Storage Time and Venting Characteristics for Cryogenic Air Supplies on Cryocooler Shutdown

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ABSTRACT

Cryogenic air supplies are a developing technology that may be able to serve as both a breathable air source and a heat mitigation strategy for refuge alternatives (RA) used in underground mines. Before cryogenic air is supplied to an occupied RA, the temperature of the cryogenic air is kept at -195°C (-318°F) inside a large dewar using a cryocooler, or cryo-refrigerator, which uses electrical power. In some cases, the cryocooler might lose power due to a planned or unplanned power outage that may occur when relocating the cryogenic air supply or during a mine emergency. Without cooling provided by the cryocooler, the temperature of the liquid air will rise and the pressure within the cryogenic air supply's dewar will increase due to the buildup of vapor pressure. To ensure safety, once the pressure in the dewar is high enough, the cryogenic air vents through a relief valve. Before deploying a cryogenic air supply in an underground mine, the maximum storage time and venting characteristics of the air supply when cooling is interrupted must be determined

In this paper, researchers at the National Institute for Occupational Safety and Health (NIOSH) investigated the maximum storage time and venting pattern for two different cryogenic systems when their cryocoolers were turned off: a 425-liter vertical dewar system and a 2,000-liter horizontal dewar system. The testing showed that about 11 liters of cryogenic air was lost per day by the 425-liter vertical dewar system. For the 2,000-liter horizontal dewar system, the cryogenic air vented about every 2 hours, and about 28 liters of cryogenic air was lost per day. The information in this paper could be useful for manufacturers and mines considering the use of a cryogenic air supply as a source of breathable air and/or heat mitigation for refuge alternatives.

INTRODUCTION

Cryogenic liquid containers, referred to as dewars, are double-walled vacuum-insulated vessels with multi-layer insulation in the annular space. They are designed for transportation and storage of liquefied gases at cryogenic temperatures, typically colder than -90°C (-130°F). For cryogenic air supplies intended for use in underground mines [1], the cryogenic air is kept in a liquid state using an electrically driven cryocooler. In some cases, the cryocooler might lose power due to a planned or unplanned power outrage. Without cooling provided by the cryocooler, the temperature of the liquid air will increase. Even though these containers are well-insulated, heat will be trans-

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ferred continuously into the cryogenic air due to the extremely large temperature difference between the cryogenic liquid and the ambient environment. In cylindrical dewars, the stratification problem is governed mainly by the rate and means of heat input from the ambient environment through the insulated wall [2]. The liquid next to the container surface is warmed and moves upward. Therefore, a warmer liquid layer collects near the vapor-liquid interface. The warmer liquid layer continuously increases in thickness resulting in a higher temperature at the vapor-liquid interface than the temperature in the bulk liquid. Heat from the surroundings will cause some vaporization to occur. Vaporized gases will collect in the ullage space (vapor space above the liquid) causing the pressure to increase. The pressure will periodically vent via the system's pressure relief valve. Vaporization rates will vary in the range of 0.4%–3% of the container's volume per day [3]. Without power, the container will lose liquid at this rate due to venting via the pressure relief valve. Eventually, the liquid will be depleted. In order to increase the liquid storage time (before venting starts), the dewar should undergo vacuum maintenance and/or heat-leak mitigation regularly to maintain and increase the insulation efficiency, since the boil-off rate is directly proportional to vacuum level.

Designed for underground refuge alternative (RA) usage, the Cryogenic Refuge Alternative Supply System (CryoRASS) allows for a supply of gaseous air introduced into the RA through an air handler box, or heat exchanger. Due to the large liquid-to-gas expansion ratio (~800) [3], the benefits of the CryoRASS are that it can provide RA cooling and dehumidification as well as breathable air (providing atmosphere oxygen). In a mine emergency when miners find it necessary to enter the RA, the first miner to enter would activate the flow of liquid air from the CryoRASS by pulling a single lever. The liquid air would be vaporized and warmed to a breathable temperature in the range of 16 to 21°C (60 to 70°F) as it passes through a heat exchanger located inside an air handler that is strategically placed within the RA. The vaporization process and introduction of cool breathable air would reduce the temperature within the RA and dehumidify the RA through the condensation of water vapor on the surface of the heat exchanger within the air handler. This water could be collected and used as an added/emergency supply of drinking water with appropriate treatment, if necessary, or drained from the RA. For mines with an elevated ambient temperature, cooling and dehumidification of an occupied RA would be necessary to reduce the risk of human heat stress.

Mine operators have expressed concern about the stability of the system in the event of an electrical power interruption, such as a mine power failure or an RA move to another location. The NIOSH research in this study has shown that even without the cryocooler in operation, the cryogenic air remains in a stable condition within the dewar for an extended period of up to 7 days. However, before a CryoRASS is deployed in a mine, the maximum storage time after turning off the cryocooler needs to be determined. Other venting characteristics, such as venting time, venting interval, daily loss of air, and pressure change also need to be determined. In this paper, NIOSH investigated the storage time and venting characteristics of two types of CryoRASS after turning off their cryocoolers.

THE CRYOGENIC REFUGE ALTERNATIVE SUPPLY SYSTEM (CRYORASS)

The CryoRASS system (Figure 1), which is located near an RA, uses a dewar to store a volume of liquid air in a stable, zero-loss condition. The liquid air, composed of 79% nitrogen and 21% oxygen (77% nitrogen and 23% oxygen in weight ratio), is cooled to a very low temperature. The liquid air is stored in a dewar designed specifically for application to RAs and sized for the expected number of RA occupants. Using a cryocooler (an electrical power driven cooling system), the temperature of the liquid air is kept at -195°C (-318°F), and system pressure is kept below 207 kPa (30 psi), which is considerably less than the $1.03\times10^{7} – 3.10\times10^{7}$ Pa (1,500 to 4,500 psi) pressure in the oxygen cylinders currently used to create a breathable air environment in portable RAs [4]. For safety, the CryoRASS uses a pressure relief valve in the plumbing circuit. If the cryocooler is off, vapor pressure in the dewar ullage space will slowly build over a period of several hours. When the relief pressure is reached, it will open and vapor will escape until the pressure drops low enough for the relief valve to close (Figure 1).

NIOSH researchers investigated the maximum storage time and venting characteristics of two different cryogenic systems after turning off their cryocoolers. The two systems differed in size and dewar orientation (vertical versus horizontal).

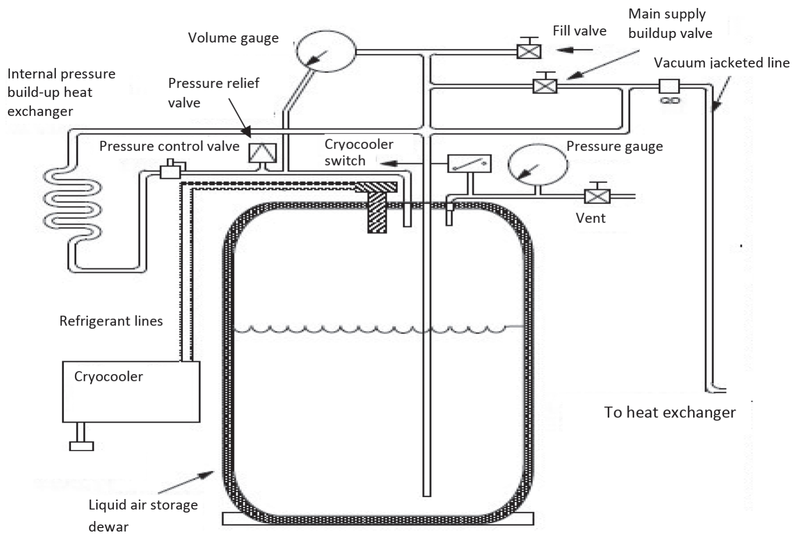

Figure 1. Basic CryoRASS schematic.

CryoRASS with Vertically Oriented 425-liter Dewar

The vertically oriented dewar has a 425-liter capacity (Figure 2). Per the structural design and associated pressure vessel safety factor of the dewar, the 425-liter CryoRASS has a spring-loaded pressure relief valve set at 717.1 kPa (104 psi).

An AL-25 Cryomech cryocooler system is installed to maintain the cryogenic air in a refrigerated state [5]. It is automatically activated based on differential pressure, providing cooling via a "cold finger" located in the ullage space of the dewar. This "cold finger" re-condenses the ullage gas back into liquid reducing the pressure, until the pressure switch eventually deactivates the cryocooler. The activation and deactivation pressures can be adjusted to any desired pressure threshold within a certain range. The system operates on 208/230 VAC-60 Hz single phase electrical power supply. The system power rating is 1.6 KW continuous (max. 1.7kW). The operation of a cryocooler system is based on a closed-loop helium expansion cycle. The complete system consists of two major components; a compressor package, which compresses refrigerant and removes heat from the system; and a GM (Gifford-McMahon) cold finger, which takes the refrigerant (high purity helium) through an expansion cycle to cool it down to cryogenic temperatures. Two flexible stainless steel lines carry compressed helium from the compressor package to the cold finger and return the low-pressure helium back to the compressor package. The pure low-pressure helium that is returned from the cold finger is compressed by an oil-lubricated compressor. The heat of compression is removed via a heat exchanger, and the oil from the compression process is removed by a set of oil separators and filters. The compressed helium is then fed to the cold finger via the high-pressure helium flex line. In the cold finger, adiabatic expansion of the helium and further heat removal allows cooling to cryogenic temperatures. The low-pressure helium then returns to the compressor package via the low-pressure helium flex line.

During normal operation, when the cryocooler is keeping the liquid air cool, the pressure in the dewar is within a range of 34.5– 172.4 kPa (5– 25 psi). If the cryocooler is turned off, the pressure in the dewar will slowly build over a period of several hours until the relief pressure is reached. When the relief pressure—717.1 kPa (104 psi)—is reached, vapor will escape until the pressure drops enough for the relief valve to close.

CryoRASS with Horizontally Oriented 2000-liter Dewar

The 2,000-liter capacity NIOSH prototype dewar has a horizontal-oriented dewar for ease of mine entry (Figure 3). The CryoRASS has a spring-loaded pressure relief valve set at 517.1 kPa

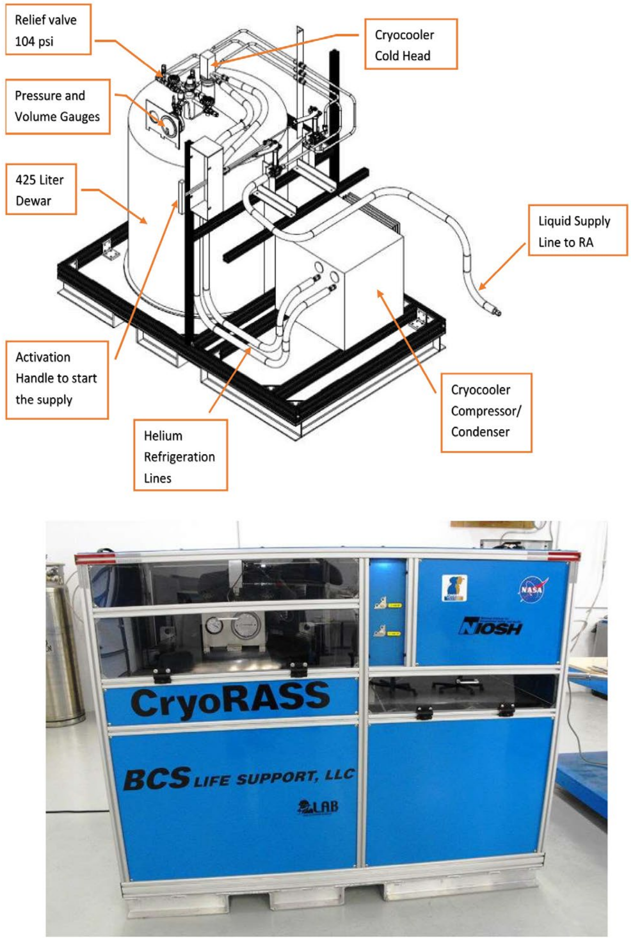

Figure 2. Vertical Dewar CryoRASS layout (above) and storage cage (below)

(75 psi). Two digital scales—one under each end—were used to monitor the weight of the liquid air remaining in the dewar.

A water-cooled cryocooler is used to maintain the liquid air. The cryocooler requires 480 V 3-phase electrical power and has a power consumption of 7.5–7.8 kW. For heat removal from the system, the cryocooler requires water in the temperature range of 5°C–25°C (41°F–77°F) to flow through a heat exchange at a rate of 6–9 L/min (1.6–2.4 gal/min). The cryocooler is controlled by a pressure switch with an adjustable set point. When the pressure within the dewar exceeds the set point, the cryocooler compressor turns on and a solenoid valve opens to allow the water flow to cool the cryocooler heat exchanger. The pressure switch is set to turn on the cryocooler at a pressure of approximately 206.8– 344.7 kPa (30–50 psi) and to turn off the cryocooler at 68.9–172.4 kPa (10– 25 psi).

TEST METHODS

Similar test procedures were followed for both CryoRASS units tested in this study. Before the tests, both dewars were filled with the necessary amounts of liquid nitrogen and liquid oxygen to create liquid air. Next, the cryocooler for each CryoRASS unit was operated to cool and maintain

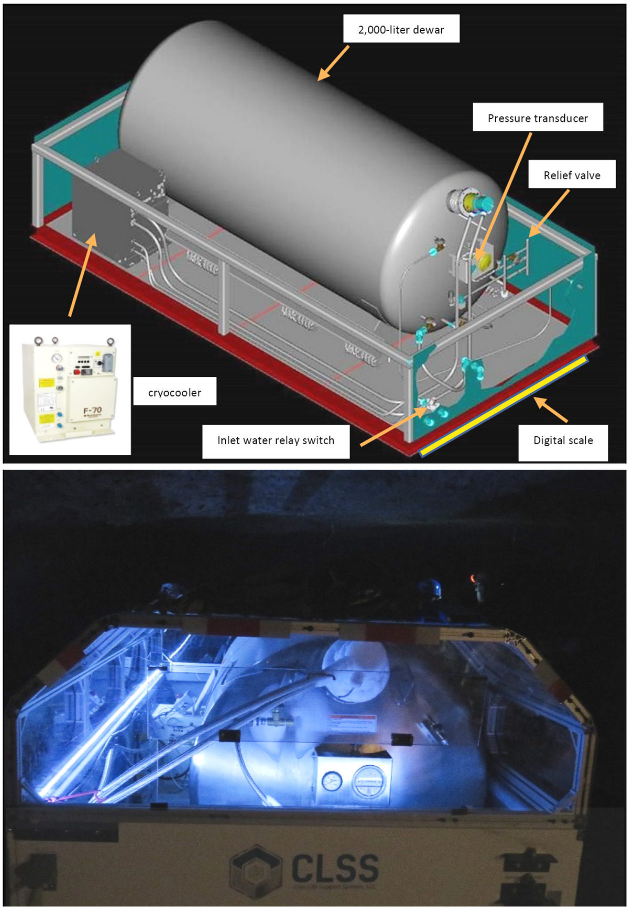

Figure 3. Horizontal Dewar CryoRASS layout (above) and storage cage (below)

the air in a liquid state. Then, power to each cryocooler was shut off, and the loss of liquid air from each CryoRASS due to periodic venting was documented.

Test Method for CryoRASS with Vertically Oriented 425-liter Dewar

The test was conducted in an indoor environment at the NIOSH Bruceton Research Center. The environment was unconditioned, and the room temperature fluctuated with the ambient air with temperature range of 12.8°C–29.4°C (55°F–85°F). The pressure of the gases in the dewar above the liquid air was measured by a pressure gauge. The volume of the liquid air was measured by a volume gauge installed at the dewar. The volume gauge reading was recorded daily. During the test, the oxygen concentration was sampled using a gas sampling device that collected the liquid air and converted it into gas.

Test Method for CryoRASS with Horizontally Oriented 2,000-liter Dewar

The test was conducted in an indoor environment at the NIOSH Bruceton Research Center. The environment was unconditioned, and the room temperature fluctuated with ambient air with temperature range of 12.8°C–29.4°C (55°F–85°F). The pressure of the gases in the ullage space above the liquid air was measured by a pressure gauge and a pressure transducer. An Omega PX309-100GI-OX pressure transducer was installed at the dewar to monitor the internal pressure

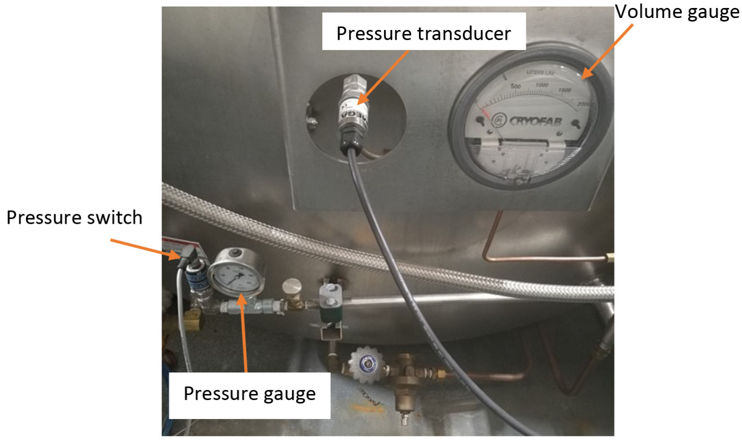

Figure 4. A close look at the dewar pressure transducer and gauges.

(Figure 4). 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 volume of the liquid air was measured by a volume gauge installed at the dewar and the weight was monitored with scales that were installed under both sides of the dewar (Figure 3). Because the volume gauge (Figure 4) was not accurate enough to measure the liquid volume inside the dewar, a new measuring system was adapted to monitor the liquid air weight using a Tufner TWB-1060 scale. It includes two weighing beams, one digital indicator, and 4–20 mA output. Each weighing beam has a capacity of 4536 kg (10,000 lbs) with 0.45-kg (1-lb) resolution. The scales were calibrated using calibration weights. In addition, the calibration weights were used to assess the stability of the scale output and its minimum recordable weight change. The 4–20 mA output was sent to the data acquisition system so the weight of the dewar could be recorded continuously during testing. During the test, the oxygen concentration was also sampled.

RESULTS

Vertically Oriented 425-liter Dewar

Tests on the 425-liter CryoRASS were initiated with approximately 325 liters of liquid air inside. After 5 to 6 days without its cryocooler operating, the 425-liter CryoRASS reached its relief pressure of 717.1 kPa (104 psi). However, the unit did not vent until Day 7. As shown in Table 1 and Figure 5, when the cryocooler power was off and after an initial period of 7 days without venting, the vaporized liquid air was lost through the relief valve at a rate of approximately 11 liters per day over a 13-day period. .

Horizontally Oriented 2,000-liter Dewar

Because the volume gauge on the 2,000-liter dewar was found to be inaccurate in previous testing, the weight change due to venting was tracked using a scale instead of using the dewar's volume gauge to track volume change. Initially, the dewar was filled with 1,440 kg (3,175 lbs, or 1,655 liters of liquid air assuming a density of 870 kg/m^3). With the cryocooler operating, the liquid air was maintained at a temperature -195°C (-318°F) with the pressure switch set to turn on when the pressure reached 172.4 kPa (25 psi) and off when the pressure reached 68.9 kPa (10 psi). To monitor the loss of liquid air due to venting, the cryocooler was turned off. This point was considered as t=0 hours.

The venting behavior of the dewar was then monitored for approximately 750 hours without cooling by the cryocooler (see Figure 6). The dewar started to vent approximately 100 hours after

Table 1. Data for CryoRASS vertical-mounted dewar after cryocooler shut off

Day/ Time	Elapsed Time (hrs)	Vapor Pressure (psi)	Liquid Volume (Liters)	Venting Occurred (Y/N)	Air Sample (O_2 %)
Day 1 - 5:10 PM	0.0	0	325	N	21.3%
Day 2 - 7:30 AM	14.3	18	325	N	
Day 3 - 8:15 AM	39.1	33	325	N	
Day 3 - 1:00 PM	43.8	36	320	N	
Day 6 - 8:00 AM	110.8	98	320	N	
Day 7 - 7:30 AM	134.3	104	320	Y	
Day 8 - 8:40 AM	159.5	104	320	Y	
Day 9 - 10:13 AM	185.1	105	320	Y	
Day 9 - 6:00 PM	192.8	104	299	Y	
Day 10 - 8:56 AM	207.8	104	285	Y	
Day 10 - 4:53 PM	215.7	104	280	Y	
Day 13 - 9:20 AM	280.2	104	255	Y	
Day 14 - 9:30 AM	304.3	104	245	Y	
Day 15 - 7:30 AM	326.3	104	235	Y	
Day 16 - 7:30 AM	350.3	104	220	Y	
Day 16 - 3:00 PM	357.8	103	215	Y	25.5%
Day 17 - 7:50 AM	374.7	104	210	Y	
Day 20 - 8:30 AM	447.3	104	175	Y	

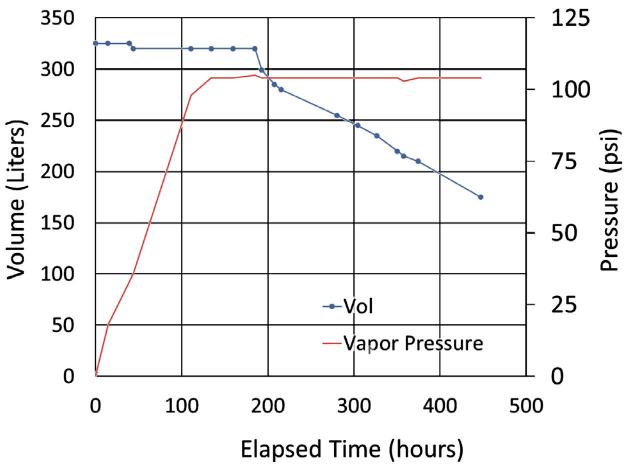

Figure 5. Dewar pressure and liquid volume changing with time after cryocooler turned off

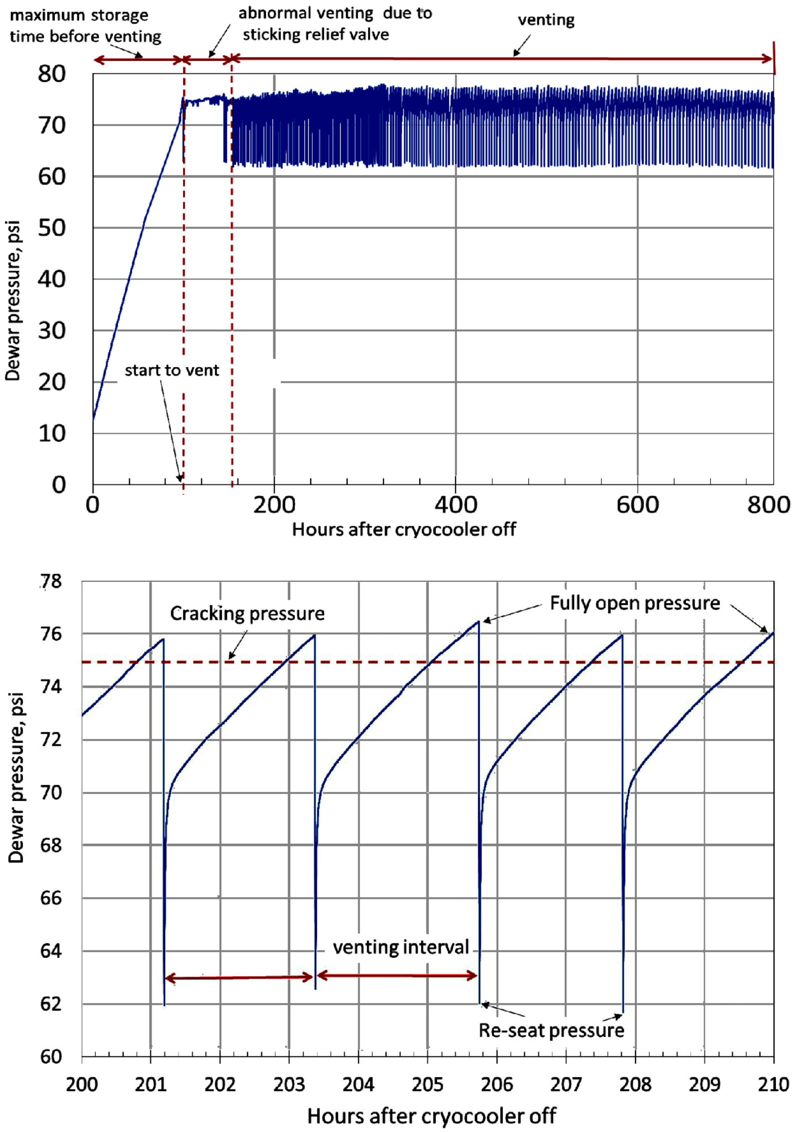

Figure 6. Dewar pressure change with time after cryocooler turned off (upper) and a zoomed-in view of the relief valve venting pattern (lower).

the cryocooler was turned off. The dewar exhibited different venting characteristics for the first 60 hours of venting and for the remaining 590 hours of venting. For the first 60 hours of venting, the dewar pressure stayed very near the relief valve cracking pressure, and the relief valve stayed at or near a "just open" condition. As the pressure in the dewar reached the relief valve cracking pressure, the relief valve opened allowing vapor to escape. Instead of resulting in a large drop in pressure due to the rapid venting of vapor with a subsequent reseating of the valve, the vapor vented slowly with a change of only a few psi (1 psi = 6.895 kPa). After the pressure dropped by a few psi, the relief valve closed and the pressure inside the dewar began to increase again until the relief pressure was reached. One explanation for this abnormal venting is that the relief valve collected moisture from the ullage vapor and became sticky. For the next 590 hours, the behavior of the relief valve changed. The dewar venting interval was 2.2 hours on average. After reaching the cracking pressure of 517.1– 524.0 kPa (75–76 psi), vapor would be released until the relief valve closed at a pressure of 427.5 kPa (62 psi) as shown in the lower plot of Figure 6. During this region of behavior, vapor was vented for approximately 30–60 seconds before the relief valve closed.

The dewar gross weight—the weight of everything above the scale, including the frame, the dewar, and the contained liquid air—time history with the cryocooler turned off for the second region of venting behavior is shown in Figure 7. The slope of the weight curve, which is the liquid air weight loss rate through venting, equals -1.03 kg/hour (-2.27 lbs/hour). With the previously mentioned venting interval of 2.2 hours, the average weight loss is approximately 2.27 kg or 5.0 lbs (2.27 lbs/hour×2.2 hours) or 2.6 liters for every venting cycle and 24.7 kg or 54.5 lbs (2.27 lbs/hour×24 hours) or 28.4 liters per day. Over 550 hours (about 23 days), the dewar lost 548.4 kg (1,209 lbs) or a volume of 630 liters of liquid air. Another observation is that for venting from a full tank to a half tank the weight loss rate was nearly constant and was independent of the remaining volume. In fact, this weight loss rate will depend on the relief valve set pressure and the environment temperature. Higher relief valve pressure will increase the venting interval time.

DISCUSSION

In this study, the venting characteristics and maximum storage time were investigated for two cryogenic systems with interrupted cooling. The two systems differ in size, dewar orientation, and relief valve cracking pressure. According to Yanisko and Croll [3], the loss rates will be in the range of 0.4%–3% of the container's volume per day. The testing showed that the 425-liter vertical dewar lost about 11 liters of cryogenic air per day after venting began. This rate is roughly 2.6% of dewar capacity per day. For the 2,000-liter horizontal dewar system, the system vented about every 2.2 hours, and about 28.4 liters of cryogenic air was lost per day. This rate is roughly 1.4% of dewar capacity per day. The venting frequency will depend on the relief valve cracking pressure and the environment parameters that affect heat transfer, including air temperature, air velocity, and solar loading.

The venting characteristics of the two systems were significantly different due to the difference in capacity and relief pressure. It took more time for internal thermal pressure to reach to the higher relief set pressure. After turning off the cryocooler for each system, it took approximately 7 days for the 425-liter vertical unit with a 717.1-kPa (104-psi) relief valve to start to vent, and approximately 4 days for the 2,000-liter horizontal unit with a 517.1-kPa (75-psi) relief valve to start to vent. However, increasing the relief valve pressure is restricted by the structural strength of the dewar and regulations governing dewar design. The 425-liter dewar lost less liquid air each day compared to the 2,000-liter dewar, which has a larger volume and lower relief pressure. However, even though the

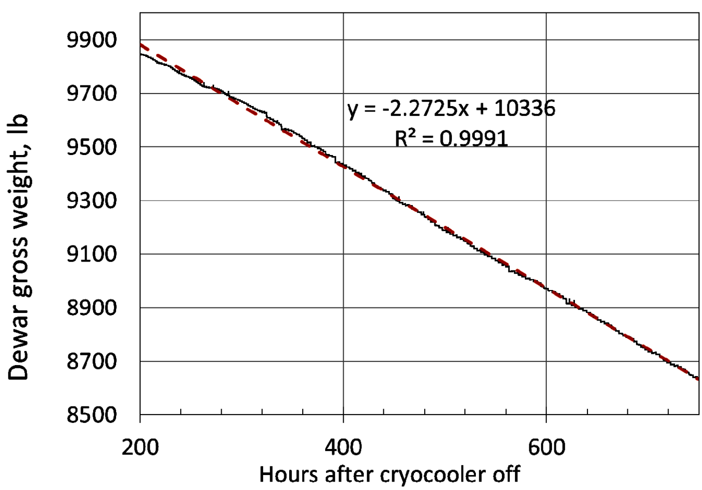

Figure 7. Dewar gross weight versus time due to venting after cryocooler turned off.

425-liter dewar has a higher relief pressure, the ratio of the lost (vented) air per day to the dewar storage capacity is higher for the 425-liter dewar (2.6%) compared to that of the 2,000-liter dewar (1.4%). In other words, without cooling, the 425-liter dewar would take less time to become depleted of liquid air than the 2,000-liter dewar.

The design of a cryogenic air supply system dictates how long the system can go without power before venting will occur. If a heavier duty tank designed for a higher pressure was used and the relief valve pressure increased for both the 425-liter vertical dewar and the 2000-liter horizontal dewar, then the system could last even longer than what was observed in our experiments without power before beginning to vent some of the liquid air.

Another aspect of the CryoRASS system for mine emergency applications when power is lost, is that when the vapor pressure in the dewar begins to vent, the nitrogen separates first due to its lower boiling point (-195.79 °C for liquid nitrogen, or LN_2, versus -182.96 °C for liquid oxygen, or LOx, at sea level). The ullage vapor become nitrogen-rich and then vents. The breathable air in the system will become slightly oxygen rich (see air sample data in Table 1 where the dewar released for nearly 16 days after power off, or 7 days after venting, and the liquid air increased by only 4% O_2 concentration). Note that the oxygen enrichment of the liquid air in this case is not detrimental to health. However, the mass flow and the volume of the air injected into the RA should be adjusted accordingly in order to follow the Mine Safety and Health Administration's (MSHA) regulation on oxygen level (18.5%–23%) for occupied RAs [6].

An RA is designed to provide breathable air for 96 hours in an emergency before mine rescue is anticipated to arrive. In order to account for potential loss of liquid air due to power interruptions, a CryoRASS unit could be designed to provide a safety factor by having an additional volume of liquid air beyond what is needed for a 96-hour emergency. This safety factor can be increased with dewar capacity above the 96-hour criteria with very little impact to RA size because of the nearly 800:1 expansion ratio associated with liquid gases. The high ratio of liquid to gas and the dewar design capability lend itself to increased flexibility in the CryoRASS design as a breathable air component to most types of refuge alternatives.

CONCLUSION

For both the vertical 425-liter and the horizontal 2,000-liter CryoRASS, regardless of the amount of liquid remaining in the dewar, the rate of air loss due to venting was almost constant. The 425-liter vertical unit lost approximately 2.6% of the dewar capacity daily. The 2,000-liter horizontal unit lost approximately 1.4% of the dewar capacity daily.

Because the vented gas contains more nitrogen than oxygen, the oxygen concentration of the liquid air left in the dewar increased with time after venting commenced. The liquid air remaining in the dewar became slightly oxygen rich. It is worth mentioning that oxygen enrichment of the liquid air was not significant in these cases and is not detrimental to health.

Venting from either of these systems during moves and power outages would not affect their ability to deliver breathable air during a disaster. For the 425-liter dewar, a power outage of up to 6 days would not cause any loss of liquid, and for the 2,000-liter dewar a power outage of less than 4 days would not cause a loss of liquid.

The information in this paper could be useful for manufacturers and mines considering the use of a cryogenic air supply as a source of breathable air and/or heat mitigation for refuge alternatives.

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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

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