TECHNICAL REPORT 73S-3

AN AIR-SUPPLIED RESPIRATOR
FOR UNDERGROUND COAL MINERS

FINAL REPORT

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FOREWORD

Pneumoconiosis or "black lung" caused by inhalation of coal mine dust has been a severe problem in underground coal mines for many years. While "engineering" controls such as improved ventilation, dust supression, and dust collection devices on mining machines contribute greatly to reduction of the hazard, the need for improved respiratory protective devices is still great. In recognition of this fact the National Institute for Occupational Safety and Health, Health Services and Mental Health Administration, Department of Health, Education, and Welfare has sponsored several research programs having the goal of providing better respiratory protective devices to underground coal miners. This report summarizes the results of one of these contracts, the development of a machine-mounted air supplied respirator for underground coal miners.

The project, performed by Synsis, Inc., Los Angeles, CA, pursuant to Contract No. HSM 99-71-42 was directed by Mr. Samuel Tobey. Mr. Richard Lester served as the Project Officer for the National Institute for Occupational Safety and Health. His significant contributions to the program were greatly appreciated and reflect favorably upon the dedication of NIOSH personnel.

Mr. T. P. Crooks and Mr. F. A. Stawitcke were the project engineers for Synsis, Inc. We were encouraged by the willing cooperation of all parties concerned including the Donaldson Company who tested the cyclone separator, the mining machine manufacturers and miners who provided much needed technical advice, and to Mrs. Dolores Kelley who typed this report.

ABSTRACT

Research has shown that coal miners often reject the use of respirators, as do other industrial workers, for reasons of discomfort such as poor or tight fit and high breathing resistance. One concept intended to improve wearer acceptance is to mount the air supply and air cleaning systems on the mining equipment, utilizing power available on the machine to reduce breathing resistance.

Such a respirator system was developed involving a machine mounted hydraulic powered air compressor and filter system. Maintenance requirements were reduced to a minimum through the use of cyclone (centrifugal separator) prefilters. A new facepiece design was also developed to achieve increased acceptance by the user. It incorporates a pair of miniature, high performance, low inhalation resistance demand regulators, mounted directly on the facepiece, to reduce breathing effort. A small continuous air flow is provided to reduce thermal burden and required seal pressures.

Trade studies were made of several concepts in machine-powered respirators which led to the selection of the described system. Special consideration was given to the harsh requirements imposed on powered respirator systems by the underground coal mine environment. Both manned and unmanned tests of system performance and acceptability in simulated mine environments were conducted.

TABLE OF CONTENTS

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TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (concluded)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (continued)

LIST OF ILLUSTRATIONS (continued)

LIST OF ILLUSTRATIONS (concluded)

LIST OF TABLES

PART ONE

INTRODUCTION AND SUMMARY

Section I

INTRODUCTION

BACKGROUND

Pneumoconiosis or "black lung" caused by inhalation of coal mine dust has been a severe problem in the coal industry for years. After surveying 9,000 miners during 1969-1970, Shoub (1971) estimated that nearly 30% of underground coal miners have observable signs of the disease. Previous studies (Lainhart, 1969) showed similar results. Doyle (1969) reported that in Pennsylvania alone, 28,000 coal miners were receiving compensation related to pneumoconiosis in the amount of 141 million dollars per year.

Dust particles in the size range from approximately 1/2 um to 10 um are generally considered to be particularly hazardous since they tend to remain in the lung. Particles in this size range are said to be "respirable dust particles". Based in some extent upon the work of Wright (1953, 1954, 1957), it is generally accepted that the incidence of pneumoconiosis is dependent upon the total amount of dust inhaled in a life time (Walton, 1970).

Over the years, increasing awareness of hazards and enlightened social attitudes have resulted in progressive attention to protective measures by miners, operators, and legislators, culminating in the Federal Coal Mine Health and Safety Act of 1969. This act establishes limits for safe concentrations of respirable coal dust which may exist within the coal miner's working environment. These standards are based upon averages over an entire work shift. In recognition of the fact that these limits may be exceeded in local areas, and for short periods of time, the act also requires that the Secretaries of Interior and Health, Education and Welfare establish standards and provide approvals for respirators which will protect individuals who are exposed to contamination levels beyond the limits established by the act. The wisdom of such action has been borne-out by experience since the act went into effect. Mine operators have found it exceedingly difficult to meet the stringent requirements currently set at 2 mg/m^3 for dust in the respirable range (Kegel, 1969; Jacobson, 1971).

A recent study by Eastern Associated Coal Corporation (1971) illustrated the unfortunate fact, however, that although approved respirators are supplied to miners they are not used routinely even in environments where their protective capabilities are needed. The basic problem has been poor acceptance by the coal miner because they are too uncomfortable for long duration wear. Breathing resistance was cited most often as a major complaint in the subjects interviewed in the above study. Other factors noted as reducing acceptance included general discomfort and cumbersomness, perspiration within the mask, interference with tobacco chewing and general task interference.

OBJECTIVE and SCOPE

The objectives for the program are to design, fabricate and test a

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prototype supplied-air respirator system for use by coal mine equipment operators. This system is to include all components necessary for processing and delivering clean breathing air to the user.

Appropriate test procedures are required to demonstrate that the system performs effectively within the coal mining environment. The overall design criteria include factors related to wearer comfort, breathing adequacy, protection, continuous operation, reliability, and compatibility with the coal miner, his tasks, his equipment and the coal mining environment.

As proposed, the program includes analysis of underground coal mining systems in setting functional and performance requirements for the respirator system, analysis of alternative concepts satisfying these requirements, and selection and construction of the most attractive concept.

As summarized from the NIOSH request for proposal and Synsis' response to it, the most basic functional and engineering requirements to be met by the supplied-air system are:

FUNCTIONAL REQUIREMENTS

- Provide protection against airborne dust. This requirement includes large-sized particles as well as respirable dust. Protection against other respiratory hazards is not a requirement. The gravimetric protection factor for coal dust in the respirable range is to be 10, or greater.

Provide a physiologically acceptable respiratory environment. This requirement implies that respiratory embarassment will not occur due to use of the system.

Maximize user acceptance and proper use. This requirement entails provision for comfortable use by all miners without perception of difficulties in using the device.

Prevent impedance of mining tasks and operations. This requirement entails compatibility with the environment, equipment, and effective task performance.

DEVELOPMENT CONSTRAINTS

The system is to be designed for use when installed on any powered mining equipment routinely used near the working face.

Powered airflow is to be used for reducing breathing resistance.

Power necessary for system operation may be derived from the mining equipment, from the general mine power supplies, or from self-contained sources.

While it was originally proposed to make use of existing facepieces or the results of facepiece development from other research programs, these were not considered adequate and the contract was amended to include the development of a facepiece designed for this specific application.

SYSTEM DESIGN PROCESS

In addition to satisfying the basic protection requirements it was necessary for the respirator system to possess a number of other attributes if it is to meet with acceptance by the mining population. A number of different basic types of respirator systems are available, or could be designed, which meet the basic requirements imposed. In order to pick the best possible candidate for the production prototype, it was necessary to carefully weigh the costs versus the benefits involved with various concepts and choose the most attractive concept. Since the program, and this report describing the program, are organized along this basic "systems engineering" process, the fundamentals of the process are described below.

REQUIREMENTS ANALYSIS

In addition to the rather straight-forward requirements placed upon the respirator design, noted previously, a large number of design requirements and constraints affect the ultimate design of the respirator and consequently its suitability for use in the underground mining environment. Some of these requirements are intuitively obvious upon careful reflection. A larger number of requirements, perhaps the most important ones, were discovered by analysis of the underground environment, mining tasks and operations, mining machine design and operation, and the attitudes of the individuals comprising the population. The importance of this task becomes clear in view of the overall level of respiratory protection currently existing in underground coal mines. While any of the Bureau of Mines approved dust respirators would provide adequate protection if they were worn correctly and for the required time period, research has shown that provision of such respirators does not indeed provide the required protection from dust inhalation. Thus, it was first necessary to find out why this condition exists before going ahead to the design of a brand new respirator system

To a large extent one would expect that resistance to the proper utilization of current respirators would be based upon subjective discomfort and inconvenience associated with the devices. Such factors as face seal comfort, breathing resistance, moisture build-up in the facepiece, harness fit and comfort, and interference with the tasks commonly performed by coal miners are all factors which may enter into relative acceptance of a respiratory protective device. Therefore, an importanat part of the program was to carefully examine the impact of each of these factors and many others upon respirator design and utilization.

In the same vein, mining machinery such as continuous miners, shuttle cars, face drills, roof bolters, and others were studied in terms of power availability, space availability, and operational patterns so that the candidate respirator system could be employed on the widest variety of machines and with varying styles of mining. It was also necessary to analyze the underground environment in terms of potential substances which might jeopardize the operation or reliability of the respirator system, or the likelihood of the miners to use the device. One example of this sort of analysis concerns the frequency of roof falls. Since a roof fall is a fairly common occurrence in underground mines it is most certainly necessary that the respirator system not impede the miner's ability to escape rapidly from the face area.

CONCEPT SYNTHESIS

In light of the myriad of requirements developed in the previous phase of the program, and in view of the fact that the respirator system was to be designed specifically for underground miners, it was desirable to start with a clean slate and synthesize several potentially suitable design concepts. For example, concepts synthesized in the course of the program included both continuous flow and demand flow systems. During this phase of the program each of the concepts is synthesized to the point of specification of size, weight, performance, power requirement, and potential developmental engineering needed. With this information on hand it is then possible to select the most attractive concept in terms of fullfilling the functional and performance requirements previously set forth.

DESIGN AND FABRICATION

Given the conceptual design, the purpose of this phase of the program was to perform the detailed design and fabrication of the prototype. During this phase of the program it was necessary to continually reevaluate the requirements and the potential feasibility of the basepoint concept. As specific factors regarding the cost of incorporation of various features became available during this phase of the program, it was necessary to perform certain costs versus benefits analyses regarding specific features to be incorporated in the design. As well, the overall feasibility in terms of costs, design effort and reliability to be expected from the base point concept were determined. It was not unexpected during this phase of the program to find that certain features of the design which satisfy important requirements could not be realized within the scope of the program. This has an important result by itself (ie. delineation of new directions for future research and development programs in the area).

TEST AND DEMONSTRATION

Within the scope of this particular program the acceptance demonstration and testing requirements were limited to an eight-hour operational test and three half-hour subjective acceptance and protection factor tests conducted in a dusty atmosphere produced in a laboratory. However, two additional prototypes are being constructed for testing in actual underground coal mines as part of another contract (HSM 99-72-88).

REPORT ORGANIZATION

While the conduct of the program involves an evolutionary type development through the requirements stage, concept synthesis stage, and the prototype fabrication and testing stages, with considerable iteration and feedback from one stage to another, the final report is orgainzed in a more direct manner. Section II provides a complete description of the final product. Section III presents a summary of the requirements developed. Section IV presents a discussion of the various approaches or concepts considered in developing a supplied air-respirator for underground coal miners. Section V describes in a more narrative fashion, some of the problems involved in implementing the features of the concept selected in the previous phases. Test results for particular components such as the cyclone separator for dust removal are discussed in this section of the report. Section VI of the report provides considerable detail as to design operations and the functional performance of the respirator system. Items such as expected reliability and maintainability considerations are discussed in this section of the report. The final section presents conclusions and recommendations resulting from the development program. It is meant as an overview of the program and provides a discussion of successes and failures of the effort.

Section II

FINAL SYSTEM DESIGN

The prototype supplied-air respirator system can be conceptualized as an integration of four subsystems, each of which performs a specific function in the operation of the system. These four subsystems are:

MOTOR/COMPRESSOR SYSTEM

Hydraulic power was selected as the primary energy source, however, electric power may be utilized as an alternate at a considerable size, weight and cost penalty. A piston-type Teflon ringed, oil-less compressor is the primary air mover. It produces a flow rate of 3.75 SCFM at an output pressure of 60 psig.

AIR CLEANING SYSTEM

The air cleaning system consists of two cyclone separators for primary coal dust removal, and one cartridge type, fibrous final filter. One cyclone separator serves for inlet air cleaning, and the second cyclone separator is down stream of the compressor.

AIR DELIVERY SYSTEM

The air delivery umbilical consists of a fifteen foot length of reinforced low-pressure air hose having an external diameter of 0.50 inch. This subsystem includes automatic quick-disconnects for emergency egress and a belt-type body attachment arrangement. Two demand regulators, in conjunction with a small plenum chamber permit the user to achieve peak instantaneous flow rates in excess of 10 SCFM for brief periods.

FACEPIECE

The half-mask type facepiece provided with the prototype was specially designed for the underground coal mining environment. It incorporates a facial access port for speech and expectoration, and a suspension harness which is compatible with coal miner's helmets. Two demand regulators are incorporated in the facepiece.

A pictorial schematic of the entire system is presented in figure 2-1 and a photograph of the prototype is shown in figure 2-2.

The system was designed with the primary goal of maximizing user acceptance. The demand regulators provide peak flow rate adequate for any work rate likely to be found in underground mining at suction pressures of less than 0.75 in H_2O. In addition, a small continuous ventilation flow

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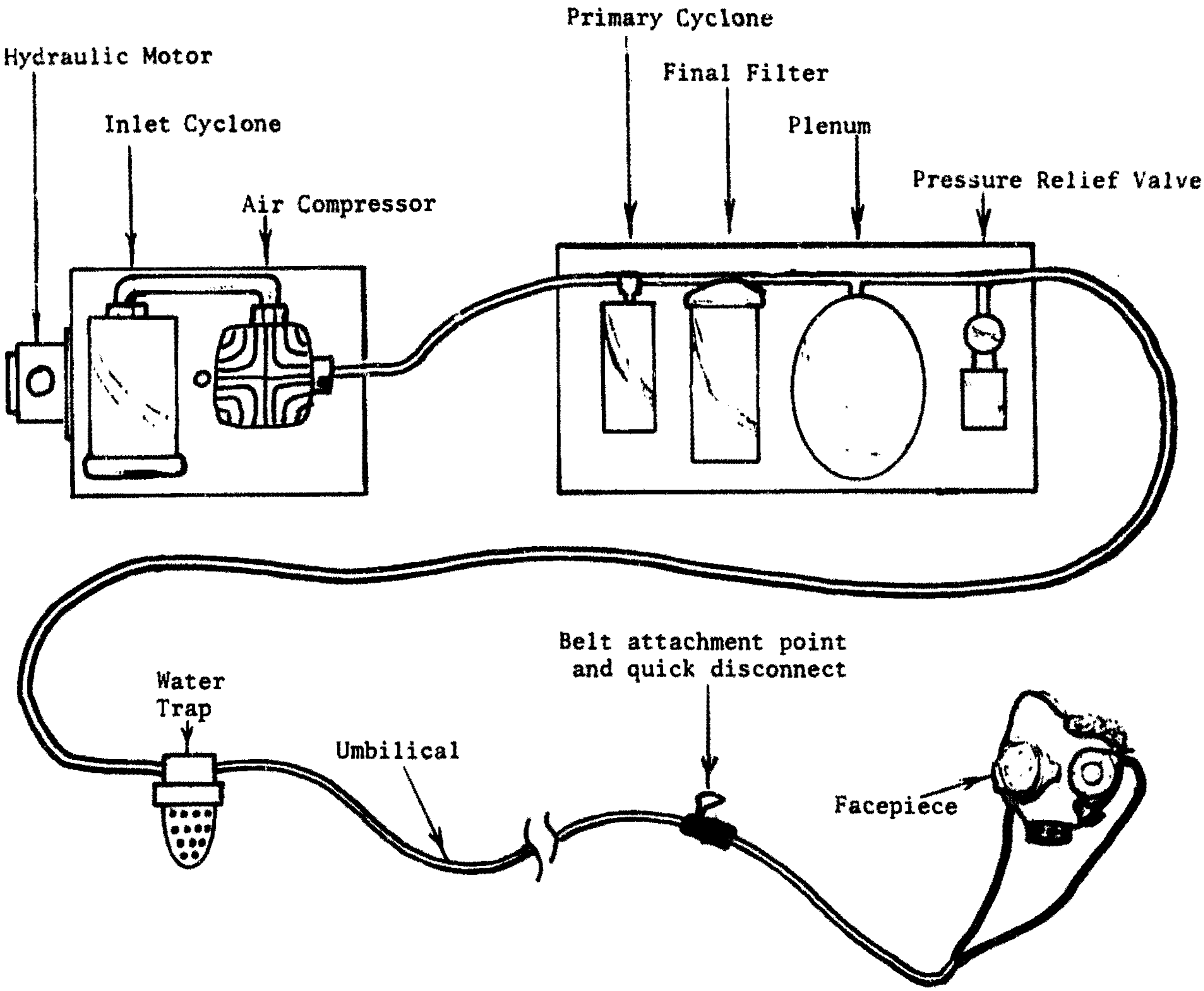


Figure 2-1. Pictorial Representation of the Supplied-Air Respirator System.

is provided within the mask to reduce heat and moisture buildup within the cavity. In the worst case, it is expected that the gravimetric protection factor for respirable coal dust will exceed 100.

In this section of the report an overall view of the system design and performance is presented. Subsequent sections of the report, specifically sections five and six provide details regarding design, operation, and performance of the various components, and more detail on overall system performance and design integration.

MOTOR/COMPRESSOR SYSTEM

The compressor and the motor are mounted on or inside of a heavy guage steel enclosure (figure 2-3) designed to protect them from roof falls and to attenuate the noise generated by the compressor.

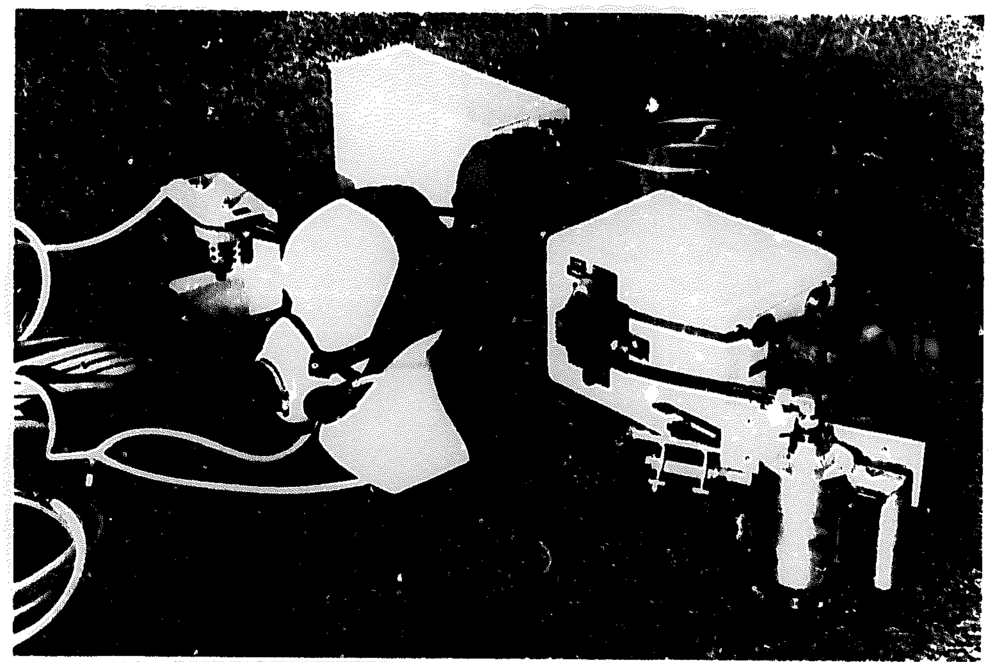


Figure 2-2. Prototype Supplied-Air Respirator System.

COMPRESSOR

The air compressor is a two cylinder, oil-less, piston-type, model PCD-10 produced by the Gast Manufacturing Corporation. It requires 1.1 hp at 2,000 RPM to produce 4.8 SCFM airflow at zero output pressure and 2.85 SCFM at 100 psig output pressure. Having Teflon piston rings, it requires no lubrication or periodic maintenance. Inlet air is cleaned by the inlet cyclone, shown in figure 2-3, which is discussed subsequently.

MOTOR

Hydraulic power was selected as the primary means of driving the compressor. The one-half inch gear face hydraulic motor, Model GC-5151-A-2-D supplied by the John S. Barnes Corporation, is rated at 1 hp at 2,000 RPM when supplied with 2.5 gallons per minute of hydraulic fluid at approximately 900 psig. This same motor can be configured with a variety of displacement rotors so that mining machine systems having higher hydraulic pressure available may conveniently make use of the pressure to reduce hydraulic fluid flow rates.

ENCLOSURE AND ACCESSORIES

Since the high RPM piston type compressor was found to be noisy, it was necessary to line the interior of the steel enclosure with a noise supressing foam sheet material. This in turn led to heat build-up problems within the compressor bearings and consequently it was found necessary to install a shrouded fan to move ambient air through the enclosure. Cooling air enters the enclosure through holes on one end and exits around the piston heads.

Finally, on the exterior of the enclosure, a hydraulic fluid flow controller is mounted. This serves to prevent potential compressor overspeed conditions resulting from varying hydraulic fluid supply pressures.

AIR CLEANING SYSTEM

The air cleaning system was designed to reduce maintenance requirements to a minimum. For that reason, two cyclone separators were specially designed for the purpose, and an off-the-shelf cartridge-type filter was employed for final filtration. Under most operating conditions the final filter cartridge should last several months before requiring cleaning or replacement. Air delivered to the miner's facepiece has no particles larger than 0.9 um and only a very small fraction of particles larger than 0.07 um.

INLET CYCLONE SEPARATOR

The inlet cyclone separator shown installed on the compressor enclosure in figure 2-3 is a reverse-flow type cyclone having a 50% collection

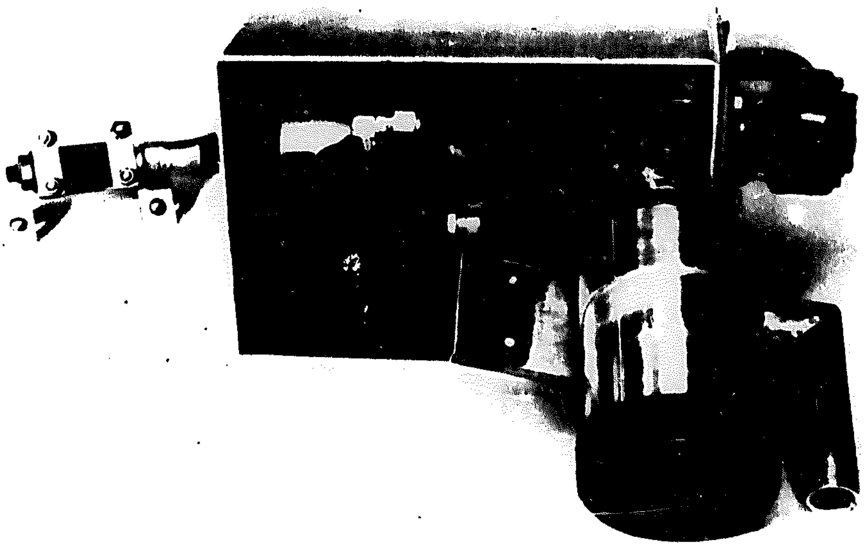


Figure 2-3. Compressor/Motor System. One side of enclosure is removed. Note the cyclone-type inlet filter in the foreground.

efficiency for 0.5 um effective diameter coal particles. Coal particles collected are retained in a large volume, elastomeric boot over the bottom port of the inlet cyclone.

PRIMARY CYCLONE SEPARATOR

As shown in the schematic (figure 2-1), the primary cyclone is located in the high-pressure portion of the system downstream of the compressor. This cyclone, while not intended to provide the total air cleaning function, is remarkably efficient. Experimental results indicate that it will remove one half of the particles having an effective aerodynamic diameter of approximately one-half micron and 95% of the particles having an effective aerodynamic diameter of 1.8 micrometers, or larger. It is installed in a protective heavy guage steel enclosure as shown in figure 2-4. The particles are collected in a collection chamber at the bottom of the cyclone which must be vented occasionally by operating a toggle valve which penetrates the wall of the enclosure.

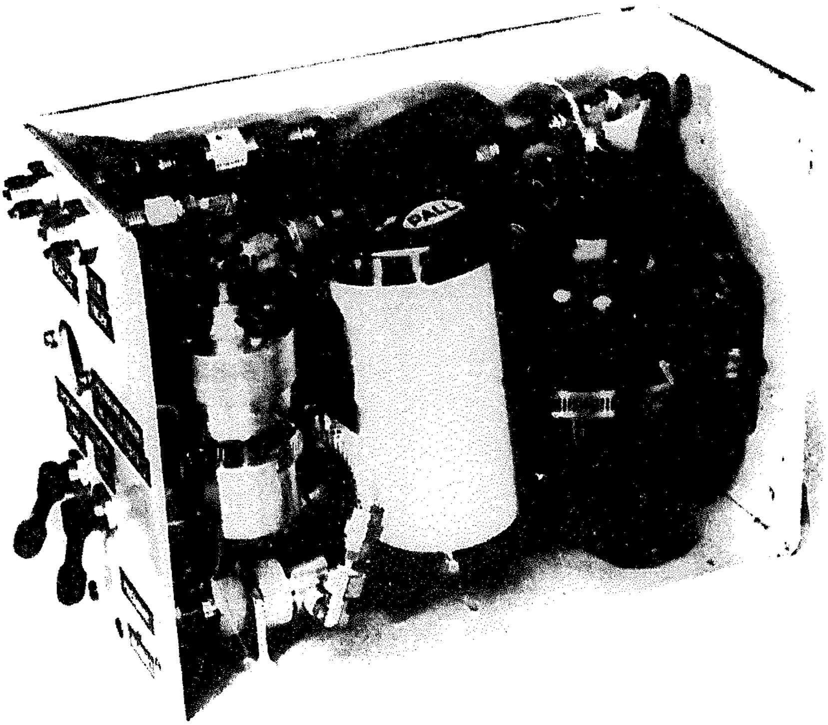


Figure 2-4. Auxiliary Equipment Housing. Elements of the air cleaning and air delivery subsystem are shown within.

FINAL FILTER

The filter element and canister employed in the prototype system are manufactured by the Pall Trinity Micro Corporation. The "Epocel", MC64463EC filter cartridge is a corrugated cylinder of resin impregnated cellulose fiber which collects dust as a surface-type filter on a 1.2 square foot collection area. The filter housing utilized, model MOA446364, is shown installed in its protective enclosure in figure 2-4. The assembly has an efficiency of 98% for particles of effective aerodynamic diameter of 0.07 um and 100% for particles of 0.9 um diameter. With the two cyclone separators upstream, it is expected that the cartridge will need to be changed only once every several months.

AIR DELIVERY SYSTEM

The air delivery system includes the umbilical hose, components for regulating system operating pressure, and the demand regulators. The demand regulators represent the key part of the system and all other components of this subsystem are designed around them.

DEMAND REGULATORS

Two regulators mounted in the facepiece are supplied by the Robertshaw Company of Anaheim, California. They are demand-flow type and are a modification of Robertshaw's Model No. 226 Aviator's Oxygen Demand Regulator. The modified regulators, seen in figure 2-5, weigh only 1.58 oz (45gm) each, and

Figure 2-5. Modified Robertshaw Demand Regulator.

each one will supply more than 6 SCFM flow rates at inhalation pressures of approximately 0.75 in H_2O. In addition to the demand flow, a continuous flow rate of approximately 0.75 SCFM is supplied in order to reduce heat and moisture build-up within the facepiece. This has the additional advantage of reducing inboard leakage.

PLENUM CHAMBER

At a system operating pressure of approximately 60 psig, the compressor output is 3.75 SCFM. While this is more than adequate to supply the minute volume for a hard working miner, the peak or highest instantaneous flow rate required is more than three times the minute volume or average flow rate. Therefore, a plenum chamber is necessary to assure adequate pressure to the demand regulators at the peak flow rate. The plenum chamber selected is a small, low-pressure oxygen bottle having a 104 cubic inch capacity. It can be seen, in figure 2-4, installed in the protective enclosure.

PRESSURE RELIEF VALVE

For all but the highest levels of energy expenditure, a miner wearing the respirator system will require less air than the compressor produces. For this reason, a pressure relief valve is a necessary component in the air delivery system. The pressure relief valve is mounted downstream of the cyclone separator so that the cyclone will see a steady flow rate at which cyclones operate most efficiently. The pressure relief port incorporates a muffler in order to reduce noise levels. As delivered, the valve is set to maintain a 60 psig system operating pressure.

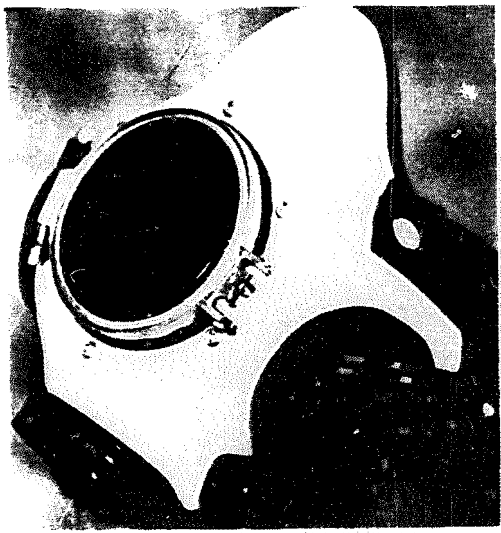
UMBILICAL HOSE

The air-supply umbilical runs from an attachment point on the mining machine to the miner where it is attached to his belt. From there it runs up the chest and branches into two smaller inlet hoses running to the demand regulators on the mask. The main air-supply umbilical, manufactured of dacron reinforced polyurethane and vinyl tubing, has a 1/4-inch bore and a ½-inch outside diameter. While it may be supplied in any desired length up to 30 feet, depending on the requirements specified by a particular installation, a 15-foot length is supplied and is expected to suffice in most instances. A quick-disconnect, manufactured by the R. E. Darling Co., is employed in the main umbilical at the point where it attaches to the belt. When an 18-pound pulling force is applied to the umbilical it parts, separating the wearer from his umbilical. It is important to note that with this quick-disconnect, no manual operations are required. For an emergency egress, all that is necessary is for the miner to begin running (or crawling) from the area. When he reaches the full extension of the umbilical, it will part. The disadvantages of this quick-disconnect stems from the fact that it is of a full-bore, flow-through design and has no provisions to shut off the air flow when disconnected. For this reason, it is necessary to provide a flow sensor within the secondary enclosure which immediately shuts off the air flow when the flow rate exceeds a certain value. When shut off, the flow sensor still permits a small air flow through the umbilical, thus, keeping the line free from excessive dust and dirt contamination.

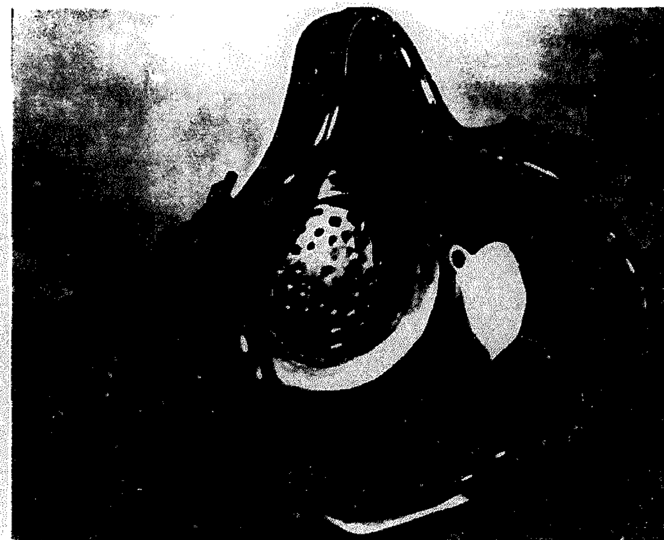
FACEPIECE

The new facepiece design, shown in figure 2-6, incorporates a number of features specifically oriented toward improved acceptance of the device by underground coal miners. Primary among these features are a facial access port (front door) and a specially designed suspension system involving a partial head cover.

The basic facepiece consists of a vinyl elastomeric mask body which includes an inturned sealing surface and a supporting shell of vacuum-formed polycarbonate plastic. The design of the facepiece centers upon incorporation of the two demand regulators and the facial access door whose bulk and weight dictate the overall configuration of the assembly.



Outer view, with the tacial access port closed



Inner view, showing the soft sealing surface

Figure 2-6. Prototype Facepiece Design.

FACIAL ACCESS PORT

The facial access port, shown opened in figure 2-7, permits a number of functions important to underground miners, including expectoration, speaking, and the capability to leave the mask in place on the face when disconnected from the air supply umbilical. The port itself incorporates a voicemitter, taken from a military respirator, to facilitate face-to-face communication. The port can be opened or closed with one hand.

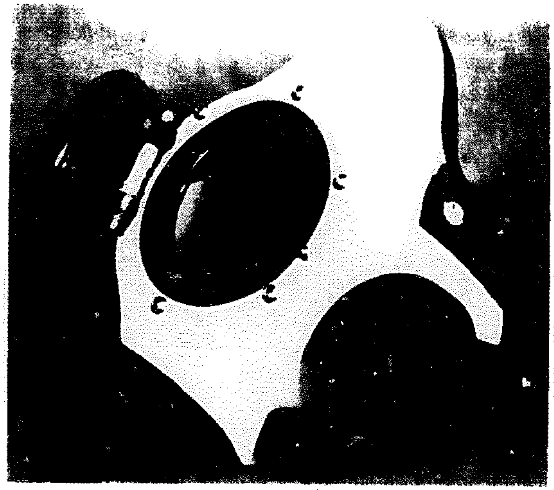


Figure 2-7. Facepiece With Opened Facial Access Port.

MASK SUSPENSION

Recognition of the fact that mining machine operators, especially, are frequently required to move their head from side to side to observe both coal cutting and loading operations, necessitates the incorporation of a fairly wide face sealing surface to add to mask stability during these movements. In order to permit comfortable wear of both the facepiece and protective helmets, the partial head-covering type of mask suspension or harness, shown in figure 2-8, was incorporated. This has another feature specific to coal miners in that they are frequently required to work in a position involving maximal posterior flexion of the neck. It is, therefore, necessary that suspension elements be kept high on the cranium as opposed to lower on the neck where posterior head flexion results in increased strap tension.

Donning and doffing of the facepiece may be accomplished in several ways. With the miner's helmet in place to support the harness cap, it is possible to loosen the hook and pile closures on one side and let the mask dangle by the suspension elements on the other side. In this mode, subsequent donning can be accomplished with one hand. Another method of doffing and donning involves sliding the skull cap down or up on the back

Figure 2-8. Prototype Facepiece with Suspension System.

of the head and permitting the mask to hang from it as it would from a lanyard around the neck.

SIZING AND FIT

While the mask is produced in only one size, it is possible to adjust the fit in several ways. With half-mask type facepieces the critical sealing surface is around the nasal ridge. Adjustment in this area and others are possible by the insertion of foam rubber pads between the outer polycarbonate shell and the inner mask sealing surface, or within the space between the inturned seal and the external mask surface. These adjustments are discussed in detail in the appropriate section of this report.

OVERALL SYSTEM PERFORMANCE

Demonstration tests involving human subjects in a dust chamber revealed an overall gravimetric protection factor ranging from a low of 156.6 to a maximum of 516.0. The lowest protection factor occurred as a result of a small leak in the nasal ridge area due to improper donning by a subject who wore spectacles. The system will supply an average flow rate or "minute volume" of at least 3.75 SCFM with inhalation pressures of less than 0.75 in H_2O. Short bursts of activity at higher minute volumes are well accommodated with the same demand pressures.

Subjective evaluations regarding overall facepiece comfort are quite positive. The ventilation flow rate of 0.75 SCFM (nominal) prevents heat and moisture build-up within the facepiece, thus, eliminating one of the major acceptance problems. While the facepiece is somewhat heavier than contemporary half mask respirators, the suspension system reacts the bulk of this load and the seal pressures are within a range which permits extended wear periods with minimum discomfort.

PART TWO

REQUIREMENTS ANALYSIS

AND CONCEPTUAL TRADE STUDIES

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Section III

REQUIREMENTS ANALYSIS

A systems engineering analysis was conducted in order to define the performance requirements to be met and to define the operational or compatibility requirements (or constraints) specific to the underground mining environment. The performance requirements in general answer the question: "What attributes must a respirator system possess in order to provide the desired protection to underground coal miners?" Implicit within this class of requirements is the general hypothesis that in order to protect the miner, the device must be accepted and worn whenever the threat exists. Because we feel that this "subjective acceptance" is an integral part of overall protection, this type of requirement is treated as a performance requirement. The compatibility requirements are directed toward smooth integration of the respirator system with mining machines, mining operations, and the threats to durability and reliable operation within the underground coal mine. It should be noted that these requirements are as important as the performance requirements in that, if the machine is to be utilized, it must be sufficiently easy to install, that mine operators will buy it, and then it must operate reliably for a sufficient period of time.

In analyzing requirements, it is necessary to distinguish between those which are absolutely mandatory and those which are desirable but not essential. Under ideal circumstances it is possible to assign values to the degree of satisfaction of requirements and then judge subsequent design concepts numerically, based on a quantitative objective function. Such a process is clearly beyond the scope of this program. However, to some extent, the same type of process is involved. The benefits obtained by satisfaction of the requirements are weighed against the cost of providing them in an informal, common sense manner. The point of this discussion is that all requirements stated in this section are not met by the prototype system delivered. The final chapter discusses these departures from the ideal and how these added requirements might be met in the future.

In this section of the report, the fundamental protection requirement is first listed in order to establish the basic goal. Next the various compatibility requirements are discussed, and finally the more complicated performance and user acceptance requirements are presented and discussed.

PROTECTION REQUIREMENTS

The respiratory threat in underground coal mines will consist of both particulate and gaseous contaminants. Alternative means are provided to coal miners for protection against gaseous and smoke particle contaminants. The supplied-air respirator is intended to provide protection against only those respirable dust contaminants which prevail during non-emergency, working conditions. This limits the device to protection against coal dust, rock dust (primarily $CaCO_3$ and $MgCO_3$) and limited quantities of quartz dust which is commonly part of rock dust. While quartz dust is related to pulmonary disease in coal miners, recent legislation limits the amount of quartz in rock dust and therefore the primary emphasis of the dust protection requirement is the removal of coal dust from inspired air.

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PNEUMOCONIOSIS

Dust particles having a mean aerodynamic diameter of less than one-half micrometer behave much like a gas in the lungs and pass in and out in nearly equal quantities with each breath. Dust particles larger than 10 um are temporarily retained by the lungs, but a healthy pulmonary system will expel them in a short time by means of the hair-like cilia lining the respiratory tract. Particles in between these sizes are less affected by these mechanisms and are retained in a manner dependent on their size as illustrated in the pulmonary deposition curve of figure 3-1. Once retained in the lung, local fibrous growths in the area of the deposition result in generalized pulmonary dysfunction.

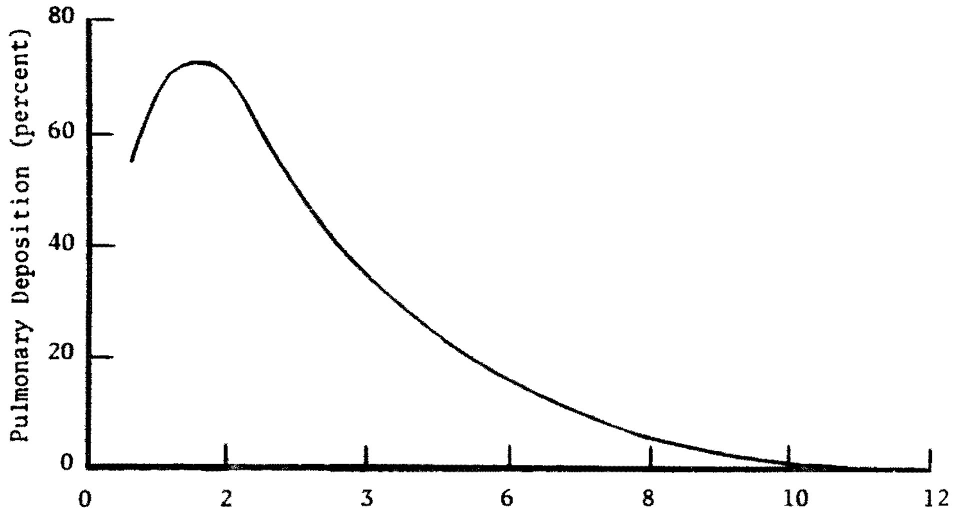

Figure 3-1. Respiratory Deposition for Small Particles.

It should be noted that protection of individuals is made more difficult because of the fact that dust within the respirable range (0.5 um to 10 um) is not visible to the naked eye even when the concentration in air is quite hazardous.

PROTECTION FACTOR

According to the contract governing this program it is required that the breathing air contain not more than 1 mg/m^3 of dust in the respirable range when the ambient air contains 10 mg/m^3. As the data on coal mine dust atmospheres presented in Appendix I clearly shows, ambient dust concentrations occasionally exceed 100 mg/m^3 and it is desirable to protect against such threats, as well.

The demonstration tests required of the system specify that the breathing air within the mask have a dust concentration of less than 10% of the dust concentration in ambient air when ambient air contains 75 ± 25 mg/m^3 of coal dust. This coal dust is sized by rejecting any not passing through a 200 mesh sieve (i.e. the dust has maximum diameter of 72 um).

COMPATIBILITY REQUIREMENTS

As stated previously, compatibility requirements have to do with such factors as installation, power sources, and the capability of the supplied-air respirator system to blend in with the stream of underground operations. Analysis of these requirements requires a careful assessment of mining procedures, mining equipment and the underground environment. In order to make this section easily understandable, much of the necessary supporting data is provided in appendices.

MINING EQUIPMENT COMPATIBILITY

The supplied-air respirator system is intended for installation on face working mining machinery. The type of machinery used depends upon the style of mining employed. Two basic styles of mining predominate in this country: 1) continuous mining, in which coal is extracted from a single face (or entry) at one time by use of a continuous miner and various loading and hauling machines, and 2) conventional mining in which coal is extracted from several faces in a serial fashion by use of undercutting machines, explosives, loading machines, and hauling equipment. A more extensive treatment of the various methods may be found in several references (Woodruff, 1966; Theodore Barry and Associates, 1971). The longwall method, while used extensively in Europe, is seldom employed in this country. The proportions of use of each style are shown in table 3-1.

Table 3-1. NUMBER OF MINERS EMPLOYED AND PRODUCTIVITY BY MINING METHOD IN 1971. (Note 1)

METHOD	EMPLOYMENT	PERCENT OF TOTAL[2]	PRODUCTIVITY (MILLIONS OF TONS)	PERCENT OF TOTAL[2]
CONVENTIONAL, HAND LOADING	2,538	2.7	8.4	2.8
CONVENTIONAL, MECHANICAL LOADING	42,146	44.8	130.4	43.1
CONTINUOUS	49,442	52.5	163.6	54.1

Note 1. Data obtained from the Bureau of Mines, Denver, Colorado, and extracted from computer formats by T. Barry and Associates, Los Angeles, CA

Note 2. Percent of total figures represent fraction among these three methods of mining. Surface mining (strip) amounts to an additional 32,445 employees and 257.6 million tons of coal produced in 1971.

Types of Machines

Based on an analysis of the various machines produced and available statistics on frequency of use (see Appendix II), the requirement for compatibility with the following types of mining machines exists:

a) continuous miners (including auger miners)
b) loading machines
c) undercutters
d) face drills
e) shuttle cars
f) conveyor heads
g) roof bolters
h) powered rock dusters

Installation Requirements

The basic installation requirements include the following:

1. When installed the system shall not increase haulage way, wall or roof clearance requirements of the machine.

2. Installation of the system shall not necessitate the relocation of any existing vehicle component.

3. Changes of operator sitting height or restrictions to his normal movement when operating the equipment, are not allowed.

4. Respirator system power requirements shall not exceed the minimum excess power available during vehicle operation at maximum load levels and durations.

5. The system must be capable of being transported to the maintenance area nearest the face for installation.

6. Only those tools readily available in underground maintenance areas, such as wrenches, welding equipment, etc., shall be required to install the respirator.

7. It must be sufficiently easy to install; the installation should be accomplished without removing the machine from service.

Requirements 1, 2, and 3 above are perhaps more stringent than might be expected at first glance. As illustrated by figures 3-2 and 3-3, many types of mining machines are constructed in a very compact fashion. This is done so that they will fit into low coal seams.

It is obvious that if a respirator system were to be installed on the top of a mining machine it would restrict the machine's capabilities to operate in low coal seams. A less obvious situation, however, is the ramification of the unevenness of seam contours. As illustrated in figure 3-4, the effect of adding thickness (or height) to a machine may cause a restriction in seam heights of greater magnitude than reflected merely in the additional added height. The net result of the above discussion, in terms of require-

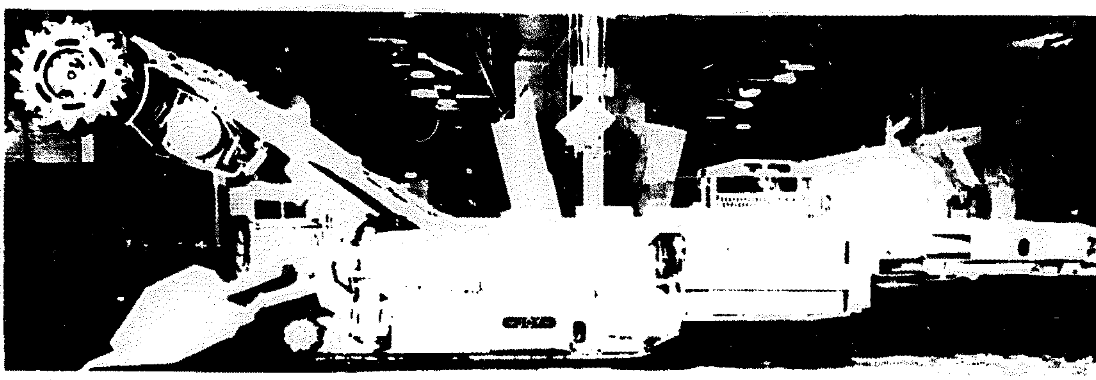

Figure 3-2. Continuous Mining Machine.

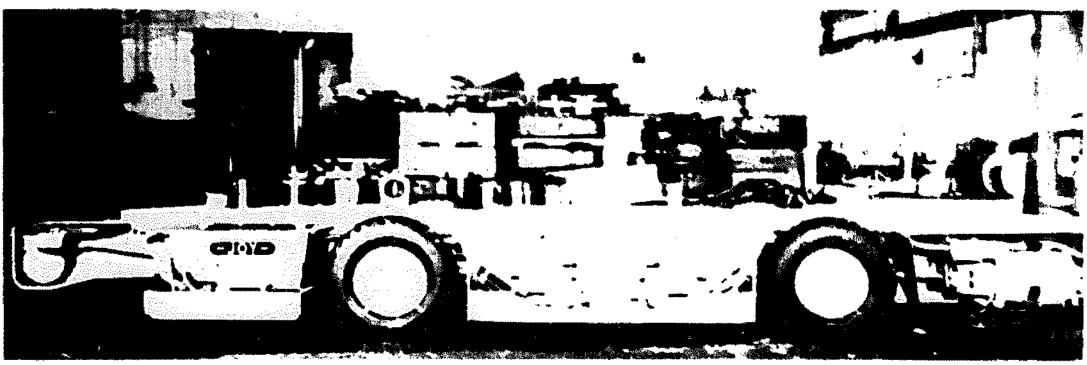

Figure 3-3. A Shuttle Car. Note the bi-directional, recumbent operator's position.

ments, is that the supplied-air respirator must be made as small as possible. And if possible, it should be made up of a number of small modules so that integration of the system with the mining machine does not impact on its clearance envelope in a serious manner.

Requirement seven implies, in general, that only the third shift each day can be devoted to installation. The majority of mines operate two shifts a day for coal extraction and a third shift (hoot-owl shift) for machine maintenance, roof bolting, and miscellaneous tasks.

Power Availability

Face equipment may be powered by hydraulic power, compressed air, or electrical power conversion. A majority of the equipment derive their primary power from electricity through trailing cables. Frequently, the electrical power is converted directly to hydraulic power for each of the functions necessary on the machine (movement, drilling, cutting, etc.).

Electric Power

Mine electrical systems vary considerably in available voltage levels and vehicle power inputs are designed for each mine in accordance with power

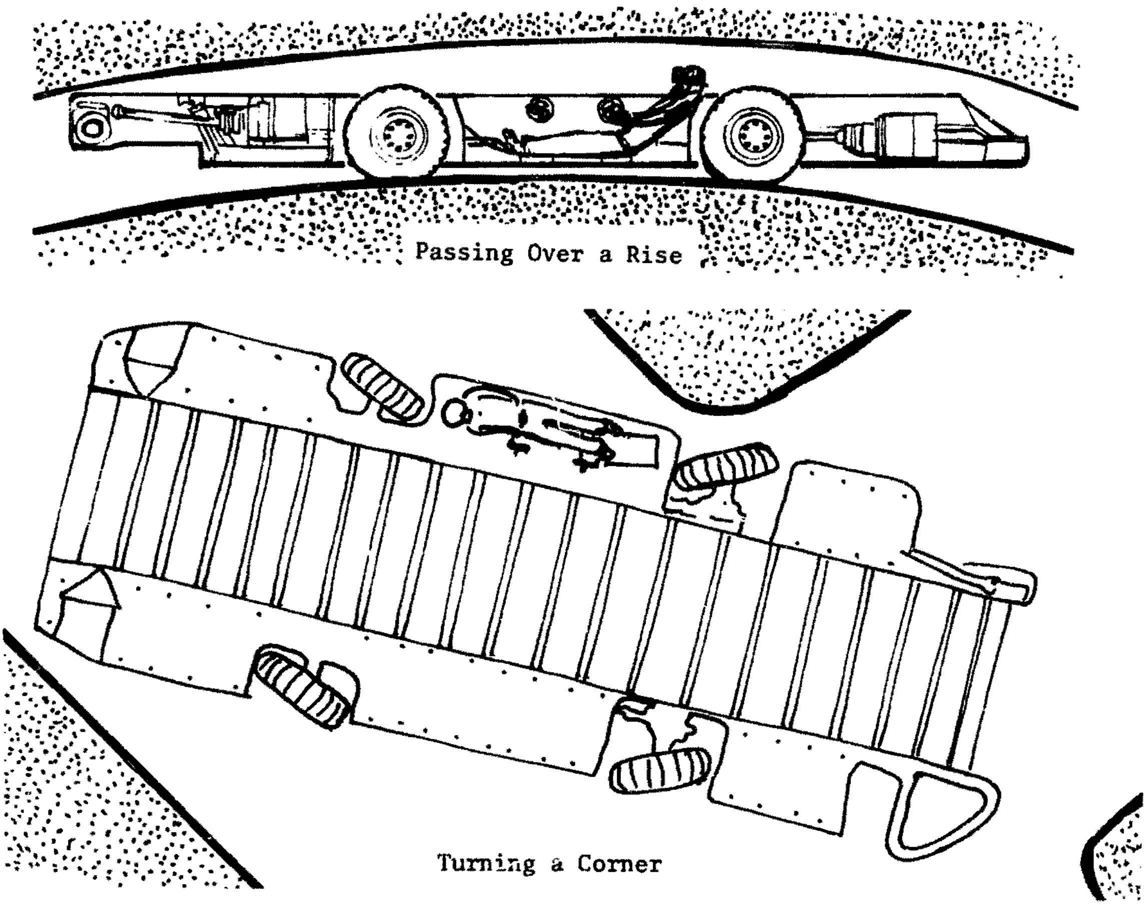

Figure 3-4. Situations Which Require a Machine Clearance Envelope.

availability. Both AC and DC power can be found, however 220 VAC and 440 VAC are probably the most common found at the mining machine input. Frequently, a limited amount of power is available at the 12 VDC level from the vehicle lighting system.

Hydraulic Power

Perhaps the most uniform source of available power found in underground coal mines is hydraulic. As evidenced in Appendix II a vast majority of the machines commonly used in underground mines have hydraulic power, of some sort, available. Discussions with several mining machine manufacturers indicated that the extraction of a flow of hydraulic fluid in the range of one or two gallons per minute would not tax the systems noticeably. Hydraulic pressure in the range of 1800 to 3000 psig appears to be the most commonly available. In many cases, several levels of hydraulic pressure are available on a given machine.

MINING TASKS AND OPERATIONS

While the basic styles of mining addressed in this program are limited to continuous mining and conventional mining styles, the specific operations involved at any mine are dependent upon a number of factors including seam height, roof integrity, and the experiences and methods adopted by the mining company and the mining supervisors. An analysis of tasks and operations involved, based upon observation in several underground mines and upon discussions with various consultants familar with a wide variety of mining operations, produced a number of requirements that a supplied-air respirator system must meet. These requirements are based more upon similarities in attitudes and operations than upon differences among the various styles of mining. The differences in tasks and operations between continuous mining and conventional mining do not necessarily result in different requirements for the supplied-air respirator.

Perhaps the most enlightening result of this analysis concerns the basic attitudes held by underground coal miners. First of all, there is a very strong team spirit among the 7 to 14 members of a mining crew. While each man may have a specific task, such as continuous miner operator, shuttle car operator, etc., his activities are certainly not limited to that function. The team members are very strongly oriented toward producing the most coal they can during each shift. Exceeding a certain production, say 400 hundred tons per shift, is cause for considerable camaraderie and bragging among compatriots and, of course, approval by management. This orientation among the operators and crew results in a number of requirements for a supplied-air respirator. These include compatibility with the hard work commonly seen and reduction of individual task interference. While these latter requirements will be treated in the next section the basic orientation toward productivity must be kept in mind during all discussions of respirator requirements and designs for meeting them.

Duty Cycle

Both continuous and conventional styles of mining result in periods of high machine activity and periods of lesser or no machine activity. The requirement for respiratory protection parallels these cycles. The order of magnitude of these cycles might be 3 to 5 minutes of heavy activity followed by 1 to 3 minutes of reduced activity.

Continuous Mining

Basically, a continuous miner can cut coal faster than it can be loaded on the haulage equipment. Additionally, as the continuous miner advances it is necessary to provide roof support in the form of timbers or roof bolting in order to prevent a roof fall. Consequently, a typical cycle involves two to five minutes of continuous cutting operations followed by several minutes of inactivity on the part of the continuous miner while several auxiliary operations are performed. These operations include installation of roof support, loading of coal onto a shuttle car, if a separate loader is required, changing from one shuttle car to the other at the output of the continuous miner and cleaning of the loose coal from the floor by hand. Shuttle car operations are similarly cyclic with some periods being spent butted against the rear of the continous miner accepting the coal that is being cut, some periods being spent tramming back and forth between the continuous miner and the secondary haulage such as a conveyor belt, or waiting. During periods of inactivity, the operators of the machines involved are likely to dismount and assist in another operation, such as setting timbers or shoveling coal from the floor. For example, the operator of an auger miner is likely to dismount and place or remove a timber prior to moving the auger machine.

Conventional Mining

Factors affecting the supplied-air respirator duty cycle requirements in the conventional mining situation are different but result in the same type of duty cycle requirements. In conventional mining, several faces are active at one time. Each machine moves from one face to another in rotation. For example, a loading machine and a pair of shuttle cars might work together as a team. Following the blasting cycle, they would load coal from one face area until all the coal resulting from the previous blast had been loaded, and then they would move on to the next face. It co' l happen that they have to wait for a few minutes until the blasting operation is complete or they might move directly from one to the other if the blasting cycle is short enough. The same type of operating cycle applies for all of the machines involved in conventional mining. Thus, as in the previous case, the duty cycle includes two to five minutes of heavy activity during which time the machine is performing its appointed function, followed by several minutes of either waiting or movement to the next area. During the waiting period or the moving time, respiratory protection, while perhaps desirable, is not needed as badly as during active operations.

Maintainability

Freedom from interuption of the normal flow of activities within the coal mine is perhaps one of the most important requirements levied upon the supplied-air respirator. Every man involved, from the mine owner down through every level of worker on the underground team, is very strongly oriented toward producing as much coal as possible on each shift. If a respirator system, either directly or indirectly, were to cause a halt in production for any sizeable period of time it would be the object of considerable hostility. Therefore, it is a requirement that the supplied-air respirator require a minimal amount of servicing. Furthermore, it must be sufficiently reliable that it does not malfunction, or even worse, cause a malfunction in the mining machine. For instance, in a hydraulically-powered device, if a major leak in the hydraulic system were to be encountered, one would expect to find the respirator system permanently disconnected and discarded shortly thereafter.

Another factor affecting maintainability requirements has to do with the logistics involved in underground coal mining operations. Articles requiring replacement during a normal operating shift must be transported to the underground site (face area) by the individual miner at the beginning of each shift. It should be recognized that, in the vast majority of mines in this country, the distance traveled from outside of the mines to the working face is several miles. The trip usually involves traveling some distance on a locomotive, in some cases a period of time riding a conveyor belt in a prone position, and a fair amount of walking or crawling to the area. Thus, items to be transported to the face are subjected to considerable abuse and, if they are of any size or weight, become a problem for the individual involved. For this reason, it appears that the supplied-air respirator system must not require frequent filter changes, or refurbishment of any other device.

MINING ENVIRONMENT

In the underground coal mine, one finds very few devices which are not specifically designed for the purposes intended. Articles of equipment are designed to withstand the hazards existing and to reduce the potential hazards such as fire or explosion which are always uppermost in the miner's mind.

Underground Safety

It is obviously a requirement that the supplied-air respirator be able to achieve the permissibility requirements imposed by the Bureau of Mines for all underground equipment. For electrically operated devices the achievement of such a condition involves the use of explosion-proof motors and explosion-proof housings for switches, and circuit overload protection. Specifics of these requirements are presented in the Code of Federal Regulations, Title 30, and will not be repeated here. Other factors to be considered among the safety requirements include capability for emergency egress, prevention of potential entanglements, placement of the air intake, and compatibility with certain sensory functions.

Emergency Egress

Although the frequency of non-injury producing roof falls in the underground coal mines has not been established, it may be inferred from the number of injuries produced by such occurrences that they are fairly frequent. According to Mangelsdorf (1972), roof falls in 1968 represented 20.6% of all lost days due to injury and resulted in 15 fatalities. Their frequency in an individual mine is, of course, dependent upon the condition of the material making up the roof. Some mines are known to have "bad top" and in these mines the individual miners are continually monitoring the roof for an impending fall. This is done by listening for creaking or groaning, and by visual observation, or tapping the top with a suitable hammer to "sound it out".

Accordingly, interviews with a number of underground coal miners indicated that their major concern with using vehicle installed respirator systems is the potential loss of the ability to escape rapidly from the vehicle in an emergency. Because of the limited warning time any significant increase in escape time imposed by "being tied" to the system will be unacceptable.

The establishment of an allowable escape time is not possible nor realistic; thus, the requirement is established for detachment of the miner from the system without involving discrete manual tasks to effect separation. This requirement implies that the miner be able to leave the vehicle by any means possible (including any direction) and that the umbilical separate in response to pull forces when he reaches the end of the umbilical. These forces can vary in magnitude depending on the focal point of the force input to the man on the one hand, and the possibility of inadvertent detachment, on the other hand.

While the facepiece retention mechanism is a possible reaction point it would be hazardous in terms of neck injury with separation forces of more than one pound.

On the basis of pilot experience in the USAF a minimum detachment force of 20 pounds is required to prevent inadvertent disconnect. Forces of this magnitude can be exerted by the torso with a low probability of introducing torque forces of sufficient magnitude to change the body's path of motion or to appreciably change its rate of travel. Similar forces reacted through the limbs are considered unacceptable in terms of rapid egress.

Any means provided for emergency egress may be used for normal egress procedures. Consequently, the quick-disconnect feature is to be designed to provide for reuse. It is estimated that under normal operational conditions that disconnect/reconnect operations may occur as frequently as 20 times per shift.

A major problem envisioned with quick-disconnect concepts, where part of the air hose remains attached to the facepiece and the belt, is the possibility of snagging the hose. For this reason, the length of hose which is free to dangle must be minimized. A 6-inch length of free hose (from the reaction point) is estimated to be a maximum permissible length, in terms of safety, which can be manually manipulated to effect connection.

Entanglement

As discussed in Appendix II and illustrated in figure 3-2, many of the mining machines offer a number of potential hazards involving entanglement of an air supply respirator umbilical with rotating machinery on the mining equipment. These considerations produce a design requirement that the umbilical be configured and managed in such a way as to reduce the potential hazard associated with entanglement. As well, it is required that in the event of entanglement, the user must not be drawn into the rotating machinery. The same type of reasoning applies to the facepiece suspension and any other parts of the respirator system.

Emergency Warning Compatibility

In addition to the requirement, already discussed, concerning a miners capability for observing an impending roof fall, he must be able to communicate with others regarding imminent dangers. This means that he must be able to shout a warning, without hesitation, and that its sound intensity be altered as little as possible. Of course, at the same time, the respirator should not interfere with hearing the warning.

Because of the high ambient noise levels within mines and the logistical problems associated with a moving work place, another sensory stimulus is sometimes used for warning devices - odor. Many underground mines employ a "stench" type warning system in which a strong odor is released into the ventilation system to signal an emergency such as fire or explosion. For this reason, it is required that the supplied-air respirator system not remove odors present in the mine environment or mask them due to odors generated by the respirator system.

Anti-suffocation Capability

In the event of a roof fall, for example, a miner might find himself in the position of having his arms rendered immobile, the respirator facepiece on his face, and the respirator supply not providing air to him. If the respiratory facepiece were of the tight-fitting variety then it might be possible for a man to suffocate under these circumstances. Therefore, the requirement exists, in the event of a respirator system malfunction, that no manual operations are required for the wearer to breathe ambient air.

Mine Atmospheric Conditions

A detailed discussion of the various results of several investigative programs regarding atmospheric dust in underground mines is presented in Appendix I. These results, as well as other factors of interest, may be summarized as follows:

1. Dust: Coal mine dust is basically comprised of small particles of coal and the various constituents of rock dust. While the rock dust is a comparatively small fraction of the overall dust, it is equally important that it be removed from the breathing atmosphere. Dust concentration near the working face is, of course, dependent upon the style of mining, the type of coal, and the machines and methods used in mining. However, one can routinely expect total airborne dust concentrations to average from 10 mg/m^3 to 50 mg/m^3. Of this, approximately 10 percent would be expected to be in the respirable range. Locations within the envelope of certain mining machines exhibit concentrations far in excess of this figure, and in some mines, the concentration will exceed 100 mg/m^3 averaged over a day.

2. Temperature: Temperature of the air at the face is dependent upon its initial temperature and how far and how fast it is transported to the working face. With high velocity ventilation flows of short distance, the ventilating air will approximate the outside temperature and thus, can range from below zero to more than 100°F depending upon the climate of the area. While these extremes may well be encountered in some mines, by far the predominant number of mines exhibit temperatures at the working face in the neighborhood of 55 to 65°F.

3. Relative Humidity: 40% to 100%.

4. Airborne Water Droplets: Water droplets generated by mining machine dust supressors, ground water being splashed, and seepages from the top and sides of the mine are commonly encountered in underground coal mines. In many cases, water droplets are mixed with rock dust or coal dust, producing a serious hazard to the integrity of respirator systems.

5. Inlet Ventilation: As discussed in Appendix I, it should be recognized that incoming ventilation air is not always free from dust contaminants in the respirable range.

Mine Physical Environment

The physical attributes of underground coal mines. including such factors as seam height, probability of roof fall, water and acid threats, as well as the airborne dust contamination, produce an environment which is hostile to both the individuals working there and to the machinery that they use. It is important to take these factors into account when establishing design and performance requirements for the supplied-air respirator.

Seam Heights

As illustrated in table 3-2, seam heights in US coal mines vary from 28 inches to over 10 feet. Half of the coal mines have seam height of less than 4 feet. A requirement then exists for the supplied-air respirator system to be designed for installation on mining machinery in a fashion that will provide the smallest change in the external dimensions of the machine. In addition, and more important perhaps, since low seam coal operations require the miners to perform their task in a stooped or crawling position, the unit must provide trouble-free operation when the user is limited to such positions. Of course, installation and maintenance activities must often be performed with the same restrictions.

Table 3-2. SEAM HEIGHT IN UNDERGROUND COAL MINES VERSUS MAN-HOURS WORKED (Data from T. Barry & Associates derived from Bureau of Mines data of 1969).

Seam Height (feet)	<3	3-4	4-5	5-6	6-7	7-8	8-9	>9
Millions of Manhours	14.9	38	39	20.7	17.4	11	3	4

Roof Falls

As mentioned previously, roof falls are a fairly frequent event in the underground environment. In addition to the matter of egress already discussed, it is essential that the supplied-air respirator system be able to withstand the impacts and crushing forces of the roof fall and still be operable when it is dug out at a later time. While every possible eventuality cannot be covered as a requirement, it is arbitrarily established that the unit should survive intact when a 400-pound rock is dropped on it from a distance of 3 feet.

Chemical Contaminants

Due to the high sulfur content in some coal seams, ground water and water leaking from the top and sides of the mine frequently contains high concentrations of sulfuric acid. A worst case for concentration of sulfuric acid is probably on the order of a pH of 4.5.

Other contaminants which must be considered include hydraulic fluid, lubricating oil, and grease, and their breakdown products. Like any heavy machinery, large quantities of oil and grease are necessary for operation of the continuous miners, undercutters and loading machines. As might be expected these lubricants find their way onto many surfaces, thus providing another potential hazard to respirator reliability. Hydraulic fluid is sometimes dumped directly on the mine floor where, in a low seam mine, it might easily be transmitted to the gloved hands of the miner and eventually to the respirator system components.

PERFORMANCE REQUIREMENTS

In the previous part of this section we have indicated the basic protection requirement and the requirements regarding limitations on the configuration and operations of the supplied-air respirator system. The remaining part of the section is devoted to the type of requirements commonly called performance requirements. This class of requirements, in general, indicates what the device must do, how much air it should provide, acceptable levels of air quality, how comfortable it must be, and what attributes it must possess so that individual miners will be inclined to utilize the device, if needed.

It should be pointed out that the supplied-air respirator system will be committed to one or two shifts underground, five days a week, for the extent of its useful life. Acceptable performance of the requirements listed below is, therefore, implied to mean maintenance of these levels for this entire period. Demonstration of the system's capability for continuous performance, required by contract, is limited to contiqued performance for 8 hours in an atmosphere containing an average of 10 mg/m^3 of coal dust. The dust size is to be such that all particles pass through a 200 mesh sieve.

AIR FLOW RATE

Stating a requirement for air flow rate entails essentially two separate statements. One concerns the minute volume and the average flow rate over some period of time, say several minutes, to be provided. The second concerns the peak instantaneous flow rate achieved during a single inhalation. In summary, the following requirements have been derived:

Minute Volume: 2.83 SCFM

Peak Instantaneous Flow Rate: 9.3 SCFM.

While these requirements might seem excessive in view of contemporary supplied-air respirator performance and performance standards, it must be kept in mind that the underground coal mining environment is not typical of the every day industrial environment. As previously stated, coal miners are known to be excessively hard working individuals. Their work is not self-paced, but is rather paced by the mining machinery cycle. The desire to produce as much coal per shift, as possible, frequently necessitates periods of hard work and, in many cases, this is performed in very cramped quarters. A more detailed statement of how these figures were produced is presented in Appendix III.

While the above flow rate requirements reflect a worst case requirement, that is, a big man working very hard, it should be kept in mind that the design goal is essentially to provide the same air flow as one would achieve if he were not wearing a respirator. Continuous air flow rates, greatly exceeding the demand, in our opinion, are uncomfortable causing such subjective discomforts as eyelash flutter (in the case of full-face masks) and drying of the skin, lips, and nasal passages. Since experimental results indicating subjective acceptance of various flow rates within the face mask are not available, it is sufficient to state the requirement that a discomfort will not be caused from the air flow rate within the respiratory facepiece.

AIR QUALITY

The temperature of the air delivered to the wearer is required to be within 5°F of the ambient air temperature. No additional odors may be added to the breathing air. Air delivered to the breathing zone should be free of water droplets. However, it is not a requirement that the breathing air be delivered at very low humidities. Rather, it is more comfortable to breathe air having some moisture content. While exact data are not available on this subject, a relative humidity on the order of 75% appears to be reasonable.

Of particular importance in design of a machine-mounted respirator system is that the air delivered to the user be free from carbon monoxide, ozone, and oil vapors which may be produced by the motors powering the heavy equipment. This requirement may necessitate the capability of providing ducting to the system inlet so that the actual air inlet port can be positioned at a more desirable location than the location selected for system installation. Contemporary standards regarding acceptable concentrations in industrial work places should be consulted for determining whether or not air quality is within satisfactory limits.

The concentration of carbon dioxide inhaled is only slightly dependent upon inlet placement, but is strongly dependent upon the effective respiratory dead space within the facepiece and respirator system. While acceptable maximum carbon dioxide concentration is sometimes set at 1%, or 1-1/2% it is our opinion that for truly stress-free conditions over a long term for hard-working persons, some of whom have reduced ventilatory function, the inspired carbon dioxide concentration must be as close to zero as possible, but in no case greater than 0.5%.

BREATHING RESISTANCE

The use of any respiratory protective device results in subjective unpleasantness which can not be reduced. The addition of breathing resistance, pressure differentials at any time, and excessive air flow rates within the confines of the facepiece add to the problem. Since the goal of this project is to provide a particularly comfortable unit, very careful attention must be given to these potential problems. The design goal is, of course, to achieve similarity with the "no-mask" condition. Since this condition can not be attained, the basic question becomes "What is a reasonable range of departure from the ideal"?

In determining these parameters the questions of environment and work levels are very important. For example, a breathing resistance that is comfortable during sedentary conditions may not be tolerable at high work rates. While some literature has been cited in preparing this section, many of the statements made, herein, reflect opinions held by the authors, based on their experience in the field.

Inhalation Resistance

The human respiratory system is a quite sensitive pressure sensing apparatus. Bennett (1962) reports that all of his sedentary subjects could detect the presence of inhalation resistance at 0.023 cm H_2O/L/min, or less. By comparison, a common inhalation resistance for military respirators (eg. M-17) is 0.09 cm H_2O/L/min. It is important to note that the greatest importance of breathing resistance has to do with comfort. Physiological results, limited exercise capabilities, or reduced cardiac output are not likely to be encountered with any but very high breathing resistances. Then, based on achievement of comfortable breathing, it is reasonable to require that the wearer not be required to exert more than approximately 2 cm H_2O inhalation for a peak flow rate of 3 SCFM (85 L/min) which corresponds to peak flows associated with "normal" minute volumes.

Exhalation Resistance

A rule of thumb, sometimes adopted, is that to achieve maximum subjective acceptance, exhalation resistance should be on the order of one-half the inhalation resistance. While little is known about subjective acceptance of exhalation resistance, human sensitivity is probably more acute to exhalation resistance than to inhalation resistance. Therefore, a tentative requirement of exhalation pressures of less than 1-½ cm H_2O at 85 L/min is stated..

Pressure Transients

With demand regulators one is ordinarily concerned with an opening or "cracking" pressure differential, as well as the pressure differential occurring during higher flow rates. This cracking pressure should not exceed 5 mm H_2O. On the other hand, demand regulators often "overshoot" once triggered, resulting in sudden bursts of positive pressure within the respirator. These are equally objectionable and it is, therefore, required that no mask positive pressures be caused by regulator overshoot.

The tendency of exhalation valve discs to adhere to the valve seat, thus creating a popping sound with each exhalation, has often been cited as an undesirable characteristic. This popping is subjectively annoying and can be demonstrated as a pressure spike preceding valve outflow during the exhalation cycle. Exhalation valve flutter is equally annoying (whether it is audible or not). This is especially true during speech and at low flow rates where the subjective aspects of breathing encumbrances are sometimes more apparent.

Detection of pressure oscillations by respirator wearers is apparently quite acute. In one limited study (Allen, 1965), it was found that the most sensitive subject could perceive oscillations within a mask as low as ±

0.05 cm H_2O at about 30 cps. The mean for ten subjects was approximately $\pm$ 0.15 cm H_2O. Instabilities, producing oscillations of this magnitude, could result from action of the exhalation valve, compressor, regulator, control valves, or be induced within hoses. Care must be exercised to prevent or to muffle such oscillations.

FACEPIECE COMFORT

While no precise design requirement can be indicated regarding facepiece comfort, the overall performance objectives are clear. The facepiece, in its entirety, must be designed for continuous wear throughout a typical coal miner's shift. Since travel time to the working face is usually quite time consuming, the actual working shift, excluding breaks, is about six hours. The facepiece and its suspension must be compatible, in terms of comfort, with the underground environment. This necessitates careful consideration of the effect of coal dust, moisture, and perhaps other contaminants, previously indicated, upon such factors as the facial sealing surface. To a large extent, it may be stated that facepiece comfort is improved by having a broad sealing area distribute the forces, and a light-weight mask to reduce the forces. Based upon subjective analysis of contemporary half-face facepieces it became clear that the most sensitive area in mask design is the area around the bridge of the nose. Therefore, this area must be stressed in evaluating candidate masks.

INDIVIDUAL TASK COMPATIBILITY

Perhaps one of the most important classes of requirements has to do with the capability of the supplied-air respirator to blend in with the tasks performed by the various equipment operators in underground coal mines. In view of the working environment and the desire to achieve high productivity on the part of individual miners, this class of requirements is easily the most difficult to achieve. While the previously listed performance requirements tend to stand alone, the performance requirements having to do with task compatibility, equipment compatibility, and anthropometric requirements must be considered in an integral fashion.

Machine Operations

As discussed below, the machine operations are ordinarily conducted from either the semi-recumbent position or a kneeling posture. The machine controls are, typically, levers arranged in a row and exhibiting little, if any, thought to the human factors of displays and controls. Operator manual requirements are to reach the correct lever and operate it. In many cases, such as with the continuous miner or a roof bolter, operations of the wrong lever can result in a catastrophe. This is primarily due to the close proximity of other personnel supporting the machine operation. For instance, swinging the cutting boom of the continuous miner in a lateral fashion, rather than straight ahead, at an inappropriate time could cause the cutting boom to strike a miner who might be setting timbers nearby.

Since miners ordinarily wear work gloves which reduce tactile sensation, location of the proper control is frequently based on visual observation. Careful visual observation of a particular objective of the machine operation is of primary importance. Visual capabilities in the underground environment are severely limited by the nature of the environment, the tasks and the machines involved. During most machine operations the atmosphere is clouded with dust. The machines are fairly large and tend to obstruct vision toward the objective. With most operations, the visual tasks involve rapid alternate observations of the objective, and the controls. This fact, in conjunction with the arrangement of the controls, indicates that rapid rotational head movements are frequently required.

In summary, essentially three respirator design requirements evolve from these considerations.

1. The respirator system must not interfere with rapid hand and arm movement forward of the body and across the chest.

2. The respirator must not impede operator vision. Since many operators must maintain the semi-recumbent position, obstruction of vision in a downward direction is especially objectionable.

3. Because of the rapid rotational head movements, it is essential that the mask suspension on the face be particularly compatible with rapid rotational head movement.

Dismounted Tasks

As mentioned previously the spirit of cooperation and goal orientation of underground coal mining crews results, to a great extent, in a situation where machine operators frequently dismount and perform some auxiliary task. Examples of these tasks include the following:

Setting timbers.

Cleaning the floor with a shovel.

Moving a heavy electric or hydraulic cable.

Inspection of the machine or some aspect of the environment.

Maintenance of the machine, such as greasing or bit replacement.

Assistance with another primary task, such as shot firing.

The requirement that the respirator be worn during these dismounted tasks is somewhat uncertain. While, from a purely physiological viewpoint, respiratory protection might be important during these periods, visual perception of the dust hazards during periods when machines are not operating is usually low. Therefore, it is unlikely that the individual miner will feel compelled to employ respiratory protection during these periods. Thus, the major requirement resulting is that the supplied-air respirator be simple to don and doff. Alternately, it may be configured in a fashion where the respirator may remain donned but, otherwise, does not impede egress from the machine for the performance of auxiliary tasks.

A primary impact of the dismounted tasks upon respirator performance requirements concerns air flow rate requirements. While the matter is discussed more explicitly in Appendix III, it is during these times that the highest energy expenditure rates are incurred and consequently the minute volumes demanded upon return to the machine reflect the work just completed.

Because of the high noise levels associated with machine operations, miners have developed a rudimentary form of communication using their cap lamps. However the team work involved in underground coal mining requires a considerable amount of verbal, face-to-face communication. Furthermore, it is sometimes necessary for miners to shout warnings or instructions over some distances. It is frequently necessary for a mining machine operator and the supervisor to discuss alternative actions in some detail. For these reasons it is a requirement that the supplied-air respirator system not impede hearing or verbal communication. While it is possible to doff a face mask in order to speak, the frequent requirement for verbal communication and thus for donning and doffing, renders this a less than desirable solution to the communication problem.

INDIVIDUAL EQUIPMENT COMPATIBILITY

The rigors of the underground environment make it necessary for miners to carry on their person a considerable amount of special equipment. In order to be acceptable to underground miners the supplied-air respirator system must be compatible with this equipment and not add significantly to an already heavy burden. A description of the basic items of personal gear follows.

1. Protective helmet or cap. Miners typically wear one of the standard industrial "hard hats". The hard hat is worn all day on a continuous basis and is fitted with accessories suitable for mounting the miner's cap lamp.

2. Cap lamp. The cap lamp system consists of a small lamp mounted on the forward part of the helmet, an electrical cable running over the top of the helmet, and a battery mounted on a waist belt. The electrical cable, which is typically 0.35 inch diameter, is secured at the back of the helmet by a small clip, then runs over the shoulder toward the front, then rearward under the arm down to the belt where it attaches to the cap lamp battery. The cap lamp battery, weighing several pounds, is attached to the miner's belt either on the side or further rearward, depending on the miner's job. The lamp is turned on at the beginning of the day and ordinarily not turned off until the miner's work is done at the end of the day.

3. Self Rescue Unit. In all mines, the self rescue unit, weighing several pounds, and mounted on the miner's belt, must be carried at all times. It is used only in emergencies when the ambient air is unfit to breathe. It is ordinarily mounted on the side opposite the cap lamp battery.

4. Some miners, particularly supervisors, wear, suspended on the belt, a flame-proof lamp whose purpose is to detect the presence of methane in the atmosphere. Again, depending on the manufacturer, it weighs several pounds.

5. Gloves. Almost all miners wear heavy duty work gloves continuously.

6. Clothing. Typical underground clothing consists of either coveralls or heavy duty work clothes. Usually several layers of clothing are worn and, in colder mines, a coat is worn, as well. Ten to fourteen-inch high rubber boots complete the ensemble.

The above list contains the items normally found during routine mining operations. Figure 3-5 shows a miner fully equipped, ready for work. Of course, the full gambit of industrial protection or environmental protection devices is sometimes seen. This includes such things as welder's visors, eye shields and goggles, ear protectors, radios, winter liners for the helmet, etc. However, most of these are of less concern because they are used infrequently.

Of special consideration in the design of a supplied-air respirator is compatibility with the helmet and cap lamp. It is, of course, required that the respirator suspension be compatible with the helmet suspension and that the two can be worn together comfortably for six to eight hours. Furthermore, it is required that donning and doffing of the respirator facepiece may be conducted without removal of the helmet. Helmet removal in an underground mine is not a simple operation. Since the helmet is attached to an electrical cord it is difficult to find a reasonably clean and dry place to lay the helmet down. Thus, one is required to hold the helmet in one hand while donning or doffing the respirator.

It should be pointed out that the only place to put things, aside from where they are worn, is on the floor or on the surfaces of a machine, both of which are covered with coal and rock dust and in many cases water. Furthermore, in low coal seams where a miner is required to crawl on all fours, his gloves become quite wet and dirty. Consequently, anything he touches becomes covered with some combination of oil, water and particulate matter. For this reason, it is required that donning and doffing of the respirator system not involve contact with the sealing surfaces of the facepiece.

ANTHROPOMETRIC REQUIREMENTS

Anthropometric requirements are of two varieties. The first has to do with miner work space or the physical dimensions of machines and the underground mining environment. The second has to do with facial anthropometry and the design of the respirator facepiece.

Miner Work Space

As shown in figures 3-2, 3-3 and 3-6, mining machine operator work-space arrangements exhibit the bare minimum in creature comforts and concern for human factors. On some machines, there is a seat for the miner upon which he reclines to operate the controls. In another type, there is no seat provided and the operator merely stands, or more likely, kneels next to the machine. In many cases, particularly shuttle cars, in order to see the work being performed the miner must lean toward the outside of the vehicle at a considerable angle. Operators of machines which provide seats are precluded from wear-

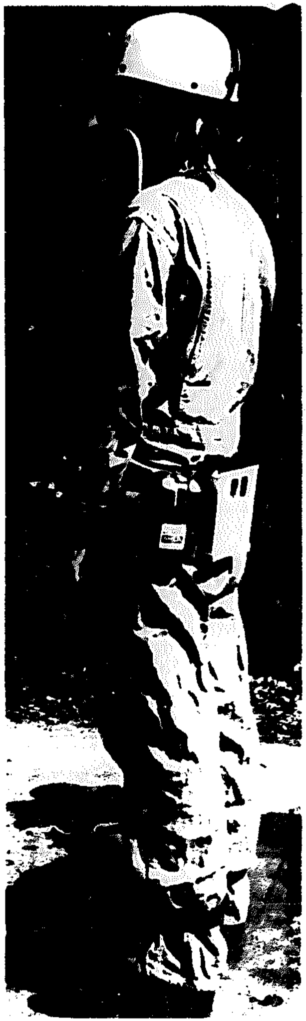

Figure 3-5. Typical Protective Equipment Worn By an Underground Coal Miner.

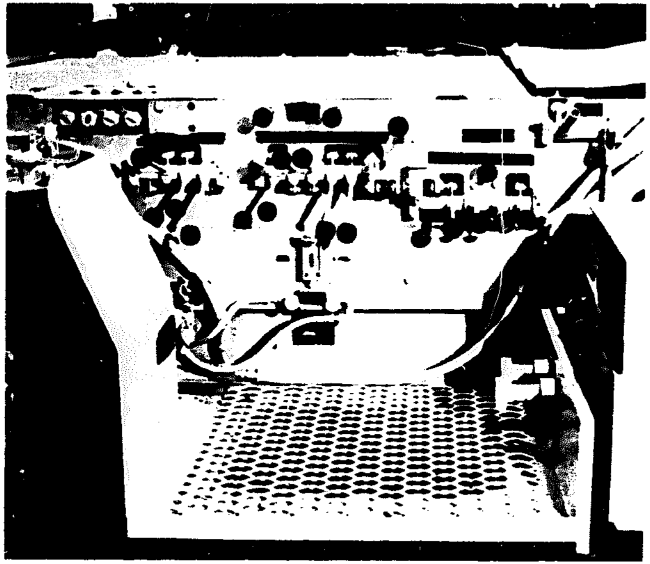

Figure 3-6. Typical Mining Machine Operator's Station.

ing any personal devices mounted on the back since they must assume the semi-recumbent position. At the same time, any but the most minimal protrusions from the chest would interfere with arm movement. Since these individuals usually wear the cap lamp battery on one hip and the self-rescuer on the other hip, these areas are precluded from consideration as likely sites for mounting respirator components. The operator kneeling at his work station could, on the other hand, utilize back-mounted respirator system components.

When dismounted from the machine, individuals are precluded from wearing back-mounted equipment to an extent based upon seam height in that particular mine. Mine roofs are often cluttered with electrical cables causing severe entanglement problems with back-mounted respirator components.

Another matter of anthropometric concern is the utilization of the cap lamp. Because miners utilize the cap lamp to observe the work in progress, they sometimes tilt the entire helmet forward or rearward on the head so as to get a better view from reclining, or crawling postures. This activity must be considered in the design of the respirator facepiece and suspension harness.

Facial Anthropometry

The facepiece of supplied-air respirator systems is to be designed to accommodate the entire underground mining population. More than one size may be produced, if required. A more detailed treatment of facial anthropometric requirements is provided in the section on facepiece conceptual design.

Section IV

CONCEPT SYNTHESIS

Supplied-air respirator systems of several configurations can be conceptualized which would meet the requirements set forth in the previous section. In fact, there are several supplied-air respirators currently on the market which in some degree meet these requirements. In the concept synthesis phase of the program, existing supplied-air respirator systems were evaluated, several new concepts were synthesized, and all were analyzed in regard to their feasibility of meeting the requirements.

Analysis of currently available supplied-air respirators revealed that none were available which met the specific requirements of this program. The requirement that the system be compatible with existing protective helmets precluded consideration of the Whitecap HYD system, and the requirement to use available machine power precluded consideration of the cryogenic respirator developed by Essex Cryogenics for underground use. Evaluation of these units and other battery-powered, portable, supplied-air respirators did, however, provide considerable insight and influenced the development of the design concepts and performance requirements.

The basic process in this phase of the program is to synthesize several alternate concepts, each of which is potentially able to meet the requirements set forth in the previous section. These concepts are carried through a rudimentary design process to the point of specifying size, weight, cost, and their potential to meet the performance and compatibility requirements. In performing this activity, it is necessary to assess the state of the art, or potential advances in it, for the various component technologies involved such as air cleaning, power sources, and facepiece design.

PRELIMINARY CONCEPT FORMULATION

At the outset, self-contained air supply systems, in which air or oxygen is stored in liquid, compressed gas or chemical form were excluded from further consideration after a brief analysis. Their inherent size, weight, and and logistical attributes preclude them from suitable use on a continuous basis. Furthermore, since the thrust of the program is to utilize power available from mining machines to reduce the respiratory burden, man-portable systems, in which battery power for continuous flow systems is carried on the body, were, as well, precluded from further analysis. This is, in part, justified by the fact that several such systems are currently available on the market.

While it is never entirely possible to separate the primary functions to be performed by the supplied-air respirator system, it is helpful in the conceptual phase and in the analysis of conceptual components to consider the systems as composed of four major functional elements as follows:

Air moving
Dust removal
Clean air distribution
Facepiece

The air mover functional element includes an air compressor (fans, blowers, reciprocating compressors, or other varieties of air compressors) and

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associated devices to power them and regulate their operation. The dust removal functional element includes whatever means might be necessary to meet the air delivery and air quality requirements. These might be filters, electrostatic precipitators, cyclone separators, or any combination of these. The distribution functional element might be thought of as the auxiliary equipment. These include the umbilical hose, quick-disconnect, pressure regulating devices, silencing equipment and demand regulators, if they are used. The facepiece element essentially involves a half or full-face mask and its associated suspension system. Integration of helmet and facepiece is essentially precluded from consideration by the contract.

THREE FUNDAMENTAL CONCEPTS

In conceptual terms, three basically different possibilities for providing breathing air to a miner exist:

Type I - Constant flow systems in which the air supply unit provides a constant flow of clean air to a facepiece (figure 4-1).

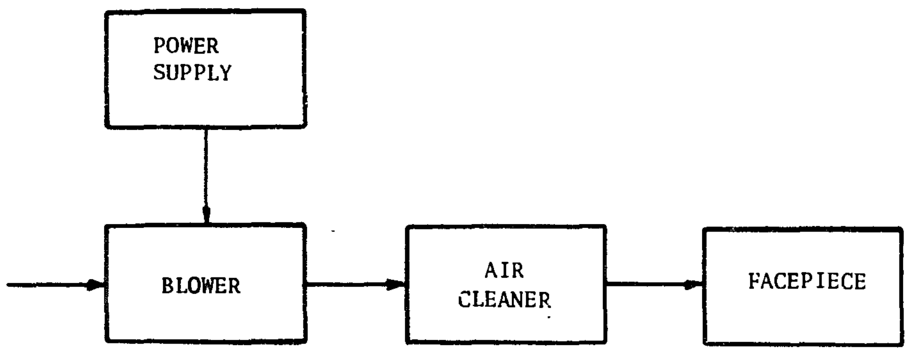

Figure 4-1. Type I System -- Continuous Flow, With Mask.

Type II - Demand flow systems in which air is supplied during inhalation only, upon demand by the user (figure 4-2).

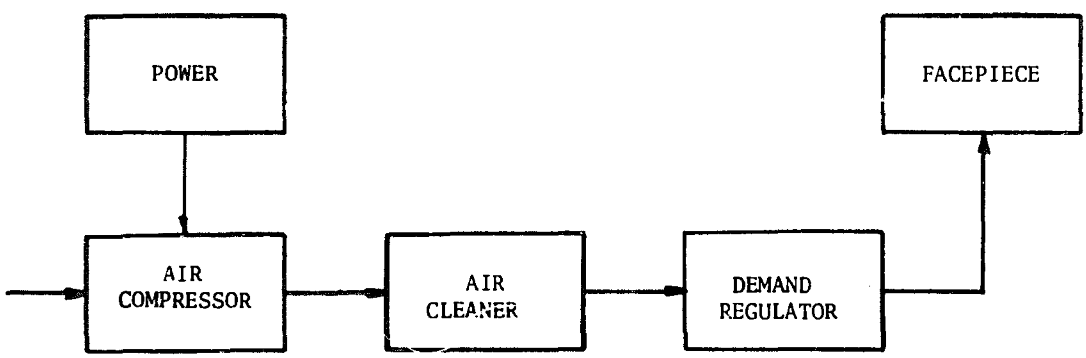

Figure 4-2. Type II System -- High Pressure Demand Flow.

Type III - Demand with ventilation flow, in which air is supplied as needed during inhalation and a smaller flow rate is provided during exhalation and quiescent periods, in order to maintain a slight positive pressure in the mask during approximately one half of the respiratory cycle (figure 4-3).

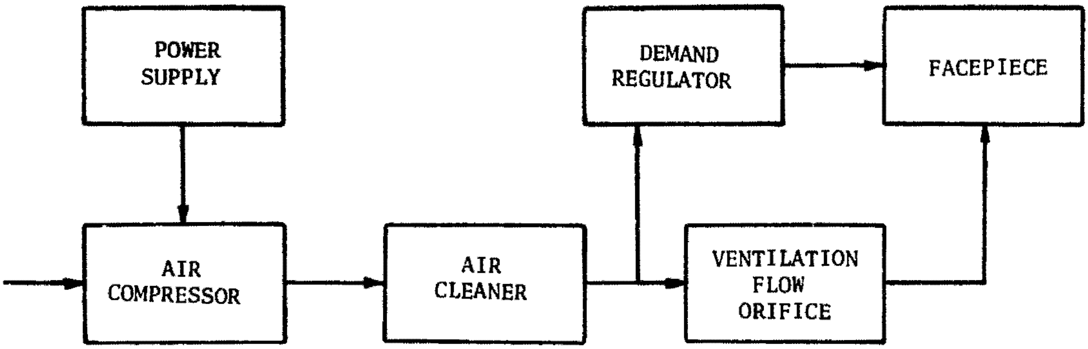

Figure 4-3. Type III System -- Demand Plus Ventilation Flow.

Within the Type III system, it should be recognized that the commonly seen "positive pressure" type of demand system may be conceptualized. Most dust respirators in current use, as well as underwater (SCUBA) regulators, are Type II demand systems in that both require the user to generate a negative pressure diferential, within the mask or mouth piece, with respect to ambient pressure in order to "demand" air flow. Under ordinary circumstances this type of supplied-air respirator would require the least amount of air to be filtered, but would be disadvantageous in that continually producing demand pressures, to any extent, is subjectively uncomfortable to the user. Thus, the subjective acceptance of this type is particularly dependent upon the quality of the demand regulator involved.

The Type I continuous flow systems are attractive in that they are extremely simple to fabricate and maintain. They require the smallest number of elements. However, they have a basic drawback in that subjective acceptance is reduced by the unpleasantness associated with continuous flow rates. Furthermore, continuous flow systems require filtration of a larger volume of air than a demand system would. The Type III systems lie somewhere between these two extremes.

As a rudimentary begining, very simple working models of each of the three basic types of supplied-air respirators were constructed and evaluated in terms of subjective acceptance only. Our reasoning, at this point, was that subjective acceptance of the method of air delivery is far and away the most important requirement to be met.

The Type I system utilized a very powerful centrifugal blower with a speed regulator so that any desired flow rate could be delivered. Air was delivered through 20 feet of 3/4-inch inside diameter corrugated tubing to a Scott-Acme half-face type mask. The Types II and III systems utilized a Rego, Teflon ring piston compressor, delivering air to a U.S. Divers half-face mask with demand regulator for the Type II system, and to a Robertshaw Model 226 Aviators Oxygen Demand Regulator for the Type III system. For the Type III system, a throttle valve was installed with a small air hose permitting adjustment of the "ventilation" flow rate. Additionally, the U.S. Divers regulator was operated in the pressure-demand mode, which is an option offered by the manufacturer. Informal evaluation by our staff members and the NIOSH project officer produced the following conclusions:

1) The Type III system was clearly superior to the Type II system and, since the components are quite similiar, future analysis should neglect the Type II system. The difference in subjective acceptance was due to the "fresh air" feeling produced by the ventilation flow of the Type III system.

2) Both of the demand regulators provided flow at low inhalation pressures and were marginally adequate for extended duration wear. While the Robertshaw regulator provided "easier breathing" it was noticeably flow limited with heavy demands. It was concluded that slight improvements in inhalation effort and flow rate would result in subjective acceptance of demand regulators.

3) In light of the time of wear requirement, the Type I continuous flow system presented a paradox. When the flow rate was set at 7 or 8 SCFM to provide for higher energy expenditure flow rates, the flow rate on the face was subjectively uncomfortable to sedentary subjects. While lower flow rates were comfortable, they would not supply sufficient air flow for exercising subjects. Therefore, it was concluded that concepts for continuous flow systems must include a solution to this dilemma.

The continuous flow system was subsequently evaluated with a full-face mask which tended to make the problem worse due to drying of the eyes and eyelash flutter, on some subjects. Experiments with baffling the flow, including an oral-nasal mask in the full-face mask, reduced the problem but certainly did not eliminate it.

PERMUTATIONS OF THE FUNDAMENTAL CONCEPTS

Of course, each of the three basic types of concepts can be conceptualized in a number of variations, each emphasizing some particularly attractive feature. Some which come to mind easily are depicted in figures 4-4 through 4-7. Type I, Model B (figure 4-4), for example would solve the basic problem of flow rate regulation by using some device to sense the average positive pressure in the mask and regulate the motor-blower speed control. In another Type I concept, Model C, shown in figure 4-5, the face mask would be replaced with nozzles providing an envelope of clean air in the breathing zone. This is indeed an attractive concept but it was excluded from consideration due to the fact that an underground miner's respirator of this general type is being developed elsewhere. Furthermore, this concept has a requirement for filtering a much larger quantity of air.

A promising Type III system, shown in figure 4-6, employs a low pressure demand regulator. This system would make use of the low energy requirements of conventional centrifugal blowers with the subjective acceptance and fil-

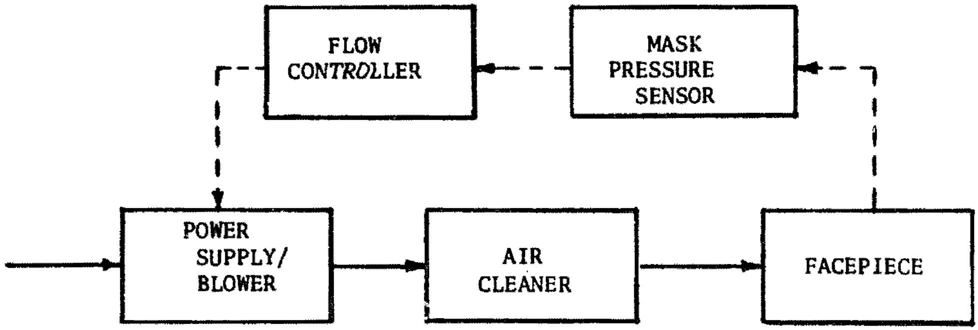

Figure 4-4. Type I, Model B System -- Continuous, Variable Flow.

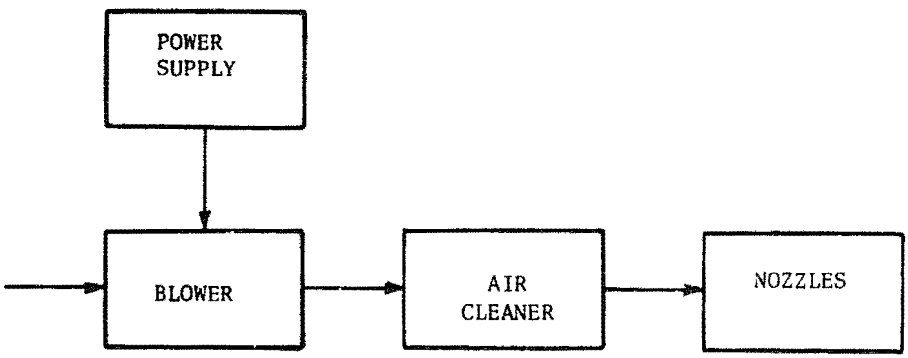

Figure 4-5. Type I, Model C System -- Continuous Flow, Face Impingement.

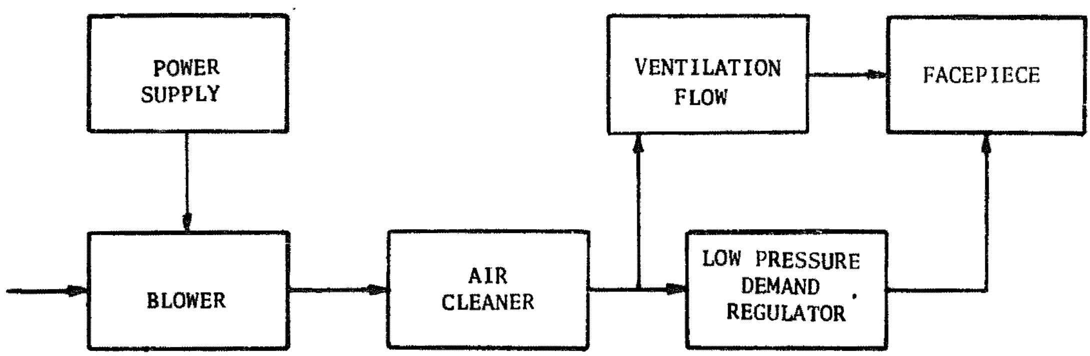

Figure 4-6. Type III, Model B -- Low Pressure Demand Plus Ventilation Flow.

ter loading advantages of providing only the air demanded by the user. A low pressure demand regulator has been developed to the working prototype stage by Synsis under another contract, but further development of the device was beyond the scope of this program.

One potential concept for a Type III system is shown in figure 4-7. In this concept a low pressure blower provides the continuous ventilation flow

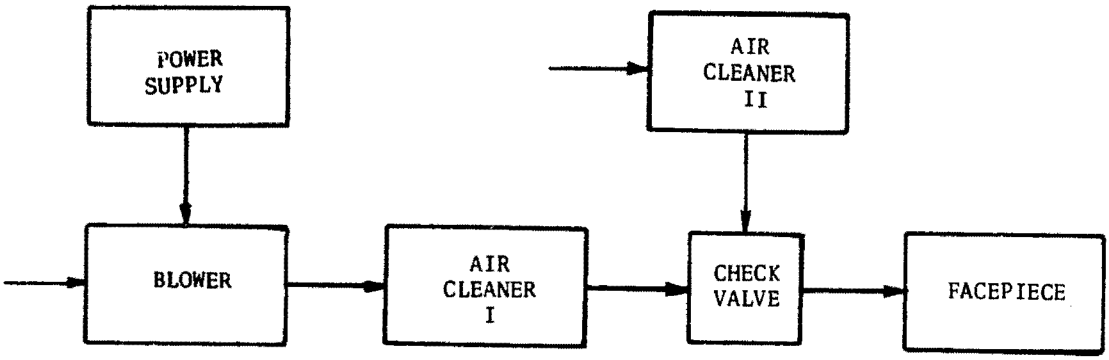

Figure 4-7. Type III, Model C -- "Lung Powered" Demand Plus Ventilation Flow.

while the additional flow demanded is drawn through a separate filter by "lung power". This has the advantage of reducing overall size of the filtering system since a high pressure drop-small size device such as a cyclone separator could be used for the primary air cleaner. The secondary air cleaner, while necessarily a low pressure drop device, could also be small in size since it processes a relatively small amount of air.

BASEPOINT SYSTEM APPROACH

Needless to say the exercise of drawing conceptual design schematics could be conducted at great length - with no way of determining which concepts should be developed further. One solution to this is to establish a measurement system for determining how well a system performs. To a large extent this activity resolves into determining what is the simplest or least expensive system that will meet the requirements. A process which has been found to be useful for this purpose is the establishment of the "basepoint design".

PURPOSE

The basepoint design is a schematic diagram delineating all of the functional components required to fulfill the requirements established. Its purpose is somewhat like a bookkeeping function. In proposing a concept for evaluation, one first ascertains that all the functions ascribed to each major functional breakdown in the basepoint design are achievable in the proposed concept. Comparison of one candidate concept's capability to perform each of the stipulated functions with another's permits a more orderly evaluation of the various possible system conceptual configurations. Perhaps, the

MAJOR FUNCTIONS | FUNCTIONAL COMPONENTS | CANDIDATE CONFIGURATIONS

POWERED, SUPPLIED AIR RESPIRATOR

- **1 POWER SOURCE** — PROVIDE ELECTRICAL, PNEUMATIC OR OTHER TYPE OF POWER TO MOTOR OF AIR MOVER AND OTHER SYSTEM COMPONENTS
  - **1.1 PRIME POWER** — ELECTRICAL, HYDRAULIC OR OTHER TYPE OF POWER TO MOTOR (2.1)
    - 1.1.1 TAP ELECTRICAL SYSTEM
    - 1.1.2 TAP PNEUMATIC SYSTEM
    - 1.1.3 TAP HYDRAULIC SYSTEM
    - 1.1.4 ELECTRIC BATTERY
  - **1.2 AUXILIARY POWER** — POWER FOR CONTROLS, DISPLAYS, AND SECONDARY MECHANICAL SYSTEMS
    - 1.2.1 BATTERY
    - 1.2.2 TAP ELECTRICAL SYSTEM
    - 1.2.3. TAP PNEUMATIC SYSTEM
    - 1.2.4 TAP HYDRAULIC SYSTEM
- **2 AIR SUPPLY** — PROVIDE AIR AT PRESSURE AND FLOWRATE SUITABLE TO SYSTEM REQUIREMENTS
  - **2.1 MOTOR** — PROVIDE MECHANICAL POWER TO PRESSURE/FLOW GENERATOR
    - 2.1.1 ELECTRIC MOTOR
    - 2.1.2 PNEUMATIC MOTOR
    - 2.1.3 HYDRAULIC MOTOR
  - **2.2 PRESSURE/FLOW GENERATOR** — PROVIDE AIR AT PRESSURE AND FLOW RATE REQUIRED OF PARTICULAR SYSTEM
    - 2.2.1 AXIAL FAN
    - 2.2.2 RADIAL FLOW BLOWER
    - 2.2.3 DIAPHRAGM PUMP
    - 2.2.4 PISTON COMPRESSOR
    - 2.2.5 SLIDING VANE COMPRESSOR
- **3 AIR DISTRIBUTION AND REGULATION** — CONSTRAIN AIR FLOW THROUGH SYSTEM AND TO THE MINER AT PRESSURES AND FLOW RATES APPROPRIATE TO SYSTEM AND TO THE USER
  - **3.1 TUBES, HOSES CONDUITS** — TRANSPORT AIR BETWEEN COMPONENTS AND TO MINER
    - 3.1.1 CONVOLUTED HOSE
    - 3.1.2 PLASTIC HOSE
    - 3.1.3 CONDUIT
  - **3.2 BREATHING REGULATOR** — CONTROL DELIVERED AIR PRESSURE AND FLOW RATE FOR COMFORTABLE RESPIRATION
    - 3.2.1 DEMAND REGULATOR
    - 3.2.2 PRESSURE DEMAND
    - 3.2.3 FLOW DIVERTER
    - 3.2.4 LOW PRESSURE DEMAND REGULATOR
    - 3.2.5 FEEDBACK CONTROL
  - **3.3 FLOW RATE CONTROL** — CONTROL FLOW RATE OF PRIME AIR MOVER (2.2)
    - 3.3.1 INPUT POWER ADJUST
    - 3.3.2 FEEDBACK TO MOTOR
    - 3.3.3 FEEDBACK TO VALVE
    - 3.3.4 EXCESS AIR RELIEF VALVE
  - **3.4 EMERGENCY AIR SUPPLY** — FACILITATE BREATHING IN EVENT OF FAILURE OF PRIME AIR MOVER
    - 3.4.1 MASK REMOVAL
    - 3.4.2 AUXILARY FILTER
    - 3.4.3 AUXILARY AIR SUPPLY
    - 3.4.4 FACIAL ACCESS PORTAL
    - 3.4.5 EXHALATION VALVE WHICH PERMITS SOME REVERSE FLOW
  - **3.5 EMERGENCY EGRESS** — PERMIT ESCAPE FROM IMMEDIATE AREA IN EMERGENCY
    - 3.5.1 UMBILICAL QUICK DISCONNECT
    - 3.5.2 MINIMUM ENTANGLEMENT DESIGN
    - 3.5.3 NON-INTERFERENCE WITH OTHER PERSONAL EQUIPMENT
    - 3.5.4 NON-INTERFERENCE WITH MINE WARNING SYSTEMS
  - **3.6 AIR QUALITY CONTROL** — LIMIT TEMPERATURE, HUMIDITY, ODOR, CO_2 AND OTHER CONTAMINANTS IN RESPIRED AIR
    - 3.6.1 HEAT EXCHANGER
    - 3.6.2 MECHANICAL COOLING
    - 3.6.3 CARBON BED
    - 3.6.4 DRYING BED
    - 3.6.5 CENTRIFUGAL DRYER
- **4 AIR PROSSESSING** — REMOVE DUST CONTAMINANTS FROM INCOMING AIR
  - **4.1 PRIME AIR CLEANING** — MAJOR DUST REMOVAL ELEMENT(S) FOR PROVISION OF RESPIRABLE AIR TO MINER
    - 4.1.1 FILTER MATERIALS
    - 4.1.2 CENTRIFUGAL SEPARATOR
    - 4.1.3 ELECTROSTATIC PRECIPATOR
    - 4.1.4 SCRUBBER
    - 4.1.5 IMPINGER
    - 4.1.6 MICROPORE MATERIALS
  - **4.2 ROUGH AIR CLEANING** — PROTECT SYSTEM ELEMENTS FROM DAMAGE DUE TO DUST
    - 4.2.1 SCREEN
    - 4.2.2 FILTER MATERIALS
    - 4.2.3 CENTRIFUGAL SEPARATOR
    - 4.2.4 SETTLING CHAMBER
- **5 FACEPIECE AND PERSONAL EQUIPMENT** — PREVENT ENVIRONMENTAL AIR FROM CONTAMINATING AIR SUPPLIED TO MINER'S FACE. MOUNTING POINTS FOR ALL COMPONENTS MOUNTED ON BODY
  - **5.1 FACE MASK** — LIMIT MIXING OF ENVIRONMENTAL DUST WITH PROCESSED AIR
    - 5.1.1 HALF FACE MASKS
    - 5.1.2 FULL FACE MASKS
    - 5.1.3 HOODS
    - 5.1.4 IMPINGEMENT
  - **5.2 SUSPENSION, ATTACHMENTS** — ATTACH MASK TO FACE, ATTACH HOSES AND CONTROLS TO BODY
    - 5.2.1 STRAPS
    - 5.2.2 SKULL CAP
    - 5.2.3 INTEGRATE WITH HELMET SUSPENSION
  - **5.3 CONTROLS &** [illegible] — WARNINGS; FLOW OR PRESSURE ADJUST- [illegible]
    - 5.3.1 FILTER PRESSURE
    - 5.3.2 MOTOR POWER
    - 5.3.3 "DUST PRESENT" [illegible]

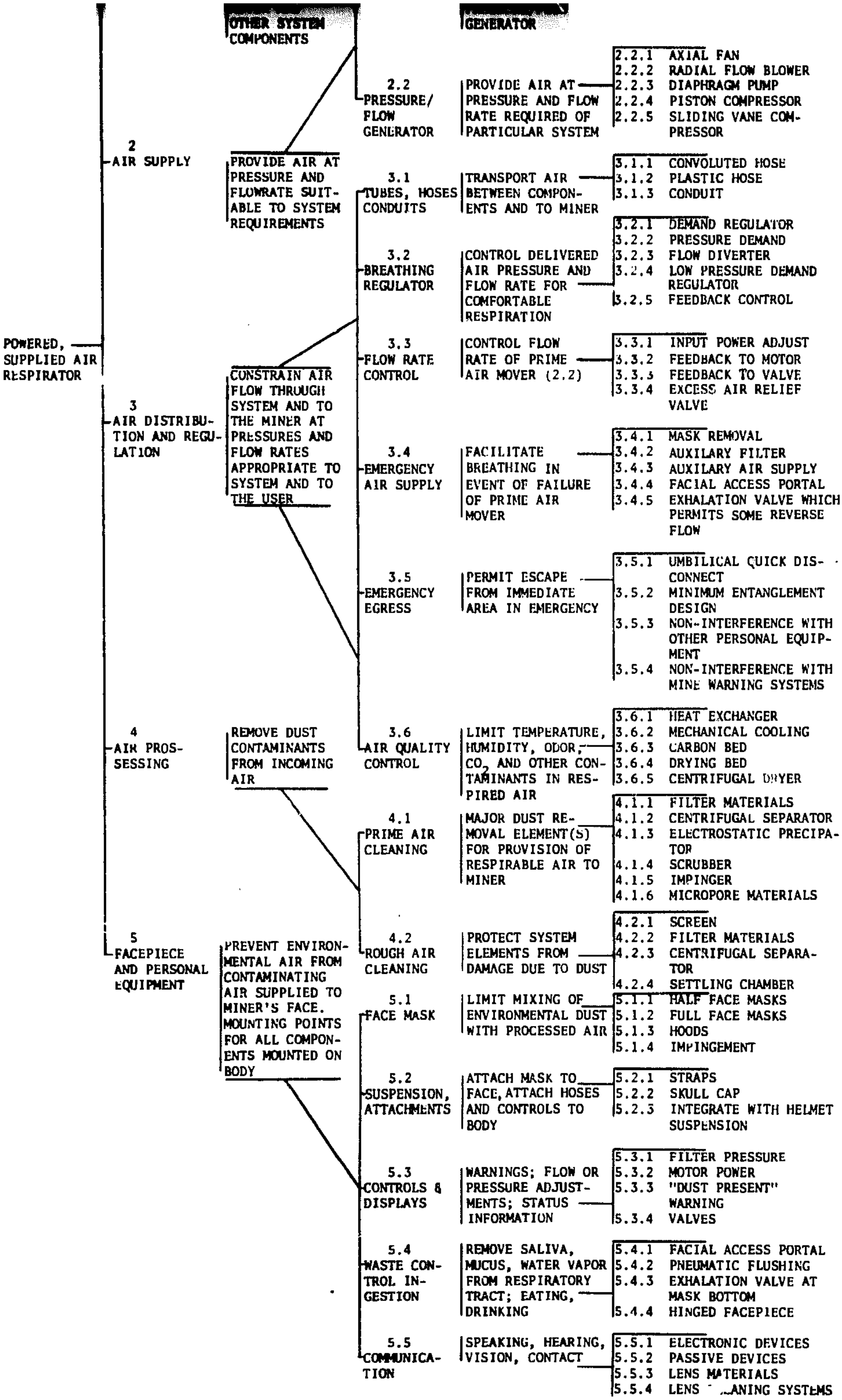

Figure 4-8. The Basepoint System Design

most pronounced benefit in proceeding in this fashion is that all of the "accessories" necessary in integrating major components are brought to light. Sometimes the accessories represent major decision points in selection of the conceptual design.

THE BASEPOINT SYSTEM

Several methods are available for describing the basepoint system. One is to draw an overall functional flow diagram; another is to list the functions to be performed in a tabular form. Both of the above methods were employed in the concept synthesis phase of the program. The tabular list of functions is, perhaps, the most easily interpreted within the context of this report and this chart is, therefore, presented in figure 4-8. While it is necessary that each of the functions listed be accounted for by each candidate system, it is not necessary that a specific component be allocated to the performance of each function. On the contrary, with some concepts, some of the functions are not necessary and with other concepts a number of functions may be accomplished with a single component.

CANDIDATE COMPONENT STUDIES

Further supplied-air respirator systems are dependent upon the availability of basic engineering data describing the performance and the attributes of the elements from which such systems are constructed. At this level, it is sufficient to provide such data in a general way, neglecting rigorous design details and emphasizing the facts necessary to determine the suitability of a concept to perform the desired function.

DUST REMOVAL ELEMENTS

The dust removal elements analyzed are limited to those which are potentially reasonable for use in underground coal mines. Small size, relatively low volumetric flow rates and potential underground safety are primary requirements. The types of dust removal elements analyzed include electrostatic precipitators, cyclone separators and various filtration media.

Electrostatic Precipitator

An electrostatic precipitator has many desirable characteristics including: very low air flow resistance, high particulate removal efficiencies, low power consumption, and simple maintenance requirements. The low air flow resistance, estimated to be less than 3 cm H_2O at flows up to 280 L/min for an appropriate precipitator, would allow the use of a very small blower or fan for the air supply system. Also, since there are no parts within a precipitator which must be replaced on a regular basis, daily maintenance can be extremely simple.

In an electrostatic precipitator, the forces on a charged particle in an electric field are used to separate solid or liquid aerosols from a gas stream. In this process, the suspended aerosol is electrically charged then passed through an electric field where the electric forces cause the particles to move toward the collector surfaces. The particles are retained on the collector electrodes and subsequently removed from the precipitator. The two

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types of precipitators currently used in industrial applications are the tubular and plate type (figure 4-9). The tubular precipitator consists of a cylindrical collector electrode with discharge electrodes located on the cylinder's axis. Gas passes through the tube and particles are collected on the inside surface of the cylinder. The plate-type precipitator consists of parallel collection plates with discharge electrodes located between the plates. In order to minimize ozone generation, two-stage designs are often employed, as shown in figure 4-10.

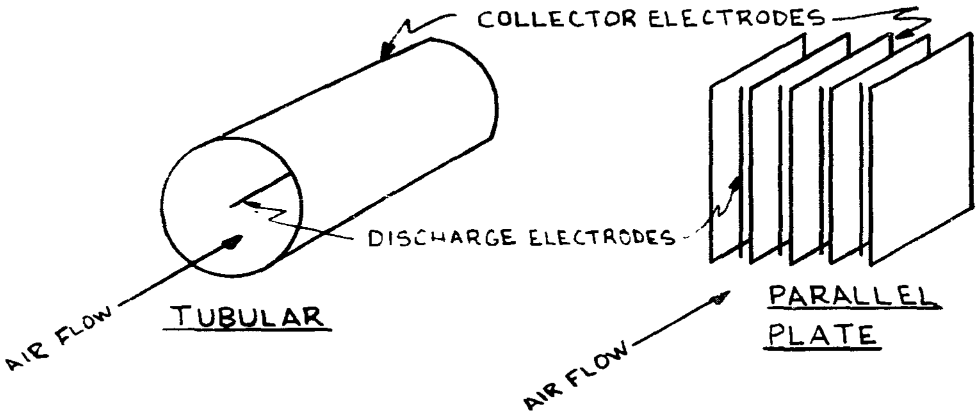


Figure 4-9. Construction of Tubular and Plate Type Electrostatic Precipitators.

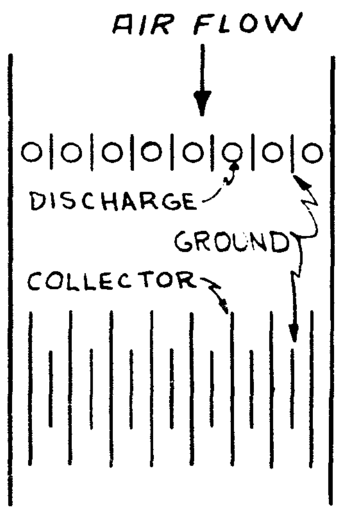


Figure 4-10. Configuration of a Two Stage Electrostatic Precipitator.

Regardless of the precipitator's physical configuration, two basic functions must be performed. The first, particle charging, takes place due to the corona created by the application of high voltage to the discharge electrodes. Particle collection, the second basic function, occurs due to the collector electrode's electric field acting on the previously charged particle. Cleaning collected particulate from the device may be as simple as reversing the polarities on the electrodes and back-flushing the precipitator with a blast of air, though numerous other methods may be employed.

The tendency for sparking to occur between the high potential electrodes and an electrical ground within a precipitator is a potential hazard within the mine environment. However, through the use of relatively low electrical potentials and explosion-proof enclosures, it may be possible to eliminate this hazard.

Since there are no commercially available electrostatic precipitators suitable for use with a supplied-air respirator system, a preliminary design was effected in order to provide fundamental data for subsequent trade-off studies. This design is based on a tubular, single-stage, negative-corona configuration. Even though a two-stage, positive corona design would be more desirable from the standpoint of ozone generation, the purposes of this illustrative design are served if the former configuration is employed. In order to take advantage of high collection efficiences and small size, this design was based on laminar flow within the precipitator. This precipitator consists of 17 sections, each section having a diameter of one inch, as shown

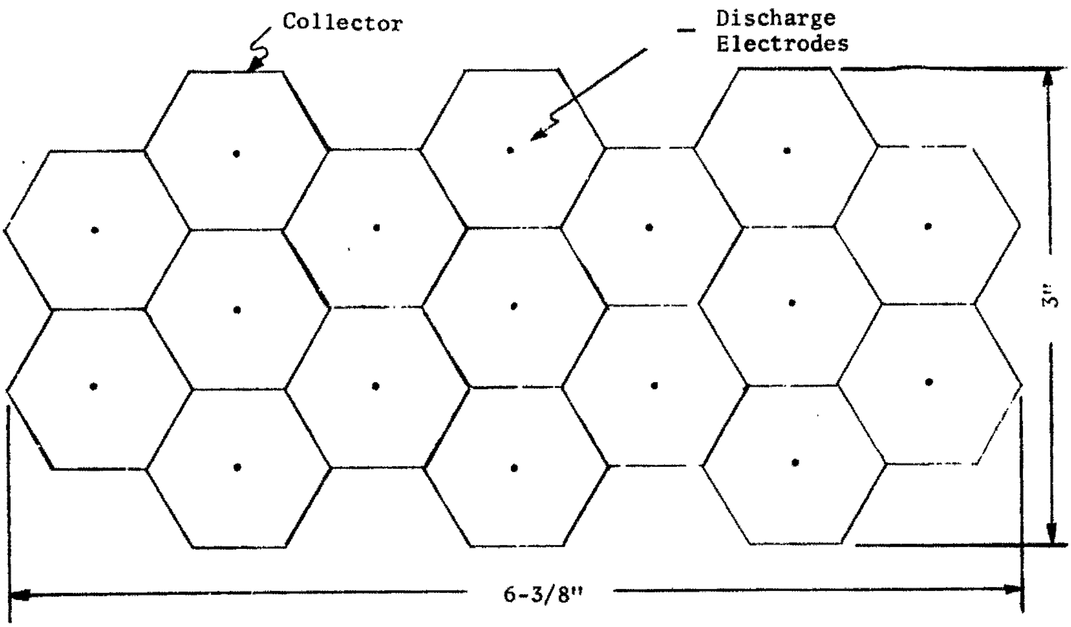


Figure 4-11. Design for a Small Size Electrostatic Precipitator Which, Potentially, Could Provide All of the Air Cleaning Capability Required for a supplied-Air Respirator.

in figure 4-11. Hexagonal, rather than circular sections, are used to achieve better packing density. The resulting design produces the following:

Size:	6-3/8 X 3 X 8 inches
Efficiency:	99% or better for respirable coal dust
Electrode applied voltage:	4 KV
Power consumption:	0.05 watt, (excluding control and power supply circuitry and assuming no losses)
Airflow resistance:	less than 1.2 in H_2O @ 9 SCFM

It should be kept in mind that the above values are an estimate made from a rather simplistic treatment of a complex design problem.

Cyclone Separator

Only a limited number of cyclone separators of appropriate performance are available on the market. Since design and performance data for these are not readily available, an analysis was conducted to determine the characteristics and design feasibility of cyclone separators suitable for use with either high-pressure or low-pressure supplied-air respirator systems.

Cyclone separation depends upon the application of large centrifugal forces to remove particulates from an air stream and is used extensively in large-scale commercial gas cleaning equipment. In its simplest form, a centrifugal collector consists of a cylindrical casing with a tangential

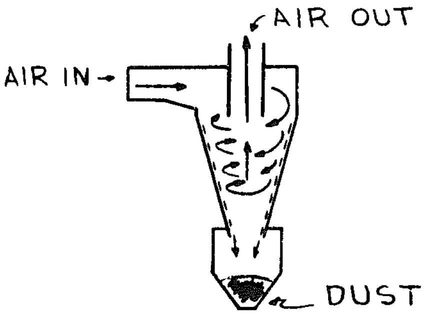


Figure 4-12. Operation of a Centrifugal Separator.

inlet, a separating chamber, and central outlet pipe, as shown in figure 4-12. Inside the separation chamber, the gas flows in spiral paths (vortex flow) with increasing velocity from outside to center. The centrifugal acceleration can range from several hundred to several thousand 'g's. Thus, even exceedingly small particles are unable to follow the gas flowlines and are, thus, forced out of the curved paths and against the separator wall. Once the particles are against the wall, they migrate down to a collection chamber at the bottom of the device.

An analysis was performed for a cyclone which would operate in both a high-pressure system (100 psig) and in a system at near ambient pressure. This analysis is presented in Appendix IV and produced the following generalized results. A high-pressure cyclone separator of the reverse-flow type can be designed which will remove 50% of all particles greater than 0.73 um mean aerodynamic diameter and 95% of all particles greater than 1.25 um. Predicted pressure drop and collection efficiency curves are shown in figure 4-13.

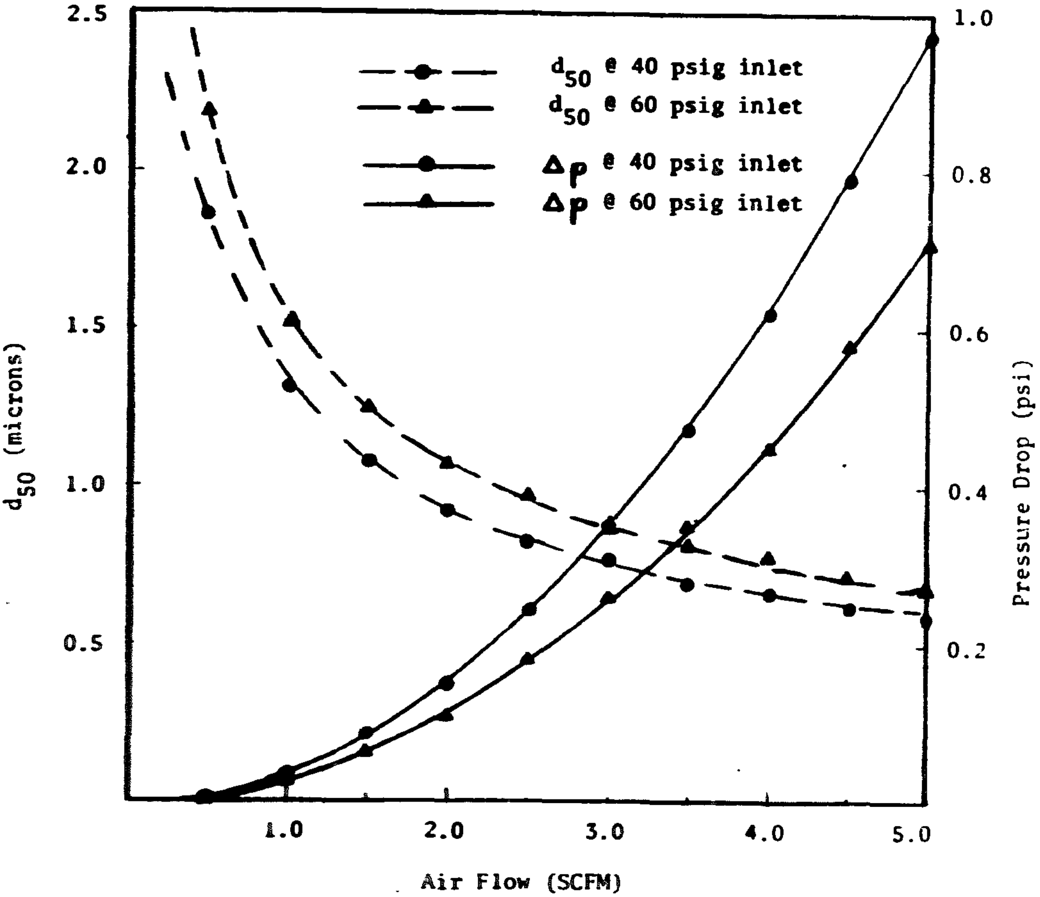


Figure 4-13. Collection Efficiency (d_{50}) and Pressure Drop vs. Flow Characteristics for a High Efficiency Cyclone, at Two System Pressures.

The size envelope of the cyclone would be approximately 3 inches in diameter by 5 inches long. Solution of the equations for the low-pressure case indicated that nearly equal collection efficiencies could be achieved with a cyclone about twice as large. Pressure drop and collection efficiency for this cyclone are shown in figure 4-14.

A centrifugal separator is almost ideal from the standpoint of routine maintenance. Collected dust can either be stored in a hopper and periodically dumped or simply expelled into the mine through an outlet port.

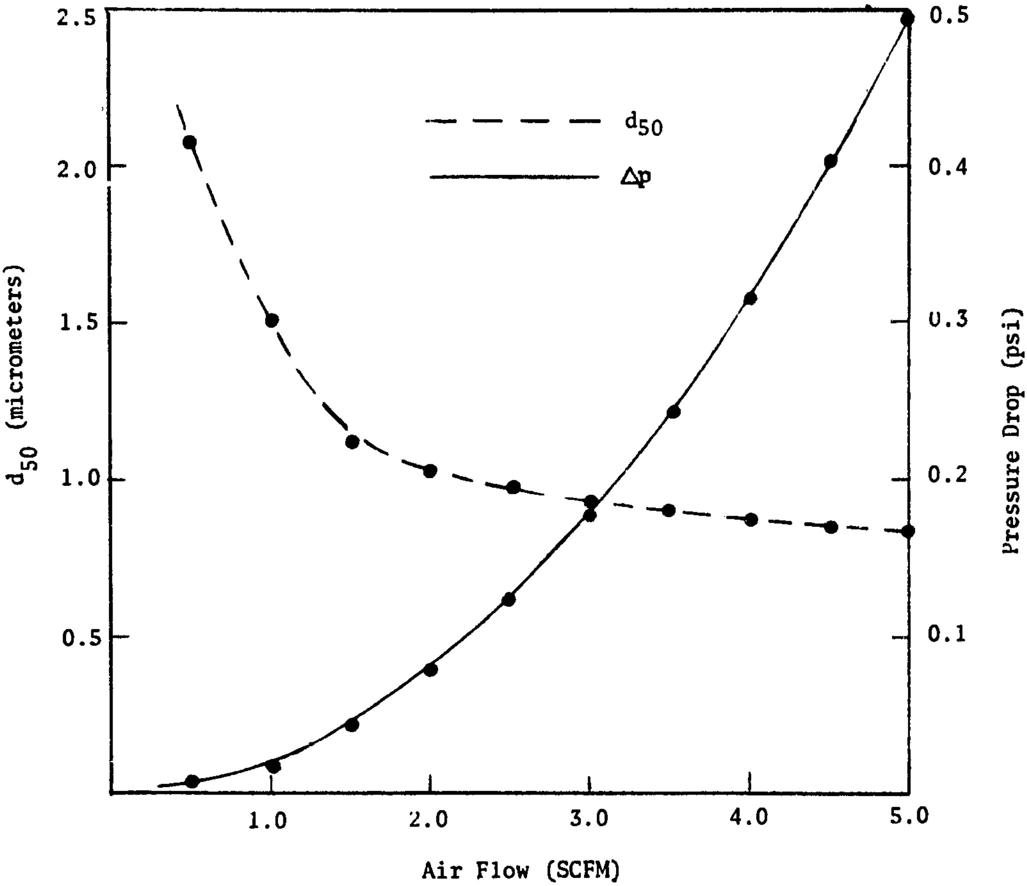


Figure 4-14. Collection Efficiency (d_{50}) and Pressure Drop vs. Flow Characteristics for a High Efficiency Cyclone, with Atmospheric Inlet Conditions.

Fibrous Filters

A large number of fibrous-type filter units and filter materials are available commercially. Filter-cartridges can be obtained in a wide variety of sizes and capacities. Generally, in the selection of a filter unit or the use of filter materials in fabricating new units, the primary considerations involve collection efficiency and pressure drop across the filter. The selection or design of an appropriate fibrous filter depend upon practical face velocity limits and will, in turn, determine the size of the filter and the output level required for the air mover.

The efficiency of a fibrous filter is strongly dependent upon the particular contaminant to be collected and upon the medium in which it is suspended. Surprisingly little data are available concerning the change in pressure drop (ΔP) versus particle loading (amount of dust collected). This is in part due to the aforementioned dependence on contaminant and medium. Unfortunately, this is precisely the data needed for analyzing the size and maintainability considerations which are quite important in the underground coal mining application.

Data describing some representative fibrous filter cartridges are presented in table 4-1. From this data it is clear that one can achieve very

Table 4-1. COMMERCIAL FIBROUS AIR FILTER CARTRIDGES.

TYPE	NOMINAL FLOW VS ΔP	EFFICIENCY (% for 0.3um)	SIZE (INCHES)	WEIGHT (POUNDS)
AIR-MAZE FILTERS MODEL CD0511500	4 in H_2O @ 90 CFM	99.9	5-1/2 D x 11-1/2	7-3/4
AIR-MAZE FILTERS MODEL H12-FB	5 psi @ 12 CFM	99.96	3-5/16 D x 8-1/2	3-3/4
AIR-MAZE FILTERS MODELS DAU & DNU	.5 in H_2O @ 20 CFM	98	6-1/2D x 7-5/8	3
DELTECH ENGR.	2-3 psi @ 12 CFM	99	2-1/2 D x 15-3/4	3
MSA AIR-LINE FILTER	1 psi @ 25 CFM	99	6 D x 7-1/2	3
FLANDER'S FILTERS, MODEL F600-700	1 in H_2O @ 30 CFM	99.97	8 x 8 x 3-1/16	N/A
FLANDER'S FILTERS MODEL J	0.4 H_2O @ 25 CFM	95	8 x 8 x 3-1/16	N/A
MICROPOROUS FILTER MODEL 4200	30 psi @ 10 CFM	(10um nominal, 25um absolute)	1 D x 1-1/2	N/A

low pressure drop accross a filter cartridge, if the size of the cartridge is made large enough. However, the particle loading versus pressure drop information represents a potential problem area. If one assumes a worst case condition of continuous flow for the entire shift, the conditions might be:

Air Flow Rate: 10 SCFM or 0.283 m^3/min

Dust Concentration (total): 100 mg/m^3

Time for One Shift: 8 hours

Then, in one shift the filter would retain approximately 13.6 grams of dust. Data from Revoir and Yurgilas (1968), when summarized, indicates that a dust loading of under 200 mg resulted in doubling the flow resistance of several simple dust respirators of the type approved under Bureau of Mines Schedules 21, 21A, or 21B. Therefore, to meet the worst case requirement described above, using the criteria that filter resistance may double during the shift, a filter having an area on the order of 2 ft^2 would be required. A filter having this area would have to be changed daily.

Membrane Filters

This concept functions through the control of flow area; thus limiting the penetration of particles by a "seiving" action. This results in a greater restriction of airflow than do fibrous filters which remove particulates, primarily, as a consequence of inertial losses.

Membrane filters are selected on the basis of pore size; it is, thus, theoretically possible to achieve 100% efficiency in removing particles larger than the pore size. The most important advantage is that it is possible to almost completely clean a membrane filter of accumulated particulate matter by reversing the flow of gas for some period of time. Obviously, this characteristic can be very important in reducing cost and time requirements for maintenance.

On the negative side, membrane filters exhibit a fairly high pressure drop. Though the amount of pressure drop depends on pore size, flow rate, and filter area, it is still apparent that membrane filters are not suitable for low-pressure systems. For example, figure 4-15 shows the pressure flow relationship for various types of General Electric Company's Nuclepore membrane filter. Using these data in a hypothetical design for a low-pressure blower type system we might postulate system characteristics as:

Blower Output: 7.1 SCFM (200 L/Min)

Pressure Drop Available: 8 in H_2O

In this case, one would need a membrane filter of more than 3.5 ft^2 surface area to pass the required flow.

A search to find a filter cartridge which employs a membrane filter was more difficult than might be expected. This stems from the fact that the primary use of membrane filters is based upon sampling of atmospheres and production of ultra-clean laboratory atmospheres. One particular unit, however, Gelman Instrument Company, Ann Arbor, Michigan, Model No. 12106, appeared to be suitable and was purchased for evaluation. This unit, it turned out, is primarily used in milk pasteurization. A pressure versus flow rate curve for this unit is shown in figure 4-16. The cartridge proved to have less resistance than would be anticipated from the curves shown in figure 4-15.

Membrane filter systems can be used in two places on a supplied-air respirator. One is as an inlet filter and the second is at some location in the high-pressure side of a fairly high-pressure system. When used in the high-pressure side one can best take advantages of the membrane filter's character-

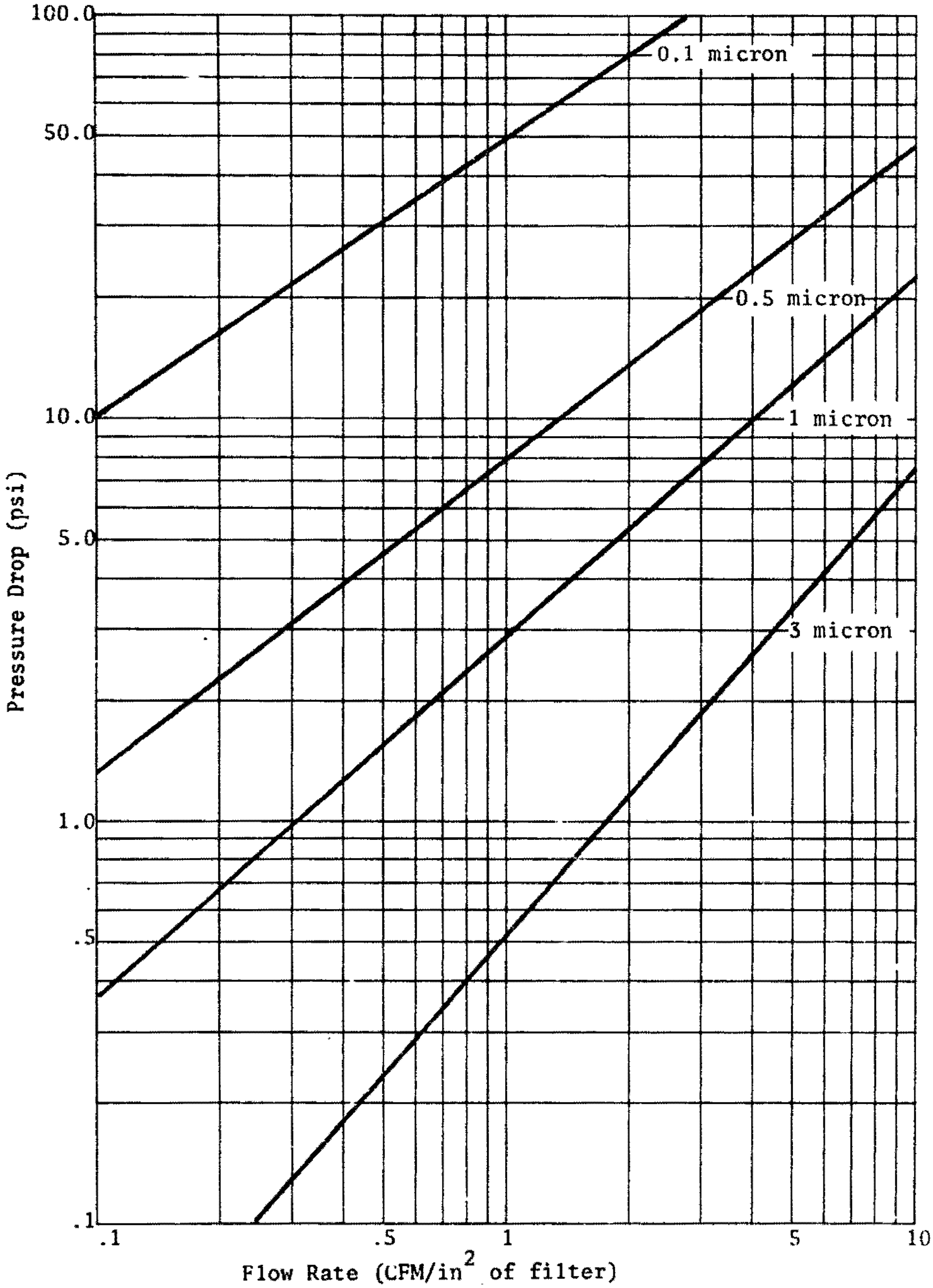


Figure 4-15. Nuclepore Membrane Filter Pressure-Flow Characteristics as a Function of Pore Size.

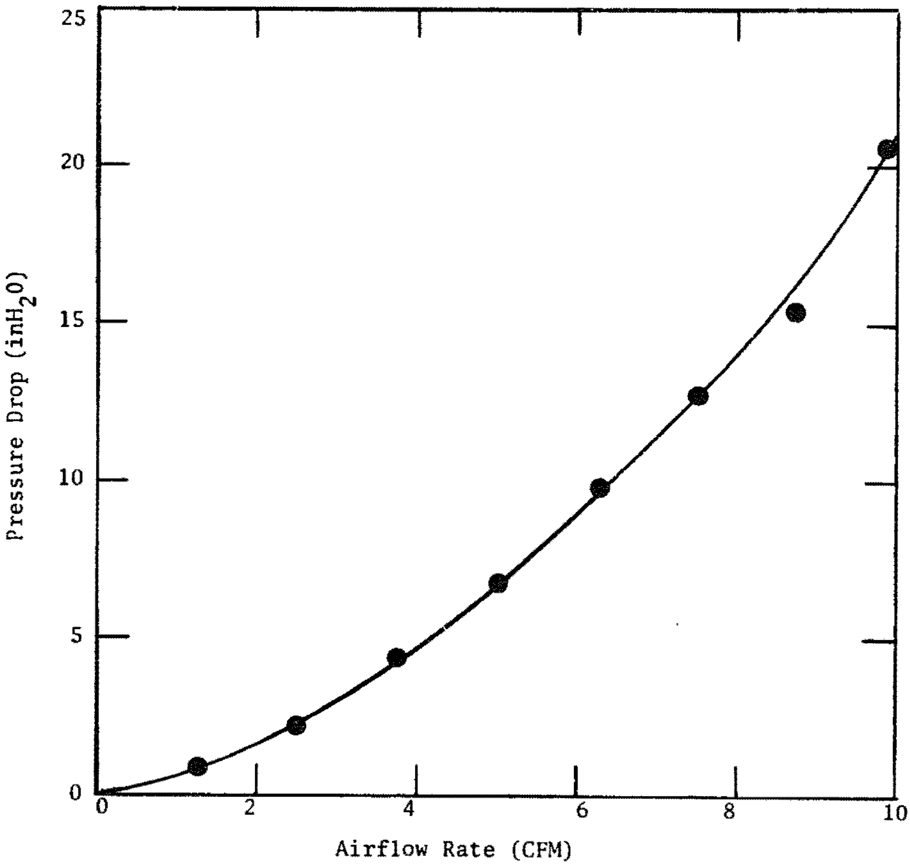


Figure 4-16. Flow Resistance for a 0.3 um Pore Size Membrane Filter Capsule. Gelman 'Acroflow' Pleated Membrane Filter Capsule (No. 12104) with 3/8 Inch I.D. Inlet and Outlet Connectors.

istics by using some sort of automatic back-flushing system. One concept for doing this is illustrated schematically in figure 4-18. A dump valve upstream of the filter element is activated either periodically by a timer, or perhaps more simply, each time the system is turned off. In this concept, enough air must be stored in a plenum chamber at high pressure downstream of the filter element so that when the dump valve is opened a sufficient quantity of air flows through the membrane filter in a backward direction to purge it. Using the Gelman filter, such a system was rigged-up in our laboratory using manual operation of the appropriate valves. Tests using three to five-micrometer silica dioxide powder (Micro Abbrasive Systems, Westfield, Mass.) were inconclusive as to the effectiveness of back-flushing. Perhaps, part of this is due to the construction of the filter element.

When used as an inlet filter one may make use of the turbulent flow concept for keeping the filter clean. As shown in figure 4-18, air is drawn

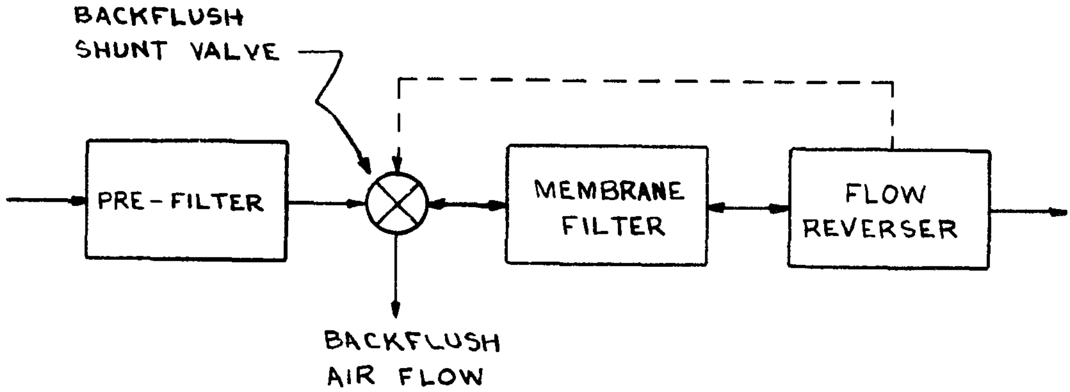


Figure 4-17. Backflushing Concept for Filter Cleaning.

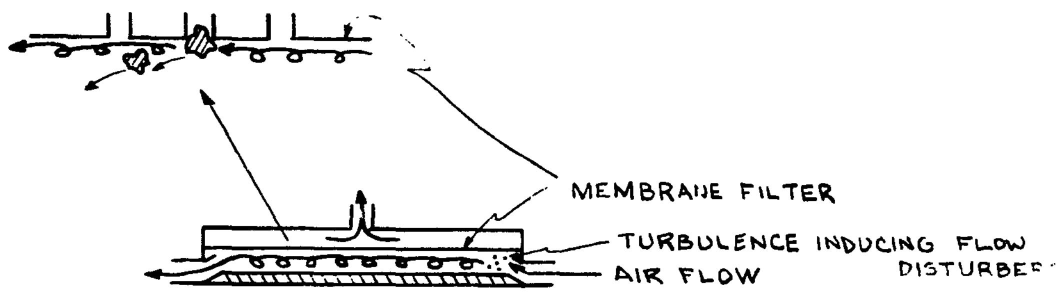


Figure 4-18. Turbulence Flow Concept for Filter Cleaning.

from a fast moving stream passing over the flat filter. This high-velocity stream of contaminant laden air serves to scrub trapped particles from the filter element. One simple way of executing this would be to use a venturi pump to provide the additional turbulent air over the membrane element. These venturi pumps (such as those produced by Air-Vac, Inc.) are fairly efficient for this purpose, in that they can pump up to four times the volume of air utilized to power them. Thus, if it were possible to select a compressor to produce half again as much flow as needed for breathing purposes, then one could produce a volumetric flow through the filter chamber of twice the volumetric flow rate required of the compressor. While this concept seems fairly attractive, it is untried in this context and, if adopted, would require significant development effort. Therefore, laboratory tests of the feasibility of such a system were deferred.

Electrostatically Augmented Filtration Methods

Electrostatic attraction is identified as a factor for improving the performance of conventional particulate removal equipment. Electrostatic augmentation has been applied to such devices as fabric filters, fibrous filters, packed-bed filters, wet scrubbers, and mechanical collectors.

Powered Non-Ionizing Electrostatic Air Filters

In this type of air cleaner, the performance of a fibrous particulate filter is improved by the application of electrostatic forces. The particles are not intentionally charged as in an electrostatic precipitator. Rather, a field is set up across the fibrous filter matte. Electrostatic forces combine with inertial forces to enhance particle collection. Commercial embodiments of the charged-fiber filter have taken the form of pleated fiber matte containing a noninsulated, grounded conductor and an insulated conductor with the insulated conductor at several thousand volts dc with respect to ground, the electric field between charged and grounded rod is concentrated within the matte, since its dielectric constant is approximately twice that of the air. The fundamental explanation for electrostatic force improvement of fibrous filter efficiency is that particles will migrate more rapidly than they would from inertial effects alone and have a higher probability of capture than when the field is not present. Typical electrical power requirements are 3 KV and 150 uA/1000 SCFM. It is particularly important to note that the greatest degree of improvement in collection efficiency occurs within the respirable dust particle size range. Data from one commercially available, electrostatically-augmented, fibrous filter indicates that the application of the electrostatic field improves the collection efficiency by a factor of approximately five for one micron dust.

Constraints on using this approach include the following:

1. The fibrous matte must possess low moisture absorptivity characteristics. In a high humidity coal mine, moisture will tend to reduce the efficiency of the electric field.

2. Electrostatic effects are highly sensitive to airflow velocity. Velocities must be kept low; normally 40 fpm.

3. Similiar to ordinary electrostatic precipitators, the danger of sparking, or of a short circuit resulting in heating an electrode, presents an unacceptable threat in the underground environment.

4. Installation of electrical equipment on underground equipment is much more difficult than might be expected due to Bureau of Mines permissibility requirements.

Non-Powered Non-Ionizing Electrostatic Air Filters, (Electret Filters).

In this type of filter, electrostatic and inertial effects are also combined to achieve filtration. However, the electric field is created through the use of an electret, rather than electrodes, and an external power supply. An electret is a device which can retain a permanent or nearly permanent dielectric polarization resulting in an external electric field about the object. Thus, an electret creates an electric field in a fashion analogous to the way a permanent magnet creates a magnetic field. In an electret filter, the actual filter fibers become polarized and create the external field. Most electret filters are thermo-electrets, which refers to the means of formation. This method involves the application of an intense electric field, while maintaining a high temperature, then allowing it to cool to room temperature while maintaining the applied electric field. Because of the high porosity characteristic of these filters, inertial effects are minimal and collection efficiency depends almost entirely upon the type and quantity of charge stored in the electret. Stability can be a potential problem. The charge stored in an electret filter tends to decay with time. Stability is, however, enhanced by using a high formation electric field (24 KV/cm or higher), as well as the highest possible formation temperature. In an unprotected state, electret filters can be stored for up to two weeks before performance is affected seriously. If an electret filter is stored in a protected state, storage time is considerably longer, perhaps indefinite. The best way to store electrets involves keeping them short-circuited, for example, by wrapping the electret filter in metal foil. Another potentially serious problem is the tendency for collection efficiency to decrease as particle loading on the fibrous matte increases. It appears that this is due to charge cancellation or charge migration between the electret fibrous matte and airborne particles.

Although electret filters are not currently available, a prototype filter has been constructed in Canada. This filter consists of a fibrous matte composed of 23 um diameter polyethylene terephthalate plastic fibers, measures 38 mm in diameter (30 mm active), and has a thickness of 2.9-3.5 mm. In penetration tests, a test aerosol consisting of 0.36 um particles of DOP smoke was used at a concentration of 23-34 mg/m^3. Under these conditions, with a face velocity of 6.4 cm/sec, the filter exhibited a pressure drop of only 1 mm H_2O.

For this particular filter collection efficiency was more than 99.9% for a particle loading of up to 100 mg. Note, that as particle loading increases, collection efficiency decreases until, ultimately, collection efficiency is determined only by inertial effects and the electret filter operates as an ordinary fibrous filter.

A possible solution to the problem of decreased collection efficiency with increasing particle loading involves placing a low pressure drop prefilter. This prevents the larger particles from impacting the electret filter and, since the larger particles remove most of the electret's charge, the filter can sustain a greater particle loading before becoming ineffective.

Based on discussions with the Canadian firm currently developing electret filters, it may be assumed that an electret filter, with prefilter, can carry a particle loading of 10 mg/in^2 and still maintain a collection efficiency of 90%, or higher. Therefore, if the dust collection requirement of 13.6 grams per shift were reduced by three-fourths by use of a prefilter, such a filter could be made using a surface area of about 2.5 ft^2 of material. Such a filter would have a pressure drop of only a few inches of water.

While the electrical hazard associated with the other electrostatically augmented methods are eliminated with the electret remain, two serious drawbacks remain:

1. Electret filter elements are not currently available on a commercial basis but are still developmental in nature.

2 The logistics of procuring the filters and transport of the fragile devices to the underground work site for installation would be a serious problem.

AIR MOVING DEVICES

At the conceptual stage, it is necessary to categorize and describe the attributes of air moving devices covering the entire spectrum from fans, which have a very low pressure output, up to piston compressors producing 100 psig, or more. There are no preestablished requirements regarding power consumption since this may range from a battery-pack mounted on the machine up through electrical or hydraulic power available from the mining machinery. Since the characteristics of hydraulic and electric power available in underground mines has already been discussed, the only new power source to be described is battery power. Motors utilizing these power sources are discussed briefly. Following that, a number of potentially attractive air compressor concepts are described. The purpose of this discussion is to present sufficient information to permit trades to be made between such parameters as size, weight and performance in designing the candidate conceptual systems.

In addition to the size and weight integration trade-offs just mentioned, a basic design criteria has to do with performance matching. Consider the diagram of figure 4-19 in which the two dashed curves represent air mover pressure versus flow rate curves and the solid line represents system pressure drop versus flow rate. The intersection of an air mover curve and the system resistance curve defines the point at which the integrated system described will operate. Thus, it is necessary to select system configuration and air mover characteristics so that the intersection of the two curves occurs at the desired flow rate.

Power Sources

The availability of electrical, hydraulic, and compressed air power within the underground environment has been discussed in the requirements section of this report. Electrical power, while available in abundant quantity, has the problem of being highly variable in terms of frequency, phase and voltage available among the several thousand underground mines in this country. A majority of the mining machinery, however, operate on 230 VAC, 250 VDC or 440 VAC. Of course, it is possible to provide a transformer to suitably condition the AC voltage. However, this would imply the design and testing of dozens of such devices.

Hydraulic power is readily available on nearly all types of underground machinery. It also may be found in a wide variety of system pressures. The advantage of hydraulic power, however, is that it is relatively easy to regulate by use of a single flow controller installed on the respirator system. On the other hand, in normal underground operations, the supply is unavailable during parts of the working shift.

Another potential source of energy is the use of batteries mounted on the machine. For example, it might be reasonable for a miner to bring a new bat-

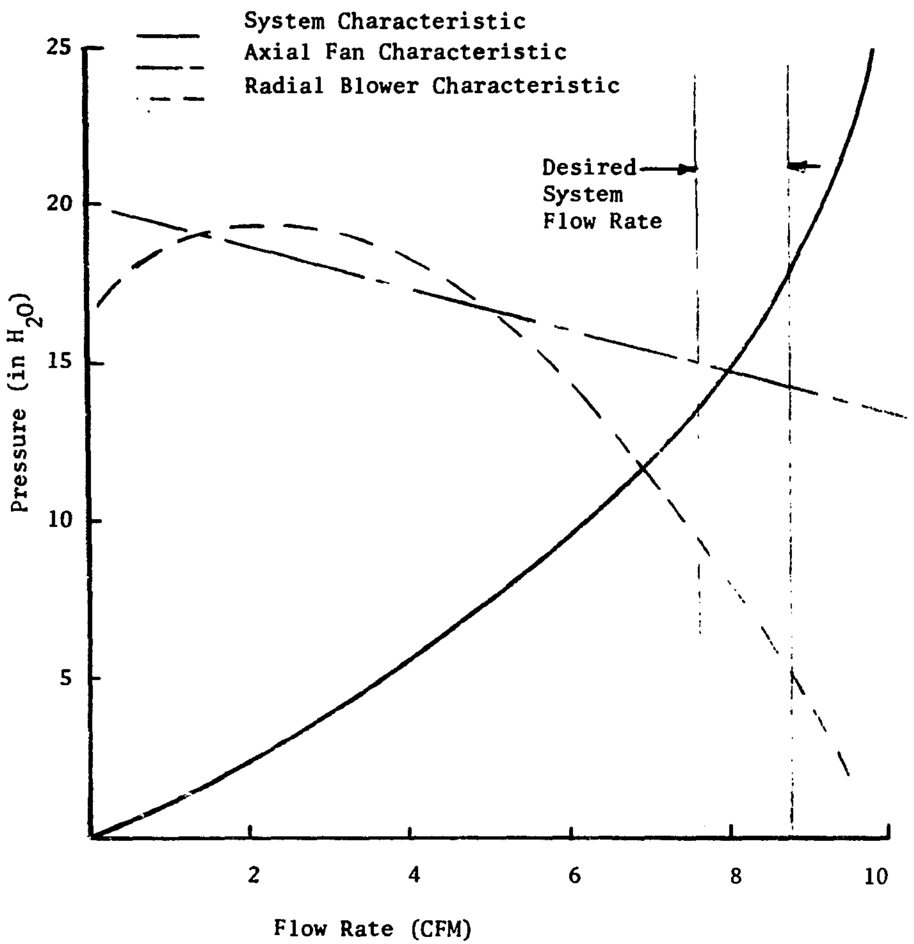


Figure 4-19. System-Compressor Characteristic Curves. The fan (hypothetical) Would be a Suitable Compressor for the System While the Radial Blower Does Not Provide Flow at Sufficient Pressure to Meet the Flow Requirements.)

tery each day to power his respirator. If this could be done handily, it would be an acceptable concept for powering a respirator system. In this section, characteristics of a number of the potential sources of battery power will be reviewed. In a subsequent section, this data will be utilized in configuring conceptual candidate systems.

Table 4-2 provides some overall generalizations regarding potential battery performance. Silver-zinc and zinc-air batteries, as may be seen from the table, produce energy densities upwards of 40 amp - hours per pound. However, these high energy densities usually result in a battery which is quite expensive and has some important limits to rechargeability. As noted in the

Table 4-2. GENERAL CHARACTERISTICS FOR SEVERAL TYPES OF RECHARGEABLE CELLS. SIZE, WEIGHT AND CAPACITY ARE LISTED FOR ONE PARTICULAR MODEL SELECTED FROM MANUFACTURERS DATA

TYPE	ENERGY DENSITY (watt-hours per pound)	VOLTAGE per cell	RECHARGABILITY	TEMP. CHAR.	STORAGE	CAPACITY	SIZE (LxWxH inches)	WEIGHT (pounds)
LEAD-ACID	11-15	2	Good		Loses 50% capacity in 60 days Special Type: 15% - Year			
NICKEL-CADMIUM	12-18	1.25	Good	0°F-115°F 93% of cap. at 40°F	May be stored charged or discharged. 80% cap. after 3 mo. at 70°F	11 amp-hr @ 1.1 amp Discharge	3.56x 1.05x 4.90	1.76
NICKEL-ZINC	25	1.68-1.50	Good	-20°F - 120°F		10-11 amp-hr @ 2-10 amp Discharge	2.06x 1.75x 4.28	0.85
SILVER-CADMIUM	11-33	1.4	More than 500 Cycles	0°F- 160°F	2 years			
SILVER-ZINC	40	1.5	100 Cycles	0°F- 160°F	2 years	25 amp-hr @ 10 amp Discharge	2.00x 1.75x 4.13	0.8
ZINC-AIR	80-95	1.5	Rechargeable by addition of a new anode	-20°F- 125°F	7 day activated stand	20 amp-hr @ 4-50 watts	9.75x4x 4.8	

table for example, the silver-zinc battery may be charged for 100 cycles. However, this number may be misleading as it is stated. One or two very deep discharges of the battery will result in a significant degradation in its overall performance. On the contrary, if it is never discharged by more than 10% of the total capacity it may last for several hundred cycles. Theoretically, the zinc-air battery may be recharged an infinite number of times by discarding the old anode and inserting a new one. This type of recharging has one basic drawback, and that is that the anodes which must be replaced are quite expensive and, therefore, would not be suitable within the economic structure of underground mining operations.

Another factor having to do with potential battery selection is the discharge rate. In many cases, the high energy densities available are dependent upon a specific current of discharge. Some types of batteries produce their best energy density when discharged very slowly, while others exhibit their best energy density when discharged very rapidly. Consequently, selection of a type of battery power is strongly dependent upon the intended use and must be made in light of the specific motor and compressor to be selected

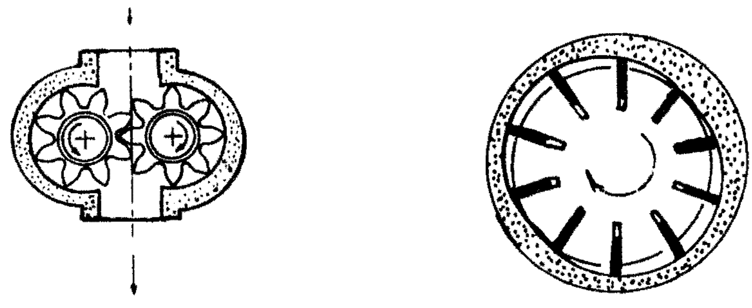
Motors

It is necessary at this stage of development to characterize both hydraulic and electrical motors suitable for use with several potential candidate respirator systems. For reasons already discussed, small electrical motors such as are used in portable, powered-respirator systems, such as the units manufactured by Air Flow Inc., Martindale Electric Co., The 3M Co., and Siebe Gorman Co., are excluded from further consideration In the interest of brevity, the results of a rather extensive analysis are summarized in the following paragraphs.

Motors for powering blowers and fans are required to produce fractional horsepowers, perhaps 1/8 hp, at shaft rotational speeds on the order of 8000 to 10000 RPM. Motors for powering reciprocating compressors must produce on the order of 1 hp at shaft rotational speeds in the range of 1500 to 2500 RPM.

Any electrical motor must be approved by the Bureau of Mines for use underground. Achievement of such permissibility ordinarily involves placing the motor in an explosion proof enclosure. These enclosures result in considerable increase in size of the motor and in its cost. For example, a one horsepower motor commercially available in a permissible configuration is more than a foot long and ten inches in diameter. Fractional horsepower motors, in a suitable power range, are not known to be produced with explosion-proof motors so that considerable development work would be required to achieve permissibility.

Hydraulic motors can be purchased in nearly any horsepower and shaft rotational speed desired. The gear face type motors illustrated in figure 4-20 are generally smaller in size and less expensive than the sliding vane type, also illustrated in figure 4-20. The sliding vane motors, however, are quieter and exhibit other advantages of lesser importance to this particular application. While most hydraulic motors are designed for low shaft rotational



Gear face hydraulic Motor

Sliding vane hydraulic Motor

Figure 4-20. A Comparison of Two Types of Hydraulic Motors.

speeds, it is possible to procure units which operate at speeds to 10,000 RPM, or more.

One hydraulic motor of particular interest for this application is a gear face type motor produced by the John S. Barnes Co. It is 4-inches long and has a diameter of 3 inches. The same motor frame can accommodate a variety of flow rates to produce nearly any power and rotational speeds which might be desired for a supplied-air respirator.

Air Compressors

A survey and analysis of air compressors was conducted in order to provide information on the fundamental characteristics, advantages, and disadvantages of the various types of compressors available on the market today. Some of the more attractive types of compressors such as axial flow positive displacement and two-lobe positive displacement compressors were not found to be available in small enough sizes to be of use in this application. Table 4-3 and figure 4-21 summarize the results of the survey and analysis. The five most attractive conceptual types of air compressor are discussed further in the following paragraphs.

Axial Flow Fans

Axial flow air compressors, commonly called fans, are perhaps the lightest weight and smallest of the air compressors examined. However, excepting multi-stage units, output pressures are the lowest, on the order of ten inches of water for a single stage unit. As shown in figure 4-22, the output pressure is fairly constant over a wide range of flow rates. A typical high performance fan must be operated at high RPM on the order of 10,000 to 15,000 RPM. The majority of fans surveyed are manufactured to provide ventilation flow rate for cooling electronic equipment, room ventilation, or marine ven-

Table 4-3. CHARACTERISTICS OF TYPICAL COMPRESSORS.

CLASS TYPE	COMMON RANGES: PRESSURE OUTPUT (psig)	COMMON RANGES: FLOW RATE (SCFM)	WEIGHT (pounds)	POSSIBLE CONTAMINANTS	REMARKS
RECIPROCATING					
PISTON	40-100	1-7	40	Oil, teflon Heat, vibration	Lower flows at reasonable sizes Oscillatory pressure output
DIAPHRAGM	6-20	1-5	5-30	Vibration, heat	Units are small and self contained Pulsatile flow a potential problem
ROTARY, FIXED DISPLACEMENT					
SLIDING VANE	3-10	1-15	20-50	Dust	Higher pressure available with water cooling
TWO LOBE	3-10	30-70	50-80		Possible poor performance at low flow
LIQUID PISTON	28	11	40-50	Water	Water is required in quantity for operation
SPIRAL-AXIAL	18	100	200		A small size unit could not be found
ROTARY, DYNAMIC					
RADIAL FLOW (Single stage)	0-20 inH_2O (0.7)	1-50	5-30	Pulsations Noise	Limited stable output range, good pressure over flow rates from 50% of rated output
RADIAL FLOW (Multi-stage)	[illegible]-100 inH_2O ([illegible].5)	10-50	15-30	Pulsations, Noise	Multi-staging results in higher pressure, however, 5000-12,000 rpm is required
AXIAL FLOW	5-8 inH_2O	10-60	3-5	Pulsations, Noise, heat, Ozone	Flow more constant with pressure than radial flow machines, 12,000-14,000 rpm required, units are very small and light, permissible motors not likely

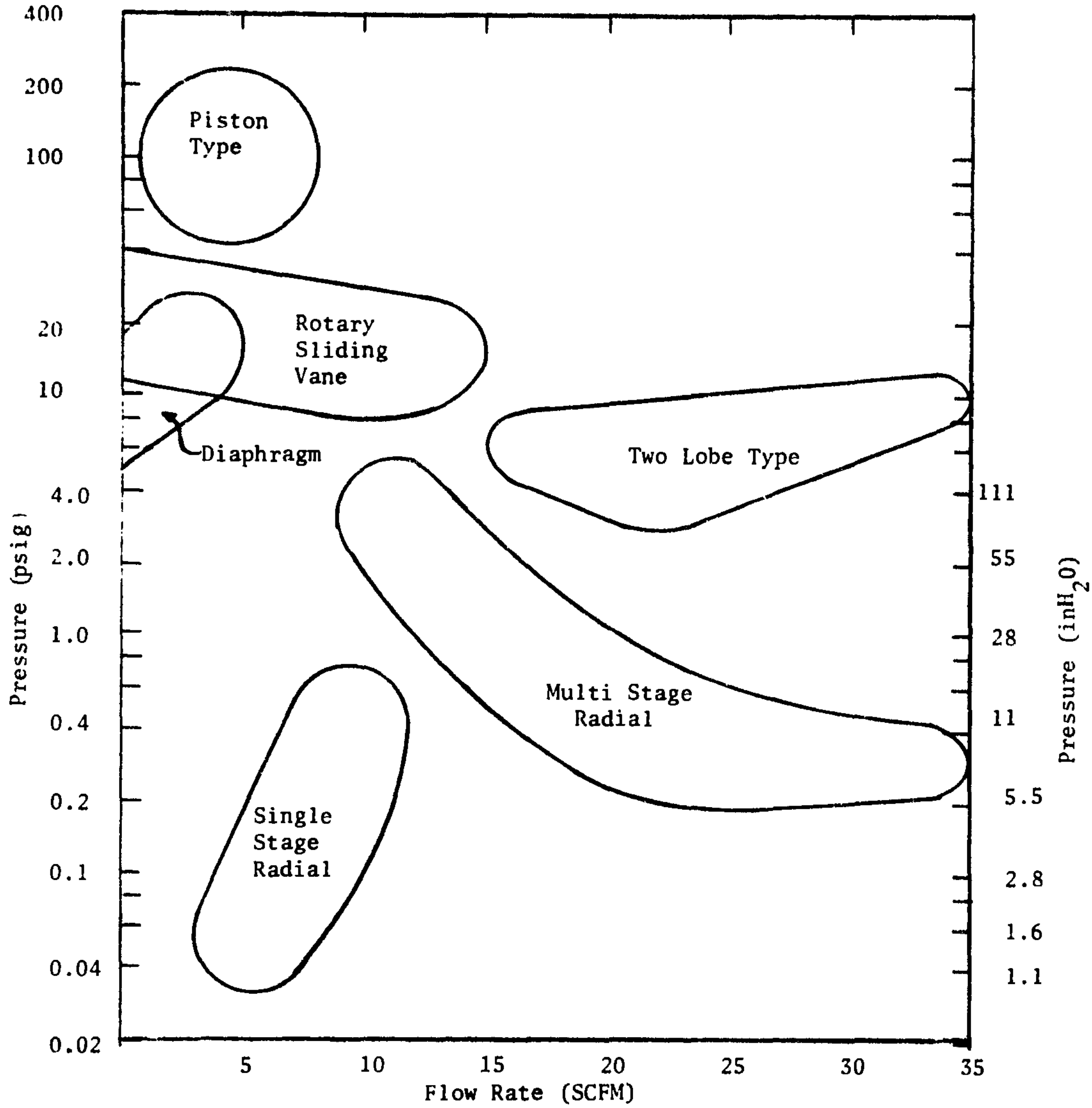


Figure 4-21. Characteristics of Commonly Available Types of Air Compressors

tilation purposes. Most of the units come with an integral electric motor presenting some problems to the designer of a supplied-air respirator in rendering it explosion proof. A fan providing suitable performance would be perhaps 5 inches in diameter and 8 inches long.

Radial Flow Compressors

The only type within this category of importance here is the rotary induced flow compressor. The usual configuration shown in figure 4-23 in-

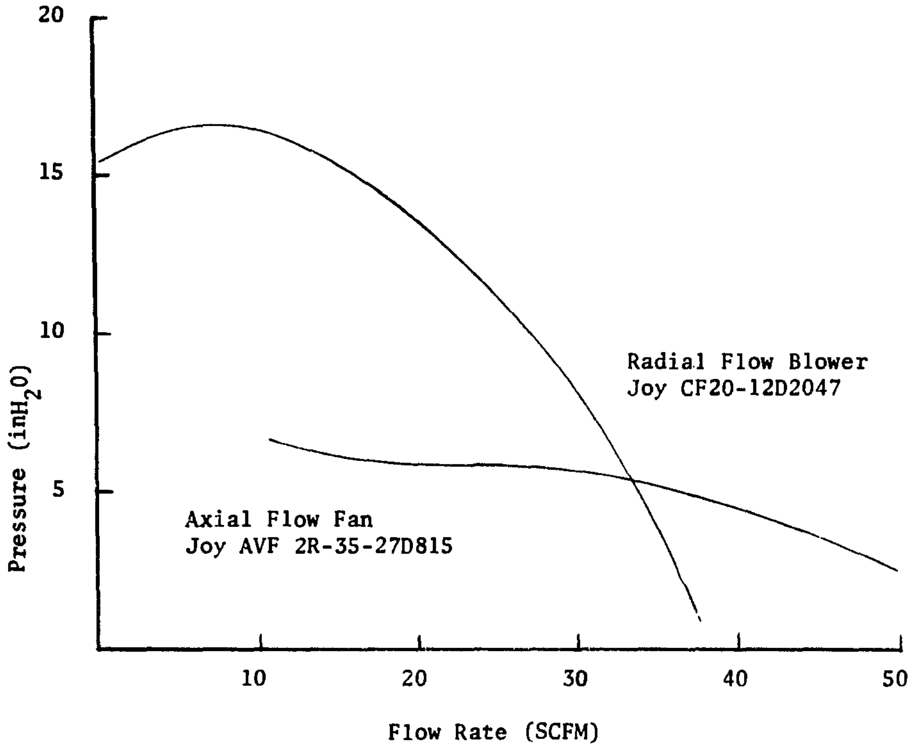


Figure 4-22. Typical Operating Characteristics for Axial and Radial Flow Compressors.

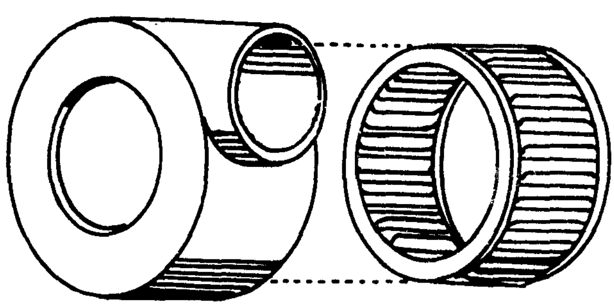


Figure 4-23. **Construction of a Squirrel Cage Blower. This is a type of radial induced flow compressor.**

cludes the category commonly called squirrel-cage blowers. These units are characterized by much more non-linear characteristic curves (output pressure versus flow rate) than axial flow fans as shown in figure 4-23. While a single stage radial-flow blower might produce more than twenty inches of water output pressure, multi-stage units having up to five stages can produce as much as 100 in H_2O pressure head. Again, high rotational speeds are required for the output. Among the various types of radial flow compressors, one must choose among forward curved, backward curved, or straight blade configurations. In general, it can be said that blowers with forward curved blades produce a rising characteristic curve, pressure increasing with flow rate, while blowers with backward curved blades have a drooping characteristic curve in which pressure decreases with increasing flow rate. For two radial flow blowers, identical in all dimensions excepting blade curvature, the compressor with forward curved blades will produce higher pressures at the same RPM. Reverse curved blades are desirable for some applications because of their self-limiting characteristics. However, for a supplied-air respirator, a blower with forward blade curvature is desirable due to size and weight considerations and the ability to deliver a more constant flow rate as system flow resistance changes.

In radial flow compressors, an instability in the form of pulsations in pressure output is frequently present when they are operated at levels below fifty percent of the design-rated flow rate. Another potential problem in this type of compressor is that the majority of the units are manufactured to operate at much higher flow rate than the 10 SCFM flow rate desired for a supplied air respirator.

Rotary Sliding Vane Compressors

While there are a number of potentially suitable types of positive displacement rotary compressors available, only the sliding vane type is deemed worthy of careful consideration. Rotary sliding vane compressors are quite common and have a number of distinct advantages for the present purpose. They operate at moderate pressures, in the neighborhood of 15 psig, and are not as heavy or bulky as the other rotary positive displacement type compressors. Oil-less sliding vane compressors, as shown in figure 4-24, are fitted with graphite vanes which are held to the chamber wall by centrifugal force so that no oil is required within the chamber. On the other hand, con-

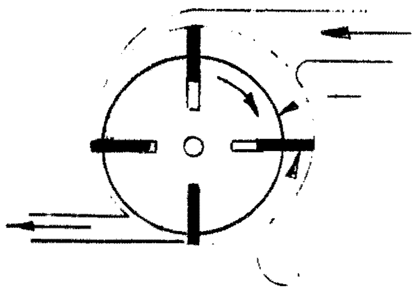


Figure 4-24. Sliding Vane Compressor

tinual wear on the graphite vane produces carbon dust which increases demand on subsequent filtering systems. One particular model produced by Gast Manufacturing Corporation was procured for laboratory evaluation. As shown in figure 4-25, its output pressure curve is quite linear with flow rate and the flow rate is adequate for the intended purpose.

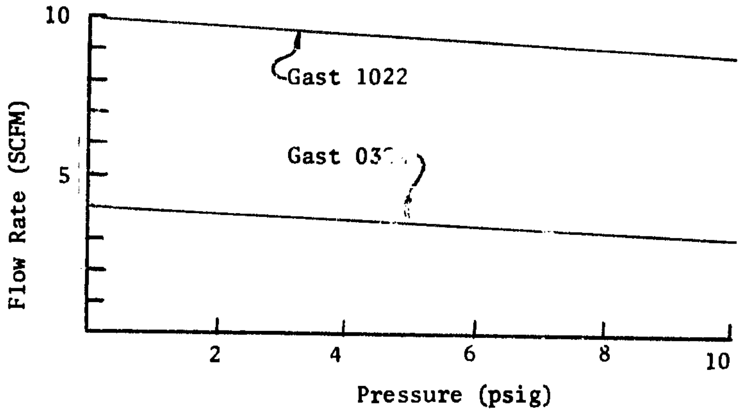


Figure 4-25. Pressure-flow Characteristics of Rotary Sliding Vane Compressors.

One potential drawback in this type of unit, which came to light in the laboratory evaluation, was the fairly high noise level and the pulsations evident in the flow.

Reciprocating Air Compressors

Within the reciprocating class of air compressors, both the piston-type and the diaphragm type are of interest to this program. Diaphragm compressors can be designed with no lubricant exposed to the compressed [illegible] cause the diaphragm must be an elastic material most diaphragm [illegible] an upper pressure limit on the order of 20 psig for continuous [illegible] number of units are available with potentially suitable flow out[illegible] this pressure range. Flow rate is essentially linearly dependent upon p[illegible], as shown in figure 4-26.

Many of the piston-type pumps are not basically suitable for the present application because a lubricant is required to reduce wear between piston and cylinder wall. The lubricant, in turn, results in oil mists being introduced into the air supply necessitating a more complex air cleaning system. However, a number of piston-type compressors of approximately the right size are constructed using Teflon piston rings and, therefore, do not require oil in the compression chamber. Several Teflon ringed compressors operating at 100 psig and producing suitable flow rates are currently available. Flow rate versus output pressure for one such unit procured and evaluated is shown in figure 4-26. As may be seen in the figure the flow rate is less dependent upon pressure in the piston compressor than for the diaphragm compressor.

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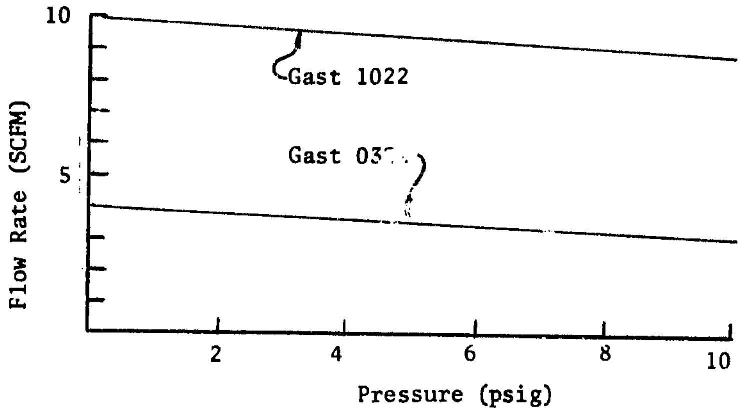

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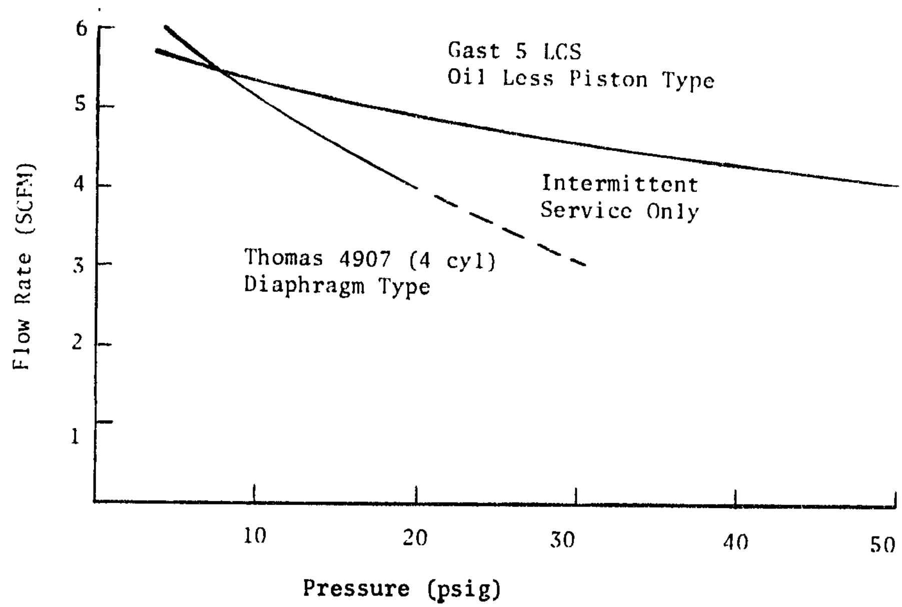


Figure 4-26. Flow Characteristics for Reciprocating Compressors.

AIR DELIVERY SYSTEM COMPONENTS

Potential components to be included in the air delivery systems of the candidate designs depend very largely on the particular type of supplied-air respirators selected for design. Components such as pressure relief valves, connectors, plenum chambers, and quick release devices, for example, are not the types of components upon which one would accept or reject one particular type of respirator. Therefore, this analysis will center upon two major components which are considered to be quite important in choosing the final design concept; the air umbilical and the demand regulator.

Umbilical Hoses

Based upon some very rudimentary simulations of underground mining operator tasks, it became quite clear that the miner's umbilical plays an important role in acceptance of the overall respirator system. While the miner's umbilical must satisfy a large number of requirements having to do with compatibility with the hazards of the underground environment, the primary concern is, of course, the length and diameter which may be utilized with given upstream pressures. Within the range of pressures and flow rates studied in this program, available tabular flow resistance data produced conflicting results. Therefore, an engineering analysis was performed. Numerical results were produced by means of a digital computer and specific examples of these numerical results were tested by experiments in the laboratory. While the bulk of this information is presented in Appendix V, a number of important results are summarized here. The first result is somewhat suprising in that pressure drop from one end of hose to another, for a given flow rate, is not linear with length of the hose. Rather, a hose twice as long as another one will exhibit less than twice the pressure drop. This phenomenon is displayed in

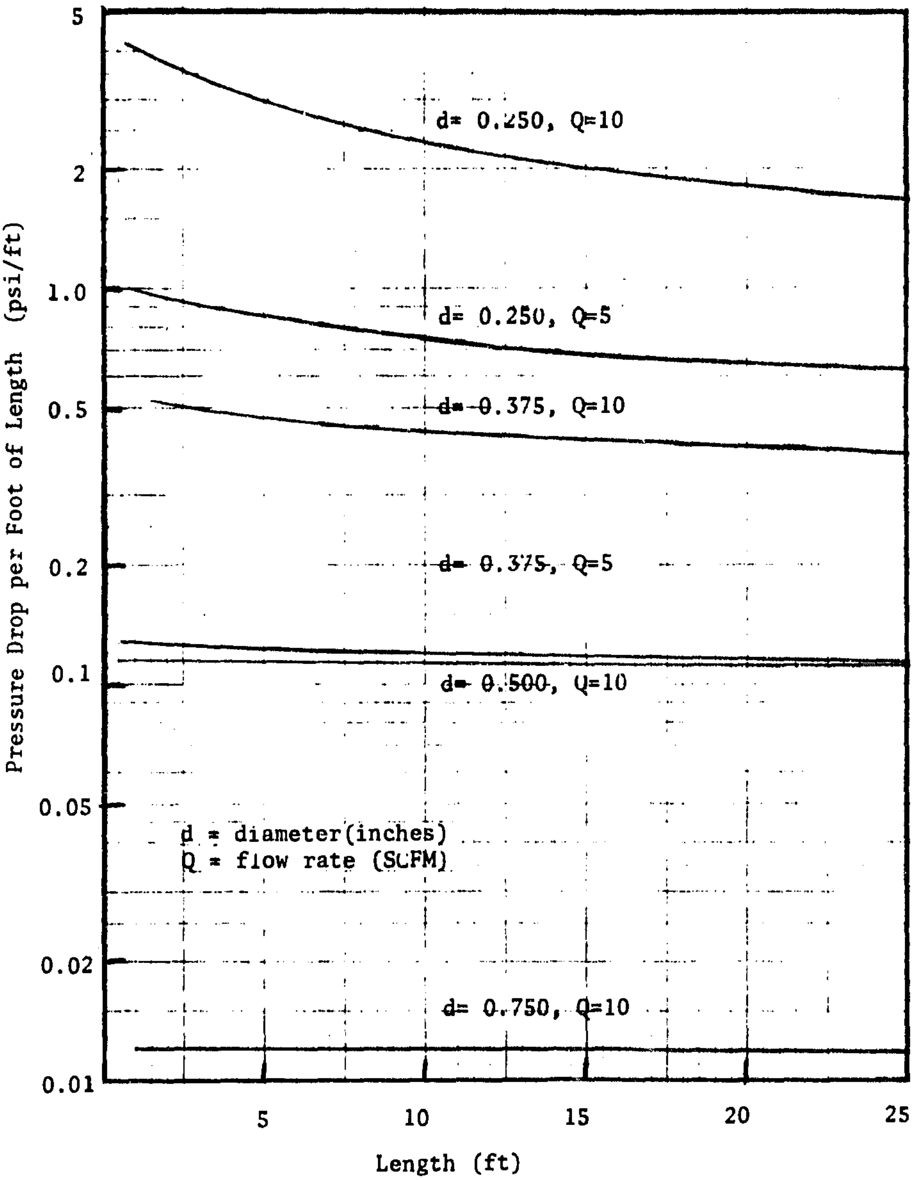


Figure 4-27. Linear Pressure Drop vs. Length of Pipe For Several Pipe Diameters and Flow Rates.

figure 4-27. The second result, which is much more obvious, is that the higher the exit pressure the less the pressure drop across the length of hose for a given mass flow rate. For example, suppose that the hose has an inside diameter of one-quarter inch, was 30 feet long, and that the mass flow was 10 SCFM. When the hose is exhausting to ambient pressure the pressure drop along the hose is 46 psi. However, when the hose exit pressure is raised to

50 psig, the pressure drop over the entire length of the hose is reduced to 21 psi. This same phenomenon is reflected in the maximum possible flow rates to be produced from the exit of a hose of any given diameter. The limiting condition at the exit of a hose is that the velocity can not be greater than sonic velocity. Computing sonic velocity and the cross-sectional area produces the curve shown in figure 4-28 for several exit pressures.

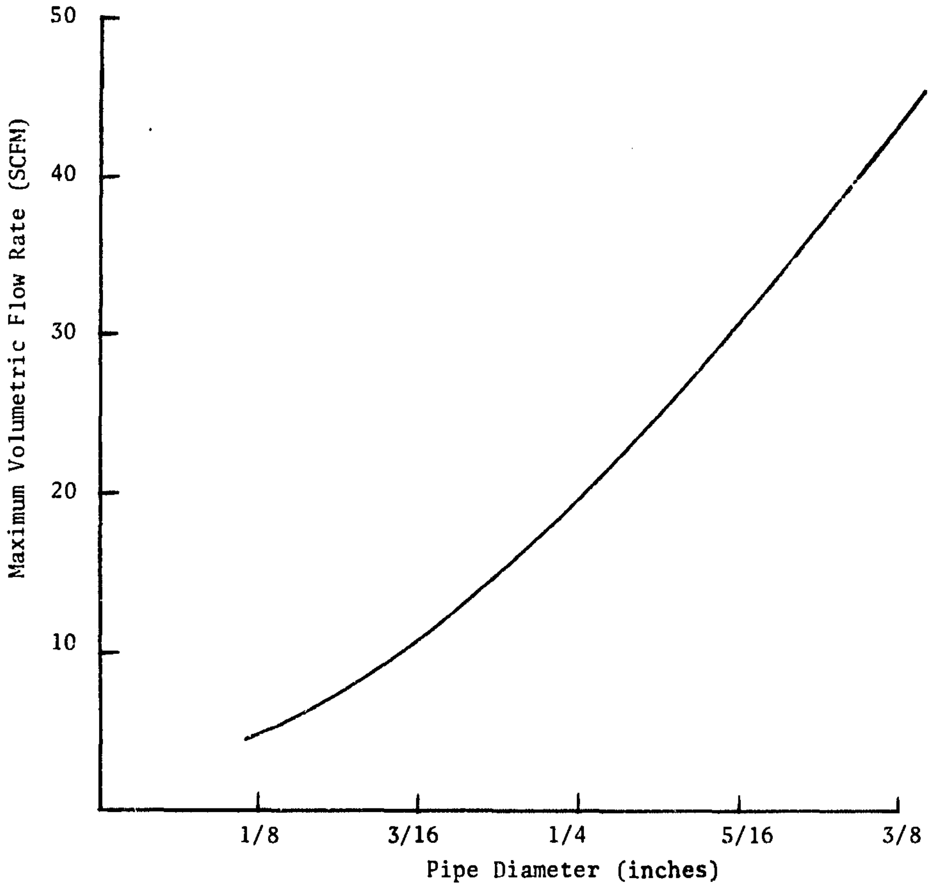


Figure 4-28. Maximum Volumetric Flow Rate for Isothermal Flow Obtainable for Various Pipe Diameters.

Another important relationship resulting from this analysis is the interrelationship of the friction factor, f, and the pipe length, L. Essentially they are totally dependent in that the product fL always appears together in the equations describing gas flow through ducts. Therefore, for any given desired flow rate and available pressure drop, the smaller the friction factor can be made the longer the duct can be. Unfortunately, with most of the types of tubing surveyed, there was no indication of what the friction factor might be. In the computer programs used in producing the flow resistance values found in Appendix V, a friction factor of 0.010 was assumed. Laboratory measurement of flow resistance for several lengths and diameters of plastic tubing corresponded closely with the computed predictions. Therefore, the assumed friction factor of 0.010 for smooth bore, plastic tubing appears to be suitable for use in conceptual design.

Pressure drop at various flow rates through a number of common connectors was also measured experimentally in the laboratory and these data are also found in the appendix.

Demand Regulators

The overall feasibility of adopting a Type II or Type III supplied-air respirator system hinges very heavily on the performance characteristics of the demand regulator employed in the unit. Therefore, it was appropriate, during the conceptual analysis phase of the program, to evaluate the demand regulators currently available on the market, and the possibility of development of a new regulator especially suited for the purpose.

One unit which has been on the market for some time, is produced by Scott-Acme Safety Products, Inc. This unit is mounted on their half-mask type facepiece. Pressure versus flow rate curves for several supply pressures with this unit mounted on a head form are shown in figure 4-29. While the

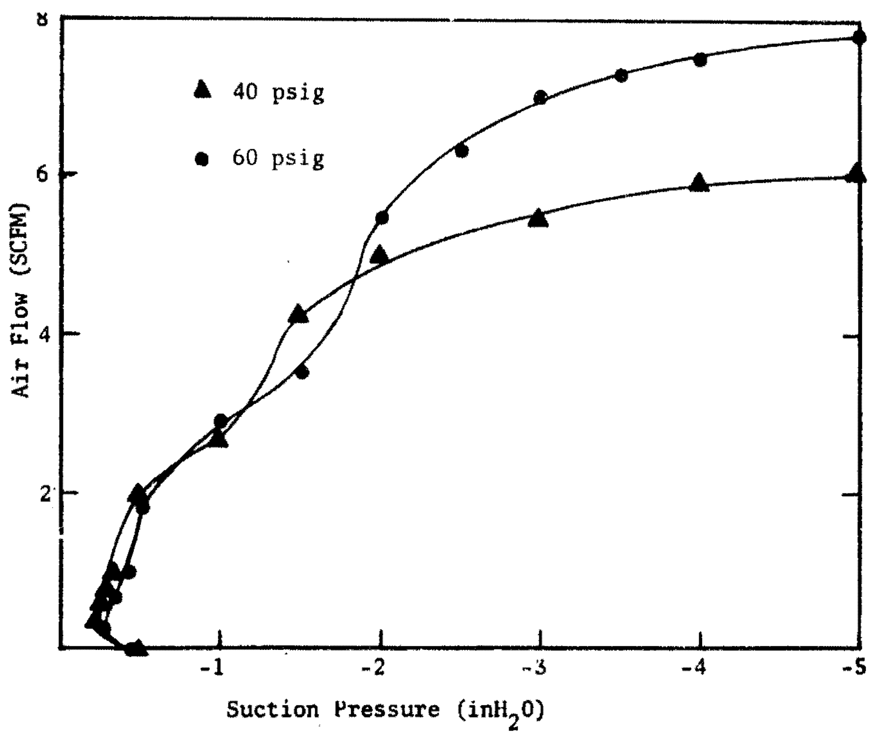


Figure 4-29. Flow Rate Versus Suction Pressure at Two Inlet Pressures for the Scott-Acme Demand Regulator.

entire unit is quite light in weight, the construction of the demand regulator leaves some doubt as to its ability to stand up to the rigors of the underground environment. The unit is 3-1/8 inches in diameter and 1-1/4 inches thick and weighs 15 ounces.

The U.S. Divers Company manufacturers, as part of their "Survivair" line, a light weight demand regulator suitable for use in either a Type II or Type III system. They were kind enough to furnish us with a sample regulator for examination, as well as curves of airflow vs. demand pressure at different inlet pressures (shown in figure 4-30). These pressure flow curves were measured

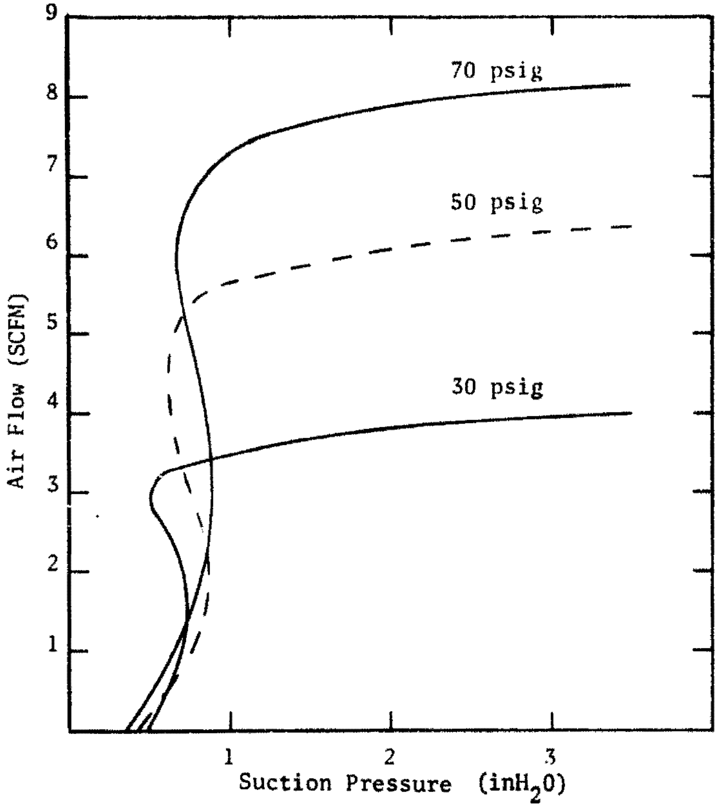


Figure 4-30. Flow Rate Versus Suction Pressure at Three Different Inlet Pressures for US Divers Co., Survivair Demand Regulator, Part No. 9104-60.

recently at the U.S. Divers plant and were not verified by us. The regulator tested had been modified and its operation was slightly sub par. Subjective response to breathing with this regulator, by a number of individuals, was one of approval.

The regulator is 3-3/8 inches in diameter and may be cut down to a thickness of 1-3/4 inches, or slightly less, if desired. The unit is strongly constructed of plastic, fairly light weight, weighing 3 ounces, and appears as if it would tolerate the underground environment with some modifications.

The Robertshaw Company also furnished a potentially attractive demand regulator. Pressure versus flow curves, from their literature, are shown in figure 4-31 and have been verified in our laboratory. Although the dif-

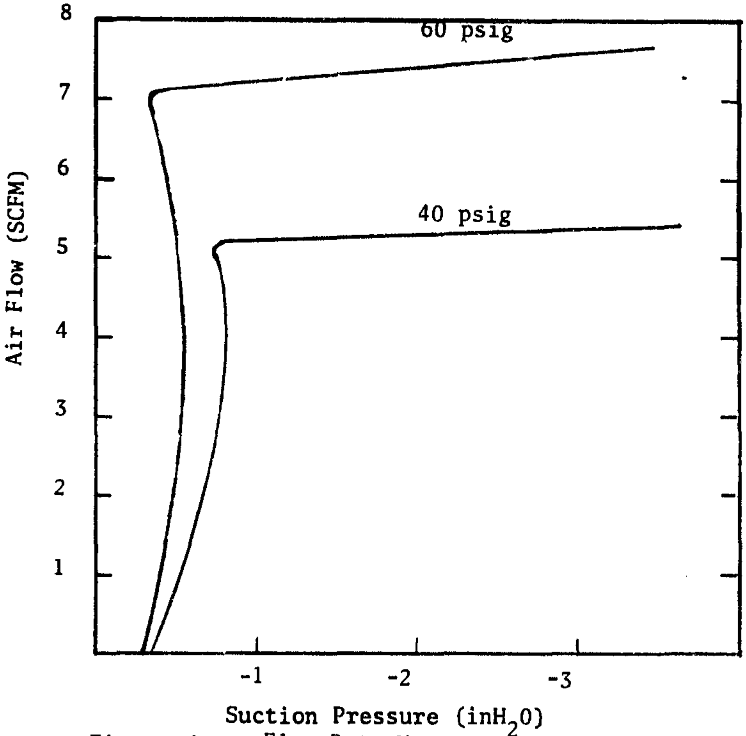


Figure 4-31. Flow Rate Versus Suction Pressure at Two Inlet Pressures for Robertshaw Model 226 Demand Regulator.

ference in inhalation effort for a given flow between this unit and the Survivair regulator is small, our subjects judged this regulator more acceptable than the Survivair unit in ease of breathing. Its small size, measuring 1.79 inches in diameter by 2.3 inches long, and light weight (1.6 ounces) are considered a significant advantage; especially since it can be made much thinner with some development.

Regulators commonly available to SCUBA divers were examined briefly and found to offer no significant advantage over the above units, except possibly durability, at the expense of considerably more weight.

While the Robertshaw and the U.S. Divers regulators appear to be the best available, both of these regulators exhibit two potential deficiencies in meeting desired characteristics: 1) they are too large and heavy for mask mounting, and 2) they do not provide sufficient flow at inlet pressures on the order of 70 psig.

After discussions with a number of regulator manufacturers, it was decided to determine if a prototype regulator meeting our requirements could be produced without an extensive development program.

Two companies, Robertshaw Controls Co., Anaheim, CA and Rego, Chicago, Ill., proposed development programs. Rego proposed a unit which would be suitable for belt mounting, weighing 8 to 9 ounces and being 3-1/8 inches in diameter by 1-3/4 inches thick. This proposal was rejected in favor of Robertshaw's proposal for modification of their type 226 Aviator's Oxygen Regulator, described above. The plan was to make the unit smaller and capable of the desired flow at lower inlet pressures. The resulting regulator, shown installed on a test mask (figure 2-6) weighs 1.56 ounces and produced the flow curves shown in figure 4-32 which were taken in our laboratory.

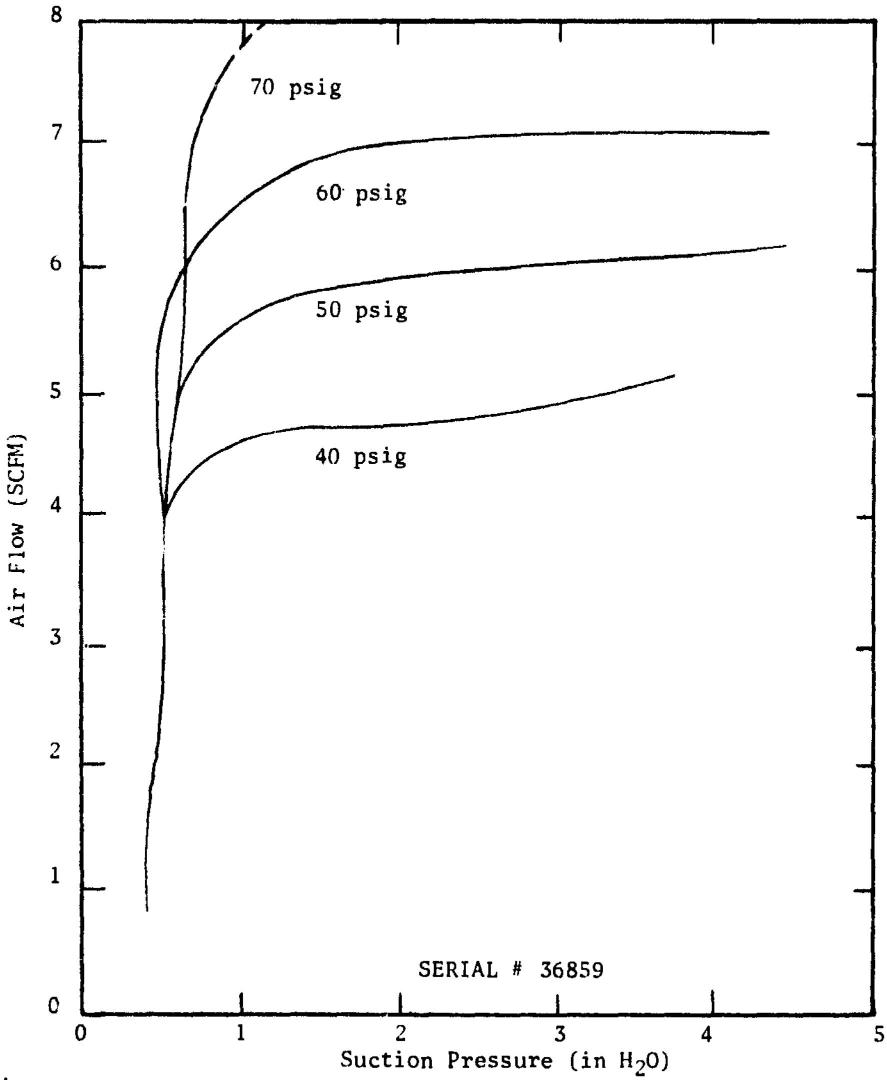


Figure 4-32. Flow Rate Versus Suction Pressure at Four Inlet Pressures For a Single Robertshaw 226 Demand Regulator.

FACEPIECE CONCEPTS

In the concept synthesis phase of the program, facepiece studies centered upon two related activities: 1) evaluation of currently available facepieces and 2) conceptual design of a new facepiece. Initially, the facepiece development effort was to make use of results of another research and development program to be funded concurrently by the Bureau of Mines. Since that program was never initiated, this contract was amended to provide additional funding for facepiece development. Prototypes of both half-face and full-face masks were to be developed. Compatibility with the miners' tasks and mining population facial anthropometry were key objectives of the effort. Part of that effort is described in this chapter and part in the remaining chapters.

Evaluation of Existing Facepieces

The first step in analyzing potential facepiece concepts for use with the supplied-air respirator system was to evaluate the half and full-face masks currently available on the market. This analysis was concerned primarily with the potential for modification of each facepiece to a form suitable for use in the underground mining environment. The analysis included discussions with manufacturers, sales representatives and some safety professionals, regarding such subjects as sizing and fit of the various facepieces. Miners and mine operators were also interviewed for their opinions regarding the acceptance of half-face masks versus full-face masks.

Sizing and Fit

In current practice for many industrial locations, selecting a respirator to fit a particular individual involves choosing among respirators produced by various manufacturers. While some half-face masks permit adjustment of the width of the mask by use of bendable metal components, the range of adaptability was not found to be sufficient to provide a suitable fit on all subjects in our test panel. With perhaps the single exception of the Scott-Acme half-face mask, it would be necessary to adapt a supplied-air respirator air distribution system to more than one mask if we were to use off-the-shelf facepieces.

Design Limitations

In speaking with sales representatives, as well as industrial users, it became quite apparent that the cost factor is very significant in the design of current half-face and full-face masks. For this reason, some design features which are potentially very important in the supplied-air respirator for underground coal miners, are not found in commercially available masks. Since the supplied-air respirator system is a moderately expensive system, it would seem appropriate that cost limitations should not be an important factor in designing the facepiece for use with the system.

Mask Suspension

Nearly all of the half-face masks and all of the full-face masks involve rubber suspension elements or mask harnesses. These were found in all cases to make donning and doffing of the facepiece more burdensome than might otherwise be the case. Furthermore, in the underground environment, which involves rapid head movements and crawling in the head-down position, many of the masks were found to be poorly stablized with existing suspension systems. This is especially important when one considers that the facepiece will be required to support demand regulators or equally heavy corrugated breathing hose.

Full-Face Mask Concepts

Based upon underground experience gained in our field surveys in the Beckley, West Virginia area, and upon discussions with other mine operators, miners, and mining consultants, it was decided that a full-face mask would achieve considerably less acceptance in the underground environment than would a half-mask type facepiece. A primary consideration in this decision is vision. It was felt that full-face mask vision would become degraded due to the combination of water and dust in the underground environment. Furthermore, in this environment there is no effective way to wipe the mask clean.

Another deciding factor dealt with donning and doffing of the mask. With currently employed masks, donning and doffing is very frequent. The size and bulk of a full-face mask and the complicated harness usually associated with such masks would make donning and doffing extremely difficult. For these reasons, full-face masks were precluded from further examination and consideration. This decision was made after considerable discussion with, and full agreement from, the NIOSH Technical Project Officer.

Facepiece Concept Synthesis

The half-mask facepiece concept formulation process involves definition of four major elements of the design process:

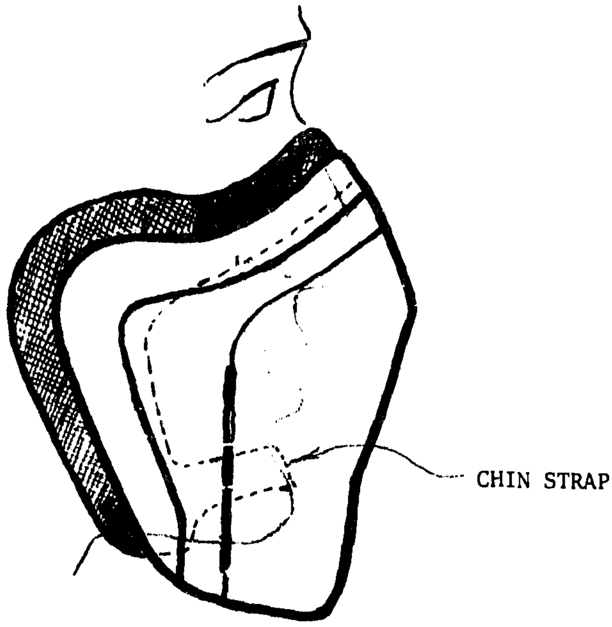
1. Mask configurations.
2. Suspension Characteristics.
3. Air supply integration.
4. Prototype model fabrication.

The basic approach to the problem was to sketch a number of different concepts, each meeting the requirements and guidelines previously stated. Each concept was oriented toward solving the problems previously discussed, as well as incorporating new features not previously identified. A number of iterative steps were taken and several candidate mask concepts were fabricated.

Basepoint Mask Concept

The basic premise in facepiece design is to reduce the burden on the wearer to a point at which unprotected exposure to the threat is more undesirable than wearing the facepiece. Achieving this level of acceptance, and at the same time ensuring the required protection factor, is the desired goal.

The conceptual elements for facepiece design, referenced to the sketch in figure 4-33, are as follows:



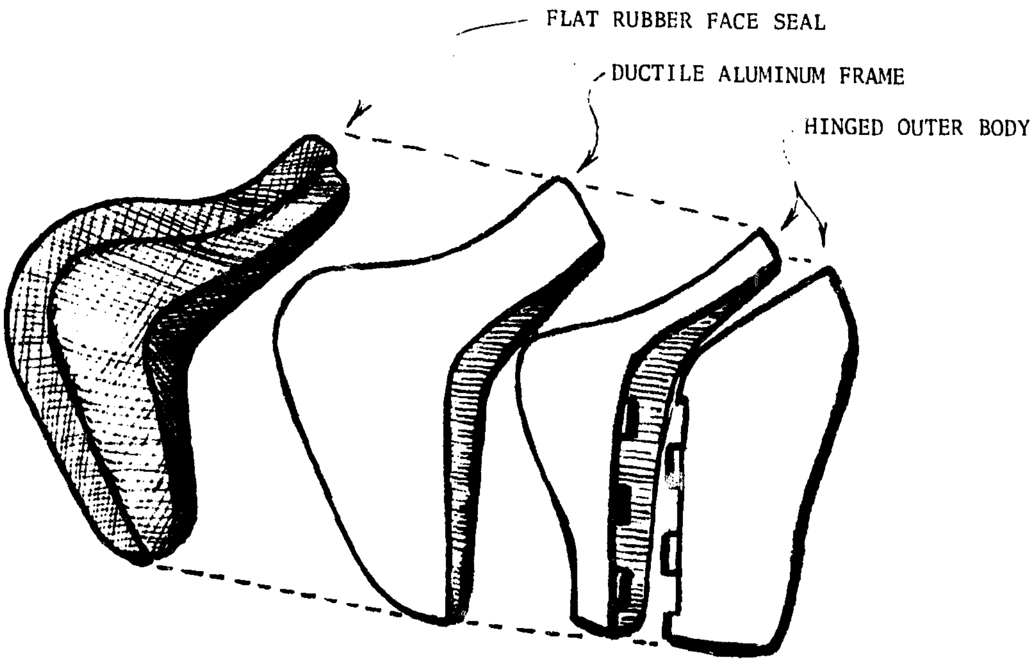


Figure 4-33. Facepiece Assembly (top) and Components From Which it is Assembled.

1. The face seal has a broad contact area and envelopes the oronasal area fitting over the cheeks and under the chin. The seal has an adjustable strap girdling the forward portion of the chin, facilitating individual fitting.

2. The metal or plastic frame or shell has a shape compatible with the face seal and is attached to the suspension. The function of this frame is to overlay the seal, applying sufficient compressive force for ensuring the positive seating of the seal on the face. The frame includes a component to permit shaping to the facial contours of the individual wearer. The frame also serves as the mounting platform for the demand regulators and/or air supply hose connectors, the airflow diffuser, the exhalation valve, and a voicemitter. The body may be attached to the frame by a permanent bonding method. The shell is to be constructed to permit opening of the forward portion (as a door), thus, providing for facial access and expectoration.

3. Stable positioning on the face is effected by the combined action of the chin strap and the portion of the seal lying along the cheek bones. Together they prevent facepiece translation on the face and provide an effective means for reacting the suspension forces. Forces on the nasal ridge are to be kept to a minimum.

Access to the face for speaking on a telephone, for expectoration, for relief of the confined feeling, or "getting a breath of fresh air", was a principal factor in conceptual design of the basepoint system. This resulted in the three-component concept already described (figure 4-33) which facilitates the incorporation of a hinged "door" in the facepiece. With somewhat greater attachment problems, the door could be removable - separating the front piece from the frame.

One possible method for providing all of the necessary functions is to construct the outer portion of the facepiece of a fabric, filter-type material. This could be based upon a skeleton type structure as shown in figure 4-34. This fabric, although making a poor exhalation valve, could eliminate the need for a separate voicemitter and will serve, as well, as an anti-suffocation device which would otherwise be an added component.

Suspension Concepts

Since either demand regulators or large diameter breathing hoses are fairly heavy, four to six ounces total, the demands upon suspension elements are much more severe than for contemporary dust respirators. As previously discussed, these demands require significant departures from current practices with half-face respirators. Consequently, a number of conceptual approaches to mask suspension and retention have been considered. The basepoint system shown in figure 4-35 provides a number of features held to be important both in good dynamic suspension and in promoting acceptance by the miner:

1. The mounting horns prevent interference with the ears and permit adjustment of chin and nasal compressive sealing forces.

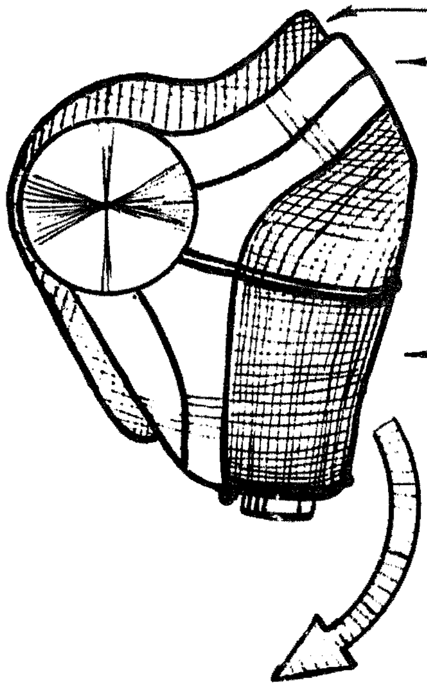


Figure 4-34. Facepiece Incorporating Fabric Cover Over Plastic Frame

2. The two strap suspension provides suitable vertical and transverse stability while evenly distributing retention forces over a broad area of the scalp.

3. Doffing may be accomplished with one hand since the two straps are connected in the rear.

4. Rotational adjustment of the horn, relative to the mask, as well as adjustment of strap tension, permits the achievement of suitable mask retention forces with a wide variety of head shapes and sizes.

Because the suspension is such an important factor in respirator acceptance by miners, considerable attention has been given to this matter, producing a number of feasible concepts. Another potentially suitable concept is to provide a comfortable harness that can be worn all day, attaching the facepiece to it, when needed. This concept, shown in figure 4-36, features a light weight net, or knitted type material for a chin pouch. Potentially, the chin strap can be "hinged" at the ring near to the joint of the lower mandible so that jaw movement does not change the tension on the strap. The ring is necessary so that the harness does not pass over the ear causing discomfort. More importantly it can be used as a mounting platform for a number of items - mainly the mask and the regulators. However, other devices such as strap tension adjustments, purge control, ear defenders, or a helmet vertical retainer ("chin strap") could, as well, be mounted on the ring.

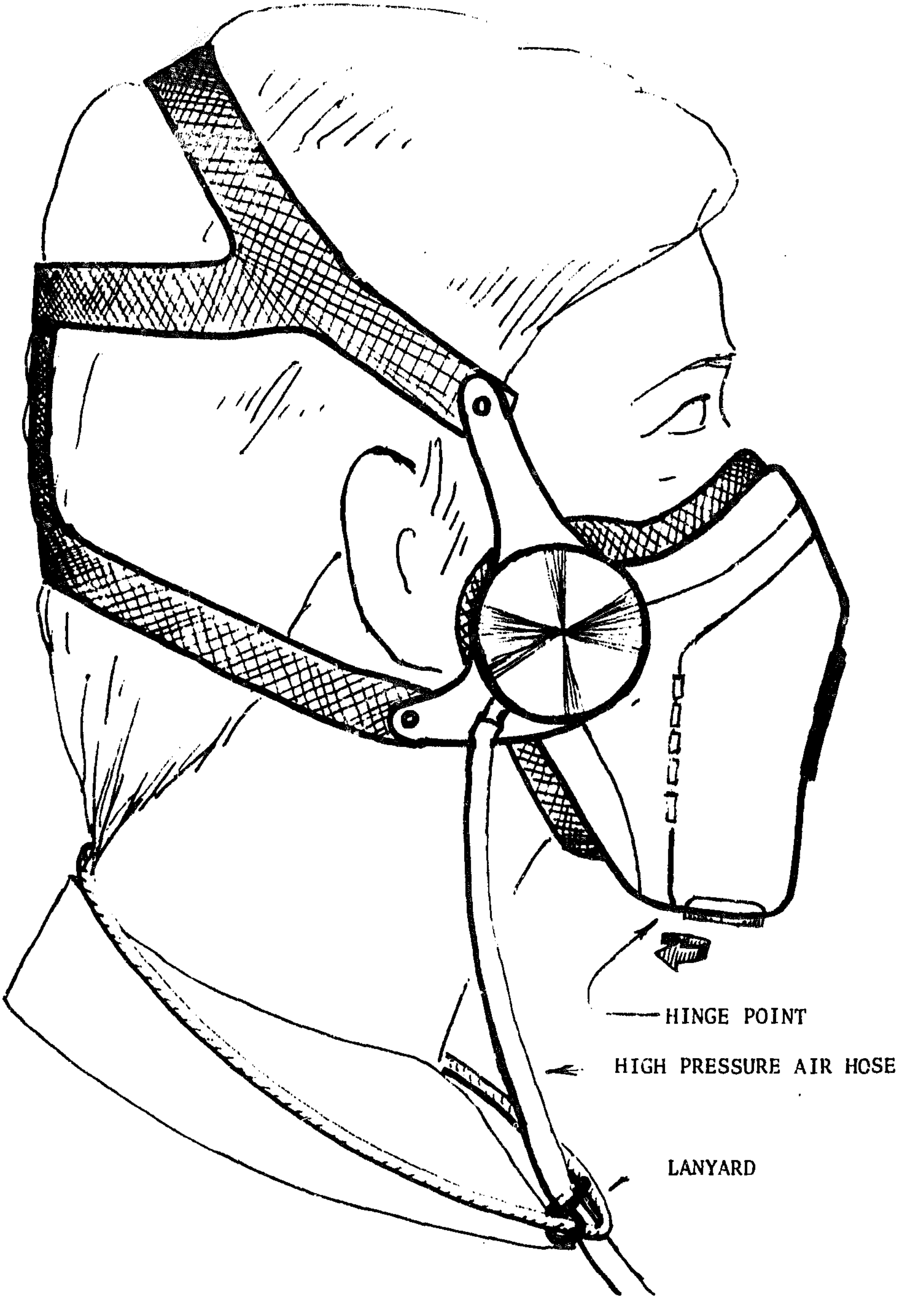


Figure 4-35. Basepoint Concept - Half Mask Supplied Air Respirator Facepiece Assembly

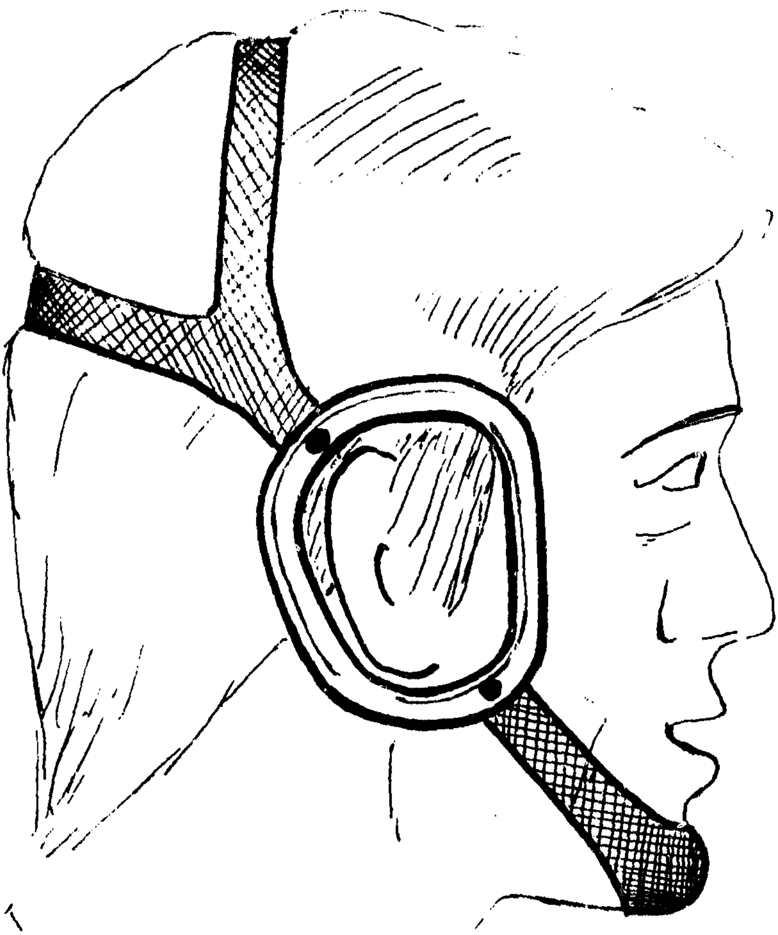


Figure 4-36. Chin Strap Type Respirator Suspension Showing "ring" for Mounting Facepiece.

A number of other attractive, potentially feasible concepts are illustrated in figure 4-37. In this drawing, the mask is shown hinged on the ring so that it can, with one hand, be swung around for access to the face, expectoration, using the telephone, etc. Alternatively, the entire front portion of the respirator may be removed from the ring and suspended by the lanyard while not in use. Feasible concepts have been developed indicating that the latching device, for either the hinged or the completely removed mask, can also serve as an adjustable mask tensioning device permitting periodic manual adjustment of the mask seal pressure on the face by the miner.

Another concept incorporated in the sketch of figure 4-37 is integration of helmet and respirator suspensions. This system, because of the chin strap, facilitates helmet security while at the same time providing a superior respirator harness. It, of course, necessitates a completely removable mask as discussed above. Unfortunately, the concept is not feasible at this time because of the great diversity in helmets, and in some cases due to unsuitable suspensions of current helmets.

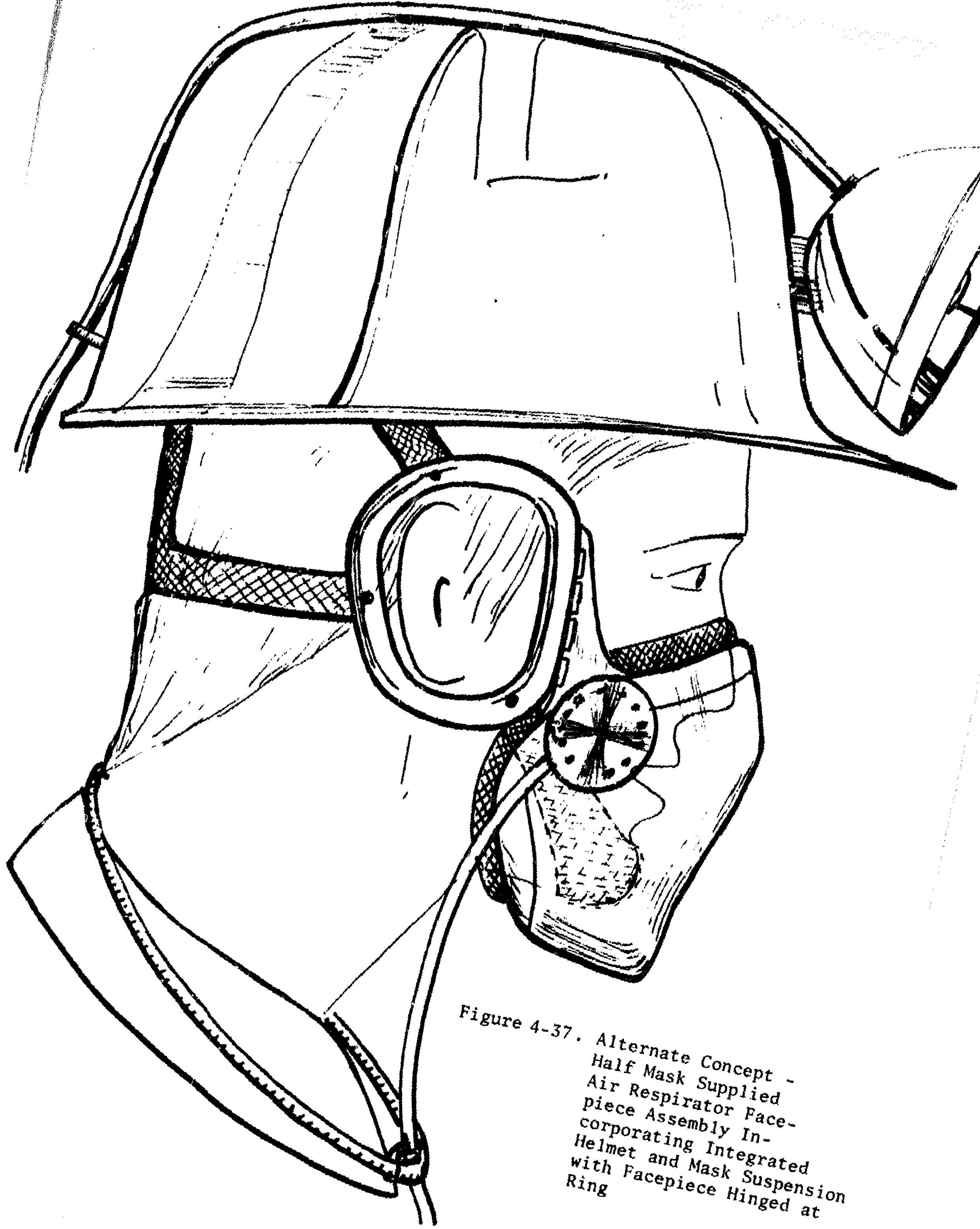


Figure 4-37. Alternate Concept - Half Mask Supplied Air Respirator Facepiece Assembly Incorporating Integrated Helmet and Mask Suspension with Facepiece Hinged at Ring

One further advantage of the "ring" concept is that it may be formed so as to permit unrestricted use of eyeglasses by allowing a channel for the stems. The major problem to development of the chin strap type of concept is the paucity of anthropometric data relating the head and facial landmarks necessary to good design of the "ring". This can be overcome by more flexible design at the cost of complexity, bulk, and weight.

Air Supply Integration

Integration of the air delivery elements with mask design is centered upon two goals: 1) reduction of forces transmitted to the face mask and 2) management of air flow inside the mask to avoid discomfort. In order to avoid the requirement for the nasal ridge to react inertial or gravitational loads, it is necessary to mount the air supply elements, regulators or supply hose attachments as rearward as possible on the mask.

In the basepoint concept, the demand regulators are externally mounted to the frame, as shown in figure 4-35. Air is ducted forward to the oronasal cavity. High-pressure air is provided to each of the regulators through a small diameter, light weight tubing system connected to the miner's umbilical at the belt.

Since either regulators or hose connectors would be about 3/4-inch thick, they result in an increased facial clearance width, but less total width than commonly found in contemporary protective helmets. However, by attaching the regulators to the frame they will be retained in a stable manner and will obviate the inertial problems noted with current mask-mounted regulators.

Air flow management within the mask is necessary to prevent local high velocity impingement of air streams on the face. Additional functional elements include devices to insure drainage of water from the mask and to keep the exhaust valve free from dirt accumulation or dust ingestion upon valve closing.

In the sketch of the basepoint design, an exhalation valve is located at the underside of the facepiece body. This location was selected for promoting moisture drainage. Although not specifically shown, the exhalation valve location is to prevent the problems of flow path occlusion due to seal interference noted with many contemporary facepieces.

The valve housing serves to protect it from damage and dirt and to serve as a clean-air plenum preventing dust ingestion.

<u>Facepiece Engineering Prototype Fabrication</u>

In a program such as this, it is necessary to keep in mind the differences between a prototype and a production version of the design. Every attempt has been made to produce prototypes which reflect easily producible items. On the other hand, many components built by hand on the prototypes could be done much better in a mass production situation. For this reason, the prototype facepiece systems delivered may not reflect the "design" produced by the program.

Three distinctly different facepiece concepts were fabricated for evaluation during this phase of the program. Each prototype represented different design methods for achieving the various goals of the facepiece design.

Methods

The masks were fabricated using a number of methods especially suited for this purpose. Rubber-like parts were molded of thermo setting vinyl elastomeric materials, plastisols, using the dip molding process. Metal parts were fabricated using the electroforming technique and hard plastic parts were vacuum formed.

Initially, it was planned to use facial clearance envelopes available (Goldberg 1966) as base-line data for producing the size and shape of the prototype facepieces. These clearance envelopes, which are essentially three-dimensional surfaces indexed to the chin and forehead, had previously proved quite valuable in the design of full-face masks. However, upon analysis it was evident that these data were not suitable for the design of half-face masks. This was basically due to the paucity of data points in the area immediately surrounding the nose. Therefore, a combination of methods was employed in arriving at mask seal and internal envelope dimensions. Basic mask mold sculpture was based upon several head and face forms, based upon US Air Force anthropometric data. Numeric facial anthropometric data summarized by McConville (1972) and new facial anthropometric data produced by Hack (1972) were utilized to augment the faceforms and in assembling a test panel from available employees and associates.

First Prototype Facepiece

Using the above methods, the facepiece assembly shown in figure 4-38 was fabricated. As shown in figure 4-39, the assembly consists of three basic components:

1) A 45-durometer vinyl mask body with an inturned seal.

2) A copper frame, or shell, with ports for mounting regulators, or hose connections, and an exhalation valve.

3) A polycarbonate harness attachment "horn" with snaps for installing a two-strap harness suspension.

The vinyl mask body, dip-molded on an aluminum mold, incorporates two flat areas for mounting hose connections or demand regulators, a bellows section under the chin to facilitate speaking and sizing, and an inturned seal which is considered desirable both in terms of fit and in terms of preventing outboard leakage. The copper alloy shell was electroformed to a thickness of 0.025 inch over the vinyl plastic component and, as shown in figure 4-39, permits mounting of both the regulators and the suspension horn. The suspension mounting horn was fabricated from flat Lexan plastic stock and riveted to the copper alloy shell. The two Robertshaw demand regulators were threaded into the copper alloy shell also. Rubber head straps used for the mask suspension were attached to the mounting horn by means of snaps. Vinyl adhesives were used to bond the vinyl to the copper frame.

Figure 4-38. Test Subject Wearing the First Prototype Facepiece

Using members of the test panel, the mask was evaluated for fit, comfort, stability and other design requirements. Due to the wide seal contour extending well rearward, stability of the mask on the face with rapid head movements was excellent. The harness attachment horn augmented this stability and provided some degree of adjustment of facial pressures. However, the lower harness strap caused excessive seal pressures upon posterior head flexion.

While fit and comfort were adequate for most subjects, the accommodation available by bending the frame was not adequate for the panel members with smaller faces. Furthermore, exhalation resistance with the single exhalation valve was considered slightly excessive. Therefore, a second prototype was conceptualized and designed.

Second Prototype Facepiece

Concurrent with the facepiece development effort, a final decision was made to employ two of the modified Robertshaw demand regulators in the prototype supplied-air respirator. Therefore, all subsequent mask development

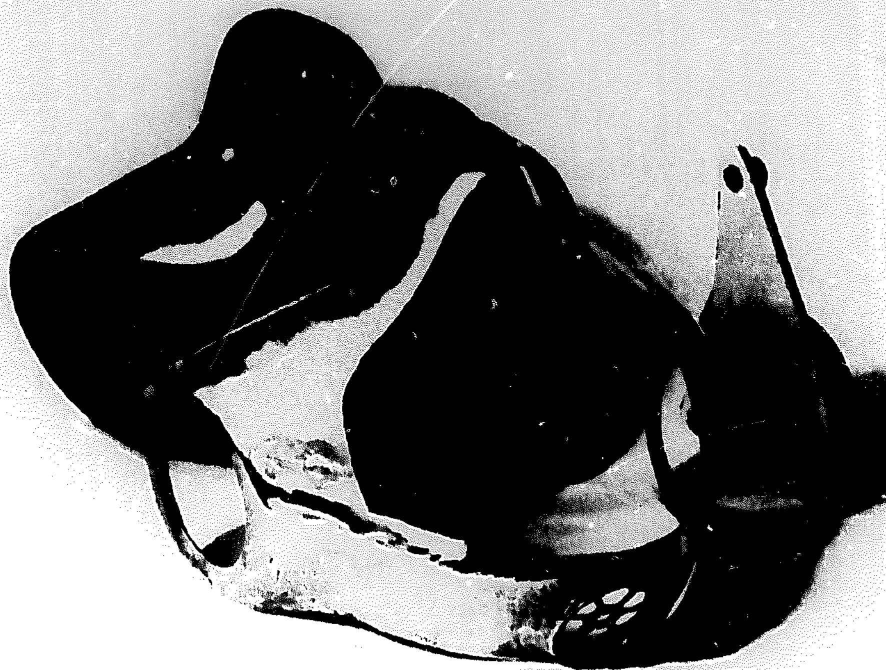


Figure 4-39. Exploded View of the First Prototype Facepiece.

work was oriented toward accommodation of this method of air delivery. While the first prototype mask allowed space for mounting the various features required, such as a voicemitter and a facial access port, it was decided that the second prototype should actually embody those features.

After consideration of a number of novel concepts for providing the required features, the following features were incorporated in the second prototype facepiece:

Space for mounting two Robertshaw demand regulators which provide a small continuous flow, in addition to their demand flow capabilities.

A spring-loaded, swing-away door at the front of the mask to permit facial access and expectoration.

A diaphragm-type voicemitter to permit speaking.

An anti-suffocation device consisting of two vent holes covered with fine mesh fabric filter material.

Two exhalation valves to reduce exhalation resistance.

A broad contact-area face seal with bellows at the chin to facilitate speaking.

A ductile metal seal-support device, or "shell," which included a number of "finger" type bendable elements to permit accommodation of a large range of face sizes and contours.

A primary difference between this mask and the first is that the metal frame is completely imbedded in the vinyl mask body. The metal frame shown in figure 4-40 was electroformed of copper and given a mild heat treatment to make it suitably ductile. The holes or open spaces seen in the frame serve to reduce weight. While the entire frame may be bent to accommodate various facial sizes, accommodation of contours in the nasal area is provided by the bendable fingers of the metal frame.

The mask body in this prototype mask is integral with the frame. Its sealing surface contours are the same as used in the previous model. The assembled mask may be seen in figure 4-41. The various features are discussed below.

Figure 4-40. The Copper Seal Support Shell of the Second Prototype Facepiece.

Facial Access Port. A swing-away door with a spring-loaded hinge and spring steel latch is located on the front of the mask. The door, which can be opened or closed with a single motion of one hand, permits facial access for expectoration, speaking on the telephone, or just "getting a breath of fresh air". Hopefully this will encourage more continuous wearing of the respirator than with currently-used respirators. The facial access door also incorporates the voicemitter and anti-suffocation provision.

The hinge for the door consists of two short tubes soldered to the copper mask frame and a rod bonded to the door. The door is spring-loaded so that it will fly open when the latch is released.

The door itself is made of vinyl covering a copper form and was fabricated in the same manner as the rest of the facepiece.

The voicemitter which is located on the door directly in front of the mouth is of the passive metal-diaphragm type and gives excellent speech transmission characteristics. It was adapted from the voicemitter used on the U.S. Army M-17 protective mask.

Anti-Suffocation Device. The anti-suffocation provision consists of two vent holes in the facial door, covered with high-density dacron felt filter material. The flow resistance of this material is high enough to insure that far more air enters the mask from the air supply system than through the vents during inhalation. Furthermore, this filter media has a nominal rating of 0.5 um, which is on the order of filtration afforded by the air cleaning system. Still, the flow characteristics are such that breathing is possible in emergency situations.

Exhalation Valves. Two exhalation valves are provided in the chin of the mask, below the facial door. They were also adapted from the U.S. Army M-17 mask. The addition of the second valve aids in the realization of very low exhalation resistance, less than one-half inch of water at the highest flow rates expected. An exhalation plenum, or shroud, was not incorporated into the design but is a necessary design feature.

Sealing Surfaces. The seal area of the mask was designed for maximal contact area to reduce the seal forces necessary to provide stability and bear the weight of the mask. This was accomplished with a 1/2-inch wide inturned seal which extends well back along the cheeks. A "bellows" fold at the chin permits seal maintenance without hampering jaw motion during speaking.

Facepiece Suspension. The suspension system consists of a single, rubber neck strap and a double strap passing over the crown, held together by a vertical strap. The "horns", on the mask, to which the straps are attached, lift the harness straps away from contact with the ears and permit the wearing of eyeglasses with the mask without the discomfort associated with straps pressing on the stems. The "horns" can also be rotated on the mask, allowing the wearer to adjust the location of the straps on his head. However, the rubber straps are not completely satisfactory as they can pinch the scalp and cannot be easily adjusted.

The design of the mask seal contour is such that the majority of the suspension forces are reacted against the cheek areas. A chin stop has not been incorporated on the interior of the mask, thus, allowing the bellows to seal well back under the chin.

Facepiece Evaluation. The second prototype mask exhibited a number of serious problems. One of the most apparent problems was the weight, 17 ounces, and bulk of the mask. The requirement for mounting two regulators, two exhalation valves and a fairly large facial access port was, therefore, revaluated. It was decided that the facial access port should be no larger than the voicemitter, 2-3/8 inch diameter, and that a single exhalation valve would have to suffice.

While the overall weight of the mask was clearly excessive, part of that weight was due to the use of an electroformed copper frame rather than light weight aluminum which could be employed on a production mask. However, upon further evaluation it was felt that an aluminum frame mask of similiar dimensions would still be too heavy. Therefore, it was decided that the overall seal contours should be made smaller by reducing the posterior extension of the sealing surface. Mask fit and comfort evaluations supported this decision in that the seal encroached into the sideburns of the smaller subjects.

Another finding of the fit tests was that, on some subjects, the seal intersected the mandible at the notch through which the facial artery and facial vein pass. Occlusion of these vessels for long periods of time is undesirable and it was decided to keep the seal surface well forward of this facial landmark.

The mask was also quite difficult to manage when not on the face. Wearing it suspended by the harness hanging from the neck was unpleasant due to both weight and size. Its size and bulk also contributed to mask deformation when not in use.

While the bendable fingers permitted forming the seal contour to fit any face in the test panel, it was found that such procedures were an unpleasant burden upon the wearer. The adjustments, it turned out, were made frequently during extended wear of the mask, tending to intensify the annoyance of using a respirator face mask. Therefore, it was decided that the next prototype should not be adjustable in the sense that changes in seal contour can be made at will. Rather, a better concept would be to provide adjustments at the time the mask is issued to a miner. If a pressure point or leak is encountered subsequently, it can be adjusted as part of a regular mask maintenance program.

Third Prototype Facepiece

The third and final prototype facepiece produced is much smaller than the previous two prototypes and weighs only 8.2 ounces with regulator installed. The overall concept is different in that the shell or frame is made from light weight plastic. The prototype mask is shown in figure 4-42. Several prototypes of this general configuration were produced before arriving at the mask shown in figure 4-42. Final development of the mask and a more complete discussion of its fabrication are presented in Section V of this report. The mask concept incorporates most of the features found in the second prototype.

Figure 4-41. Second Prototype Facepiece.

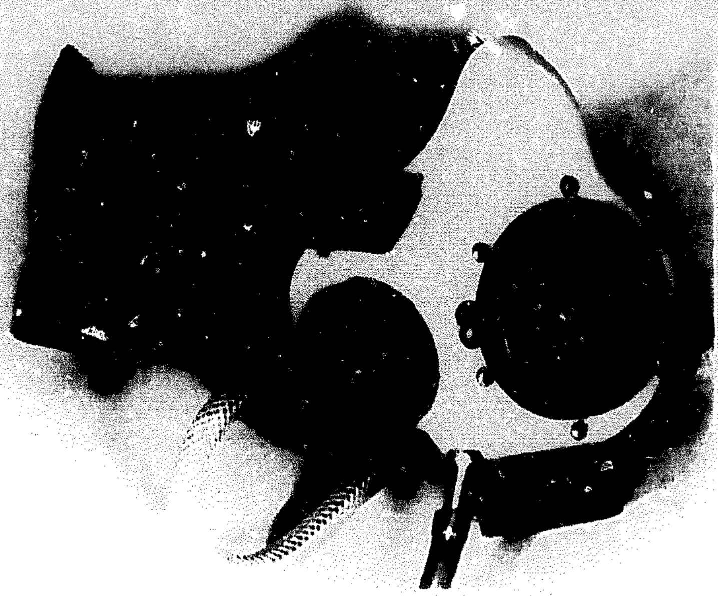


Figure 4-42. Third Prototype Facepiece. (Note the dust sampling tube attached to the mask in the foreground of the picture).

Facial Access Port. The facial access port in the third prototype consists mainly of the voicemitter and a support ring. The latch is configured so that the port may be opened or closed with one hand.

Exhalation Valve. In order to reduce bulk, only a single exhalation valve is incorporated in the prototype mask. It is situated at the bottom of the mask to promote drainage of any water which might collect in the mask.

Sealing Surfaces. The vinyl mask body, incorporating an inturned seal, was fabricated from a different mold than used in the first two prototype masks. The bellows feature in the chin cup of previous masks was omitted. While the seal contour does not extend as far back as previous prototypes, it remains 1/2 to 1-inch posterior to contemporary masks and runs higher on the cheek bones.

Mask Shell. The mask support shell is vacuum formed from 0.060-inch thick polycarbonate sheet. On either side of the shell a "V" shaped elastic strap suspension element is riveted to the shell. The shell includes two ports to facilitate mounting the Robertshaw regulators and a port for installation of the exhalation valve.

Fit and Sizing Adjustment. While the shell cannot be deformed to facilitate fitting, several methods of adjustment are available. The mask seal contour and interior clearance envelope are designed so that the mask may be donned by positioning it on the bridge of the nose and then rotating it downward until the chin and cheek sealing surfaces contact flesh. In this way, a large percentage of the population range in face length can be accommodated.

Additional accommodation in face length, face width, and most importantly in the area around the nose, may be achieved by use of foam rubber inserts. These inserts may be glued in place on the seal support shell to exert additional pressures on the seal against the face. Another possibility is to insert the foam rubber inserts within the folds of the inturned seal. This latter method was found to be particularly successful in accommodating poor fit in the nasal areas. Accommodations for fitting particularly short faces is best achieved by placing a 1/2-inch wide by 3-inch long strip of foam along the inside of the bottom edge of the shell.

SYSTEM SYNTHESIS TRADE STUDIES

Using the basic engineering data and concepts presented in the previous pages, the next step in the systems synthesis process is to produce tentative designs for Type I continuous flow and Type III demand with ventilation flow supplied-air respirators. At this level of design it is appropriate to actually specify particular components or type of components which could be used in the design. This permits identification of potential problem areas resulting from one design or another. It also permits one to establish an order of magnitude for the cost and complexity of the system.

Based on previous work, the Type II system was eliminated from the competition at this point since, in all probability, it would result in a system very similar to a Type III system. It should be recognized that while particular components are specified in these designs, a more detailed design process might result in better components than those listed here. However, we feel that the components specified are sufficiently representative to make the competition between the two types of systems a fair one.

TYPE I CANDIDATE DESIGN

A schematic drawing of the Type I system design is shown in figure 4-43 and details regarding the various components are listed in table 4-4. The high output-pressure blower was incorporated in order to make effective use of the cyclone separator preliminary dust removal element. This was incorporated in order to reduce the loading on final filter and to reduce the amount of maintenance necessary on that filter. The hydraulic motor was selected due to its ease of adaptability in the underground environment and the small-size envelope compared to the size required for an explosion-proof electric motor of equivalent output.

The miner's umbilical was restricted in length because a longer length umbilical would be quite heavy and require considerable amount of storage space in the crowded mining machine operator's work space. As a result, the Type I system does not permit the miner to continue wearing the respirator when he is working a short distance away from his mining machine.

The roughing filter presents some problem in design. Since ingestion of the larger size coal particles by the blower could cause severe damage to the high-speed blower, the roughing filter must remove a considerable amount of dust from the inlet air. Data are not available which would permit specification of blower life as affected by ingested particulate matter. In order to reduce maintenance requirements to a minimum, a reverse flow cyclone is specified as an inlet roughing filter.

Table 4-4. COMPONENTS OF THE CANDIDATE TYPE I SYSTEM

Item	Manufacturer and Model Number	Size	Weight	Remarks
Inlet Filter	Synsis Inlet Cyclone	8 in x 6 in x 4 in	5-1/2 lb	. Designed by Synsis especially for this application . 50% collection efficiency for 3 um particles . Pressure drop only a few inches of water
Blower	Torin Corp. m/n SC 560-30058	10-1/8 in long x 7-1/2 in dia.	8-1/2 lb	. 3-stage centrifugal blower . 4 SCFM air flow against a back pressure of 9 inH_2O . Power input required is 1/3 hp @ 5000 rpm
Hydraulic Motor	John S. Barnes Co Series GC-5155	4 in long x 3 in dia.	approx. 3 lb	. 1/8-inch gearface pump run as a motor . Requires 1.7 gpm @ 425 psi hydraulic oil supply
Final Filter	HEPA Corp. m/n C4-6MAD	6 in x 4 in x 3 in	Depends on Housing	. 5 SCFM air flow @ .25 inH_2O pressure drop . 99.99% efficient in 0.3 um DOP test
Auxiliary Filter	Same as the final filter	-	-	. Air enters the umbilical line through a low pressure check valve if mask pressure becomes negative
Umbilical Hose	Not specified	1 in inside dia. x 8 feet long	-	. Light weight, inexpensive hose that can be easily replaced in case of damage
Facepiece	Scott-Acme Safety Products "Acme Duo-Seal"	-	Less than 6 oz	. Could be replaced by unit designed by Synsis especially for this application . Half-mask variety

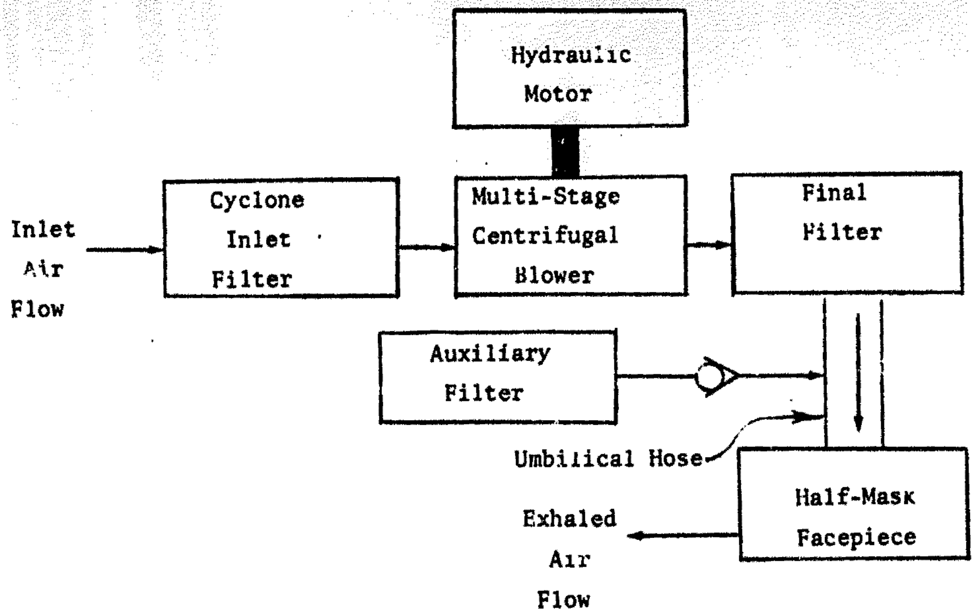


Figure 4-43. Candidate Type I System Design.

Despite the desirability of providing a blower speed control to regulate air flow rates, such a device is not considered feasible at this time. Demand for inhalation flow rate in excess of the blower output is provided by the auxiliary filter.

TYPE III CANDIDATE SYSTEM DESIGN

The candidate design proposed for a Type III system is shown schematically in figure 4-44 and component specifications are given in table 4-5. Its primary features include the small, light weight, demand regulators produced by Robertshaw, which result in the smallest amount of encumbrance to the individual. A small ventilation flow rate, less than 1 SCFM, is provided continually into the mask to reduce moisture accumulation and thermal build-up.

The basic rationale behind system design centers upon minimizing encumbrance to the user and achievement. Prototypes of the Robertshaw regulators indicate that they exhibit a cracking pressure of less than 1/2-inch H_2O and maintain that level of pressure, or less, until they reach their maximum flow rates. Unfortunately, they are somewhat flow rate limited and, therefore, it was necessary to utilize two of these regulators in order to achieve the desired 10 SCFM peak flow capability. Their light weight, it is felt, will not contribute appreciably to the overall weight of the mask.

Perhaps the key component in this design is the use of a small diameter, long length umbilical. It is felt that in the cramped quarters of the underground mine, this umbilical will meet with considerably more acceptance than would one of a shorter and larger diameter.

Table 4-5. COMPONENTS OF THE CANDIDATE TYPE III SYSTEM

Item	Manufacturer and Model Number	Size	Weight	Remarks
Inlet Filter	Synsis Inlet Cyclone	8 in x 6 in x 4 in	5-1/2 lb	. Designed by Synsis especially for this application . Pressure drop only a few inches of water . 50% collection efficiency for 3 um particles
Compressor	Gast Corp. m/n PCD-10	12 in x 9-1/2 in x 7 in	19-1/2 lb	. 2-cylinder, piston type compressor with Teflon rings . 3.5 SCFM air flow at a system pressure of 60 psig. . Power input required is 1 hp @ 2000 rpm
Hydraulic Motor	John S. Barnes Co. m/n GC-5155-A-2-D	4 in long x 3 in dia.	Approx. 3 lb	. 1/2-inch gearface pump run as a moto . Requires 2.5 gpm @ 900 psi hydraulic oil supply
Cyclone Pre-Filter	Synsis Primary Cyclone	3-3/4 in long x 2-1/4 in dia.	1-1/4 lb	. Designed by Synsis especially for th application . Pressure drop only a few inches of m cury . 50% collection efficiency for 0.70 u particles
Final Filter	Pall Trinity Micro Corp. m/n MC 64463EC	7-1/2 in long x 4 in dia.	1-1/2 lb	. 6.7 SCFM air flow at a system pressu of 50 psig causes a pressure drop of 4 inH_2O . 100% efficient for 0.9 um particles 98% efficient for 0.07 um particles
Umbilical Hose	Not specified	10-30 ft long 1/4 in I.D.	-	. Lightweight, flexible, and able to w stand the underground mine environme
Demand Regulators	Robertshaw Controls Co. m/n 226-22004	1-1/2 in dia.	1.56 oz	. Two regulators mounted on each face-piece . Demand plus continuous flow supplied
Facepiece	Synsis Facepiece	-	8.6 oz	. Especially designed by Synsis for th application . Half-mask variety . Incorporates a facial access portal a passive voice transmitter

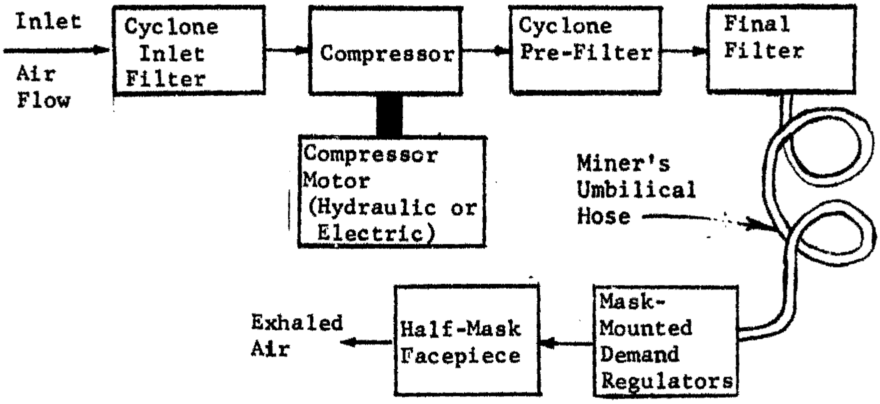


Figure 4-44. Candidate Type III System Design.

The use of the small-diameter umbilical and the demand regulators necessitates the use of a high-pressure piston-type compressor. Due to the cumbersomeness and difficulty of installation, in regards to achieving permissibility, a hydraulic motor was selected to power the compressor rather than an electric motor. One pays the penalty in doing this since for some machines hydraulic power is intermittent in nature. Therefore, respiratory protection using the system may not be provided at all times. However, it was decided, in this design, that during the periods when the hydraulic power is not available, the need for respiratory protection will be much reduced and miners might be tempted to remove their masks under any circumstance. The size and maintainability requirement of the fabric-type final filter are reduced significantly by use of the cyclone separators. While the inlet cyclone separator is, in fact, adequate to reduce the requirements significantly, the additional cyclone in the high-pressure side of the system augments this capability and provides for redundancy in the event of a malfunction of one or the other elements.

CONCEPT SELECTION

If indeed, the two candidate conceptual systems discussed in the previous pages represent optimal designs within their class, then all that remains is to select one or the other for subsequent detailed design. Common systems engineering practice at this point is to choose the lowest cost system which meets all of the requirements (Asimow, 1962). However, in this case, that procedure is not appropriate. In the first place, the costs are nearly similiar since most of the components are quite similiar (cyclone separators, filters, hydraulic motors). Secondly, in judging miner acceptance, there is no non-interference condition. One must, therefore, decide which system is most acceptable. Each of the systems has been designed to meet or exceed a large number of the more basic requirements. It is, therefore, not necessary to include these requirements in the trade-off study, but rather to compare their level of meeting the remaining requirements. To assist in this process, table 4-6 was prepared and summarizes results of the trade study. From this chart it appears obvious that a Type III system is the better choice.

Table 4-6. CANDIDATE SYSTEMS TRADE ANALYSIS

REQUIREMENTS	TYPE I	TYPE III
COMPATABILITY		
EQUIPMENT		
installation	large diameter breathing hose potential problem	
reliability	machine vibration a potential hazard to high speed blower	
TASKS AND OPERATIONS		
duty cycle	seated operator may have filtered air but higher breathing resistance	potential for supplying clean air during short down time
dismounted tasks	large diameter hose hard to use if long	better for dismounted operations
maintainance	more frequently, perhaps weekly	monthly or less filter change
ENVIRONMENTAL		
safety		more chance of entanglement
anti-suffocation	somewhat automatic provision for it	must be built into mask
atmospheric contaminants	some hazard to respirator due to high rpm rotor	some hazard to pistons and cylinders
abrasion	hard to make big hose abrasion resistant	hose can be made abrasion resistant
PERFORMANCE		
AIR FLOW RATE	adequate	more than adequate
BREATHING RESISTANCE	exhalation higher than inhalation inhalation resistance depends on minute volume	less than 1/2 in H_2O on inhalation for all minute volumes

Among the numerous compatibility requirements, essentially two features stood out, weighing against a Type I system, having to do with installation and reliability in the underground environment. It was felt that the larger diameter hoses required to pass the given flow rate in a Type I system, on the order of one-inch diameter and larger, when properly protected, might present somewhat of a burden when installing a respirator system on the compactly designed mining equipment. One example of this would be in the case of a continuous mining machine where it could turn out that the only reasonable place to install the compressor and air cleaning equipment would be at a distance quite remote from the operator's station. In this case one would then be required to route a quite large diameter hose, perhaps several inches in diameter, from the blower output to the work station. A large diameter hose would, of course, be necessary to prevent excessive pipe flow losses to that point. In addition to the mechanics of installation, which of course need only be performed one time, it would be necessary to take some pains to protect that hose from roof falls which are a fact of life in an underground coal mine. It would certainly be undesirable to have to change the hose each time a roof fall occurred.

The reliability factor in a Type I system is concerned primarily with very violent accelerations exhibited by certain types of mining equipment; particularly continuous miners, under cutters, and roof bolters. It is felt that a blower with high rotational speeds on the order of 5000 to 10,000 RPM, would exhibit extremely punishing bearing loads in this situation. Thus, in order to achieve reliable operation for such equipment, fairly extensive compressor bearing development would be required. This was beyond the scope of the program.

Considerations having to do with compatibility with underground mining tasks and operations are somewhat more straight forward. Trade-offs concerning duty cycle seem to be a toss up, to some extent. While the Type I system design provides the user with filtered air when the machine is shut down, it does so at a higher breathing resistance and with a reduced capability to dismount the machine during these periods. A Type III system currently provides no such capability. On the other hand, it is entirely possible if space permits, to install a plenum chamber as large as might be desired in order to provide breathing air when the hydraulic power is not available. Furthermore, since it appears to be common practice for a miner to dismount his machine during these brief periods, a Type III respirator would permit this practice while still providing respiratory protection. In providing respiratory protection during dismounted tasks, it could be argued that the same level of protection is provided with each type of system. However, it is our opinion that if a larger diameter umbilical is used, such as on the Type I system, that the miners preference would be for a short hose. If this is true, then the Type III system provides for better compatibility with dismounted tasks.

Because of its capability to produce much higher output pressures, thereby admitting larger pressure drops with the various components, the Type III system can be designed for much longer maintenance intervals than can a Type I system. This factor was weighed quite heavily in making our decision for a Type III system.

The Type III system was judged to present a slightly greater hazard than a Type I system, in regard to entanglement of the breathing umbilical. However, it is felt that this hazard can be reduced to a bare minimum through proper use of emergency disconnects. The Type I system has a slight advantage in regard to the provision of the required anti-suffocation characteristics due to the fact that it is possible to draw air through the system when the hydraulic power is off. Such a capability in the Type III system must be built into the mask in the form of a valve or small filter disc which would provide sufficient air to support life in the event of a catastrophic malfunction of the system in conjunction with a roof fall, or some such event.

Although there is some uncertainty concerning hazards to the respirator system due to atmospheric contaminants, the two systems appear to share a weakness in regard to ingestion of large particles of coal. If a sufficiently large particle of coal were to be ingested in the rotor blade of the high RPM blower, a blade could be destroyed causing an imbalance which could destroy the blower. In the same regard, it would be possible for the piston compressor to have the walls scored severely by an ingested coal particle. This probably would not result in compressor failure. However, it would exhibit a reduced level of performance until it was repaired.

Compatibility with the abrasive factors in the underground coal mines is a very strong consideration for both systems. While each system could be designed to resist abrasion, such as dragging the breathing hose accross loose coal or over sharp edges of the mining machine, satisfactory design in this area results in heavy penalties in meeting the other requirements. A large-diameter breathing hose, such as used on a Type I system, highly resistant to the abrasive environment, kink-proof, and resistant to the chemical environmental contaminants, would be a stiff, heavy hose. If a Type I system were indeed selected, our design approach would probably not include such a hose, but rather a lighter weight hose which is inexpensive and easy to replace on, say, a bi-weekly basis. It should be kept in mind that the primary goal in this program is to achieve miner acceptance. Therefore, the same line of reasoning applies to the miners umbilical designed for a Type III system. Even with the above proviso, it is clear that the umbilical hose for a Type III system can always be made more acceptable to the miner than the umbilical for a Type I system.

Perhaps, one of the most important factors in the comparison of the two systems has to do with breathing resistance. It is, indeed, unfortunate that so little is known about the subjective acceptance of the various levels and types of breathing resistance. This paucity of data makes it extremely difficult to compare one system with the other and we must rely upon previous experience and a small amount of data available. The Type I, while providing essentially zero inhalation resistance at minute volumes up to some level, would probably, in the final design, exhibit a higher exhalation resistance during all levels of flow. This is essentially due to the fact that the exhalation valve must pass not only the exhaled air, but at the same time, must pass the supplied-air flow rate. This results in a situation which has been said, by some, to be undesirable. The Type III system on the other hand employs demand regulators which, by definition, require the wearer to exert some suction in order to breathe. In making the choice, between the two systems, on this factor, the subjective response of a number of persons to breathing on prototype systems of each type weighed heavily in favor of the Type III system.

It should be kept in mind that the decisions made in the trade-off analyses are necessarily tentative conclusions based upon predictions of the performance to be expected from a given design. The validity of the analysis can only be demonstrated if the resulting system works as well as predicted and, at the same time, it can be shown that the alternate system would not work any better than predicted. Furthermore, as one becomes embroiled in the detailed process, new design factors, which might be thought of as design requirements or performance requirements, emerge and must be considered. For this reason, it is always necessary in the final analysis of a system to decide if it remains better than the alternate considered previously.

Section V

PROTOTYPE DESIGN AND FABRICATION

This section describes the details of the design arrived at for the Type III, demand with ventilation flow, supplied-air respirator system and provides some rationale for the particular components employed. Test results pertaining to specific components are presented; overall system operation and performance is discussed in the following section. The section is organized by functional element of the supplied-air respirator system; air moving element, dust removal, air distribution, and facepiece. Readily available production components were used for all major elements of the system except for the two cyclone separators and the facepiece, both of which were specifically designed as part of this program. For most of the production items employed, similar components were available from alternate manufacturers and our choice depended upon such factors as delivery time.

An overall schematic diagram of the final design is shown in figure 5-1 and a photograph of the prototype system appears in figure 2-2. As stated

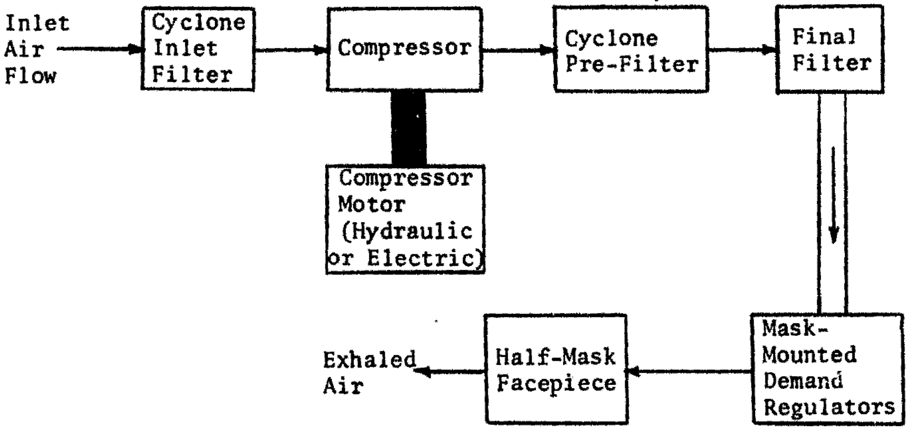


Figure 5-1. Schematic of the Supplied-Air Respirator System.

previously, the basic rationale behind the design is to employ a high pressure compressor so that: 1) a small diameter, long length umbilical may be used in improving potential acceptance by the wearer, and 2) high pressure drop air cleaning systems may be employed to reduce the maintenance requirements. Other important considerations in the rationale for the design include the requirement for modularity in order to simplify installation of the system on the compactly built underground mining machinery, freedom from routine maintenance, and problem-free integration of the personnel-mounted components of the system. Supplementing this basic rationale are the compatibility and performance requirements, as stated in section three.

MOTOR/COMPRESSOR SYSTEM

The motor/compressor system includes a hydraulic motor and its associated control devices, and a two-cylinder piston compressor. This entire subsystem is mounted on, or inside, a heavy guage steel enclosure for noise reduction and protection from mine hazards. This module, measuring approxima-

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tely 13 X 11 X 9-1/2 inches, can be mounted at any convenient location on the mining machine.

MOTOR

The air compressor selected requires approximately 1 hp at a shaft rotational speed of approximately 2,000 RPM for the required pressure and flow rates to be produced. Choices for the type of power supply were essentially between electric and hydraulic. A very fundamental trade-off in this choice exists. The majority of underground mining equipment obtains its primary power from electrical cables which trail behind the machine. This electrical energy is then converted to hydraulic power for performing the various functions ascribed to each machine. The electrical energy is available during the entire shift and, therefore, an electrical-powered respirator system would be available for respiratory protection during the entire shift. As discussed previously, mining machines operate in a cyclic fashion and since the large hydraulic pumps utilized are fairly noisy, they are frequently shut off when not needed. Consequently, hydraulic power is available only when the machine is actually operating. In general, this makes hydraulic power much less desirable than electric power. However, the other side of the argument is that a permissible 1 hp electrical motor is quite large. The compact design of typical underground mining equipment makes it very difficult to find sufficient space on the machine to install such a motor. This basic choice is illustrated in figure 5-2 which

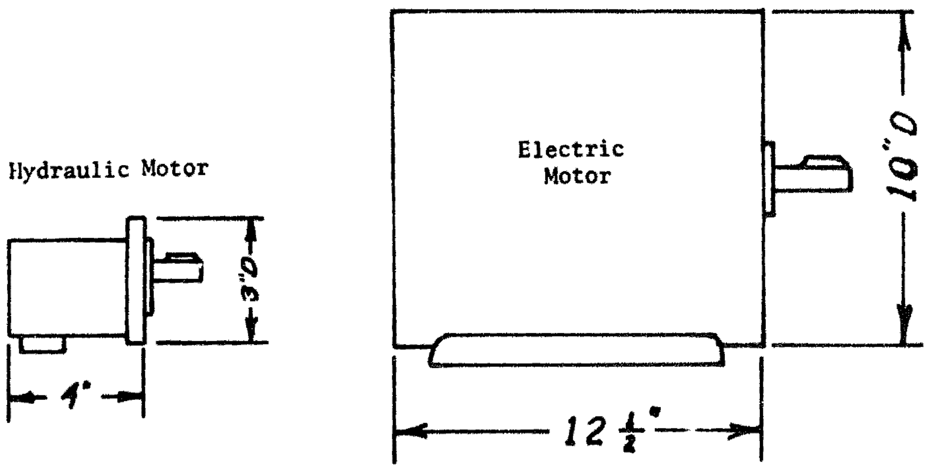


Figure 5-2. Size Comparison Between Typical 1 hp Hydraulic and Electric Motors.

shows the size comparison between the hydraulic motor utilized in this system and an electric motor which could have been used. Furthermore, electric motors are much more costly than the hydraulic motor chosen.

The motor chosen, manufactured by the John S. Barnes Company, Model No. GC-5155-A-Z-D, requires a flow rate of approximately 2.5 gallons per minute, depending upon the viscosity of the hydraulic fluid utilized at an operating pressure of 900 psig. The desired flow rate is achieved through use of a flow controller produced by Auto-Ponents, Inc. (Model PCS-2). A particular advantage of this hydraulic motor is that the same motor frame can be purchased with a variety of different displacement rotors. Therefore, when a mining machine employs higher hydraulic pressures the hydraulic fluid consumption can be reduced accordingly. This attribute is important because there appears to be no consistency in hydraulic pressures utilized with various underground equipment.

AIR COMPRESSOR

The 100 psig, Teflon-ringed air compressor, Model No. PCD-10 produced by the Gast Manufacturing Company, shown in figure 5-3, was selected for the

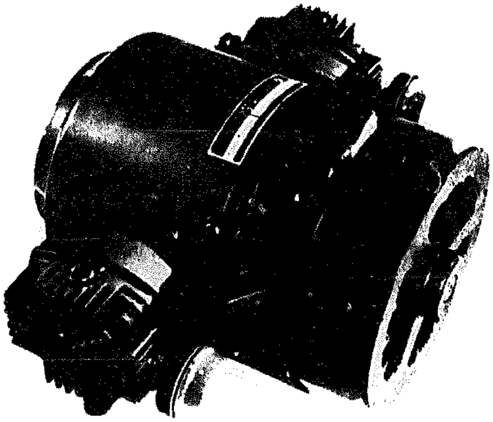


Figure 5-3. Gast PCD-10 Air Compressor.

prototype supplied-air respirator. As previously stated, the requirement for a long, small diameter umbilical and demand regulators necessitated a fairly high-pressure compressor. Once this was established it was quite easy to arrive at the figure of 100 psig since the choice is either less than 50 psig or 100 psig. This particular compressor has the pressure versus flow rate curve, shown in figure 5-4, when powered by the hydraulic motor described previously. While compressors having similar output curves are produced by other manufacturers, no manufacturer produces a similar-sized, Teflon-ringed compressor with greater output. Compressors of smaller output are not significantly smaller in overall dimensions and there are no compressors available with larger output within the required dimensional envelope.

The compressor is ordinarily configured by the manufacturer with an electric motor supplied. For this reason, mounting flanges and the bearing support structure, which are integral with the pump head, are somewhat larger than desired for this application. However, the manufacturer indicated that modification to these structures would require an extensive development effort and, thus, some compactness in the compressor enclosure was sacrificed. Were the supplied-air respirator to be made on a production basis,

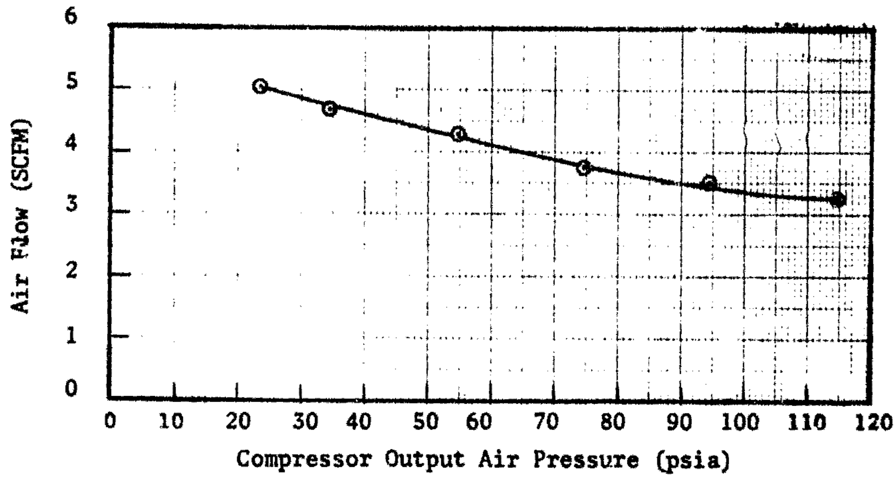


Figure 5-4. Performance of Gast PCD-10 Compressor when Driven at 2000 RPM by the Barnes Hydraulic Motor.

it would be possible to commit the development effort and achieve a more compact design.

In ordinary usage, the manufacturer guarantees the compressor for one year of continuous operation at maximum output. It is understood that in actual use, the reliability is considerably better than this.

There was concern, at first, regarding the potential health hazard resulting from the use of Teflon piston rings. It was discovered, however, that the toxic fumes generated from heated Teflon could not occur in this application. The rings would malfunction causing the compressor to stop at lower temperature than that at which hazardous fumes are generated. The piston ring reliability in the presence of coal dust is a matter of some speculation. A considerable amount of protection is afforded by cleaning the inlet air with the inlet cyclone, as discussed in the air cleaning section of this report. More positive methods of providing dust-free air to the compressor would result in considerably greater degradation in overall system performance.

While the hydraulic motor and piston compressor appear to be an extremely simple combination in terms of engineering design, two problems involved in their use required considerable developmental work. One had to do with air quality in terms of temperature and moisture, and the other had to do with the noise generated by both the hydraulic motor and piston compressor.

SUBSYSTEM INTEGRATION

The final configuration of the unit as ready for installation on a mining machine, is shown in figure 2-3. While extensive testing was not conducted, it appears safe to say that the 1/4-inch thick steel enclosure should protect the compressor against most roof falls.

Compressor overheating, which was found to be a problem, is prevented by use of the fan and fan shroud which is provided with the compressor head. The shroud is modified slightly to reduce its overall size and the ports in the end of the enclosure permit inward flow of cooling air. Air is exhausted from the enclosure past the compressor heads which extend through the walls of the enclosure.

Noise produced by the compressor is attenuated by lining the enclosure with 1/2-inch thick lead-polyurethane foam sandwich material produced by Sound Coat Co., Inc., and mounting it on rubber supports. Noise produced by the gear face hydraulic motor, which was found to be quite significant, is reduced by use of the rubber-isolated mounting plate.

DUST REMOVAL COMPONENTS

Two cyclone separators and one fibrous filter have been incorporated in the supplied-air respirator design. A cyclone separator is provided at the inlet to the compressor in order to protect the compressor itself from damage to piston rings and cylinder walls due to ingestion of dust laden air. The primary cyclone separator is placed downstream of the compressor in the high-pressure portion of the system. It is much smaller, exhibits a higher pressure drop, and is much more efficient than the inlet cyclone. While the two cyclones together provide more than adequate dust removal capabilities, flow rate transients resulting from start-up and shut-down will permit the cyclones to pass some dust into the system since cyclones do not work efficiently at low flow rates. Therefore, a final fibrous filter element, which is not dependent upon air flow rate, is provided as the final measure in the dust removal system. Due to the overall efficiency of the two cyclones, it is possible to make the fibrous filter element quite small.

While it is not certain how much dust may be collected in the final filter before it is necessary for it to be replaced, it is possible to predict a service interval of several months for this element. The requirement for maintenance of the cyclone separators could not be predicted. This is a matter which must be learned by trial and error within the coal mine. However, routine maintenance procedures simply involve emptying the dust receptacles at the bottom of each cyclone.

A difficult decision to be made in designing the dust removal components, concerned the trade-off between system bulk and overall reliability and maintainability. For instance, the inlet cyclone could have been made smaller in size and more efficient so that the primary cyclone would have been less important; however, doing so produced two essential problems. The first was that compressor flow rate is linearly dependent upon inlet pressure. Thus, increased efficiency of the inlet cyclone and reduced size could only be obtained through reduction in compressor output. On the other hand, it is possible to obtain any reasonable efficiency in the high-pressure portion of the system since the relative pressure drop in that range is not as important to overall system performance. In the second case, it was observed that, being exposed to the mine environment, the inlet cyclone was much more likely to become fouled, thus, degrading its performance and exposing the final filter to a much higher loading rate. While it is realized that excessive bulk of the system is undesirable, it was felt that reliable performance and low maintenance requirements were more important in this case than the potential reduction in size by removing one air cleaning element.

PRIMARY CYCLONE SEPARATOR

The purpose of the primary cyclone separator is to remove nearly all of the coal dust from the air presented to it, so that dust loading on the final filter will be as small as possible. The final filter will, of course, receive some loading, as discussed previously, due to transients in air flow rate. The primary cyclone separator is located in the auxiliary equipment enclosure and, thus, situated, perhaps, some distance from the air compressor. Between the air compressor and the primary cyclone separator, air cooling coils have been installed in order to precipitate some of the moisture from the air. The primary cyclone separator removes this moisture from the system. Removal of the collected dust and moisture from the primary cyclone is performed by opening a relief valve which protrudes through the enclosure. This relief valve should be operated daily.

Construction

The primary cyclone separator shown in figure 5-5 is 2.25 inches in diameter and 3.5 inches long, exclusive of fittings. As shown in the exploded view of

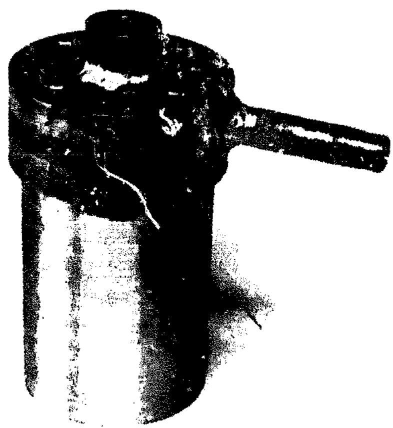


Figure 5-5. Primary Cyclone Separator.

the cyclone, figure 5-6, the body of the cyclone is machined in two halves. They may be separated easily, by removal of four screws, so that the interior of the unit may be cleaned with a rag or a blast of water or other solvent.

The prototypes were machined at our facility from aluminum stock and the inlet and outlet tubes were welded in place. In a production version. of course, it would be possible to produce these units in a more cost-effective fashion so that the net cost of the units would easily be in the range of a few dollars or less.

Consideration was given to casting the cyclone from urethane or machining them from a harder metal such as stainless steel, however, the obvious

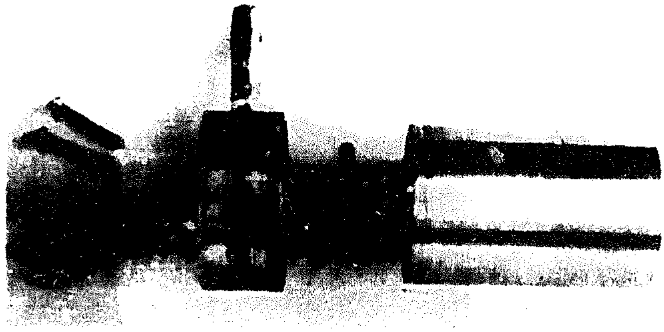


Figure 5-6. Exploded View of the Primary Cyclone Separator.

advantage of working in aluminum was elected for the prototype units. It is known that there is a considerable amount of abrasion on the walls of the cyclone, but is felt that the aluminum will survive sufficiently long for the present purposes.

Performance

While cyclone dust removal efficiency depends upon flow rate, and flow rate through this system varies depending upon demand, we would estimate that on the average, the primary cyclone separator will remove more than 95% of the dust presented to it. The collection efficiency curve is shown in figure 5-7. This curve is based upon data taken at the Donaldson Company Minneapolis, Minnesota. Specific test results upon which this curve was based are presented in table 5-1.

Table 5-1. PRIMARY CYCLONE SEPARATOR TEST CONDITIONS AND RESULTS

	Run #1	Run #2
Total dust fed	0.135 gms	0.426 gms
Total dust collected	0.130 gms	0.411 gms
Total dust penetrated	0.005 gms	0.015 gms
Resulting gravimetric efficiency	96.3%	96.47%
d_{50} (cut size)[1]	0.505 um	0.402 um
d_{95}	1.75 um	1.80 um

[1] Extrapolation from measured data due to inability to count particles in this range accurately.

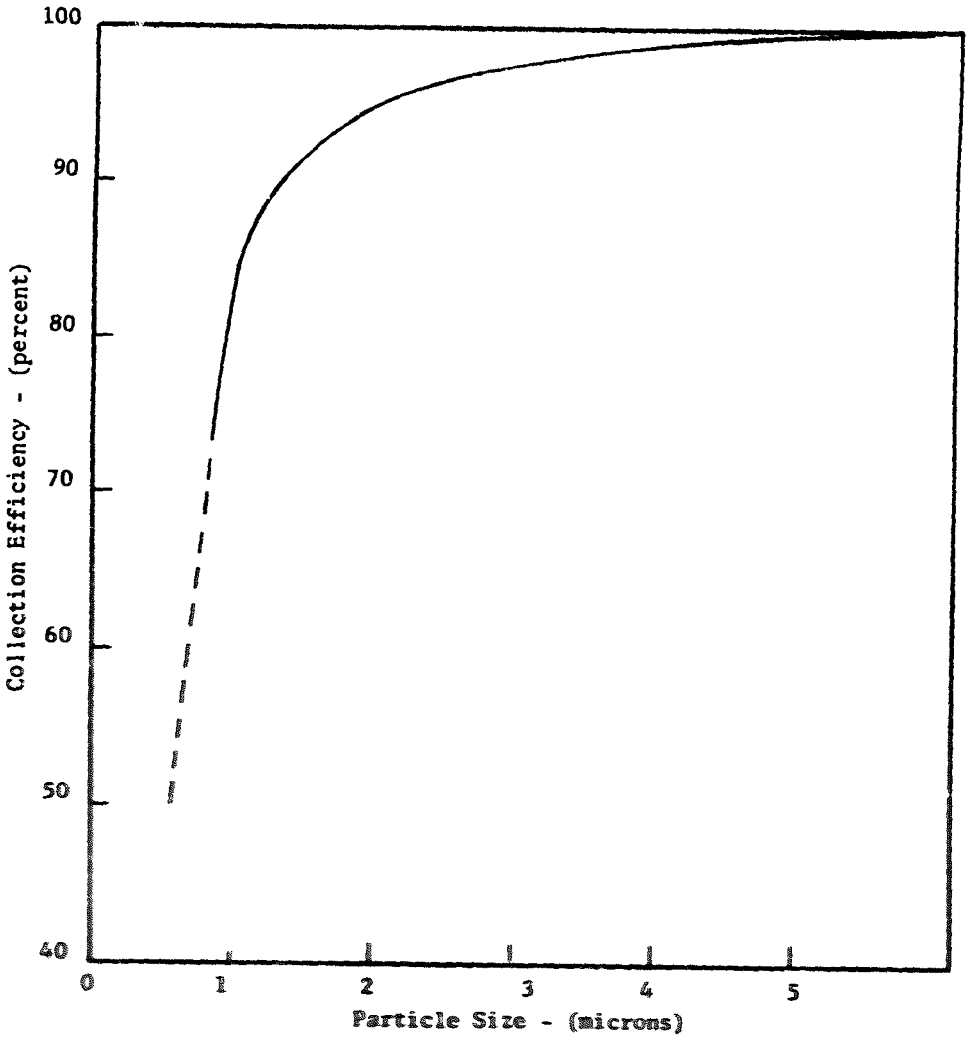


Figure 5-7. Experimentally Determined Fractional Efficiency Performance of the Primary Cyclone Separator.

Although the cyclone was designed to operate with air at approximately 60 psig pressure, the test was conducted with the inlet air flow at atmospheric pressure. This was done because the apparatus for testing at high pressure was not available. To create equivalent conditions to the high pressure situation, it was only necessary to alter two input variables. One was the mass flow rate of air which was reduced to allow an inlet tube air velocity of 35 feet per second; approximately that which will be realized during actual use. The other was the dust concentration which was increased to simulate the concentration increase that will occur upon compression.

Two tests were conducted in order to cross-check the results. In both tests, the flow rate was 0.5 SCFM and all of the coal dust was within the respirable range, 0-10 um. Coal dust concentration in the inlet air was 940 mg/m^3 which resulted in a dust feed rate of 0.0135 grams per minute. This value is an order of magnitude greater than might be experienced in actual underground operations for this cyclone; but was as low as the available dust feeding equipment could produce.

Cyclone separator efficiency is strongly dependent upon the velocity of the air entering the tube. For this reason, a more efficient cyclone can be made if the inlet and outlet tubes are of small diameter with the result being that cyclone efficiency is directly dependent upon pressure drop across the unit. As it is used in the supplied-air respirator system, the flow rate through the primary cyclone is inversely related to the pressure at the inlet to the cyclone. However, in terms of absolute velocities, the lower inlet pressures result in higher velocity and, thus, a higher pressure drop. This is somewhat unfortunate in that, during periods of heavy demand, the compressor output pressure is reduced and, at the same time, the pressure drop across the cyclone is increased. Thus, the air pressure delivered to the regulators under these conditions is markedly reduced. For this reason, it is necessary to design the cyclone to have an acceptable pressure drop at higher flow rates and lower pressures than occur in normal operation. Predictions, based upon the analysis of Appendix IV, indicated little need for concern with the proposed design. However, measured pressure drops taken at a variety of pressures and flow rates, as shown in table 5-2, were about twice as high as the predicted values. This was still felt to be no cause for concern and the design was readily adopted rather than to make the cyclone larger. Certainly, a pressure drop of less than 2 psi at a system flow rate of 3.5 SCFM is most acceptable.

Table 5-2. PRESSURE DROP VS. FLOW FOR THE PRIMARY CYCLONE, WHILE SUPPLIED BY THE GAST COMPRESSOR.

Cyclone Inlet Pressure (psig)	Air Flow (SCFM)	Measured Pressure Drop across Cyclone	Predicted Pressure Drop Across Cyclone
20.0	4.00	3.1	1.72
27.0	3.87	2.6	1.34
35.0	3.77	2.2	1.07
45.7	3.57	1.8	0.79
55.5	3.33	1.5	0.59
67.5	3.11	1.2	0.44
80.7	2.86	0.8	0.32

INLET CYCLONE SEPARATOR

Due to the high dust content of the mine atmosphere, some type of inlet filter will be required to protect the compressor piston ring and cylinder walls from unduly rapid wear. The felt pads which are ordinarily supplied with the compressor are unsuitable because of unnecessarily high pressure losses and because they would become clogged very quickly. Based on a fundamental requirement for minimal maintenance other types of fibrous filters were precluded from consideration and the decision was made to use a cyclone separator as the inlet dust removal element.

Two alternate approaches are possible. One is to design and construct a reverse-flow cyclone based upon the computer programs developed in designing the primary cyclone separator. Another concept is to employ a commercially available cyclone separator, of which at least two are available. Both the Donaldson Company, Inc. and the Paul Trinity Micro Corp., produce axial flow cyclones in the performance range which would be suitable for this application. The flow in an axial cyclone is entirely along the axis of the tube with the swirling component being added by vanes at the inlet, as illustrated in figure 5-8. The cyclones produced by the above manu-

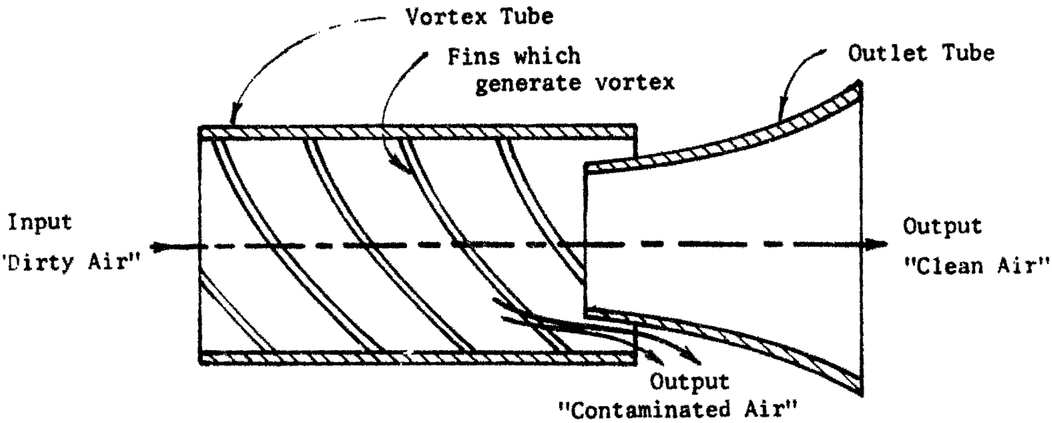


Figure 5-8. Typical Axial Flow Cyclone Separator

facturers are typically four or five inches long, one inch in diameter, have a 50% collection efficiency (d_{50}) for 10 um particles and handle flow rates of 10 to 30 SCFM. How well they function at the lower flow rates of 3 to 5 SCFM, required for this application, was not determined.

The main difficulty with axial flow cyclone tubes is that an underfeed, or slight suction at the port where the dirty air is expelled, is required. A number of concepts for providing the necessary underfeed, such as an auxiliary blower, or a venturi pump operating from the high pressure compressor output, were investigated. Because of the complexities in providing underfeed, the reverse flow-type cyclone appeared to be much more suitable for this particular application. Therefore, a new cyclone was designed and produced.

Construction

In order to achieve a very low pressure drop, thus preserving the largest proportion of compressor output, a fairly large cyclone design was produced. This cyclone, shown in figure 5-9, was machined from aluminum and the inlet and outlet ports were welded in place. Due to the use of 1/2-inch

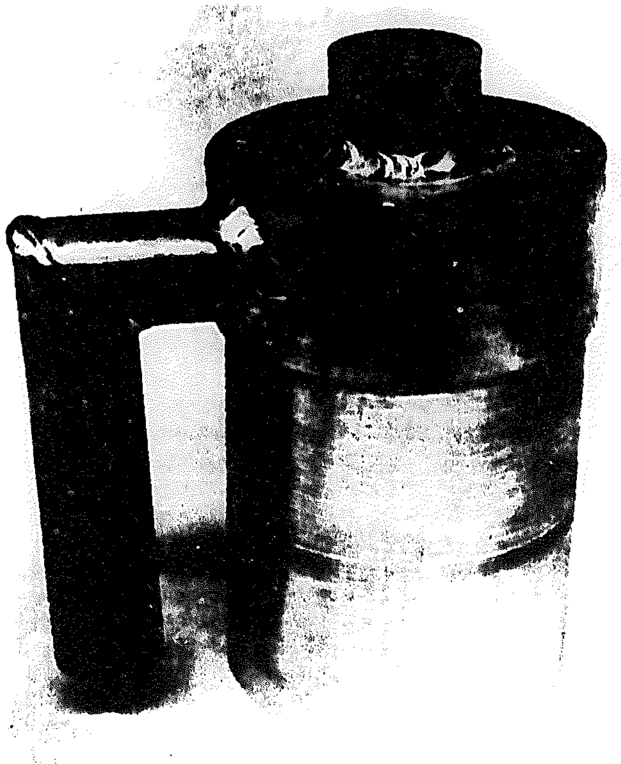


Figure 5-9. Inlet Cyclone Separator.

inside diameter inlet and outlet ports, the pressure drop at typical system flow rates is less than 2 in. of water. Since no underfeed is provided, the dust collection is accomplished by use of a specially designed and fabricated elastomeric cap situated on the bottom of the cyclone tube. The volume of this cap is large enough that it should only need to be serviced (emptied) on a weekly or a monthly basis. This is accomplished by merely loosening the hose clamp with a screwdriver and dumping out the collected dust.

Performance

The desired low pressure drop was achieved as illustrated by the flow versus pressure drop curve shown in figure 5-10. While the efficiency was not experimentally determined, the analysis indicated that at a flow rate of 3.0 SCFM the unit would have a 50% efficiency (d_{50}) for 2.5 um particles. Based on the good correlation of predicted and experimentally determined collection efficiencies experienced in the design, and evaluation of the primary cyclone separator, it was felt that experimental verification of this particular cyclone performance was not warranted.

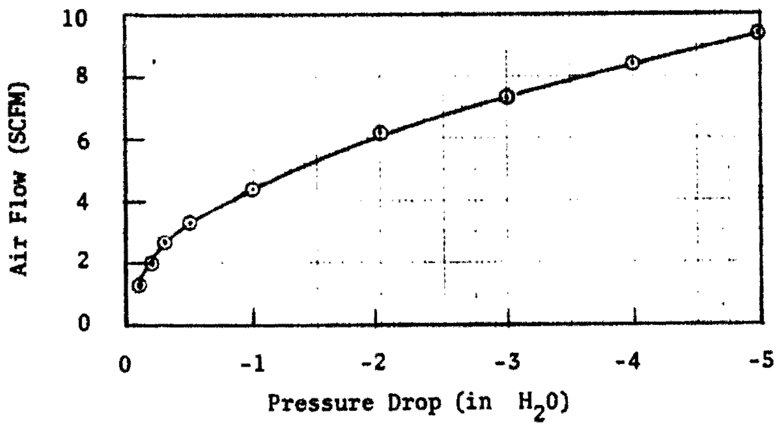


Figure 5-10. Pressure Drop Versus Air Flow for the Inlet Cyclone.

FINAL FILTER

In selecting a final filter, it was desired to procure a commercially available, small-size unit with high filtration efficiency for 1 um coal dust particles. The unit selected, housing Model MDA 446364 and element Model MC64463EC, is produced by the Pall Trinity Micro Corp. The filter element is pleated paper having a surface area of 2.2 ft^2 and is an absolute filter (100% collection) for 0.9 um particles and is 98% efficient for 0.07 um particles. For a clean filter element passing 6.7 SCFM at 50 psig the pressure drop is only 4.2 in H_2O.

The unit, which may be seen in figure 2-4, is approximately 7-1/2 inches long and has a diameter of 4 inches. Filter elements may be replaced by removing a hose clamp and installing a new element. Based on preliminary system tests, the filter element should need to be replaced only once every several months.

AIR DISTRIBUTION COMPONENTS

If there were a single key to acceptance in the design of the supplied-air respirator system, it would have to lie within the area of air distribution components. The small diameter, light weight, breathing umbilical, and the low inhalation resistance demand regulator certainly qualify as the most readily apparent components of the system presented to the user. Other components within this system, such as the quick-disconnect, the body attachment method, and the pressure regulation devices, are equally important to the success of the system, in terms of reliable operation and system management.

UMBILICAL DESIGN

There are essentially three interacting factors to be considered in selecting the miners umbilical: length of the umbilical, desired flow resistance, and material and construction.

Flow Resistance

Since the goal of choosing an air umbilical having a minimum inside diameter for a particular length is obvious, it became necessary to examine the relationship between flow resistance, or pressure drop along the hose, to inside diameter. Basic inconsistencies were found in some of the standard equations and charts and graphs available for ready reference. Therefore, it was necessary to perform a detailed engineering analysis of pipe flow resistance in the domain of interest. This analysis appears as Appendix V. The analysis produced two results important to this program:

1) Within the range of flow rate and pipe diameter of interest to this program, flow resistance is not linear with the length of the pipe.

2) Flow resistance and maximum flow obtainable can be improved considerably by increasing the exit pressure.

Flow resistance for 20 and 30-foot lengths of 1/4-inch inside diameter tubing are presented in figure 5-11. After careful consideration of the alternatives available, it was decided that the umbilical tubing should have a 1/4-inch inside diameter with the smoothest bore possible. It was further decided that the length of the umbilical need not depend heavily upon the flow resistance and that factors having to do with miner acceptance should dictate the length. These will be discussed subsequently.

Umbilical Construction

Perhaps, one of the most difficult problems faced in designing this system concerns the type of construction of the miner's umbilical. On one hand, it is possible to select a heavy-duty medium-pressure hose which will withstand the abrasion, rough handling, and chemical environment within the mine, remaining kink-free and leak-free for an indefinite period of time. Such a hose would be of a composite construction with perhaps a vinyl core, several layers of fabric braid reinforcement, and a urethane outer covering. Unfortunately, hoses of this category are large diameter, perhaps 0.75 inch, quite heavy, and hard to manage in a confined work space. Low-pressure air hoses, on the other hand, are lighter, have a smaller diameter (0.50 inch) and are much easier to manage. Hoses made with no fiber reinforcement, such as the homogenous vinyl or polyurethane, are particularly attractive in this regard. However, these low-pressure hoses would require more frequent replacement than the heavier hoses. While a medium-pressure hose could be expected to last up to a year in the underground environment, the best of the low-pressure, lighter weight hoses would have to be replaced, perhaps, as often as bimonthly. Unfortunately, there are no suitable methods available for making this prediction with any accuracy.

In view of the overall mission and requirements of the system, the cost of the miner's umbilical, a few dollars, is not significant. Therefore, based on the performance requirements for ease of handling of the umbilical, the choice of using the lighter weight low-pressure air hose was made. It should be noted that hoses classed by manufacturers as "low pressure"

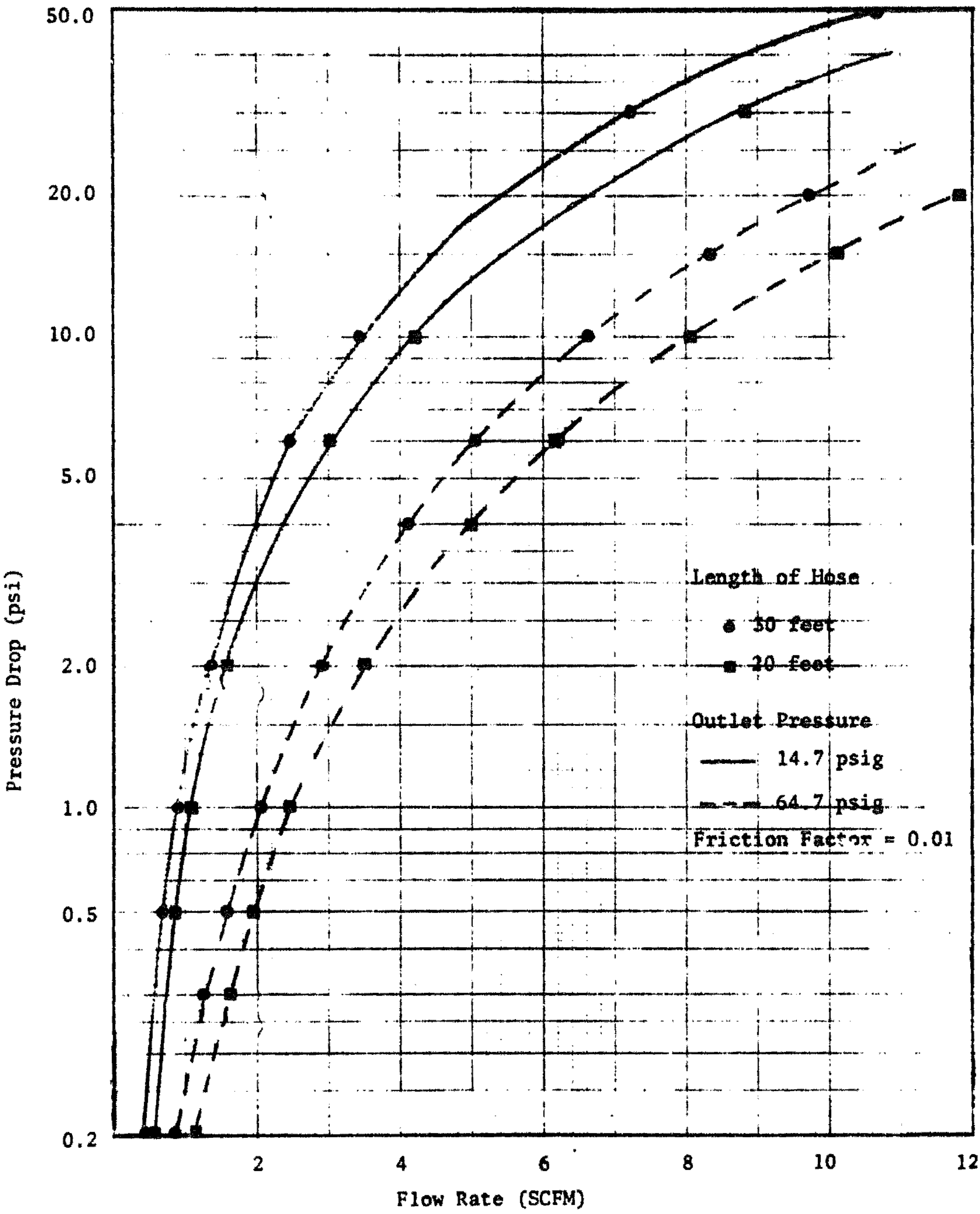


Figure 5-11. Predicted Pressure Drop for 0.250" Inside Diameter Hose.

are ordinarily rated for a working pressure of 200 psig and a burst pressure of 500 psig, or more.

Air hoses are manufactured from a wide variety of material, only some of which are compatible with the chemical and physical environment of coal mines. With synthetic materials, it is especially important that the particular compounding process employed is suitable for use with breathing air. This is a matter which can best be determined at the time a large order for the hose is being negotiated with a manufacturer. A summary of the properties of some of the basic materials employed in hose construction is presented in table 5-3. From this chart alone, it would appear that polyurethane is the most attractive material based upon its excellent abrasion resistance.

Table 5-3. PROPERTIES OF SEVERAL COMMON PLASTIC HOSE TYPES.

HOSE TYPE	WORKING PRESSURE @ 70°F	ODOR	FLAMMABLE	ABRASION RESISTANCE
Poly-urethane 1/4" X 1/2"	70 psig	Nil	Self-Extinguishing	Excellent
PVC W/Dacron Braid 1/4" X 3/8"	210 psig	Some	Self-Extinguishing	Very Good
Nylon "11" (Semi-Flexible) 3/8" X 1/2"	250 psig	Nil	Self-Extinguishing	Excellent
Poly-Ethylene (Semi-Flexible) 3/8" X 1/2"	65 psig	Nil	Slow Burning	Very Good
Stabilized Poly-Propylene (Semi-Flexible 3/8" X 1/2"	185 psig	Nil	Faries	Very Good

The fact that it can be procured in a translucent compound permits examination of the hose for water or dust to check on system performance.

One-quarter inch inside diameter hoses constructed of polyurethane, vinyl, neoprene and nylon were procured for laboratory evaluation. The most flexible nylon hose obtainable was far too stiff for consideration as the miner's umbilical, but was selected for other ducting purposes. While fabric reinforced neoprene hose is potentially suitable, it is heavier and less abrasion resistant than either vinyl or polyurethane. All of the several types of vinyl hose procured produced a slight odor. Some of them, however, can be procured with the "food grade" compound of vinyl which exhibits no odor. For reasons which are not clear, there are a very limited number of hose products utilizing polyurethane. One product tested was a homogeneous, non-reinforced polyurethane hose having a 1/4-inch ID and a 1/2-inch OD. While the hose was rated at a working pressure of only 70 psig, it was utilized on the prototype respirator system for a number of operational tests. It proved to be exceptionally durable and quite suitable for the intended application. It can be obtained with an imbedded inner braid of dacron and an inner lining of food grade vinyl which are molded in place during fabrication of the hose. In this configuration, a hose of 3/8-inch O D is rated at a working pressure of more than 200 psig. Unfortunately, procurement of this product, which can be manufactured by several companies, requires a special production run and a minimum order of 1000 feet. Such a procurement was considered imprudent for construction of a single prototype, so further evaluation of the product centered upon a hose produced from vinyl which is quite similiar, except for a lower abrasion resistance. From this evaluation it was decided that the reinforced polyurethane hose meets the requirements and, therefore, it is incorporated in the design. The construction of the desired hose includes a transparent food grade vinyl inner lining, a dacron braid, and a translucent polyurethane covering. The product is similar, except for materials, to several products readily available such as Tygon B-44-4X "Inner Braided" tubing. The vinyl inner lining is necessary because a "food grade" polyurethane is not currently available.

Umbilical Assembly Design

Based upon consideration of miner's tasks, miner work space consideration, and the necessity of managing the umbilical in terms of precluding task interference and snagging, it was decided that the umbilical should be supplied in a standard 15-ft. length. Additional ten-foot sections may be provided for those miners who find it desirable. One example of the necessity for longer umbilical lengths is compatibility with some of the newer continuous miners, such as the new Lee Norse miner, which provide a remote operator control station to the rear of the machine. The design assembly is depicted in figure 5-12. It incorporates the R. E. Darling Co emergency disconnect device which is also used for routine connect-disconnect operations.

DEMAND REGULATORS

Perhaps one of the more rewarding portions of the program was the procurement and evaluation of the demand regulators used in the system. An initial design proposed by the Robertshaw Company, Anaheim, California was nearly perfect in meeting the requirements. The only potential shortcoming of the prototype unit produced for evaluation was a deficiency in maxiumum flow rate obtainable. Flow rate versus suction pressure at several different supply pressures are shown for the prototype in figure 4-34.

Again the paradox is encountered that at the time when the highest flow rates are needed, the system supply pressure is necessarily reduced. It was decided that while this regulator exhibits remarkably good pressure flow curves in comparison with other demand regulators, the peak flow requirement

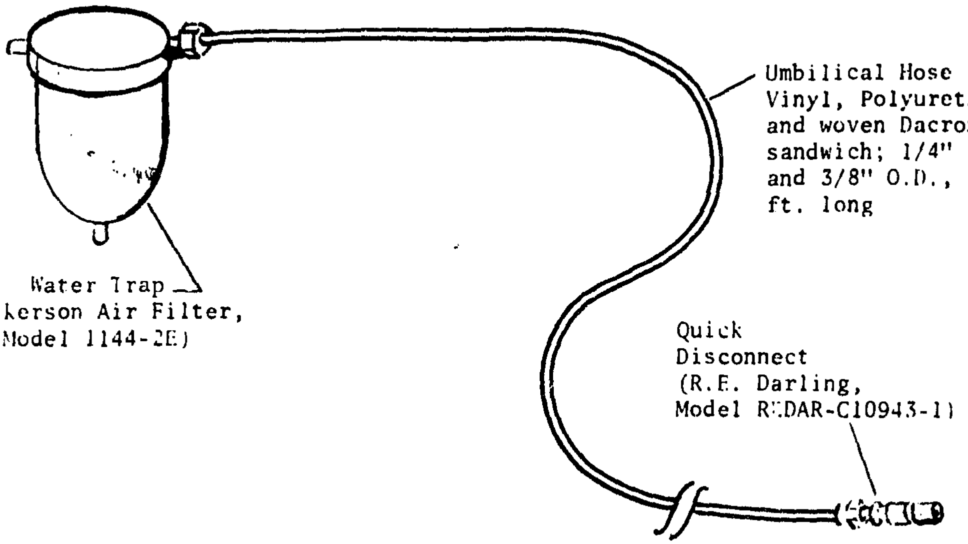
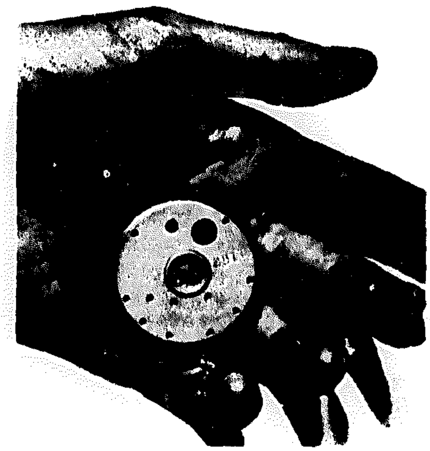


Figure 5-12. Umbilical Hose Assembly

should not be sacrificed. Since Robertshaw had done all that was possible in improving the flow rate of this particular unit, other manufacturers were contacted once again. A better regulator could not be found. Therefore, in view of the fact that the Robertshaw models, shown in figure 5-13, are quite small and light weight, it was decided to employ two of them in the air delivery system. Two units were installed in a prototype face mask mounted on a head form and the flow rate versus suction pressure curves at various supply pressures for this assembly are shown in figure 5-14.

Outside View



Inside View

Figure 5-13. Modified Robertshaw Regulator.

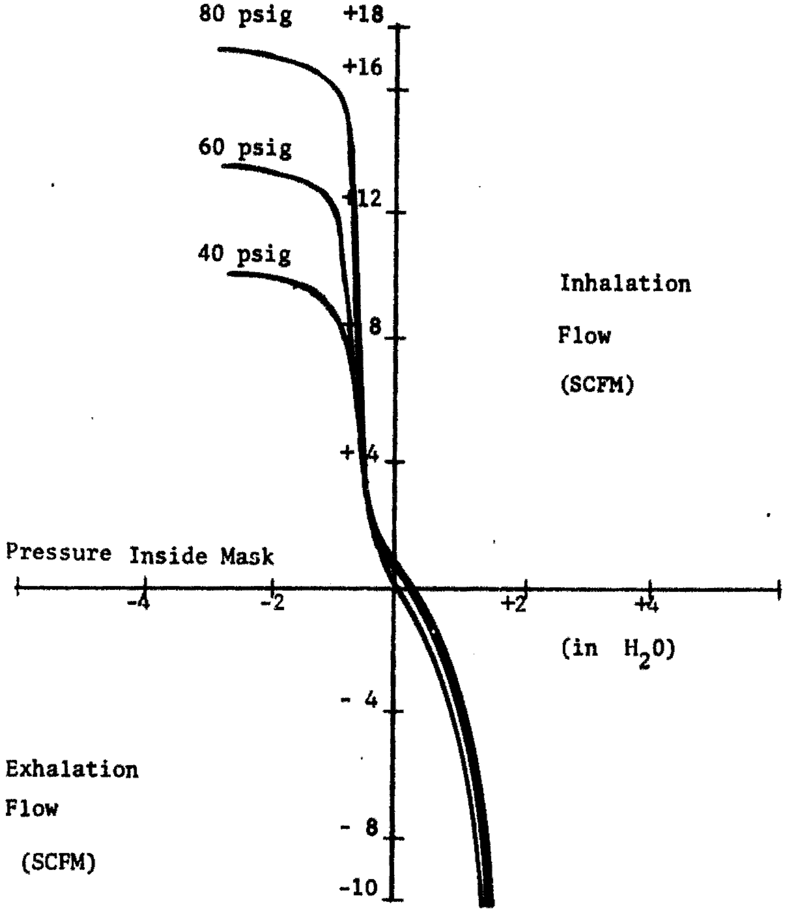


Figure 5-14. Flow Rate vs. Mask Pressure at Three Regulator Supply Pressures.

Ventilation Flow

As discussed previously, it was determined that ventilation flow should be incorporated into the air delivery system in order to reduce thermal and moisture build-up within the facepiece. A search of the available literature produced no applicable results describing how to choose a suitable flow rate under this circumstance. Therefore, an experiment was conducted in our laboratory. A rudimentary simulation of the underground working environment was constructed using plywood and other laboratory furniture. The interior was darkened so that it was necessary to use a miner's cap lamp, and the relative humidity was increased by flooding the floor with water. Subjects were dressed in full mining equipment, including helmet, cap lamp, coveralls, safety equipment, rubber boots and one of the prototype facepieces. The facepiece included two of the Robertshaw demand regulators. The mask was modified so that the individual subject could set the ventilation flow rate at whatever he desired. The ventilation flow was introduced through two 1/8-inch diameter ports mounted near the demand regulators, one experimental run was made with no air flow baffles within the mask, so that the ventilation flow impinged directly on the cheeks of the wearer; a second series of runs was made with suitable baffles over the regulator input and the ventilation flow inlet so that the sensation of air flow velocity was reduced to a minimum.

The simulated work space was approximately 25 feet long and 8 feet wide. A work station at one end of the enclosure involved a small display with a control function to keep the subjects occupied during the non working phase of the underground exposure. The display consisted of a voltmeter at the work space directly in front of the subjects location, and another voltmeter at the far end of the work space. The meter at the far end of the work space was controlled by the experimenter, so that he could set the indicator for any voltage desired. The miner's task was then to continually monitor the controlled meter and set his own meter to match it, the task was made more difficult by providing two non-linear controls for voltage to the subjects' meter. As desired, it was found that the control task was fairly demanding. Alternating with the control task was a task involving a fair amount of energy expenditure so that the subjects' choice of ventilation flow rate would reflect some combination of his desire for flow rate during sedentary and working tasks. The working task involved moving a 25-pound weight from one end of the simulated mine to the other and back again. Subjects' activities were controlled by the experiment, using a light signaling system so that no verbal communication would be necessary. A single subject-exposure lasted one-half hour, and was conducted according to the activity profile shown in table 5-4. The subject had five opportunities to adjust his ventilation flow rate. The experimental data are also shown in table 5-4. Since the variation in flow settings for the last two opportunities to do so in the experiment showed little variation, it was decided that the experimental period was sufficiently lengthy to extract data. As might be expected, the flow rate settings the subjects chose for the baffled condition were higher than for the non-baffled condition. All of the subjects reported that this was a much more pleasant condition.

Based upon discussions of the matter with the experimental subjects, it was decided that setting the flow rate at the average flow rate of the experimental subjects would result in half of the subjects being uncomfortable due to having a ventilation flow rate that was too high. The converse did not appear to be true; most subjects felt that having the flow rate too low was less objectionable than having it too high. Therefore, a compromise was decided upon of setting the flow rate at approximately 30% of the range between the minimum and the maximum. Thus, a final flow rate for ventilation flow was set at 0.75 SCFM. It should be immediately stated that this flow rate is dependent on supply pressure at the regulator and will be less than the design value when the subjects are working hard and the system pressure has dropped below its normal operating value.

Regulator Installation

In order to make the demand regulators compatible with the prototype face mask and its suspension harness, it was necessary to modify the regulator inlets from those normally supplied with the unit. This was performed

Table 5-4. VENTILATION FLOW SELECTION TEST

ELAPSED TIME (Minutes)	ACTIVITY	ELAPSED TIME (Minutes)	ACTIVITY
1	Set Flow 1	12	Carry
3	Monitor	14	Monitor
4	Set Flow 2	15	Set Flow 4
5	Carry	16	Carry
7	Monitor	17	Carry
8	Carry	19	Monitor
9	Set Flow 3	20	Set Flow 5
11	Monitor		

Activity Schedule for Test Subjects

VENTILATION FLOW ADJUSTMENT	FLOW (SCFM) WITHOUT BAFFLES			FLOW (SCFM) WITH BAFFLES		
	MIN.	MEAN	MAX	MIN.	MEAN	MAX.
1	0.25	1.03	1.7	0.75	1.34	2.1
2	0.20	1.03	1.7	0.75	1.49	2.2
3	0.20	1.12	1.7	0.80	1.69	2.7
4	0.30	1.09	1.7	0.80	1.73	2.7
5	0.30	1.09	1.7	-	-	-
Mean	0.25	1.07	1.7	0.775	1.56	2.4

Ventilation Flow Chosen by Test Subjects; With and Without Baffles.

by cutting off the inlet tube and welding it to its base in a different orientation. The modified inlets are visible in figure 5-13.

The regulators are supplied with a threaded body. A mounting plate was machined to accept these threads and to provide for installation of the flow baffles. The baffle plates are formed of 0.030-inch thick polycarbonate plastic. Further flow diffusion and noise attenuation were achieved by installation, by Robertshaw, of fine mesh screens in the regulator outlet ports. A photograph of the regulator assembly installation is shown in figure 5-15.

PLENUM CHAMBER DESIGN AND FABRICATION

A plenum chamber, in a system such as this, can serve two functions. One function is to provide storage for a sufficient volume air, at a pressure adequate to supply the regulators, to provide for a period of time during which the air compressor is not operating, or when the demand far exceeds the supply rate. The second function is to even out the supply pressure

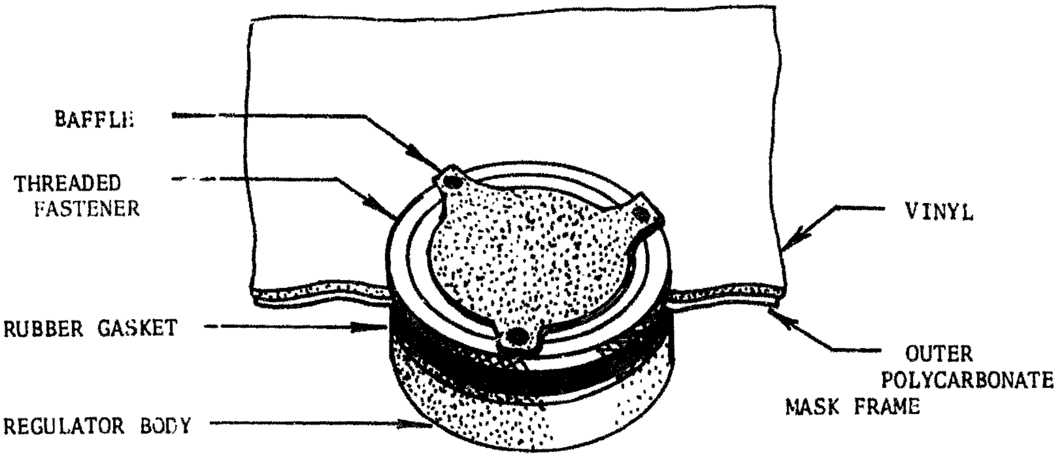


Figure 5-15. Regulator Assembly Installation.

seen by the regulators from breath-to-breath. If a plenum chamber were not provided for this purpose then the flow rate could never exceed the compressor output flow rate of approximately 3.5 SCFM.

In evaluating the feasibility of providing the first type of feature, a simple engineering analysis was performed relating size of the pressure chamber, system output pressure, and length of time that breathing air could reasonably be provided for user. As shown in figure 5-16, which describes some of the results of the analysis, it would take an unacceptably large plenum chamber to provide even a few minutes supply of breathing air. While this is most certainly a very desirable feature to have on the supplied-air system, the provision of such large plenum chambers could be utilized on only a small number of machines. Therefore, it was determined that the prototype design should not include such a chamber. However, when properly integrated with the mining machine during manufacture or a retrofit situation, such a plenum chamber should be incorporated.

A plenum chamber serving the second function mentioned above, smoothing of the air supply pressure to the demand regulators is, of course, a necessary element in the design of the supplied-air respirator system. To determine an appropriate size for the plenum chamber, it was necessary to perform a mathematical analysis of the situation. The compressor's supply pressure and flow rate, while slightly non-linear, as shown in figure 5-4, may be approximated by the relation

$$\dot{m}_1(t) = M_1\left[1 - K_1 p(t)\right] , \qquad (5\text{-}1)$$

where M_1 and K_1 are constants describing a particular compressor.

The system output, or the air supplied to the user, may be approximated by sine waves and a constant flow as shown in figure 5-17. The mathematical function used to describe this flow in the simulation is

$$m_2(t) = \begin{cases} M_2 \sin\omega t + M_o, & \sin\omega t > 0 \\ M_o, & \sin\omega t \leq 0 \end{cases} \qquad (5\text{-}2)$$

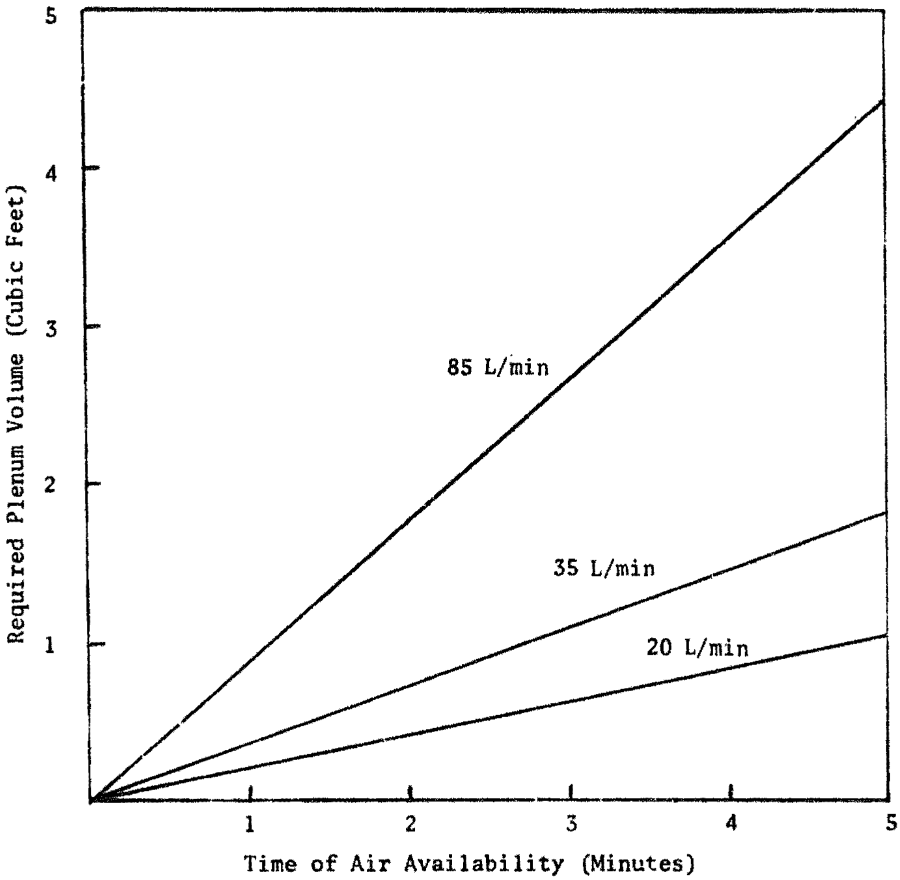


Figure 5-16. Required Plenum Size vs. Length of Time Air Availability (Based on a 50 psi pressure change).

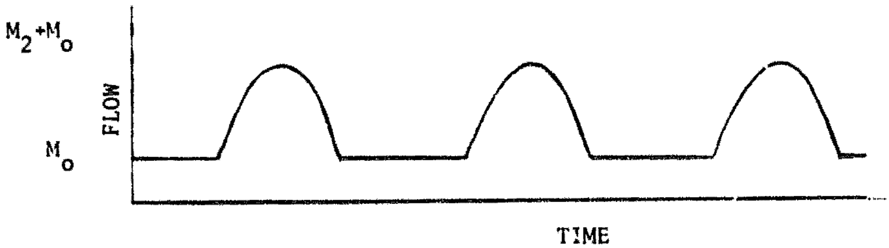


Figure 5-17. Approximate Model of the Air Flow Supplied to the User.

Equation 5-1 represents flow into a plenum chamber and equation 5-2 represents flow out of the chamber. Therefore, this system of differential equations can be solved for instantaneous pressure within the plenum chamber. The solution was obtained and the resulting equation was programed for numerical solution on a Wang Model 600 programmable calculator. Sample results from these computations are shown in figure 5-18.

Based on the regulator supply pressures required, at least 45 psig, and the pressure losses through the umbilical hose, one can then determine the relationship between the time period for which any minute volume can be supported, and the size of the plenum chamber. Consideration of these physiologic and engineering parameters resulted in a selection of the plenum chamber of approximately 110 in^3. In the design of the system, it was found convenient to procure a suitable plenum chamber having a volume of 102 in^3. This plenum chamber is a surplus stainless steel oxygen bottle rated at a burst pressure of 500 psig. Several of these units were procured, refurbished and hydrostatically tested before incorporation into the prototype system.

AUXILIARY EQUIPMENT

A number of components such as pressure relief valve, attachment points, and other such items are part of the air distribution components and will be discussed briefly below.

Pressure Relief Valve

The miner's respiratory minute volume is normally less than the output rate of the compressor. To prevent a catastrophic build-up of system pressure, the excess air must be bled off in a controlled fashion. This is achieved by means of a spring-and-diaphragm type pressure relief valve. Such units are commercially available with slight variations from several manufacturers. The prototype system employs a Norgren Co. Model Number V06-200-NNK.

It is essentially the same as their miniature air-line regulator, with internal modifications so that it regulates upstream rather than downstream pressure. This type of regulator was chosen over the spring-loaded "poppet" type of pressure relief for two reasons. One is that it affords a more accurate and reliable control of system air pressure. Additionally, it is suitable for continuous operation, while the "poppet" type is ordinarily employed for intermittent use only.

As shown in the system schematic, figure 5-1, the pressure relief valve is located downstream from the cyclone separator, the final filter, and the plenum chamber. There are several reasons for this. Most importantly, it insures that the cyclone separator is exposed to a more continuous flow rate. Pressure relief valve reliability and noise generation are more acceptable when it is exposed to a non-cyclic flow rate and clean air.

A muffler was found to be necessary to reduce noise generated by the pressure relief valve. A model MO-1 manufactured by Allied Witan Co., Cleveland, Ohio, is employed for this purpose.

Flow Sensor

The emergency quick disconnect employed is a full-bore type which does not incorporate a device to stop the flow when it is disconnected. There-

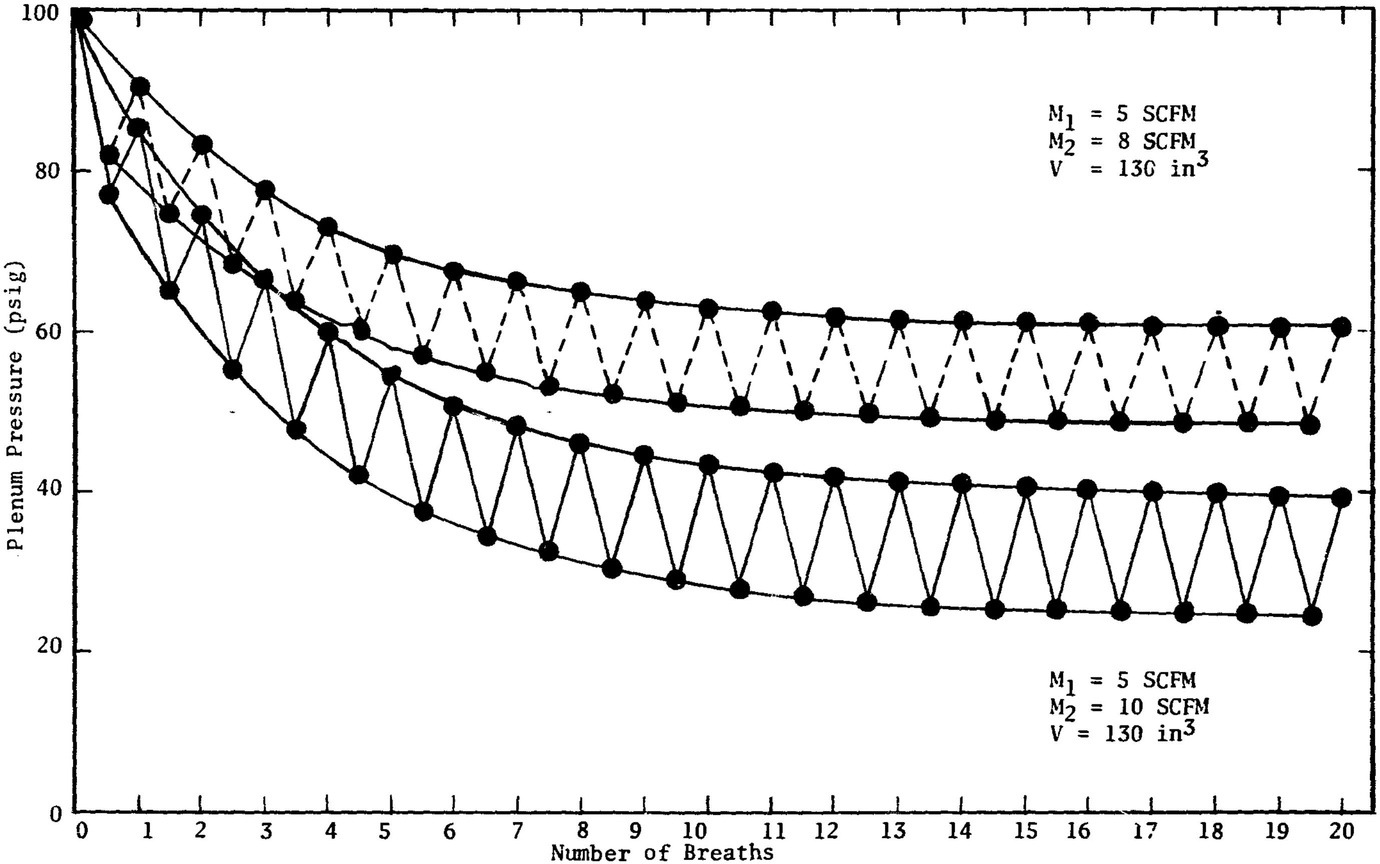


Figure 5-18. Plenum Chamber Pressure After the Onset of Breathing When the Initial Pressure P_o is 100 psig. Upper Envelope is for Minute Volume of 2.8 SCFM and lower Envelope is for Minute Volume of 3.4 SCFM

fore, it is necessary to provide a device to reduce the flow in the umbilical when disconnected (or broken) so that it will not flail. A Hansen Flow Sensor, mounted in the auxiliary enclosure is employed for this purpose. A spring-loaded check valve closes when the flow rate exceeds 20 SCFM. A small orifice in the device allows a small flow to continue. This serves two purposes in the system. It keeps dirt from entering the loose end of the umbilical and it permits the reconnected umbilical to restore pressure, opening the flow sensor to a full-flow condition.

Machine Attachment

Recognizing that it may be necessary to mount the auxiliary enclosure some distance from the operator's station, a small machine attachment point for the miners umbilical is included in the system. It includes a water trap and a swivel. The water trap is located at this point, rather than within the auxiliary enclosure, to allow more chance for condensation through the necessary ducting to that point.

FACEPIECE DESIGN AND CONSTRUCTION

Following modification of the contract in February 1972, considerable effort was expended in developing a facepiece suitable for use with the supplied-air respirator system. As previously discussed, the requirement for this effort stems from the fact that currently available facepieces fall short of the desired performance for the present purpose on several counts, mainly:

- Capability to mount and support, comfortably, the weight and bulk of demand regulators,
- Seal type, seal contours, and suspension suitable for use with regulators under the stresses of rapid and varied head movements found in the underground mining tasks,
- Capability for speaking, and expectoration.

These requirements have been discussed more fully in previous sections and lead to the necessity of developing a new facepiece which can satisfy the requirements specific to the underground environment.

To review the concepts presented previously, the facepiece to be produced must facilitate the incorporation of a number of features each imposing demands upon the configuration and, thus, upon the prototype fabrication techniques. These features include:

- A suspension harness permitting comfortable continuous wear and ease of doffing & donning
- Broad contact area face seal,
- Space for mounting two Robertshaw demand regulators,
- Provision of a door to permit speaking and expectoration,
- A rigid seal support device or "shell",
- Space for mounting exhaust valves and an anti-suffocation device.

Based on the conceptual designs presented previously, the development work progressed in an evolutionary fashion, as shown in figure 5-19. This process was performed through a total of three facepiece design prototypes

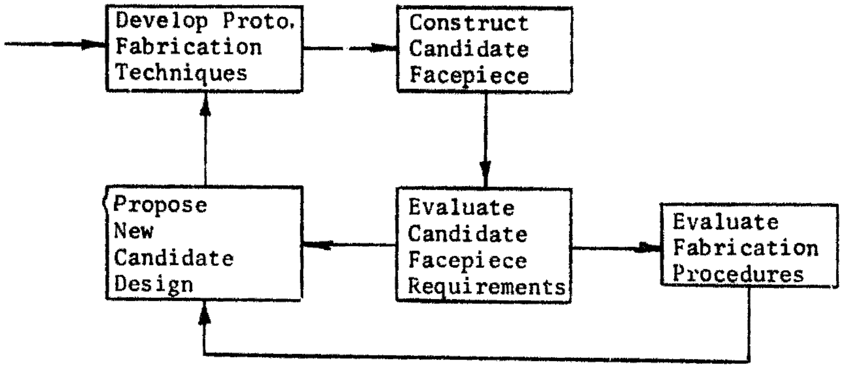


Figure 5-19. Steps in Development of the Prototype Facepiece.

culminating in the design shown in figure 2-8.

FINAL FACEPIECE DESIGN

The final facepiece design consists primarily of a vinyl elastomeric body supported by a vacuum formed polycarbonate shell. The overall facepiece assembly including the suspension elements weighs 8.5 ounces, including the demand regulators. The unit is best described by discussion of the various design features. In these paragraphs, each of the features important to the design and performance of the facepiece assembly will be discussed in terms of their overall impact upon the design and its performance. In the next section, detailed designs will be provided and the development involved in arriving at that design will be presented.

Facial Access Port

One of the primary features affecting overall mask design was the facial access port, or front door. The facial access port permits the wearer to open the port for expectoration, when necessary, take "a breath of fresh air", carry on face-to-face conversation, or use a telephone. The facial access port is composed primarily of a voicemitter and, thus, permits speaking even with the port closed. Although not measured in a quantitative sense, it is possible to conduct a face-to-face conversation in a fairly noisy environment with the facial access port closed. Another reason for providing the voicemitter was so that a miner's warning shout in an emergency situation would be transmitted.

The latch holding the door closed was designed so that it can be operated with one gloved hand.

Sealing Surfaces

The vinyl elastomeric body incorporating the sealing surfaces is of approximately 45-durometer material and varies in thickness. Since the sealing surfaces are required to support at least part of the weight of the mask assembly, they are designed to cover a broad area of the facial structure. Particular emphasis is placed on providing a significant amount of area near the cheek bone to react downward forces on the mask. In doing this, it is intended to reduce the forces exerted on the nasal bridge. The seal is designed to extend quite far backward along the cheeks so that inertial forces resulting from twisting the head from side-to-side are reacted with a sizeable moment arm, thus, reducing the pressure on the face.

An inturned type of seal is used in order to provide better fit accommodation and to prevent outward leakage of positive pressures.

While the mask is produced in only one size, adjustments to the sealing contours may be achieved by the use of foam rubber inserts between the shell and the body or, if desired, within the inturned seal.

Regulator Integration

The primary goal of the facepiece shell design is to locate the mass of the demand regulators as far rearward as possible. The shell is made from polycarbonate plastic vacuum-formed over an aluminum mandrel. Being only approximately .055-inch thick the shell is quite light in weight but surprisingly resilient.

Suspension Harness

After considering a number of quite novel approaches to facepiece suspension, the design shown in figure 5-20 was adopted. A moderately elastic knit cap is worn on the head. On either side of the head, near the ears, the cap incorporates a large patch of hook and pile type fastening material. Two elastic straps on either side of the facepiece terminate in mating patches. With the miner's helmet in place, the suspension cap is firmly held in place, so that either side of the harness may be loosened and the mask permitted to dangle by the other strap. Subsequent donning may be accomplished with one hand. This suspension system also affords another mode of donning and doffing in that the cap may be utilized much as an elastic strap-type harness would be and that it may be pulled down so that the entire respirator is suspended from the neck. This would of course be the desired mode of wearing during periods when the respirator was not frequently held on the face. One of the considerations in the design of the facepiece was to permit it to be tucked under the coveralls while suspended from the suspension so that it would be protected from accumulating dirt from the mine environment.

DEVELOPMENT AND FABRICATION

The following paragraphs describe the detailed design of the components of the facepiece assembly and give some background as to how the particular design was derived. This particular prototype design evolved from three prototypes produced previously, each being quite different from one another, Furthermore, within this particular design several masks were produced with minor modifications among them.

Figure 5-20. Facepiece with Suspension System.

Facial Access Port

Components included in the facial access door assembly include the support ring, which provides the basic structure for attachment of the shell to the mask body, and hinge and latch components for the door. The door, itself, is composed of a support ring and a voicemitter, a hinge and a clasp, and a foam rubber sealing ring. These components are shown in an exploded view in figure 5-21. The support ring and the access port support ring are machined from aluminum flat stock. The voicemitter is bonded into the support with Eastman 910.

Sealing Surfaces

The method of fabrication of the mask body is essentially a combination of procedures used in the previous prototype construction with some modification to achieve better quality control and appearance. The fabrication procedure proceeds in the following steps:

- The aluminum mandrel on which the previous prototype had been made was reshaped slightly, extending the sealing surface slightly farther back on the cheeks, increasing the sharpness of the corner where the seal turns in, extending the mandrel further forward about 1/4 inch to provide better clearance for the nose, and extending it downward by 1/4 inch and providing a flat area for mounting the exhalation valve. The mandrel was then finished to the desired surface finish.

- The aluminum mandrel is heated to 360°F in an oven and the first layers of the vinyl elastomeric material (Hastings Plastic, Inc., Polyvinyl Plastisol No. 1951), painted on with a brush. The painting is alternated with re-heating, for several steps and then finally the entire mandrel is dipped in the container of liquid vinyl.
- The hot mandrel is then attached to a machine which continually rotates it in all possible orientations so that runs in the vinyl do not occur while it is setting. This entire process occurs within an oven at 360°F.
- Finally, the vinyl is stripped from the mandrel and trimmed to the desired finish contours. The inturned seal width is maintained at approximately 3/4-inch along the entire contour.
- Using a previously developed pattern, the required ports for regulators and valves are cut in the vinyl mask body.

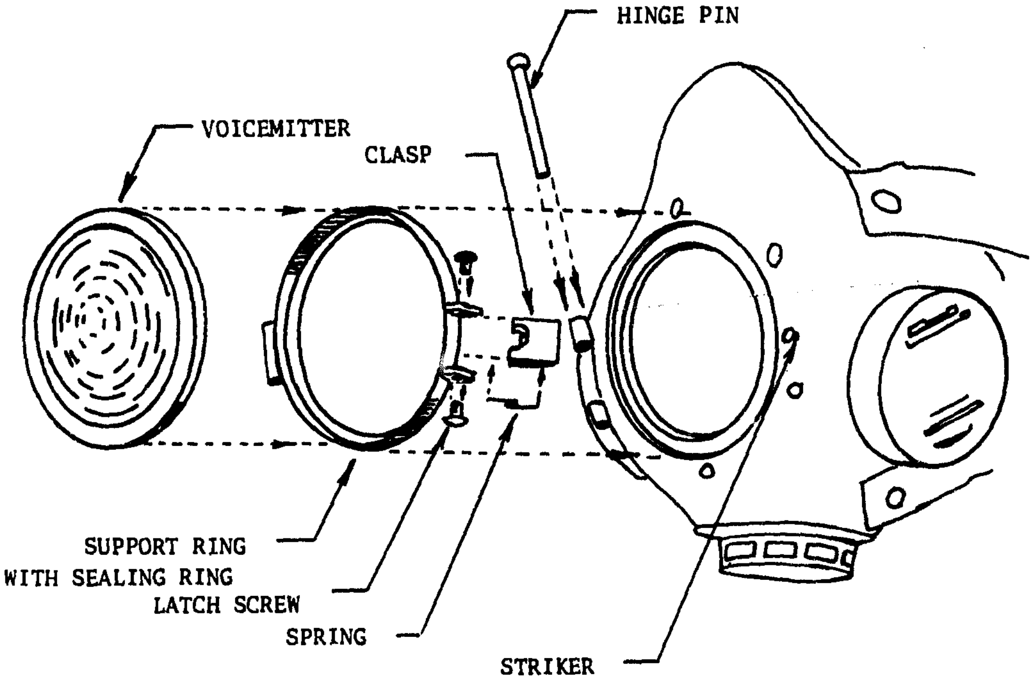


Figure 5-21. Exploded View of the Facial Access Port Construction.

It should be noted, in doing this process by hand, that the rejection rate required to obtain a good quality mask body is quite high. However, using the technique of painting on the first coat, and the multi-axis rotational device, which is essentially part of a rotomoulding machine within the oven, it was possible to obtain very good surface finishes and good thickness control. This amount of effort is certainly necessary to produce a comfortable seal which depends upon a thin, smooth sealing surface. The net result of this process, the mask body, is shown in figure 5-22.

Figure 5-22. Molded Facepiece and Tooling.

During production of the final prototype we attempted to use a silicone elastomeric material based on the belief that its properties, regarding tactile sensation on the skin, are superior to vinyl. Unfortunately, we were not able to produce a good quality product using the silicone materials due, primarily, to an inability to achieve respectable tear resistance.

Facepiece Support Shell

The facepiece support shell shown in figure 5-23 is fabricated from 0.060 inch thick polycarbonate (G.E. Lexan) by vacuum-forming over an epoxy pattern. The pattern is sculpted from a model of the vinyl mask body pattern by addition of material to form flaired edges along the periphery. The polycarbonate is trimmed to the desired contours after forming and the various ports are located by use of a template.

Exhalation Valve

The exhalation valve chosen for the final design is a model produced by Wilson Manufacturing Company. It was selected solely on the basis that it had the least flow resistance of any potentially suitable exhalation valve tested. The valve seat was further modified to reduce flow resistance by removing part of the valve support structure and smoothing some of the sharp edges exposed to air flow. The final flow resistance curve, shown in figure 5-24, however, continues to exhibit more resis-

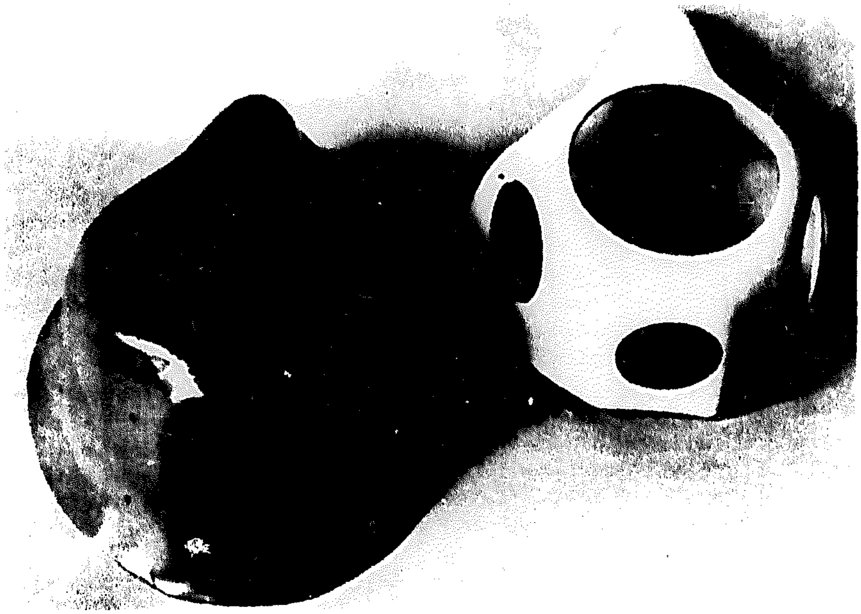


Figure 5-23. Facepiece Support Shell with its Tooling.

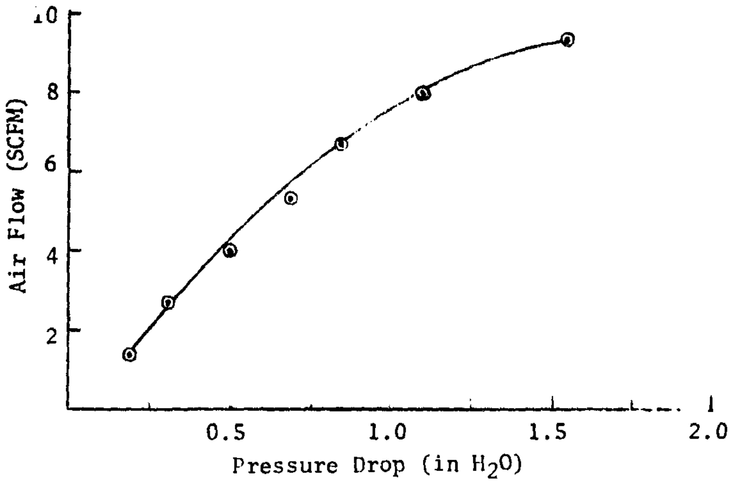


Figure 5-24. Flow versus Pressure Drop Characteristic of the Modified Wilson Exhalation Valve.

tance than desired. As discussed previously, the only reasonable means for further reduction in exhalation resistance is to incorporate dual exhaust valves. This concept was rejected for reasons of excessive facemask bulk and weight.

Anti Suffocation Device

Modification of the exhalation valve, as previously described, resulted in a unique type of anti-suffocation device. When a suction pressure of approximately 8 in H_2O is presented to the modified exhaust valve, the valve disk is deformed and pulled into the valve seat support bars. When this happens, a two-way free flow of air is permitted through the deformed exhalation valve. In this way, the miner has the capability to breath when the system is in operation and he is unable to open the facial access port.

Facepiece Suspension Harness

The cap-type suspension harness shown in figure 5-20 was found to be considerably more comfortable and convenient to use than any of the potential harnesses involving straps which were evaluated. The contours of the cap are designed in a way so that, with tension on the harness, the cap will not slip up or down on the head. While a single cap will suffice in fitting people with a wide variety of head sizes, it is most appropriate to supply the unit in two sizes. With either cap size, if a cap is too large, it is possible for the individual to cut a portion of the hook fastening material away with a pair of shears.

The portion of the harness attatched to the mask utilizes two elastic bands, on each side, riveted to the mask on one end and to the pile portion of the hook and pile fastener on the other. A small loop is sewn to the attachment top to support the weight of the air supply leads.

Breathing Air Leads

High-pressure air leads from the miner's belt to the face mask are constructed from the same vinyl and polyurethane reinforced tubing as is used in the miner's umbilical. A suitable, lighter-weight, smaller-diameter tubing could not be found. The lead is bifurcated near its midpoint rather than near the mask, in order to provide less resistance to head movements. A sketch of the air-lead design is shown in figure 5-25.

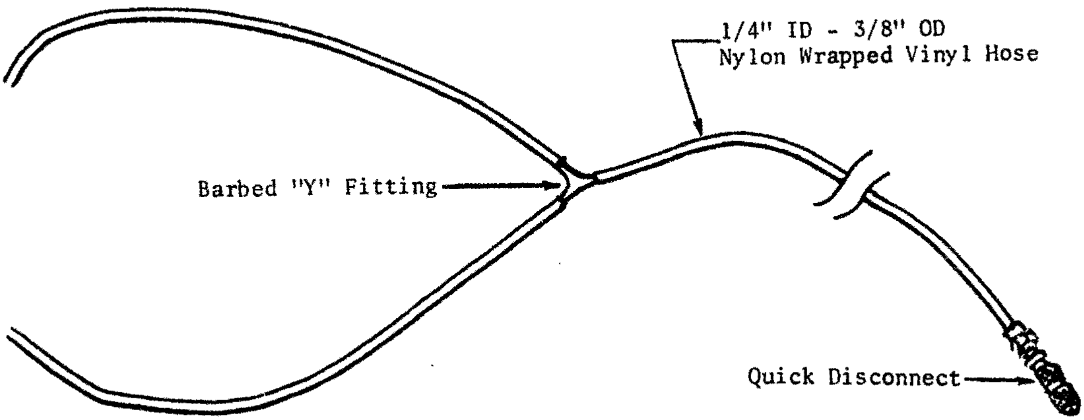


Figure 5-25. Inlet Air Leads.

Small clips are provided along the lead so that it can be clipped to the front of the miner's clothing to reduce the incidence of entanglement or impediments to hand and arm movements. Consideration was given to routing the umbilical along the same path commonly used for the cap lamp electrical cable. However, this would result in the possibility for neck injury in the event of entanglement since the mask does not easily slip off the face when subjected to a rearward pulling force. On the other hand, when an entanglement results in a forward pull, the suspension can more easily slip over the head relieving the potential hazard.

PART THREE

CONCLUSIONS AND RECOMMENDATIONS

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Section VI

PROTOTYPE TEST AND EVALUATION

Formal test and demonstration objectives include measurement of the protection factor and demonstration of the system's ability to function for extended periods of time in a simulated mine environment. Noise production tests, fit and comfort tests, and evaluation of the unit for compatibility with the miners' tasks were included and a summary of the methods and results are presented in this section.

PROTECTION FACTOR

Measurement of the protection afforded by the system were conducted in a dust chamber at Wyle Laboratories, El Segundo, CA. The test report issued by Wyle is presented in Appendix VI and is discussed below.

PURPOSE

The purpose of the dust chamber testing was to measure the protection factor afforded by the total system and by the facepiece independent of the air supply system. The protection factor is defined as the ratio of the mass concentration of dust in the breathing zone (inside the facepiece) to the mass concentration of dust in the atmosphere immediately surrounding the test subject. The protection factor for the facepiece, independent of the air supply system, may be determined by the same principal if the air supply to the facepiece is dust free.

METHOD

Three experimental subjects were exposed to a dusty environment for 30 minutes each in a small dust chamber. The entire respirator system was situated within the chamber. Gravimetric samples were obtained from the chamber atmosphere and from inside the mask.

Environmental Control and Measurement

The three subject tests were conducted within a 6 X 8 X 8 foot dust chamber equipped with temperature, humidity, and dust concentration controls. Bituminous coal dust admitted into the chamber, as needed, was prepared by grinding, then sieving through a U.S. Standard Sieve, Number 230, which has openings of 63 um. Dust was injected with a compressed-air delivery unit.

Gravimetric dust concentration within the chamber and within the mask was obtained by drawing air samples through Gelman Instrument Model 4323 dust sampling cartridges. Air samples from within the facepiece were drawn continuously for the 30-minute test period at a rate of 0.25 SCFM. Chamber atmosphere dust samples were taken at higher flow rates, at least three times during each test period. Sample cassettes were weighed with an analytical balance having an accuracy of 0.05 mg.

Subject Activities

Mining tasks and work place environment were simulated by use of the "operators station" shown in figure 6-1. The subject's control task was to

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Figure 6-1. Simulated Operator's Work Station Used During System Test Program.

switch one of four indicator lamps on or off in order to match a pattern displayed above the controlled lamps. The subject-controlled lamps were operated by four levers "borrowed" from a surplus aircraft engine control console. The task was made more demanding by perturbing the control-display positional correspondence. The display pattern was controlled manually by the experimenter from outside the dust chamber so that, during the control activity phases of the test program, the subject was constantly busy moving his head, arms, and hands.

A second activity required of the subjects was designed to stimulate his metabolic rate and to simulate the movements likely to be exhibited during miner's dismounted tasks. In this activity, the subject stood up and walked to a corner of the room. From there he carried a 25-pound weight to the other corner of the room, a distance of 10 feet, and returned to his semi-recumbent position at the operator's station. He then got up again and returned the weight to its origin, assumed his seat and had a few seconds rest before the control function resumed.

This activity cycle, consisting of dismounted exercise and operator control functions, lasted six minutes and was repeated five times during the course of the 30-minute experiment for each subject.

Subject Profiles

The three subjects were Synsis personnel familiar with underground mining operations and the use of respirators. Facial anthropometric dimensions of the subjects are shown in table 6-1. The percentile scores as-

Table 6-1. SUBJECT FACIAL ANTHROPOMETRIC DATA

DIMENSION	SUBJECT	MEASUREMENT	PERCENTILE
MENTON-NASAL ROOT DEPRESSION (FACE LENGTH)	GG WS TC	12.4 cm 13.3 cm 11.5 cm	69% 88% 23%
BIZYGOMATIC BREADTH (FACE BREADTH)	GG WS TC	14.0 cm 14.5 cm 14.1 cm	30% 71% 30.5%

signed to the measurements are based upon values produced at Los Alamos Scientific Laboratory (Hack, 1972). One subject, TC, wore spectacles throughout the test. All subjects were dressed in coveralls and rubber boots and wore all of the usual miner's personal equipment including helmets, cap lamps and self-rescue units.

RESULTS

Test results and test environmental conditions are shown in table 6-2.

Table 6-2. EXPERIMENTAL CONDITIONS AND RESULTS

SUBJECT	TEMPERATURE RANGE (OF)	HUMIDITY RANGE (% RH)	AVERAGE ATMOSPHERIC DUST CONCENTRATION (mg/m^3)	AVERAGE DUST CONCENTRATION WITHIN MASK (mg/m^3)	GRAVIMETRIC PROTECTION FACTOR
WS	84 - 89	85 - 90	78.5	0.3	262
GG	81 - 88	81 - 85	51.6	0.1	516
TC	79 - 86	87 - 91	78.3	0.5	156

The effect of facepiece leakage was determined by measuring the dust content of the air supplied to it under the test conditions. At the conclusion of the test series, when the dust chamber dust concentration ranged between 5.5 mg/m^3 and 48 mg/m^3, averaging 17.3 mg/m^3, a five-minute sample was collected from the miner's umbilical. This sample, weighed to an accuracy of 0.05 mg, indicated that no dust was being delivered to the facepiece.

Consequently it was concluded that the mask protection factor is the same as the system protection factor.

DISCUSSION

The lowest protection factor, 156, was achieved with the only subject who wore spectacles. While this value is an order of magnitude greater than required, the cause for the difference between this subject and the others was investigated. In no case were particularly stringent procedures for donning the respirator utilized. Suspension forces were adjusted for a comfortable fit rather than a tight fit and resulting better seal. Consequently, this subject had donned the facepiece without removing his spectacles. The result was that a slight interference caused the respirator to ride too high on the face and a small leak occurred along the dorsal portion of the nasal ridge. This was evidenced by a narrow black line (accumulated coal dust) along the nose. More careful donning procedures would have prevented this leak entirely.

It should be noted further that the mask was specifically designed to be worn with safety glasses and subjective evaluation by a number of subjects who wore glasses, was one of acceptance.

OPERATIONAL TEST

While rigorous operational performance and reliability tests were beyond the scope of the program, an eight-hour test of the equipment in a dusty atmosphere was required. Therefore, on the day after the subject testing in the dust chamber, the unit was attached to a breathing machine and run continuously for eight hours.

PURPOSE

The purpose of this experiment was to demonstrate the ability of the prototype supplied-air respirator system to operate continuously and in a satisfactory manner for eight hours in a dusty environment.

METHOD

The respirator system was placed in the dust chamber previously described. Over the eight-hour period, temperature ranged from 67°F to 85°F and humidity ranged from 80% to 86%. Dust concentration ranged from 5.5 mg/m^3 to 48 mg/m^3. The average dust concentration computed from twelve samples was 17.3 mg/m^3.

A one-inch diameter hose passed through the wall to a breathing machine outside the dust chamber. The breathing machine, operating at 12.5 cycles per minute, produced a minute volume of 40 L/min (1.41 SCFM). Hydraulic hoses for powering the supplied-air respirator system penetrated the chamber walls. The system pressure regulator was set at 70 psig.

RESULTS

With the exception of a ruptured hose, which was merely an oversight in assembly, the unit performed well throughout the duration of the eight-hour test. Inspection of the dust removal elements, at the conclusion of the test, supported the predictions made regarding performance. The inlet filter dust receptacle was heavily laden with collected coal dust. The primary cyclone exhibited less collected dust and the final filter was only slightly soiled. Unfortunately, it was not possible to accurately measure the dust collected by each element.

Pressure drop across the final element was not significantly different from the pre-test measures; however, a sizeable experimental error was involved in this measurement.

Regulator performance appeared to be unaffected by the exposure both in maximum flow rate attainable and in demand inhalation pressures required.

DESIGN REVIEW

Having finished the detailed design and testing, the question is often raised, "Is this what was originally intended?" This question was answered by comparing system attributes with the requirements generated at the outset of the program. A summary of this analysis is presented in table 6-3.

Table 6-3. DESIGN EVALUATION

REQUIREMENT	MEASURED OR ESTIMATED LEVEL OF ACHIEVEMENT
PROTECTION	Gravimetric protection factor, measured with 30 minute tests on each of three human subjects, ranged from 156.6 to 516.0.
MINING EQUIPMENT COMPATIBILITY	Intended for either continuous or conventional style of mining.
Types of Machines	Suitable for all face-working machines.
Installation	Use of three small modules facilitates machine integration with no change in envelope, or relocation of existing equipment. Hydraulic power requires less than 3 gal/min. Each module can be hand carried, bolted, clamped or welded in place. Electric power available.
MINING TASKS AND OPERATIONS	
Duty Cycle	Has approximately 30-second reserve as delivered, longer reserve supply available if machine envelope permits installation of larger plenum chamber. During power-down periods, air provided by opening facial access port. Not necessary to remove mask.
Maintainability	Filter element replacement less often than monthly. Daily maintenance consists only of opening drain valves. Weekly dumping of inlet cyclone dust receptacle, visual checks of system integrity required.

Table 6-3. DESIGN EVALUATION (continued)

MINING ENVIRONMENT COMPATIBILITY	
Underground Safety	No electricity utilized. "No-hands" quick-disconnects used in several places. Long, small diameter, light-weight hose does not impede egress. Hearing not impaired. Voicemitter and facial access port permits good transmission of verbal warnings. Anti-suffocation device provided.
Mine Atmosphere Conditions	Piston compressor and hydraulic motor not subject to fouling from external airborne contaminants. Inlet cyclone separator removes majority of dust and water particulate contaminants. Inlet can be located anywhere on machine with compressor located elsewhere.
Mine Physical Conditions	Respirator system is modular so that it can fit within external clearance of most machines working in low coal. All components enclosed in steel enclosures to protect against damage from roof falls. Materials are acid, oil and water resistant. Abrasion-resistant air umbilical.
PERFORMANCE	
AIR FLOW RATE	Maximum minute volume for sustained period 3.75 SCFM, short periods at higher minute volumes available. Peak instantaneous flow rates greater than 10 SCFM possible.
BREATHING RESISTANCE	
Inhalation Resistance	Less than 0.75 in H_2O (2 cm H_2O) at all flow rates up to 10 SCFM. No resistance to inhalation for flow rates less than 0.75 SCFM.
Exhalation	Resistance linear with flow rate at 0.33 in H_2O/SCFM (0.012 cm H_2O/L/min) or 1.02 cm H_2O @ 85 L/min.
Pressure Transients	Ventilation flow prevents exhalation valve popping. No others observed.
FACEPIECE COMFORT	Single size with adjustments fits test panel comfortably for extended test periods.
INDIVIDUAL TASK COMPATIBILITY	
Machine Operations	One-half inch diameter umbilical and smaller diameter facepiece air leads do not interfere with hand and arm movements. Downward vision not impaired. Wide sealing surface and rearward center of gravity of mask provide

Table 6-3. DESIGN EVALUATION (concluded)

	good stability for head movements. System generates less than 80 dBA while operating. Noise transmitted to wearer through regulators and facepiece less than 70 dBA.
Dismounted Tasks	Respirator facepiece may be worn in two modes during dismounted tasks: 1) with air supply connected and facial access port closed, and 2) with air supply disconnected and facial access port open breathing ambient air. Facial access port may be opened or closed for speaking or shouting warnings. Fifteen foot, small diameter umbilical is easy to handle during dismounted tasks.
INDIVIDUAL EQUIPMENT COMPATIBILITY	Suspension-cap type harness rather than straps can be worn comfortably with helmets. Single-handed donning and doffing possible with helmet in place. Facial access port may be opened with gloves on. Umbilical attach point requires small space on miner's belt.
BIOMECHANICAL REQUIREMENTS	
Miner Work Space	Minimal visual restrictions. No components mounted on miner's back. Fifteen-foot length of miners umbilical permits any posture for operator. Donning and doffing utilizes tabs separate from respirator body.
Facial Anthropometry	A single-size facepiece with adjustments fits a panel of subjects representing the 23rd to 88th percentile in face length and the 30th to 71st in facial breadth. Mask sealing capabilities afforded overall protection factor ranging from 156.6 to 516 in manned dust chamber tests.

Section VII

CONCLUSIONS AND RECOMMENDATIONS

This program culminated in the production of a prototype supplied-air respirator for underground coal mines. The respirator system, which includes a specially designed and fabricated facepiece, is especially suited for installation on underground mining machinery, such as continuous miners, shuttle cars, undercutters, and loaders. The prototype design incorporated concepts resulting from a combination of task and environmental analyses and evaluation of a number of alternate candidate designs.

The research and development activities produced a number of potentially important insights into powered respirator technology, as a whole, and to the specific application of supplied-air respirators to underground coal mines. While the majority of these comments are contained within the body of this report, certain conclusions and recommendations are repeated for emphasis in this part of the report.

CONCLUSIONS

The prototype supplied-air respirator exceeded the majority of its performance goals. Demonstrated protection efficiency was an order of magnitude greater than required. Maintenance intervals for filter replacement are on the order of monthly, rather than daily, as required initially. Based upon tests and evaluations performed at this time, the basic concept of a machine-mounted supplied-air respirator system appears to be quite attractive. It should be possible to achieve excellent levels of miner acceptance and minimal resistance by mine operators. While the supplied-air system is larger and more costly than contemporary respiratory protective devices, it's low maintenance requirements and minimal task and operational interference should contribute to it's overall acceptance by the mining community.

The size of both the compressor modules and the air-cleaning modules are slightly larger than could be achieved in a production version of the unit, if some additional component development were undertaken. Currently available components and the necessities of prototype production resulted in a unit which, if produced in small quantities, would be inordinately expensive. The expense is primarily due to small quantity production of the facepiece and the demand regulators.

RECOMMENDATIONS

The fundamental recommendation resulting from the program is that several units be constructed and used continuously in underground coal mines for evaluation. This recommendation will be fulfilled, in part, by another program funded by the Health Services and Mental Health Administration, HSM 99-72-88, in which this supplied-air respirator and nine other supplied-air respirators will be evaluated under working conditions in coal mines.

ADDITIONAL DEVELOPMENT

Should quantity production be anticipated, several changes in the design would be recommended. Each of these changes would involve a significant amount

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of development work in specialized areas. The changes are:

1. A single high-performance demand regulator should be utilized in order to reduce the cost of the system. Operating pressures, size and weight of such a regulator should be close to the units supplied with the prototype but higher flow rates must be available.

2. The oil-free piston compressor should be reworked to reduce its overall dimensions. A higher flow rate compressor would reduce the size required of the plenum chamber and, thus, the size of the whole system.

3. While a vinyl and polyurethane fiber reinforced breathing umbilical hose was specified in the design, a substitute all-vinyl, dacron reinforced hose was provided on the prototype system. In either case, there is some degree of incompatibility among the hose, the fittings, and the flow rate requirement. The basic problem is that "inner-braid" types of hose are poorly suited to fittings which seal on the outside circumference of the hose. On the other hand, the use of barbed fittings which seal to the inside of the hose result in greater pressure drop due to the reduced diameter of the flow path within the fittings. Two solutions exist to this dilemma. One is to use a larger diameter breathing hose with barbed fittings. However, a better solution would be to use a more suitable hose or fittings, retaining the specified 0.250 inch inside diameter. This would require additional development work which is recommended.

4. The hydraulic motor supplied with the prototype unit represents a compromise between difficulty of installation and system performance An electric motor would be more desirable because of its capability to operate continuously. However, the required one horsepower permissible electric motor was judged to be too large for installation on compactly designed mining machines. Consequently, it is recommendedthat development of smaller size permissible motors be encouraged.

USE IN OTHER INDUSTRIES

While the dust removal requirements and many of the compatibility requirements specific to underground coal mines, such as facial access, have had significant impact on the system design, similiar requirements exist in other industries. Adaptation of this supplied-air respirator system is especially suitable for vehicle or machine operators. For workers who must move about within a limited workspace, the breathing umbilical may be extended, to as much as thirty feet in length, with minor modifications to the system. For situations in which hydraulic power is not available or in which explosion-proof motors are not necessary, adaptation to electric motors is quite simple and is recommended.

When configured for operation in less hostile environments than underground coal mines, many components of the system could be produced at a much lower cost. Therefore, it is recommended that a number of units be produced for protection of workers in other industries such as coke ovens or paint spraying.

INTEGRATED HELMET/RESPIRATOR SYSTEM

During development and evaluation of respirator facepiece suspension concepts, it became quite apparent that significant advantages could be achieved by combining helmet and respirator suspension systems in a single unit. This is particularly true for this facepiece because of its size and weight and the requirement for frequent donning and doffing. An integrated helmet/respirator suspension system could be developed which would permit very simple donning and doffing. This would, in turn, reduce the requirement for the facial access port on the existing facepiece and reduce its cost, weight and complexity quite dramatically.

The fundamental advantage of such concepts is that both helmet and respirator suspension would be improved. Better protection performance and comfort would be achieved for both devices. The primary drawbacks to integration of helmet and respirator suspensions is the wide variety of helmets and helmet suspensions in current use. While retrofit modifications might be possible, it seems most reasonable at this time to develop a fully integrated system unencumbered by existing concepts. This is especially true when considering the potential improvements in helmet design proposed by Mangelsdorf (1972).

FACIAL TOPOGRAPHY

Current anthropometric data summarized by McConville (1973) and new anthropometric data by Hack (1973) were utilized in designing the facepiece for the prototype supplied-air respirator system. These data were utilized mainly to select and evaluate members of a subject testpanel which was used to aid in design and evaluation of candidate mask contours.

A different approach would be recommended for future facepiece design. The type of information desired for facepiece design is a set of actual three-dimensional topographic "maps" of a variety of faces. It is possible to produce a series of representative facial contours which represent the range of population facial topographies much like Sheldon's somatotypes representing various bodily dimensions.

One method for producing these contours would be the use of stereo-photogrammetry and computer analysis. The net result of such a program would be a series of fifteen to twenty, or more, faceforms. These rigid three-dimensional faceforms would substitute in part for the human subject test panel used in this program and would produce mask contour designs more likely to fit the entire population.

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PART FOUR

APPENDICES

Appendix I

COAL MINE DUST CONCENTRATIONS

A number of sources were reviewed for data pertaining to coal mine dust concentrations within which the supplied-air respirator system must operate. The purpose of this survey was to ascertain the requirements of a typical "worst case". In other words, since the unit must operate satisfactorily in most any underground mine it was desired to determine the highest dust concentrations which might be encountered in routine operation.

Since methods of measurement of the respirable dust content of atmospheres vary among the devices used there is poor consistency from one data source to another. Within a given atmosphere, measures of the respirable dust concentrations, by different devices, vary by as much as a factor of two, or more. Furthermore, the total airborne dust concentration might be from 10 to 20 times the measured respirable dust concentration. In this appendix, all measurements are converted to measures which would be made with the "personal sampler" by dividing measures made with the British Mines Research Establishment (MRE) instrument by a factor of 1.88, as suggested by Doyle (1970). A more precise comparison of the operation of various sampling devices is provided by Tomb, et al (1973).

TRENDS IN RESPIRABLE DUST CONCENTRATION

As might be expected, recent legislation and awareness of health hazards have resulted in better engineering dust control methods. Comparison of samples from the same 29 mines taken in 1968 and 1972, shown in tables I-1 and I-2, exhibit a marked decrease in respirable dust concentration for all job descriptions listed. The data in table I-1 are single shift averages; the data in table I-2 are the means of a number of single-shift averages. Jacobson's data, table I-2, was based on the MRE instrument and, accordingly, was divided by 1.88 for presentation here.

DUST EXPOSURE BY JOB DESCRIPTION

Based on data, reported by Jacobson (1971), collected over a one-year period ending June 1971, it is possible to list the mining jobs for which the dust exposure hazard is most severe. The thirteen occupations for which the dust concentration (MRE equivalent) were greater than two are:

Continuous miner operator,
Cutting machine operator,
Laborer,
Roof bolter helper,
Coal drill operator,
Loading machine operator,
Roof bolter operator,
Cutting machine helper,
Continuous miner helper,
Shot firer,
Rock duster,
Timberman,
Conveyor operator, beltman.

Table I-1. DUST EXPOSURE BY JOB TITLE, 1968 SURVEY OF 29 MINES (Doyle, 1970)

JOB TITLE	RESPIRABLE DUST CONCENTRATION RANGE (mg/m^3)	MEAN (mg/m^3)
Continuous Miner Operator	0.02 - 21.44	4.08
Continuous Miner Helper	0.44 - 18.90	3.47
Cutting Machine Operator	0.71 - 15.42	3.69
Cutting Machine Helper	0.77 - 14.70	4.45

Note: Values are average concentrations for a single shift.

Table I-2. DUST EXPOSURE BY JOB TITLE, 1972 SURVEY OF 29 MINES (Jacobson, 1972)

JOB TITLE	RESPIRABLE DUST CONCENTRATION
Continuous Miner Operator	1.38
Continuous Miner Helper	1.17
Undercutter Operator	1.17
Shuttle Car Operator	0.80
Timberman	0.90
Roof Bolter	1.01

Note: Values are average concentrations for an average shift.

TOTAL DUST CONCENTRATION

Samples obtained by Doyle (1970) indicate that total airborne dust concentrations in the area of a cutting machine averaged 63 mg/m^3 and, for a continuous miner, averaged 128 mg/m^3. Corresponding respirable dust samples were 3.02 and 5.25 mg/m^3 when measured with the personal sampler. The ratio of total airborne dust to respirable dust was 20.9 and 24.4 for the two machines, respectively. Based on MRE instrument samples, the ratios would be approximately half of these values (ie. 10 to 12).

WORST CASE ANALYSIS

The data given in Table I-2 and the last column of Table I-1 represent the mean of a number of single-shift samples taken with samplers operating for an entire shift, excluding the man-trips. As the data of the first column of Table I-1 indicates, there is a considerable variance in shift-to-shift average dust concentrations. Doyle's data (1970), Table I-1, shows a worst case of 21.44 mg/m^3. Total airborne dust concentrations would be approximately 20 times this value (ie. more than 400 mg/m^3).

A recent report, Tomb et al. (1973), supports the above data in more detail. Of 816 single-shift measurements performed simultaneously with five sampling devices, 41.9% of the readings made with the MRE instrument exhibited respirable dust concentrations in excess of 4 mg/m^3; 4.4% exhibited respirable dust concentrations in excess of 10 mg/m^3; some readings exceeded 20 mg/m^3. Of course, as the author explained, some fraction of these readings were erroneous for various reasons. However, it is safe to conclude that the supplied-air respirator system will frequently be required to function in atmospheres containing 100 mg/m^3 of airborne dust and, occasionally, in atmospheres containing upwards of 200 mg/m^3. For short periods, during cutting operations for example, it is reasonable to expect local concentrations in the range of 500 to 1000 mg/m^3.

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Appendix II

MINING MACHINE CHARACTERISTICS

Advertising literature and manufacturers' specifications were acquired and reviewed from a number of major producers of underground coal mining machines. A summary of some of the design factors presented in these sources is shown in table II-1. It is important to note that many machine purchases involve modifications of the basic configuration to the individual customer's requirements.

Data supplied to Synsis by Theodore Barry and Associates, Los Angeles, a management consulting firm, giving some indication of the market distribution of machines produced by various manufacturers, is shown in table II-2. These data are based upon survey responses received from approximately 900 mines in 1970.

Further insight was gained from a field trip, to the Beckley, W VA area, to witness underground operations in several mines and discuss the feasibility of supplied-air respirator installation and use. Additionally, a number of manufacturers and retail sales and maintenance service organizations were contacted. In summary, several factors of importance emerged:

1) Since more than 30% of U.S. coal mines have seam heights of 48 inches, or less (Synsis, 1972), it is necessary that the supplied-air respirator not increase vehicle vertical clearance requirements.

2) Installation of the unit would be facilitated if it were modular; modules could be located within the machine envelope in the limited number of small spaces available, in most cases.

3) Great care must be exercised that the respirator umbilical not prevent emergency egress from the machine, or present a hazard due to entanglement with the massive rotating components of the machines.

4) Installation of electrical apparatus in the field requires acquisition of Bureau of Mines approval and can be burdensome.

5) Many machines now in use have been modified extensively thereby making respirator system installation a matter of individual custom installation for each machine.

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Table II-1. UNDERGROUND MINING EQUIPMENT DESIGN FACTORS

MANUFACTURER	POWER SOURCE	AUXILLARY POWER	OPERATOR POSITION	OPERATOR LOCATION	MACHINE DIMENSIONS (LXWXH) in.
MINE LOCOMOTIVES					
Jeffrey Mining Machine Co. # 50866	250 VDC Battery 37 KWH		Seated	Cab at end of Machine	168x58x57
# 50666	80 VDC Battery 37 KWH		Seated	Cab at end of Machine	144x54x26
# 50266	250 VDC Battery 126 KWH		Seated	Cab at end of Machine	252x79x55
# 6606D	Electric Trolley	32V	Seated	Cab at end of Machine	440x90x79
# 7056F	Cable Electric		Seated	Cab at end of Machine	224x78x38
ROTARY ROOF DRILL					
Acme Machine Co. Model D-1	AC DC		Standing Kneeling	By Side of Machine	113x53x27
Acme Machine Co. Model D-2	AC DC		Standing Kneeling	By Side of Machine	144x66x32
Acme Machine Co. Model D-3	440,550 VAC,250 VDC		Standing Kneeling	By Side of Machine	157x69x27
Acme Machine Co. Model SPHRD-1			Standing Kneeling	By Side of Machine	113x53x27
CONTINUOUS MINER					
Joy Mfg. Co. 10 CM-2A	440,500 VAC 60	Hydraulic; 25 HP Electric Take off	Standing Sitting	Forward Facing Seat in Rear	384x120x54

Table II-1 (continued)

MANUFACTURER	POWER SOURCE	AUXILLARY POWER SOURCE	OPERATOR POSITION	OPERATOR LOCATION	MACHINE DIMENSIONS (LXWXH) in.
CONTINUOUS MINER (contd)					
Joy Mfg. Co.	440,550 VAC,60	Hydraulic; 25 hp Electric Take-off	Standing Sitting	Forward Facing Seat in Rear	485x130x
Jeffrey Min. Mach. Type 100-M	440Vac, 250VDC	Hydraulic	Standing	Side of Machine Near Center	198x105x30
Jeffrey Min.Mach. Type 100-L	440VAC	Hydraulic	Standing	Side of Machine Near Center	200x100x 20-1/2
Jeffrey Min.Mach. Type 120 Heliminer	440,550, 1000 VAC	Hydraulic	Sitting	Seat in Rear Facing Forward	396x100x37
LOADERS					
Joy Mfg. Co. Model 11A (14Bu10-41A)	440VAC 50,60 DC	Hydraulic	Standing Sitting etc.	Optional Side Seat off Machine	340x105.5 x24
Joy Mfg. Co. Model 11B (14Bu10-41B)	250 VDC: AC	Hydraulic	Standing Sitting etc.	Optional Side Seat	326x94.5x 33
Joy Mfg. Co. Model 11C (14BU10-41C)	250 VDC; AC	Hydraulic	Sitting Standing etc.	Optional Side Seat	33,5x105x 40.
Wabco Model 968	460,575, 995 VAC 60 3 250,500 VDC	Hydraulic	Standing Sitting	Optional Side Seat	290x96x33
Wabco Model 970	460,575 VAC 60 3 380, 440,500 550 VAC, 50 250,500 VDC	Hydraulic; 30 AMP Optional Electric Power Take-off	Standing Sitting etc		304x94x 30x38

Table II-1. (continued)

MANUFACTURER	POWER SOURCE	AUXILLARY POWER SOURCE	OPERATOR POSITION	OPERATOR LOCATION	MACHINE DIMENSIONS (LXWXH) in.
CONTINUOUS MINER (contd)					
Jeffrey Min. Mach. Co. Type 202-L	AC,DC		Standing Sitting	Side Seat	325x97x30
Jeffrey Min. Mach. Co. Type 203	AC,DC		Standing Sitting		330x108x46
SHUTTLE CARS					
Joy Mfg. Co. Model 1-SC-26	AC,DC		Sitting, Standing	2 Seats, Facing Forward & Rear on Side of Car	314x98x49
Joy Mfg. Co. Model 16SC-4	AC,DC		Sitting, Standing	2 Seats, Facing Forward & Rear on Side of Car	300x100x33
Joy Mfg. Co. Model 18SC-7	AC,DC		Sitting	2 Seats, Facing Forward & Rear on Side of Car	324x126x24
Joy Mfg. Co. Model 21SC	AC,DC		Sitting	2 Seats, Facing Forward & Rear on Side of Car	300x114x28
Wabco Haulmor	250 VDC	Hydraulic	Sitting	2 Seats, Facing For- & Rear, on Side of Car	318x110x36
Jeffery Min. Mach. Type 440,405,406	240 VDC Battery		Sitting	Single Seat Center of Cab Facing Sideways	367x117x47

Table II-1 (concluded)

MANUFACTURER	POWER SOURCES	AUXILLARY POWER SOURCES	OPERATOR POSITION	OPERATOR LOCATION	MACHINE DIMENSIONS (LXWXH)in.
<u>SHUTTLE CARS</u> (contd)					
Jeffrey Min. Mach.Type 404-HR2	240 VDC		Sitting	Single Seat, Center of Cab Facing Sideways	366x121x60
Galis Mfg.Co. Model 5 L			Sitting	2-Forward & Rear Facing Seats, Side of Car	288x118-3/4 x28-1/2
Acme Mach. Co. Model 'BUT'	96 VDC Battery 432 AMP HR		Sitting	2-Forward & Rear Facing Seats, Side of Car	204x91x 40-1/2
<u>UNIVERSAL CUTTER</u>					
WABCO Model 2500	AC	Hydraulic	Sitting Standing	2 Cabs on Sides	386x122 x34-1/2
Jeffrey Min. Mach. Type 300-UL,-UM, -UH	250VDC, 440,550 VAC, 60 3		Standing	Cab on Left Side of Machine	384x100x34
Joy Mfg. Co. 15 RU	AC,DC	Hydraulic	Sitting Standing	Cab on Side of Machine	300x104x36
Joy Mfg. Co. 16 RB-3	AC,DC	Hydraulic	Sitting Standing	Cab on Side of Machine	339x111x26
Joy Mfg. Co. 17 RU	AC,DC	Hydraulic	Sitting Standing	Cab on Side of Machine	348x120x39

Table II-2. APPROXIMATE PERCENTAGE OF MARKET FOR VARIOUS MINING MACHINES FOR SELECTED MANUFACTURERS

	TYPE OF MINING MACHINE				
MANUFACTURER	CONTINUOUS MINER	CUTTING MACHINE	LOADER	SHUTTLE CAR	ROOF BOLTER
ACME					13
FLETCHER					22
GALIS				1	41
JEFFREY	9	14	6	7	
JOY	24	66	80	67	6
LEE NORSE	54				
NATIONAL MINE SERVICE	2			11	
WABCO	3	10	7	5	
WILCOX	6				
OTHER	2	10	7	9	18

Appendix III

AIR FLOW RATE REQUIREMENTS

The determination of the maximal or "peak" flow rate required is one of the more important factors in respirator design; in this case, perhaps, one of the more interesting factors. Because coal mining is not self paced, but rather a continuing effort to keep up with equipment cycles, it often involves periods of near maximal energy expenditure. If the respirator system is to be acceptable to miners, it must provide the peak flows demanded with the smallest respiratory burden possible.

There are no experimental results available describing observed minute volumes and peak flow rates in actual underground coal mines. Therefore, it is necessary to estimate the work rates likely to be encountered and to further estimate the minute volume and peak flow rate requirements.

While a comprehensive review of the experimental evidence on the subject is not presented in this appendix, it is intended to provide sufficient evidence, in very general way, to justify the performance requirements set for the supplied-air respirator.

ENERGY EXPENDITURE RATES

In the only experimental data available, Passmore and Durnin (1955) summarized data, taken up to 1955, to illustrate that energy expenditure rates in mining may run as high as:

9.4 kcal/min for loaders,
6.8 kcal/min for shoveling,

and possibly up to 10 kcal/min for walking in the stooped position underground. While this data apparently describes measurements made on miners involved in manual operations, it is important to note that modern mining machine operators frequently dismount their machines and engage in periods of heavy work. This is due to the fact that the work is not self paced, but rather a constant effort to keep the machine-paced cycle from being interrupted. Consequently, it is reasonable to assume that values of energy expenditure classed as "strenuous" are sometimes encountered. Data presented in Consolazio (1963) indicates that so called "exhausting" work which can be kept up for only a few minutes produces energy expenditure rates higher than 15 kcal/min while the 10-12 kcal rate is classed as "strenuous" and can be kept up for 4 hours, on occasion. The 10-12 kcal/min rate produces an average minute volume on the order of 60 L/min according to their reference.

CORRESPONDING FLOW RATES

Oxygen consumption values, while depending on a number of factors, may be computed approximately by dividing the energy expenditure rate in kcal/minute by a factor of 5. Furthermore, minute volumes required by healthy subjects in good condition range from 20 to 30 times the oxygen consumption. For subjects with pulmonary dysfunction, the minute volume may be 40, or more, times the oxygen consumption. If one is willing to accept these assertions and set the "worst case" energy expenditure rate at 12 kcal/minute, oxygen consumption would be 2.4 liters/minute and the minute volume would be 2.4 X 30, or 72 L/min, or 2.54 SCFM.

The determination of peak flows from minute volumes is a complex task subject to many variables. A review of this process by Goldberg et al. (1965) indicates that the equation

Peak Flow Rate = 3.1 X MV + 16 L/min

is a suitable relation; it correlated well with Silverman's (1945) measures. Applying this equation produces a peak flow rate of 239 L/min, or 8.45 SCFM. Based on experimental results by Silverman (1945) it is reasonable to assume that the variance among subjects could account for an additional 25 L/min, bringing the estimate of a nominal "worst case" to 264 L/min, or 9.3 SCFM.

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Goldberg, M. N., Kendall, J. I., Santschi, W. R., Individual Respiratory Protection Against Chemical and Biological Agents, Second Quarterly Progress Report, Contract DA 18-035-AM)-286 (A), Chemical Research and Development Laboratories, Edgewood Arsenal, MD, 1965.

Silverman, L. Lee, G. Plotkin, T. Amory, L. Yancey, A. R. Fundamental Factors in the Design of Protective Respiratory Equipment, Inspiratory and Expiratory Air Flow Measurements on Human Subjects With and Without Resistance at Several Work Rates, Report O.S.R.D. 5732, National Defense Research Committee, August 1, 1945.

Appendix IV

CYCLONE SEPARATOR TESTS

Cyclone separation depends upon the application of large centrifugal forces to remove particulates from an air stream and is used extensively in large-scale commercial gas cleaning equipment. In its simplest form, a centrifugal collector consists of a cylindrical casing with a tangential inlet, a separating chamber, and central outlet pipe, as shown in figure 4-12. Inside the separation chamber, the gas flows in spiral paths (vortex flow) with increasing velocity from outside to center. The centrifugal acceleration can range from several hundred to several thousand 'g's. Thus, even exceedingly small particles are unable to follow the gas flow lines and are forced out of the curved paths and against the separator wall. Once the particles are against the wall, they migrate down to a collection chamber at the bottom of the casing.

There are essentially two parameters of performance which are important in cyclone design. The first is d_{50}, or the particle size (equivalent aerodynamic diameter) for which the collection efficiency is 50%. For particles larger in size than d_{50}, collection efficiency approaches 100%; conversely, for particles smaller than d_{50}, collection efficiency approaches zero. The other parameter is Δp, the pressure drop of the air stream thru the cyclone. The terminology used in the remainder of this section is given in table IV-1.

DESIGN

Equation IV-3 (Ref. 4) below was used to predict the d_{50} performance of the cyclone separators of interest in this program.

$$d_{50} = \frac{3}{V_i \alpha}\left[\frac{Q \mu R_e}{2\pi(\rho_c - \rho_a)(L-\ell)R_c}\right]^{1/2} \qquad \text{(IV-1)}$$

Equation IV-2 (Ref. 1, 3, & 4) gives the expected pressure drop.

$$\Delta p = \frac{\rho_a}{g}\left[V_i^2\left\{0.5 + \alpha^2\left(\frac{2(R_c - R_i)}{R_e} - 1\right)\right\} + V_e^2\right] \qquad \text{(IV-2)}$$

The velocity loss factor (in equation IV-1) was not found to be a governing factor in design, but it was calculated (according to Ref. 4) using equation IV-3 below.

$$\alpha = \frac{-\left(\frac{R_E}{(2)(R_C - R_I)}\right)^{1/2} + \left(\frac{R_E}{(2)(R_C - R_I)} + \frac{2GA_S}{A_I}\right)^{1/2}}{2GA_S/A_I} \qquad \text{(IV-3)}$$

The term A_s, the total "wetted" area of the cyclone interior is calculated in equation IV-4.

Table IV-1. SYMBOLOGY

SYMBOL	UNITS	DEFINITION
Q	ft^3/sec	Volumetric flow rate
μ	lb /ft-sec	Absolute viscosity of air
R_e	ft	Exit pipe inside radius
R_c	ft	Maximum cyclone radius (at top)
R_i	ft	Inlet pipe inside radius
L	ft	Length of cyclone
ℓ	ft	Length of exit tube (inside cyclone)
ρ_c	lb/ft^3	Density of coal (dust)
ρ_a	lb/ft^3	Density of air
V_i	ft/sec	Inlet gas velocity
V_e	ft/sec	Exit gas velocity
g	ft/sec^2	Acceleration of gravity
a	(non-dim.)	Velocity loss factor
Δp	lb/ft^2	Pressure drop across cyclone
G	(non-dim.)	Friction factor
A_1	ft^2	Cross-sectional area of inlet tube
A_s	ft^2	Total surface area of cyclone interior
d_{50}	microns	Particle size for which collection efficiency is 50%

$$A_S = (\pi R_c)\left\{R_c^2 + (L-2R_c)^2\right\}^{1/2} + (2R_c)(R_c) + (\pi)(R_c^2 - R_E^2) + 2\pi R_c R_E \quad \text{(IV-4)}$$

According to Rietma (Ref. 2) "optimum" cyclone performance is achieved by a design with the following proportions:

$$L = 10R$$
$$R_I = .28R_c$$
$$R_E = .34R_c$$

Table IV-2. PRESSURE DROP VS. FLOW FOR THE PRIMARY CYCLONE WHILE SUPPLIED BY THE GAST COMPRESSOR.

Cyclone Inlet Pressure (psig)	Air Flow (SCFM)	Measured Pressure Drop across Cyclone	Predicted Pressure Drop Across Cyclone
20.0	4.00	3.1	1.72
27.0	3.87	2.6	1.34
35.0	3.77	2.2	1.07
45.7	3.57	1.8	0.79
55.5	3.33	1.5	0.59
67.5	3.11	1.2	0.44
80.7	2.86	0.8	0.32

It was found in our design analysis, however, that a considerable divergence from these values had relatively small adverse affects on the performance. Since our design goals included a desired value for d_{50} with the smallest possible Δp and smallest possible physical size for the unit, we departed from the optimal dimensions by shortening the tube length and enlarging the inlet and outlet ports.

Two different designs were developed for this project. The first was an inlet cyclone to remove the bulk of the airborne particulate matter before it enters the compressor. The second was the primary cyclone which was intended to remove nearly all the dust larger than 1 micron in size.

The inlet cyclone had the following dimensions:

$$R_I = 0.4375 \text{ inches}$$
$$R_E = 0.412 \text{ inches}$$
$$R_C = 1.250 \text{ inches}$$
$$L = 5.125 \text{ inches}$$

Its performance is shown in figure IV-1. A photograph is given in figure 5-9. The primary cyclone had the following dimensions:

$$R_I = 0.09675 \text{ inches}$$
$$R_E = 0.1345 \text{ inches}$$
$$R_C = 0.400 \text{ inches}$$
$$L = 3.0 \text{ inches}$$

a photograph (figures 5-8 and 5-10) are presented in Section V. Table IV-2 is a list of pressure drop characteristics for operation with a Gast 5HCD compressor (the electric version of the compressor used in the respirator system). Since the performance of a cyclone separator is highly dependent upon air velocity and the primary cyclone is downstream of the compressor makes it sensitive to system pressure. Its performance at two system pressures is shown in figure IV-2.

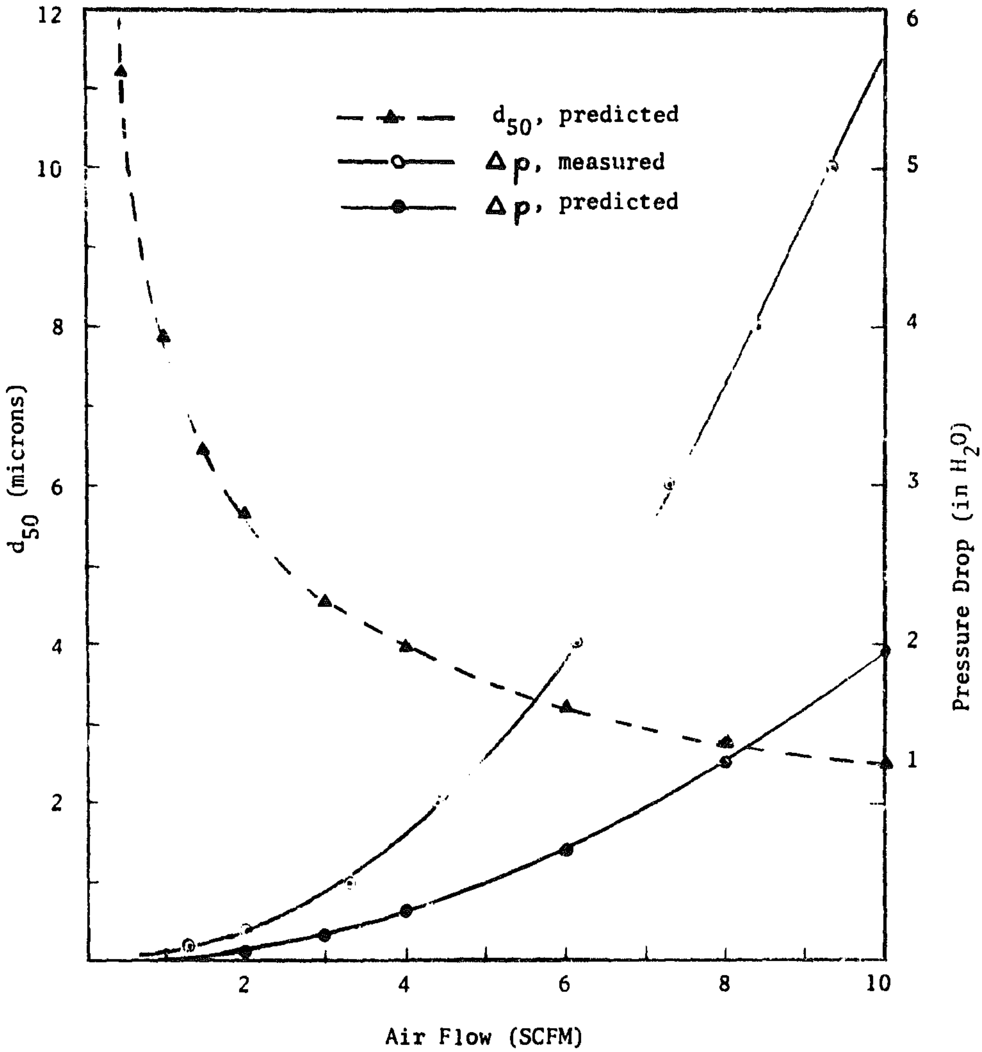

Figure IV-1. Collection Efficiency (d_{50}) and Pressure Drop vs. Flow Characteristics of the Inlet Cyclone.

Tests of dust collection efficiency were conducted by an independent testing laboratory (Donaldson Co., Minneapolis, Minnesota). The important criteria of dust collection performance are gravimetric efficiency and fractional efficiency. Gravimetric efficiency is the percent by weight of the dust entering a cyclone which is collected or separated out of the main air flow. It is comparatively simple to determine, but relatively meaningless in that it is highly dependent upon the test conditions and the particle size distribution of the test dust. Fractional efficiency of collection is the fraction of dust collected of any particular aerodynamic diameter. Knowing that and the dust concentration versus size for the ambient air

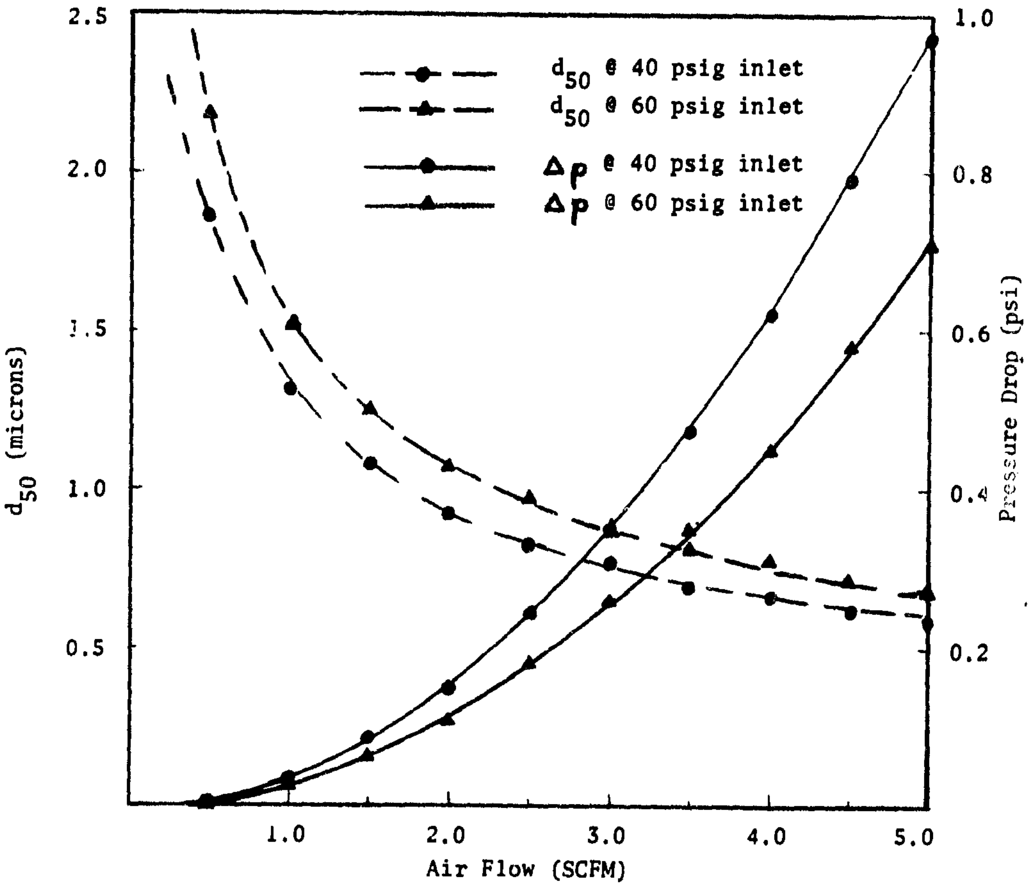

Figure IV-2. Collection Efficiency (d_{50}) and Pressure Drop vs. Flow Characteristics for the Primary Cyclone at Two System Pressures.

allows a calculation of the dust load that will be passed downstream to the final filter. However, the fractional efficiency can only be determined empirically.

The conditions of the test are given in table IV-3. Although the cyclone was designed to operate with air at 40 psig to 70 psig, the test was conducted with the air flow at atmospheric pressure. This was done because the apparatus for testing at high pressure was not available. To create equivalent conditions to the high pressure situation, it was only necessary to alter two input variables. One was the air flow which was reduced to allow an inlet tube air velocity of 35 feet per second, approximately that which will be realized during actual use. The other was the dust concentration which was increased to simulate the concentration increase that will occur in the compressor. The results of the test are shown in figure 5-7 and in table IV-4.

Table IV-3. TEST CONDITIONS FOR DETERMINING FRACTIONAL EFFICIENCY OF THE PRIMARY CYCLONE SEPARATOR.

RUN	AIR FLOW (SCFM)	PRESSURE	TOTAL QUANTITY OF COAL DUST FED (grams)	COAL DUST SIZE RANGE (microns)	COAL DUST CONCENTRATION (mg/m^3)
1	0.5	Ambient	0.135	0-10	940
2	0.5	Ambient	0.426	0-10	940

Table IV-4. COLLECTION EFFICIENCY OF CYCLONE PROTOTYPE

	Run #1	Run #2	Prediction
Total dust collected (grams)	0.130	0.411	--
Total dust penetrated (grams)	0.005	0.015	--
Gravimetric collection efficiency (%)	96.3	96.47	--
d_{50} (microns)	0.505	0.402	0.73

REFERENCES

1. Bradley, D., A Theoretical Study of the Hydraulic Cyclone, The Industrial Chemist, Sept., 1958, pp 473 - 479.

2. Rietma, K. and Verver, C. G., eds., Cyclones In Industry, Amsterdam, Elsevier, 1961.

3. Stairmand, C. J., Pressure Drop in Cyclone Separators, Engineering, Oct. 21, 1949, pp 409 - 412.

4. Strauss, W., Industrial Gas Cleaning, Chap. 6, Oxford, Pergamon Press, 1966.

Appendix V

PIPE FLOW RESISTANCE

In order to improve miner acceptance and, thus, promote utilization of the supplied-air respirator system, it is desirable to select the smallest diameter umbilical hose possible. In doing so, it is necessary to establish the relationship between flow resistance, hose length and diameter, and system operation pressure.

Two commonly used pipe flow resistance equations, The Darcy-Weisback equation (Baumeister, 1967),

$$h_f = f \frac{LV^2}{d2g} \tag{1}$$

and an equation given by the Compressed Air and Gas Institute (1954),

$$h_f = 0.125 \frac{LQ^2}{rd^{5.31}} \tag{2}$$

were not found to correlate well with experimental results in the range of flow rate and pressures important in this particular design application.

For this reason a theoretical analysis was conducted in more detail. This analysis was oriented toward finding the upper limits of flow rate through a given diameter hose and toward finding an equation which could reliably predict pressure drop in any length and diameter hose desired for use in this program.

LIMITS TO FLOW RATE

Gas flow through a pipe is commonly analyzed as either adiabatic (zero heat flow) or isothermal (zero change in temperature). In reality, the flow is more nearly adiabatic for short pipes and high flow velocities, and isothermal for longer pipes and slower flow velocities, with many applications falling between the two theoretical cases. The basic matter of limits applies to either case. Adiabatic flow within any uniform pipe (constant area) is either entirely subsonic ($M<1$) or entirely supersonic ($M>1$). The exception being at the exit which may be sonic ($M = 1$) at the limit. The speed of sound is given by:

$$c = \sqrt{gkRT} \tag{3}$$

In air at normal pressure

$$c = 49.02\sqrt{T} \quad \text{ft/sec} \tag{4}$$

The Mach number M is defined by

$$M = \frac{V}{c} \tag{5}$$

Symbols are given in table V-1.

Table V-1. SYMBOLS

c = speed of sound in air, ft/sec
d = pipe diameter, ft
f = friction factor, experimental
g = gravimetric constant, 32.2 $\frac{lb_m}{lb_f}\frac{ft}{sec^2}$
h_f = head loss, feet of air
k = the ratio of specific heats, 1.4 for air
L = length of pipe, ft
M = Mach number
Q = the volumetric flow rate, SCFM
r = the inlet pressure to outlet pressure ratio
R = the gas constant, 53.3 $\frac{lb_f}{lb_m}\frac{ft}{^oR}$, for air
T = temperature of the gas, ^oR
V = velocity, ft/sec
W = mass flow rate, lb_m/sec,
ρ = density of air, lb_m/ft^3,

In isothermal flow in pipes, the previous limits are slightly lower. For subsonic flow the maximum velocity that can be attained is (Shapiro, 1958)

$$M_{max} = \sqrt{\frac{1}{k}} = 0.845, \text{ or} \qquad (6)$$

$$V_{max} = 0.845\ c$$

Since it is unlikely that this project will include a device to accelerate air to supersonic velocities prior to entry to a pipe, the maximum exit velocity may be set at 0.845c. Furthermore, for delivery of air to the miner, a long, small diameter hose is desired, which is best described by the isothermal condition. Assuming the hose exit to be at one atmosphere and a 70°F ambient temperature,

$$c = 1130 \text{ ft/sec.}$$

The maximum volumetric flow rate Q_{max} would, therefore, be

$$Q_{max} = 0.845\ cA = (954.85\ ft/sec)A \qquad (7)$$

thus, $$Q_{max} = 398\ d^2\ ft^3/min$$

where d is now the pipe diameter in inches. A plot of the maximum volumetric flow rate versus pipe diameter, for isothermal flow, is shown in figure 4-28. The minimum pipe diameter which can transport 10 cfm, no matter how short, has a diameter of 0.1757 inches (about 3/16-inch). In the case of adiabatic flow, the above limit is not valid since the temperature along the pipe, in subsonic flow, decreases resulting in a lower sonic velocity and an increased density.

In addition to the above limit on maximum exit velocities, there exists a limit on the ratio of length to diameter, L/d, versus the initial (entrance) Mach number for constant value of the friction factor f. These are shown in table V-2. This is not to be construed as a maximum length of pipe that can be used, but rather to show the decrease in entrance velocity with increasing length. In the case of supersonic velocities, however, in which pressure increases along the pipe in the direction of flow, the limit is a real upper bound on L/d.

Table V-2. MAXIMUM L/d RATIOS FOR AIR FLOW IN PIPES (ADIABATIC).

The Friction Factor is f = 0.0025. (after Shapiro, 1958)

Entrance Mach Number	.25	.50	.75	1	1.5	2	3
Maximum Ratio L/d	850	110	12	0	14	31	52

PIPE FLOW RESISTANCE

Since the conditions expected to prevail in the range of flow rate, pressure drop and pipe length, are expected to closely approximate the isothermal conditions, pipe flow pressure drop was calculated for the isothermal case. An easily reproducible dimensionless equation for isothermal pipe flow is produced by Shapiro (1958, page 102)

$$\frac{4fL}{d} = \frac{1 - \left(\frac{P_2}{P_1}\right)^2}{kM_1^2} - \ln\left(\frac{P_1}{P_2}\right)^2 \qquad (8)$$

Making the substitutions

$$V = \frac{W}{\rho A} \qquad (9)$$

and

$$c = \sqrt{gkRT} \qquad (10)$$

and employing the ideal gas law

$$P = \rho RT \qquad (11)$$

equation (8) can be rearranged to produce an expression for the mass flow rate of air through a pipe:

$$W^2 = \frac{g\pi^2 \; d^4 \; P_1{}^2\left[1 - \left(\frac{P_2}{P_1}\right)^2\right]}{16RT_1\left[\frac{4fL}{d} + \ln\left(\frac{P_1}{P_2}\right)^2\right]} \qquad (12)$$

Solutions for mass flow rate, W; volumetric flow rate at standard condition (ρ = 0.075 lb_m/ft^3) in SCFM and exit velocity (ft/sec) were obtained for a variety of pipe lengths and diameters, and inlet and exit pressures. Temperature was assumed constant (for isothermal flow) at 70°F or 530°R and the friction factor, f, was set at 0.01. Since an explicit solution was obtained only in mass flow rate, W, the equation was programmed for computer solution on an IBM System 360 computer using the PL/1 language.

The lengths and diameters for solutions produced were:

L = 1, 2, 4, 6, 10, 15, 20, 25, 30, 50, 100 and 300 feet;

and d = 0.125, 0.187, 0.250, 0.375, 0.500, 0.750, 1.00 and 1.250 inches.

Solutions for flow rate are presented in which the exit pressure, P_2, was one atmosphere (14.7 psia), 5 psig, 10 psig, and 50 psig. Inlet pressures (P_1) varied through:

P_1 = 0.05, 0.1, 0.2, 0.4, 0.6, 1.0, 2.0, 4.0, 6.0, 10.0,

15.0, 20.0, 30.0, and 50.0 psi

above the exit pressure. In this way, the pressure ranges covered conditions for continuous flow Type I systems, as well as those expected for Type II and Type III systems, in which a demand regulator is employed.

Samples of the output, in which computed inlet pressure required to produce varying flow rates for pipes of various lengths and diameters are shown in figures V-1 through V-5. In these figures, the exit pressure was held at one atmosphere.

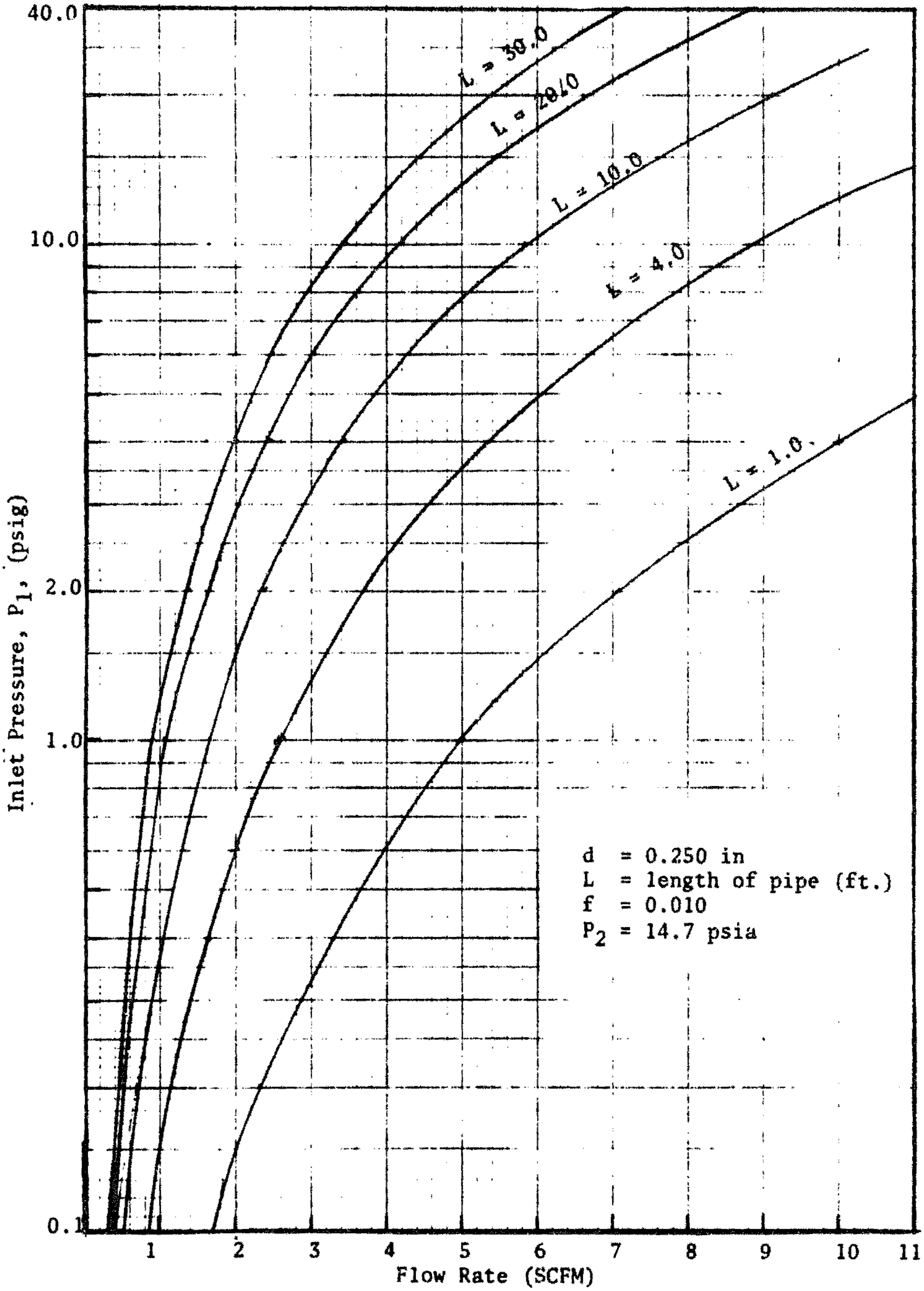

Figure V-1. Pressure Drop Versus Flow Rate for Pipes Having a Diameter of 0.250-inch and Various Lengths.

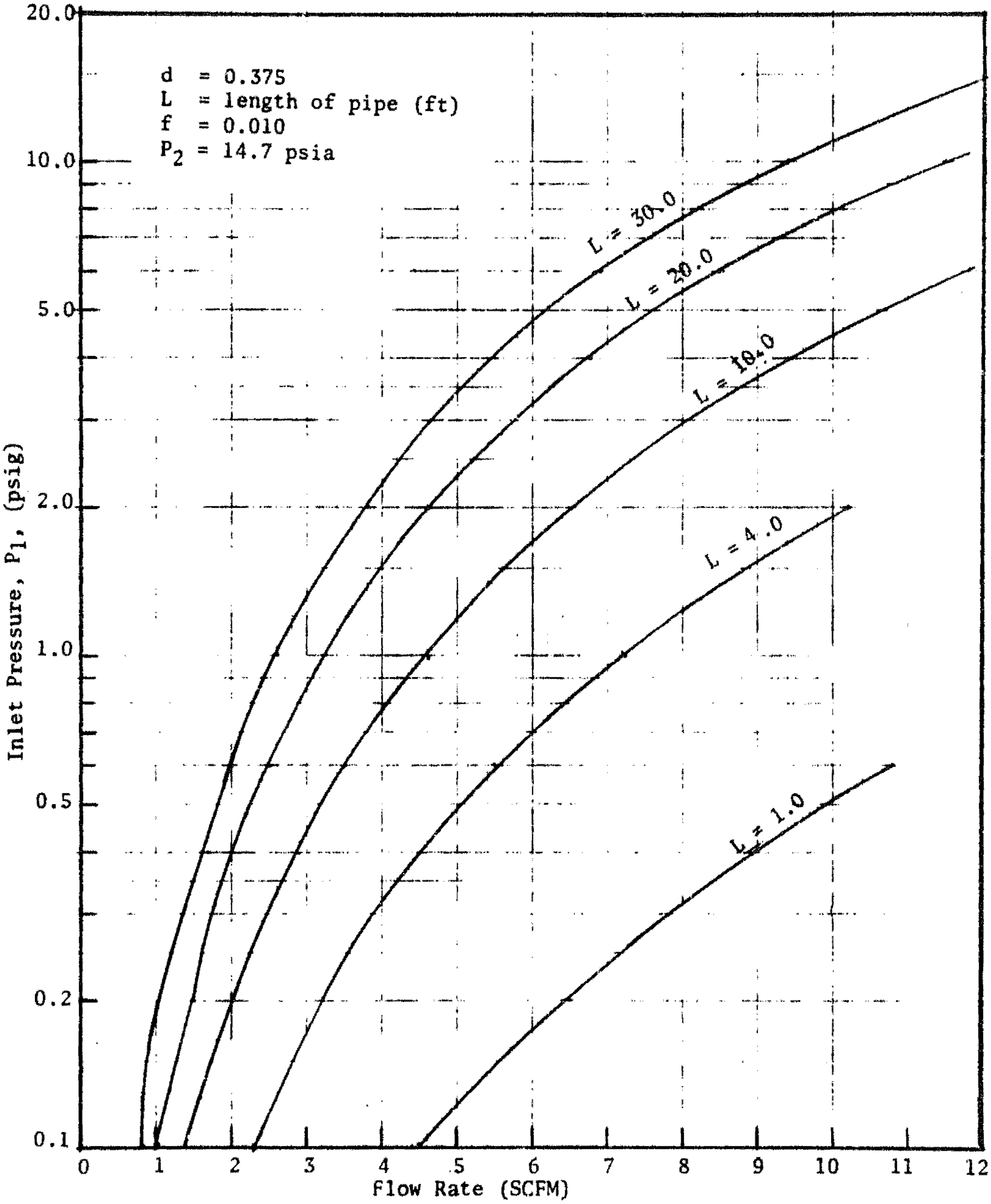

Figure V-2. Pressure Drop Versus Flow Rate for Pipes Having a Diameter of 0.375-inch and Various Lengths.

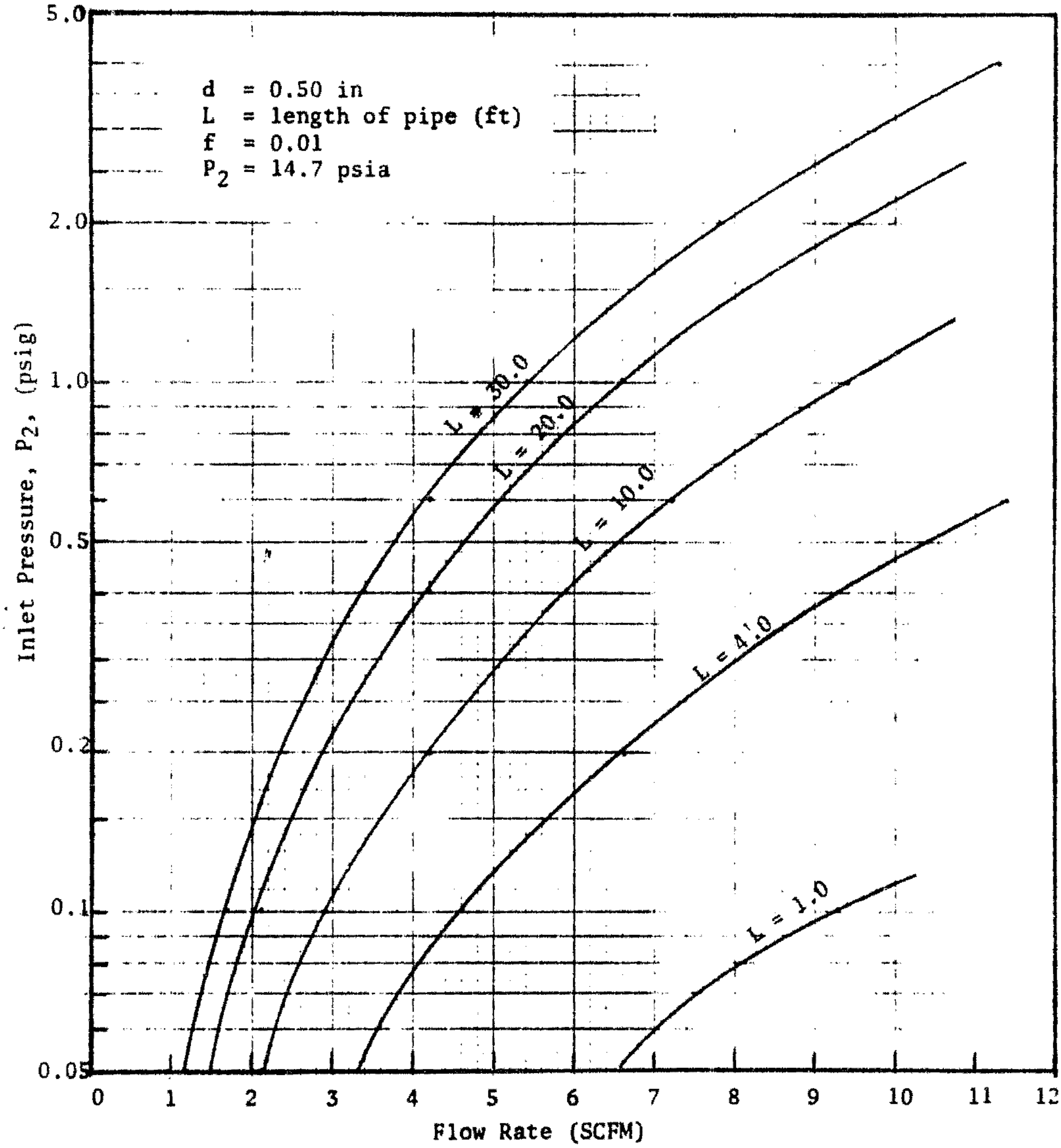

Figure V-3. Pressure Drop Versus Flow Rate for Pipes Having a Diameter of 0.500-inch and Various Lengths.

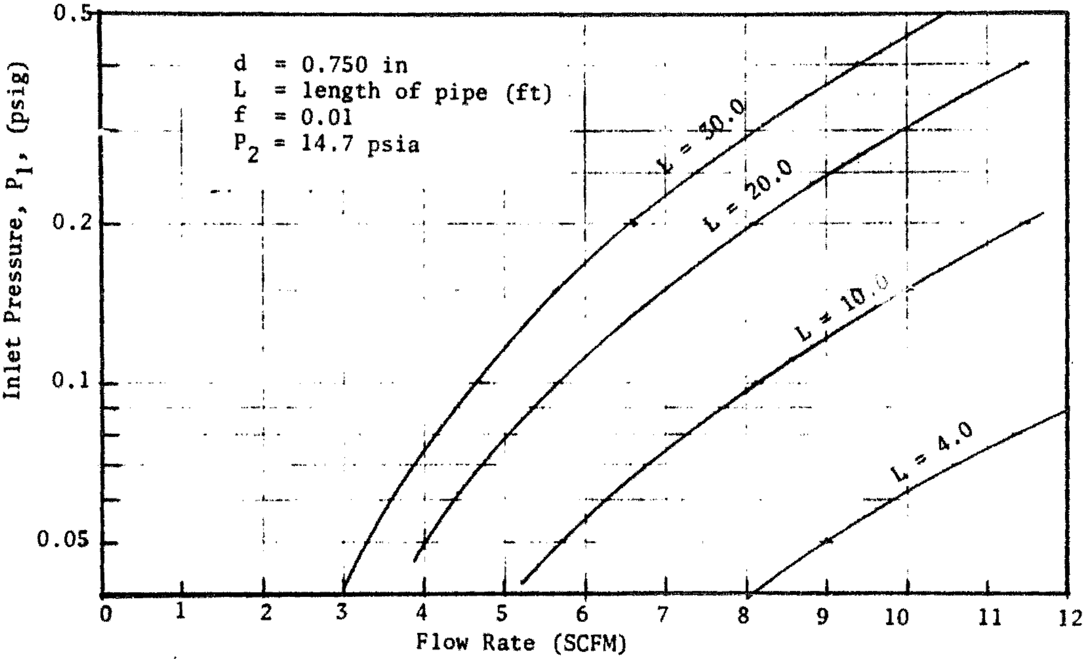

Figure V-4. Pressure Drop Versus Flow Rate for Pipe Having a Diameter of 0.750-inch and Various Lengths.

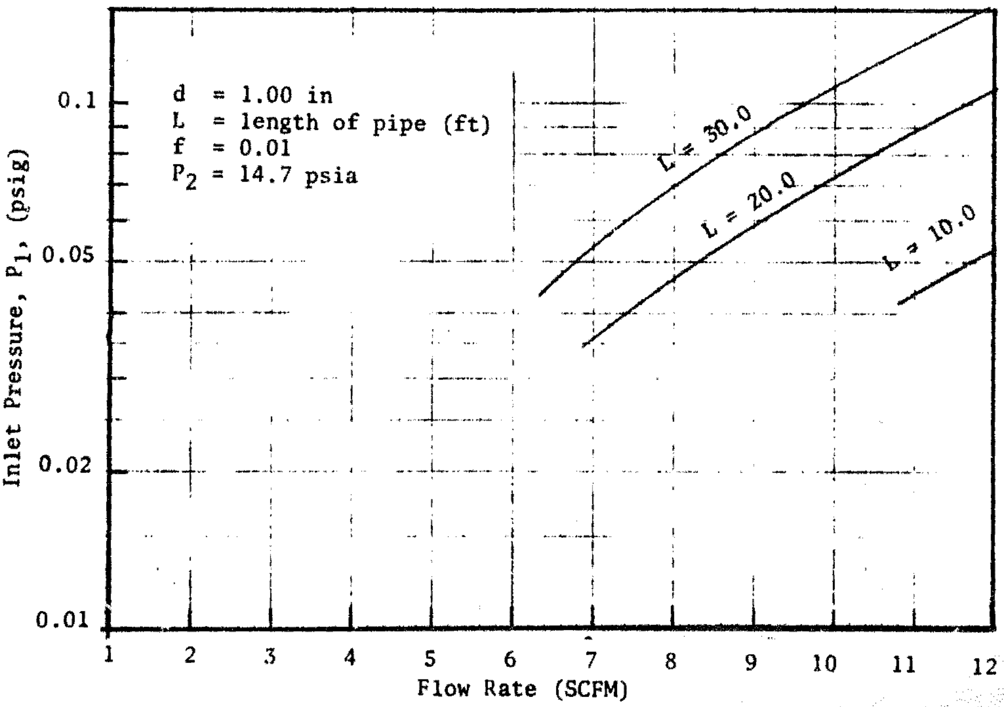

Figure V-5. Pressure Drop Versus Flow Rate for Pipe Having a One-Inch Diameter and Various Lengths.

LINEARITY

Equation (12) illustrates the fact that pressure drop is non-linear with pipe length when the inlet pressure is markedly different from the outlet pressure. The extent of this non-linearity is illustrated in figure 4-27, in which it is seen that the smaller diameter pipe exhibits the most marked non-linearity in the ranges of flow rate of interest. From this figure, one may deduce that the non-linearity occurs when the pressure drop along the pipe exceeds 2 or 3 psi. This may be explained as follows. Friction losses are proportional to velocity. When the pressure drop is significant, the velocity along the pipe increases in the direction of flow due to decreased pressure and resulting decreased density. Conversely, for a given exit velocity (ie. mass flow rate), with higher inlet pressures, the velocity at the entrance end of the pipe is lower than it would be for a smaller initial pressure. Therefore, the higher the inlet pressure, the lower the "average" pressure drop per foot of pipe.

EXIT PRESSURE EFFECTS

For a given mass flow rate, the average velocity can be decreased by increasing the exit pressure. The reduced velocity results in a lower pressure drop. This fact is illustrated in figure V-6 which gives pressure drop versus flow rate for one-quarter inch diameter pipe when the exit pressure, P_2, is 50 psig. The inlet pressure on the left margin of the figure is the difference between inlet and exit, pressures $P_1 - P_2$.

Pressure drop for a 30 ft long, one-quarter inch inside diameter pipe, when the exit pressure is 50 psig, is approximately 23 psi at a flow rate of 10 SCFM. For the same pipe, with its exit at one atmosphere, the pressure drop is 46 psi at the same flow rate. For shorter lengths of pipe, the difference in pressure drop is even more dramatic.

FRICTION FACTOR

As can be observed in equations (8) and (12), which describe pipe flow pressure losses, pipe length, L, and pipe friction, f, always appear together in the form 4fL/d. The diameter, d, appears elsewhere in the equation, but f and L appear only in this term. Therefore, in using the data presented herein for pipes having different friction factor from the one used here ($f = 0.01$), it is necessary only to adjust the length accordingly. For example, to find the pressure drop for a 10-foot pipe having a friction factor of $f = 0.02$, use the present charts for the 20-foot length.

EXPERIMENTAL VALIDATION

Before equation 12 and the tabulated results produced by using it can be used in system design trade studies, it is necessary to validate the relationship by laboratory experimentation. Towards that end, pressure drop measurements were conducted using one type of compressed air hose under one set of conditions; with the premise that, if the theory could be validated under one set of experimental conditions, the theory must also be correct under other, similar conditions.

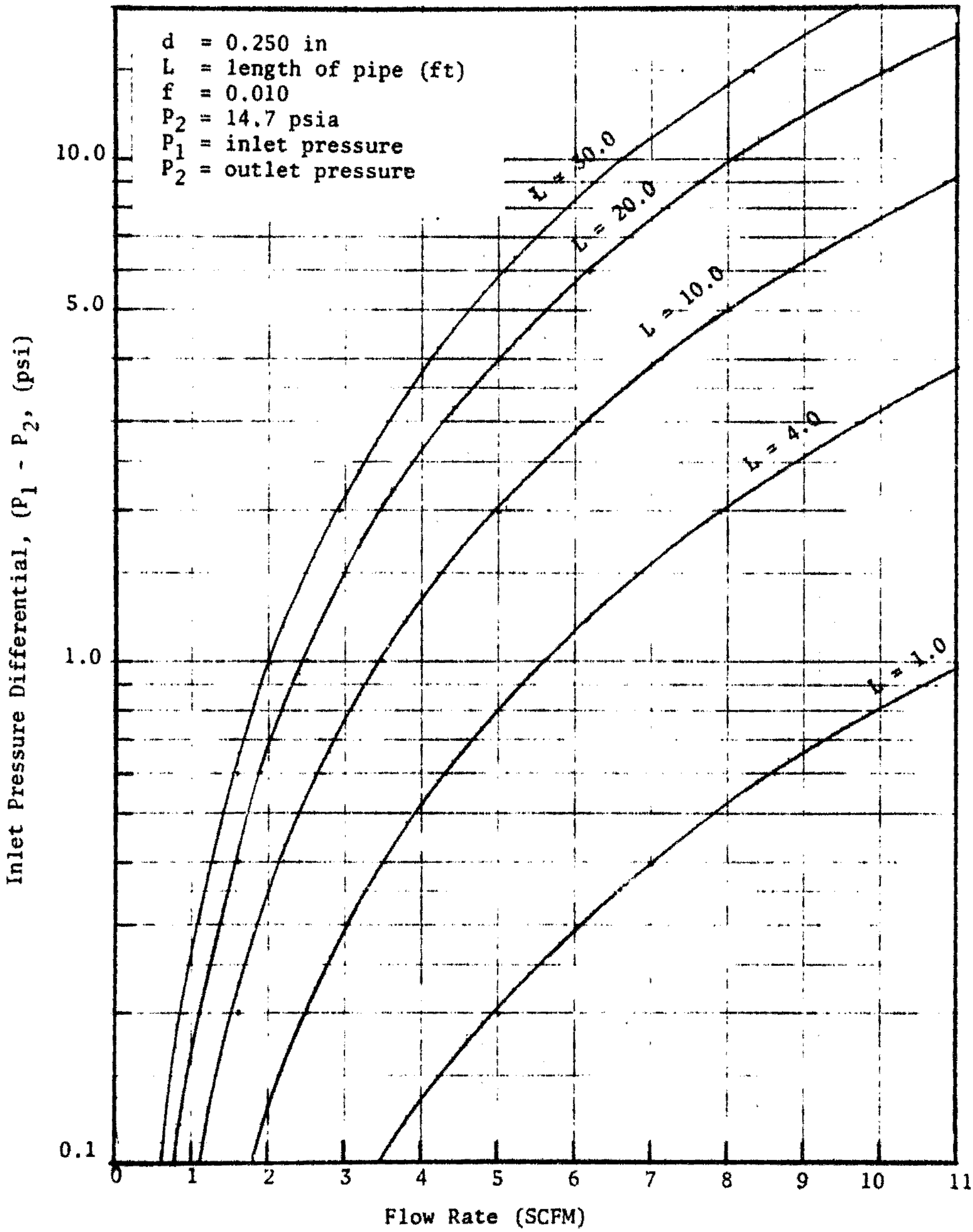

Figure V-6. Pressure Drop Versus Flow Rate for a 0.250-inch Diameter Pipe of Various Lengths when Outlet Pressure is 50 psig.

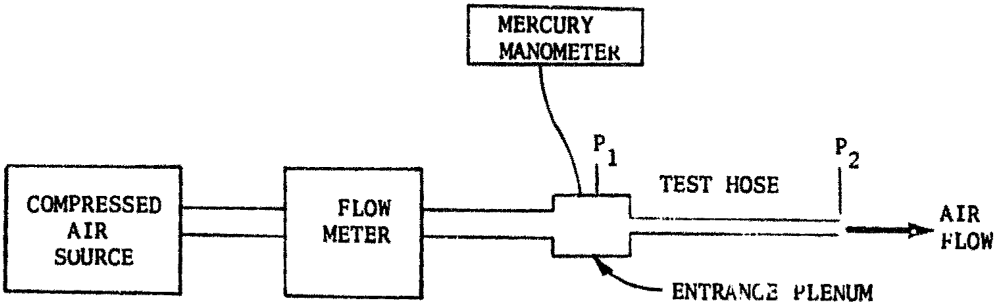

Figure V-7. Arrangement of Test Apparatus for Pipe Flow Pressure Drop Experiments.

The experimental test setup is shown in figure V-7. The following conditions were employed:

1. Type of Hose: Parker 'Push-Lok' 801-4

2. Hose Diameter: 1/4-inch I D

3. Hose Length (L): 4 ft., 10 ft., 20 ft.

4. Air Flow Rates: (SCFM) Q
   1.34
   2.79
   4.46
   5.61
   7.46
   8.53
   10.40
   14.25

5. Exit Pressure, $P_2 \approx 1$ atmosphere

Test runs were also conducted using standard male-thread 'Push-Lok' fittings. Since these fittings cause a restriction to flow in the form of a 3/16-inch ID 1-inch long tube, it was deemed desirable to determine how much of an increase in pressure loss would be caused by these fittings. Accordingly, test runs were conducted on the various lengths of hose using zero, one, and two hose fittings.

The results of these test runs were subjected to regression analysis to determine relations between the experimental results and the theoretical curves. For example, figure V-8 shows pressure drop as a function of flow rate for the different lengths of hose employed. The solid lines represent the theoretical curves derived from the computer analysis and the dashed lines represent regression curves derived from the experimental data. These curves are of the form:

$$P = XQ^N \qquad (13)$$

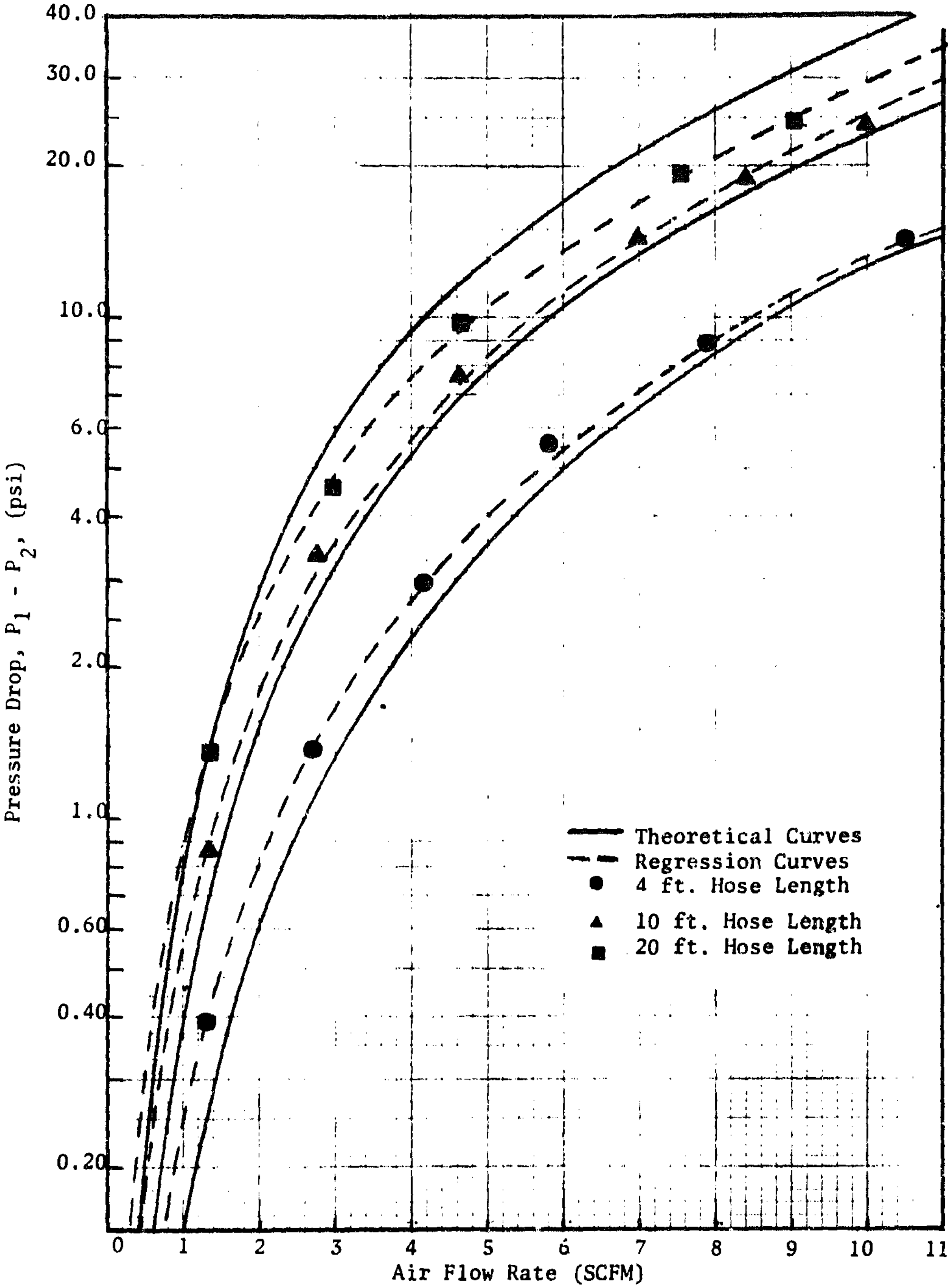

Figure V-8. Pipe Flow Pressure Drop for Various Lengths of 1/4-inch Hose. Solid Lines are from theoretical Computations.

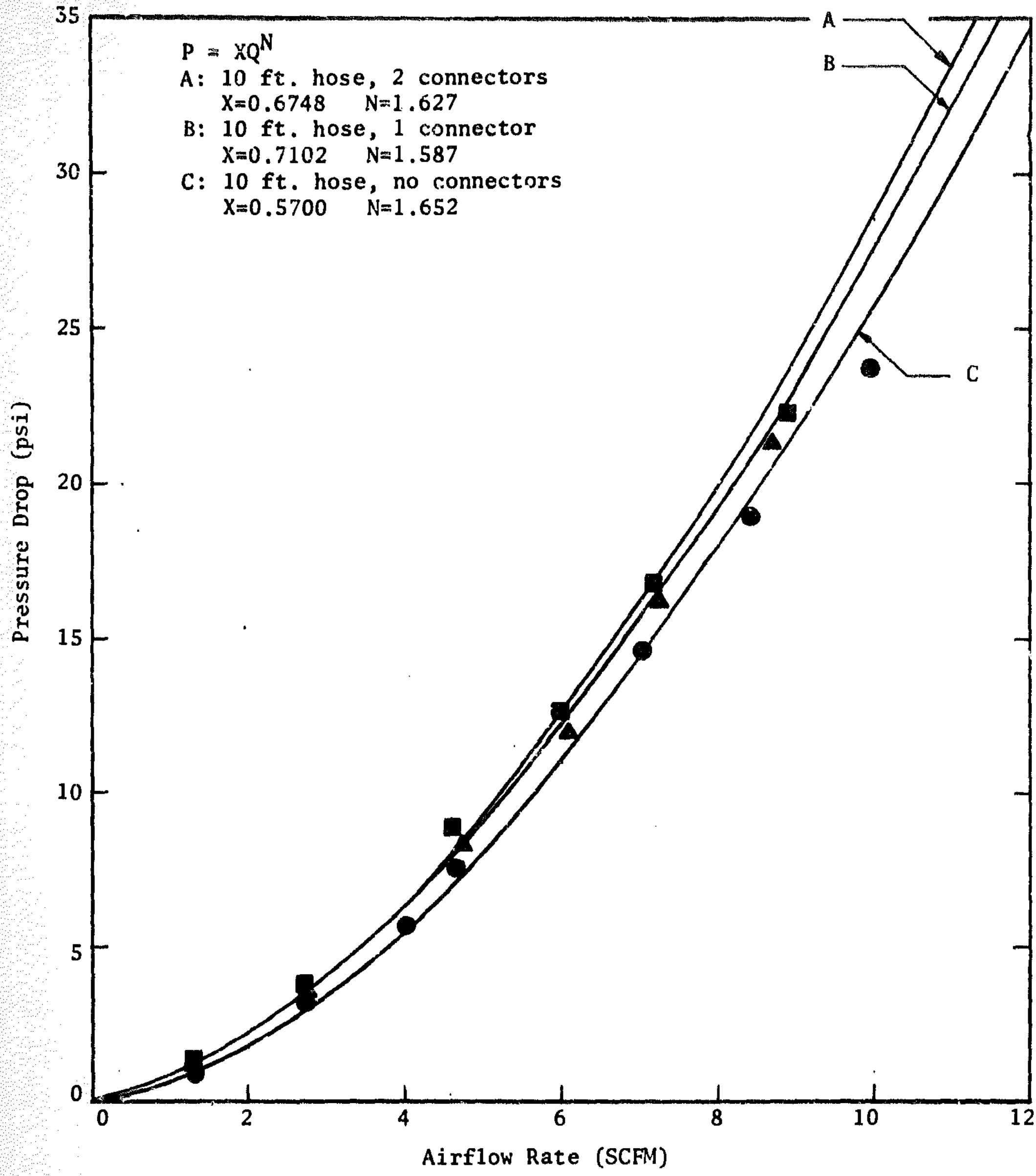

Figure V-9. Experimental Data Points and Associated Regression Curves Showing the Effect of Standard Hose Fittings on Pipe Flow Pressure Drop.

where P corresponds to pressure drop and Q to air flow rate. This form is suggested by theoretical considerations and produced by a least squares fit to the data on a desk top computer. An examination of figure V-8 reveals that the curves formed by the experimental data points have a shape similar to the theoretical curves. It is, therefore, possible to conclude that the theoretical expressions are generally applicable in the pressure and flow ranges of interest. It may also be concluded that the friction factor of 0.01, used in the computations, is close to the actual friction factor of the hose used in these experiments.

Figure V-9 shows the effects of placing the aforementioned hose connectors on a 10-foot length of test hose. Again, the solid lines represent regression curves of the form:

$$P = XQ^N$$

fitted to the experimentally measured data points. Examination of figure V-9 reveals that the increased pressure loss, due to this type of connector, is indeed significant. It also reveals that the increase in pressure drop, due to adding a second connector, is not as great as the increase due to the addition of the first connector.

REFERENCES

Baumeister, Theodore (Ed), Standard Handbook for Mechanical Engineers, McGraw-Hill Book Company, 1967.

Compressed Air and Gas Institute, Compressed Air Handbook, McGraw-Hill Book Company, 1954.

Shapiro, Ascher H., The Dynamics and Thermodynamics of Compressible Fluid Flow, Volume I, New York, N.Y., The Ronald Press, 1958.

Appendix VI

PROTOTYPE SYSTEM TEST DATA

Testing of the prototype system within a coal dust environment was accomplished by Wyle Laboratories. Their report on these performance tests are included in the following pages.

DATA SHELT REPORT

WYLE LABORATORIES

23 APRIL 1973

SYNSIS, INC.
1845 SAN FERNANDO ROAD
LOS ANGELES, CALIFORNIA 90065

ATTENTION: MR. F. A. STAWITCKE
TEST TITLE: OPERATIONAL EFFICIENCY
REFERENCES: Your Purchase Order No. 270
Wyle Laboratories Job No. 53473
Government Contract No. N.A.
Wyle Laboratories Report No. 53473

Gentlemen:

This is to certify that the enclosed Test Data Sheets contain true and correct data obtained in the performance of the test program as set forth in your purchase order.

Where applicable, instrumentation used in obtaining this data has been calibrated using standards which are traceable to the National Bureau of Standards.

Test Results:

ONE RESPIRATOR SYSTEM, SUPPLIED BY SYNSIS, INC., WAS SUBJECTED TO OPERATIONAL EFFICIENCY TESTS TO DETERMINE ITS ABILITY TO REMOVE COAL OUST FROM A CONTROLLED DUST ENVIRONMENT. ALL TESTS WERE PERFORMED IN ACCORDANCE WITH THE REFERENCED PURCHASE ORDER. THE RESULTS OBTAINED ARE PRESENTED ON THE ENCLOSED DATA SHEET FOR YOUR EVALUATION.

Enclosures: Data Sheets (1 Pages) ; EQUIPMENT LIST (1 PAGE)

STATE OF CALIFORNIA
COUNTY OF LOS ANGELES } ss.

C. D. YIAKAS, being duly sworn, deposes and says: That the information contained in this report is the result of complete and carefully conducted tests and is to the best of his knowledge true and correct in all respects.

SUBSCRIBED and sworn to before me this 23 day of APRIL, 19 73

OFFICIAL SEAL
William H. Vanderberg, Jr.
NOTARY PUBLIC-CALIFORNIA
PRINCIPAL OFFICE IN
LOS ANGELES COUNTY
My Commission Expires June 24, 1974

W-781

DEPARTMENT MECHANICAL SYSTEMS

TEST ENGINEER N. KIEFER

TEST WITNESS

NOT APPLICABLE
DCAS-QAR VERIFICATION

QUALITY CONTROL

WYLE LABORATORIES

DATA SHEET

Test Title: OPERATIONAL EFFICIENCY

Customer: SYNSIS, INC. | Job. No. 53473
Date Test Started: 4-11-73
Part No. N.A. | Date Test Completed: 4-12-73
S/N: N.A. | Amb. Temp: NOTED BELOW
Spec. CUST. P.O. Rev. | Photo: N.A.
Para. N.A. | Test Med. BITUMINOUS COAL DUST
Specimen Temp. AMBIENT

Specimen: RESPIRATOR SYSTEM

THE FOLLOWING TESTS WERE CONDUCTED IN AN ENCLOSURE 6' x 8' x 8' HIGH, WHICH WAS EQUIPPED WITH TEMPERATURE, HUMIDITY, AND DUST CONTROLS.

THREE (30) MINUTE TESTS WERE PERFORMED WITH HUMAN SUBJECTS WEARING THE RESPIRATOR MASK IN THE CONTROLLED ENVIRONMENT WHILE PERFORMING SIMULATED EXERCISES AND OPERATING A SIMULATED CONTROL PANEL. DURING THESE TESTS, A SAMPLING DEVICE WAS COUPLED TO THE MASK WHICH WITHDREW AIR AT A METERED RATE OF 0.25 SCFM. THE DUST CONCENTRATION WITHIN THE MASK WAS THEN GRAVIMETRICALLY DETERMINED FROM THE WITHDRAWN SAMPLES AS INDICATED IN THE FOLLOWING TABLE.

TEST No.	TEMPERATURE RANGE (°F)	HUMIDITY RANGE (% RH)	DUST CONCENTRATION (MG/CUBIC METER) MAX.	MIN.	AVG.	MASK DUST CONCENTRATION (MG/CUBIC METER)
1	+84 TO +89	85 - 90	85	66	78.5	0.3
2	+81 TO +88	81 - 85	55	50	51.6	0.1
3	+79 TO +86	87 - 91	100	58	78.3	0.5

A TEST WAS ALSO PERFORMED WITH THE RESPIRATOR MASK INSTALLED ON AN ANTHROPOMORPHIC HEAD WHICH WAS COUPLED TO A BREATHING MACHINE. THE SYSTEM WAS OPERATED FOR A CONTINUOUS EIGHT HOUR PERIOD WITH A CONTROLLED TEMPERATURE, HUMIDITY AND DUST ENVIRONMENT. DURING THE EIGHT HOUR TEST PERIOD, THE TEMPERATURE AND HUMIDITY CONDITIONS RANGED FROM +67 TO +85°F AND 80 TO 86%, RESPECTIVELY. DUST CONCENTRATION RANGED FROM 5.5 TO 48 MG/CUBIC METER WITH AN AVERAGE CONCENTRATION OF 17.3 MG/CUBIC METER, FROM 12 SAMPLES, TAKEN PERIODICALLY THROUGHOUT THE EXPOSURE DURATION. AT THE CONCLUSION OF THE EIGHT HOUR PERIOD, AND WITH THE DUST CONCENTRATION MAINTAINED, A SAMPLE OF AIR WAS WITHDRAWN FROM ONE OF THE MASK FEED LINES OVER A FIVE MINUTE PERIOD. THIS SAMPLE, WEIGHED TO AN ACCURACY OF 0.05 MILLIGRAMS, INDICATED NO DUST PARTICULATE PASSING THROUGH THE SYSTEM.

THE COAL DUST USED DURING THE PERFORMANCE OF ALL TESTING WAS SCREENED THROUGH A U.S. STANDARD SIEVE, NUMBER 230, WHICH HAD OPENINGS OF 63 MICRONS OR 0.0025 INCHES.

Tested By: H. Pierson
Specimen Meets Spec. Requirements. YES ☒ NO ☐
Witness ____ Date: ____
Sheet No. ____ of ____
Q. C. Form Approval ____ Approved [signature] Date: 4-24-73

SPECIMEN RESPIRATOR SYSTEM
CUSTOMER SYNSIS, INC.
PART NO. N.A.
S/N N.A.

JOB NO. 53473
DATE 4-11-73
TEST BY H. PIERSON
WITNESS

WYLE LABORATORIES

TEST: OPERATIONAL EFFICIENCY

EQUIPMENT	MANUFACTURER	MODEL NO.	RANGE	WYLE NO.	CALIBRATION LAST	CALIBRATION DUE	ACCY.
ANALYTICAL BALANCE	A. DAIGGER	41249	0 TO 50 GRAMS	6531	4-3-73	4-3-74	±0.1%
WEIGHTS	A. DAIGGER	CLASS "P"	2 TO 50 GRAMS	1513	4-3-73	4-3-74	±0.1%
ROTAMETER	FISCHER & PORTER	B5-27-10/77	0 TO 5 SCFM	7063	10-4-72	10-4-73	±1%FS
ROTAMETER	BROOKS	R-8M-25-2	0 TO 4.44 SCFM	1511	6-19-72	6-19-73	±1%FS
HYGROCON	PHYS-CHEMICAL RESEARCH	PCRC	0 TO 100%	31682	1-16-73	1-16-74	±2.5%
TEMPERATURE INDICATOR	DORIC	PS-300	-100 TO +1595°F	30497	3-1-73	9-2-73	±1°F