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A PORTABLE LIFE SUPPORT SYSTEM FOR USE IN MINES

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INTRODUCTION

This paper describes the life support system designed, developed, and tested by Westinghouse Electric Corporation for the Bureau of Mines as a part of contract H0101262. The prototype auxiliary survival chamber for use in mines consists of a mobile, collapsible, modular quonset hut-shaped shelter (fig. 9.1) containing atmosphere conditioning and monitoring equipment, communications and location equipment, battery-powered lights, food and water supplies, and a chemical toilet. The principal features of the system are simplicity, reliability, and shelter from toxic atmosphere and explosion.

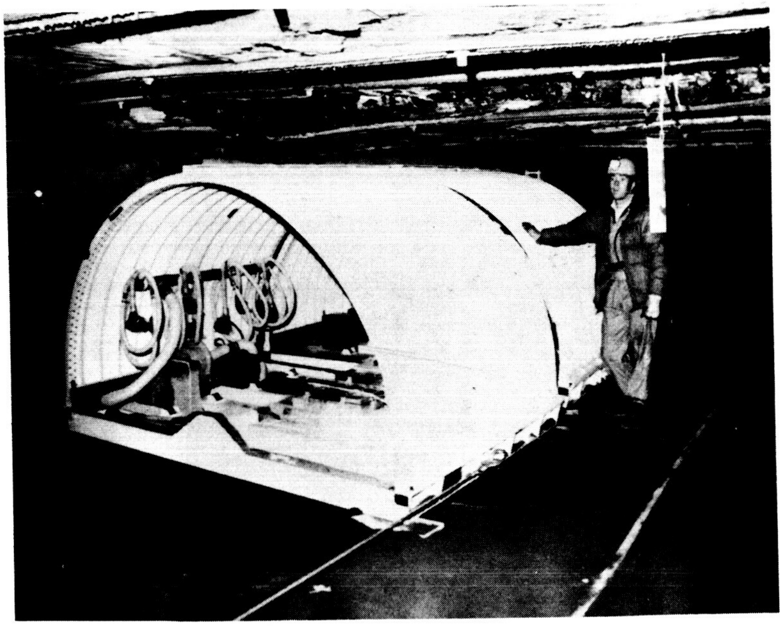

Figure 9.1 *Auxiliary survival chamber.*

The design and development of this system were undertaken to fill the need for protecting miners from blast, rockfall, flash fire and other conditions resulting from mine fires and explosions. This system is a potential improvement over barricading after a disaster.

The basic system requirement is life support for 15 miners for 14 days. Other requirements include mobility (to allow the system to follow the mine working faces), low production cost, long service life, short set-up and maintenance times, simplicity of operation, little training requirement, and tamper-proof supplies.

Chamber Structure

The chamber structure is made entirely of steel. The roof, divided in half at the midline with pinned connections, is made of corrugated steel 0.1 in. thick. Hinges connect the roof to the reinforced floor. The 9×6-ft floor of each module is a flat plate 1/4-in. thick, reinforced internally by 6×6-in. I-beams, 16 in. on centers. The chamber end walls are corrugated and reinforced externally by four vertical posts, four struts, and a reinforced platform bolted to the floor of the mine. Each of the end walls has a ship's hatch, which can be opened or closed tightly from either side, with a 4-in. diameter view port.

Each module and end bulkhead has mounts for two wheels with stub axles and a towing fitting. For transport, the modules are unpinned at the roof centerline and folded to an overall height of 42 in. The end bulkheads also fold down to a height of 28 in. This prototype chamber has been tested for habitability, operability, and explosion resistance in a Bureau of Mines test mine.

ATMOSPHERIC CONDITIONING UNIT

Two atmospheric conditioning units (ACU) are provided for each survival chamber (fig. 9.2). These units chemically remove carbon monoxide and carbon dioxide from the chamber air, supply oxygen, provide a facemask breathing mode, and circulate the air within the chamber by means of a blower. The ACU was designed for the following performance parameters:

Figure 9.2 *Atmospheric conditioning unit.*

1. Inlet carbon monoxide concentration of 1000 ppm.
2. Inlet carbon dioxide concentration of 1.0 percent.
3. Inlet air flow of at least 15 SCFM.
4. Inlet humidity of 80 percent.
5. Inlet temperature of 50° to 80° F.
6. Outlet carbon monoxide concentration of less than 100 ppm.[1]
7. Outlet carbon dioxide concentration of less than 0.1 percent.
8. Outlet temperature of less than 100° F.
9. Control of the chamber seal leakage.

The design constraints included:

1. The blower must be manually powered.
2. An operational facemask breathing mode must be available.
3. The ACU must fit into the auxiliary survival chamber when the chamber is in the folded-down transportation position.
4. The oxygen supply will be connected to the unit, to increase the oxygen concentration of the air flow during the facemask breathing mode.
5. Only the correct assembly will be possible.
6. The assembly must be rapid even in low light levels.

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[1] TLV is 50 ppm, but ACU design is based on 100 ppm.

7. One unit must be capable of removing all the carbon dioxide produced by 15 men, in case one of the two units should fail.
8. The unit will have sufficient flexibility to be used in other applications for various numbers of users.

The detailed design and selection of the ACU components is discussed below.

Oxygen Generation and Measurement

A tradeoff study was made to select a suitable oxygen supply. High-pressure storage of oxygen was eliminated by considerations of portability, reliability, and safety factors. Potassium superoxide was eliminated because the required development effort was precluded by program constraints. The final selection was a sodium chlorate oxygen-generating candle. The size of each candle was a compromise between the miners' oxygen requirement and constraints of storage space, handling, overpressure relief, and cylindrical shape. The result is a candle that generates 70 cu ft of oxygen in approximately 40 min.

The total quantity of candles was based on an oxygen consumption rate of 1.78 lb/man-day for 210 man-days plus 46 lb of oxygen for the oxidation of carbon monoxide. The concentration of oxygen in the surrounding mine air, which leaks into the chamber, affects the quantity of candles required; for the worst case of no oxygen in the mine, 14 additional oxygen candles are required. The candle is connected to the ACU so that the oxygen concentration of the airflow is increased by about 10 percent for facemask use. A candle holder, primarily a heat sink, is supplied to prevent the candle wall temperatures from reaching the ignition temperature of coal dust.

The oxygen-generating candles were bench-tested by the vendor and at two Westinghouse facilities. Analyses demonstrated that the effluent gases contained oxygen in sufficient purity and quantity, and were released at adequate rates and temperatures. Candle operation was found to require little training. The candle holder successfully kept the candle wall temperatures below the ignition temperature of coal dust during all bench and manned tests.

The effluent gas from the oxygen-generating candles was analyzed by spectrophotometers to assure that the composition was within the requirements of metabolic oxygen supplies. An internal flow restriction in the candle filter material will necessitate additional design effort before these candles can be put into general use.

The oxygen concentration meter was calibrated at 21 percent concentration and bench-tested with a gas of 98 percent oxygen. This meter was a small, portable fuel-cell type of oxygen analyzer. Manned tests indicated that the analyzer must be calibrated and used in the horizontal position to maintain the required 2 percent accuracy. This restriction on its operation was not considered too severe, so the analyzer was used in the shelter.

CARBON DIOXIDE ABSORPTION AND MEASUREMENT

The carbon-dioxide absorption method selected for use in the chamber atmospheric conditioning unit had to meet the following criteria: capacity for 210 man-days, short assembly and disassembly time, low cost, good portability in a mine, minimum development, and high safety and reliability.

There are three principal methods of carbon dioxide removal: chemical absorption, cryogenic condensation, and osmotic diffusion (refs. 1-6). A tradeoff study of available methods indicated that chemical absorption by means of baralyme in vertical, axial-flow, refillable canisters was the best means of absorbing the carbon dioxide produced by 15 men in 14 days in the survival chamber.

In the tradeoff analysis of available methods, cryogenic condensation and osmotic diffusion were summarily rejected for reasons of cost, portability, and safety. The method of chemical absorption remained. Available chemical reactions utilized potassium superoxide, baralyme, sodasorb, and lithium hydroxide. Potassium superoxide was eliminated because of cost and required development. Baralyme was selected over sodasorb for final consideration because of lower dusting, higher efficiency, lower corrosion risk, and lower cost. Baralyme was selected over lithium hydroxide because of lower cost. To preclude the possibility of channelling in the canister, a vertical, axial-flow canister with laterial baffles was designed and developed.

The size of each canister is based on a design duration of 8 hr, manual handling considerations, and the available storage space in the chamber. The rate of carbon dioxide removal is based on generation of 1.26 lb of CO_2/hr from 15 men, 0.12 lb CO_2/hr from the carbon monoxide removal canister, and 0.10 lb CO_2/hr from the outside air drawn in through the leakage control hoses. The outside concentration of carbon dioxide is assumed to be a maximum of 10 percent. Forty-two baralyme canisters are required for the 14-day mission duration.

The carbon dioxide removal canister was bench-tested successfully, removing all but 0.06 percent carbon dioxide from an inlet air flow of 17 SCFM containing 1.0 percent calibrated carbon dioxide gas for 8 hr. The manned tests indicated that the canister required an initial temperature of at least 40° F to remove 90 percent of the incoming carbon dioxide. This requirement was not considered to be a problem for the expected mine storage conditions. Actual testing with 15 men for 2 days in a Bureau of Mines test mine demonstrated the operability and performance of the carbon dioxide removal canister.

The sampling pump and test tubes for measuring carbon monoxide and carbon dioxide concentrations were bench tested with certified calibration gases, giving accuracies of within ± 0.1 percent carbon dioxide and ± 25 ppm carbon monoxide. The manned tests revealed that simplification of operation was required for unskilled use of the instrument. This difficulty was overcome merely by changes in the packaging and operating instructions; after one reading of these instructions the test subjects had no trouble operating this instrument.

CARBON MONOXIDE REMOVAL CANISTER DEVELOPMENT

The available means of removing carbon monoxide from an air stream are absorption and catalytic oxidation. The method of carbon monoxide removal by absorption on solid molybdemum trioxide or tungsten is efficient at high carbon monoxide concentrations, but its performance is not known at the low concentrations expected in the chamber. This absorption method was rejected because of the requirement for basic research on its performance at the design conditions. The method of catalytic oxidation using hopcalite was acceptable in performance and operating requirements. Hopcalite is a coprecipitated mixture of manganese dioxide and cupric oxide with small percentages of cobalt and silver oxides added. It has the ability to catalyze the oxidation of carbon monoxide at mine temperatures. The hopcalite catalysis is used in portable respirators, high-pressure air filters, and submersible vehicle air conditioners.

Since hopcalite is poisoned by water vapor and by traces of antimony (ref. 1), these chemicals were eliminated from the materials, finishes, and assembly of the canister, and provisions were included for removal of water vapor during operation. Other design constraints of overall dimensions and manual operation were evaluated and incorporated into the canister design. Preliminary test results indicated a need for increased efficiency, so the original design was revised to include a hopcalite bed depth of 2.5 in. and a diffusing baffle, producing a canister of sufficient efficiency and duration.

In air conditioning systems for submersibles, carbon monoxide removal is combined with combustion of other contaminants. In high-pressure air filters, carbon monoxide removal is combined with particle and oil mist filtration. Since no applicable standard design existed, the carbon monoxide removal canister for the shelter required a new filter bed design.

The canister performance requirements were (1) removal of all but 100 ppm of carbon monoxide from an inlet concentration of 0.1 percent (1000 ppm) carbon, and (2) a duration of approximately 4 hr. The design constraints were:

1. No antimony can be used in the materials, finishes, construction, or assembly of the canister.
2. The canister must be capable of being installed, removed, and handled entirely by hand.
3. The canister must not cause or become a fire hazard.
4. The canister must be refillable.
5. The design must be cost effective.
6. One overall dimension must be less than 7 in. and the other dimensions must be small enough to fit in the available shelter storage spaces.

The design conditions were:

1. An air flow rate of about 17 SCFM.
2. A relative humidity of the air flow of 80 percent.
3. An inlet carbon monoxide concentration of 1000 ppm.
4. Vibration and shock from transporation and blast.
5. Long-term storage at 60° F and 80 percent relative humidity.

Other desirable features were:

1. Hardware, finishes, and assembly methods should be similar or identical to the carbon dioxide removal canister to reduce costs.
2. The canister should have a size or shape different from the carbon dioxide removal canister to eliminate errors in operation in darkness.

The inlet carbon monoxide concentration is based on an assumed 10 cu ft of 10 percent carbon monoxide mine air entering the shelter with the miners, giving an initial concentration of 800 ppm.

The canister housing was designed to overall dimensions of approximately 6-3/4 by 9 by 13 in. The construction was of zinc-plated sheet steel, using spotwelded and soldered seams, reinforced points of wear, a latched, spring-loaded cover with gasket seal, "O" ring seals at both ports, and a spring-loaded filter bed retained by two metal screens. A wall baffle was included to prevent channeling of flow along the walls. All solder used contained no antimony.

The canister filter bed consisted of a metal top screen, a 1-1/2 in. thick layer of activated charcoal, a 5-1/2 in. thick layer of silica gel, a 1-1/2 in. thick layer of molecular sieve, a 1-in. thick layer of hopcalite, and a metal bottom screen. The flow direction was axially downward.

The charcoal layer was intended to absorb hydrocarbons and prevent their possible reaction with hydrogen, catalyzed by the hopcalite. Since neither hydrocarbons nor hydrogen will be present in the chamber in the high concentration required for a reaction, the charcoal layer was judged to be an unnecessary precaution in the revised canister design. The silica gel and molecular sieve layers are intended to absorb water vapor at high and low relative humidities, respectively. The quantities of these components determine the duration of the canister, since hopcalite is not used up in its catalysis of carbon monoxide. When the silica gel and molecular sieve layers are saturated with water vapor, the excess water vapor that passes through them poisons the hopcalite, resulting in a slow increase of carbon monoxide concentration at the outlet. The rate of this increase depends on the amount of time the airflow is in the hopcalite layer.

The hopcalite layer must be thick enough to complete the catalytic oxidation of carbon monoxide. The reaction requires close contact for a period of time between the gas stream and the hopcalite. To achieve this contact time existing hopcalite beds from 1/2 to 5 in. thick, maintain ambient temperatures to 650° F, and permit low flow speeds.

The results of the first bench test indicated low efficiency of carbon monoxide removal. In the revised design, the charcoal layer was removed and more hopcalite added to make a 2-1/2 in. thick bed. This revision also incorporated a baffle plate at the canister inlet to distribute the air flow. Test data showed that this design efficiently removed carbon monoxide at nearly the design conditions for exactly 6 hr. The data show that the breakthrough occurred slowly as humidity attacked the hopcalite bed.

Two atmospheric conditioning units operating simultaneously at 17 SCFM each would reduce an initial chamber concentration of carbon monoxide of 3 percent to 0.01 percent within 4 hr in the shelter volume of 1260 cu ft. Figure 9.3 shows the time required for removal of unsafe carbon monoxide and the formula used for the calculations, using 0.617 air change per hour.

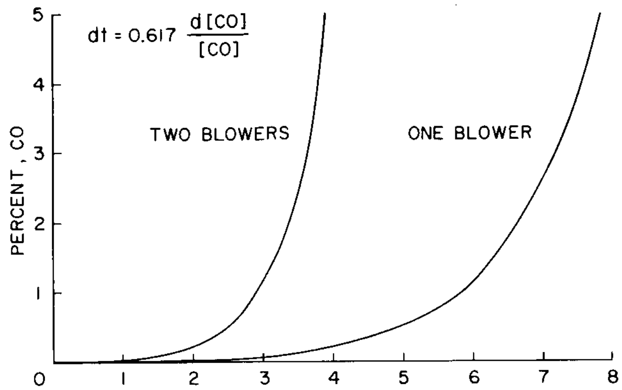

Figure 9.3 *Time required to remove unsafe carbon monoxide.*

The intermittent supply of oxygen gas from the chlorate candles reused shelter seal leakage, which was corrected by means of a 0.375-in. inner diameter leakage control hose leading through the chamber wall to a fitting at the inlet of the carbon monoxide removal canister in each atmospheric conditioning unit. When the chamber seals are properly installed the leakage control hoses provide lower resistance leakage paths than do the seals, so the inward flow of mine gas is immediately scrubbed. When the ACUs are in operation, the hoses will act as suction lines, maintaining a slight positive pressure and outward leakage through the seals.

Outward leakage through the hoses during candle firing results in the loss of about 12 cu ft of oxygen per firing. Check valves in the leakage control hoses (or no hoses) would result in the loss of about 10 cu ft of oxygen through the seals as the internal pressure rises. The 2 cu ft difference in oxygen loss is small compared to the 72 cu ft of oxygen produced by each of the candles. Also, it was decided that the risk of plugging, the added maintenance, and the difficulty of clearing any plug outweighed the possible oxygen savings from a check valve, so none was included in the hoses.

Under normal conditions of expected leak rates through both the seals and the leakage control hoses, activity levels, and gas contamination, the ACUs must operate about 51 min/hr to maintain the carbon dioxide and carbon monoxide concentrations below their design values of 1.0 percent and 100 ppm, respectively. Continuous operation is required when the gases exceed these levels. Because carbon monoxide concentration in a mine after a blast normally decreases with time, a design duration of 5 days of carbon monoxide removal was selected for the prototype shelter. Thus, the prototype survival chamber is equipped with 28 of the 4.5-hr carbon monoxide removal canisters.

VENTILATION COMPONENTS

The duct, hoses, manifold, and facemasks of each ACU are fireproof, easily attached and repaired, and spaced to avoid overcrowding. The blower outlet hose is disconnected from the distribution manifold and is used as a ventilation duct in normal operation. The blower is a hand-cranked fallout shelter ventilator requiring about 0.10 hp. This gear-driven centrifugal blower is operated at 40 rpm by one man at a time for 30 min.

The other components of the ACU, such as the flexible hoses, facemask fittings, mountings, duct, and blower, performed well in bench tests and manned tests with the exception that the hand-cranked blower, which was developed for fallout shelter use, developed a seized bushing in its gear box after 4 hr of use. This bushing and its mounting were remanufactured by Westinghouse. After this modification, the blower was used in the chamber. Subjects had some difficulty in rapidly donning the facemasks, but this was corrected by preadjusting the straps on all facemasks.

TEMPERATURE AND HEAT BALANCE

The temperature and humidity inside the chamber are primary factors in determining whether the chamber is suitable for human habitation over long periods of time. A heat transfer analysis showed that, for a mine temperature range of 50° to 65° F, the interior temperature range of 60° to 81° F and the interior relative humidity range of 85 to 100 percent will be well within the limits of human tolerance. These calculations were verified in an 8-hr manned test and a 2-day field demonstration.

The nearly stagnant layers of air near the chamber walls act as insulation between the inhabitants and the surrounding mine walls, so the temperature inside the chamber is warmer than in the surrounding mine. The interrelating effects of temperature, humidity, and confined space on human beings were analyzed. By analyzing the heat sources and heat transmission methods, an estimate of 81° F dry bulb chamber temperature was made for 60° F dry bulb ambient. By estimating moisture evaporation and absorption rates, a relative humidity of 100 percent was calculated. By reference to experimental data including volume and area requirements, this environment was shown not to represent a stressful condition, so that no heat exchanger was required.

The chamber area of 21.6 sq ft per man is above the values proven acceptable for 15-day periods. The 84 cu ft volume per man in the chamber is above the Office of Civil Defense minimum recommendation of 80 cu ft (ref. 7).

CONSUMABLE SUPPLIES AND WASTE DISPOSAL

The food supply is a military food ration, MIL-F-43231, Food Packet, Survival, General Purpose. This ration was chosen primarily for its packaging density, packaging quality, and low desirability: It is not as much an object of pilferage as many other food supplies are. The supply provides two 12-oz cans per man-day, containing 1740 cal. These cans are packaged in boxes of 24, which fit into the floor of the survival chamber.

The water supply is 2 qt per man-day of chlorinated tapwater, in 5-1/4 gal plastic jerricans. These containers were chosen to fit into the floor of the chamber. The food ration cans serve as drinking cups.

The chemical toilet uses replaceable plastic bags as liners. All solid and liquid wastes are disposed of in this way, except for sharp metal and glass debris, which are packed in empty food boxes. The half-gallon of mouthwash provided is used as a bacteriostat and deodorant in the toilet after use. One plastic liner is used as a vapor seal across the top of the container when the toilet is not in use. The liners are changed at 8-hr intervals or when half full, whichever occurs first.

These supplies were all rated as acceptable for survival use by the manned test subjects after 8- and 48-hr tests. Two of the foods supplied were objectionable to some subjects because of their taste. This result agrees with data from the U.S. Army Natick Laboratories ration design specialist, Mrs. Mary V. Klicka, who helped greatly in the food ration selection.

CONCLUSIONS

1. The portable life support system described in this paper represents a potential increase in the probability of survival for miners who are trapped underground by a fire or explosion.
2. The habitability and life support capability of the prototype shelter have proved excellent.
3. Development of survival chamber life support systems for wide use in coal mines is definitely within the capabilities of current technology.

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