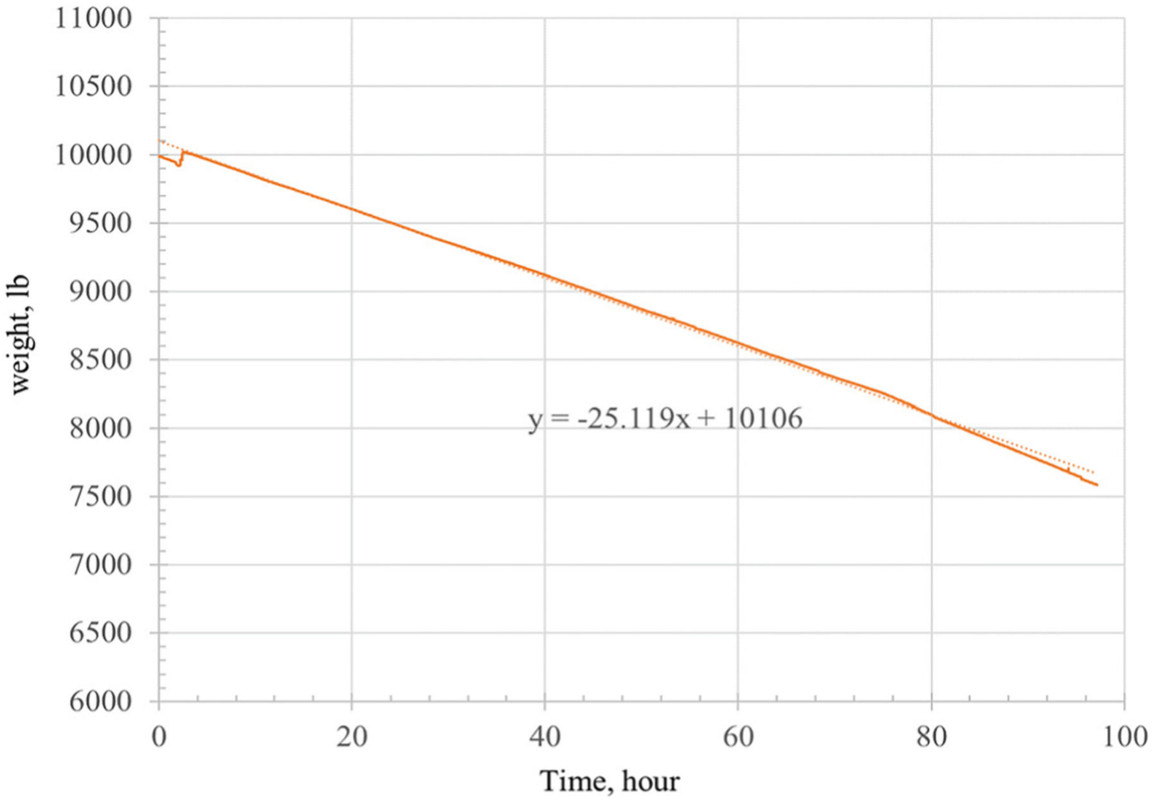

Fig. 10.

The recorded gross weight during the test. The slope of the line showed the dewar lost 25.1 lb of cryogenic air per hour, i.e., the system supplied the shipping container with cryogenic air at a rate of 25.1 lb/h.

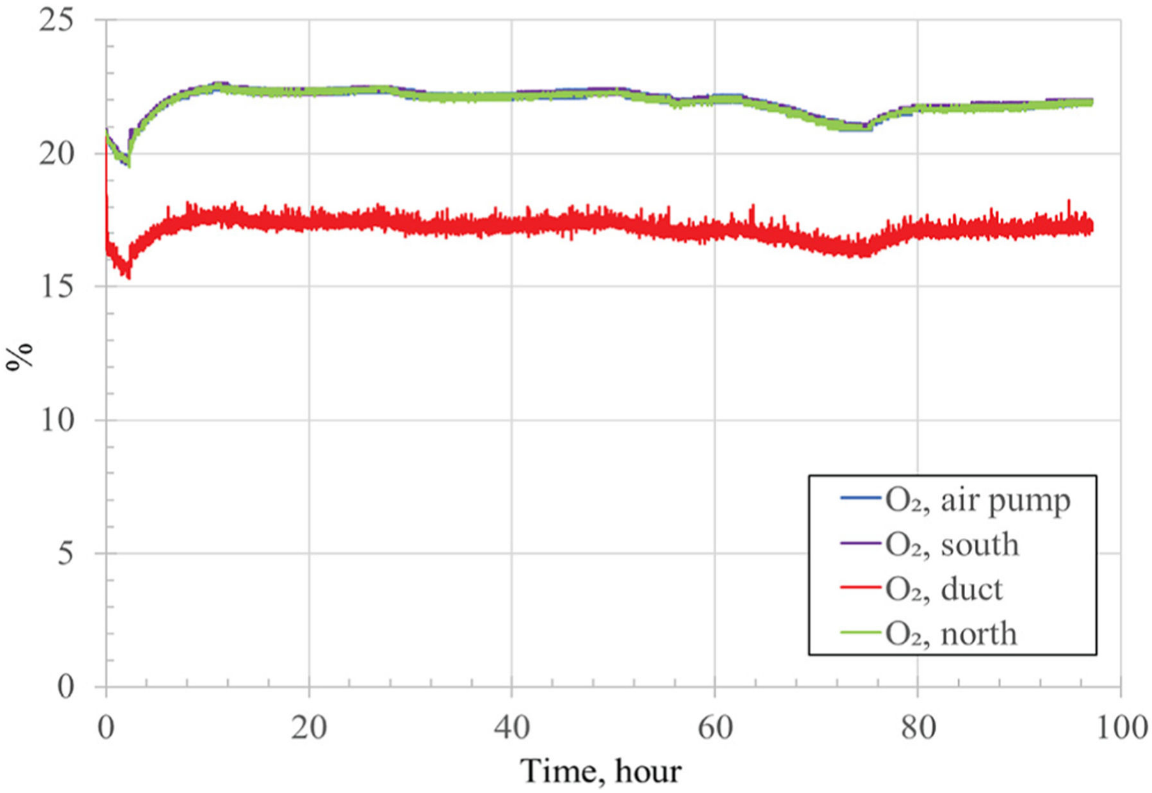

Fig. 11.

The %O_2 measured at various locations during Test #2

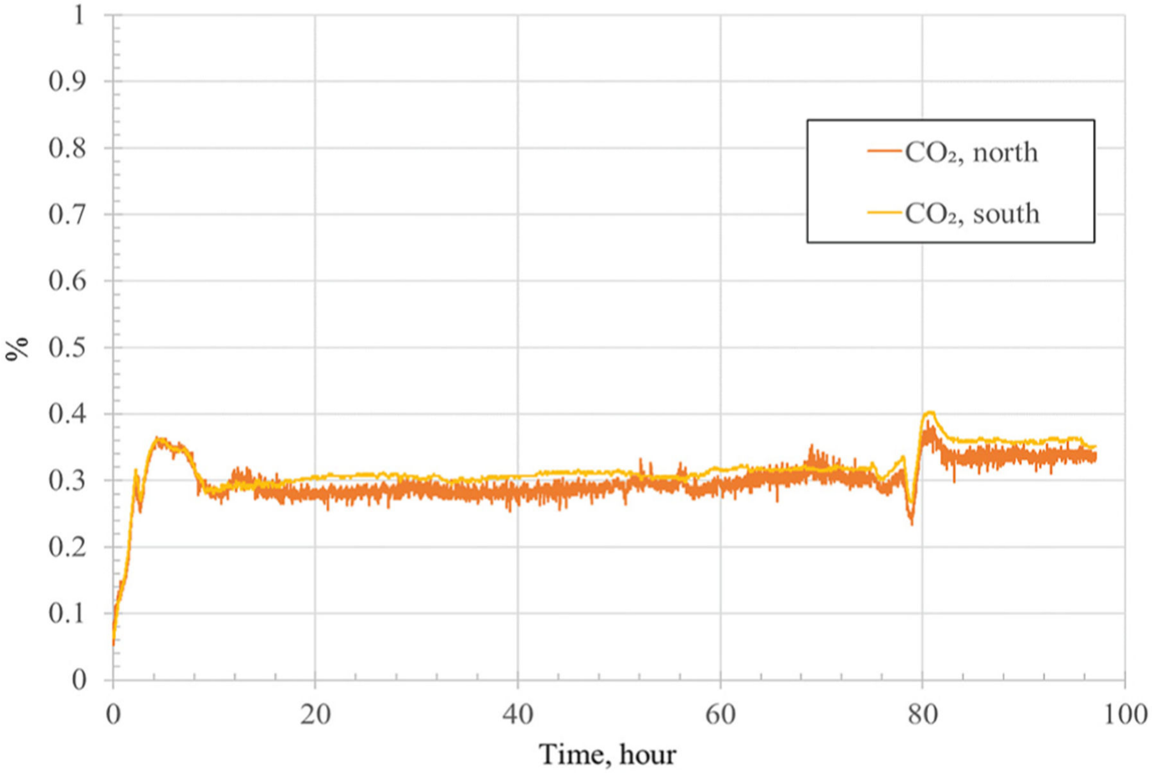

Fig. 12.

The %CO_2 measured at various locations during Test #2

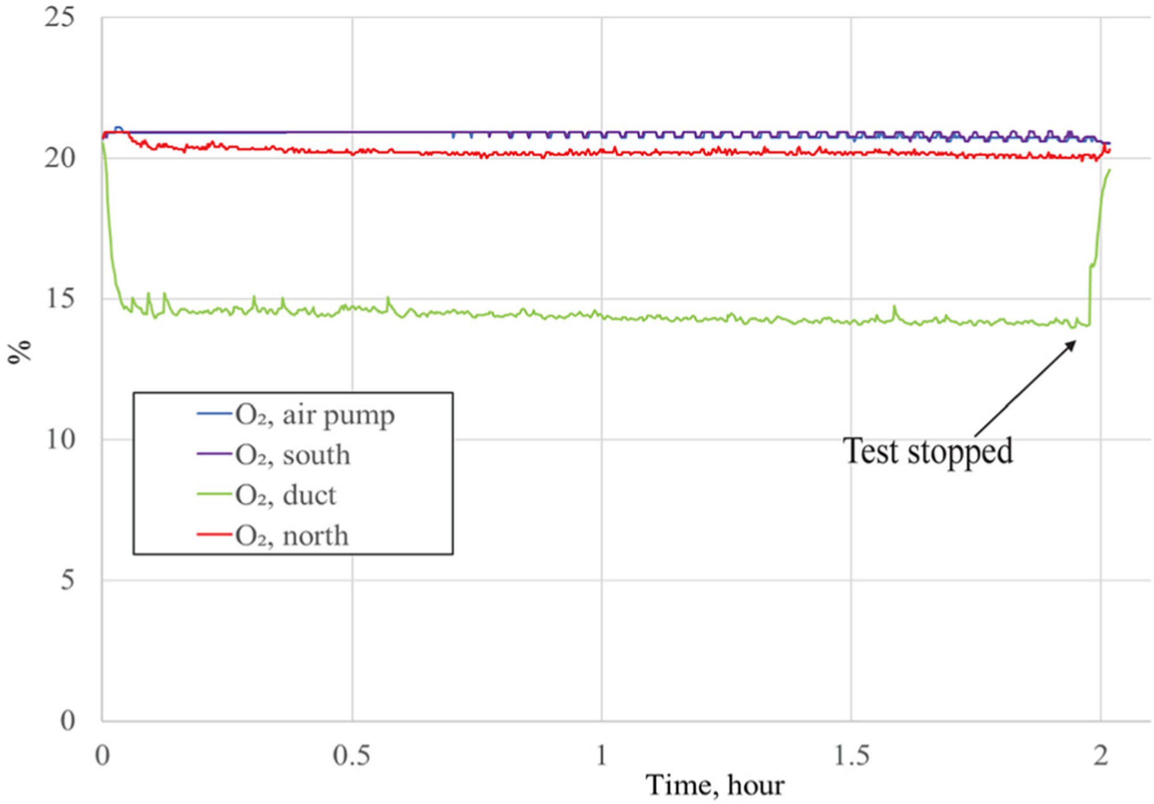

Fig. 13.

The %O_2 measured at various locations during Test #3

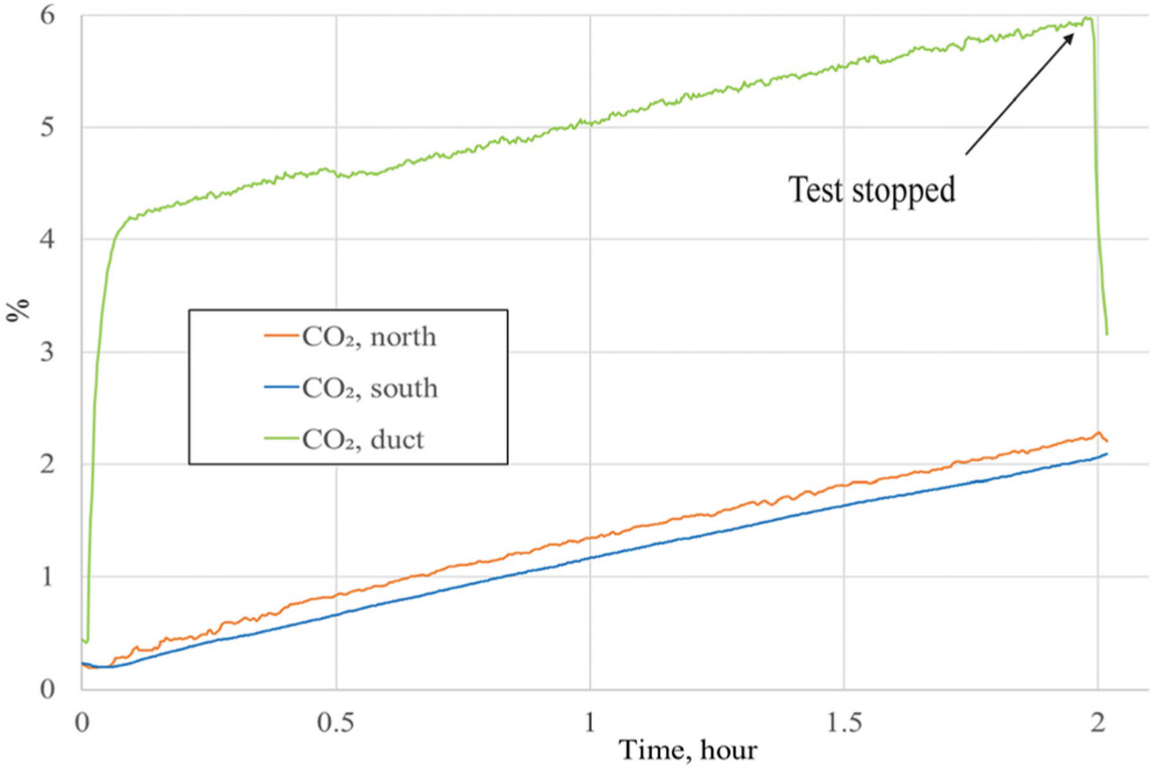

Fig. 14.

The %CO_2 measured at various locations during Test #3

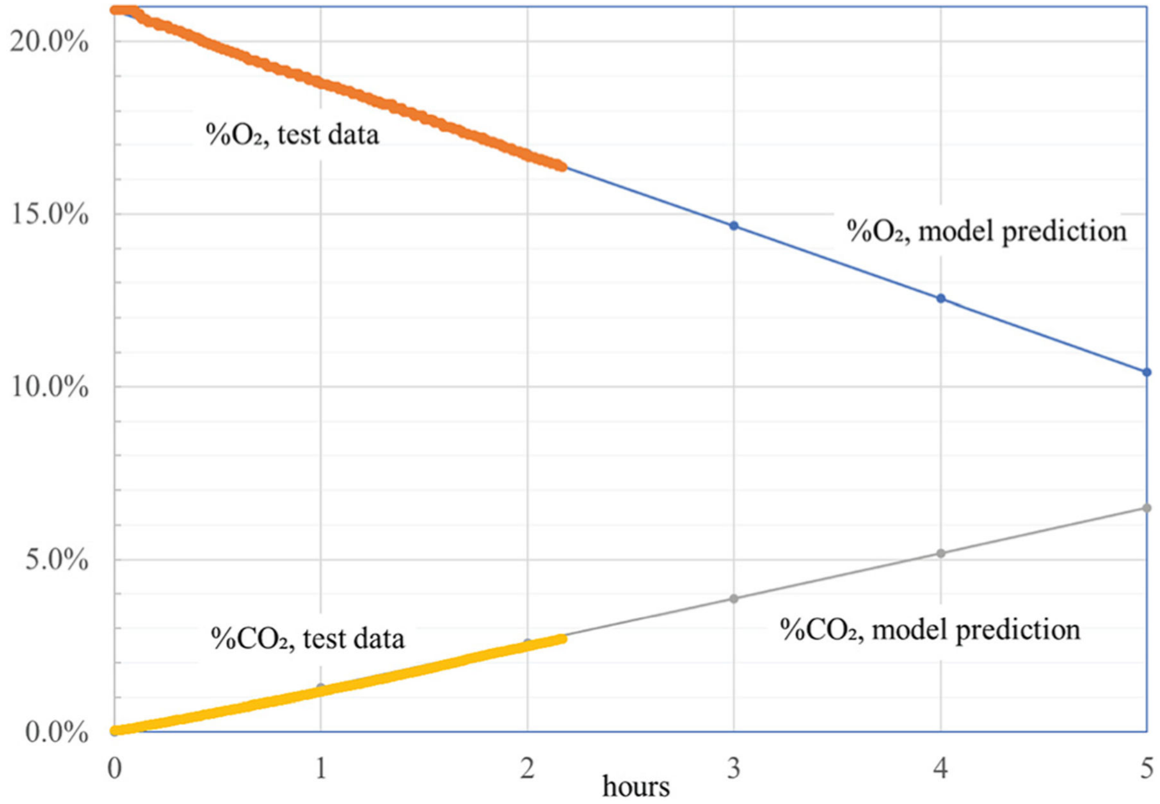

Fig. 15.

The %O_2 and %CO_2 measurements compared with model predictions for Test #4

Table 1

The mass ratio of the gases involved in combustion

Gas	Weight, gram	Normalized to propane mass
C_3H_8	44.1	1
O_2	160	3.63
Air	686.69	15.57
CO_2	132.1	2.99
H_2O	72.1	1.63

Table 2

The desired propane mass flowrate to represent the breathing of 21 people, and the difference on CO_2 generation based on two O_2 consumption rates

O_2 consumption rate	1.32ft^3/h/person (or 37.38 liter/h/person) [9]		0.67 ft^3/h/person (or 18.97 liter/h/person) [14]	
CO_2 generation rate	1.08 ft^3/h/person (or 30.58 liter/h/person) [9]		0.60 ft^3/h/person (or 16.99 liter/h/person) [14]	
Human versus HBS	21 Miners	Propane burner	21 Miners	Propane burner
Fuel burning rate	NA[a]	0.28 kg/h	NA[a]	0.14 kg/h
CO_2 mass generation rate	1.1 kg/h	0.8 kg/h	0.63 kg/h	0.42 kg/h
O_2 mass consumption rate	1.01 kg/h		0.52 kg/h	

[a] Not applicable.