

EVALUATION OF A CRYOGENIC AIR SUPPLY AS A BREATHABLE AIR SOURCE FOR A CONFINED SPACE

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ABSTRACT

A breathable air source is required for confined space such as an underground refuge alternative (RA) when it is occupied. To minimize the risk of suffocating, federal regulation requires 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 hours. 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-hour 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 will 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 96-hour 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 [1] (0.67 cu ft of pure oxygen per hour per person).

The test data shows that during both 96-hour 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.

Keywords: Confined space, gas concentration, breathable air, cryogenic air supply

NOMENCLATURE

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

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 refuge alternative (RA). In considering the breathing activities of the occupants of such confined spaces, the oxygen level and carbon dioxide level are the major concern. Numerous research studies have been

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conducted to address that concern in the past decades [2-9]. The federal regulations require that the oxygen concentration be maintained at levels between 18.5% and 23% for 96 hours in an occupied RA, and the concentration of carbon dioxide not to exceed 1% [10, 11]. The breathing activities by occupants will deplete the oxygen and generate carbon dioxide within the confined space. Without a breathable air supply and CO₂ mitigation, the oxygen level will drop below the safety limit, and the CO₂ level will also quickly increase beyond the safety limit [12].

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 refuge alternatives (RAs) that are used in underground mines. Before cryogenic air is supplied to an occupied RA, the temperature of the cryogenic air is kept at a -195°C (-318°F) inside a large dewar using a cryocooler. System pressure is kept below 207 kPa (30 psi), which is considerably less than the pressure in the oxygen bottles 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 the cooler in operation, the liquid air remains in a stable condition within the dewar for an extended period of up to 7 days [13].

CO₂ mitigation will be needed to maintain the CO₂ level below the 1% limit in an RA. Without mitigation, the CO₂ concentration can exceed the 1% limit even when the oxygen level is within the 18.5%–23% range [11].

In this paper, researchers evaluate the cryogenic air supply as a breathable air source in a sealed shipping container (the confined space) to simulate a 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 Equation (1) shown below. The process will also generate heat, but this paper focus on the gas concentration only. To simulate the breathing activity by a certain number of people, the propane mass flow rate 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 flow rate can be determined as follows. Assume the oxygen consumption rate is 1.32 ft³/hr/person (or 0.623 L/min/person) [10]. 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 x 1.291 g/L x 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 $\frac{8.043 \text{ g/min}}{3.63} = 2.216 \text{ g/min}$

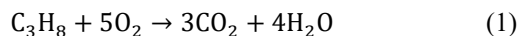


Table 1. The mass ratio of the gases involved in combustion.

| Gas | Weight, gram | Normalized to propane mass |
|-------------------------------|--------------|----------------------------|
| C ₃ H ₈ | 44.1 | 1 |
| O ₂ | 160 | 3.63 |
| Air | 686.69 | 15.57 |
| CO ₂ | 132.1 | 2.99 |
| H ₂ O | 72.1 | 1.63 |

A Cryogenic Air Supply Evaluation (CASE) Lab was built to perform the tests. The CASE Lab was a composite of a shipping container (the confined space), a human breathing simulator (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 (Figure 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 breathings of 21 people.



Figure 1. The tests were conducted in the shipping container. The shipping container was modified to represent a refuge alternative or other confined space.

2.2 The human breathing simulator (HBS)

A human breathing simulator (HBS) was developed to simulate human breathing by using a double-burner propane smoker (Figure 2a). The propane flow rate can be adjusted to simulate breathings of the desired number of people by using a propane mass flow controller (Figure 2b). 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.

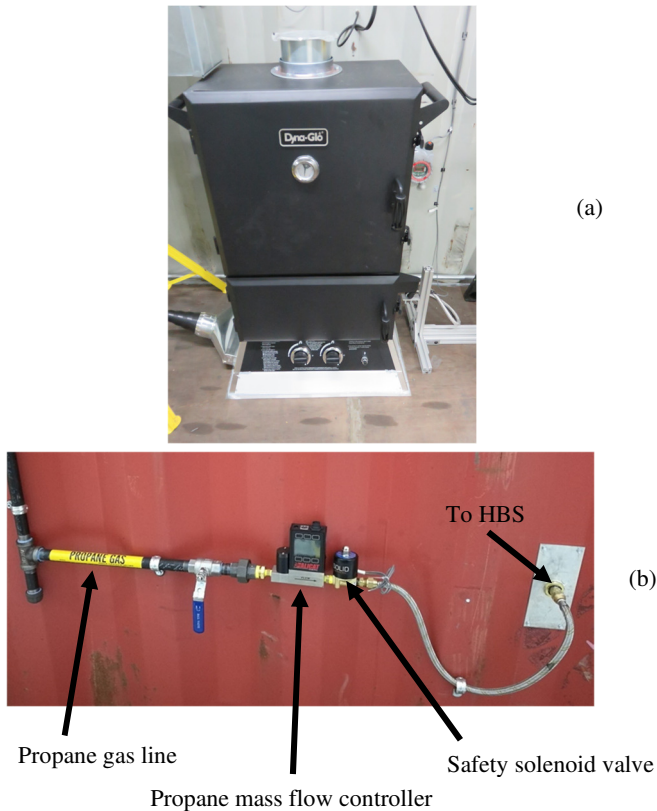


Figure 2. The human breathing simulator (HBS) (a) and the propane mass flow controller and the gas line to which it was connected (b).

2.3 The cryogenic air system

The cryogenic system has a 2,000-liter horizontal-oriented dewar (Figure 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 (Figure 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 through a vacuum-jacked hose (Figure 4). To start the test, the cryocooler was turned off and the internal pressure built up. The liquid air inside the dewar was pushed out due to the increased pressure and delivered to the heat exchanger. 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 Figure 4). This collected water could be an added or emergency supply of drinking water if necessary.

More details on the construction of the CASE Lab can be found in [14].

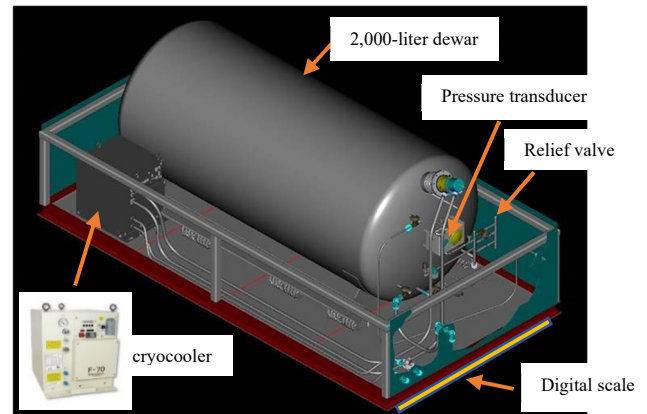


Figure 3. The cryogenic air system had a 2,000-liter dewar and an electrical cryocooler. The gross weight was monitored using the digital scales located underneath.

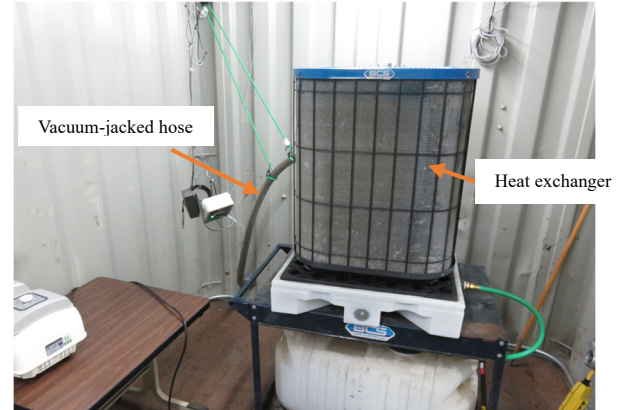


Figure 4. The heat exchanger located inside of the shipping container. The cryogenic air was delivered to the heat exchanger through a vacuum-jacked hose from the dewar. The liquid air vaporized at the heat exchanger and turned into gaseous air. The collected water was drained to the storage tank underneath.

3. TEST SETUP

Multiple gas sensors were used to measure the %CO₂ and %O₂ at various locations inside the CASE lab (Figure 5). To measure the %CO₂, two CTI GG-CO₂ 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 %O₂, 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 O₂ monitor was positioned near the air pump to document the %O₂ 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.

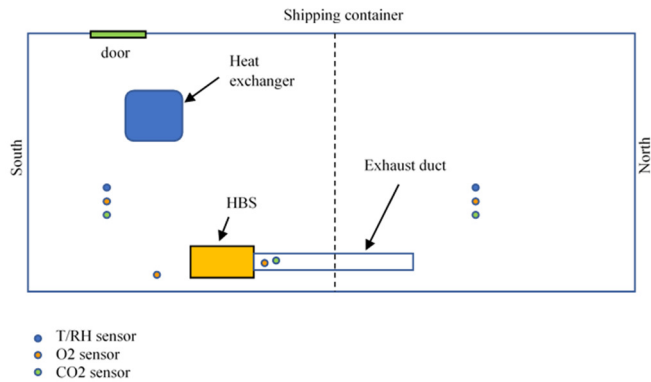


Figure 5. Sensor locations inside the shipping container.

Procedures were taken to ensure safety during the tests. A Beacon 800 gas monitoring system with multiple CO₂ sensors, an O₂ sensor, a carbon monoxide sensor, and percentage 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 O₂, CO₂, CO, and propane levels were at safe levels.

A group of CO₂ scrubbing curtains (soda lime curtain) were used to absorb and maintain the %CO₂ level during the test (Figure 6). As mentioned early, the CO₂ 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 CO₂ mitigation. Each curtain weighs 10 lbs and has a dimension of 3.3 ft long x 1.8 ft wide x 0.5 inch thick. According to the manufacturer, one (1) curtain is required per person/day. To absorb the CO₂ generated by 21 people, 105 pieces of curtain (21 people x 5 days x 1 piece/person/day) were used for each 96-hour test.



Figure 6. The CO₂ scrubbing curtain, or soda lime curtain, was used as CO₂ mitigation to absorb the CO₂ generated during the 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-hour tests were conducted using two oxygen consumption rates. The federal regulations specify the O₂ consumption rate to be 1.32 ft³/hr/person and the CO₂ generation rate to be 1.08 ft³/hr/person (Test #1) [10]. The research conducted by the University of South Florida specifies the O₂ consumption rate to be 0.67 ft³/hr/person and the CO₂ generation rate to be 0.60 ft³/hr/person (Test #2) [1]. Two additional tests were performed (Test #3 and Test #4) for a shorter time (< 96 hours). The purpose of those two tests was to investigate how fast the CO₂ level will exceed the safety limit (1%) if no CO₂ scrubbing curtain was presented, and how fast the O₂ level will drop below the safety limit (18.5%) if no breathable air source is available.

4.1 Test #1 (96-hour test, 1.32 ft³/hr/person O₂ consumption rate)

The cryo tank was filled with approximately 2,000 liters of cryogenic air before the test. The cryogenic air was kept in a liquid status by the cryocooler. To start the test, the cryocooler was turned off. The pressure build-up valve was then opened, and the internal pressure went up. The increased pressure then pushed out the liquid air inside to the heat exchanger located in the shipping container. A 1.32 ft³/hr/person O₂ consumption rate was used in this test. The propane flow rate was set to be 21 x 1.32 = 27.72 ft³/hr to simulate the breathing of 21 persons with the O₂ consumption rate specified above. Figure 7 shows the weight change of the cryogenic tank during the test. As shown in Figure 7, the cryogenic system delivered cryogenic air to the shipping container at a rate of 25.5 lb/hr (11.56 kg/hr) during the 96-hour test period.

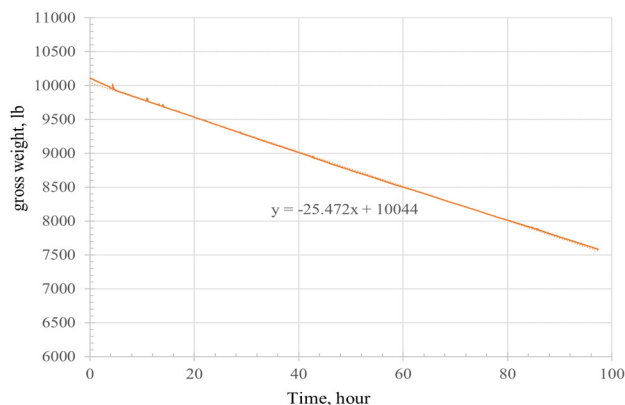


Figure 7. The recorded gross weight during the test. The slope of the line showed the dewar lost 25.5 lb of cryogenic air loss per hour, i.e., the system supplied the shipping container with cryogenic air at a rate of 25.5 lb/hr.

The internal %O₂ level changing with time is plotted in Figure 8. The test showed that, while the HBS simulated the breathing of 21 persons at 1.32 ft³/hr/person O₂ consumption rate, the cryogenic air supply maintained the %O₂ level in the 20.5%–23% range during the 96 test hours. The red line in Figure 8 refers to the measurement within the combustion duct in which the %O₂ was significantly low. However, the %O₂ levels at other locations were within the safety limit (18.5%–23%) during the test.

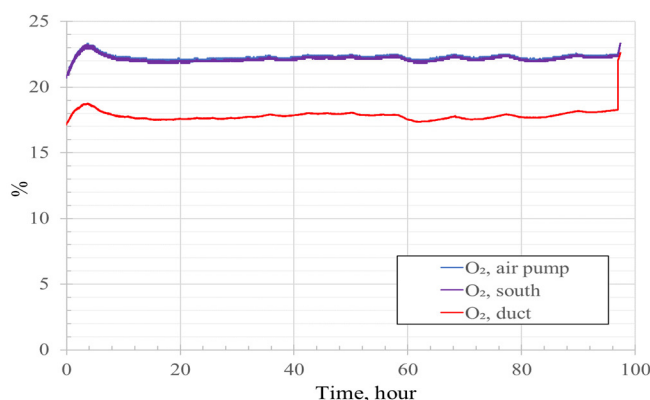


Figure 8. The %O₂ measured at various locations during the test.

Figure 9 shows the internal %CO₂ level changing with time during the test. With a rate of 25.5 lb/hr (11.56 kg/hr) of cryogenic air supply, the shipping container internal %CO₂ level maintained at 0.3%–0.5% during the 96 test hours, which is below the 1% limit.

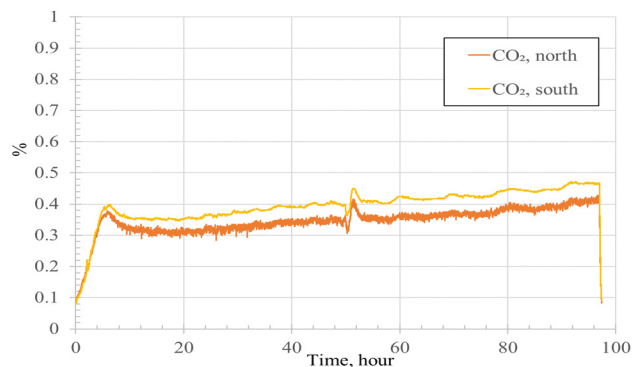


Figure 9. The %CO₂ measured at various locations during the test.

4.2 Test #2 (96-hour test, 0.67 ft³/hr/person O₂ consumption rate)

Test #2 basically duplicated Test #1 except the O₂ consumption rate. The cryo tank was refilled with cryogenic air under full storage capacity (2,000 liters). A 0.67 ft³/hr/person O₂ consumption rate was used in this test. The propane flow rate was set to be 21x0.67= 14.07 ft³/hr to simulate the breathing of 21 persons with the O₂ consumption rate specified above. Figure 10 shows the weight changes of the cryogenic air during the test. As shown in Figure 10, the cryogenic system delivered cryogenic air to the shipping container at a rate of 25.1 lb/hr (11.38 kg/hr).

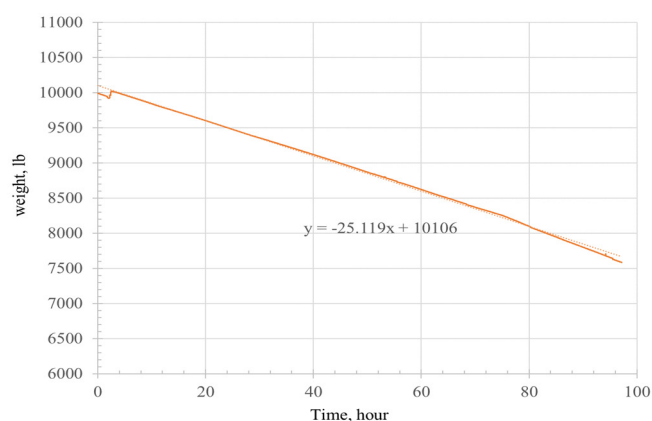


Figure 10. The recorded gross weight during the test. The slope of the line showed the dewar lost 25.1 lb of cryogenic air per hour, i.e., the system supplied the shipping container with cryogenic air at a rate of 25.1 lb/hr.

The internal %O₂ level changing with time is plotted in Figure 11. The test showed that while the HBS simulated the breathing of 21 persons at 0.67 ft³/hr/person O₂ consumption rate, the cryogenic air supply maintained the %O₂ level in the 20%–23% range during the 96 test hours. The red line in Figure 11 refers to the measurement within the combustion duct in

which the %O₂ was significantly low. However, the %O₂ levels at other locations were very uniform and within the safety limit (18.5%–23%) during the test.

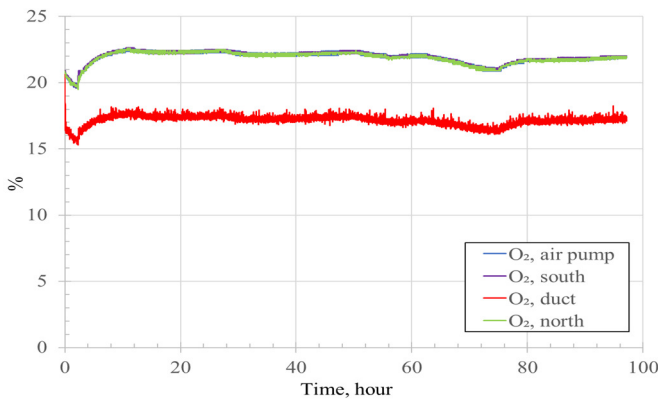


Figure 11. The %O₂ measured at various locations during the test.

Figure 12 shows the internal %CO₂ level changing with time during the test. With a rate of 25.1 lb/hr (11.38 kg/hr) of cryogenic air supply, the shipping container internal %CO₂ level was maintained in the 0.2%–0.4% range during the 96 test hours, which is below the 1% limit.

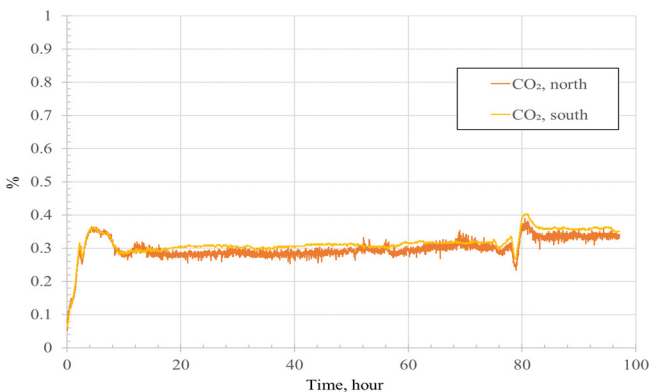


Figure 12. The %CO₂ measured at various locations during the test.

4.3 Test #3 (2-hour test, same setting as in Test #1, but no CO₂ scrubbing curtain)

To investigate how fast the CO₂ level will exceed the safety limit (1%) if no CO₂ mitigation, this test used the same setting as in Test #1 (1.32 ft³/hr/person O₂ consumption rate, HBS to simulate the breathings of 21 people, ~25.5 lb/hr (11.56 kg/hr) rate of cryogenic air supply), but all the CO₂ scrubbing curtains (the soda lime curtains) were removed from the shipping container. As shown in Figure 13 and Figure 14, the CO₂ concentration exceeded the 1% limit in 1 hour when there was no CO₂ 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 %CO₂ level was maintained well below the

1% limit during the entire 96-hour test period if CO₂ mitigation was used. The test was terminated at 2 hours.

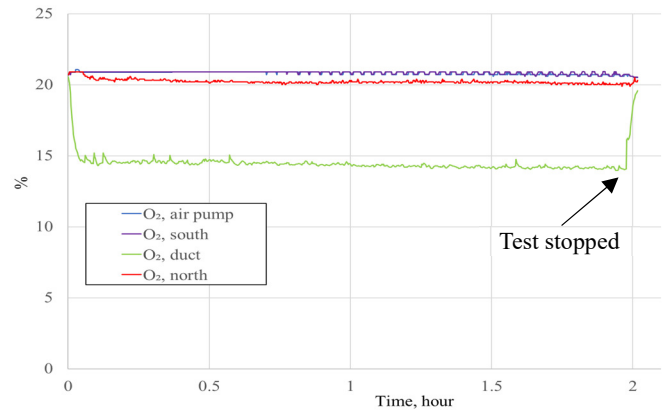


Figure 13. The %O₂ measured at various locations during the test.

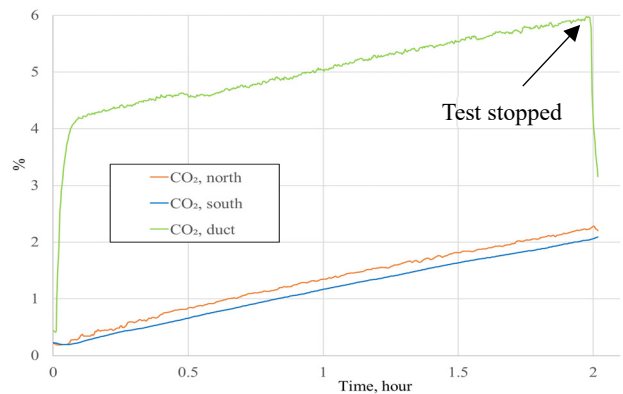


Figure 14. The %CO₂ measured at various locations during the test.

4.4 Test #4 (2-hour test, same setting as in Test #1, but no cryo air supply, no CO₂ scrubbing curtain)

In this test, the same setting was used as in Test #1 (1.32 ft³/hr/person O₂ consumption rate, HBS to simulate the breathings of 21 people), but the cryogenic air supply to the shipping container was shut off (no cryogenic air supply), and all the CO₂ 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 %O₂ level will drop below the safety limit quickly (Figure 15). The plot shows that the %O₂ level dropped below 17% and the %CO₂ level exceeded 2% in 2 hours after the test started. The test was terminated at approximately 2 hours because the gas concentration already exceeded the safety range. Figure 15 also shows the test data compared with a mathematical model. The model predicted well the gas concentration as shown in the plot. More details about the model can be found in [15].

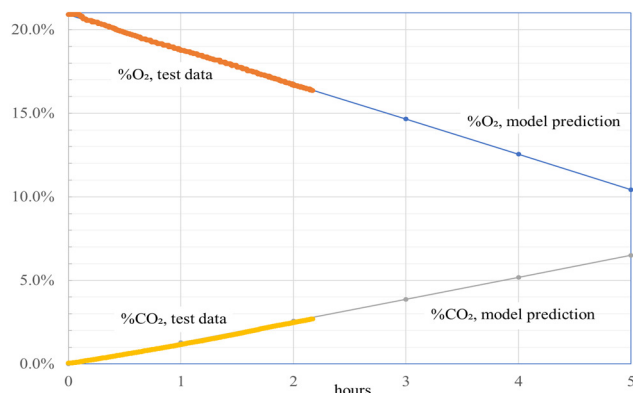


Figure 15. The %O₂ and %CO₂ measurements compared with model predictions for Test #4.

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-hour 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 O₂ consumption rates—1.32 ft³/hr/person and 0.67 ft³/hr/person. The CO₂ generation rates are also listed in the table. Because burning propane generates less CO₂ than human breathing for a set oxygen consumption rate, supplemental CO₂ was added to match both oxygen consumption and CO₂ generation.

Table 2. The desired propane mass flow rate to represent the breathings of 21 people, and the difference on CO₂ generation based on two O₂ consumption rates.

| O ₂ consumption rate | 1.32 ft ³ /hr/person (or 37.38 liter/hr/person) [10] | 0.67 ft ³ /hr/person (or 18.97 liter/hr/person) [1] |
|--------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------------|
| CO ₂ generation rate | 1.08 ft ³ /hr/person (or 30.58 liter/hr/person) [10] | 0.60 ft ³ /hr/person (or 16.99 liter/hr/person) [1] |
| Human versus HBS | 21 Miners | Propane Burner |
| Fuel burning rate | NA* | 0.28 kg/hr |
| CO ₂ mass generation rate | 1.1 kg/hr | 0.8 kg/hr |
| O ₂ mass consumption rate | 1.01 kg/hr | 0.52 kg/hr |

*Not applicable

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-hour period. During both tests, the cryogenic air supply fed the shipping container with cryogenic air at a rate of approximately 25 lb/hr (11.34 kg/hr), which was the minimum flow rate 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 flow rate more. An improvement for the cryogenic air system is to have the capacity of adjusting the cryogenic air flow rate from inside. Currently, the CASE Lab can only adjust the cryogenic air flow rate from outside of the shipping container during the test or occupancy. For application purposes, it would be desired 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 CO₂ scrubbing curtain on maintaining the CO₂ level. The CO₂ level will increase dramatically if there is no CO₂ mitigation used, and even the oxygen concentration is kept in the safety range. For occupied confined spaces, a suitable CO₂ mitigation strategy is needed to absorb the CO₂ generated by breathing and to maintain the CO₂ level below the safety limit.

Test #4 shows that without the cryogenic air supply, the %O₂ level will drop down quickly below the safety limit in less than 2 hours. 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. 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 %O₂ and %CO₂ level within the safety range specified in [9, 10] during the entire 96 hours based on different oxygen consumption rates. The CO₂ mitigation is critical to keep the %CO₂ level from exceeding the safety limit. The tests also demonstrate that the 2,000-liter cryogenic air system has the capacity of providing breathable air for 21 people for at least 96 hours. For the point of application, the cryogenic air system would need the capacity of adjusting the cryogenic air flow rate from inside the confined space.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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