COAL MINE RESCUE AND SURVIVAL SYSTEM

VOLUME I

SURVIVAL SUBSYSTEM

FINAL REPORT

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CHAPTER 1
INTRODUCTION

CONTRACT INFORMATION

This volume constitutes the Survival Subsystem portion of the final report for the Coal Mine Rescue and Survival System (CMR&SS) program, which was conducted by the Westinghouse Electric Corporation under contract to the United States Bureau of Mines (Contract Number H0101262 dated June 17, 1970). The program was directed by the Special Systems Department of the Westinghouse Baltimore, Maryland, facility.

The basic objectives of the CMR&SS program were to develop and test hardware to determine the efficacy of a variety of coal mine rescue and survival concepts and techniques. These concepts were drawn from two major sources: the Request for Proposal from the Bureau of Mines[1] and the final report on the Mine Rescue and Survival Study conducted by the National Academy of Engineering[2] (NAE).

Both of these documents recommended that the overall Coal Mine Rescue and Survival System comprise three subsystems; the Survival Subsystem, the Communications Subsystem, and the Rescue Subsystem. These subsystems are covered by Volumes I, II, and III, respectively, of this final report.

Each of the major tasks, corresponding to the three subsystems, was conducted by a subcontract organization. The Westinghouse Ocean Research and Engineering Center, in Annapolis, Maryland, was selected to conduct the design and development effort on the Survival Subsystem because of their wide experience in life support technology. The Westinghouse Geophysical Research Laboratories, in Boulder, Colorado, specializes in the technologies required for the Communications Subsystem, and they were selected for this part of the system. The Rowan Drilling Company, Inc., of Houston, Texas, was responsible for the work on the Rescue Subsystem.

The program was completed within the extremely tight time constraints required by contract, and it culminated in demonstrations of the Communications and Rescue Subsystems at the US Steel Mine number 14, southeast of Gary, West Virginia; and of the Survival Subsystem at the Bureau of Mines experimental and safety research mine at Bruceton, Pennsylvania.

PROGRAM BACKGROUND

During the period from 1950 to 1969, there were 28 major mine disasters (i.e., five or more deaths) and several minor accidents (fewer than five deaths) that resulted in a total of 644 deaths in the United States during this period. In those cases in which cause of death is known, 20 percent could have survived by knowing escape routes through training, by using selfrescuers, or by barricading, according to the NAE report.

In mine explosions, lethal gases are forced throughout the immediate area, the oxygen level is reduced, stoppings are destroyed, and normal ventilation is disrupted. The regular communication system is often destroyed. While trying to escape after an explosion, miners are apt to encounter lethal gas.

GENERAL SYSTEM DESCRIPTION

The Survival Subsystem is divided into three parts; a Personal Breathing Apparatus, an Auxiliary Survival Chamber, and a Large Central Chamber. The Personal Breathing Apparatus is a unit lighter and more compact than the units used by rescue teams, originally intended for miners to carry at all times, which provides oxygen for a breathable atmosphere and a full head mask for protection from toxic gases. The Auxiliary Survival Chamber is a transportable unit that is maintained close to actual working areas. It provides basic life support for 15 men for 14 days. The Large Central Chamber is conceived to be permanently installed in a central location in the mine, providing life support for 50 men indefinitely. These Survival Subsystem units are covered fully in this volume from the viewpoint of design, manufacture, test, and evaluation.

The Communications Subsystem provides three major functions; communications from the miners to the surface, and location on the surface of a position directly above the trapped miners. This location is used as the basis for the actual rescue operations. An electromagnetic system provides downlink (surface to miner) communications, with a voice receiver in the survival chamber and on the miners' battery packs. A beacon transmitter in the survival chambers can transmit six pushbutton selected coded messages, thus enabling miners to respond to questions from the surface.

A seismic signaller (thumper) is also provided as backup to the electromagnetic and communication system elements. Seismic reception and data processing capabilities on the surface are the principal elements used to determine the location of the drilling site. The Communications Subsystem is the subject of another volume of this report which completely describes it, including the interfaces with the Survival Subsystem.

The Rescue Subsystem consists basically of two complete drilling rigs, with all ancillary equipment, for drilling two holes directly from the surface to the trapped miners. The first is an 8-3/4 inch probe hole, used to locate the miners and to supply air, food, water, medical supplies, and other immediate needs. The other hole is a 28-1/2 inch hole, through which a rescue basket is lowered to pull the miners to the surface. Another volume of this report provides a complete discussion of the Rescue Subsystem.

SURVIVAL SUBSYSTEM DESCRIPTION

Personal Breathing Apparatus

The Personal Breathing Apparatus (PBA) is an emergency unit designed to provide a breathable atmosphere in a contaminated gaseous environment, particularly in coal mines, into which carbon dioxide, carbon monoxide, and other gases are released by fire or explosion. It is a closed-circuit oxygen-generating recirculating system that is worn on the chest when in use, with a strap around the shoulders and waist and a hood over the head. When not in use, it hangs from the shoulder by a strap within a hermetically sealed carrying case. The PBA uses a sodium chlorate candle to produce the oxygen. This candle is ignited after the apparatus is removed from the carrying case for use, and it is fitted with a shield to protect the user from heat. Oxygen is produced at a rate sufficient for a typical adult man working at maximum effort level. The oxygen passes via filters, heat exchanger plates, and the CO_2 scrubbing canister, into the breathing bag. The user breathes through a valved mouthpiece so that when he inhales, CO_2 is scrubbed, and O_2 laden gas is drawn from the breathing bag, and when he exhales, the exhaled gas passes into the exhalation side. From here the CO_2 laden exhaled breath passes through a carbon dioxide removal canister, while filtered oxygen is released into this same chamber. Excess gas mixture is vented through a relief valve if the man is not at maximum activity, because the chlorate candle is a fixed rate producer of oxygen. The PBA candle will liberate oxygen for approximately 1 hour.

A plastic hood, treated to prevent fogging in the eyepiece area, fits over the user's head. A rubber seal around the neck prevents entry of contaminated gases. The mouthpiece seal permits the user to remove the mouthpiece for intermittent communication. A nose clip is built into the hood to aid in the prevention of nasal inhalation.

The PBA (exclusive of breathing bag and hood) is 3.5 inches deep, 9 inches high, and 11 inches wide, and weighs 6.9 pounds in the operational mode. It is hermetically sealed for storage prior to use. Temperature may vary from -40 to + 140°F during storage without affecting operation of PBA. In the stored mode, it weighs 8.5 pounds and measures 4.5x12x11 inches.

Auxiliary Survival Chamber

The Auxiliary Survival Chamber (ASC) is a portable self-contained 15-man refuge for trapped miners. It is to be located near the working face in a place that affords it some protection from explosion and where it will not interfere with normal mining operations (e.g., an unused crosscut). In concept, it will usually be located 350 feet or more from the working face, and should be moved at approximately 2-week intervals, or as required to remain reasonably accessible to its associated working section personnel.

The ASC contains two atmosphere conditioning units that, through hand-operated pumping of the internal atmosphere, adds oxygen and removes carbon dioxide. Provisions for clearing initial or leaking carbon monoxide can also be accomplished with these units. The ASC contains enough food and water to supply 1,740 high-carbohydrate calories and 2 quarts of water per man per day. Sanitation facilities are included and equipment is provided to measure concentrations of carbon monoxide, carbon dioxide, methane, and oxygen in and immediately around the ASC. Fire-fighter and first-aid supplies are also included. Lighting is provided by battery-powered miner's cap lamps attached to a storage battery system. Chemical light packages are also included as a backup. Interior surfaces are white to make maximum use of available light. Provisions are included for the installation of Communications Subsystem equipment.

Each of the two atmosphere conditioning units in the ASC has a built-in breathing manifold with eight breathing masks. These are used if the interior atmosphere is contaminated, such as may be the case after initial entrance. If the chamber is not contaminated, the manifold is removed and the oxygen is freely released. The atmosphere conditioning units use sodium chlorate candles to produce oxygen, a Hopcalite canister to remove carbon monoxide, and a baralyme canister to remove carbon dioxide.

In operation, turning the blower draws in air from the ASC through the carbon monoxide and carbon dioxide removal canisters. The scrubbed air and candle-generated oxygen are then released into the ASC, or into the breathing manifold and masks.

The ASC consists of six matched pairs of arcs from a semicircular configuration. They fold down from hinged joints attached to the reinforced platform floor to which wheels can be fitted. The shells are curved and attached at the top to form a quonset-hut-like structure. Seals are provided throughout the chamber in an effort to minimize leakage. Two end bulkheads that also fold down for transport are bolted and braced into place when the shelter is erected. One bulkhead contains the entrance door and a viewing port. When assembled, the ASC is designed to withstand explosive forces of 20 psi (uniform loading) and roof falls up to 1,000 psf.

Large Central Chamber

The Large Central Chamber (LCC) is a design for a permanent fixed installation to provide life support for as many as 50 men indefinitely. In concept, it would be located so as to offer greatest accessibility to the largest number of miners, assuming the main exit shafts are closed or inoperative.

The LCC contains food and water for 1,740 high carbohydrate calories per day for 50 men and 3 quarts of water per man per day. Sanitation facilities are included. Equipment is provided to measure the concentration of carbon monoxide, carbon dioxide, methane, and oxygen in and immediately around the LCC. Fire fighting and first aid supplies are also included. Miners can communicate with the surface through sound-powered phones. The LCC is connected directly to the surface through a ventilation borehole that can be used to supply air, food, water, medical supplies, temperature control, and other needs. If an emergency situation closes this borehole, the supplied atmosphere conditioning units can maintain a breathable atmosphere for the 50 men for 5 days. This should allow time to reopen the borehole so that the ventilating and cooling equipment on the surface can take over the life support functions. Spare PBA units are also included in the LCC for use in missions outside the chamber.

The surface ventilating equipment consists of an air-cooling unit and thermostat, a compressor, a duct air heater and thermostat, and a supply hatch in the shaft. The borehole is 8 inches in diameter, fully cased. In operation, the compressor drives 800 cfm of cooled (summer) or heated (winter) air through the shaft to the LCC. When pressure in the LCC exceeds 2 inches of water, one-way valves open to exhaust the air into the mine. The air cooling unit is a standard thermostatically controlled evaporator, compressor, and condenser unit. The heater is a thermostatically controlled 6-kW electric heater. The air cooling unit and the heater are interlocked with the compressor so they cannot be operated until the compressor is operating and supplying air.

Five atmosphere conditioning units and a chilled-water air-cooling unit are included in the LCC. The atmosphere conditioning units are essentially the same as those used in the ASC, except that the breathing manifold has 10 masks instead of 8. The air-cooling unit is capable of removing 16,000 Btu per hour. It requires no electricity; it operates on a centrifugal pump that is direct-coupled to the fan, and both are driven by a bicycle pedal arrangement.

The LCC has concrete floor and footings, reinforced concrete blast walls at each end, and an arched galvanized steel liner plate roof. One blast wall has two steel ship-type doors; the other has one. The blast walls are 12 inches thick, while the floor is 5 inches thick (75 feet long, 12.7 feet wide). Footings are 13.35 inches wide and 9.1 inches top to bottom. The ventilation pipe is welded into the roof, which is 12 gauge galvanized steel liner plates. Seals are installed throughout the LCC to maintain airtight integrity. Grouting is injected between the roof and the tunnel walls to ensure maximum support. The LCC is designed to withstand blasts up to 20 psig with no loss of airtight integrity and roof falls up to 1,000 psf. Lighting is battery powered, and provisions are included for the installation of Communications Subsystem equipment.

REFERENCES

All reference materials cited in this volume are listed, in order of their appearance, in Appendix B.

CHAPTER 2
DESIGN

This chapter is a discussion of various facets of the design program which led to the currently configured Survival Subsystems of the Coal Mine Rescue and Survival Systems (CMR&SS).

The general background discussed in Chapter 1 and the long history of coal mining deaths both attest to the urgent need to provide the coal miner with as much assistance as possible in surviving coal mine disasters. One major cause of deaths in these disasters is the presence of toxic gases, another is fires. The Survival Subsystem described herein provides individual and group protection in both these areas.

SECTION I
DESIGN CONSIDERATIONS

GENERAL

The single major consideration in the design of the Survival Subsystem is human survival in an environment that offers little or no natural assistance and may be entirely hostile. To this end, the miner must have some means of receiving a breathable atmosphere while he makes his way to safety. If escape is immediately cut off, there must be provisions for an entire crew to survive while outside rescue efforts proceed. The three-part Survival Subsystem makes all these provisions available. The Personal Breathing Apparatus (PBA) provides a breathable atmosphere for the individual miner; the Auxiliary Survival Chamber (ASC) provides life support for 15 men indefinitely; and the Large Central Chamber (LCC) provides life support for 50 men for 5 days should the borehole be closed as a result of the accident, indefinitely if the borehole can be reopened.

SYSTEM REQUIREMENTS

At the outset of the CMR&SS program, basic requirements were developed from several sources. Principal among these were the Request for Proposal from the Bureau of Mines [1], the NAE final report[2], the Bureau of Mines contract [3], the Westinghouse proposal for the program[4] (made part of the contract by reference), and Section 13E of Title 30 of the Code of Federal Regulations (CFR) [5]. As the program progressed, and the store of pertinent information grew, system requirements changed; some were deleted, while several were added. The initial system requirements and limitations were outlined in the Preliminary Survival System Outline chart (ref. 4, pp 2-62). This document underwent continual updating, having been revised and republished twice. The requirements as they existed at the design-freeze point in the program are discussed in the following paragraphs.

Personal Breathing Apparatus

The basic requirements for the PBA remained unchanged throughout the program. These requirements are that it provide a respirable atmosphere; that it exclude smoke, dust, and toxic gases and protect the face; that it remove carbon dioxide; that it be easy to activate; that it provide safe partial oxygen pressure immediately; and that the fit be essentially universal from the 5th to the 95th percentile of human adult male heads), and that it be small and light enough to be carried by a man.

Originally, one requirement stipulated that the PBA provide a 1-hour oxygen supply for a miner using 3 liters per minute (at labor) or an 8-hour supply for a user at rest. If further required that the oxygen be USP grade and constitute at least 20.5 percent of the breathing air. This latter requirement has not changed; however, the supply requirement was changed to 1 hour, regardless of work rate. This is compatible with CFR, Title 30, Table 4, Test 4, which requires a flow rate of at least 3 liters per minute for 1 hour.

The initial PBA concept called for a circle flow or pendulum flow unit with a superoxide revitalizer. An assured supply of high quality superoxide could not be found and design of the superoxide canister could not meet schedule; therefore, this concept was changed to use a chlorate candle plus a CO_2 removal canister instead of superoxide.

The maintenance of a comfortable breathing air temperature and maximum breathing resistance of 2 inches (5 cm) of H_2O in and 1 inch (2.5 cm) out at 85 liters per minute were both specified from the outset. Because a man whose life is endangered will readily accept some discomfort, these stringent requirements were relaxed to an acceptable breathing air temperature and to 2 inches of H_2O exhaling resistance of no more than the difference between 4 inches and the actual exhaling resistance (ref 5, para 11.21 (2) ii and (4).

Weight and dimension specifications for the PBA were set at 4.6 pounds and 9x8x3-1/4 inches. Since the chlorate candle and canister alone weigh 6 pounds, new design goals were established of 6.9 pounds and 11x10x3-1/4 inches.

Aluminum was to be avoided in the PBA because of a potential thermite reaction on contact with iron oxide.[5A] However, aluminum offers optimum heat transfer characteristics for maintaining reproducible chlorate candle burn rate and duration. Therefore, this restriction was lifted to allow use of aluminum for the outer candle casing. It is, however, shielded by a piece of light perforated plastic from external contact so that the aluminum surface cannot become easily abraded and subsequently undergo a thermite reaction.

The requirements stated that the PBA should permit intermittent voice communications among miners. During the course of the program, it was determined that reasonable communication could be accomplished without the aid of any device as long as the smoke-hood concept for man-apparatus interface was utilized.

Auxiliary Survival Chamber

During the CMR&SS program, a great many of the original requirements and constraints for the ASC were modified; one was eliminated. Provisions for trace contaminant removal, humidity control, temperature control (85°F), pressure relief at 0.75 inches of mercury, and a differential manometer were included at the start.

Trace contaminants, odors, are not a real problem due to rapid fatigue adjustment of the olfactory system. Manometer readings were not needed due to automatic relief provided by design; temperature and humidity control is not critical to this design under typical mine ambient conditions (see Appendix A); therefore, these requirements were excluded.

The ASC was originally required to withstand a 20-psi shock and maintain its airtight seal. Because both positive and negative pressure waves result from mine explosions, this requirement now includes a 5-psi negative pressure.

Using no aluminum was an initial constraint on the ASC, but the penalties this would cause in cost, weight, strength, heat transfer, and delivery schedule for some components made compliance impractical. Therefore, the constraint was relaxed so that aluminum could be used in some components, so long as they were not exposed to vigorous contact with iron oxide.

The ASC structure concept called for it to fit into a crosscut 14 feet wide (bottom), 10 feet wide (top), 7 feet high, and 35 feet long. Information on mine layouts and seam thickness gathered during the program and the need to allow adequate space for each occupant led to change in this requirement. The ASC must now be assembled or disassembled in a crosscut 10 feet wide, 6 feet high (adaptable to 4.5 feet), and at least 50 feet long. These same considerations brought about another structural concept change. The ASC was to be portable, or easily dismantled, and transportable a few thousand feet through openings 3.5 feet high, and 9 feet wide.

The electrical system specifications specified three sealed lamps (25 W, 6.5 V), seven silver-zinc batteries (9800 Wh), one pedal-operated 6V 75Wdc generator, and chemiluminescent light sources for backup. Further analysis determined that, in order to implement compatibility with the communication equipment (Communications Subsystem), a 12-volt supply would be required. The generator specified would have been costly, large, and heavy; whereas zinc-air batteries are less costly and instantly rechargeable simply by mechanical replacement of spent anodes. Because of these factors, the electrical system now includes 3 miner lamp arrays, each having 2 lamps in series protected with a current-limiting resistor, 1 zinc-air, 12-volt battery (96 Ah) with eight (8) recharge kits, and 52 chemiluminescent packets for 2 hours backup each.

Several changes have occurred in the various life support aspects of the original ASC requirements; however, all factors have continued to be based upon supporting 15 men for 14 days (210 man-days).

The Westinghouse proposal called for providing 105 cubic feet per man giving a total of 1,575 cubic feet for the ASC internal volume. Studies by civil defense authorities [6] on the volume per man required in this type shelter and the overall size limitations of the ASC brought about the more generalized requirement that the internal air volume be sufficient for life support and accommodations of 15 men.

The initial estimate for 316 pounds of oxygen supply was increased to 420 pounds of oxygen. The capacity for removal of carbon dioxide was increased from 368 pounds to 432 pounds carbon dioxide. The design capability of scrubbing carbon monoxide down to acceptable levels from high inlet concentrations is partially responsible for this since oxygen is consumed in the Hopcalite conversion of carbon monoxide to carbon dioxide. In addition, the modified supply allows for a higher average metabolic level for chamber occupants than was originally considered.

Accommodations were reduced from seven (7) 2-tier bunks, 15 blankets, and 15 pillows to six (6) 2-tier bunks, 6 blankets, and 12 pillowcases, because the work schedule and general conditions indicate that at least 3 men will be up and engaged in chamber operation activities at all times.

Human wastes were to be rejected through chutes and tubes to the outside; however, to avoid the risk of the added wall penetrations developing leaks, a portable toilet with disposable plastic bags is now specified.

A nutritionally balanced supply of food and beverages equalling 1,800 calories per day per man, including juices and three 35-gallon water tanks (two installed outside, one inside), was part of the initial ASC concept. Selecting military rations as a proven source of nutrition brought the calorie requirements down to 1,740. The 35-gallon water tanks were rejected in favor of twenty (20) 5-1/4 gallon tanks that can all be stored inside and can be used for waste disposal when empty.

Large Central Chamber

Many of the design requirements for the LCC changed during the course of the CMR&SS program;several of these changes coinciding with the same or similar changes in the requirements for the ASC.

Among the more significant changes to the LCC requirements was increasing the 4-day secondary support (with the air borehole to the surface blocked) to 5 days capability. This resulted from drilling studies and tests which indicated that, with the air borehole badly damaged or blocked, 5 days is a more reasonable time allowance for setup and drilling of a new shaft. Specifications and equipment developed for ASC atmospheric control were modified to meet expended handling characteristics of the LCC secondary control.

The Westinghouse Proposal specified a gross space allocation of 170 cubic feet per man, equalling 8,500 cubic feet total for the LCC. This was changed to 137 cubic feet per man, 6,850 cubic feet total, on the basis of civil defense[6] and cost effectiveness.

The same restrictions against aluminum were imposed on the LCC initially as were imposed on the PBA and ASC, and they were changed for similar reasons to those stated in the ASC and PBA discussions.

Structurally, the LCC was initially required to withstand a 20-psig shock and maintain an airtight seal, while the roof was to hold 1,000 pounds per square foot uniform load. The crosscut leading to the LCC carried the same loading requirements. The whole structure was to fit into a 40x20x11-foot area, with all parts transportable through 3x9-foot openings. All parts were to be easily handled, be assembled from inside, and require little or no welding. The loading and blast requirements remain essentially the same, except that an overhang has been added beyond each end bulkhead to protect against roof falls and to keep the access areas relatively clear of obstructions. The shoring of the crosscut is a mine requirement and no longer part of the LCC. To reduce costs and provide better heat conduction and ventilation, the basic envelope of the LCC has changed; therefore, space requirements for the LCC are now a 75 x 14 x 8 foot area, with parts transportable through 3 x 5 x 9 foot openings.

With the air borehole operative, atmospheric control for the LCC is accomplished from the surface. The surface equipment was originally expected to deliver 650 cfm of air at 75°F and 55 percent relative humidity (RH); however, the cooling unit must maintain the internal temperature between 40 and 85°F. The 650 cfm flow was deemed insufficient for the cooling requirements, and was therefore increased to 800 cfm.

Water, power, and atmospheric monitoring were also originally part of the surface requirements. Water, power, and monitoring equipment are now installed within the LCC as this approach is both more cost effective and less vulnerable to accidental failure (borehole collapse).

Food requirements in the LCC are the same as for the ASC, and the same type of military rations are used. The original LCC requirements for four 35-gallon water tanks (two outside, two inside) were rejected in favor of eleven 17-1/2 gallon cans inside the chamber. The cans are readily available and can be used for waste disposal when empty.

Accommodations in the LCC called for twenty-one 2-tier bunks, 12 straight chairs, 4 reclining chairs, two 6-man folding tables, 50 blankets and pillows, 2 wash basins, 2 water toilets, 1 chemical toilet, and 4 relief tubes. These remain essentially the same, except for the wash basins, water toilets, and relief tubes. To avoid excessive wall penetrations and to reduce complexity and cost, these items have been eliminated. A second chemical toilet was added for waste disposal.

At the start, 12 lights (110 W, 75V) backed by 3 lights (6V, 25W) driven by pedal driven dc generators (6V, 75W) were required, along with silver-zinc batteries. All switches and lamp housings were to be sealed. As with the ASC, further analysis determined that the most efficient, cost-effective system would be the following: 6 battery-powered lamp assemblies, each having two miner lamps in series protected with a current limiting resistor. Two zinc-air batteries with 16 recharge kits are furnished.

SECTION II
DESIGN IMPLEMENTATION

This section describes the study, design, development, research, and analytical efforts that led to the decisions on the various design aspects of the Survival Subsystem. In these discussions, a complete description of each of the components of the Survival Subsystem is given.

PERSONAL BREATHING APPARATUS (PBA)

The PBA must supply a safe breathing mixture for not less than 1 hour, regardless of ambient atmosphere, for a man working at a high metabolic rate. This requires the availability of an oxygen source. The potassium superoxide (KO_2) originally proposed was further investigated, along with compressed oxygen and chlorate candles. Seven manufacturers of breathing apparatuses were solicited for proposals. Only three responded; two were not responsive to the requirements, and one, Mine Safety Appliance Company, was considered technically responsive, although exceptions were taken both to CFR Title 30 and to schedule/contractual constraints. Therefore, based on a re-assessment of in-house capability and the need for tight developmental control, Westinghouse decided to develop a PBA system in-house, using subcontractors for components. During the conduct of a tradeoff study, KO_2 was determined to be an unnecessarily high risk approach. This, and other factors discussed below, led to the choice of the chlorate candle.

Oxygen Generation

There were three primary candidate systems for generating oxygen in the PBA. These were KO_2, compressed oxygen, and chlorate candles. More exotic systems (e.g., lithium peroxide) were not investigated due to the inordinate amount of development effort involved under schedule constraints.

A tradeoff study based on rated factors of reliability, portability, costs, and schedule was conducted and scored. Table 2-1 shows the ratings and scores assigned the three candidate systems. These four major criteria had previously been broken down into many component subfactors from which the respective ratings were derived. The chlorate candle/LiOH system prevailed primarily because of good scores in all areas related to schedule or development requirements while being at least equivalent with KO_2 as regards subfactors such as maintenance, durability, heat contribution and fabrication cost. The results of this tradeoff combined with lack of assurance in securing acceptable KO_2 chemical or developed KO_2 canister designs, led to the decision for a chlorate candle as oxygen source.

TABLE 2-1
PBA TRADEOFF STUDY ON OXYGEN GENERATORS

CRITERION	%	KO_2 W. Rating	Initiator x%	Chlorate/LiOH Rating	x %	Bottled O_2/LiOH Rating	x%
Reliability	25	705	17,625	690	17,250	605	15,125
Portability	20	650	13,000	270	5,400	0	0
Cost	25	485	12,125	495	12,375	420	10,500
Schedule	30	360	10,800	690	20,750	800	24,000
TOTALS	100		53,550		55,775		49,625
(high score wins)							

<u>The PBA Chlorate Candle</u>

As shown in figure 2-1, the chlorate candle configuration chosen for the PBA is L-shaped. This geometry facilitates volume minimization in packaging. Alternate configurations considered included two separate, parallel 30-minute duration candle packages and two parallel $NaClO_3$ segments enclosed within the same envelope but connected by means of a "crossover" mixture. The former was rejected due to increased bulk requirements while the latter required undesirable chemical formulation compensation for complex thermal effects induced by the first segment's decomposition influencing burn rate of the segment.

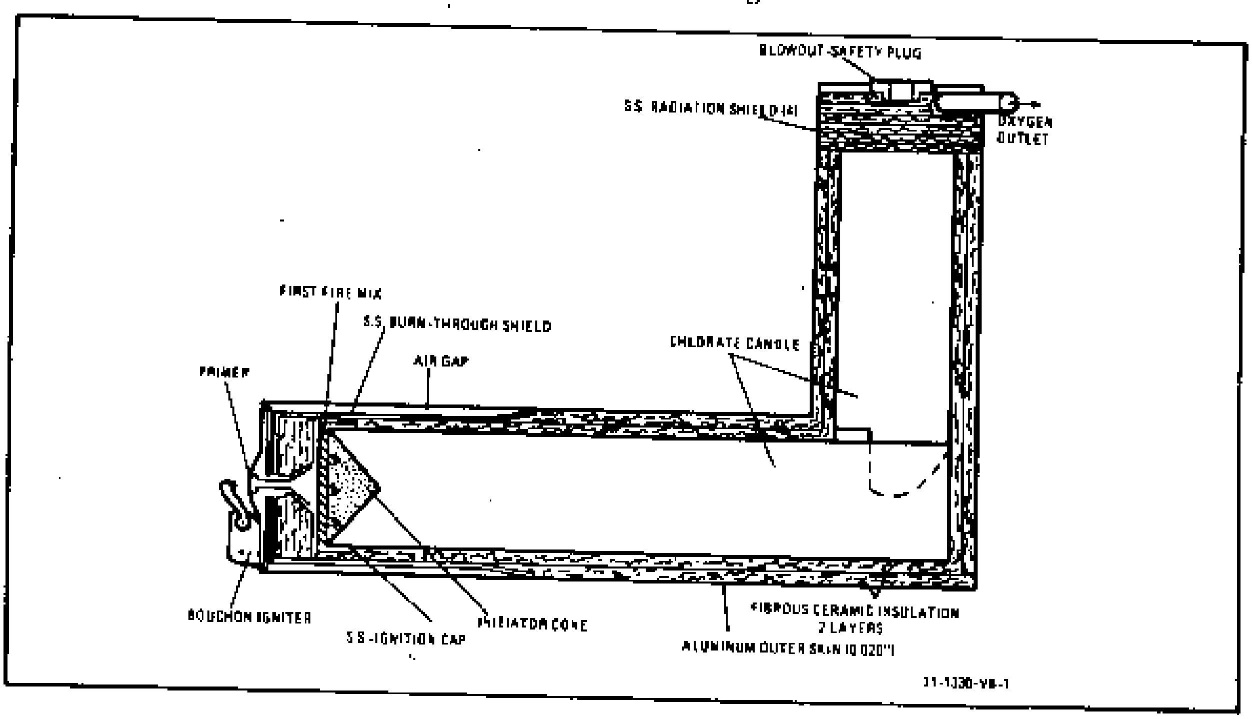

Figure 2-1. PBA Chlorate Candle

Candle activation is a multiple stage requirement. The first stage includes a modified handgrenade-type Bouchon which utilizes a munitions primer immediately producing a flash of hot gases releasing about 800 calories of heat. This heat energy is sufficient to ignite a pyrotechnic "first-fire" composition of zirconium and barium chlorate. The heat energy released by this reaction (~ 500 calories) then ignites a "cone" portion of the oxygen candle, which is a fuel-enriched composition of chlorate. Enough heat is finally generated to initiate and sustain the main portion or "core" composition of the candle. The reaction then proceeds until the supply of chlorate is exhausted. The entire candle is wrapped in layers of a high-temperature resistant, ceramic-type insulation material. The insulation serves to retain sufficient heat within the generator housing to sustain chemical decomposition, and also to help maintain generator wall temperatures within design goal.

This rather fine balance of heat containment (via insulative materials, radiative shields, and air gaps) versus heat dissipation (via skin material selection and surface emissivity) in order to maintain a 350° F maximum envelope skin temperature played the largest role in the magnitude of development required. Too much heat containment resulted in very rapid decomposition, while too much heat dissipation would result in too slow decomposition and at times premature extinquishment of the reaction. Moreover, the balance that was achieved had to be matched to a chemical formulation with heat content sufficient to guarantee reliability and yet meet the flow rate and duration requirements.

These requirements, as stated in Title 30 are as follows: whenever O_2 is produced from a nondemand-type source, flow rate shall be at least 3.0 Standard Liters Per Minute for a duration not less than the stated apparatus duration (in this case, 60 minutes). Our own in-house calculations have indicated that either or both of these requirements could be relaxed (extent dependent on total system volume) and still possess an apparatus that would retain enough residual O_2 in its 4 liter breathing bags to sustain comfortable respiration, even under high work rate conditions for the 60-minute duration. However, the Title 30 requirements were retained as contract objectives.

The maximum envelope skin temperature of 350°F was derived from a worst case analysis of coal dust auto-ignition (Bu Mines Report of Investigation No. 5052 Figure 2) in which it is assumed that a coal dust layer composed exclusively of particles <75 microns diameter with 52 percent volatiles content but 0 percent water has collected on the candle surface. Even though it is recognized that this constitutes an improbable situation, this specification also was retained as a design objective.

In order to satisfy these multiple requirements and yet retain reliability, a wide assortment of chemical formulations was evaluated. These included mixtures of low fuel with cobaltous chloride catalyst, mixtures with potassium perchlorate, and mixtures with silicon dioxide inert and several permutuations thereof.

An addition of SiO_2 inert (40 mesh granules) constituted a unique method of stabilizing the decomposition front, thus controlling burn rate. Visual examination of spent clinkers and burns-in-progress confirmed that this incorporation maintained the front in an attitude transverse to the candle axis. Without its presence, the front often progressed in a random fashion, producing large variations in burn rate and consequent loss of duration. No premature extinguishments were experienced over 26 candle decompositions.

It had earlier been established that the preferable container material was black anodized aluminum due to its preferred heat dissipation qualities as contrasted with the more conventional candle container material - stainless steel. The combination of this container with the proper insulative materials and candle formulation produced the construction shown in figure 2-1.

The data accumulated from a series of 6 candle qualification tests indicate that this construction successfully approximated all design objectives: production of the initial 4 liters of oxygen was accomplished within 20 to 35 seconds; burn duration averaged 59.5 minutes over a range of 57 to 64 minutes; and maximum surface temperature recorded at any point was 368°F with most temperatures recorded below 350 degrees.

However, surface temperature of 350°F and duration of 60 minutes cannot be reliably specified as minimum values without further development.

These two parameters can be met by a relatively simple redesign of the container with little or no additional development of the chlorate mix. In fact, solving the temperature problem, which our calculations have shown can be accomplished by the addition of fins to the aluminum casing, should also solve the duration problem since the burn rate of the candle is partially a function of heat dissipation. The more efficient the dissipation, the slower the burn. Should the duration not be achieved with the lower surface temperature, the case could be increased slightly to accommodate increased length of the candle.

Evolved Oxygen Purity

The normal exit path for O_2 evolved from the candle is through flexible tubing attached at the far end of the short leg. Also located in this vicinity is a pressure-relief assembly provided in the event that gas pressure buildup occurs through any possible exit path blockage.

The flex tubing attaches to a separate "U"-shaped gas impurity scrubbing cartridge, which is designed for installation within the inlet plenum of the PBA's CO_2 removal canister as shown in figure 2-2. This scrubbing unit contains baffled beds of Purafil and Hopcalite for removal of chlorine and carbon monoxide, respectively. Its performance has proven quite efficient as shown by gas analysis data in table 2-2. All gas impurity levels are well within standards applicable to breathing mixtures with the exception of carbon dioxide.

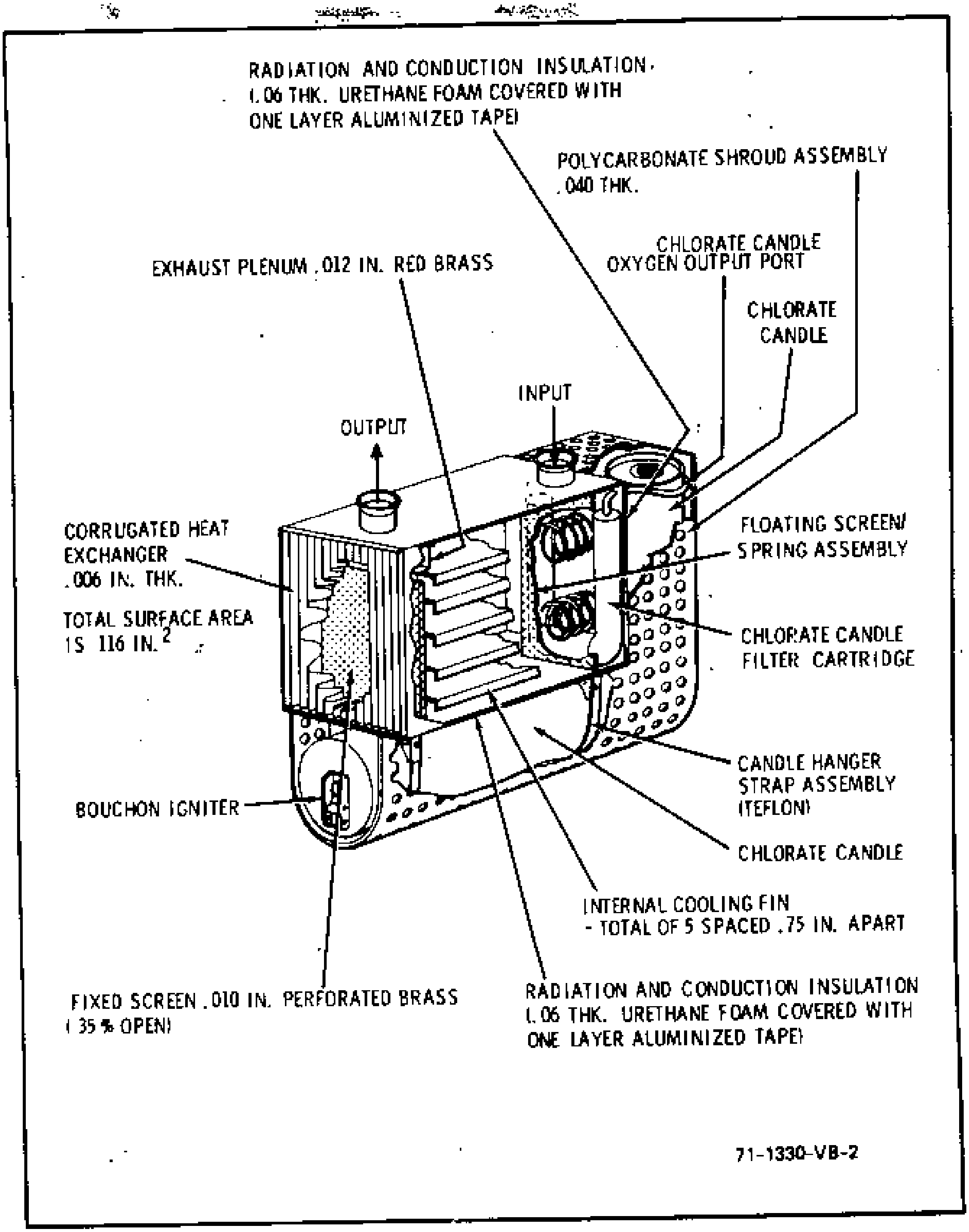

Figure 2-2. PBA Canister/Candle Assembly

TABLE 2-2.
PBA CHLORATE CANDLE GAS ANALYSES

Sample Time (min)	O_2 (%)		CO_2 (%)		CO (ppm)		H_2O (ppm)		Hydrocarbons (ppm CH_4)		Cl_2 (ppm)
	A	B	A	B	A	B	A	B	A	B	A&B
5	99.90	99.93	0.10	0.07	0.60	0.55	0.0	15.0	2.5	6.4	<0.1
10	99.89	99.92	0.11	0.08	0.65	0.60	5.0	20.0	3.2	6.1	"
15	99.86	99.90	0.14	0.10	0.70	0.70	14.0	35.0	4.2	6.0	"
20	99.86	99.89	0.14	0.10	0.75	0.75	30.0	55.0	4.7	6.3	"
25	99.84	99.87	0.15	0.12	0.90	0.90	60.0	90.0	5.6	6.6	"
30	99.67	99.84	0.32	0.14	1.05	1.10	110	150	6.4	7.3	"
35	99.52	99.77	0.46	0.20	1.30	1.40	190	245	7.4	11.0	"
40	99.52	99.70	0.44	0.26	1.65	1.75	420	405	8.6	11.7	"
45	99.46	99.57	0.46	0.37	2.15	2.30	600	615	9.9	13.5	
50	99.32	99.40	0.62	0.52	2.95	3.15	630	820	12.2	15.7	"
55	99.12	99.15	0.86	0.75	4.85	4.75	200	915	15.0	18.6	"
60	Candle out		Candle out		Candle out		Candle out		Candle out		

Oxygen by Beckman O_2 Analyzer, Model E2.

Carbon Monoxide by Beckman Model GC-5 Gas Chromatograph (helium ionization detector).

Water Vapor by Beckman Trace Moisture Analyzer P_2O_5 Electrolytic Cell.

Chlorine by General Electric Halogen Detector, Type H.

Hydrocarbons by Beckman Model 109 Flame Ionization Total Hydrocarbon Analyzer.

Carbon Dioxide by Beckman IR 20.

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No provision was made within the gas scrubbing cartridge for carbon dioxide removal under the rationale that the lithium hydroxide bed downstream of the cartridge could readily accomplish this task.

Carbon Dioxide Absorbent Selection

Three state-of-the-art chemical absorbents applicable for PBA use, lithium hydroxide, baralyme, and sodasorb, were evaluated in the criteria shown in table 2-3. Lithium hydroxide is by far the most efficient CO_2 absorbent by weight. Its theoretical absorption capacity is 0.92 pounds CO_2/pound absorbent as opposed to a capacity of 0.50 pounds CO_2/pound of baralyme. Its density, however, is quite low, giving it slightly less efficiency than baralyme in terms of volume.

Although LiOH costs more and has a higher heat of reaction than other candidates, these are compensated by the assignment of less development risk. The lower development risk rating was achieved primarily because of preliminary testing done for us by Foote Mineral Co. This testing produced an experimentally derived figure for the amount of LiOH required to meet PBA input conditions.

Even so, the tradeoff overall results were very close. As noted in table 2-3, sodasorb is comparable to all parameters to baralyme. All other conventional CO_2 absorbent systems were considered either less efficient or not applicable to PBA use without entailing undue development risk. Accordingly, lithium hydroxide (LiOH) was selected as the absorption material, primarily because of higher probability of successful development.

LiOH Canister Design Requirements

In contrast to the chlorate candle, which must generate O_2 at a fixed rate based on highest expected work load, the CO_2 absorbent is sized to accommodate fluctuations in work load and the total amount of CO_2 produced. Accordingly, the amount of CO_2 liberated during a 60-minute high work rate program was estimated as shown in table 2-4. This was accomplished by first estimating from Bioastronautics Data Book the O_2 expenditure per activity, totaling the result and applying an average respiratory quotient value of 0.85 to arrive at 82 liters CO_2.

In actuality, a safety factor of nearly 25 percent above this was included in our design considerations in order to cover the following:

1) The stated O_2 consumption rates are estimated for specific tasks and do not account for recovery time required in progressing from greater to lesser work rates.

TABLE 2-3
CO_2 CANISTER ABSORBENT TRADEOFF STUDY

CRITERION 1-5-10	%	LiOH		Baralyme	
		Rating	x %	Rating	x %
1) Sensible heat BTU/ft^3 CO_2 absorbed	10	7	70	9	90
2) Cost Effect on PBA	20	4	80	6	120
3) Non Operational Reliability	15	9	135	9	135
4) Theoretical Weight req'd for 1-hour mission	20	9	180	5	100
5) Theoretical Bulk volume req'd for 1-hour mission	15	7	105	9	135
6) Development Risk (high low)	20	10	200	8	160
TOTALS	100%		770		740

2) Simulation of Title 30 work tasks was accomplished on a bicycle-type ergometer (see table 2-4 for ergometer settings). Since the ergometer requires continual use of the same musculature, recovery times are yet more difficult to estimate.

3) Respiratory quotient (RQ) may reach values of 0.9 to 1.0 at high work rates.

4) RQ may vary dependent on individual test subject. Therefore, in consultation with our Physiology Dept., a figure of 102 liters (0.41 pounds) of CO_2 was estimated as the worst case amount the canister would have to accommodate.

Pressure drop across the canister was another important design parameter. The theoretical plate area based on a 4x14 mesh size reactant material was computed to be 15 sq in based on an instantaneous flow rate of 85 SLPM air and a pressure drop not exceeding 2 inches H_2O. The bed depth, given an experimentally derived figure for required LiOH volume, was computed to be 6 inches. By adopting a canister geometry within these dimensions, we were confident of maintaining pressure drop below 2 inches H_2O at even the highest work rate called out by Title 30 (at which a velocity of 40 SLPM could occur).

Finally, a circle flow breathing circuit was selected over pendulum flow, and axial flow through the canister was selected over radial flow. Since we anticipated some problem in dissipating the heat of reaction generated within the LiOH bed (sensible heat = 875 Btu/lb CO_2), circle flow appeared preferable due to greater opportunity for heat transfer as contrasted to the reduced circuitry of pendulum flow. In addition, pendulum flow would have presented an opportunity for formation of depleted reactant dead spaces within the canister. Axial flow through the canister was chosen primarily because it afforded fewer fabrication difficulties, minimal bulk, and greater opportunity for internal canister modification. Some canister modification in the form of internal finning was contemplated, due, once again, to anticipated heat transfer difficulties. During breadboard testing, it soon became apparent that 5 internal fins would be required.

The body of the canister is made of red brass which has a thermal conductivity of 92 Btu/hr/sq ft/°F. The wall thickness is 0.0126 inches. The amount of heat that will be generated in the canister reaction by a man working to table 2-4, Title 30 computes to be approximately 357 Btu/hr. Considering the worst case of laminar flow convection cooling, which would be the case if the miner were not moving but standing in a stagnant air environment, the exposed surface area of the body of the canister is not enough to transfer this quantity of heat. Therefore, a corrugated heat exchanger surface affording 116 square inches of additional surface area was built into the output end of the canister housing to help cool the effluent breathing gas.

Two plies of Air-Mat No. 12 fiberglass mat are installed over the stationary output end screen to serve as filters for LiOH dusting. The canister is then charged with lithium hydroxide and closed by soldering the end cap at the inlet plenum side; thus compacting the input screen against the bed by means of springs (2 to 3 psi pressure).

Figure 2-2 depicts detail of the internally-finned canister in its final configuration and, in addition, shows how it interfaces with the chlorate candle. The candle is hung under the canister and is thermally insulated from the canister by the Teflon cradle and hanger strap assemblies (two each) and by Urethane foam and Mystik reflective tape radiation and conduction insulation (located on the candle sides of the canister). A 0.040-inch-thick perforated polycarbonate shroud covers the candle assembly offering some slight protection against possible contact burns and protection against abrasion of the aluminum surface while still providing convection cooling for the candle assembly. Not shown in figure 2-2 is a polycarbonate standoff on the back face of the canister which protects the wearer against canister surface temperatures.

Carbon Monoxide Removal

Since there is some chance of the miner being exposed to carbon monoxide (CO), a CO scrubber was considered for inclusion in the PBA. However, the PBA is designed to generate 4 liters of oxygen within 30 seconds which means that by the time the user has the rig donned and is ready to draw his first breath, the breathing bags will be filled with 4 liters of oxygen. Man's

TABLE 2-4

O_2 CONSUMPTION/CO_2 LIBERATION ESTIMATE FOR TITLE 30, TEST 4, TABLE 4 WORK SCHEDULE

Activity	Time (min)	SLPM O_2	Total O_2 (ℓ)	Total CO_2	Ergometer Setting (Kiloponds)
1) Sampling & reading	2	0.7	1.4		0
2) Walk at 3 mph	2	1.2	2.4		1.5
3) Climb 75° treadmill	1	2.5	2.5		3.5
4) Walk at 3 mph	2	1.2	2.4		1.5
5) Pull 45 lb. wt. 5 ft. 60 times	5	2.1	10.5		3.0
6) Walk at 3 mph	3	1.2	3.6		1.5
7) Carry 50 lb. wt. over overcast 4 times	8	1.9	15.2		2.75
8) Sampling & reading	2	0.7	1.4		0
9) Walk at 3 mph	4	1.2	4.8		1.5
10) Runs at 6 mph	1	2.7	2.7		3.75
11) Carry 50 lb. wt. over overcast 6 times	9	1.9	17.1		2.75
12) Pull 45 lb. wt. 5 ft. 36 times	3	2.1	6.3		3.0
13) Sampling & reading	2	0.7	1.4		0
14) Walk at 3 mph	6	1.2	7.2		1.5
15) Pull 45 lb. wt. 5 ft. 60 times	5	2.1	10.5		3.0
16) Carry 45 lb. wt. walking at 3 mph	3	1.9	5.7		2.75
17) Sampling & reading	2	0.7	1.4		0
TOTAL	60		96.5	82 liters	

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lung capacity is comparable to the PBA's volume thus after a few short breaths of about a liter each the CO exhaled will be diluted at least 50 percent. The oxygen generation rate is at a minimum of 3 liters per minute which exceeds the amount that man can continuously consume. This excess, which is vented, will carry with it some CO causing further dilution of CO in the breathing mixture. Further operating instructions (refer to Chapter 3 Section 1) for the PBA require that the user exhale fully before donning the unit; so the likelihood of his lungs retaining an appreciable amount of CO is further reduced.

Not only does it appear by this analysis a reasonable risk to exclude CO scrubbing capability from the PBA, but inclusion of such capability would be complicated and costly. For example, the addition of a CO scrubber such as Hopcalite to the PBA also requires the addition of dessicant to prevent poisoning of Hopcalite by water vapor. However, input water vapor is essential to efficient operation of the lithium hydroxide bed. Therefore, dessicant, by reducing water vapor level within the apparatus, would be expected to adversely affect CO_2 scrubbing capability.

Based upon this analysis, the lack of CO removal provisions was considered both a reasonable risk, and a cost-effective decision.

Contaminant Sources

All parts and materials used in the PBA underwent test and analysis for possible contamination of the breathing gas, with special emphasis on the solder and flux used in final welding and on the fiberglass filter. The flux used (Nokorode Soldering Paste, Federal Specification O-F-506) presents no hazard primarily because it is present in very small quantities and upstream of the LiOH bed, which would absorb any contaminants generated therefrom. In addition, flux ingredients will not vaporize under PBA operating conditions, and even if they did, the vapor toxicants are not at dangerous levels. The solder (National Lead Company, Dutchboy SN-50) also presents no major difficulties, because although both antimony and lead are present in the solder, their potential for ingestion (respiratory or digestive) is practically zero. There is almost no formation of caustic solution in the PBA in which these elements could dissolve and neither element could vaporize under PBA operating conditions. The fiberglass in the filter is tightly packed and chemically bound and, moreover, is compacted under 2 to 3 psi against a perforated backup plate. Therefore, pickup of fibers by air flow is highly improbable. A reasonable conclusion is therefore derived that the present PBA design constitutes no undue hazard as a contaminant source.

Man-Machine Interface

For the PBA application, interface requirements included not only the means to conduct breathing gas to and from the man but also to allow communications, provide visibility, and prevent inhalation through the nose. Other factors considered were universal fit, dead space, comfort, cost, weight and bulk, and development risk. The tradeoff study (table 2-5) considered the use of six different interface means as follows: (1) mouthpiece, (2) smoke hood, (3) oral mask, (4) oral-nasal mask, (5) full face mask, and (6) fright mask. The study showed that for this application the smoke hood is the best choice.

The vendor selected to manufacture the PBA hood was the G. T. Schjeldahl Co., which had previous experience with this type of product and had worked with the FAA on hood developments. However, the PBA hood was a new development in view of the requirements for incorporation of a mouthpiece and eyepiece and means to prevent fogging. The original concept to solve the fogging problem was incorporation of an eyepiece of CR-39 allyldiglycolcarbonate into the hood and application of the antifogging compound "DeMist" manufactured by A.I.D. Ltd. This combination was the result of an extensive literature search and contacts with NASA and the U.S. Army Night Vision Laboratory. However, difficulties were encountered in applying "DeMist" to the selected standard MSA lenses. In order to meet delivery commitments, an alternative compound, Hydrazorb (also from AID) was selected for application on cellulose acetate butyrate lenses; this coating ranks right behind "DeMist" in NASA ratings.

Other hood materials selected included a 1.5-mil laminated construction of Mylar[R] for the hood proper and a polyurethane elastometer for neck seal. The eyepiece was laminated to the inside surface of the hood so that all hood materials in direct contact with ambient atmosphere are of the self-extinguishing category. The nosepiece is designed as an integral part of the lens and is constructed of nylon, while the mouthpiece is constructed of polyvinylchloride.

Acceptance testing performed on the hood included bond strength of lens, bond strength of mouthpiece, haze of lens, luminous transmittance of lens, pressure drop through mouthpiece, and leak integrity of neck seal. All specifications were met.

The bond strength tests performed on the mouthpiece actually constituted a test of hood tear strength as its weakest design point. The nature of the hood material is such that its resistance to tearing is least at penetration points such as at the mouthpiece or at puncture points, either of which may serve as stress concentration loci for tear propagation. It was found that the mouthpiece could withstand substantial force applied against it whether from a sudden or gradual load. The Instron tensile tester with a cross head speed of 2 inches per minute registered a force of 33 pounds when the hood material was torn away from the mouthpiece. With the sudden drop of a 10-pound weight attached to the mouthpiece, a terminal velocity of 1.64 ft/sec was required for hood material failure. It is not feasible to conduct controlled laboratory examination of all parameters which could contribute to hood material failure such as presence of puncture, type of puncture, magnitude of applied force, momentum, direction of force; however, it is felt that the mouthpiece tests are representative of the hood material's minimum tear resistance. As such, it is deemed acceptable.

TABLE 2-5

MAN-MACHINE INTERFACE TRADEOFF STUDY

CRITERION	%	Mouthpiece* Rating	Mouthpiece* x%	Plastic Hood* Rating	Plastic Hood* x%	Oral Mask** Rating	Oral Mask** x%	Oral-Nasal Mask*** Rating	Oral-Nasal Mask*** x%	Full Face Mask Rating	Full Face Mask x%	Fright Mask Rating	Fright Mask x%
Universal Fit and Seal	20	9	180	7	140	5	100	2	40	5	100	6	120
Dead Space	10	9	90	5	50	8	80	7	70	7	70	7	70
Non-powered communications	30	1	30	9	270	7√	210	8√	240	8√	240	8	240
Weight	5	8	40	9	45	6	30	5	25	1	5	7	35
Bulk	5	9	45	8	40	6	30	5	25	1	5	7	35
Vision	10	7	70	1	10	7	70	7	70	9	90	7	70
Comfort	5	7	35	6	30	6	30	5	25	9	45	8	40
Cost	5	9	45	8	40	5	25	7	35	6	30	4	20
Development Risk for Improvement (high-low)	10	2	20	9	90	4	40	4	40	4	40	3	30
TOTALS (high score wins)	100		385		715		615		560		625		660

* Schjedahl Hood
** Requires noseclip and goggles
*** Requires goggles

(√) with voice disc

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Other test results on the hood are as follows:

1) Lens peel strength (per ASTM-D-903): 2.6 lb/in.

2) Lens haze (per ASTM-D-1003): additional 2.7-percent haze after lamination.

3) Lens luminous transmittance (ASTM-E-308): loss of 3 percent after lamination

4) Mouthpiece flow resistance: 0.75 in. H_2O at 85 SLPM.

5) Neck seal leak integrity: withstands average 1.6 in. water internal pressure without leakage (mated to 4.75-inch-diameter mandrel).

During manned testing of the PBA, it was shown that the hood could be easily donned and doffed without tearing, provides an adequate seal without discomfort, does not interfere with the wearing of a hard hat, and allows good communication. However, light fogging of the lens was experienced after about 20 minutes into the tests. This light fog continued for about 5 minutes and then cleared somewhat by drain-off. Approximately 8 ounces of perspiration collected within the hood during this time. It is felt that use of DeMist antifog on CR-39 lenses as originally planned would alleviate this problem.

Carrying Case Configuration and Materials

The carrying case must protect the PBA from damage before use, it must be hermetically sealed, and it must be easily carried. To supply the greatest degree of utility in emergency situations, the PBA should be nearby the user and, ideally, should be attached to his person.

Originally, plans called for the PBA to be carried on the miner's belt. However, current state-of-the-art limitations on O_2 generation and CO_2 absorption set limitations on weight and bulk which made it apparent that this approach was not really workable for a 60-minute duration apparatus. For the prototype, a shoulder strap arrangement was designed, but it is clear that this approach does not lend itself to continuous carry either.

Several materials, both metals and plastics, were considered candidates for use. The study considered weight, strength (dent resistance), cost, process development, and number of fabrication steps. The combination finally selected is a fiberglass case with a heat-sealed bag around the PBA, resting on foam rubber padding (see figure 2-2). The bag is a hermetically sealed barrier bag notched along the top for easy tear-opening. The sides of the case are slightly bowed to add deflection resistance, and the two halves are joined by a tongue-and-groove joint, secured by quick action snaps.

Fabrication and Assembly

During the design of the PBA, the factors affecting choices in fabrication and assembly were production costs, weight, size, material life, sealing, human engineering, toxicity, and quantity. These all had to be traded off against the overriding considerations of cost and schedule. Therefore, the design effort aimed at achieving sound basic designs and materials that lent themselves to low cost production methods. This rationale applied to each major subassembly, as discussed in the following subparagraphs.

Carbon Dioxide Absorbent Canister

The canister must be light in weight, with good heat transfer characteristics and only minimal structural strength. The canister is described earlier (see figure 2-2). For prototypes, all forming was done manually. The perforated screen is stocked material, and all joining is soldered. Assembly was done manually also, with some spot welding. In production, shapes can be stamped, and assembly can be done by furnace soldering or a similar process.

Shroud

The candle shroud must allow gas circulation around the candle and must be tough, light, and withstand 350°F temperatures at a distance of 1/8 inch. Lexan was chosen, because it has the best combinations of these factors, and it is readily formable. In prototype, the shroud was made in two pieces cemented together. In production, it could be made as one piece.

Breathing Bags

The bags must be lightweight, gas-tight, and able to withstand long-term folding. Nylon, impregnated with polyurethane, was used for the prototype. Seams were cemented. A number of entirely acceptable materials and processes can be used in production, including blow molding and heat sealing.

Chlorate Candle/Case

The compounding and forming of the candle lends itself readily to production techniques. The candle case is fabricated from standard tubing, and all welds to the case can be automated. The procurement specification for the candle required quantity production considerations in the design.

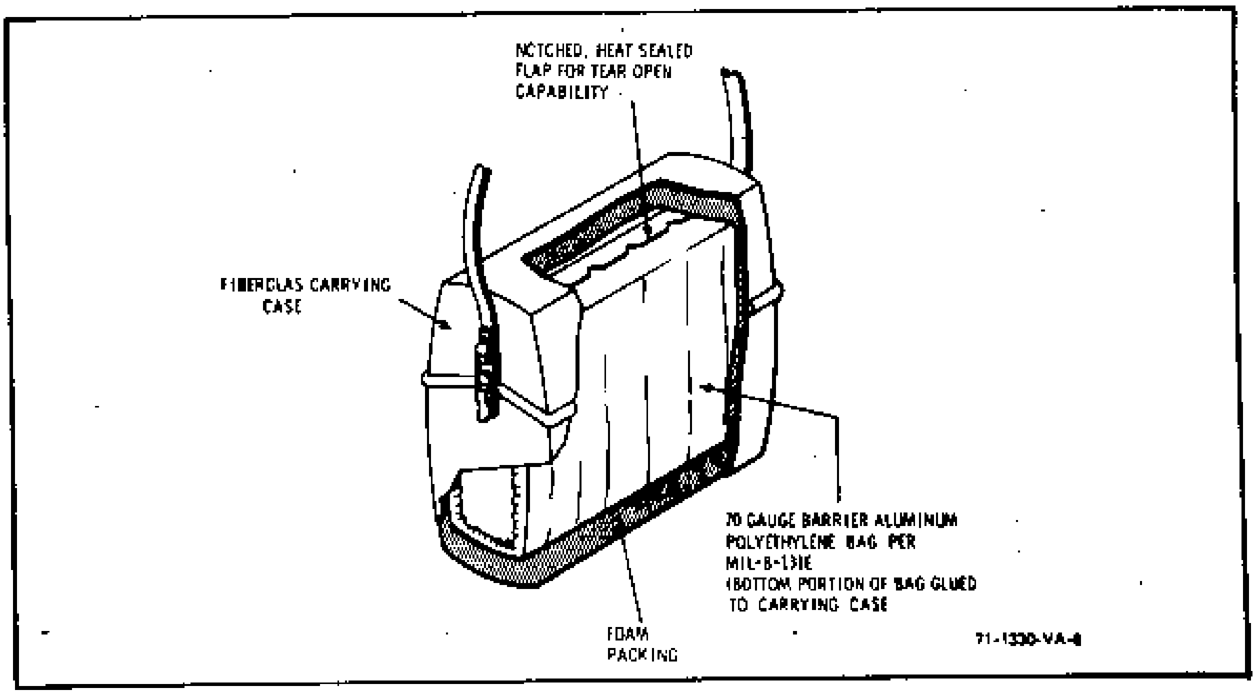

Figure 2-3. PBA Package

Hood

The prototype hoods were also handmade, but the design is very similar to hoods that have been produced in quantity. Therefore, no problems are foreseen in this area.

Accessories

All accessories (filter, hose, clamps, etc) are standard items and present no problems.

PBA Assembly

The joints between breathing bags, hoses, mouthpiece, and canister are cemented (leak tight), tied with wire (strength), and taped (safety). The joint between the breathing bag and the canister, which carries the canister load, is made by bending over tabs on the canister and passing them through grommets on the bags. The canister is secured by hangers riveted to the canister and straps welded to the candle case. The straps are secured to the hangers by self-tapping screws that also hold the shroud. The other end of the shroud is secured by tabs to the canister. The carrying case snaps are secured by heating and compressing lugs provided with the snaps. Table 2-6 lists component weights for the PBA.

As part of the design, a preliminary cost analysis was conducted, based upon production lots of 15,000. The study concluded the $35 to $40 per unit would be possible. It appears that there will be some increase in the hood cost, but the target $50 per unit is still very likely.

AUXILIARY SURVIVAL CHAMBER (ASC)

The following paragraphs contain descriptions and discussions of the selections and decisions made that led to the ASC supplied in prototype to the Bureau of Mines.

Structural Concept

The ASC must withstand hydrostatic or uniformly distributed pressure of from -5 to +20 psi and the end bulkheads must withstand -5 to +20 psi uniform dynamic pressure. It must provide 80 cubic feet of space for each of the 15 men in addition to the 120 cubic feet of space filled with equipment. It must be movable through 3.5x9-foot openings and capable of assembly in areas 6 feet high and 10 feet wide. In movement, the towing load limit is 4,000 pounds per module, and the wheel load limit is 5,000 per module.

Four basic designs were evaluated for the ASC structure. These are shown in figure 2-4. Each is a series of modules latched together to form a closed chamber.

Concept A is composed of five identical corrugated shells braced internally at each end by two compression members and five tension members. Longerons were to be used to transmit longitudinal loads and to provide sealing surfaces and structural continuity. Bulkheads are latched to each end of the assembled chamber.

Concept B is essentially of six flat-bed cars with flat walls and curved roofs. The floor and sides are standard I-beams, channels, and plates.

TABLE 2-6
OVERALL PBA WEIGHT (POUNDS)

Item	Quantity	Actual Weight	Estimated Weight
Canister Assembly	(1)	6.200	--
Body	(1)		0.520
Cooling Fins	(5)		0.416
Exhaust Plenum	(1)		0.018
Exhaust Screen	(1)		0.051
Intake Screen	(1)		0.057
Heat Exchanger	(1)		0.210
Ports	(2)		0.054
End Closure	(1)		0.071
LiOH	--		1.480
Candle and Filter	(1 each)		3.100
Heat Shroud	(1)		0.102
Solder and Shroud Assembly Clips			0.300
Carrying Case	(1)	1.400	--
Carrying Case (Redesign)	(1)		1.437
Straps	(1)		0.060
Man-Apparatus Interface	(1)	0.120	0.120
Breathing Bags and Hoses	(1 set)	0.450	0.400
Carrier Bag	(1)	0.070	0.063
		8.280	8.459

The roof is a single corrugated panel, preloaded with tension ties to the floor. Bulkheads at each end of the shelter are braced by the side walls and by A-frame bracing to the floor.

Concept C is similar to concept A, except that the sheet consists of two pairs of identical corrugated panels; top and bottom are one pair, two sides are the other pair. For height variation, the side panels can be replaced, but this also requires different members for internal bracing. This bracing consists of four compression members and four tension members at each end of the module.

Concept D is a modified concept B. Each module has a volume of 230 cu ft and is a flat-bed car with curved panels that form walls and ceiling like a quonset hut. The floor is I-beams, channels, and plates, with wheels or skids for movement. Two identical corrugated curved panels, hinged along the floor, form the sides and roof. For stowing or movement, the panels are disconnected and folded down onto the floor. To vary height,

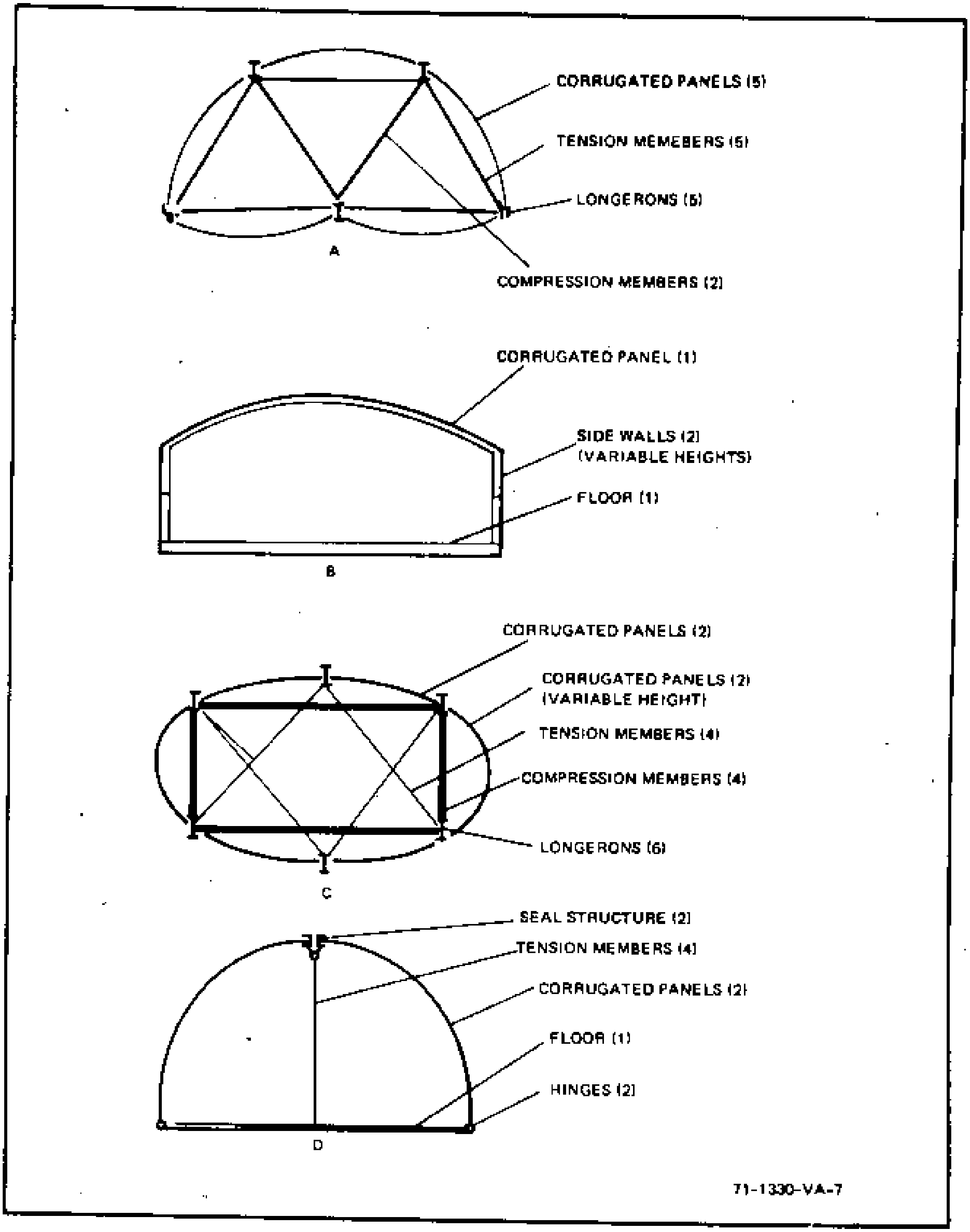

Figure 2-4. Candidate ASC Structures

different panels are used. Bulkheads are attached at each end of the assembled chamber, braced by A-frames either internally or externally. Internal bracing is attached to the floor.

Table 2-7 summarizes the tradeoff study conducted to select the ASC structure. Assembly and disassembly were rated on number of operations and man-hours required. Cost estimates were based upon the assumption that all material was structural steel. Portability was rated by man-hours and other equipment required to move the shelter. As can be seen, concept D was selected. A more complete diagram of this concept is shown in figure 2-5.

The material used is low carbon steel in standard structural shapes. Welding is used extensively to connect structural members. The panels are 6 feet long, with a radius of 53 inches and have an arc of 93.5 degrees. Each panel is reinforced to support the hinges.

The floor is standard I-beams welded to a flat plate, 6x9 feet. The open-beam construction is used as storage space. Axle supports installed at the open ends allow for wheel and axle assembly installation prior to towing operations.

Assembled, the panels are pinned together at the top with four detent pins for an erect height of 68.5 inches. Disassembled, the panels can be folded down onto the floor for low-profile movement.

Bulkheads are flat reinforced corrugated sheet steel and consist of the bulkhead, a platform, and braces. Reinforcing is by rectangular tube beams at four vertical locations. One bulkhead has a hatch that can be sealed from either side and that opens inward for rapid entry. (Production

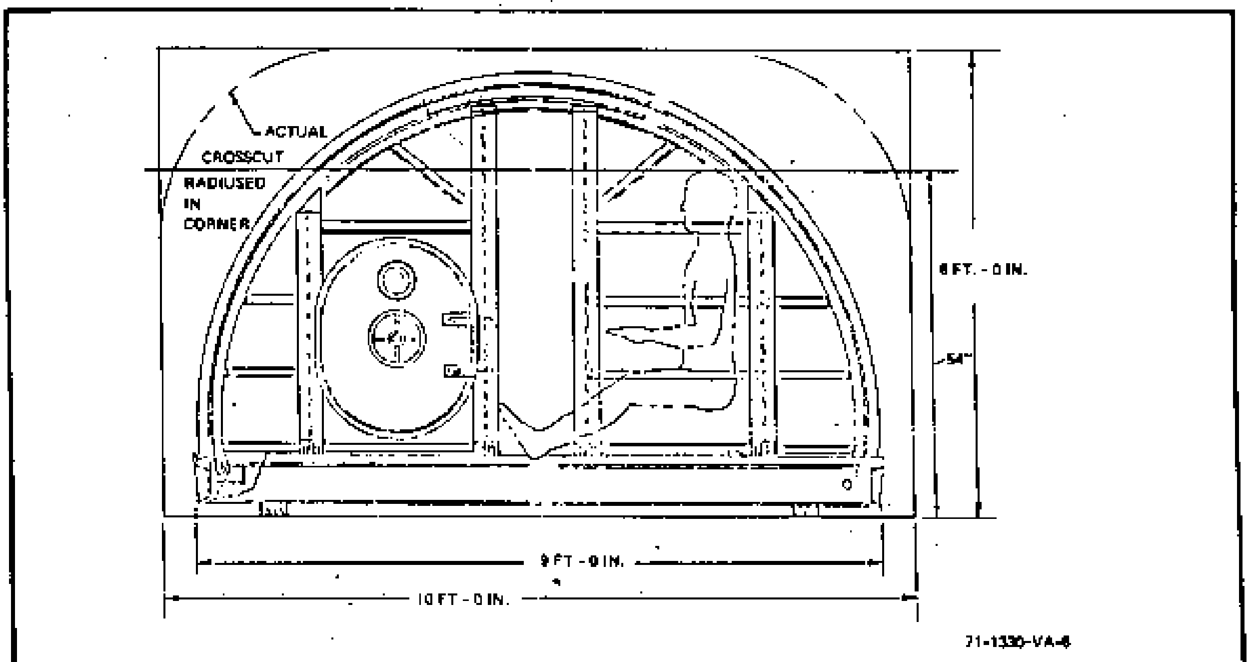

Figure 2-5. Selected ASC Structure

TABLE 2-7
ASC STRUCTURAL CONCEPT TRADEOFF STUDY

	%	A Curved Segment Truss		B Flat Car		C Curved Segment		D Flat Car Mod	
		Rating	X%	Rating	X%	Rating	X%	Rating	X%
Assembly & Disassembly	20	4.40	88	8.30	166	3.20	64	8.55	171
Size Flexibility	7	2.80	20	3.80	27	2.80	20	2.80	20
Cost	20	6.50	130	3.50	70	6.50	130	6.00	120
Portability In Mine	20	2.60	52	5.20	104	2.60	52	5.20	104
Schedule	8	6.30	50	6.50	52	6.30	50	6.90	55
Habitability	5	4.10	21	7.60	38	4.40	22	6.35	32
Sealing Reliability	12	2.60	31	4.20	50	3.10	37	4.60	55
Durability	8	3.60	29	5.80	46	3.00	24	6.50	52
TOTAL	100		421		553		399		609

71-1330-T-9

ASC's would have hatches in each bulkhead.) The bulkheads are shaped to fit the modules and are hinged to the platform. The platform is secured to the mine floor with roof bolts. Braces (3-inch steel tubes) are installed between the platform and bulkhead to provide a closed end and are secured by detent pins. These braces are installed with one end at the top of the vertical bulkhead beams and the other end on the platform, opposite the anchor bolts, so that most pressure loading transmits to the anchor bolts.

Each module, including the bulkhead assemblies, can be towed like a two-wheel cart. Towing lugs are included, and the axle supports accept stud axles and wheels. Equipment is stowed in the modules so that they can be towed fully loaded. With the shells folded down, height is 37 inches, with a nominal 2-inch ground clearance.

Internal Volume Requirements

An integral part of the internal volume requirements for the ASC is the heat created in the chamber over a 14-day period and the chamber ability to handle it. A complete mathematical analysis of heat transfer characteristics of the chamber was performed as a part of the program. Data used in this analysis are as follows:

a. Chlorate candles generate 70 cubic feet of oxygen every four hours and produce 100 Btu of heat per cubic foot of oxygen.

b. Carbon dioxide removal canister produces 1,240 Btu of heat per hour based on 130 Btu/cubic feet of CO_2 absorbed and 10.1 cubic feet of CO_2 produced per hour by 15 men plus 0.9 cubic feet of CO_2 per hour from one CO removal canister.[9]

c. Carbon monoxide removal canister produces 1.19 Btu of heat per cubic foot of CO absorbed.[9]

d. The 15 men at low metabolic rates produce 5,870 Btu of heat per hour.[10]

e. Other equipment in the ASC (light, batteries, communications) generates 100 Btu per hour.

f. Total heat produced from all sources is 8,578 Btu per hour.

Calculations established that, as configured, the ASC can maintain an ambient temperature (of 81° F) if the mine wall has an ambient temperature of 60° F.[12] and an emissivity of 0.88. This does not constitute a stressful environment. If actual metabolic rates or other factors result in higher temperatures, the easiest way to correct this is to add fins to the outer surface of the chamber to aid in radiative and convective heat conduction to the outside.

Kansas State University conducted a series of tests to determine the effect of relative humidity, temperature, and population density conditions upon man's stress limits.[13] The results of tests of these parameters are summarized in table 2-8. In these tests, a 2-degree rise in rectal temperature or illness were used as the measures of stress.

TABLE 2-8
NUMBER OF SUBJECTS EXHIBITING A 2°F-RISE IN RECTAL TEMPERATURE OR SICKNESS IN LESS THAN 8 HOURS

Dry Bulb Temp of	RH %	ET of	PACK CONDITION I 8 subjects 36 sq ft/man 288 cu ft/man		II 18 subjects 16 sq ft/man 128 cu ft/man		III 32 subjects 9 sq ft/man 72 cu ft/man		IV 48 subjects 6 sq ft/man 48 cu ft/man	
			+2°F	Sick	+2°F	Sick	+2°F	Sick	+2°F	Sick
95	60	86.8	1	0	0	0	0	0	0	0
95	70	88.8	1	0	0	0	0	0	6	0
98	60	89.1	0	0	2	0	0	0	3	0
95	80	90.8	0	0	1	0	1	0	30	0
98	70	91.3	8	0	3	1	1	1	38	0
95	90	92.9	7	1	6	1	1	2	46	1
98	80	93.5	8	0	17	0	9	0	46	2
98	90	94.5	8	0	18	0	28	4	46	0

Data from reference 13 correlate well with data from other temperature-humidity duration tests in which population density was uncontrolled and which lasted up to 2 weeks.[10] This indicates that numbers of occupants has little effect on temperature and humidity tolerance. In US Navy-conducted tests of a 100-man shelter over a 14-day period, 12 square feet per man was found adequate.[14, 15] Civil defense authorities state that "At least 12.5 square feet and 80 cubic feet per person" are adequate for fallout shelters.[6] Based upon these results and a comprehensive comparison with known survival shelter parameters that have been shown to be livable, the final choice of parameters for the ASC was 84 cubic feet per man, 21.6 square feet per man, 81°F maximum temperature, and 100-percent maximum relative humidity.

Sealing and Reinforcement

The ASC must be airtight and maintain the airtight seals against blasts from -5 to +20 psi. Since the six modules cannot accommodate longitudinal loads of this force, the brunt of the force is absorbed by the bulkheads. Each bulkhead is anchored to the floor with 12 standard roof bolts, driven at 45-degree angles as shown in figure 2-6. In this way, the bolts can carry the load for either horizontal or vertical pressure and can overcome moments of force in both directions resulting from positive or negative pressure.

A variety of concepts was explored for sealing the ASC, including compressed rubber strips, zippers, inflatable seals, permanent adhesive, and rubber seals with "Pull-a-Dot" fasteners. The last two of these were selected to seal the 283 feet of seal required (see figure 2-6).

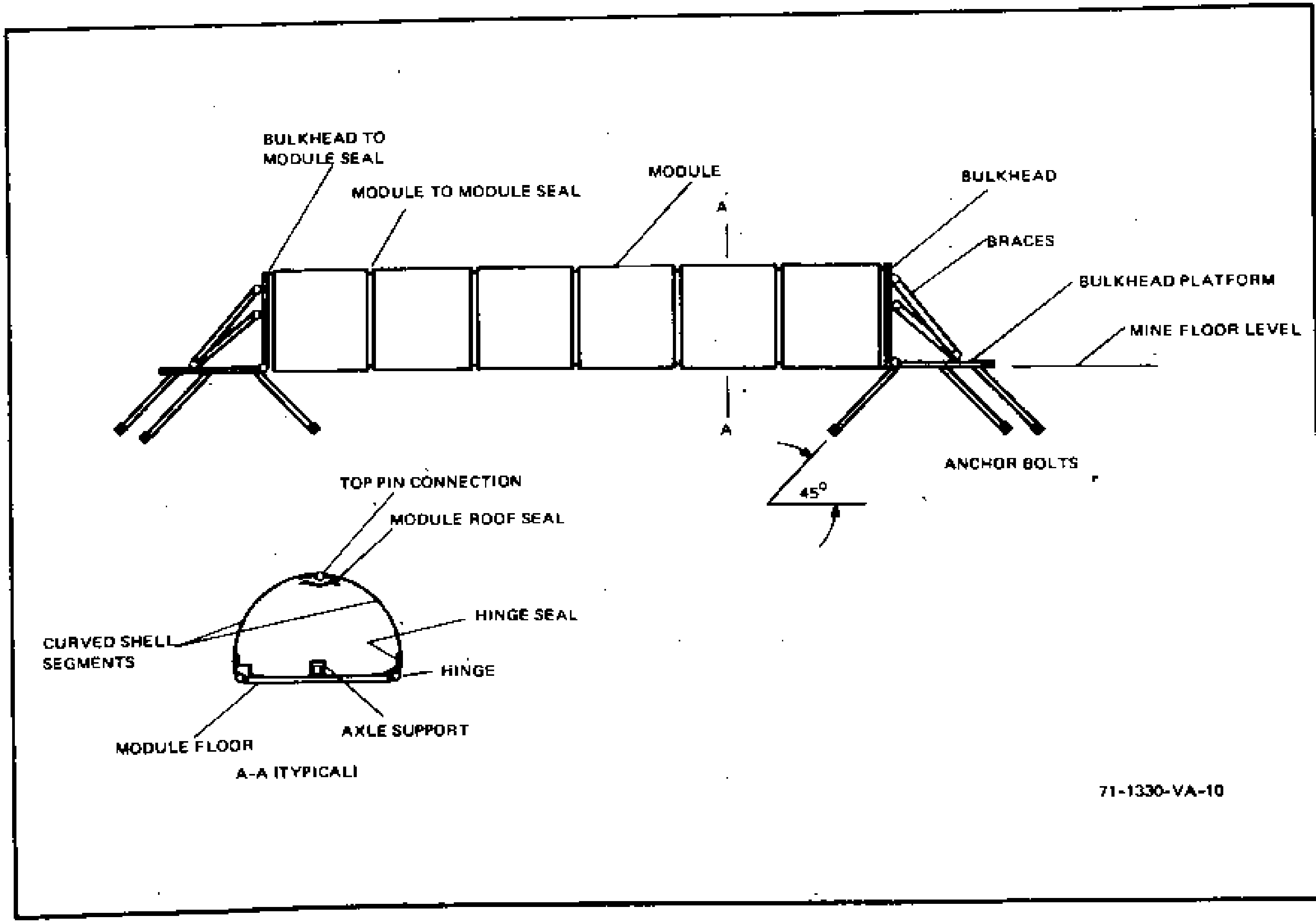

Figure 2-6. Assembled ASC

Seals are secured by permanent adhesive, or Pull-a-Dot fasteners, or both. Permanent adhesive is used in hinge areas where seals are not removed in disassembly. The seals are bonded to the floor and to the shell segments, becoming permanent parts of the module. The Pull-a-Dot fasteners are used where seals are removed in disassembly, for example, in the roof and module-to-module joints. Engaging the snaps with permanently installed mating parts compresses the rubber seal. The fasteners can be oriented so that they can be opened from both inside and outside the chamber.

Module roof joints are about 5 inches wide, with 6-inch gaps at each end. The gaps are temporarily sealed with tape before installing the seals. The seal used to seal the gap is shaped like a race track, providing a continuous seal all around the opening. Continuous seals are also used between modules. The fasteners are secured to each module, and excess material between the inner rows of fasteners is provided to accommodate gapping. Nominal gap is 1 inch; the seal permits 1.5 inches. The fabric connecting the seals is cut on a bias to allow for vertical and side mismatch up to 0.5 inch.

Bulkhead-to-module seals use a combination of snaps and adhesive. One edge of the seal is bonded to the bulkhead and secured with retaining plates. The other edge is held by the Pull-a-Dot fasteners when the bulkhead is joined to the module. The hatch seal is a soft rubber strip built into the hatch that compresses when the hatch is closed.

In the axle support area, a wing nut is tightened against a bearing plate that is supported by the inner axle lug. A rubber lined seal plate is then screwed tight over the opening, compressing the rubber to form the seal. Another soft rubber strip is secured to the outer edge of each module hinge so that it is compressed when the shell section is erected so as to protect the inner hinge seal against overloading when exposed to sudden high pressures.

Atmosphere Conditioning Unit (ACU)

Two atmosphere conditioning units are included in each ASC to produce oxygen, remove carbon dioxide, remove carbon monoxide, and circulate internal air. The ACU also prevents inward leakage of poisonous gases by maintaining a slight positive pressure in the chamber by drawing in some outside air through leakage control hoses.

The design parameters for the ACU are listed below:

a. Inlet CO concentration of 1,000 ppm; outlet less than 50 ppm
b. Inlet CO_2 concentration of 1 percent; outlet less than 0.1 percent
c. Inlet air flow of 15 SCFM or more
d. Inlet humidity of 80 percent
e. Inlet temperature of 50 to 80°F; outlet less than 100°F
f. Control of seal leakage
g. Manually operated and easy to assemble
h. Built-in-breathing (BIB) system with mask outlets for 8 men each.

Oxygen Supply

The objectives of the oxygen supply were capacity for 210 man-days, easy assembly, low-cost, portability, minimum development time, and high safety and reliability. There are four basic practical methods of supplying oxygen in this kind of application: high pressure storage, cryogenic storage, electrolysis of water, and chemical reactions that give off oxygen (ref. 5, 9, 11, and 16).

Cryogenic methods were rejected on the basis of cost. Electrolytic methods were not safe enough for the ASC. High pressure storage does not afford enough portability, reliability, or safety.

Among chemical reactions, potassium superoxide and sodium chlorate were considered most applicable. Potassium superoxide was eliminated on the basis of inordinate development time required. Therefore, the ACU uses chlorate candles to produce oxygen. Each of the candles used produces 70 cubic feet of oxygen. Seventy (70) candles will be required based on normal oxygen consumption rate of 1.78 pounds per man-day for 210 man-days, plus 46 pounds of oxidation of CO. Assuming the worst case for the surrounding atmosphere (no oxygen in the mine) 14 more candles would be required. The candles are connected to the ACU so that if the built-in-breathing manifold is in use, oxygen in the system is increased by 10 percent.

Carbon Dioxide Removal

The ACU must remove 90 percent of the CO_2 produced by 15 men, and each unit must be capable of accomplishing this alone, in case one unit breaks down. The same general design objectives apply here as applied for the oxygen supply. The three most likely candidate methods of removing the CO_2 are chemical absorption, cryogenic condensation, and osmotic diffusion (ref. 5, 9, 14, 16, 17, 18). All will handle the CO_2 generated by 15 men.

Cryogenic condensation and osmotic diffusion were rejected on cost, safety, and portability. Chemical reactions considered were potassium superoxide, baralyme sodasorb, and lithium hydroxide. Potassium superoxide was rejected on the basis of cost and development required. Sodasorb shows too much dusting, too much corrosion risk, high cost, and low efficiency. Baralyme and lithium hydroxide were very close candidates, with baralyme holding small advantage in assembly-disassembly time, cost, schedule, and safety.

The baralyme canister is a vertical axial-flow refillable type with lateral baffles. The axial-flow type was chosen to preclude the possibility of channeling in the canister. The size of each canister was based on available storage space, manual handling considerations, and an 8-hour duration. The rate of CO_2 removal was based on generation of 1.26 pounds of CO_2 per hour from 15 men, 0.12 pounds from the carbon monoxide-removal canister, and 0.1 pound drawn in through leakage hoses (outside concentration assumed to be 10 percent). For the 14-day mission, 42 canisters are supplied with each ACU.

Carbon Monoxide Removal

An extensive literature study and a design, test, and development program formed the background for the CO removal canister supplied with the atmosphere conditioning units for the ASC.

Carbon monoxide can be removed from an air stream by absorption or by catalytic reaction. Catalytic reaction, using Hopcalite as the catalyst, performs acceptably and within the operating requirements. Hopcalite is a coprecipitated mixture of manganese dioxide and cupric oxide, with small amounts of cobalt and silver oxides, and it can catalyze CO oxidation at mine temperatures.

Hopcalite is attacked by water vapor at temperatures below 250°F and can be poisoned by traces of antimony.[9] Below 350°F, Hopcalite may absorb unsaturated hydrocarbons, which may ignite if hydrogen is also present.[19] In other applications, no standard design existed for this use of Hopcalite; therefore, a new filter-bed design was required. All traces of water vapor and antimony were eliminated from materials, finishes, and assembly of the canister, and provisions were included to remove water vapor during operation.

The canister housing was designed to 6-3/4 x 9 x 13-inch dimensions of zinc-plated sheet steel. Seams are spot welded and soldered; points of wear are reinforced; and the spring-loaded filter bed is held by two metal screens. A wall baffle is included to prevent channeling. The filter bed originally consisted of a 1-1/2 inch layer of activated charcoal, a 5-1/2 inch layer of silica gel, a 1-1/2 inch layer of molecular sieve, a 1-inch layer of Hopcalite, and metal screens top and bottom. Flow is axially downward. The charcoal layer was intended to absorb unsaturated hydrocarbons, but since neither these compounds nor hydrogen will be present in quantity, the charcoal layer was eliminated. The silica gel and molecular sieve absorb water vapor at high and low humidities, respectively. When they saturate, the water vapor attacks the Hopcalite, and the CO at the outlet increases.

When the charcoal layer was removed, the Hopcalite layer was increased to 2-1/2 inches, and a baffle plate was added at the outlet to distribute flow. In testing of this configuration, breakthrough (start of increase in CO at outlet) did not occur until 6 hours of operation had elapsed under design conditions.

The effects of chamber seal leakage resulted in a 3/8-inch leakage control hose being added between the chamber wall and the carbon monoxide canister. With the chamber seals installed, the hoses provide lower leakage resistance than the seals; so the inward flow of mine gas is immediately scrubbed. When the ACU's are operating, the hoses draw in mine air to maintain a slight internal positive pressure and seal leakage occurs in the outward direction only. Under normal conditions, considering leakage, activity levels, and other sources of contaminants, the ACU's require about 51 minutes operation per hour to maintain both CO_2 and CO below maximum limits. Because CO in a mine decreases with time after a blast, a design duration of 5 days was considered adequate. Therefore 28 CO removal canisters are supplied.

Built-In-Breathing Manifold

For emergencies, a built-in-breathing (BIB) manifold is included in each ACU. In operation, the manifold is connected directly to the ACU outlet so that the air supplied contains an additional 10 percent of oxygen. Each ACU manifold feeds eight hoses and facemasks.

Ventilation Components

All ducts, hoses, manifolds, and facemasks are fire resistant, easy to attach or repair, and spaced to avoid crossing. The blower hose is disconnected from the manifold and used as a ventilation duct to the chamber when not in the BIB mode. The blower is a hand-cranked gear-driven centrifugal bomb shelter ventilator, and it can be operated at 40 rpm for about 30 minutes by one man using one arm.

Furnishings

Personal necessity items required in the ASC are minimal; bunks, blankets, and personal hygiene kit. Double bunks are used to conserve space. Blankets are fireproof "Nomex". The hygiene kit is primarily used to ensure cleanliness in treating wounds.

To overcome the stress of forced inactivity, Bibles, pencils and paper, playing cards, and some games are supplied. Radio broadcasts may also be piped in through the Communications Subsystem equipment.

Fire extinguishers, first aid equipment, and tools are also provided. A water-type extinguisher is supplied in the chamber for wood and paper fires; a chemical extinguisher is supplied outside for electrical fires. First aid equipment is a standard miner's kit, to which have been added aspirin, a cleansing agent, tincture of merthiolate, a resuscitube, and a Foille burn kit. A collapsible stretcher is provided outside the chamber, and the bunks can also be used as stretchers. Inside the chamber, a standard tool kit consisting of pliers, wrenches, hammer, saw, and nails is supplied for repairs. Outside, shovels, axes, and other heavy tools are supplied, along with six PBA units.

Electrical System

The electrical system for the ASC was originally going to be a 24-volt off-the-shelf permissible system, but lack of availability of acceptable equipment led to the choice to design a system for intrinsic safety. System voltage was dropped to 12 volts, and current-limiting resistors were added to the circuit to hold energy levels under 100 millijoules per branch (see figure 2-7). Each load branch is also fused and switched. Battery and control circuits are integrated in one box.

In this system all components work at less than 50 percent of their ratings. The battery is a 12-volt 96-ampere-hour-per-charge zinc-air unit that is mechanically recharged. Eight recharge kits are supplied for a total of 768 ampere-hours. Oxygen required for this battery system will not exceed one cubic foot per day. The lamps used are 4-volt units, used two in series in each of three lines (lines 1, 2, and 3 of figure 2-7). Using one line 24 hours, one line 16 hours, and one line 8 hours per day requires recharging every 48 hours, depending upon how much power is supplied to the communications equipment (line 4). Line 4 can be used to power the communications directly, or it can be used to direct power from the communications battery to the lights. All jacks and lamps are color coded.

A back-up lighting system is provided. Cyalume panels, a chemical-emitting light source, will provide 224 hours of low level illumination.

This system complies with reference 5 (schedule 2G); it is simple to operate; it uses low-cost off-the-shelf components; and it requires almost no maintenance.

<u>Food and Water</u>

Food was selected for nutrition, shelf life, packaging, cost, and availability. Several candidates (dehydrated, pemmican camping goods, Pillsbury's "Space Stick") were considered, but the standard proven military ration (MIL-F-43231, Food Packet, Survival, General Purpose) was chosen as most applicable. Each packet contains about 870 calories, and 2 per man per day are supplied to give each man 1740 calories per day.

The water supply is twenty (20) 5-1/4 gallon plastic containers that fit readily into the ASC and can be used for waste disposal when they are

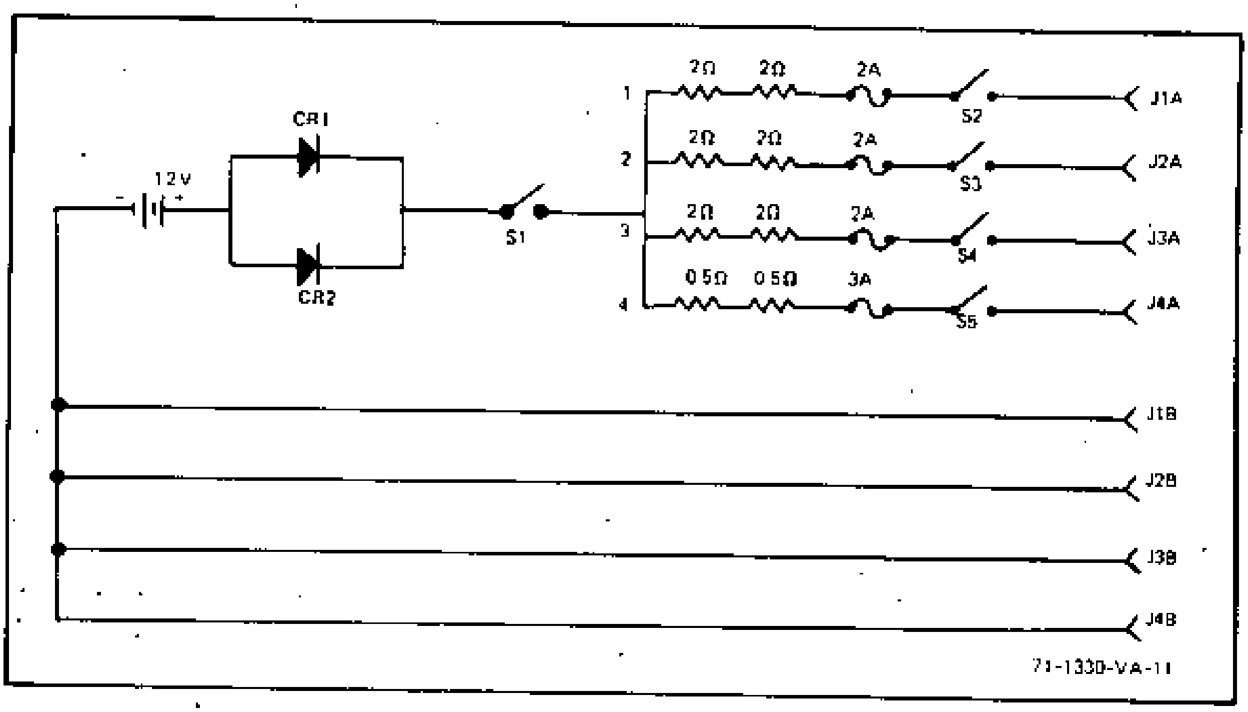

Figure 2-7. ASC Electrical System

empty. The water is regular tap water with 1 teaspoon of chlorox per container added to assure long storage life in the absence of significant sunlight exposure.

Waste Disposal

For simplicity, low cost, and reliability, the Stello Products portable toilet is used. Ordinary Listerine[12] mouthwash can be used as the bacteriostat and deodorant. The disposable bags are double-sealed plastic, and they may be thrown out the hatch if the outside atmosphere will permit.

Fabrication and Assembly

The design of the ASC was directed toward ease of fabrication with methods available in a common welding shop. The material used is low carbon steel, and all welding was done to Specification AWS D1.0-6.9. The three sections of the module, floor, right panel, and left panel, were fabricated in parallel and joined together.

The floor of each module is 6x9 feet and is fabricated of standard I-beam and channels welded to a flat plate.

The side panels are standard low carbon corrugated steel curved on a radius of 53 inches and subtending an arc of 93.5 degrees. Off-the-shelf panels could not meet the arc requirements, so the panels are fabricated from two smaller sections, welded lengthwise at mid-height. They are then bent to the proper curvature in the welding shop. The panels are connected to the floor with hinges and pins. The hinges were welded with the round bar in place, which provided near perfect alignment.

Bulkheads are flat corrugated sheet steel, reinforced by four rectangular tube beams. The bulkhead platform is a standard rectangular tube beam welded to a flat steel plate.

Seals were fitted by a cut-and-try method, which was time consuming but not difficult. Templates were used to locate and install the Pull-a-Dot fasteners.

Final assembly of the life support center, outfitting and power supply systems in the chamber is a straightforward process, requiring no special skills and creating no significant problems. As the equipment is laid out, shock cords are installed to hold movable items in place. Materials and assembly of ACU components were noted in the functional descriptions. Particular care was exercised in their fabrication and assembly to prevent contamination from any source.

LARGE CENTRAL CHAMBER (LCC)

No large central chamber has been built to date. The Coal Mine Rescue and Survival System contract required a comprehensive and workable design and layout for the LCC but no hardware. The procedures followed to fulfill this requirement were the same as required to design and build an actual chamber. The following paragraphs discuss these processes.

Structural Concept

The function of the LCC is to protect up to 50 trapped miners for as long as 14 days, while rescue operations attempt to free them. The LCC

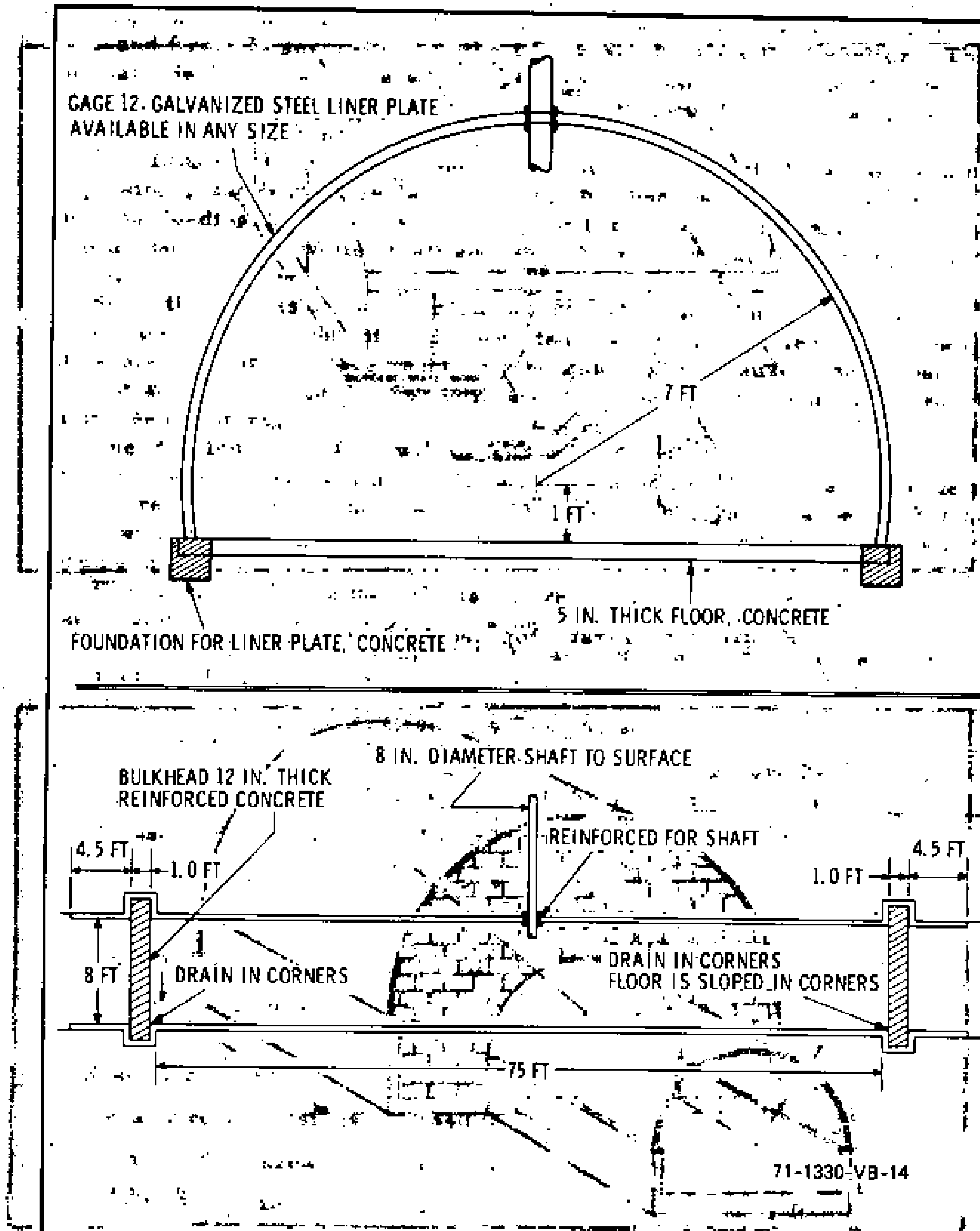

Figure 2-10. Selected LCC Configuration

Structural efficiency is determined by how strong a structure must be to carry a given load. In this area, an arch shape is most efficient, and the shorter the space, the lighter the structure can be.

The selection of floor space and volume for the LCC was based on the same considerations as for the ASC (see refs. 6 and 10-15 and section on Structural Concept for Auxiliary Survival Chamber). The selected configuration gives each of the 50 occupants 137 cubic feet of space which is greater than that allotted in the ASC but recommended because of larger number of occupants.

A basic cost analysis shows the configuration in figure 2-10 to be least expensive, because the arch span is less (thickness of material less) and because no end walls are required (as in figure 2-9).

Excavation costs will be less if coal is excavated for the construction and more if waste material has to be excavated. Therefore, structure shape should be tailored so that waste excavation is held to a minimum. The selected concept accomplishes this.

Heat transfer characteristics are a significant consideration to life support and are discussed in some detail later. Ventilation is also extremely important, and it, too, is discussed in detail under the next paragraph heading. However, in both cases, the basic structural concept selected (figure 2-10) performs well.

Several construction materials were considered for the LCC. Wood was summarily rejected. Brick was rejected on the basis of cost and insufficient strength to carry the required loads. Pre-stressed concrete was rejected, because it is prefabricated, and the components would be much too large and heavy to handle. From a cost and simplicity viewpoint, cement blocks would be best, but they are not strong enough to support the required loads. They are now used as stoppings, and blasts usually blow them out. All metals except steel were rejected on the basis of cost.

In the program proposal,[4] reinforced concrete was specified for the LCC. Sand, aggregate, cement, and reinforcing steel can be carried into the mine easily. The steel can be wired into place, the forms built, the concrete electrically mixed and pumped into place[20, 21]. However, during an investigation of tunnel construction techniques,[22, 23] a better material was found for parts of the chamber; it is called liner plate.[24]

Liner plate is corrugated curved steel plate that comes in 18x50-inch sections that weigh about 37 pounds each. It is already in use in mines in sloping entries to provide ample width to accommodate track, walkway, air ducts, electrical conduits, and belt conveyors. Semicircular liners are also used as underground vaults. Circular liners are used as vertical entries and shafts (see reference 25 for further details on liner plate).

The structure made with liner plate will use reinforced concrete for both the floor and blast walls. Only the ceiling and side walls will use liner plate. Some of the advantages of liner plate over other materials are listed below.

a. Better heat transfer
   1. Steel has high thermal conductivity
   2. Surface area increased 12 percent by corrugations
   3. Adaptable to adding fins, if required
b. Easy construction
   1. Lightweight, easy to handle
   2. No special tools
   3. All bolting from inside (designed that way)
   4. No forms or temporary supports needed
c. Liner plate can be removed from the inside, allowing miners to construct a tunnel from the chamber if needed for escape
d. Liner plate is available to make tunnels that are within 2 inches of any desired rise of span (more than 4, less than 30 feet).

Based upon the 1,000 psi loading and a safety factor of at least 2, calculations indicated that Gage 12 Armco liner plate should be used. It should be galvanized and painted with a high integrity paint for corrosion control. It must be back grouted after installation to develop buckling resistance.

The blast walls should use 3,000 psi concrete with 40,000 psi yield no. 7 steel reinforcing bars at 10-inch spacing. General blast wall design follows references 20 and 21. The shape of the blast walls is shown in figure 2-10. They will be 12 inches thick and will be supported by the beams that support the doors and by the side of the tunnel. Figure 2-11 shows one wall with two doors, the other wall with one.

Commercially available ships doors can be used for all three doors. The door frames are 3x2x5/16-inch angles that come with the doors. A subframe of 36,000 psi yield steel will be required. A wide flange I-beam (12WF22) has a section modulus of 25.3 cubic inches and should therefore be used for the subframe. This will carry the load of 700 pounds per inch from the door and concrete wall.

The door frames can be welded to the subframe and then carried into the mine. The unit shown in figure 2-11 weighs about 1,100 pounds.

There should be one small quick-acting door in each bulkhead. The size of these doors is 24x30 inches, with 8-inch radius corners. These are the doors to be used by the miners in case of emergency. Being small and quick acting, they will restrict the amount of contamination that enters during use. The other door is 36x60 inches with 8-inch radius corners. It is not quick acting and should be used only during construction to carry equipment and supplies into the chamber.

The floor will be plain 3,000 psi concrete, reinforced only for temperature and shrinkage. It will be 5 inches thick with number 3 steel bars on 10-inch centers in both directions. It will slope 1 inch per 7 feet from the center to the corners for drainage.

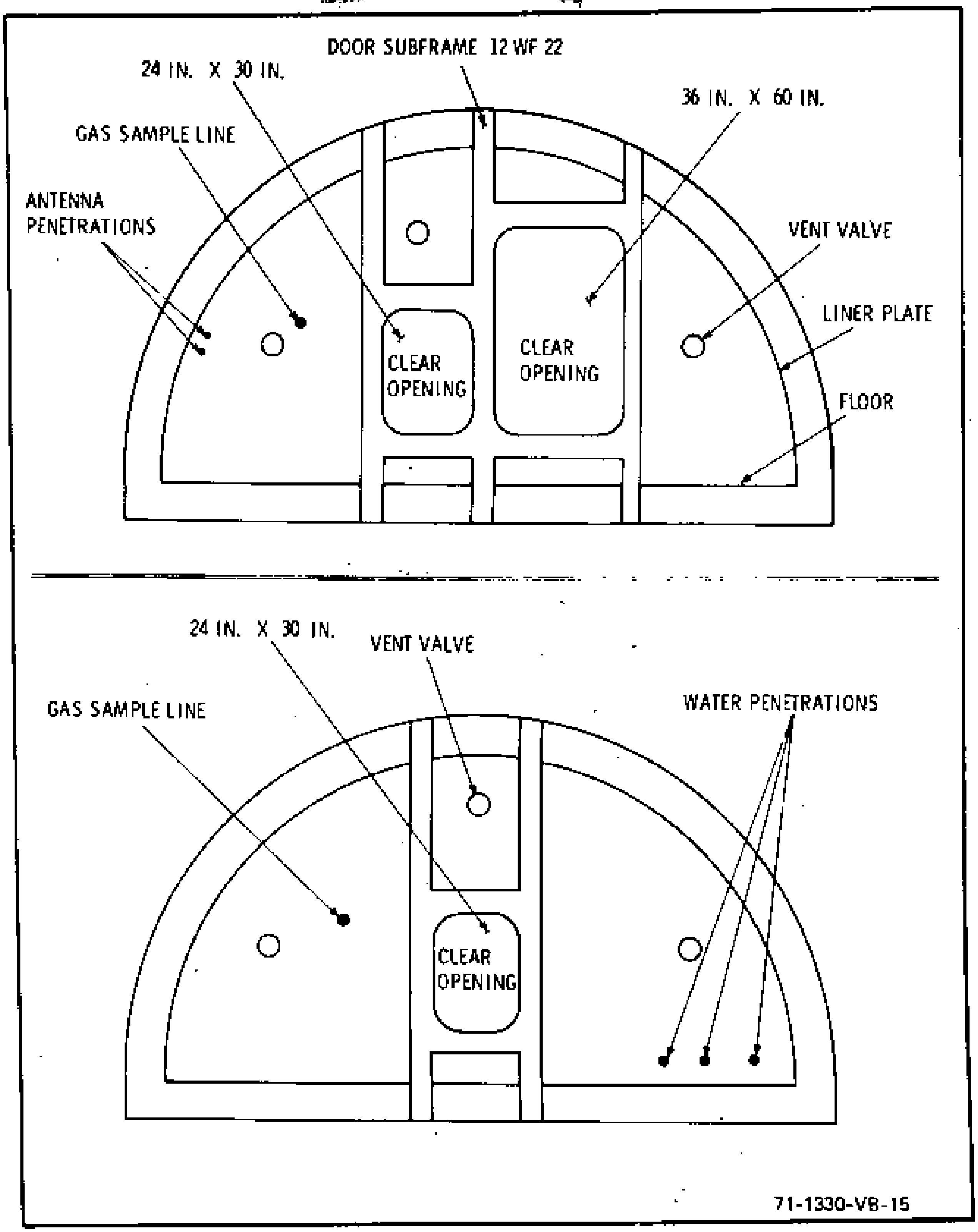

Figure 2-11. LCC Structure and Dimensions

The footings for the liner plate will be plain 3,000 psi concrete, reinforced for temperature and shrinkage with number 3 steel bars on 5-1/2-inch centers. The ground is assumed to be capable of carrying 6 tons per square foot loading. To accommodate the loading (7,000 pounds per foot) and the safety factor, the footings should be 10 inches thick and 12.6 inches wide.

The crosscut leading to the LCC is also reinforced to keep the areas around the doors free of rubble. It is reinforced for 4.5 feet in each direction with the same materials as used in the main chamber (liner plate roof and side walls, concrete floor, and footings).

The liner plate has one penetration; the 8-inch shaft to the surface. The liner plate is reinforced with a 10-inch pipe welded to the plate at this opening. The floor has four penetrations; water drains in each corner. These are 1-inch galvanized iron pipe with hexagon head plugs that are removed to drain the water. Each bulkhead has three 8-inch pipes used as ventilation valves. One bulkhead also has three 26-inch sections of 1-1/4-inch galvanized iron pipe for water (two for supply, one drain). Each bulkhead will also hold 1/8-inch iron pipe for gas sampling. One bulkhead will also hold the communications antenna (two 1/2-inch penetrations).

Excavation of the site for the LCC will, of course, depend upon the specific requirements of the particular mine. Standard mining techniques can be used, such as undercutting, drilling, and blasting or a continuous miner can be used to cut rectangular shapes as shown in figure 2-12, wherein the shaded area can be grouted for support. Blasting can also be

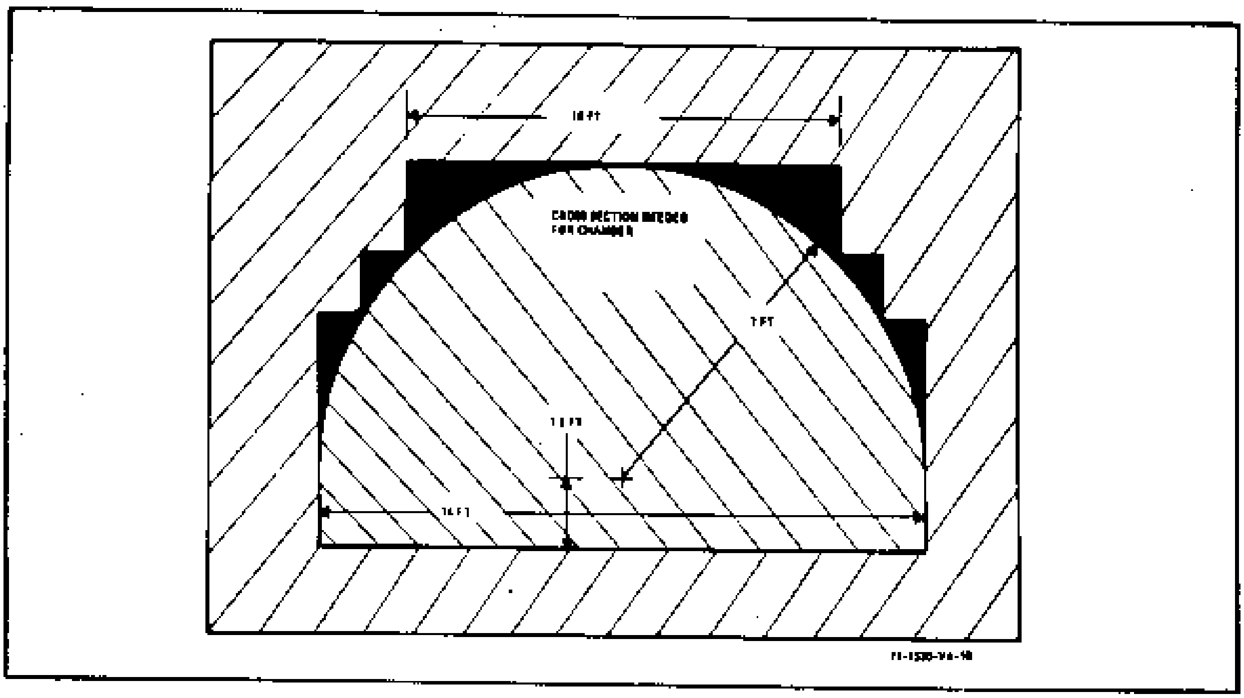

Figure 2-12. Required Excavation

used after the continuous miner to obtain the required shape. The cost of grouting could increase the LCC cost by as much as $840.

Ventilation and Heat Transfer

Ventilation and heat transfer for the LCC must be considered in two phases; with surface ventilation equipment in operation and without. Basic design parameters under consideration are listed in tables 2-9 and 2-10. Analysis showed that if surface air and cooling were cut off, and no emergency ventilating mode was provided, temperatures could rise above survivable levels.

The actual analysis of the thermal characteristics is included as Appendix A to this volume. The analysis is written so that mine owners can review the parameters given in tables 2-7 and 2-8 and then substitute values that correspond to his mine conditions to arrive at an ideal system for his application.

Metabolic heat loss used was 400 Btu/hr[11]. The range for the LCC is from sleeping (280 Btu/hr) to cranking (860 Btu/hr). Actual tests have shown a mean metabolic rate of 485 Btu/hr.[26] The activity in the LCC is much less than in the tests described; so, 400 Btu/hr appears a reasonable figure.

The selection of the design limit on effective temperature was critical. The Office of Civil Defense[11], describes an effective temperature of 85°F as causing casualties in men of middle-age. Tests at Kansas State University[13] indicate that a dry bulb temperature of 85°F and an 80-percent relative humidity did not cause undue stress. The limits set were 84°F and 100-percent relative humidity.

For the analysis, the typical mine was assumed to have a 5-foot coal seam, with the balance of the strata being shale (see reference 27, table 5), because 50 percent of coal mined in 1965 was mined from seams less than 5 feet thick.

Several approaches were considered for temperature control within a chamber which is isolated from the surface, including enlarging the surface area, adding fins, using heat pipes, and water cooling.[28,29] Ground rules stated that power and water lines to the surface might be damaged; so, they could not be relied upon for cooling.

Enlarging the surface area was rejected because of the large volume it would require in the chamber. Fins were rejected because of the excessively large area of fins required. Heat pipes were rejected because of degradation of the vacuum system required, because heat pipes have not been used in this type of application, and because of cost.

A schematic of the two-part system selected is shown in figure 2-13. The two basic parts of the system are the surface equipment and the equipment in the chamber. The surface equipment consists of an air-cooling unit and thermostat (for summer use), a compressor and a duct air heater and thermostat (for winter use), and an 8-inch ventilating shaft with a hatch.

TABLE 2-9
LARGE CHAMBER ATMOSPHERE CONDITIONING SYSTEM

			50 Men, 14 Days Total Stay	
			Normal Operation	Emergency (without shaft or elec)
Oxygen	Supply Rate (1.5 lb/man day)		3.125 lb/hr 0.633 CFM at NTP	3.125 lb/hr 0.633 CFM at NTP
	Total, In 15 Days		1,050 lbs	1,050 lbs
	Fract'n % O_2 p O_2, mm Hg		18 - 21 137 - 160	18 - 26.3 (1) 137 - 200
CO_2 (R Q =.85)	Generation Rate	Wt	3.66 lb/hr	3.66 lb/hr
		Vol	0.539 CFM at NTP	0.539 at NTP
	Frac'n, % CO_2		0.25 - 1.00	0.25 - 1.50
Trace Contam	CO, ppm CH_4, % Vol		0 - 25 0 - 1.5	0 - 200 (2) 0 - 3.5 (3)
Chamber Air	TEMP	Design Limit	82°F 55° - 84°F	82°F 52° - 84°F
	R. H.	Design Limit	50% 35 - 75%	100% 50 - 100%
Meta-bolic	H_2O lb/man-hr		0.13, Design; 0.05 - 0.20, Range	
	Heat BTU/hr x man		400, Design; 280 - 800, Range	

(1) Fire risk limit

(2) 24 hr limit, NAVSHIPS 0900-028-2010

(3) Proximity to explosive limit

71-1330-T-17

TABLE 2-10
LARGE CHAMBER ENVIRONMENTAL AND SIZE CONSTRAINTS

SURFACE AIR		DESIGN	RANGE
Dry Bulb Temp	F	90	15 - 105
Rel. Humidity	%	70	20 - 90
Humidity Ratio	lb/lb	0.0218	
Rock Strain at Depth			
Temp	°F	60	50 - 75
Spec. Ht. (All Strata) C_1	$\frac{\text{HrBtu}}{\text{ft x °F}}$	0.2	
Conductivity, k, Btu/Hr x ft x °F			
Coal		0.15	
Shale		0.80	0.60 - 1.5
Density, ρ lb/ft^3			
Coal		82.5	
Shale		165	155 - 190
Diffusivity, $\alpha = \frac{k}{\rho c}$ Btu/lb x °F			
Coal		0.0091	
Shale		0.0242	
Transmission Coeff. U $\frac{\text{Btu}}{\text{Hr x ft}^2\text{x °F}}$			
Air to Metal (Ref 3. p. 58)		0.77	
Grouting (=1/2 Gypsum Brd Seven & Fellows, 11.8)		0.38	0.3 - 0.55

Chamber Size = 75 ft x 14 ft x 8 ft High

Volume = 6,850 ft^3 (137 ft^3/Man)

Total Surf. Area = 3,054 ft^2 (61 ft^2/Man)

Floor = 1,043 ft^2 (20.9 ft^2/Man)

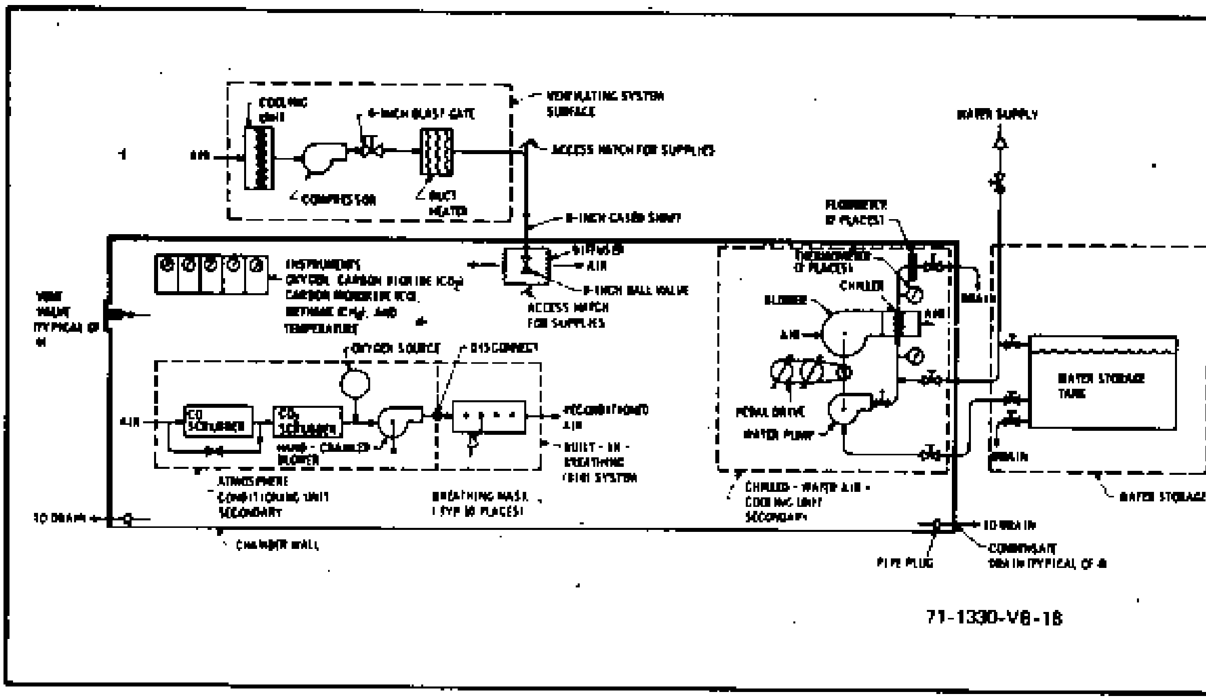

Figure 2-13. LCC Atmosphere Control System

The shaft is fully cased for maximum protection. In normal operation, the compressor (standard off-the-shelf) drives 800 cfm of cooled or heated air through the shaft into the LCC. When pressure in the LCC exceeds 2 inches of water, one-way valves in the bulkheads open to exhaust the air. This minimum internal pressure helps assure no leakage from outside. The valve release also allows carbon dioxide and carbon monoxide to be purged by the normal circulation of fresh air. The cooling unit is a standard commercially available 8-ton chiller (evaporator, compressor, condenser), and it is thermostatically controlled. The heater is a standard 6-kW electric unit, and it is also thermostatically controlled. A diffuser is located in the chamber to circulate the air.

The emergency equipment in the chamber will not be used unless the shaft is closed by explosion or the surface equipment is inoperative for any reason. Water for air cooling is supplied from a tank just outside the chamber. Water at 60°F is supplied to a heat exchanger and blower; the pump and blower are driven by two men on a bicycle-type drive arrangement.[30] Five atmosphere control units, like the ones supplied in the Auxiliary Survival Chamber, are supplied for the LCC. The only difference in the units is that the LCC units have built-in-breathing manifolds with 10 output hoses and facemasks. They operate in exactly the same way, generating oxygen from chlorate candles, scrubbing carbon dioxide with baralyme, and scrubbing carbon monoxide with Hopcalite. These units are also hand-cranked. Supplies of the emergency system are adequate for 5 days of operation. It is assumed that this will be enough time to drill another shaft or reopen the original.

Electrical System

The design of the electrical system for the LCC is the same basic battery box circuit used in the ASC (see figure 2-7). Two of these units are included in each chamber. Enough recharge kits are supplied in the LCC for 1,536 ampere-hours of normal operation. Lamps for the LCC are standard miner's cap lamps (without external batteries). Two lamps are used in series with a current-limiting resistor in each of six branches (two circuits). Lighting schedule is the same as for the ASC and it will require recharging batteries every 48 hours, depending upon the power requirements for communications. A back-up lighting system of the same cyalume lights (ASC) is supplied for up to 448 hours of low-level illumination.

For two-way communications, a MIL-T-15514, Type H203/U Sound Powered Telephone is used. It will transmit for distances well in excess of the deepest mine, and requires almost no maintenance. The only disadvantage is that there should be continued monitoring at both ends.

The high-voltage wiring for the surface equipment is shown in figure 2-14, and the low-voltage wiring is shown in figure 2-15. All wiring should be done according to NEC, NEMA, and local wiring codes and standards. Throughout the system, all requirements of Schedule 2G of Title 30[5] have been met and simplicity of operation has been maintained.

Accommodations

The accommodations and arrangement of equipment for the LCC were developed according to the same constraints and concepts as for the ASC, except for modified quantities of everything required.

The same MIL-F-43231 military-type food packets are supplied for both the LCC and ASC, enough for 1,740 calories per man per day. Regular tap water (with 1 teaspoon of chlorox per 5-1/4 gallons of water) is stored in eleven (11) 17-1/2-gallon plastic containers.

The same Stello Products portable toilet is used for both the LCC and ASC, for the same reasons. Two are supplied in the LCC.

Fourteen triple free-standing steel bunks are spaced in pairs about 2 feet apart along one wall. The bunks bolt together and are easily assembled or dismantled. Although the bunks can stand alone, lashing each pair together and jamming them into the wall curvature is recommended for stability.

Chlorate candles are stored under the bunks. The baralyme and Hopcalite canisters are stored between bunk ends and the curved chamber wall. The 14 spare Personal Breathing Apparatus units can be hung on the bunks. The 20 fireproof "Nomex" blankets and spare coveralls are stored on the mattresses. An open aisle is provided at about maximum chamber height, and the remaining wall space is used to store food and water supplies.

The air diffuser is located directly beneath the shaft for maximum effectiveness and is structured to direct incoming air up and toward the chamber ends. Space under the diffuser is designed as the central control point for power and communications. One chemical and one water-type

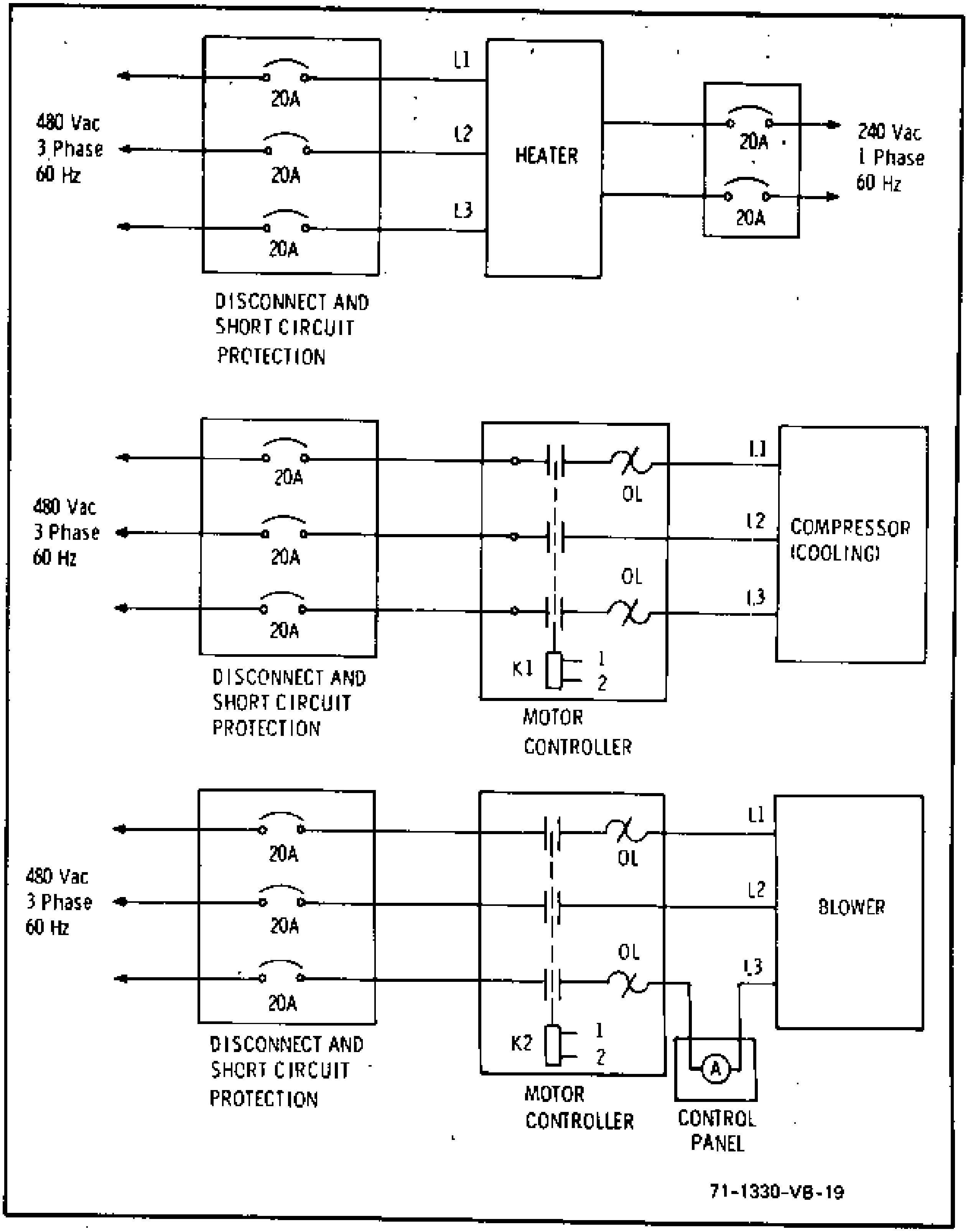

Figure 2-14. Surface High-Voltage Wiring

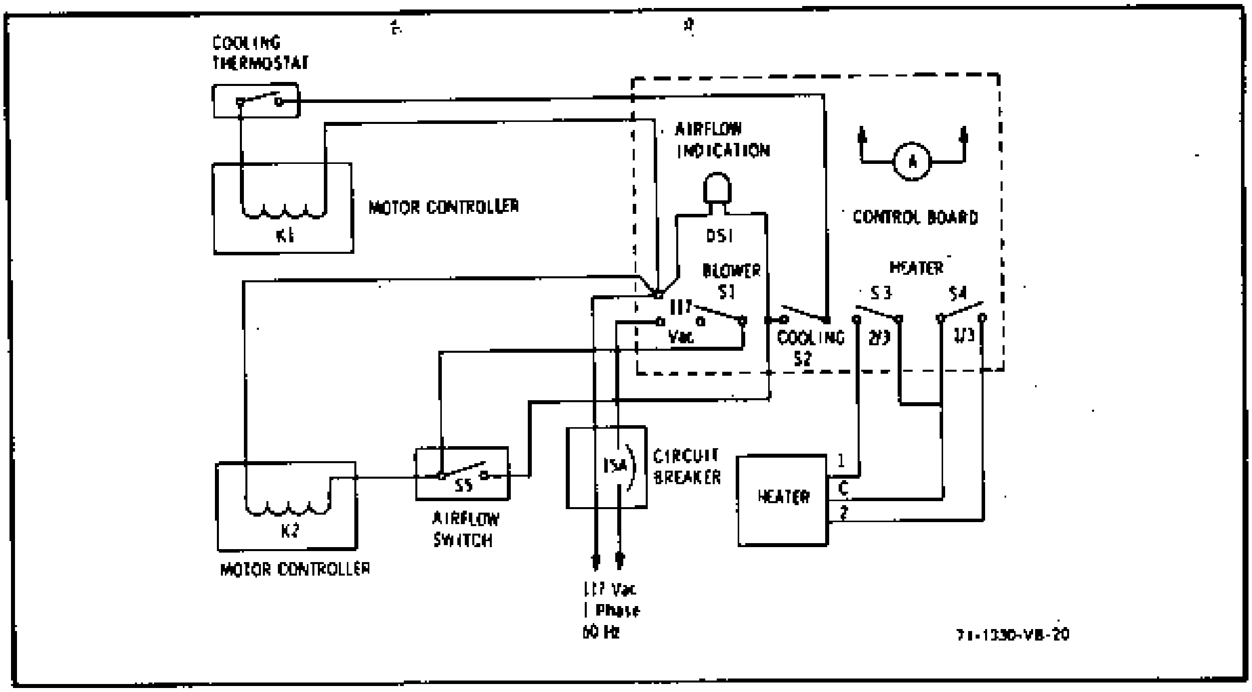

Figure 2-15. Surface Low-Voltage Wiring

fire extinguisher, the gas sampling equipment, and some furnishings are located against the wall opposite this area. The 5 atmosphere control units are spaced about equally along the chamber and on opposite walls to permit easy access and optimum gas diffusion.

One chemical toilet is located at each end. A water-type fire extinguisher and bundle of tools is also located at each end. Outside each end, a chemical extinguisher and several large tools (shovels, axes) are located.

The bulkhead with two doors contains the seismic and electromagnetic communications penetrations (see Volume III of this report). The EM equipment is stored in a large fiberglass box near the end until it is used.

The seismic transmitter and gas bottle are located near the EM equipment, with controls mounted to the wall. Because the transmitter-generated percussion may be detrimental to personnel, especially shock or concussion victims, this equipment may be kept and used outside the chamber.

Except for the diffuser, the chilled-water air-cooling system, and bulkhead penetrations, all equipment is mobile and can be moved to suit the immediate situation.

Cost Estimate

As part of the program effort, a preliminary cost analysis was conducted on the cost to construct the LCC. The results of this analysis are shown in table 2-11.

TABLE 2-II
ESTIMATED LCC CONSTRUCTION COSTS

Roof and side walls		
(Cost $107/ft - 84 ft needed)		$ 9,000
Floor and footings		
(Cost $25/ft - 84 ft needed)		2,100
Bulkhead with one door		
(Reinforced concrete)	$550	
(1 small door)	400	
(Door subframe assembly)	150	1,100
Bulkhead with two doors		
(Reinforced concrete)	$550	
(1 small door)	400	
(1 large door)	600	
(Door subframe assemblies)	300	1,850
Total estimated cost of structure for large chamber, less labor		$14,050

CHAPTER 3
OPERATION

This chapter is divided into two sections. The first presents a summary discussion of the operation of the Survival Subsystem portion of the Coal Mine Rescue and Survival System. Operation of these units is a straightforward process and does not require special skills. The second section of this chapter is a discussion of the various tests conducted on Survival Subsystem units during the design effort and as part of the demonstration. The results of these tests are also discussed in terms of their application to the conclusions and recommendations covered in Chapter 4.

SECTION I
ON-SITE OPERATION

This section describes the operating procedures for the units of the Survival Subsystem. Both normal and emergency procedures are included when applicable.

PERSONAL BREATHING APPARATUS

The Personal Breathing Apparatus (PBA) was designed for simplicity of operation and reliable performance. It was also designed to fit 90 percent of all adult males; so, the chances of encountering much difficulty in using the PBA are small.

The normal sequence of operations for the PBA is pictured and described in figure 3-1. As can be seen, the procedure is simple and requires little concentration. Even if the miner is injured or partially overcome by gases, he should be able to don and use the PBA.

If it is necessary for the user to vomit while wearing the PBA, he removes the mouthpiece, holds it up and away from his mouth, and vomits into the hood. Under no circumstances should he loosen the neck seal or remove the hood.

If the hood is damaged or suspected of leaking, the user must retain the mouthpiece in his mouth at all times. He may not remove it to talk unless it is absolutely necessary.

If a breathing bag is punctured, the user can maintain safe operation by pinching the puncture shut and holding it. If necessary, he can inhale to deflate the bag, as long as he does not inhale more than necessary (to avoid inhaling toxic gases). Detailed PBA operating procedures are contained in reference 31.

AUXILIARY SURVIVAL CHAMBER

There are several units within the Auxiliary Survival Chamber (ASC) that require instruction for use during the time the miners are confined. There are also some general procedures that should be followed to minimize problems and add the security that grows from a regimented and patterned life.

The procedures to be followed upon entry into the ASC are detailed, in flow-chart form, in figure 3-2. These procedures are mandatory in any disaster in which toxic gases are set free, because they offer the only certain means to guarantee a livable atmosphere within the ASC.

Obviously, as soon as it is possible, first aid should be administered to all who need it. Also as soon as possible, attempts should be made to contact the surface.

Figure 3-1. Operating Sequence

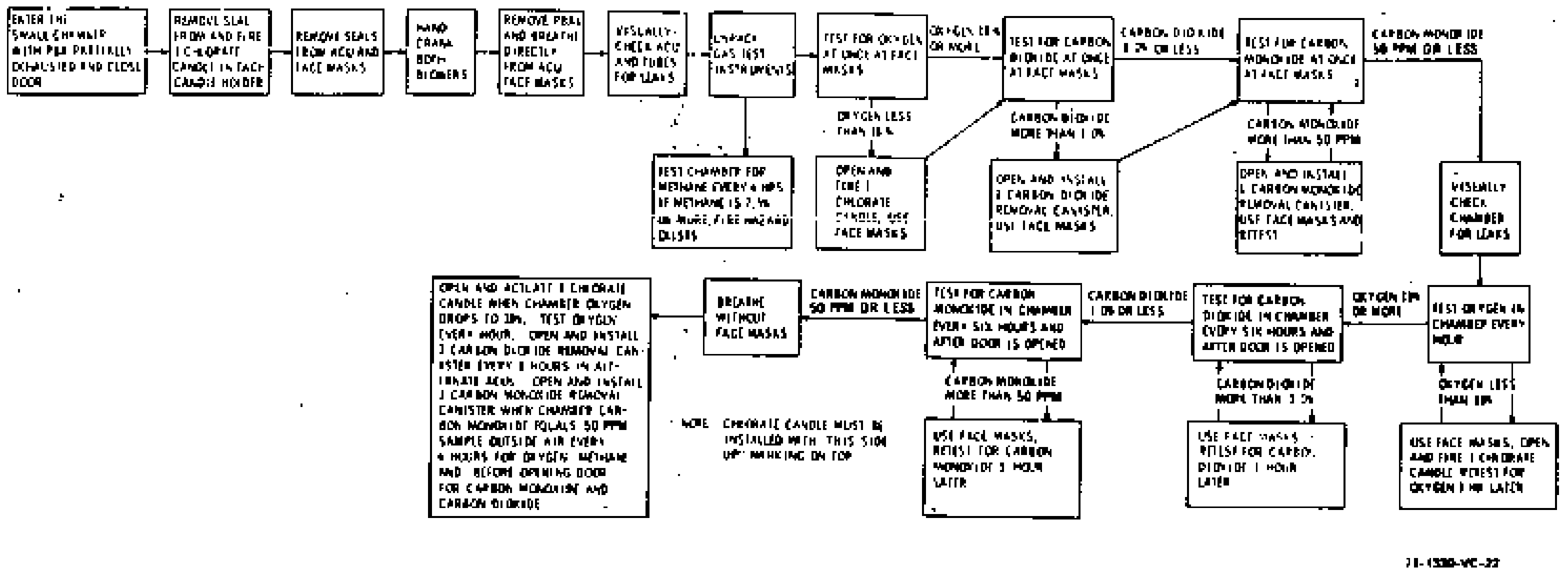

Figure 3-2. Initial ASC Procedures

The group leader establishes the format and routine of life in the ASC when all immediate needs are filled. He assigns monitors and operators to all equipment and designates the frequency of tests to be made and the schedule of rotating assignments. He also sets up a rationing schedule for all consumables. Suggested rations are 2 food packets (1,740 calories) and 2 quarts of water each per day.

Among the tasks that must be assigned on a regular schedule are the following:

a. Change carbon dioxide (CO_2) removal canisters every 16 hours (assuming a 30-minutes-on/30-minutes-standby cycle for each atmosphere conditioning unit (ACU)).

b. Replace carbon monoxide (CO) removal canisters whenever CO in the chamber exceeds 50 ppm. Remove and do not replace when CO level in chamber remains less than 50 ppm for 6 hours.

c. Change chlorate candles whenever oxygen content of chamber drops below 18 percent.

d. Check CO and CO_2 content reading every 6 hours and whenever the door is opened.

e. Check methane gas content every 6 hours and whenever the door is opened. (Fire hazard exists if methane is between 5 and 15 percent.)

f. Check oxygen level every hour.

g. After contact is made with the surface, the listening speaker should be monitored continuously.

h. All occupants of the chamber should be put on a rotating 30-minutes-on schedule for cranking the ACU's.

i. Lighting should be set up so that all 6 lamps are on for 8 hours, 4 lamps for the next 8 hours, and 2 lamps and 1 chemiluminescent panel at a time for the next 8 hours (4 panels are required for 8 hours).

Basic operating procedures for each of the units in the ASC are outlined below. These units are the atmosphere conditioning unit (ACU), oxygen analyzer, gas detector kit, methanometer, and the lighting-power system.

Atmosphere Conditioning Units (ACU)

The two ACU's supplied are identical. They are operated normally in alternating 30-minute shifts. Until the chamber atmosphere is clean, both units are operated continuously, and as often as required thereafter. The time required to scrub CO and CO_2 from the chamber air with both blowers operating is approximately 5 hours (CO) and 2.25 hours (CO_2).

To start the ACU's, the user simply fires the chlorate candle, removes the seals from the CO and CO_2 removal canisters, checks to see that each canister is properly seated, makes sure that the leakage control hose is properly connected, and starts cranking the blower at about 40 turns per minute counterclockwise.

To use the built-in-breathing apparatus, the miner connects the manifold hose to the blower output, removes the plastic containers from all breathing masks, holds the facemask in place, and breathes normally.

Replacing chlorate candles is just a matter of removing the expended one and taking a new one from its container, setting it in place (with "This Side Up" marking on top), igniting it (pull-ring), and closing the burner door (being careful not to damage the spring-loaded pressure pins). Each candle should burn about 1 hour and provide 70 cubic feet of oxygen. Candles should be sequentially replaced in alternate ACU's to ensure uniform oxygen concentration within the chamber.

The CO_2 removal canister is replaced every 16 hours during normal operation. To do this, the miner disconnects the flexible hose, grasps the canister with both hands, and lifts it free. He then removes the sealed end caps from the new one, sets it carefully in place, and attaches the flexible hose. The canister will mate with the ACU from canister top or bottom, either of which is acceptable.

When CO concentration in the chamber exceeds 50 ppm, the CO removal canisters must be replaced. They should be replaced in alternate ACU's. Replacement is simply a matter of grasping the canister firmly in both hands (wearing gloves to avoid possible burns) and lifting it free, followed by opening the new canister and setting it in place. If the CO concentration remains under 50 ppm for 6 hours, the canister should be removed with no replacement. The CO removal canister will fit where the CO_2 canister belongs; therefore, care should be exercised not to confuse the two (CO canister is smaller than CO_2 canister). One CO removal canister will last nominally for 4 hours.

Oxygen Analyzer

The oxygen analyzer supplied in the ASC is a Biomarine Model OA-202, and it should be calibrated daily for best results. To calibrate it, the miner disconnects the oxygen line from the ACU, flows oxygen over the sensor, and adjusts it for 98-percent indication. A squeeze bulb and valve are provided in module 1 of the ASC to draw in outside air for sampling. Operation of the analyzer requires only that it be held horizontal while the air is passing over the sensor. Oxygen content is read directly from the dial in percentages.

Gas Detector Kit

The gas detector kit is a Unico No. 400, and it consists of a pump, a carrying case, tubes for gas tests, a manual, and spare parts, The kit contains 90 tubes for CO tests and 90 for CO_2 tests. Both types of test are conducted in the same way. The pump is used to draw 100 cc of gas (one full stroke of pump handle) through the tube. The tube has a red band at each end to indicate the upper safe limit of gas tested (50 ppm CO, 1.0 percent CO_2). If any part of the indicating stain goes beyond the red band, the gas being tested is at an unsafe concentration. Chamber air is tested directly; outside air is drawn in through the test valve.

Methanometer

A National Mine Service Company Model G-70 Methanometer is supplied in the ASC. It tests chamber air directly and outside air through a tube adapter for the valve in Module 1. To test the air, the miner simply pushes a button; the gas content is read directly from the dial in percentages.

Lighting-Power System

Separate switches for each of the three lines of lights are contained on the front of the battery box. To activate the battery, the miner removes the battery box cover, removes the battery top plate, loosens the pressure control, spreads the cells apart, removes the dummy anodes, fills the battery with water, inserts the real anodes, reassembles the battery and battery box, and makes sure all connections are properly made. After about 30 seconds start-up time to read maximum voltage after activation, he turns on the battery and any lights he wishes. To recharge the batteries, the process is the same as for activation, removing the spent anodes instead of dummies. Care must be exercised in handling wet electrodes since they are covered with caustic potassium hydroxide. New anodes are supplied in the recharging kits, along with polyethylene bags for disposal of the used anodes. The chemiluminescent panels are activated by removing the pull-tab on each panel and kneading the contents.

Waste Disposal

Waste from the portable toilet is held in a heavy-duty polyethylene bag that fits into the pail that forms part of the toilet. These bags should be replaced every 12 hours, tying the used one securely and disposing of it outside the chamber if possible. If the outside atmosphere is contaminated, the bags must be stowed inside the chamber, out of the way as much as possible.

Emergency Procedures

Two kinds of fire extinguishers are supplied; a water type, marked DO NOT USE ON ELECTRICAL FIRES, and a chemical type, marked DO NOT USE INSIDE CHAMBER. Two of each type are supplied; the chemical type just outside the door, the water type just inside. Each is operated by removing a safety pin, rotating a control valve, and directing the spray at the fire.

First aid kits and a Foille burn kit are provided in the ASC. A pamphlet on basic first aid procedures is contained in the kits, but advice on more complex problems can be requested over the communications lines.

Fully detailed operating procedures for the ASC are contained in reference 32, and instructions for each unit are supplied with the unit.

LARGE CENTRAL CHAMBER

There is a variety of equipment within the LCC that must be operated by the trapped miners if they are to survive until they are rescued. For the most part, operation of these units is straightforward, requiring no special skills. In some instances, however, it is best that the operator be at least familiar with the equipment and procedures (e.g., Communications Subsystem equipment). There are also some general procedures that should be followed to minimize problems and add the security that grows from a regimented and patterned life.

The procedures to be followed upon entry into the LCC are detailed, in flow chart form, in figure 3-3. These procedures are mandatory in any disaster in which toxic gases are set free, because they offer the only certain means to guarantee a livable atmosphere in the LCC.

Clearly, first aid should be administered to all who need it as soon as possible, and attempts should be made to contact the surface to instruct them to start the surface ventilating equipment and to apprise them of the general conditions in and around the chamber.

The group leader establishes the format and routine of life in the LCC when all immediate needs are filled. He assigns monitors and operators to all equipment and designates the frequency of tests to be made and the schedule of rotating assignments. He also sets up a rationing schedule for all consumables. Suggested rations are 2 food packets (1,740 calories) and 3 quarts of water per man per day.

There are two modes of operation for the LCC; with surface air and without it. The general procedures for operation without surface air are exactly the same as for the Auxiliary Survival Chamber. The general procedures for operation with surface air are as follows:

a. Check CO, CO_2, methane, and oxygen levels every 3 hours and report conditions to the surface.

b. If the temperature rises above 85°F or gas levels become intolerable, the chilled-water air cooler or atmosphere conditioning unit, respectively, must be started.

c. Set up lighting schedule so that 12 lamps are on for 8 hours, 8 lamps for the next 8 hours, and 4 lamps and 1 chemiluminescent panel for the next 8 hours (4 panels are required for 8 hours).

The equipment in the LCC that may have to be operated is exactly the same as the equipment in the ASC, except for the chilled-water air cooler and sound-powered telephone. The operating procedures are also exactly the same.

Air Cooler

Two men are required to operate the chilled-air water cooler. They sit in tandem on a bicycle-pedal arrangement and pump (as on a bicycle) to run the air cooler. The pedals drive both the centrifugal pump for the water supply and the blower fan for the air.

Sound-Powered Telephone

Operation of the sound-powered telephone requires only that it be picked up and spoken into.

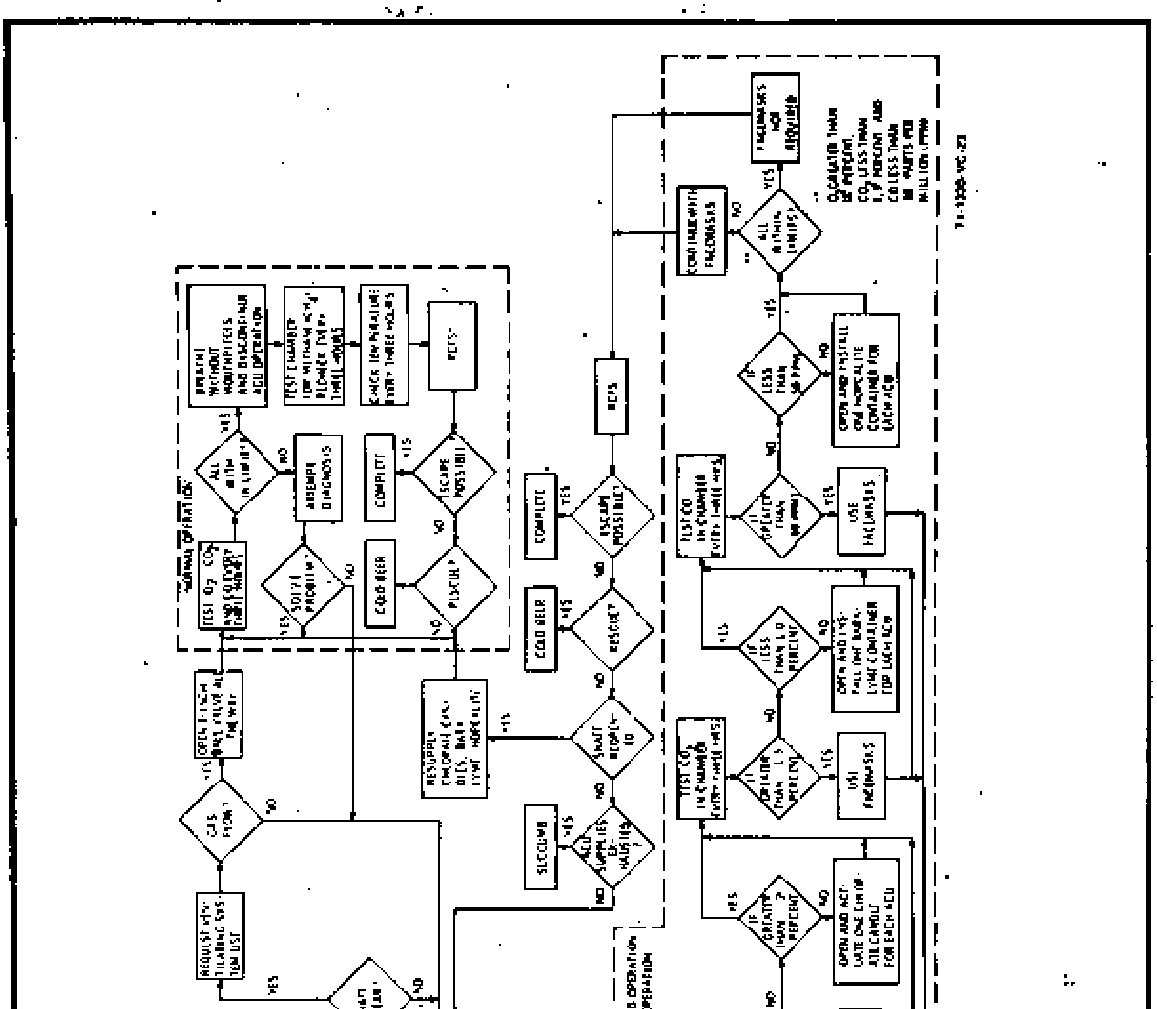

Figure 3-3. LCC Operation Flow Chart

Surface Equipment

In addition to the equipment in the chamber, LCC operation also includes the ventilating equipment on the surface. This operation includes the power junction boxes, a compressor (blower), an air cooler, a heater, a control panel, and an access hatch.

Junction Box

Power for all equipment passes through a circuit-breaker junction box. It must be turned on first to start the other equipment.

Blower

To operate the blower, the user makes sure the blast gate is fully closed and turns on the switch. After about 10 seconds, he opens the blast gate gradually to increase air flow. The air flow velocity must reach 500 fpm to close the air flow switch, which is required before the air cooler or heater can be operated.

Air Cooling Unit

The air cooling unit is turned on with a switch on its compressor. Thereafter it is controlled by a thermostat located in the ventilation shaft air flow.

Heater

The heater is activated by two heater switches that provide settings for 1/3, 2/3, or full heat (turns on 1, 2, or all 3 heater elements). It is then controlled by a thermostat that samples the air in the ventilation shaft.

Control Panel

The control panel requires no operation; it contains three indicators. An ammeter monitors the blower motor current; an air flow indicator lights when air flow reaches 500 fpm; and a thermometer with a sensor just outside the LCC indicates the need for heat or cooling.

All other procedures and equipment are exactly the same as for the ASC. Fully detailed operating procedures for the LCC are contained in reference 33.

SECTION II
TESTS AND DEMONSTRATION

Tests were conducted on parts and components of the Survival Subsystem throughout the program, covering developmental, qualification, pre-demonstration, and demonstration testing. The Personal Breathing Apparatus (PBA) and Auxiliary Survival Chamber (ASC) were the subjects of these tests, because they were the two parts of the Survival Subsystem that constituted deliverable hardware. The Large Central Chamber (LCC) was never actually built or demonstrated, but a great many of the tests conducted with the development of the ASC in mind apply directly to the LCC.

DEVELOPMENTAL TESTS

During the developmental phases of the Coal Mine Rescue and Survival System (CMR&SS) program, testing was conducted on both the PBA and ASC components. These tests included the PBA carbon dioxide removal canister (manned and unmanned tests) and tests of the ASC atmosphere conditioning unit (manned and unmanned), instrumentation, and life support supplies.

PBA Carbon Dioxide Removal Canister

In all, 7 manned tests, 2 bench tests, and a heat transfer analysis were conducted for the CO_2 removal canister, with changes incorporated along the way. The established test parameters were as follows:

a. Pressure drop across the canister less than 2.0 in H_2O at a flow rate of 85 SLPM/air or oxygen.

b. No lithium hydroxide (LiOH) dust penetration through filter before or after vibration testing.

c. Adequate heat transfer from canister while being worked at CO_2 absorption rates equivalent to table 4, test 4 of reference 5.

d. No CO_2 channeling through LiOH bed after vibration testing.

Initial calculations indicated that 1.36 pounds of LiOH were required for a 1-hour operating life; however, this did not fill the canister to the design level (1 inch from open end). LiOH was added to bring it within the 1-inch area, bringing the total weight to 1.76 pounds. Three layers of number 12 Air-Mat glass cloth filter were added, the canister was closed and blown through with dry air at 85 SLPM. The pressure drop across the inlet and outlet parts was 1.5 inches of water. Therefore, even with the excess of LiOH, the 2.0 inches maximum drop was not exceeded.

In the dust test, the setup shown in figure 3-4 was used, with a fresh piece of number 12 Air-Mat filter over the outlet part. The canister was purged with 85 SLPM dry nitrogen at the inlet for 3 seconds. The used

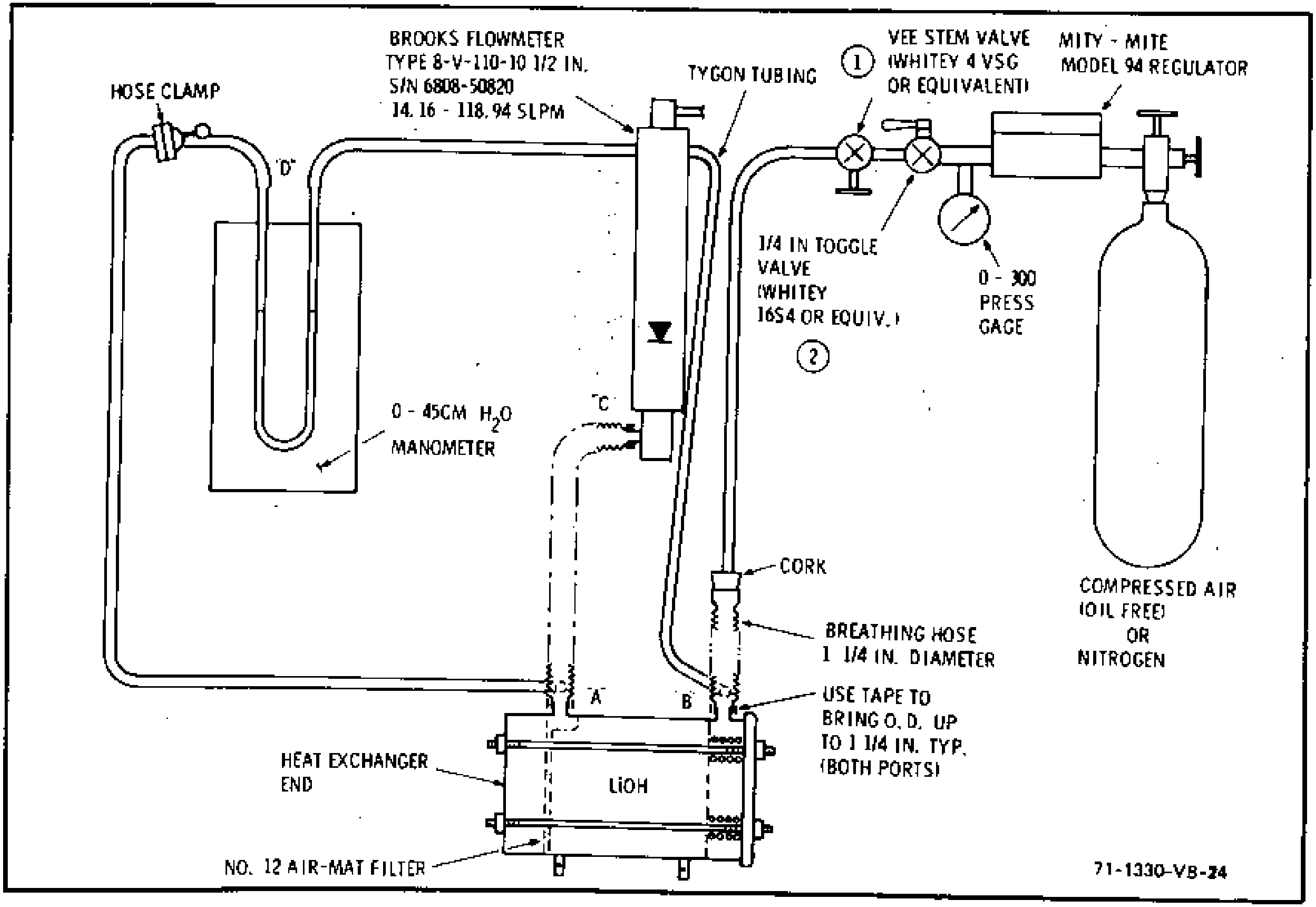

Figure 3-4. Dust and Pressure Drop Test Setup

filter and a new piece of filter were subjected to titration pH analysis. Both consistently registered the same; therefore, the filter design was deemed acceptable.

The next test was a manned test of the canister. Because the final breathing bags, man/apparatus interface, and chlorate candle were not delivered yet, these items were simulated with in-house comparable components. A candle simulator was built to the same configuration as the deliverable unit and was fitted with two electric-resistance heaters which would bring the surface temperature up to and beyond 350°F. The breathing bags consisted of two rubber anesthesiology bags and man/apparatus interface was a standard scuba-type mouthpiece. Aside from these developmental modifications, the experimental setup was as shown in figure 3-5, with O_2 and CO_2 being monitored continuously and then being returned to the system. Breathing resistance and gas inhalation temperature were also continuously monitored. Canister wall temperatures and LiOH bed temperatures were spot-checked. The test subject was simulating the work schedule of reference 5 by riding a bicycle ergometer throughout the test at various kilopound settings.

The data in figure 3-6 (Runs 1, 2, and 3) on inspired gas temperature vs test duration show that the canister as then constructed possessed inadequate heat transfer characteristics. The canister was then modified for runs 4, 5, and 6 to produce acceptable results.

The first man test ran for 33 minutes and 45 seconds and was aborted due to the inhalation temperature exceeding 115°F.

The second man test was run the same way as the first except that the candle simulator was not energized. This run lasted 34 minutes and was aborted also due to the inhalation temperature exceeding 115°F. Comparing the two sets of data showed that the heat generated by the candle simulator contributed little to the overall heat load of the canister and that the exothermic reaction of the LiOH and the conductivity of same had to be determined.

The third set was conducted like the second except that thermocouples were strategically imbedded into the LiOH charge. This test lasted 40 minutes. The data showed center bed temperatures as high as 270°F while canister wall temperature remained typically 180°F. By contrast, the optimum bed temperature range under PBA input conditions had been calculated at 113-149°F.

From this data, heat transfer calculations were run which established thermal conductivity of the absorbent bed at 0.465 Btu/hr/ft/°F. From this, further calculations determined that, by internal addition of copper fins, bed temperature could be maintained much closer to the optimum range.

For the fourth test, five 0.21-inch copper fins were installed axially in the canister, 0.833 inch apart along the 8-inch side of the canister.

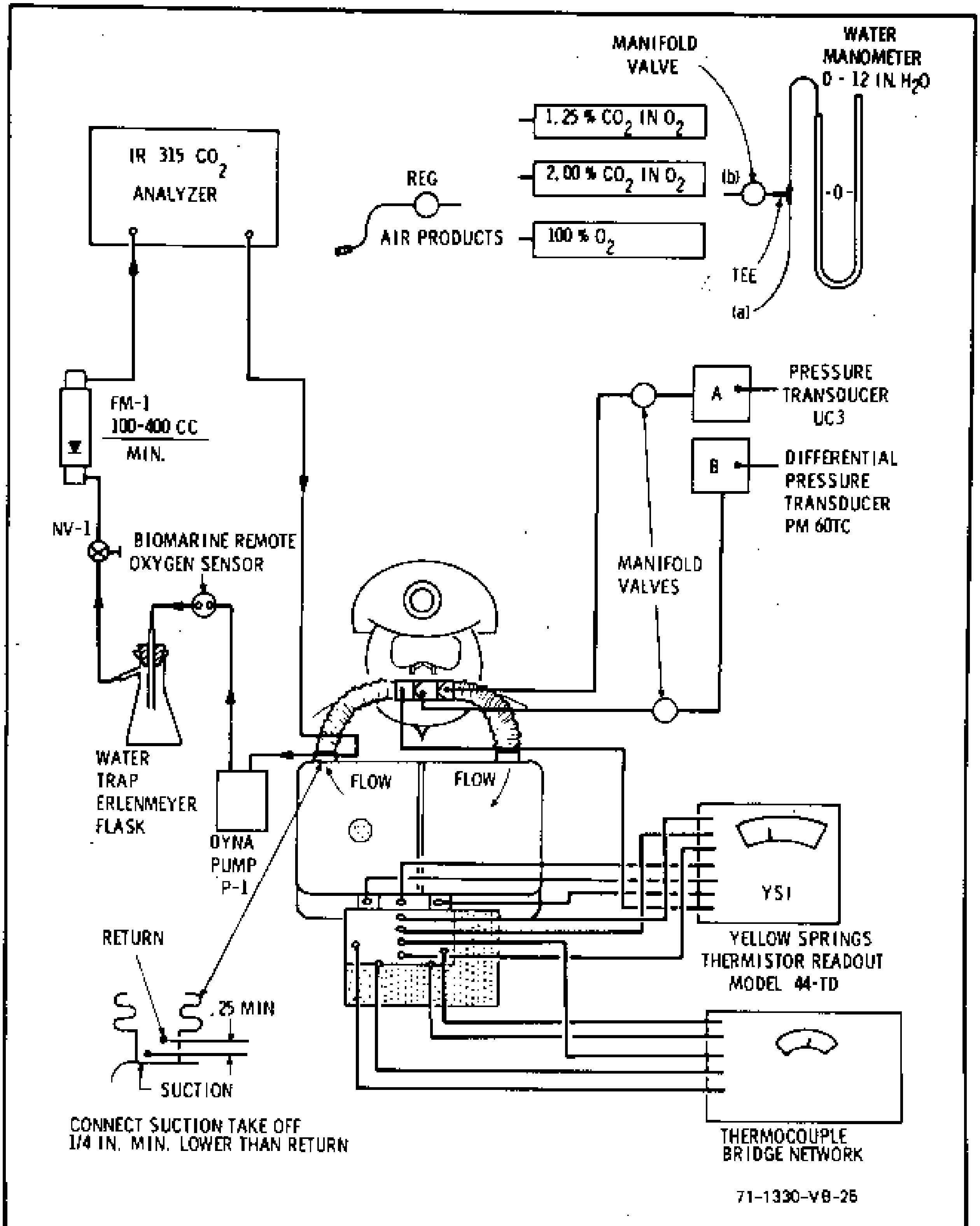

Figure 3-5. Manned Test Setup

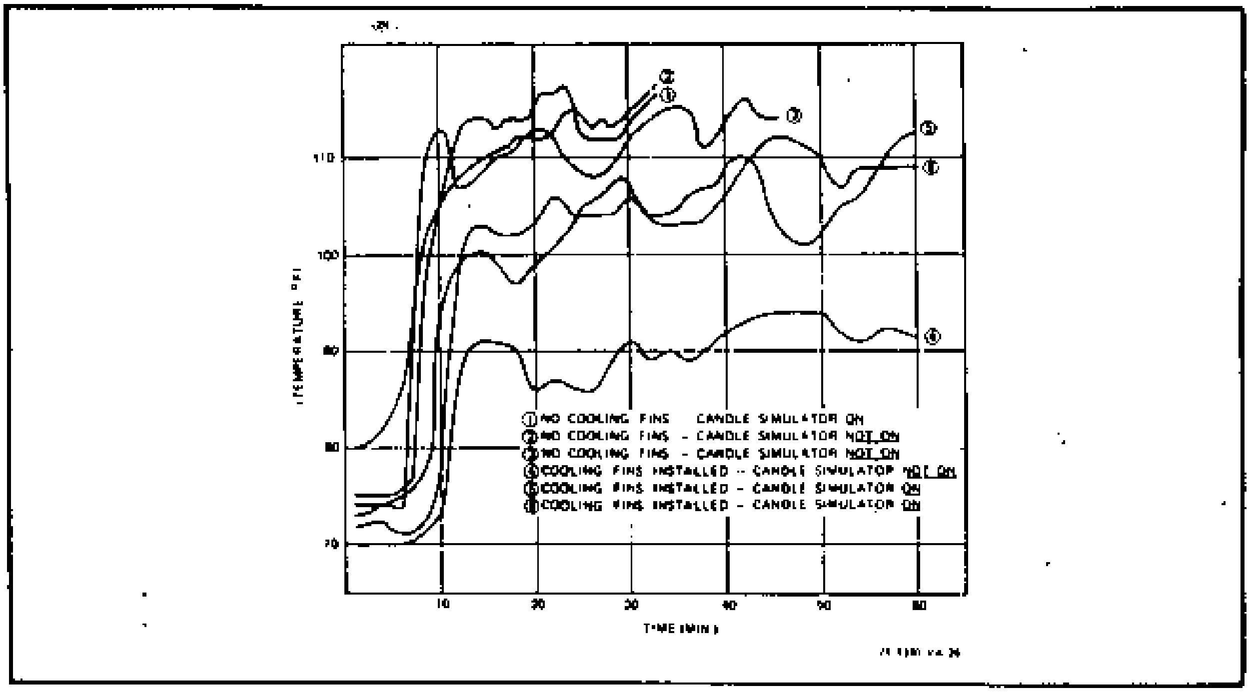

Figure 3-6. Inspired Gas Temperature vs Canister Finning

Thermocouples were imbedded in the LiOH bed, and a fan was located 15 feet away and turned on during work periods. Otherwise, the test was run like test 3, and it lasted 60 minutes. A mean LiOH bed temperature of 187°F was achieved, and breathing air was 94°F. The fifth test was like the fourth, except the simulated candle was energized. The inspired gas temperature was 112°F. The sixth and final test was run like the fifth, with equally good results.

Further evidence that the internal cooling fins did indeed maintain bed temperature much closer to the optimum operating range was produced from the CO_2 analyses. For tests 1-3 (no fins), CO_2 breakthrough occurred at a 1.0-percent level within 30-40 minutes into the test. By contrast, tests 4-6 (with fins) maintained CO_2 below 1.0 percent for the entire 60-minute duration.

As a result of these tests, the final design used five copper fins 0.030 inch thick, spaced 1 inch apart along the 8-inch side of the canister.

Finally, packed canisters were vibrated according to MIL-STD-810 Method 514, Procedure X, Figure 514-6, Curve AB modified. They were vibrated in all three X, Y, Z axes. Z was up and down, X was sideways along the short axis, Y was longitudinally along the long axis. The input acceleration in all three axes was from 2 to 5 G's wherein the frequency ranged from 2 to 500 Hz. The fundamental reasonant frequency at which the canisters had the highest output acceleration was 115 Hz and 36 G's. This was noted to exist in the X axis. Following vibration testing, the canisters were X-rayed, dust tested, and CO_2 tested. The X-rays showed no LiOH settling, and the dust tests proved negative. Lastly, 2.25 percent CO_2 in O_2 was caused to flow through the canisters at 300 cc/min for 6 minutes. The effluent gas was monitored with a Beckman 315 CO_2 analyzer and read zero CO_2, indicating no breakthrough had occurred.

ASC Units and Life Support

Both manned and bench tests were run for the ASC atmosphere conditioning unit (ACU) components and gas measuring devices. The ACU components were tested with air of known humidity, volume, and CO and CO_2 concentrations. The measuring devices were calibrated with certified calibration gases. The oxygen from the candles was analyzed by mass spectrometry and gas chromatography to ensure proper composition.

The oxygen analyzer was calibrated at 21 percent and tested with nearly 100-percent oxygen gas. All indications were within 2 percent. During manned tests, it was found that the analyzer had to be calibrated and used in the horizontal position to maintain 2-percent accuracy, but this is an acceptable constraint.

The gas detection kit pump and test tubes were bench tested with certified calibration gases and performed acceptably (± 0.1 percent CO_2 and ± 25 ppm CO).

The CO removal canister for the ACU removed all but 2 to 50 ppm CO from inlet gas (17 cfm) containing 1000 ppm CO at 70-percent relative humidity for 5 hours in the bench tests. This unit was approved for a 4.5-hour usage life in the ASC.

The CO_2 removal canister removed all but 0.06 percent CO_2 from inlet gas (17 cfm) containing 1 percent CO_2 for 8 hours. This provided a large safety factor in the approval of this unit for 8 hours use in the ASC if operated alone and for 16 hours use if the load is shared by two ACU units running simultaneously (recommended procedure).

The oxygen-generating candles were bench tested at three separate locations; the vendor and two Westinghouse facilities. In each case, the candles performed according to requirements, and the candle holder, which conducts heat away from the candle to prevent fire hazards, also worked well. This unit was approved for use in the ASC.

Two manned tests were conducted; one with 8 men for 8 hours and one with 2 men (and 0.073 cfm injected CO_2) for 1 hour. For these tests, one of each of the supplied instruments was used, along with 1 chlorate candle, 1 CO removal canister, and 1 CO_2 removal canister.

During these tests, some changes and constraints were included in the equipment and procedures. Minor packaging modifications and changes to the operating instructions for the gas detector kit were made for simplification. After the changes, an unskilled operator can easily use the kit after reading the new instructions. The hand-cranked blower for the ACU seized after 4 hours operation; the seized bushing and mounting was modified, with no further problems.

Throughout the manned tests comments from the participants were noted, and each one completed a detailed questionnaire at the finish.

All instruments performed well, and the test subjects found each unit easy to read and simple enough for an untrained operator to use. The atmosphere conditioning units were fully acceptable during these tests (after seized bearing was replaced).

Food and water rations were found generally palatable and adequate for use in the ASC. The portable toilet was also acceptable, but several test subjects recommended the use of a vapor seal over the top.

Chamber temperature and humidity were accepted as livable by all test subjects. It became evident that temperature depended directly upon activity levels in the chamber, but the chamber is fully acceptable for outside temperatures between 46 and 71°F.

As a result of these tests, all tested units and procedures were accepted for use in the demonstration tests.

PBA QUALIFICATION TESTS

The Personal Breathing Apparatus underwent complete qualification testing. There were 5 of these tests run, monitoring inspired gas temperature, total pressure, and the differential pressure at the mouthpiece. The general test setup was as shown in figure 3-5, except that no thermocouples were used in the CO_2 removal canister.

The first test lasted 60 minutes. At 58 minutes, CO_2 reached 0.4 percent (at canister effluent), and inspired gas reached 120°F at the 1-hour point. The eyepiece fogged after 15 minutes but cleared about 5 minutes later.

The second test was run like the first, but it was aborted at 38 minutes, because the test subject felt nauseous. The temperature of the inspired air was 115°F, and the CO_2 concentration was 1.5 percent. Examination revealed that the inhalation check valve had leaked, allowing CO_2 back into the breathing air.

The third test was aborted, because the chlorate candle burned through the generator housing 12 seconds after start. Dissection and X-ray showed that the molten first fire mix and initiator cone had extruded into the Bouchon end of the generator housing. Rework of the design eliminated possible recurrence.

Test 4 was also aborted, at 19-1/2 minutes, because the inspired gas reached 125°F, due to inadequate environmental control. Test 5 encountered the same problems as test 4 even though an attempt to provide room air circulation at 2 mph air flow had been made. By an examination of the room, it was determined that the PBA under test happened to be located in a stagnant air area. After the subject was relocated to a 2-mph area (without interrupting his work program), the temperature of the breathing air receded. Mean inspired gas temperature for the remainder of the test was 117°F. Table 3-1 shows the tabulated record of test 5.

ASC PRE-DEMONSTRATION TESTS

Before formal demonstration of the equipment, the Auxiliary Survival Chamber underwent two series of leak tests, testing the two bulkheads and three of the six modules at a time. The first tests were to determine seal effectiveness, and the second tested the effect of a 3/8-inch hole in a module.

For these tests, the 3-module ASC was arranged as shown in figure 3-7 (modules 1, 2, and 6 were used together, and 3, 4, and 5 were used together). The test equipment used was set up as shown in figure 3-8.

For the internal pressure tests, the internal pressure of the joined modules was set at 1 psig (15.7 psia), valves were closed, and both pressure and time were recorded until the pressure reached 0 psig.

For the vacuum tests, the internal pressure was set as low as the pump would take it (-1 psig, approximately), the valves were closed, and both pressure and time were recorded until the pressure reached 0 psig.

In general, the units performed acceptably. The worst leaks occurred at the roof joints and hinges, "duck seal" was applied at these points. The 3/8-inch hole increased the leakage rate by a factor of 6 for the internal pressure test and a factor of 2.5 for the vacuum test. More specific test data are tabulated in table 3-2.

DEMONSTRATION TESTS

Demonstration of the Survival Subsystem took place in February 1971, at the U.S. Bureau of Mines Experimental Mine at Bruceton, Pennsylvania. Equipment and logistics problems were all handled according to a detailed operations plan. These included fitting the test chamber for the instrumentation, procuring all materials, arranging for shipping and manpower, summary training and medical exams for test subjects, planning data collection, and preparing the test sites.

The tests were conducted in two parts. The first part was to demonstrate portability and performance of the structure and seals of the Auxiliary Survival Chamber, and the second part was to prove out the life support equipment, accommodations, and furnishings. Included in the structural integrity tests was a series of 6 gas-shot type explosions. Portability was graded on the time and manpower required to tear down, move, and set up the chamber.

Throughout the tests, safety precautions were observed. Sound-powered and direct phone lines were included in the test chamber, and a medical office was manned at all times by a qualified physician. First aid materials were available at test sites at all times, including resuscitation equipment.

The portability and performance tests were conducted in one mine room, and the blast tests were conducted in a crosscut 250 feet from the explosion point (see figure 3-9). All appropriate power, tools, and equipment were available at each site for the tests to be conducted.

TABLE 3-1
LOG OF A PBA QUALIFICATION TEST PLAN

2/5/71

Elapsed Time (Min.)	CO_2%	O_2%	Inhalation Gas Temp. (°F)	Room Temp.	Comments
3	.0	62*	75	60	Start test 1.46 PM
5	.0	69	75	58	(Resistance over 2.5 in/water)
8	.0	72	79	56	
10	.0	73	85.5	56	Helmet fogged
12	.0	73	115	56	
14	.0	73	120	55	
16	.0	76	122.5	55	
18	.0	76	125	56	Eyepiece fogged
20	.0	70	118	56	Moved subject closer to door
22	.01	70	117	55	
25	.0	78	114	56	(Fanned test subject)
28	.02	82	105	52	
30	.01	84	110	52	
32	.03	82	120	54	
35	.03	77	118	50	
37	.04	74	120	54	(Fanned subject)
40	.06	74	119	52	
41	.08	74	121	52	(Fanned subject)
45	.06	72	115	54	Stop
47	.06	77	117	50	(Eyepiece not fogged, just watery)
50	.05	81	118	50	
52	.13	81	118	50	(Fanned subject)
55	.24	76	110	52	
57	.50	73	114	52	(Fanned subject)
59	.86	73	116	50	Candle out.
60	.10	67	120	50	

* Nitrogen due to leakage in sampling system.

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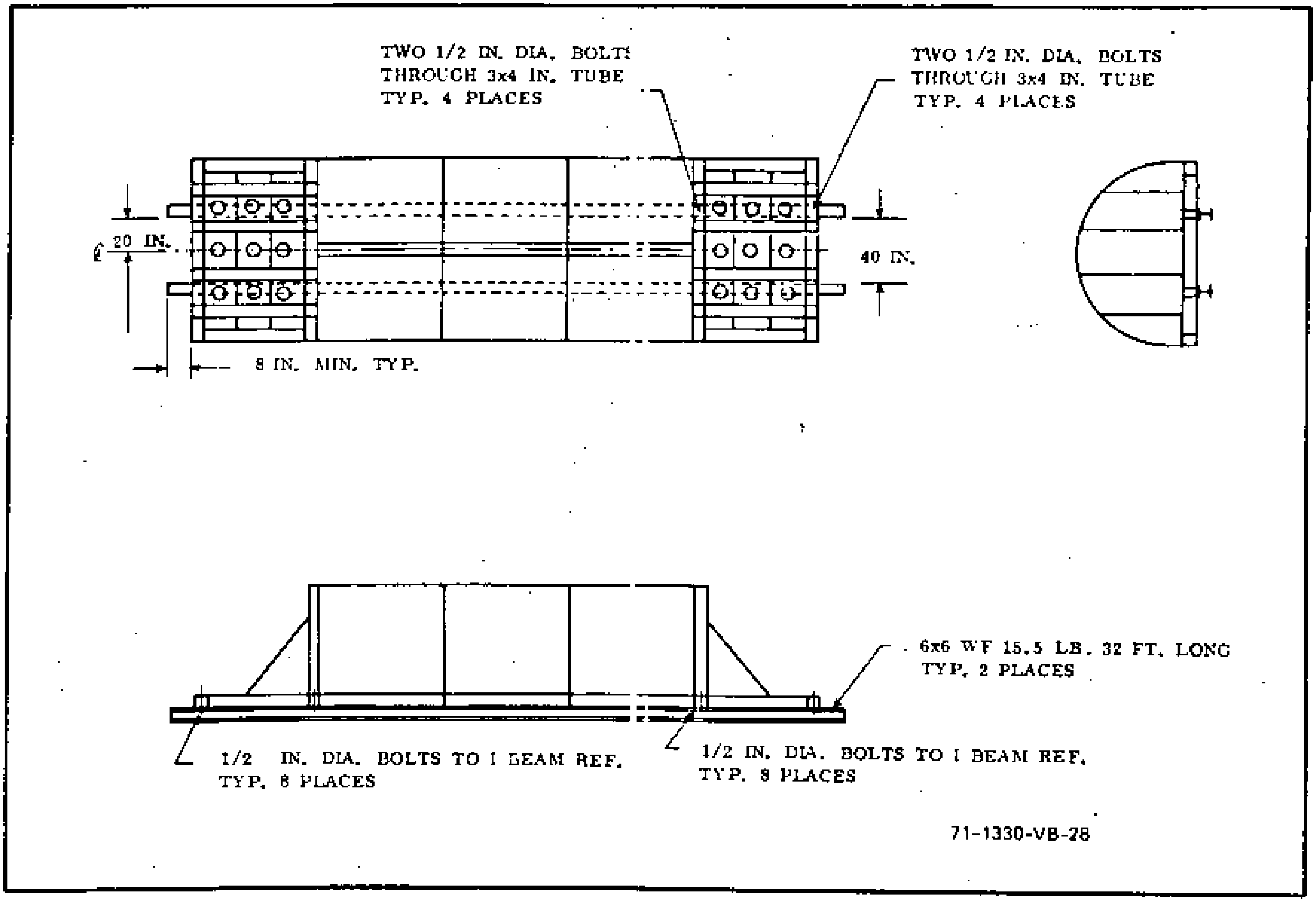

Figure 3-7. Tie-Down Arrangement for ASC Leak Tests

TABLE 3-2
ASC LEAK TEST DATA

PRESSURE		LEAK RATES (CU FT/MIN)					
		INTERNAL PRESSURE			VACUUM		
CM (H_2O)	PSIG	With Plug	Without Plug	Without / With	With Plug	Without Plug	Without / With
70	.986						
68	.957	8.46					
66	.929	6.77					
64	.901	6.17					
62	.873	6.77	54.14	8.0			
60	.845						
58	.817	6.77	45.11	6.7			
56	.788	5.21					
54	.760	4.84	19.29	4.0			
52	.732	5.21					
50	.704	4.50	45.11	10.0			
48	.676	4.50					
46	.648	3.76	22.57	6.0	33.84		
44	.620	3.99					
42	.591	3.76	27.07	7.2	33.84		
40	.563	3.99					
38	.535	3.38	16.92	5.0	15.02		
36	.507	3.08					
34	.479	3.08	19.32	6.3	45.01		
32	.451	2.81				27.07	
30	.422	2.81	15.02	5.3	22.57		
28	.394	2.61				33.84	
26	.366	2.71	16.92	6.3	19.32		
24	.338	2.27				27.07	
22	.310	2.06	15.02	7.3	15.02		
20	.282	2.17			11.27	22.60	2.0
18	.253	1.90	10.42	5.5	9.68	16.92	1.8
16	.225	1.69	11.27	6.7	8.46	16.92	2.0
14	.197	1.46	8.46	5.8	8.46	13.54	1.6
12	.169	1.42	11.27	7.9	6.16	16.92	2.7
10	.141	1.29	6.16	4.8	5.65	11.27	2.0
8	.113	0.95	6.77	7.1	4.50	11.27	2.5
6	.084	0.91	5.21	5.7	3.76	9.68	2.6
4	.056	0.64	3.99	6.3	2.50	6.77	2.7
2	.028	0.47	2.94	6.25	1.32	3.99	3.0
1.0	.014	0.30	1.90	6.3	0.58	2.27	3.9
.5	.007	0.17	0.68	4.0	0.20	0.58	2.9
0	0						

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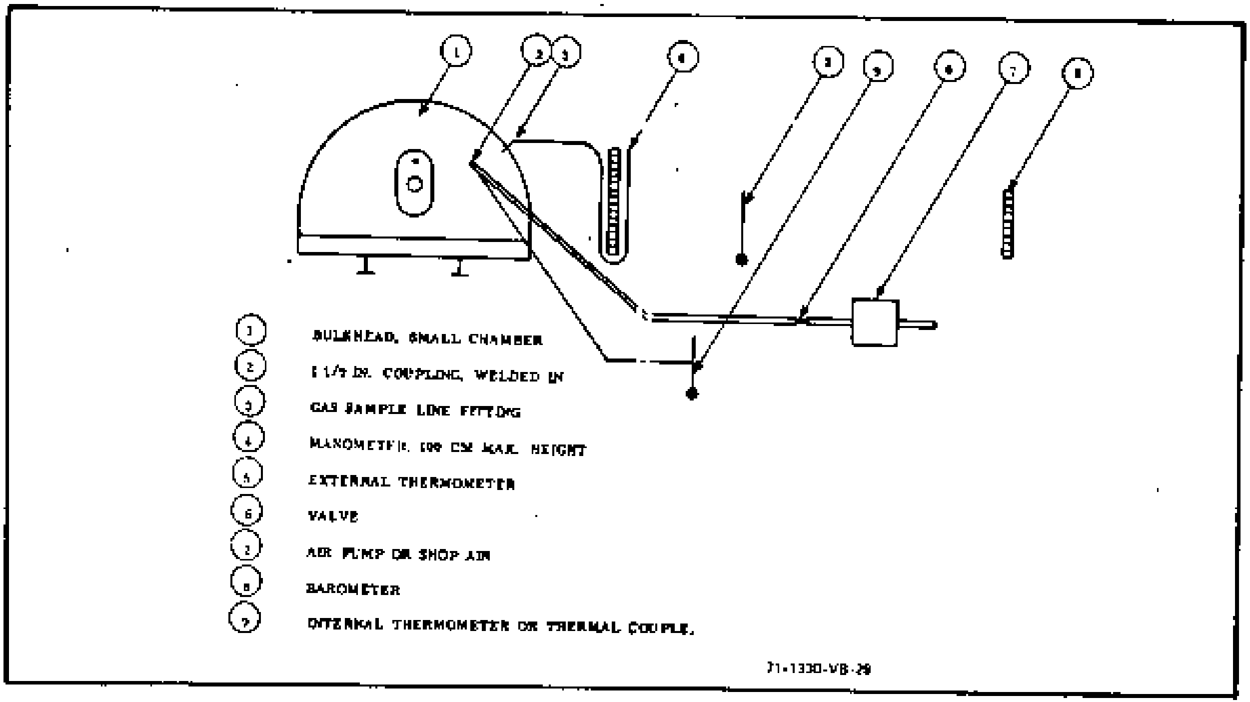

Figure 3-8. Leak Test Equipment Setup

Data collection was accomplished in several ways, including written observances, photography, tape recorded debriefing sessions, and strip chart recordings of such data as thermistor output, strain gage indications, and pressure and motion transducers.

Portability Tests

The basic procedure for the portability test is outlined in table 3-3, which includes estimates of the number of men required for each operation and the time it will take. At the start, bulkhead number 1 and module number 1 were on wheels, everything else was on blocks. The area was measured, a site was selected, and the centerline was marked with string on the roof.

Although it is possible to erect the ASC one module at a time, efficient manpower use dictates that some steps overlap. The total time required for assembly was 10 hours and 25 minutes, minus 1 hour and 37 minutes for breaks (8 hours and 58 minutes working time). Of this 3 hours and 30 minutes were spent installing seals between module 6 and the bulkhead. Therefore, ordinarily, 5 to 6 hours is a reasonable estimate for 6 men to assemble the ASC, not including installation of seals, floor leveling, and floor bolting. Much of the problem with the seals was due to the material used, which was not elastic and pliable at mine temperatures.

Disassembly of the ASC was a straightforward effort, taking 6 men a total working time of 3 hours and 57 minutes. As is the case for assembly, disassembly can be done by 4 men, but the other 2 provide a safety margin.

Six men can push a module on wheels but it required a great effort and a perfectly flat and level surface, such as that provided in the test area which would not exist in a normal mine. However, winches can be used as illustrated in figures 3-10 and 3-11.

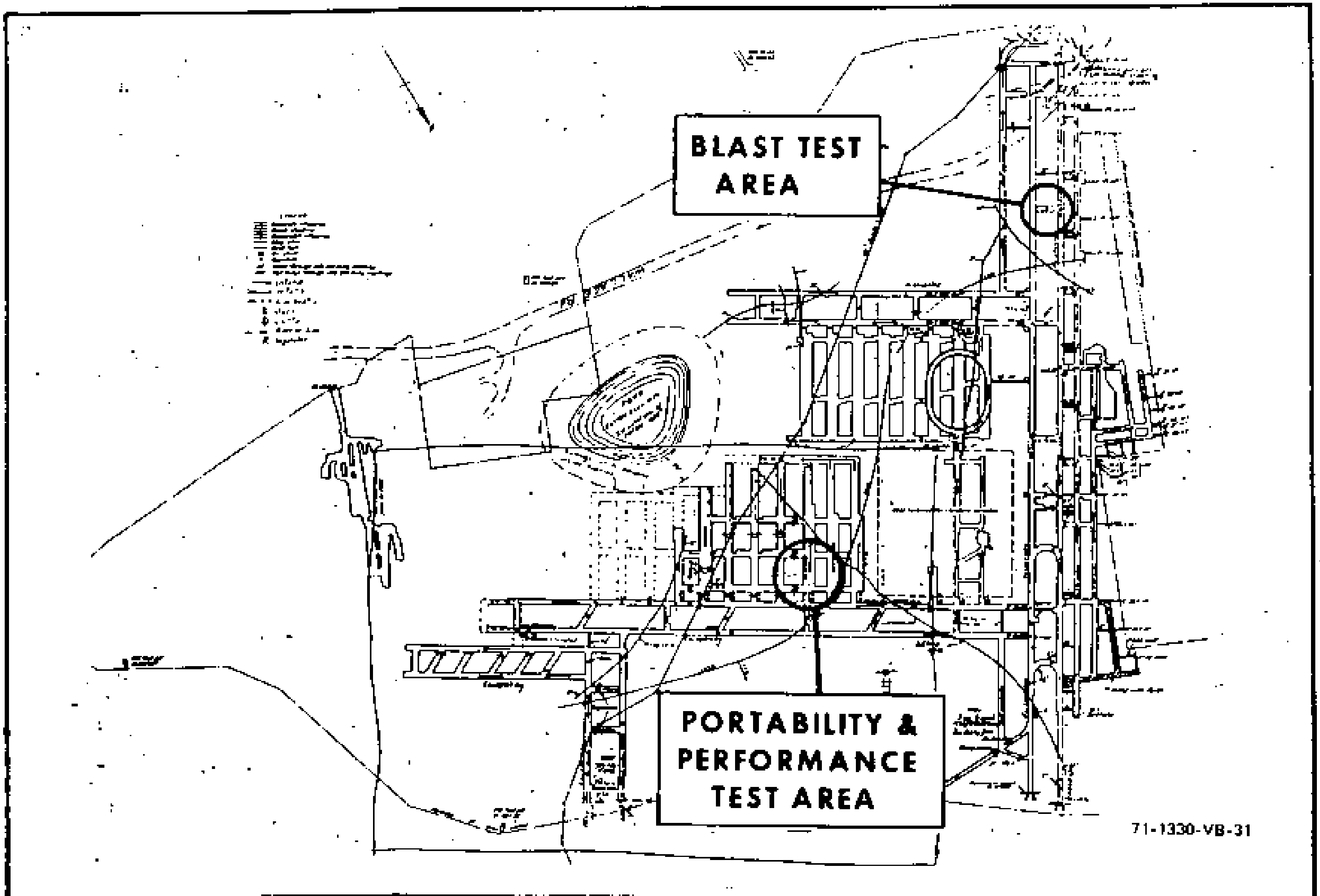

Figure 3-9. Demonstration Test Site

TABLE 3-3
PORTABILITY TEST PROCEDURE

Step	Procedure	Time Required (Minutes)	Men Required
1	Install roof jack on the bulkhead/module centerline in the vicinity of the intended location of the unit.	1-2	2
2	Use mechanical/pneumatic jacks to raise the bulkhead/module to install the wheels and remove the blocks.	5	2
3	Hang comealong from the roof jack.	5	1
4	Connect comealong cable to bulkhead/module with shackle and winch unit into approximate position.	8-15	2
5	Rotate bulkhead/module 90 degrees to proper orientation with previous unit.	2	4
6	Remove roof jack installed in Step 1. Install two roof jacks adjacent to the sides of the previously positioned unit.	2	2
7	Remove bulkhead/module wheels using mechanical/pneumatic jacks. Use pry-bars to steady the unit while on the jacks and to raise the unit momentarily when removing the jacks. Erect the module.	5-8	6
8	Install comealongs on the two roof jacks and connect to shackles at either side of the bulkhead/module. With one man inside the unit guiding comealong operators, winch the unit into final position.	5-8	4
9	Install seals. Use prybars and wedges to level bulkhead/module if fine adjustment is required.	(refer to text)	6

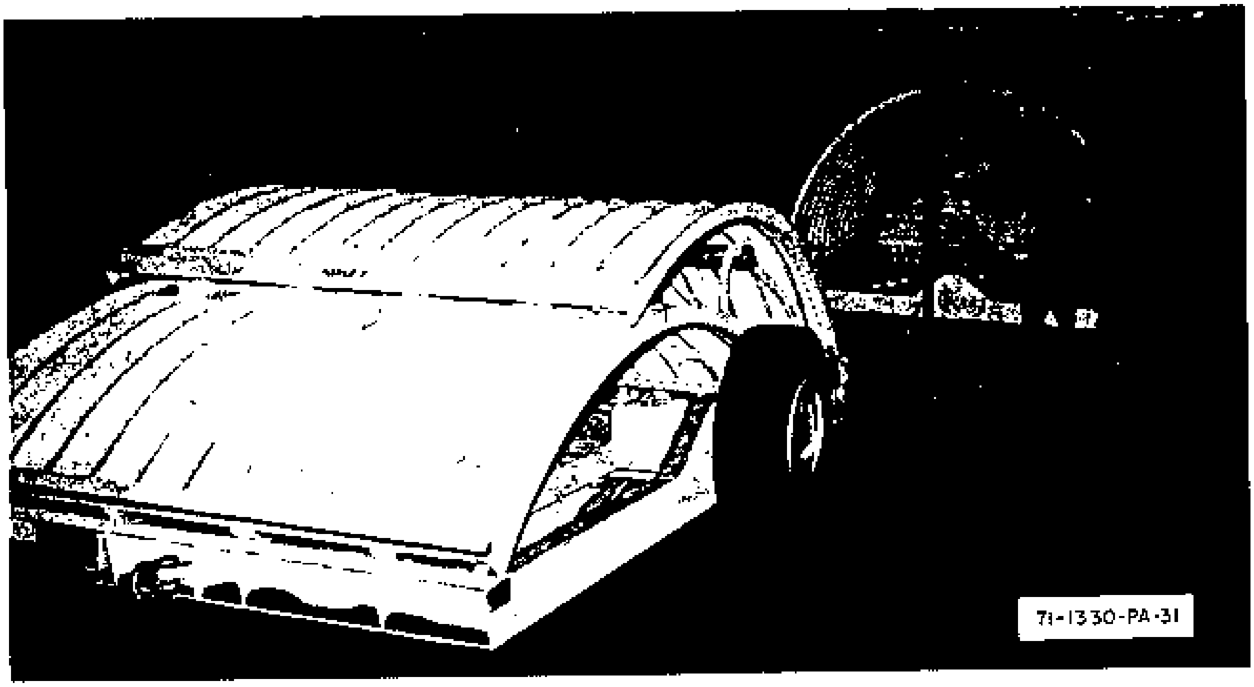

Figure 3-10. Module Pulled by Single Comealong

Figure 3-11. Winching Modules Into Position (Module Pulled by Comealongs Mounted to Roof Jacks)

The drilling and floor bolting were accomplished only on the chamber used for the blast tests. Total time required, minus breaks, was 10 hours and 28 minutes. Average drilling time for a single bolt hole was 11 to 15 minutes. The drilling can be handled by 2 or 3 men, but all 6 are required to drive the bolt home after the resin packages are inserted. Average time to drive home a bolt was 2 to 4 minutes.

Combining times gives a total of 17 hours and 15 minutes, to which must be added seal installation, movement, and floor preparation times. With proper training 6 or 7 men should be able to complete the operation in 24 hours. A module being erected is shown in figure 3-12 and 3-13 shows method of installing ASC seals.

Performance Test

The purpose of the performance test was to demonstrate the life support capabilities of the Auxiliary Survival Chamber. It was originally scheduled to last for 5 days, but based on the results of the pre-demonstration tests, it was decided that the test could be adequately conducted in 2 days. All participants were given a medical and psychological examination before starting the test, and they were made generally familiar with all equipment.

A test stand was set up 20 feet from the chamber, from which oxygen and carbon dioxide levels in the chamber, chamber temperature, and temperature around the chamber were monitored. Phone connections with the chamber were also maintained here. Emergency exit provisions were also included for safety.

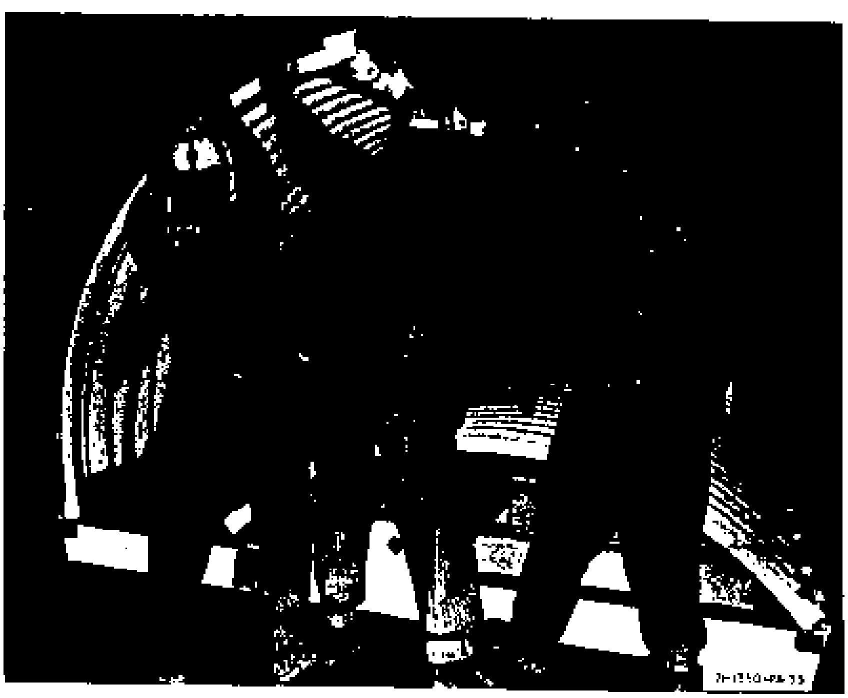

Figure 3-12. Erection of Module No. 3

Figure 3-13. Installation of Seals

Participants worked 8-hour shifts in groups of 5. The entire group of 15 volunteers (8 from Westinghouse, 7 from Bureau of Mines) entered at 9:15 the first morning and immediately set up regular procedures according to instructions (refer to Chapter 3). One group is shown entering module in figure 3-14.

A chlorate candle was installed in one atmosphere conditioning unit each time the oxygen level neared 18 percent. Seven different men tried this installation. In all, 9 candles were used, 6 of which ruptured the blow-out plugs, allowing oxygen to flow freely into the chamber instead of through the filter bed and circulation hose. This produced a slight chlorine odor. Dangerous levels of chlorine were not detected by chromatographic tube analysis, however, either within the chamber atmosphere or in the candle exit gas flow. Deterioration of the candle filtration system is the suspected source of this problem and should undergo re-design.

A bearing on the hand-cranked blower seized, because some metal particles had jammed between a retaining ring and a hub. The blower was disassembled to clean the bearing and add silicone lubricant. The crank still worked hard; so, axle grease was requested and used, and no further problems were encountered.

A leak in two cells of the battery was noted while changing anodes. The leak continued throughout the test with no permanent effect to the lighting.

Oxygen and CO_2 readings in the chamber were compared with those taken at the test stand, and all equipment proved usable. The accuracy of the

Figure 3-14. Test Group Entering ASC

oxygen analyzer in the chamber was not within the ± percent limits, but this is felt to have been caused by unit damage.

The CO and CO_2 removal canisters for the atmosphere conditioning units were found easy to install and use, and they performed without trouble throughout the test. The built-in-breathing apparatus was tested by eight participants, four of whom did so while lying in bunks. Intelligible communications presented no problem. None of the men noted any breathing difficulties, even when all men tried breathing deeply simultaneously to simulate a high air flow.

Participants in bunks during performance test are shown in figure 3-15 while figure 3-16 shows the ASC interior from hatch and oxygen supply system.

The food was rated as good as could be expected. One man experienced headaches that he attributed to lack of protein. The cardboard boxes the food packets are contained in became saturated with condensation from the walls and floor.

Six Nomex blankets were supplied, but nine additional blankets were added, because the high humidity and the average chamber temperature of 67°F made it quite chilly for sleeping. Blankets were also used as pads to ease the discomfort experienced in operating the hand-cranked blower.

When the test ended, each man was debriefed to obtain his immediate reactions to the life support capabilities of the chamber. These comments are listed in tables 3-4, 3-5, and 3-6.

Figure 3-15. ASC Interior During Performance Test

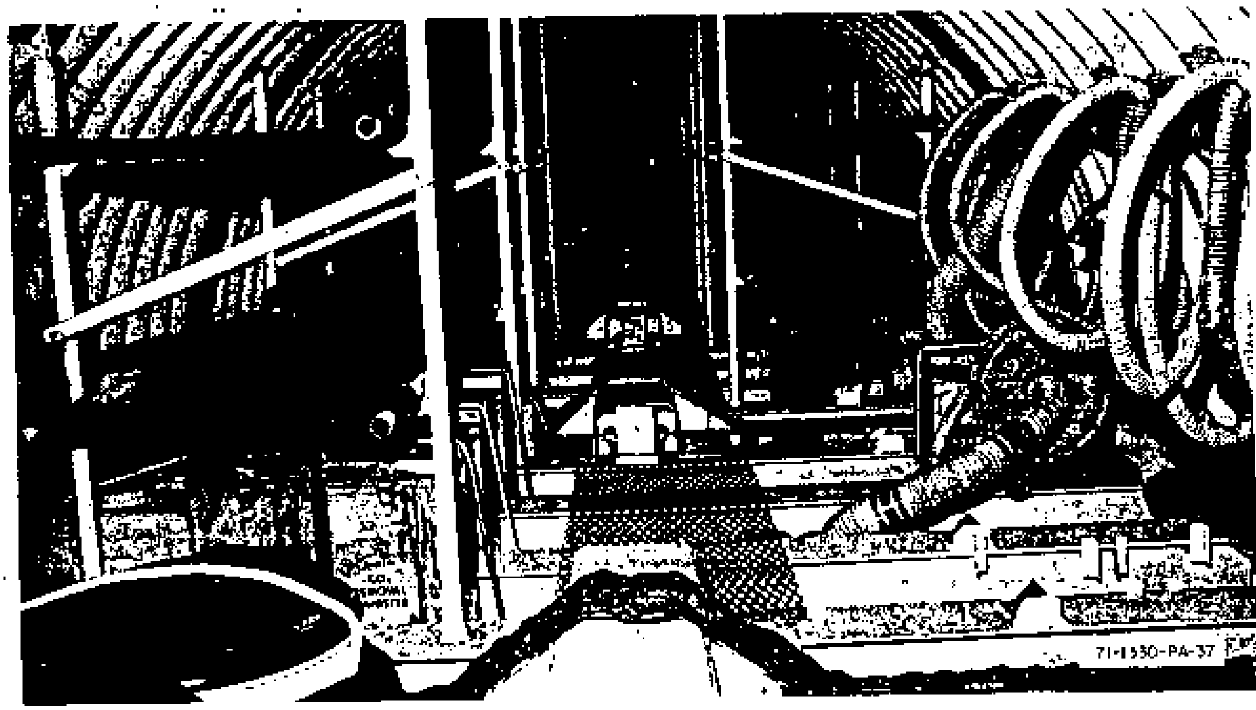

Figure 3-16. ASC Interior from Hatch

TABLE 3-4
DEBRIEFING SUMMARY

TEST SUBJECT	DUTIES	BATT. OPS.	ACU CANISTER	CHLORATE CANDLE	MECHANICAL HAZARDS	CHAMBER LIGHTING	GAS ANALYSIS
1	Shift leader	No participation	Easy	Straightforward	Bunk bars	Adequate	Rel. easy
2	Shift leader	No participation	Very easy	Modified holder	Wheel mounts	Adequate	B–M O_2 inaccurate
3	Blower; readings	No participation	Easy	No problems	None	Adequate	Simple
4	Shift leader	No problem	No trouble	Plugs blew	None	Very adequate	B-M unsatisfactory
5	Blower, readings	No participation	No problem	No problems	[illegible]	Adequate	Pretty adequate
6	Blower; readings	No participation	No problem	Quite adequate	Wheel mounts	Very Adequate	Adequate
7	Chlorate candle	No participation	Quite good	Very smooth	None	Very adequate	B-M substandard
8	Blower, readings	No participation	No problem	No problems	Low ceiling	Adequate	C1. analyzer problem
9	Blower, readings	Complicated	No problem	Plugs blew	None	Adequate	CO_2 pump slow
10	Pump blower	No participation	No part.	No participation	Bunk bars Wheel-wells	Adequate Not for reading	No participation
11	Blower, readings	No participation	No difficulty	No participation	None	Adequate	No participation
12	Blower, readings	No participation	Excellent	No participation	Bunk bars	Quite adequate	Quite adequate
13	Blower, readings	No participation	No part.	Real simple	None	Adequate	No participation
14	Blower	No participation	Easy	No participation	Low ceiling Wheel wells	Adequate	Okay
15	Blower; readings	No participation	Simple	No participation	None	Adequate	Simple

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TABLE 3-5
DEBRIEFING SUMMARY

TEST SUBJECT	BIB TEST	ACU BLOWER	READ OPS. MANUAL? WAS IT CLEAR?	TEMP. & HUMIDITY	WASTE DISPOSAL	EQUIP. LAYOUT	BUNKS
1	Worked well	Operation easy Needs back support	Yes	Comfortable, condensation irritating	Acceptable	Adequate	Adequate
2	Comfortable mask Seal inadequate	Very tiring	Yes	Somewhat cold	Nauseating	Adequate	Poor stitching
3		Hurt back	No	Cold in bunks	Adequate	Need chart	Uncomfortable
4	Adequate	Easy Simple repair	No	Cold, condensation irritating	Odorous	Missing items	Adequate
5	No problems	Easy	No	Woke up cold	Adequate	Adequate	Okay
6	Uncomfortable	Quite adequate	No	Too humid	They stunk	Acceptable	Very comfortable
7	Comfortable Itchy, effective	Tiring Adequate	Yes. Clear.	Condensation bad	Not objectionable	Quite adequate	Adequate
8	No problems	Adequate	No	Dripping water	Not very adequate	Adequate	Too small
9	No problems	Hard to operate Hard on back	Yes. Not very	Comfortable, wet blanket	Bad odor	–	Comfortable
10	No participation	Blower inadequate	No	Cold	Inadequate	Unused space	Too short
11	Comfortable	Adequate Got sore	No	Comfortable	Smelled occasionally	Real adequate	Too tight
12	Comfortable Irritated nose	Hard on rump Backache	Yes. Clear.	Comfortable, condensation irritating	Livable	Seals unprotected	Too small
13	Comfortable Irritated beard	–	Yes. Clear.	Much condensation	Bad odor	Adequate	Tight
14	No participation	Loud, awkward	No	Comfortable, condensation irritating	Increasingly bad odor	No good	Too small
15	Very good	Operation difficult	Yes. Clear.	Comfortable	Increasingly bad odor	Okay	Adequate

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TABLE 3-6
DEBRIEFING SUMMARY

TEST SUBJECT	AIR CIRCULATION	FOOD	INGRESS & EGRESS	MOST EFFECTIVE	LEAST EFFECTIVE	RECOMM.	COMMENTS
1	No reaction	Very distasteful	Adequate	All adequate	Boredom	ASC too heavy	Design good
2	No problem	Bad taste	Adequate	O_2, CO_2 systems	Food	-	Condensation prob.
3	Adequate	Tastes bad	No problem	Chlorate candles	Toilet	Stiffen bunks	–
4	Good	Adequate	Awkward	CO_2 canister	B·MO_2 analyzer	-	–
5	Alright	Terrible - no protein	No difficulty	CO_2 canister	No opinion	Provide pillow	Had headache
6	No problem	Miserable taste, but adequate	Awkward	ACU	Humidity	Lower humidity	-
7	Quite fine	Plenty	Quite fine	Excess space	Food quality	Improve blower	Improve food
8	Adequate	Poor, adequate	No problem	Nothing	Bunks	Improve toilet	-
9	Adequate	Edible, satis.	No problem	Comfort	Sanitary fac.	Plastic gloves	–
10	Pretty good	Tried one can	Inadequate	Nothing	Blower, batt	Improve everything	Rats will eat food
11	No trouble	Adequate	Alright	Blower, BIB	Bunks	Another hatch	–
12	Pretty good	Potato cheese loaf	Easy	Plenty of room	Bunks		5 6 days easy
13	Good	Adequate	No problem	Blower	Toilet	Bunks bigger	Wheel well hazard
14	Not good	Survival qual.	Very easy	Getting out	None	Blower stren.	Use only to survive
15	Adequate	Okay	No problem	BIB system	Candles	Larger BIB masks	Batt. sys. bad

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Blast Tests

The blast tests were run to demonstrate the structural integrity of the ASC. Only two modules and two bulkheads were used due to space restrictions, and these were fitted with strain gagés, relative motion potentiometers, and transducers to measure structural reaction. A motion picture camera filmed the chamber interior (at roof joints). A series of six blasts was used, created by methane-air or methane-air-coal dust mixture at a variety of explosive pressures and impulse loadings. The test chamber withstood all blasts, but each blast broke open some seal sections. A new seal between modules was installed after the third blast, producing better results. The basic chamber setup and site dimensions are shown in figure 3-17. The instrumentation used and its arrangement are shown in figures 3-18, 3-19, 3-20, and 3-21.

Of the six blasts, only the fourth and sixth added coal dust to the explosive mixture. This was to make the blast last longer and create greater impulse pressure. These two explosions produced a flame front that passed over the test chamber, even though a zone 25 feet on each side of the crosscut was not dusted. The flame did no apparent structural damage to the chamber. The six blasts are listed below, with the peak explosive pressure and impulse loading for each.

No.	Explosive Pressure (psig)	Impulse (psi-sec)
1	7	1
2	8	1
3	16	1
4	7	3
5	18	1
6	10	6

Leak tests were conducted on the test chamber before and after each blast. Gas samples were drawn and bolts were retorqued to assure proper loading for the next blast. Three 18-channel oscillographs recorded data from the strain gages, transducers, and motion potentiometers. All blasts put some dust into the chamber, but oxygen never got below 20 percent. A gas analysis performed inside the chamber after blasts is summarized in table 3-7.

Peak pressure values for the transducers are given in table 3-8, and calculated impulse pressures are listed in table 3-9. A summary of relative motion potentiometer reactions is provided in table 3-10, and module

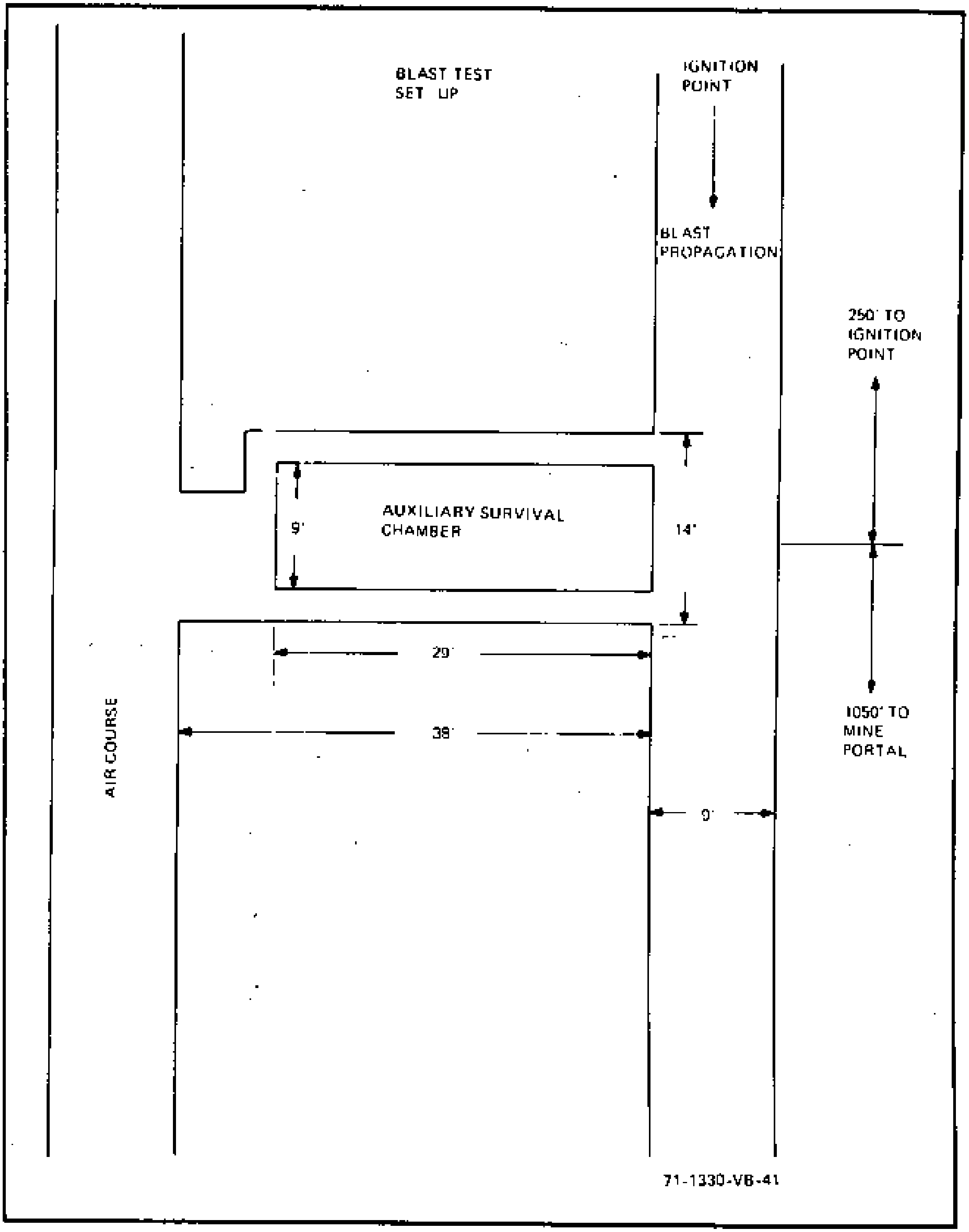


Figure 3-17. Blast Test Area Arrangement

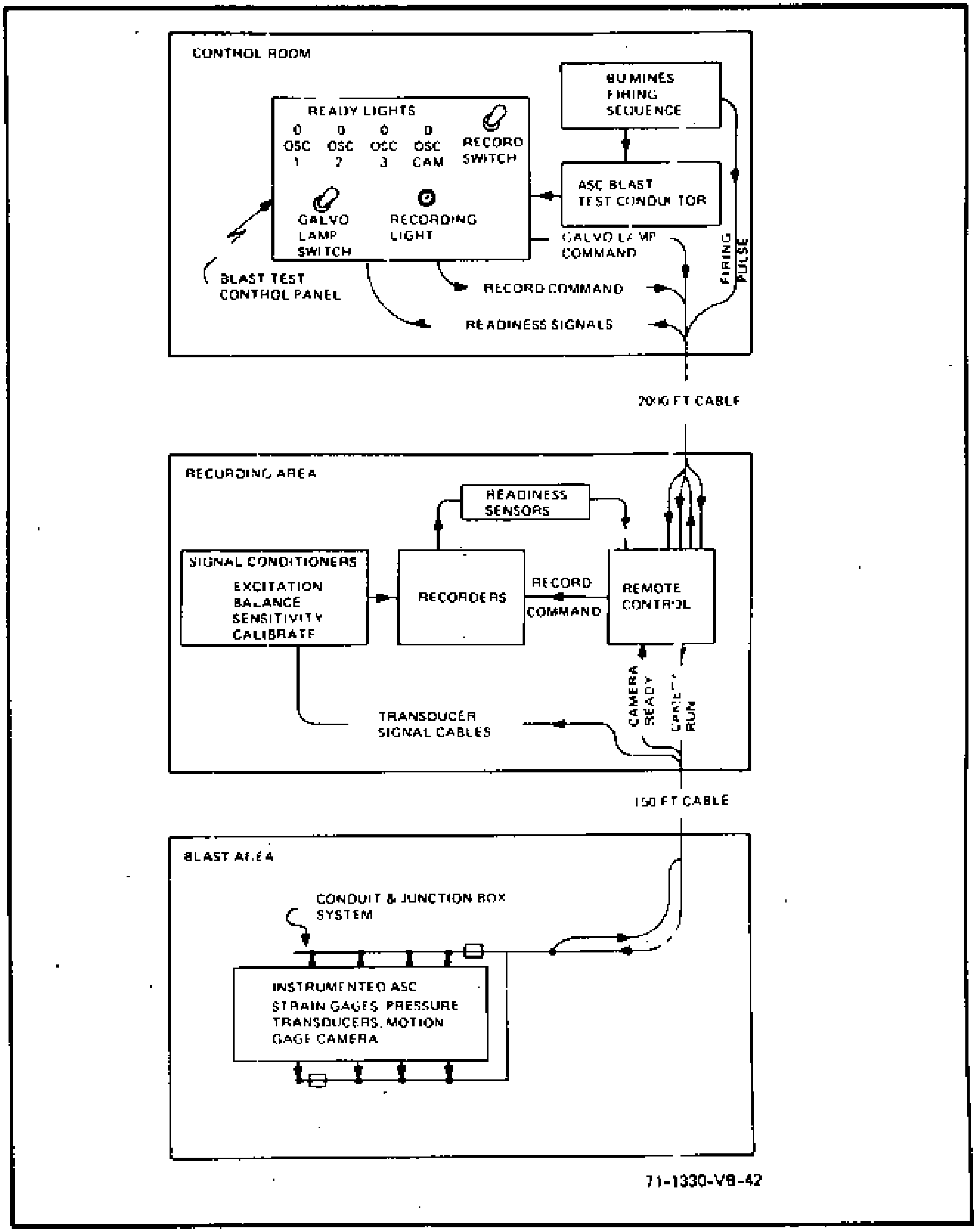


Figure 3-18. Blast Test Instrumentation

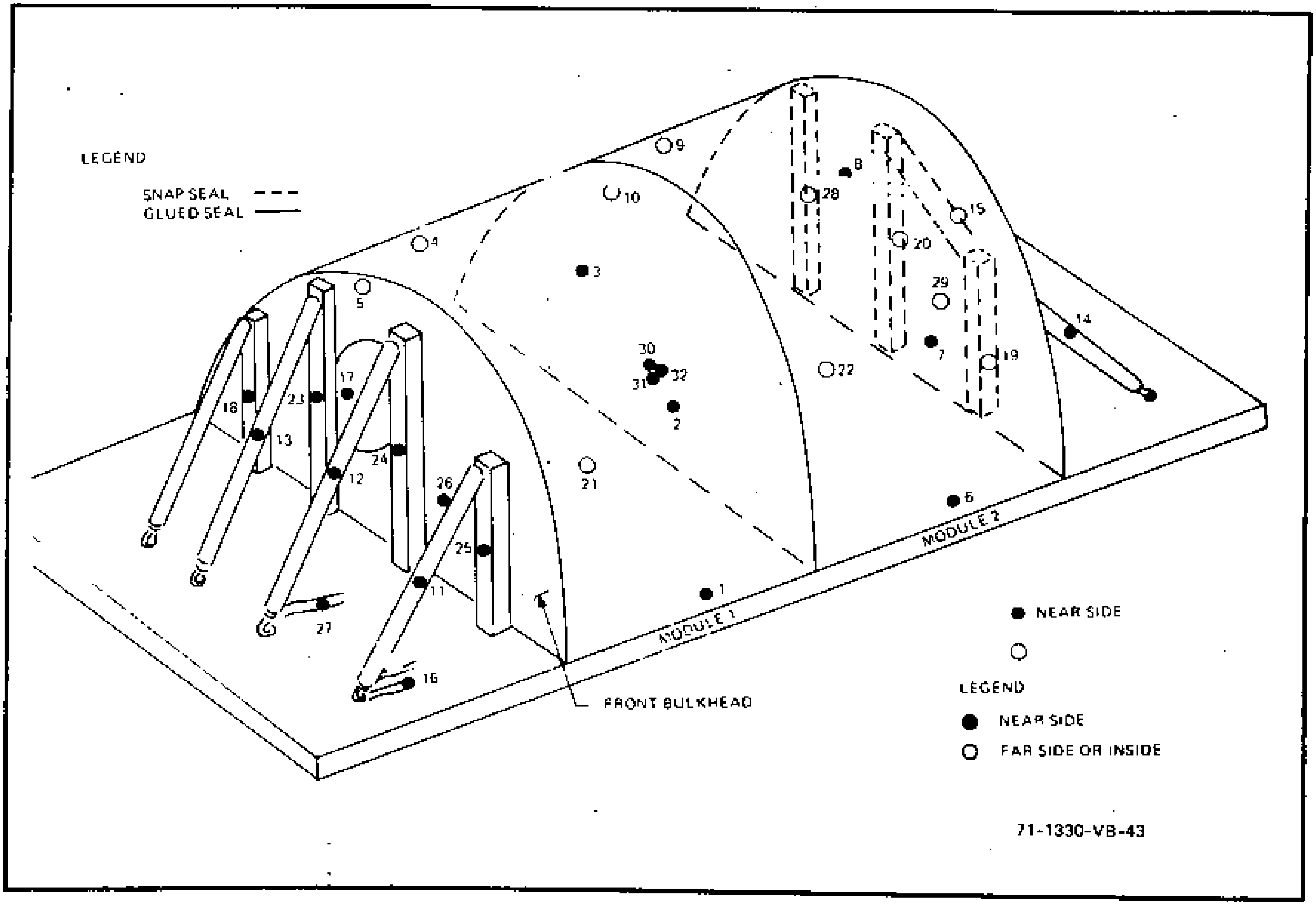


Figure 3-19. Location of Strain Gages

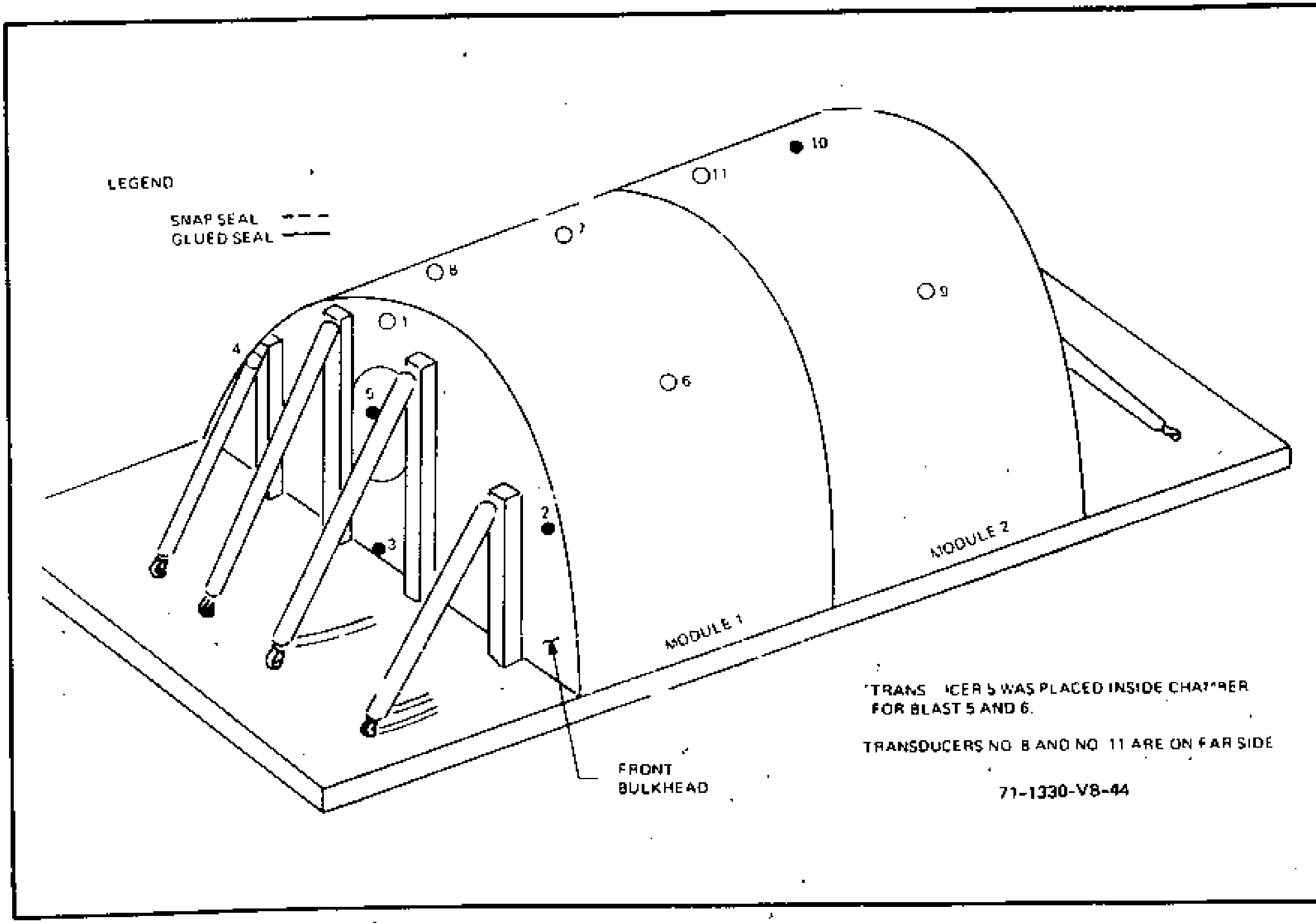


Figure 3-20. Location of Pressure Transducers

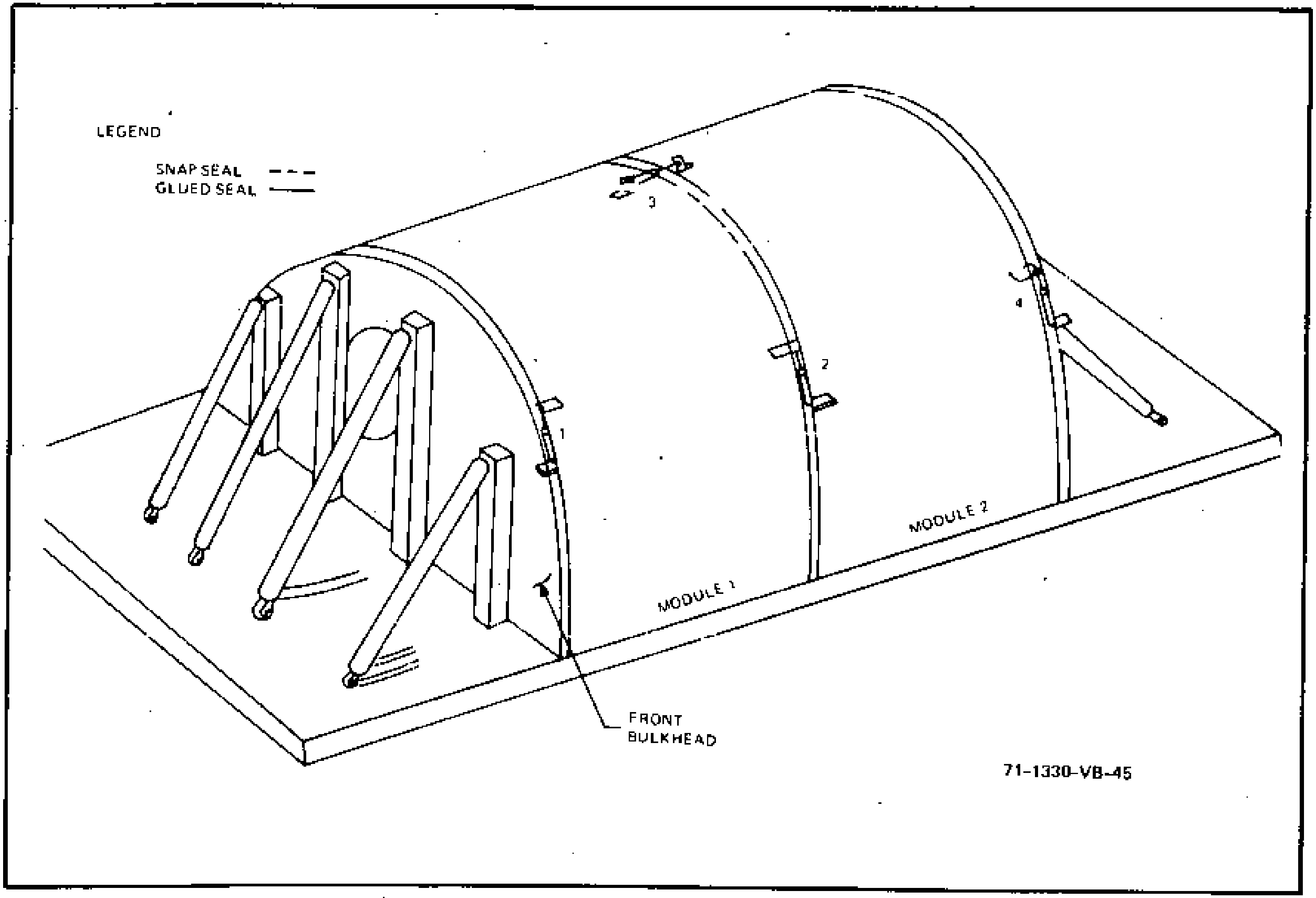


Figure 3-21. Location of Motion Potentiometers

displacements are shown in table 3-11. Leak rates before and after each test are shown in table 3-12. Leak rates were normally taken at a pressure differential of 0.2 psi (5 inches of water). Leakage rates after blasts 1 and 2 were too high to measure accurately and not less than values in table.

TABLE 3-7
GAS ANALYSIS

BLAST NUMBER	GAS CONCENTRATION					
	H_2(%)	O_2(%)	N_2(%)	CH_4(ppm)	CO(ppm)	CO_2(ppm)
1	0.1	21.8	78.05	-	-	500 ppm
2	0.1	21.8	78.00	<50	-	1000 ppm
* 4	0.1	21.4	78.10	<50	400	0.4%
5	0.1	21.6	78.20	-	<20	0.1%
6	0.1	20.8	78.20	131	868	0.8%

ANALYSIS PERFORMED BY U.S. BUREAU OF MINES, BRUCETON, PA.

*(No gas samples taken after third blast)

Blast 1 opened small sections of the snapped seals and unfastened parts of the glued seals on the hinged module halves. Blast 2 dislodged more snaps in the same area. Blast 3 completely opened 2/3 of the module-to-module seal and unsnapped large portions of the roof seals. The module-to-module seal, now badly worn, was replaced, and blast 4 unsnapped only 10 snaps. Blasts 5 and 6 unsnapped significant parts of the module and roof seals. For these tests, all seals were installed with an extra foam strip between the seal and sealing surface. When the new seal was installed after blast 3, this strip was removed. Results indicate that the strip has no real effect.

Systematic errors were virtually eliminated by physical calibrations and end-to-end electrical simulation calibration of transducer channels. Random errors have been evaluated, and they consist of the following:

a. Bonding errors on strain gages, ±5 percent of indication

b. Signal conditioner and galvanometer nonlinearities, ±3 percent of indication

c. Resolution error in readings, ±2 percent full scale.

No structural damage was incurred by either bulkhead or by the modules, in spite of considerable motion experienced in the blasts. Since sections of seals became unfastened by blast and had to be replaced after third blast, they

TABLE 3-8

PEAK PRESSURES AT TRANSDUCERS IN PSI

SHOT	BUMINES** 250	GAGE 1	GAGE 2	GAGE 3	GAGE 4	GAGE 5	GAGE 6	GAGE 7	GAGE 8	GAGE 9	GAGE 10	GAGE 11
1	6.3 psi	6.8 psi	4.2	6.75	6.75	8.7	3.45	4.5	4.8	3	3.75	3.90
2	-	6.3 psi	4.35	4.5	7.5	5.25	3.60	4.2	6.0	3.6	3.9	5.55
3	15.7 psi	15 psi	8.25	*24.5	*19	*20.5	5.25	12.75	14.25	9	9	12
4	6.1 psi	6.9 psi	6.9	*9	7.5	*9	5.4	6.0	5.1	4.8	5.4	6.6
5	18.8 psi	12 psi	18	17.4	*9	-	6	7.5	16.5	7.5	8	13.5
6	-	7.2 psi	*not active	15	10.5	3	5.4	13.5	7.5	6.9	9	9.3

*Inexact readings not considered valid due to disturbance.
**Bumine Pressure Transducer 250 feet from blast.

TABLE 3-9

IMPULSE LOADING DATA IN PSI-SEC.

SHOT	BUMINES 250	GAGE 1	GAGE 2	GAGE 3	GAGE 4	GAGE 5	GAGE 6	GAGE 7	GAGE 8	GAGE 9	GAGE 10	GAGE 11
1	.67	.33	.34	.26	.30	.35	.17	.20	.20	.13	.13	.19
2	-	.33	.24	.78	.31	.57	.16	.11	.18	.17	.18	.23
3	1.29	.78	.66	-*	-*	-*	.41	.48	.41	.52	.42	.57
4	2.62	1.36	1.95	-*	-*	-*	1.42	1.19	1.01	1.34	1.30	1.46
5	1.34	.52	.52	-*	-*	-*	.33	.20	.39	.32	.22	.40
6	-	1.78	-*	-*	-*	-*	1.36	-*	1.32	1.74	1.44	1.32

*Pressure reading too erratic for valid impulse values.

TABLE 3-10
MODULE MOTION SUMMARY (INCHES)

RELATIVE MOTION POTENTIOMETER	SHOT 1	SHOT 2	SHOT 3	SHOT 4	SHOT 5	SHOT 6
1	1.34	.62	1.86	.50	2.0	2.14
2	1.20	.20	1.60	.28	.4	.44
3	.32	.26	.90	.24	.6	.58
4	1.62	.18	.60	.28	.6	.76

TABLE 3-11
DISPLACEMENTS RECORDED BY SCRATCHING DEVICE

	SLOT 1	SLOT 2	SLOT 3	SLOT 4	SLOT 5	SLOT 6
DISPLACEMENT (INCHES)	0.125	0.275	0.60	0.10	0.20	0.625

TABLE 3-12
LEAK RATES

	BEFORE BLAST	AFTER BLAST
	CFM	
SHOT 1	1.27	48*
SHOT 2	1.38	33*
SHOT 3	1.12	-
SHOT 4	13.2	26.5
SHOT 5	1.44	-
SHOT 6	8.25	-

*Not less than

require improvement in reducing blast resistance as well as deterioration due to aging and handling.

It was generally concluded that while the Bruceton site was not completely typical of most mines today, the demonstration tests did evaluate the Auxiliary Survival Chamber concept and its implementation. After the tests, all bulkheads and modules were disassembled, cleaned, and completely re-assembled in room 8 of the Bruceton mine.

CHAPTER 4
CONCLUSIONS AND RECOMMENDATIONS

This chapter is divided into two sections. The first section presents the conclusions about the Survival Subsystem drawn from the Coal Mine Rescue and Survival System (CMR&SS) program, and the second offers some general and specific recommendations for the general improvement of the Survival Subsystem and expansion of capabilities.

SECTION I
CONCLUSIONS

The conclusions presented in this section are broken down according to subsystem component and fall into two categories; related to the component or its performance and related to the design concept.

PERSONAL BREATHING APPARATUS (PBA)

Generally, it must be concluded that the PBA meets its design requirements. It provides a safe breathing mixture regardless of the ambient atmosphere; it meets breathing resistance requirements; it is self-contained; it excludes smoke, dust, and gases; it maintains carbon dioxide at less than 2 percent; and it has a nominal working life of 1 hour. The accelerated generation of oxygen for the first 30 seconds provides ample oxygen for immediate use.

The hood provides a good universal fit, adequate vision, full mobility, and protection from toxic gases. The combination of the hood and other parts of the PBA represents a significant technological advance in this program.

The overall size and weight of the PBA are beyond the design limits, the unit weighs 6.7 pounds, 8.3 with carrying case. However, under the current state of the art, this approach is the best achievable.

In large quantity production, the PBA can be marketed at about $50.00 per unit.

The stability of the reaction in the chlorate candle and the general unit configuration both represent major advances in technology and in the safety of miners. Although the packaging is nearly optimum for a 1-hour unit, it is probably true that miners would more readily accept shorter duration for decreased weight.

AUXILIARY SURVIVAL CHAMBER (ASC)

The ASC represents a major first step in the direction of aiding miners to survive mine calamities. It will support life for 15 men for 14 days when installed fully equipped; it does withstand explosive blasts up to 20 psi with the exception of seals; it is portable; and it can be assembled and disassembled in a crosscut 10 feet wide, 6 feet high, and 50 feet long. There are also some major problems.

Although, structurally, the ASC withstood explosive blasts, seal integrity was not good. Snap fasteners blew apart in the blasts. Gasket material cold-flowed and set up, degrading the airtight integrity. Further, installing seals of the type used is time-consuming and not easy.

While the ASC is portable, moving it without powered assistance is no easy task. Securing the ASC bulkheads with roof bolts in the floor is time-consuming and quite difficult, although it does work. The interior modules of the ASC are not restrained, and under some asymmetrical loading, the modules shift, which adds to seal failure.

The blower for atmosphere conditioning unit proved somewhat unreliable, requiring too much maintenance. The chlorate candles used show a tendency to blow out the relief plugs. The BioMarine oxygen analyzer proved somewhat inadequate, due to damage.

Fabrication was a problem, because curved corrugated panels could not be found large enough to make one-piece sides. Further, the curvature of available panels was not closely controlled, and each one had to be reformed.

LARGE CENTRAL CHAMBER (LCC)

An evaluation of the LCC such as those conducted on the PBA and ASC cannot be conducted until a chamber is constructed. However, based upon the evaluation of components common to the LCC and ASC and the design concept for the LCC, we conclude that the LCC would be habitable and operable and that it would meet specified requirements.

Construction of the LCC is well within the current state of the art. However, in view of variations in population distribution and traffic patterns in a developing mine, it appears that the LCC would not be of lasting value in enhancing survival.

SECTION II
RECOMMENDATIONS

The recommendations offered in this section are also divided according to subsystem component.

PERSONAL BREATHING APPARATUS

To achieve a PBA unit that can be carried at all times, a separate development effort should be undertaken with size and weight reduction as its primary goal.

Further development should be directed toward improving heat dissipation from both the CO_2 removal canister and chlorate candle. This would reduce the temperature of the breathing air and help extend the candle life.

DeMist anti-fogging compound, as specified by design, should be used on the eyepiece in production. Further, the existing open-cell foam standoff inside the breathing bags should be enlarged slightly to ensure that the bags do not collapse.

AUXILIARY SURVIVAL CHAMBER

Before a production design is finalized, the ASC is subject to some further development that should concentrate on several alternate concepts that would be responsive to the wide diversity of mine environments and be compatible with evolving rescue and survival systems and methods.

One area of immediate major concern is the seals. Efforts in this area must improve shelf life, improve handling capabilities and endurance, simplify assembly and disassembly, expand tolerance to module misalignment, and develop resistance to blasts.

Ground clearance for trailer-mounted ASC should be increased by lowering axle mounts so that they penetrate the structural members of the module floor. Further development of the basic ASC structural concept is recommended to enhance adaptability to thin seam mines.

The hand-cranked blower for the atmosphere conditioning unit needs some redesign in mechanical areas to increase reliability and reduce maintenance. The units should be considered a candidate for incorporation into operational survival shelters. Incorporation would require only interface modifications, production engineering, and testing.

Further study is needed in the methods of restraining the ASC. The most promising alternate appears to be a combination of roof jacks and roof bolts driven vertically into the floor. The blast tests indicated that the modules should also be restrained individually. Indexing pins between modules might suffice. Also, the jack used to drill the holes for the bolts should use a support rack with adjustable legs. These recommendations, along with new seals, will greatly decrease the man-hours required to assemble one chamber.

Structural materials used should undergo investigation. If steel is retained, corrugated panels of sufficient size to make one-piece sides should be developed. For greater corrosion resistance, reinforced plastic and new low-cost stainless steels are likely alternates. To provide a solid base for future structural changes, further explosive tests should be run and studied.

The chlorate candle should undergo redesign to eliminate blowing out the relief plugs. This might entail no more than filter path rework and a new filter material. This filter redesign should also consider more complete elimination of the chlorine odor. The oxygen analyzer used should be subjected to further testing before incorporation into final design.

LARGE CENTRAL CHAMBER

As with the conclusions, recommendations for the LCC are based upon tests of components common to the ASC and a design analysis. Generally, further LCC development should be deferred until one is erected and tested. In its place, movable chambers, such as the ASC, should be considered for fulfilling any such requirements.

APPENDIX A
LARGE CENTRAL CHAMBER
THERMAL ANALYSIS

CHAMBER ISOLATED - AIR SHAFT BLOCKED, NO PIPED WATER FROM SURFACE

The following analysis determines if cooling is required for the chamber when it is isolated from the surface. Changes can be easily made to the data for specific mine conditions.

Cooling Load

The cooling load for a 50-man chamber utilizing Atmosphere Conditioning Units follows. This can be factored for different numbers of men.

Cooling load	
50 men x 400 Btu/hr	20,000 Btu/hr
Chlorate candle	3,800
Baralyme bed	750
Battery & lights (100 W)	340
Total	24,890 Btu/hr

Rock Contact

The chamber is assumed to have 5 ft of contact with a coal seam on each side with the remainder shale. The end walls are taken to be equivalent to shale contact:

Areas:

Coal: 754 ft^2

Shale: 2300 ft^2

Values from table 2-8.

Coal: $C_p = 0.2$, $\rho = 82.5\ lb/ft^3$

$k = 0.15\ Btu/hr \times ft^2 \times\ ^\circ F$

Shale: $C_p = 0.2$

$\rho = 165\ lb/ft^3$

$k = 0.80\ Btu/hr \times ft^2 \times\ ^\circ F$

Steady State

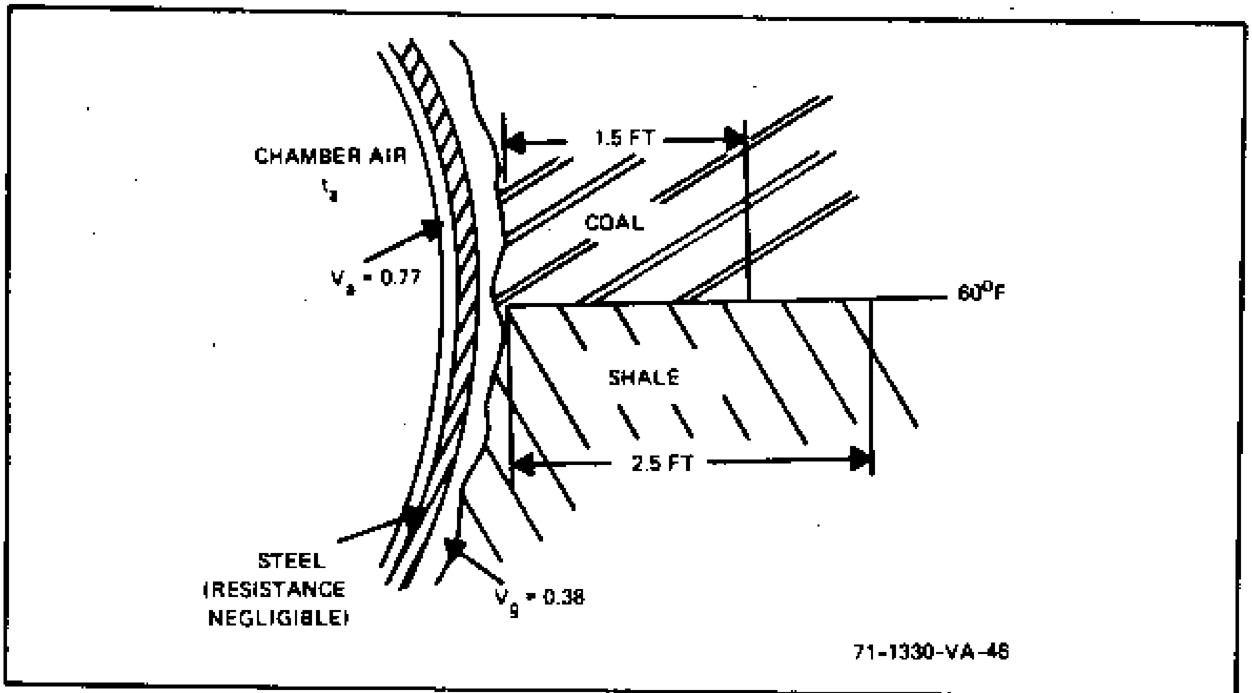
Let Qc and Qs equal the heat flow to the coal and shale, respectively.

$$Ac + Qs = Q = 24,890\ Btu/hr$$

Values from table 2-8

U (Air to metal)	$0.77\ Btu/hr \times ft^2 \times\ ^\circ F$
U (Grouting)	$0.38\ Btu/hr \times ft^2 \times\ ^\circ F$

The strata base temperature is 60°F. Assume this is reached inside 1.5 ft of coal and 2.5 ft of shale.



$$Qc + Qs = Q = 24,890 \text{ Btu/hr}$$

$$Qc = \frac{Ac\ \delta t}{\frac{1}{Ua} + \frac{1}{Ug} + \frac{x_c}{k_c}}$$

$$Qs = \frac{As\ \delta t}{\frac{1}{Ua} + \frac{1}{Ug} + \frac{x_s}{k_s}}$$

Solving the above

$$Qc = \frac{754\ \delta t}{\frac{1}{0.77} + \frac{1}{0.38} + \frac{1.5}{0.15}} = 54\ \delta t$$

$$Qs = \frac{2300\ \delta t}{\frac{1}{0.77} + \frac{1}{0.38} + \frac{2.5}{0.80}} = 326\ \delta t$$

Therefore $54\ \delta t + 326\ \delta t = 24,890$

$$\delta t = \frac{24,890}{380} = 65.5$$

Chamber temperature = 60 + 65.5 = 125.5°F

REQUIRED ENLARGEMENT OF CHAMBER FOR PASSIVE TEMPERATURE CONTROL

This analysis was made to determine the feasibility of enlarging the chamber to maintain an allowable effective temperature.

Allowable effective temperature	84°F
Mine temperature	60°F
	$\delta t = 24°F$

$$Q = Q_C + Q_B$$

$$= 54\,\delta t + 326\,\delta t$$

$$= 380\,\delta t$$

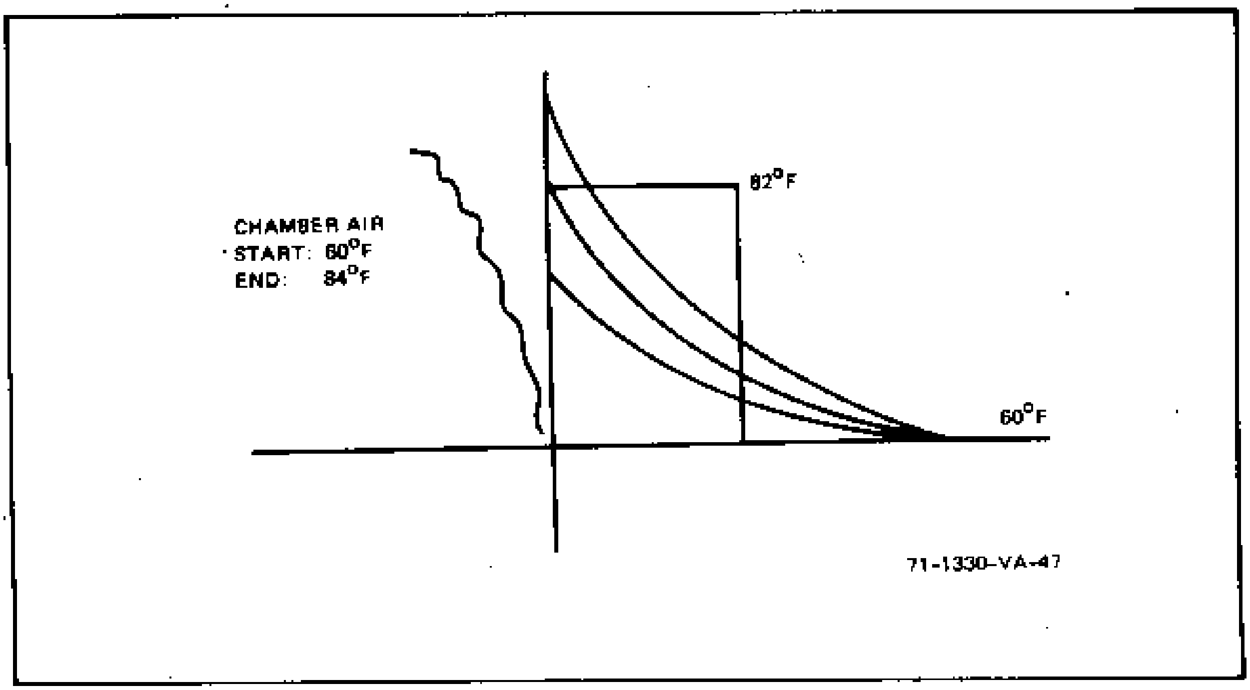
$$= 380\,(24) = 9100 \text{ Btu/hr}$$

Required area increase

Therefore

$$= \frac{24,890}{9100} = 274\%$$

TRANSIENT HEAT SOAK TO STRATA



Assume uniform heating to within 2 degrees of air temperature for a depth of 0.5 ft for coal and 0.75 ft for shale.

$$\text{Heat soak} = \Sigma C_p \quad m\,\delta t$$

$$= [(0.2 \times 754 \times 0.5 \times 82.4) + (0.2 \times 2300 \times 0.75 \times 165)]\ 22° + [0.24 \times 6,850 \times 0.075]\ 24 = 1,389,000 + 22,200 = 1,411,200 \text{ Btu}$$

$$\text{Elapsed time} = \frac{1,411,200}{25,550} = 57.5 \text{ hours}$$

NORMAL OPERATION-VENTILATING AIR THROUGH AIR SHAFT, SUMMER AND WINTER

The following analysis sizes the surface ventilating system. Changes can easily be made to the data to take into account such things as different surface conditions and different chamber heat loads.

Heat load

Metabolic - 50 men x 400 Btu/hr. = 20,000 Btu/hr.

Battery and lights = $\frac{340}{20,340}$ Btu/hr.

Moisture load

50 men x 0.13 lb/man hr. = 6.5 lb/hr.

Summer

Ambient air entering cooler: 90°F, 70 percent relative humidity, 58 lb/min, $\rho = 0.0721$ lb/ft^3, 804 cfm

Location \ Parameter	Temperature Dry Bulb (°F)	Temperature Wet Bulb (°F)	Relative Humidity (%)	Pressure In. Wg
Cooler entry	90	81.6	70	
Cooler exit	54 (sat)		100	
Turbo compressor exit	59			13.8
Shaft entry	60	56.5	80	13.5
Shaft exit	62	57.0	75	2.1
Chamber	81.5	66.0	44	2.0

Enthalpy at cooler entry = 45.4 Btu/lb dry air

Enthalpy at cooler exit = 22.4

23.0 Btu/lb dry air

Heat rejected = 58 x 23 x 60 = 80,000 Btu/hr

Heat loss from chamber

Reference 26 gives 69 percent heat loss to air

31 percent to rock wall

Because of differing wall area and chilled ventilating air, we assume air takes 80 percent.

Heat to ventilating air

$Q = 0.80 \times 20,340 = 16,272$ Btu/hr.

$Q = Cpm\, dt$

$$dt = \frac{16,272}{0.24 \times 58 \times 60} = 19.5°F$$

Chamber air temperature = 62 + 19.5 = 81.5°F

Moisture in incoming air = 0.009 lb/lb

$$\text{Metabolic moisture} = \frac{6.5}{58 \times 60} = 0.0019$$

Final moisture in chamber = 0.0109 lb/lb
44% R.H.

Winter

Ambient air entering turbo compressor:

15°F, 25% R.H., 800 CFM, $\rho = 0.0836$ lb/ft^3, 66.9 lb/min

Air leaving compressor is 20°F.

Air entering chamber is 24°F.

Using the same heat load in the chamber, Q = 16,272 Btu/hr

$16,272 = 0.24 \times 66.9 \times 60\, \delta t$

$\delta t = 16.9°F$

Chamber temperature = 24 + 17 = 41°F which is too cold.

Additional heating is required to raise the temperature to 71°F or

δt elec = 30°F.

$$\delta t\ \text{elec} = \frac{Q_{elec}}{0.24 \times 66.9 \times 60} = 30$$

$$Q_{elec} = 28,900\ \frac{\text{Btu}}{\text{hr}} = 8.5\ \text{kW}$$

Provide only 6 kW because metabolic rate can easily be raised above 400 Btu/man hour which will raise the chamber temperature.

OXYGEN SUPPLY AND CO_2 REMOVAL, VENTILATING AIR THROUGH AIR SHAFT

Reference 11 recommends absolute minimum air flow for O_2 and CO_2 control as 3 CFM/man.

Ventilating system supply:

$$\frac{800 \text{ cfm}}{50 \text{ men}} = 16 \text{ cfm/man}$$

CHAMBER VENTING

The vent values are set to pass 58 lb/min of ventilating air at 82°F and 2 in. Wg above ambient mine pressure from the chamber to the mine..

Vol. flow - 800 cfm maximum

Use 6 vent valves, 6 in. dia. x 0.6 in. left

Flow area = 6 x 11.3 = 67.8 in^2 = 0.471 ft^2

Discharge velocity

$$V = \frac{800}{0.471} = 1650 \text{ ft/min, which is acceptable}$$

EMERGENCY OPERATION CHAMBER SEALED, AIR SHAFT BLOCKED, WATER COOLING

This analysis sizes the water cooling system. The water flow and stored water tank volume are determined, air flow requirments are set and a water coil selected.

Cooling load

50 men x 400 Btu/hr	= 20,000 Btu/hr
Chlorate candle	= 3,800
Baralyme bed	= 750
Battery & lights	= 24,890 Btu/hr

Design dry bulb temperature = 82°F. At this temperature we can assume that 35 percent of the heat goes directly to the rock walls. Residual cooling load

= 0.65 x 24,890 = 16,100 Btu/hr

Water

In: 60°F Out: 74°F $\delta tw = 14°F$

$qw = Cp\ m\ \delta t = 16,100$

Therefore

$$m = \frac{16,100}{14} = 1,150 \text{ lb/hr} = 2.3 \text{ GPM}$$

To cover 3 days, 72 hours

Stored water mass = 83,000 lb
= 9,940 gal
= 1,320 ft^3

Air side of coil, required values from psychrometric chart.

	Temperature Dry Bulb (°F)	Temperature Wet Bulb (°F)	ENTHALPY h Btu/lb	DENSITY $\rho \frac{lb}{ft^3}$
Air entering coil 90% R.H.	82	79.2	43.2	.073
Air at outlet	72	SAT.	35.8	.0746
Differential	10		7.4	

$$\text{Air flow} = \frac{16,100}{7.4} = 2,180 \text{ lb/hr}$$

$$= 490 \text{ cfm at } 72°\text{F}$$

Oxygen Supply

65 chlorate candles supply 70 ft^3 each over a four-hour period

$= 4550 \ ft^3 \ O_2$

The metabolic requirement for 50 men at 1.5 lb/man day

$= 0.633 \text{ cfm} \times 60 \text{ min} \times 120 \text{ hr} = 4,558 \ ft^3 \ O_2$

Rate of generation

1 candle	1.75 ft^3/hr
10 men require	7.6 ft^3/hr
50 men require	38 ft^3/hr

With 50 men in the chamber, two candles will leave a deficiency of 3 ft^3 at the end of one hour. In a chamber of 6,850 cubic feet the oxygen level would decrease to 20.89 percent which is negligible.

APPENDIX B
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