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## **COOLING SYSTEMS FOR REFUGE ALTERNATIVES IN HOT MINE CONDITIONS**

**Lincan Yan, David Yantek, Miguel Reyes, Nicholas Damiano, Justin Srednicki, Joseph Bickson,  
Bruce Whisner**

The National Institute for Occupational Safety and Health (NIOSH)  
626 Cochran Mill Road  
Pittsburgh, PA, USA  
[LYan1@cdc.gov](mailto:LYan1@cdc.gov)

**Eric Bauer**  
BCS Life Support LLC  
1325 White Drive, Suite A  
Titusville, FL, USA

### **1. ABSTRACT**

The accumulated heat and humidity inside occupied refuge alternatives (RAs) can impose risk of heat stress to the occupants. The accumulated heat could be from the metabolic and environmental sources. For hot mines, the high ambient temperature makes it more difficult to dissipate heat accumulated inside the RA. A cooling system is then needed to reduce the interior heat and humidity. Two types of cooling systems were tested out for their cooling capacity. One cooling system is a portable, battery-powered, air conditioning system and the other is a portable cryogenic air supply. During the testing, the mine air temperature surrounding the RA was elevated to and maintained at 85°F to simulate hot mine environment. The tests demonstrated that both cooling systems were able to control the air temperature inside the RA even though they did not last the entire duration of a 96-hour test. This paper provides an overview of the test methodology and findings as well as guidance on improving the performance of both cooling systems, including: optimizing the cooling cycle for the battery-powered AC system and increasing the flow rate and tank storage capacity for the cryogenic system. The information in this publication is useful for RA manufacturers and mines to develop the cooling systems that will enable providing the life sustaining environment in mines with elevated temperatures.

### **2. INTRODUCTION**

The Mine Safety and Health Administration (MSHA) requires mines to provide

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mines. Refuge alternatives (RAs) are required to provide miners with breathable air and supplies to sustain life for 96 hours. If a mine accident, such as a fire, explosion, inundation, or roof fall, would occur and miners could not escape, miners could enter a refuge chamber to wait for help from a mine rescue team or to plan an alternate escape pathway. One of the biggest concerns with occupied RAs is the possible severity of the resulting thermal environment inside a refuge chamber. To minimize the risk of heat stress, MSHA mandates a maximum allowable apparent temperature (AT) for an occupied RA of 35°C (95°F) [1]. The National Institute for Occupational Safety and Health (NIOSH) has conducted extensive research on the thermal environment of occupied RAs intended for use in underground coal mines. NIOSH research has demonstrated that fully occupied RAs can exceed the AT limit at mine temperatures above 15.6°C (60°F). In these cases, the occupancy of the RA could be reduced to ensure the AT limit is not reached. This would require mines to purchase additional RAs to accommodate all personnel in the mine. For mines with temperatures above 26.7°C (80°F), the occupancy might have to be reduced so much that the necessary number of additional RAs would be impractical. In these cases, RA cooling systems could provide a solution.

NIOSH has been involved in the development of two cooling systems for RAs. One cooling system is a portable cryogenic air supply and the other is a portable, battery-powered air conditioning system. To examine the performance of these systems under extreme test conditions, both systems were evaluated by conducting 96-hour heat/humidity tests on a 20-person portable tent-type RA using 30 simulated miners in a

mine with its temperature artificially elevated to 29.4°C (85°F). The tests demonstrate that both cooling systems were able to control the air temperature and relative humidity inside the RA. However, the performance of both systems need to be improved in order to extend their cooling capacity to cover the whole duration of 96 hours.

### 3. NOMENCLATURE

<i>AT</i>	apparent temperature
<i>BTU</i>	British thermal unit
<i>RH</i>	relative humidity

### 4. HEAT/HUMIDITY ISSUE AND AIR QUALITY CONTROL FOR OCCUPIED RA

If an accident occurs in an underground coal mine, miners who fail to escape from the mine can enter an RA for protection from adverse conditions, such as high carbon monoxide levels. One of the main concerns with the use of mobile RAs is the temperature rise inside the RA from the metabolic heat of the occupants and the heat released by the carbon dioxide (CO<sub>2</sub>) scrubbing system. Moreover, the humidity within the RA will increase through occupants' respiration and perspiration and from the chemical reaction within the CO<sub>2</sub> scrubbing system. The accumulation of heat and humidity could result in miners suffering heat stress, heat stroke, or even death. MSHA regulations require that RAs must be designed to ensure that the internal apparent temperature (AT) does not exceed 35°C (95°F) when the RA is fully occupied [1]. Apparent temperature (AT) is a temperature-humidity metric for the perceived temperature caused by the combined effects of air temperature, relative humidity (RH), and air velocity. It is used to assess the perception of indoor temperatures when workplaces are not sufficiently heated, cooled, or insulated to provide comfortable or healthy conditions.

The control of temperature and humidity within a confined space such as a RA is critical because of the relatively narrow range within which the unprotected human body can operate without developing heat stress [2]. The human body maintains a normal core temperature between 36°C (96.8°F) and 38°C (100.4°F) [3]. Heat transfer to and from the body occurs from convective transfer (air movement), radiant transfer, and respiration (heat in exhaled/inhaled air). The differential between skin and core temperature allows heat to move from the body's core to the skin, where it can be lost through convection, radiation, conduction, and perspiration. In hot environments, sweating occurs when convection, radiation, and respiration become insufficient to dissipate the accumulation of heat from metabolic and environmental sources. Evaporation of sweat absorbs significant amounts of heat from the skin—far more than convection, radiation, and respiration combined—hence, it allows the body to lose heat rapidly. As the ambient temperature approaches or exceeds skin temperature, sweating becomes the body's primary mechanism of heat loss. However, the rate of sweat evaporation is limited by the relative humidity of the

surrounding air. As the relative humidity increases, the rate of sweat evaporation slows, reducing the body's ability to cool itself. Evaporation of sweat becomes very slight at high relative humidity. For example, the maximum sweat evaporation rate drops from ~2.5 L/hr at 50% RH to ~1.3 L/hr at 80% RH at an air temperature of 35°C (95°F) [4]. Therefore, a cooling system is required to maintain the interior air temperature and humidity in an occupied RA in a hot environment.

### 5. TEST SETUP

The tests were conducted in NIOSH's Experimental Mine (EM) in Bruceton, PA. The RA was installed at the intersection of an entry and a crosscut (Fig. 1). To prevent bulk airflow into the test area, the RA was isolated from the mine ventilation system using polystyrene walls. The RAs were centered within the entry so that the sides of the refuge chamber were equidistant from the ribs.

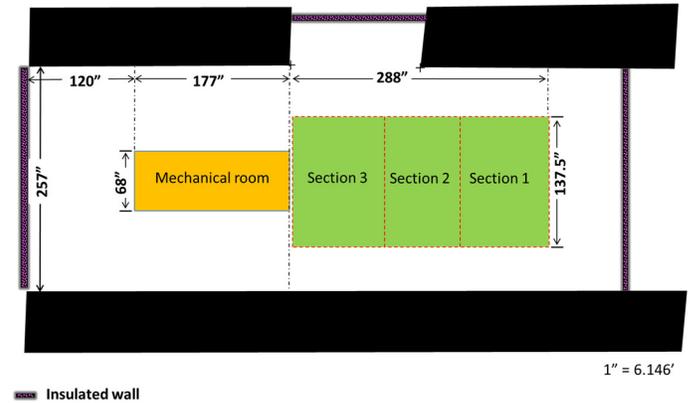


Fig. 1. The tested 20-person refuge alternative located at the Experimental Mine (EM).

The 20-person tent RA is 7.3 m long by 3.5 m wide by 1.6 m high (24 x 11.5 x 5.5 ft), with an internal volume of ~41 m<sup>3</sup> (1,444 ft<sup>3</sup>) and a floor surface area of ~26 m<sup>2</sup> (280 ft<sup>2</sup>). The RA was internally divided into two parts: the mechanical room and the tent part (Section 1 through Section 3). The mechanical room is used to store compressed oxygen cylinders that would be used to provide occupants with oxygen. After inflation, the tent part would be the areas (Section 1, Section 2, and Section 3) occupied by miners. Section 1 would also serve as an air lock. Thirty (30) simulated miners and five (5) heated water tanks were used during the testing to represent the heat and moisture generated by actual miners. More details about the layout of simulated miners and water tanks can be found at [5].

For ease of reference, the tent was divided into three sections—Section 1, Section 2, and Section 3. Resistance temperature detectors (RTDs) and wireless data logger temperature/humidity sensors were used to record the internal air temperature and relative humidity (RH) at various locations within the three sections. The external air temperature and RH nearby the tent were also monitored and recorded during the test. The mine air and mine strata (roof, rib, and floor) temperatures

at various depths were also measured using RTDs. More details about the arrangement of the temperature and humidity sensors can be found at [6].

To simulate a hot mine environment, the temperature of the enclosed test area was artificially elevated to and maintained at 29.4°C (85°F) during the test using a group of electric heaters. This represents the maximum operating temperature expected in North American coal mines [7].

## 6. RA COOLING SYSTEMS

### 6.1 Cryogenic liquid air system

The Cryogenic Liquid Air Breathable Air Supply and Cooling System for use in portable refuge alternatives (RAs) and built-in-place (BIP) shelters was initially developed for the National Institute for Occupational Safety and Health (NIOSH) under contract with NASA. The system is currently dubbed the Cryogenic Refuge Alternative Supply System, Iteration No. 3 or CryoRASS-3.

The CryoRASS-3 system (Fig. 2) utilizes a volume of liquid air that is maintained in a stable, zero-loss condition by use of an electrically operated cryogenic cooler. Liquid air is air comprised of 79% nitrogen and 21% oxygen that has been cooled to a very low temperature. The liquid air is stored in a dewar (well-insulated, double-walled, low-pressure vessel) designed specifically for this purpose, stored at the RA/BIP shelter, and sized for the expected number of refuge occupants. The cryo cooler keeps the temperature of the liquid air at a constant 78°K (-318°F). As currently designed and tested, heat that is extracted by the cryo cooler is removed from the system using clean, filtered, mine-temperature mine water that flows through the cryo cooler and is expelled to a mine sump. System pressure is kept below 207 kPa (30 psi), which is considerably less than the pressure in the oxygen bottles currently used. 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.

In a mine emergency when miners find it necessary to enter the refuge chamber, the CryoRASS-3 system is activated by the first miner(s) to enter the refuge, initiating the flow of liquid air from the dewar. The liquid air is sent to the air vaporizer supply box (also referred to as the heat exchanger and/or air handler) that is placed within the refuge. As the liquid courses through the heat exchanger, the heated air from the RA warms and expands the liquid air to gas, which is subsequently routed to the air amplifier(s). Note that the aim of the tests were to show the cooling effects only. Other tests need to be conducted to show that the cryo air would be the primary source of breathable air inside a refuge.

During this process, the air is warmed to a temperature in the range of 16° to 21°C (60° to 70°F). In addition, as the vaporized air is pushed back through the air vaporizer box a venturi effect pulls ambient refuge air through the vaporizer box as well. The vaporization process, venturi effect, and

introduction of cool air not only reduce the temperature within the refuge chamber, but also dehumidify the refuge chamber as the warm ambient air is drawn through the heat exchanger. Frost and ice form on the heat exchanger fins, subsequently melting and draining into the collection chamber below. This collected water could be an added or emergency supply of drinking water if necessary, or it can be drained from the refuge chamber.

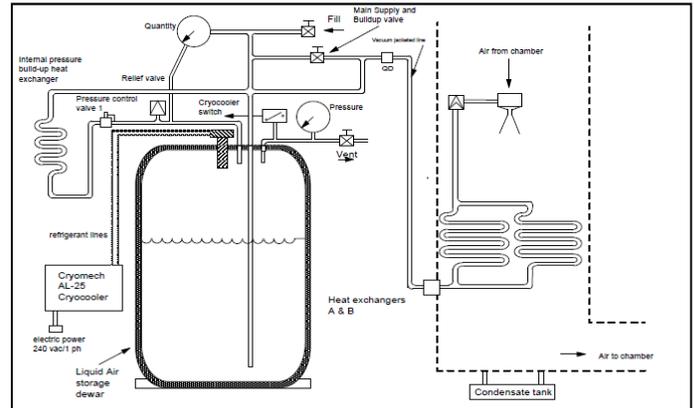


Fig. 2. Basic CryoRASS schematic (upper drawing) and the CryoRASS positioned for the 20-person tent RA test (lower photo). The liquid air delivery hose can be seen in the lower right corner of the photo.

### 6.2 Battery powered A/C unit

The Refuge Alternative Electrical Cooling System (RAECS) includes a battery tray designed to power the entire cooling system for 96 hours and is designed to maintain the temperature inside RAs below the maximum limit for human health and safety. In order to maintain the RA interior apparent temperature below 95°F, the cooling capacity was designed to be 12,427 BTU/hour (3,639.1 watts) in the fully occupied 20-person tent RA.

A backward inclined centrifugal fan was selected for the evaporator fan due to its flow and pressure capabilities to

overcome the conditioned air flow pressure drop within the ECS cabinet and the pressure drop of external ducting leading to the RA. An axial fan design was used for the condenser fan since the condenser coil requires a higher air flow rate with reduced pressure capability relative to the evaporator fan. Two axial condenser fans were used due to the required condenser air flow and limited product offerings for the 48 Volts DC power source. Fig. 3 shows the arrangement of major components inside the RAECS cabinet. The cabinet is bisected by a center partition that divides the evaporator compartment from the condenser compartment. The partition is thoroughly sealed to prevent mine ambient air that is passing through the condenser section from entering the evaporator section where it could enter the RA's conditioned air stream. The evaporator fan was placed at the return air entrance to the ECS cabinet. This placement creates positive pressure in the majority of the ECS evaporator compartment, which further isolates this compartment from potentially contaminated mine ambient air. Air is forced through the evaporator coil and then into the supply air duct.

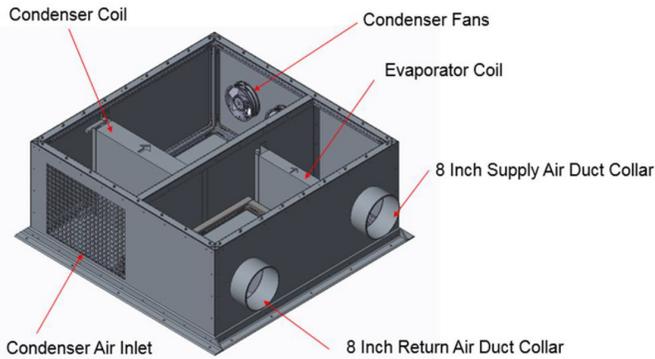


Fig. 3. Component arrangement in RAECE cabinet.

The condenser coil is placed upstream of the two axial fans that pull air through the coil. The refrigerant compressor is located upstream of the condenser. This allows relatively cool mine air to flow over the compressor to assist in compressor motor cooling. The explosion proof electrical enclosure is mounted exterior to the main ECS cabinet due to its size. Power and control lines feed to the ECS cabinet through electrical openings that are sealed from ambient mine air. The ECS cabinet and explosion proof housing are mounted on a rugged skid surrounded by a protective cage. The battery tray is also enclosed in a rugged frame suitable for the mine environment.

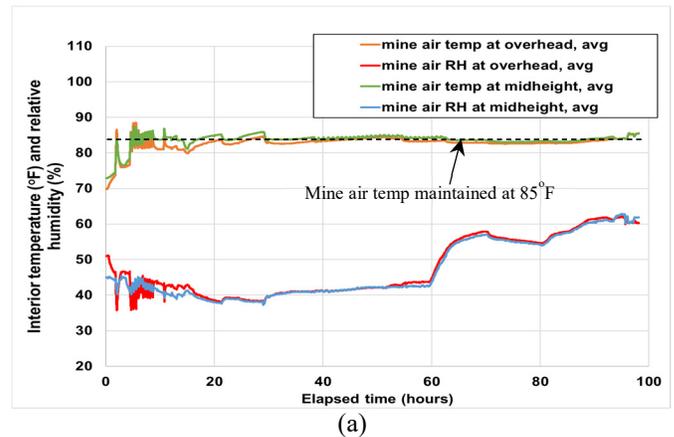
The 20-person RA was occupied by 30 simulated miners to test out the cooling system under an extreme condition. Batteries were fully charged prior to the testing. Similar to the cryogenic air system test, the space immediately surrounding the inflatable RA and the RAECS was isolated from the rest of the mine, and electric heaters were placed in the isolated area to increase the mine ambient temperature to 85°F.

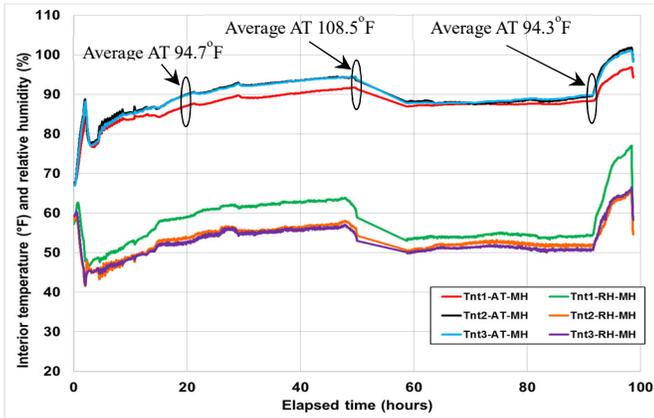
## 7. RESULTS

### 7.1 Cryogenic air system

During the test, the CryoRASS-3 was positioned outside the portable tent RA and on the outby side of the isolation (insulated) wall. The system was connected to the air vaporizer supply box by a 30-ft-long, vacuum-jacketed cryogenic liquid transfer hose. The air vaporizer supply box was positioned at the end of Section 1 near the airlock entrance because of hose length restrictions and positioning of the CryoRASS. It provided flow rate of 220 liters (6.2 ft<sup>3</sup>)/min of air at a pressure of 60 psi. This flow rate would require approximately 1,740 liters (61.5 ft<sup>3</sup>) of liquid air based on a volumetric expansion ratio for liquid to gaseous air of 728:1. Mine opening dimensions restricted the CryoRASS-3 to utilizing a 2,000-liter dewar. For this test, it was estimated that approximately 1,850 liters of liquid air were in the dewar at the start of the test. In addition, a flow rate greater than 220 liters (6.2 ft<sup>3</sup>)/min of air was occurring due to a lack of accurate flow measurement.

The tent interior air temperature and relative humidity at midheight of the center of each tent section (Section 1 through Section 3) and the mine air temperature and relative humidity are plotted as shown in Fig. 4. While the mine air temperature in the enclosed area was maintained at around 85°F, the cryo system kept tent interior apparent temperature (AT) below 35°C (95°F) (averaged) for the first 20 hours after the test began (Fig. 4b). That temperature then exceeded the 95°F limit, approaching to 42.5°C (108.5°F). This was probably caused by the frozen air handler, which reduced the air flow rate and hence the cooling efficiency. The clogged air handler was cleaned at ~50 hours, and the tent interior temperature started to decrease. The interior AT maintained below 95°F again for the rest of testing until the liquid air was depleted at ~91 hours after the test began.





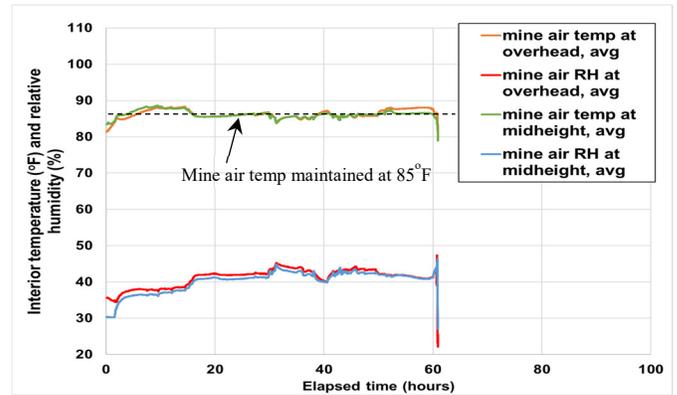
(b)

Fig. 4. The mine air temperature and relative humidity (a) and tent interior air temperature and relative humidity (b) versus time for 20-person tent RA tested with CryoRASS-3.

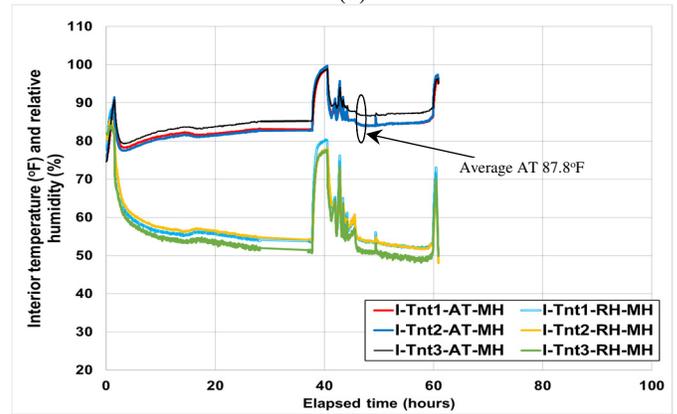
### 7.2 Battery-powered A/C unit

The planned test duration at elevated ambient temperature was 96 continuous hours. However, the RA ECS power consumption was greater than anticipated, causing the batteries to be depleted in 47.25 hours. The RA ECS demonstrated the ability to maintain conditions within the RA ECS at or below 35°C (95°F) apparent temperature while operating from its 48-volt DC battery tray for 47.25 hours. Higher than expected power consumption by the RA ECS caused the main circuit breaker to trip and accelerated the battery depletion rate. These factors prevented the unit from operating for the full 96 hours.

The tent interior air temperature and relative humidity at midheight of the center of each tent section (Section 1 through Section 3) and the mine air temperature and relative humidity are plotted as shown in Fig. 5. The tent interior AT was kept below 95°F for the first 38 hours after the test started. About 38 hours after the test, a trip of the RA ECS main circuit breaker due to high power consumption caused the A/C unit to stop working. Both the temperature and relative humidity inside the tent began to increase and the interior AT increased to above 65.6°C (150°F). The circuit was then reset and used low fan mode. The temperature and relative humidity inside the tent decreased and the interior AT dropped below 35°C (95°F) and approached 31.1°C (88°F) before the batteries were completely depleted at 47.25 hours.



(a)



(b)

Fig. 5. The mine air temperature and relative humidity (a) and tent interior air temperature and relative humidity (b) versus time. The batteries were depleted in 47.25 hours after the beginning of the test. The tent interior air AT was maintained at about 31°C (87.8°F) when the batteries were depleted.

## 8. DISCUSSION

Both the CryoRASS-3 cryogenic air system and the RA ECS battery-powered A/C unit demonstrated the ability to maintain the refuge alternative interior at or below 95°F apparent temperature during operation in a hot mine condition. As we can see in the test data, without the cooling systems, the tent interior temperature will increase dramatically above the 95°F AT limit under hot mine conditions.

The utilization of liquid air is extremely advantageous for reducing the apparent temperature inside an RA and, subsequently, for the survivability of miners utilizing the refuge chamber because it involves a two-fold approach:

1. Liquid air provides cooler air than the conventional air systems (i.e. compressed oxygen bottles) used in current RAs and BIP shelters; and
2. Liquid air dehumidifies as it is vaporized in the air vaporizer box. The result is that in some cases, de-rating of RA/BIP shelter capacity may not be necessary.

The CryoRASS-3 system is designed to function without the need for electricity which allows it to operate in post disaster conditions where power may not be available.

The liquid air was depleted at 91 hours after the test began. A higher air flow rate would have made further improvements to humidity and temperature. To extend the duration of the air supply or increase the flow rate, the addition of extra liquid air commodity would be needed for the system.

Unexpected high power consumption prevented the RAECs from operating for 96 hours. Under the hot mine environment, it operated for 47.25 hours before the batteries were discharged. The RAECs include a large 48-volt battery and is intended to sit outside the RA near the electrical cooling system.

1. This unit is not designed to meet the intrinsic safety or explosion-proof requirements, specified in MSHA regulations [1], so design considerations to achieve permissibility are needed.

2. Redesign the system so it can meet the 96 hour requirement. This can be achieved by optimizing the cooling cycle, or increase the size of battery package. A smaller refrigeration system will result in a reduced need for stored electrical energy (batteries) and an overall reduction in the physical size of the RAECs.

## 9. CONCLUSION

The tests demonstrate that both cooling systems were effective in controlling the air temperature inside the RA even though neither system lasted for the entire 96-hour test. For the cryogenic cooling system, the interior air AT was maintained under 95°F before the liquid air was depleted at about 91 hours. For the battery-powered air conditioning system, the interior air AT was maintained under 31.1°C (88°F) before the batteries were depleted after 47.25 hours of testing. Increasing the flow rate and tank storage capacity would improve the performance of the cryogenic air system. For the battery-powered A/C system, optimizing the cooling cycle would reduce battery usage and extend cooling cycle time. However, since neither of these two systems lasted the required 96 hours, improvements must be implemented and more testing needs to be conducted before either system can be considered a viable option.

The information in this publication could be useful for RA manufacturers and mines to develop cooling systems that will enable RAs to meet the 95°F AT limit in mines with elevated temperatures.

## DISCLAIMER

Mention of a company name or product does not constitute an endorsement by the National Institute for Occupational Safety and Health (NIOSH), Center for Disease Control (CDC). The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the NIOSH, CDC.

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