

RESEARCH LEADING TO THE DEVELOPMENT OF A CONTINUOUSLY WEARABLE SCBA

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ABSTRACT

Research leading to the development of a wearable escape unit for use by workers in case of toxic chemical leakage is reported. The objective is the development of an emergency self contained breathing apparatus (SCBA) which does not interfere with nor encumber the worker's activities. The highly toxic nature of many current volatile chemicals allows response times of only seconds before a worker would be overcome by the vapors resulting from a significant leak or spill. The best solution to this problem is quick response; i.e., shorten the time needed for the worker to recognize the emergency and don a protective respirator.

An SCBA prototype has been developed to minimize the time between hazard recognition and equipment donning. The SCBA is built into the worker's protective hard hat and is thereby immediately available for use. The prototype utilizes a chlorate candle oxygen source, a soda lime carbon dioxide scrubber, and a full transparent hood. All of SCBA is incorporated into the hard hat except for a tethered chlorate candle which is mounted on a belt pack.

INTRODUCTION

Currently there are no emergency respirators which provide a fully adequate safety margin for workers involved with volatile, highly hazardous chemicals. For example, hydrazines are currently used as propellants for many military rockets. If a

significant propellant fuel leak occurs the gantry workers will only have seconds to respond before being overcome by toxic fumes. Presently, individuals working around hydrazines are supplied with self-contained breathing apparatus (SCBA). These SCBA's may consist of a simple gas mask or, more recently, a 5-10 minute compressed air tank connected to a transparent hood. The hood is drawn over the head, sealed around the neck, and compressed air is vented through the hood at initial rates in excess of 38 liters per minute (1pm) to flush out metabolically generated carbon dioxide. These newer hood systems require minimal training while eliminating the face fit problems associated with conventional gas masks. The major concern surrounding even these newer units is the time required to retrieve and don the SCBA. Because of its bulk, weight, and configuration, workers cannot carry the SCBA at all times without it interfering with their ability to work effectively. In principle, placing the SCBA units strategically throughout the work locations is a logical and sensible approach and is the approach currently utilized. Unfortunately, experience in similar situations has clearly demonstrated that when an actual emergency occurs, the majority of workers tend to panic and attempt to leave the hazard area without using an emergency respirator. A recent example, was the 1984 coal mine fire in Utah: only one miner responded to the emergency "logi-

cally and sensible" the way he had been trained, and lived because he did. More than two dozen others apparently failed to make any attempt to find or don their emergency breathing apparatus and died. At least three other miners in this mishap located their SCBA's but died while attempting to don and activate their units.

Situations similar to the mining example can occur in any manufacturing or transportation industry where sudden and unexpected exposure to hazardous chemical spills or leakage are possible. It could occur in any military or civilian location which might be targeted for a surprise chemical warfare attack including airbases, field hospitals, forward staging areas, and aboard ships, as well as the front line soldier. In each case, the behavior of the individual (literally within the first few seconds of exposure) may determine his survival potential.

There is no foolproof protection possible in the emergency situations envisioned around highly toxic volatile chemicals or in deep coal mines. The best that can be accomplished is minimizing the delay between recognizing the emergency and donning the protective gear. The best way to minimize this delay is to require that workers wear the protective gear at all times; a solution which is impractical at best with existing devices. Even if a conventional SCBA were simply carried at all times, there is still considerable time needed to recognize the emergency situation,

unpack the device, and deploy it. If an emergency respirator were built into worker's present equipment ready for immediate deployment, this would reduce the response time drastically. In most cases, protection for as little as 5 to 15 minutes would be sufficient to allow secondary protective action to be undertaken.

DEVELOPMENT RATIONALE AND DESIGN CONCEPTS

Essentially all heavy industries, including the chemical, civil, and construction as well as the mining industry require all workers to wear protective hard hats. Protective hard hats have become prevalent, and often required in many non-industrial activities including sports and leisure pursuits such as motorcycling, racing, canoeing, and rock climbing; any activity where there is potential for head injury. The underground miner has an added requirement; the need for light. As a result, every miner also wears an equipment belt which, as a minimum, will carry a battery with sufficient capacity to power his hat-mounted light for a full 8-hour shift. The belt may also include provisions for an oxygen deficiency monitor, a Hopcalite canister for short-term protection against carbon monoxide, and an assortment of tools. In some cases a miner may work with 10, 15, or more kilograms of equipment on his belt in very cramped and confined spaces.

Because all gantry workers and chemical industry workers are required to wear hard hats, we have patterned our design after the miner's hard hat in which the battery pack is replaced with a tethered belt pack chemical oxygen supply. If an emergency occurs the worker need only start the oxygen supply, pull down a transparent hood packed within the hard hat brim, and exit.

In addition to the transparent hood and circumferential brim hood storage compartment, the hard hat contains a venturi aspirator and a carbon dioxide scrubber chamber molded into its crown — additions which add

slightly over 0.5 kg to the hard hat weight. The chlorate candle is belt-pack mounted and adds an additional 0.5 - 1.0 kg (depending on desired capacity) to the system. The oxygen produced by the chlorate candle is exhausted into the hat through the venturi aspirator creating a vacuum which pulls the air from the hood and recirculates it through the scrubber chamber as indicated in Figure 1. Figure 2 pictures the SCBA prototype.

In use, the hat is worn conventionally with the exception that it is connected to the belt by means of an oxygen hose just as the light is tethered to mining hard hats. This hose acts as a tether and encourages the continuous wearing of the hat, a practice which is common in the construction and mining industries but less common in other industries. Upon deployment, excess oxygen vents around the neck seal thereby help to prevent the ingress of haz-

ardous vapors. Because the aspirator generates low level noise during operation, the user is immediately aware when the oxygen source is nearly exhausted.

Areas of Research

ASPIRATOR DESIGN:

During an initial feasibility study it was determined that a rebreather system would best fit the specified requirements. A positive pressure rebreathing system was chosen over negative pressure systems to avoid fit problems and excessive back pressure found in scrubber beds during high metabolic rate use which can make breathing difficult. The chlorate candle oxygen supply was chosen over compressed oxygen or oxygen enriched air because of its long storage life, small size, low weight, and constant in-flow over time of the candle, a requirement for effective performance of the aspirator.

Figure 1
Flow Schematic of hard-hat SCBA

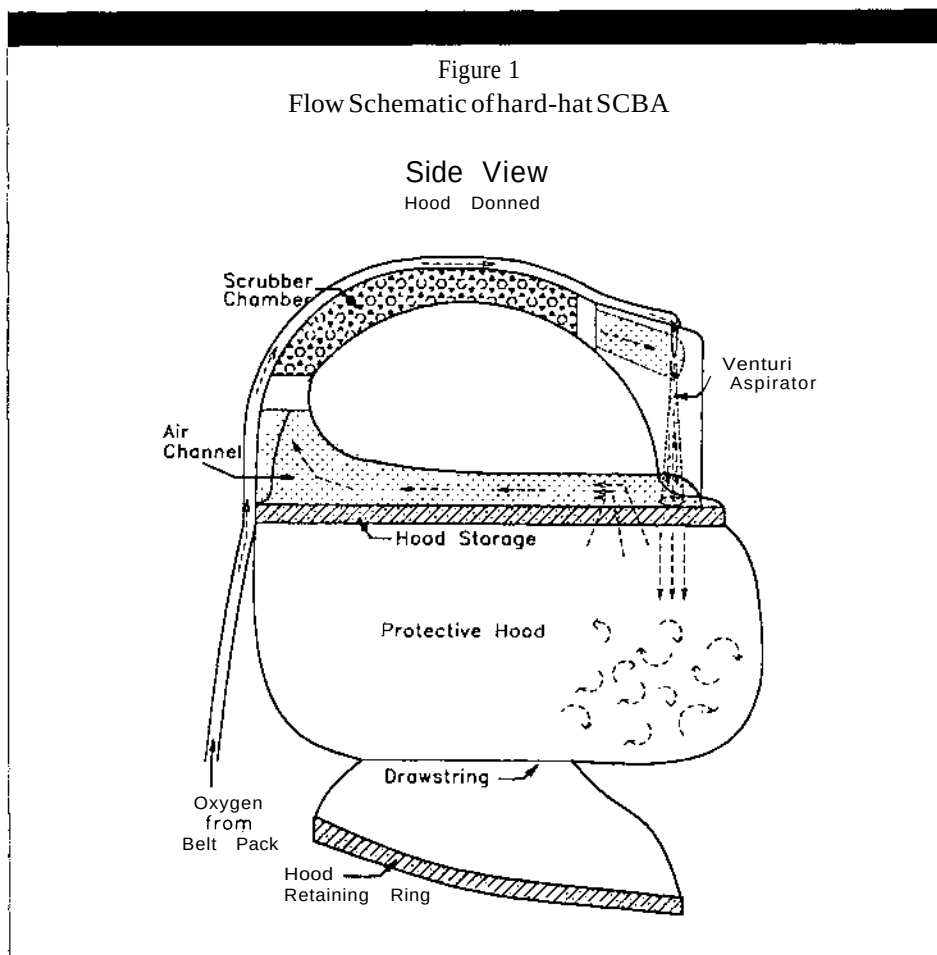
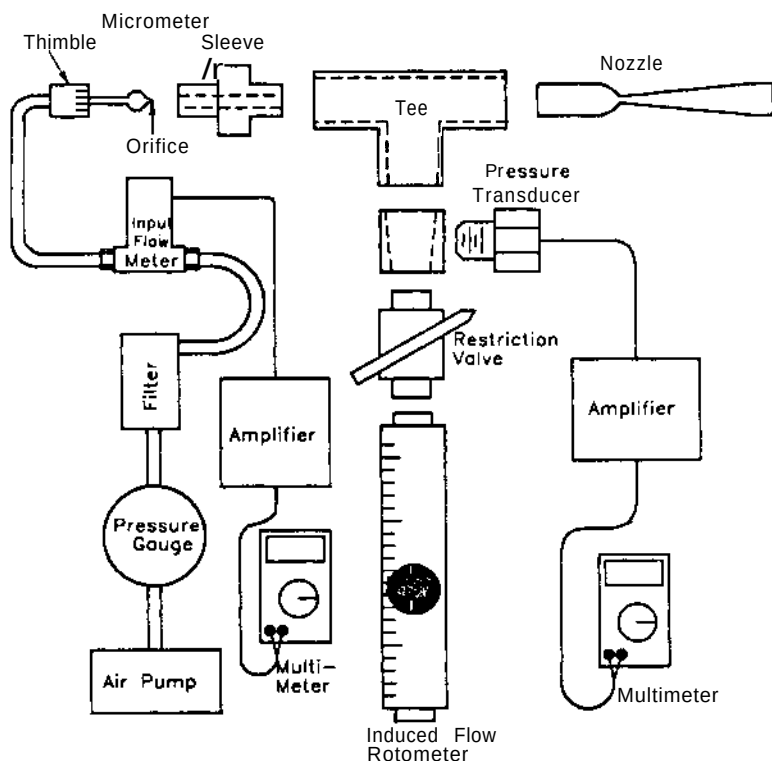


Figure 2
Prototype Hard-hat SCBA



Figure 3
Aspirator Test System Schematic



The aspirator is a key component in making the hard hat SCBA concept practical. Most self-contained re-breathing apparatus rely upon the user's lungs to force air through the carbon dioxide scrubber compartment. At low metabolic rates, this results in noticeable, but generally acceptable back pressures the user must work against. For high metabolic rates where large tidal volumes of air must be moved through the scrubber, the back pressure can add substantially to the user's workload. In addition, the effective use of the lungs to recirculate the air through the scrubber necessitates a more leak-free system and thereby has some of the deficiencies of conventional gas masks. The use of the aspirator system allows the user's lungs to function without additional pressure loads, reduces the stringent requirements for leak-free sealing, provides an audible indication of the approach of oxygen depletion, and facilitates optimization of the scrubber chamber for high scrubbing efficiency. The aspirator system design used in this prototype is patterned after a similar system used in the Scott Aviation emergency respirator designed for the U.S. Navy (Harwood, 1976).

The aspirator design study investigated orifice size, orifice position, throat diameter and length, as well as outlet nozzle taper and length to find the optimum aspirator dimensions which create the greatest possible induced flow through the SCBA system. Design parameter testing employed an orifice jet holder incorporated into a micrometer used to adjust the jet position. A Brooks model 5811B electronic mass flowmeter measured input flow oxygen flow rates and a Gilmont rotometer measured the induced flow rate. Various sized machine orifice jets and aspirator bodies were made to be interchangeable. The test system is illustrated schematically in Figure 3.

Because metabolic requirements can vary from as little as 1 liter per minute (1pm) at rest to as much as 6

1pm under extreme exertion, oxygen input flow rates through the aspirator orifice were varied over a range of 1 - 10 liters per minute with most data accumulated for oxygen inputs from 4-10 liters per minute. A design which provides a high induced flow rate at a pressure well within the chlorate candle safety limits was then chosen. The present aspirator system produces a free recirculation flow rate of approximately 140 lpm using an 8 lpm oxygen supply operating at 24 psi. The filled scrubber adds flow resistance and results in a decrease in the recirculation rate through the scrubber bed to 80 lpm. At 80 lpm the hood is flushed approximately 17-20 times per minute.

The aspirator orifice diameter and its position in the venturi throat, and the throat diameter, were the most important variables and are a function of the design oxygen flow rate.

CARBON DIOXIDE SCRUBBER SELECTION:

A literature search was initially performed comparing different CO₂ scrubber characteristics. Although a number of adsorption-type materials such as molecular sieves and certain ion-exchange resins can function as carbon dioxide scrubbers, scrubbers relying upon non-reversible chemical reactions are most satisfactory for respirator applications. Chemical scrubbers are basically metal hydroxides which react with carbon dioxide to produce carbonates and bicarbonates with the liberation of water as indicated by the following generalized reactions for the alkali metal hydroxides:

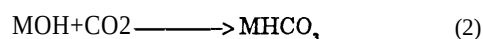
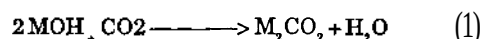


Table 1 summarizes the major properties of the most commonly used scrubbers.

Lithium hydroxide was the first chemical tested because of its light weight and high carbon dioxide capacity. Anhydrous LiOH absorbs CO₂ in-

put exceptionally well but creates dangerously high temperatures when CO₂ input flow rates exceed 1.5 lpm for a 200 gram scrubber. At 2.5 lpm the scrubber compartment molded into the prototype hard hat reached 180°C, sufficient to melt the molded chamber and char the underlying fiberglass hat shell. Air temperatures exhausting from the scrubber into the hood compartment were correspondingly intolerable. At high metabolic oxygen consumption rates which can occur under panic situation, carbon dioxide production rates in excess of 2.5 lpm are likely. Our testing is conducted under con-

sodalime scrubber is the large amount of water released during CO₂ absorption. Soda lime is a commercially produced CO₂ scrubber containing mostly Ca(OH)₂, small percentages of KOH and/or NaOH, as well as 15-19% water. Although controversy remains about the mechanism of CO₂ reaction with soda lime, it is generally accepted that the reaction proceeds by a mechanism in which the carbon dioxide first dissolves in free water contained within the scrubber granules producing the bicarbonate ion, which in turn reacts with the sodium and potassium hydroxides to form the soluble alkali-metal carbon-

TABLE 1
Properties of Major CO₂ Scrubbers (Wang 1966)

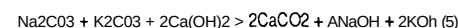
Compound	Formula Wt	Capacity (gCO ₂ /g)	Reaction Heat (cal/gCO ₂)
LiOH	23.9	0.919	512
NaOH	40.0	0.550	694
KOH	56.1	0.392	814
Ca(OH) ₂	74.1	0.594	376
Mg(OH) ₂	58.3	0.754	106
Soda Lime	46.8 (typ)	0.488	*
Baralyme	87.5 (typ)	0.503	*

*Reaction Heat calculated from, heats of formations the CRC Handbook, 63rd edition, lists.

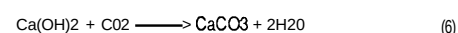
ditions which produce 2.75 lpm carbon dioxide, a generation rate resulting from moderately high, but sustainable, work rates.

As can be seen from Table 1, both sodium and potassium hydroxides exhibit even higher heats of reaction than does lithium hydroxide. In addition, sodium and potassium hydroxides require complex scrubber bed designs to prevent caking of the material with subsequent increase in back pressure and decreases in efficiency. Calcium hydroxide scrubbers (soda lime) were tested extensively. Calcium hydroxide has a lower heat of reaction, but is more than twice as heavy and has a smaller CO₂ capacity than LiOH. The major concern when using a

ates. These carbonates in turn react with calcium hydroxide to produce the insoluble alkaline-earth carbonate.



The net reaction:



produces 2 moles of water for each mole of carbon dioxide absorbed.

Combined with the large amount of water initially added to the scrubber in order to facilitate a reasonable reaction rate, the result can be a very uncomfortable 100% relative humid-

ity in the hood under high metabolic work loads. Because of this, several different options were investigated to reduce the water level in the soda lime system.

Scrubber formulations were tested with a fully humidified gas mixture of oxygen and carbon dioxide through an approximately 1/4 scale cylindrical glass scrubber bed 25 mm in diameter by 200 mm length. Gas flows were 2 liters per minute (1pm) oxygen with 0.2 1pm carbon dioxide. Scrubber chamber temperature was recorded using a thermocouple converter and stripchart recorder. The exit gas was usually analyzed by gas chromatography, but occasionally a Bechman LD2 nondispersive IR analyzer was used depending on availability of the respective instruments. The breathing simulator used in testing of the scrubbers as well as the prototype designs consisted of a variable capacity artificial lung constructed with a pneumatically driven rolling diaphragm piston. Attached to the top of this artificial lung is a humidifying chamber into which the oxygen/carbon dioxide mixture is produced. This chamber in turn is connected indirectly to a mannequin head with an internal artificial trachea connecting the lung-humidifier combination and the nose. The CO₂ sampling tube passes through the mannequin mouth, thence the neck, and connects to the gas analyzer. Generally, both a Horiba gas analyzer (for averaged CO₂ concentrations) and the Beckman LD2 (for breath-by-breath concentrations) were operated simultaneously. Up to 20 thermocouple temperature locations were monitored simultaneously using a Keithly data acquisition board, Labtech Notebook software, and a personal computer.

Several different options were investigated to reduce the soda lime exhaust water level during operation. Drying agents, such as molecular sieve, silica gel, and calcium sulfate, were tested but none could be stored side by side with the soda lime without unacceptably decreas-

ing absorption rate and capacity. The desiccants removed water contained in the soda lime lowering its reactivity to CO₂. To have the water absorbent and scrubber separated during storage as well as have an open pathway during use, greatly complicated the design and increased the mechanical failure possibilities. Also the drying agent increases the scrubber chamber temperature. Soda lime by itself reached 55°C but when used in combination with calcium sulfate, molecular sieve, or silica gel the temperature reaches 98°, 80° and 77° respectively. The increase in temperature and the dry air the water absorbent creates, is more uncomfortable to breath than the 100% humidity at a lower temperature.

Anhydrous LiOH has a high heat of reaction with CO₂ and also liberates water. We therefore investigated the possibility of using a layer of LiOH at the scrubber inlet followed by dry soda lime, the reasoning being that the LiOH would react first, liberating water which would reactivate the soda lime. All of our tests, however indicated that reactivation did not in fact occur with sufficient rapidity to be used. Water equilibration times approaching an hour appear to be required for reactivation of dry soda lime.

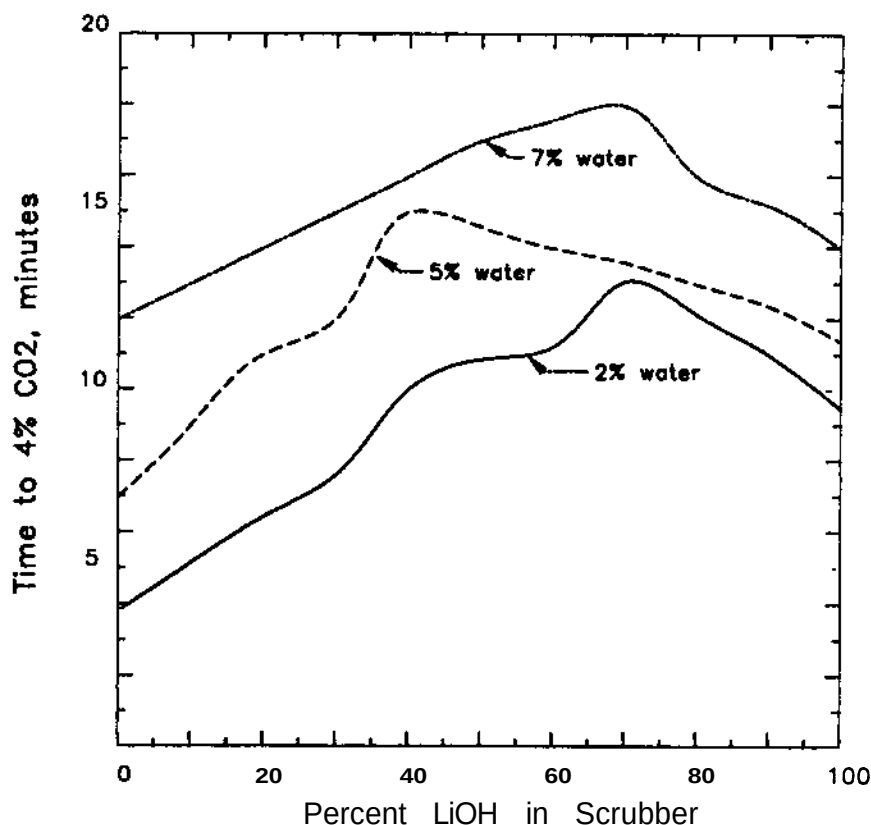
Laboratory test quantities of various scrubber chemical combinations were produced in an effort to find a scrubber which would have a relatively low heat of reaction along with a low initial water content. The first materials were calcium hydroxide and lithium hydroxide combinations. The scrubber granules were produced by combining calcium and lithium hydroxide powders with water and allowing it to fully hydrate over approximately a 1-2 hour mixing period. The stiff paste mixture was then extruded onto a metal mesh belt and passed through a conveyor

oven to dry. After drying thoroughly, the particles were crushed and sized. Known amounts of water were then added back to the now uniformly sized particles. Varying ratios of Ca(OH)₂ and LiOH were used and varying percentages of water added to the particles. Figure 4 summarizes the data collected during this study. The combination of 57% Ca(OH)₂, 38% LiOH, and 5% added H₂O performed well in a 10 minute SCBA, while containing 1/3 the water content of soda lime and at lower temperature than anhydrous LiOH. The high temperature for this mixture was 70°C, 15 degrees higher than soda lime but 20 degrees lower than LiOH under identical conditions.

Another series of scrubber formulations using magnesium hydroxide as the base material were also conducted. Mg(OH)₂ is lighter in weight and has a significantly lower heat of reaction with carbon dioxide than does Ca(OH)₂, but the rate of reaction with carbon dioxide is too slow to be practical. An early study by Colombo and Mills (1966) indicated that the addition of alkali metals, particularly lithium, to the mix improved the reaction rate. Even after locating one of the original investigators and obtaining additional unpublished details, we were unable to reproduce their results or obtain any favorable results with the magnesium hydroxide formulations. A magnesium hydroxide/lithium hydroxide combination particle was finally produced, but the water content needed to achieve adequate results was twice the amount required in the calcium hydroxide/lithium hydroxide scrubber with no reduction in scrubber chamber temperature.

As a result of the mixed-hydroxide scrubber results it was decided to test a series of lithium hydroxide scrubbers containing varying quantities of added water. Adding as little as 5% water by weight to the anhydrous LiOH particles, the reaction temperature chamber dropped from

Figure 4
Ca(OH)₂/LiOH Scrubber Study



99°C to 70°C under the standard test conditions. Increasing the water content to 10% resulted in a temperature decrease to 65°C with no reduction in reaction efficiency.

While the above noted tests were in progress a low moisture content soda lime sample, Sofnolime, was obtained from an English supplier (Molecular Products, Ltd, Mill End Thaxted Essex CM6 2LT). This material contains approximately 8% water, which is half the amount most soda lime scrubbers contain. Tests of this material showed that it performed equally as well as the high moisture soda lime in the prototype design. Man tests were then conducted comparing the subjective environmental comfort provided by the two different moisture level products. All of our test subjects noticed a significant increase in comfort of the low moisture English material during the first 5 minutes of the

standard test protocol.

Although none of the scrubber materials tested approached an ideal scrubber, additional scrubber development studies were not possible within the time and funding constraints of the program. Upon completion of the noted studies that various alternatives were compared on scrubber chamber temperature, water production, and the caustic nature of the scrubber. Comparing the scrubbers on a temperature basis, the soda lime products have the lowest reaction temperatures (see Table 2). The low moisture Sofnolime product reduces the water content and in man test results in a noticeable comfort improvement, particularly during the first five minutes of usage at high metabolic rates.

The low moisture Sofnolime has two significant advantages over the scrubbers containing lithium hy-

droxide. First the lithium hydroxide containing scrubbers produce temperatures 10° to 45° higher in the standardized 1/4 size test units than the soda lime scrubbers. Second, they lack the highly caustic, respiratory tract irritant behavior of the lithium hydroxide inclusion scrubbers. All the lithium hydroxide scrubber including those containing only small percentages of lithium hydroxide result in respiratory tract irritation unless highly efficient filters are included in the output from the scrubber. Filters which satisfactorily remove the fine carry-over lithium hydroxide dust reduce the aspirator induced recirculation rate and result in increased carbon dioxide levels in the hood.

The mesh size and uniformity of particle size is of significant importance to this aspirator-assisted design. Tyler mesh size 4-8, 8-10, and 10-14 were compared. Reducing the mesh size from 4-8 to 8-10 the CO₂ concentration at the outlet of the scrubber was reduced significantly with only a 4 1pm drop in recirculation rate. Reducing the mesh size further (to 10-14) substantially reduces the recirculation rate, without a corresponding improvement in scrubber outlet CO₂ concentration as illustrated in Figure 5.

HARD HAT SCBA DESIGN CONSIDERATIONS:

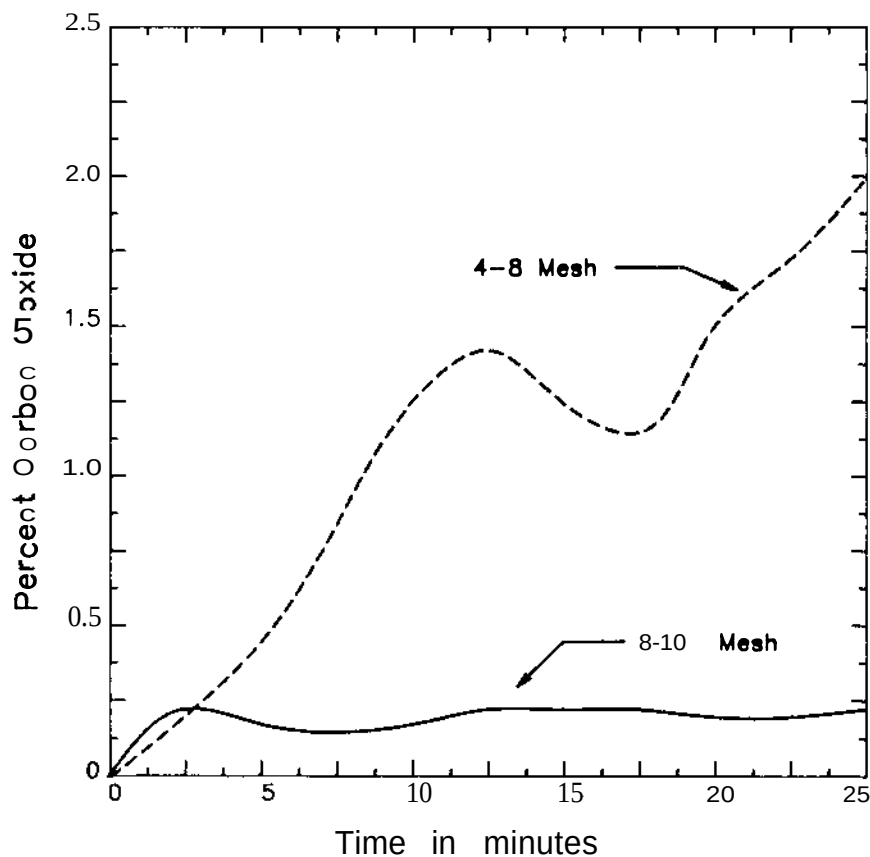
The basic design of the hard-hat SCBA has not changed radically since an initial feasibility study in 1985. It still consists of a conventional construction style hard hat with an overlaying shell into which the scrubber chamber is molded as a slightly raised chamber across the top of the hat leading from the rear to a point essentially above the beginning of the brim as can be seen in previous Figure 2.

Thermoformed into this same shell are two air return passages which pick up return air at the brim and allow it to flow around the edge of the hat where it joins at the scrubber inlet. The exit end of the scrubber is

TABLE 2

Characteristics of Various CO₂ Scrubbers

Scrubber	High Temperature ° C	Moisture Content % by weight
Sodasorb HM	55	12-19
Sofnolime	55	15-19
Sofnolime Low Moisture	55	8
LiOH/H ₂ O	65	10
Ca(OH) ₂ -47.5%/LiOH-47.5	70	5
Anhydrous LiOH	99	0

Figure 5
Effect of Mesh Size on Scrubber Efficiency

sealed with an expanded foam particle barrier which communicates directly with the aspirator. A shallow molded chamber completely around the hat brim for hood storage is included. The oxygen delivery tube which supplies the make-up breathing oxygen and simultaneously provides the driving power for the aspirator is bonded to the shell from the back edge of the hat, over the top and terminates

in the aspirator jet orifice.

Although the basic design has not changed, significant improvements in scrubber efficiency and recirculation flow rates have been achieved through a concerted trial-and-error modification test program. The major effect on the scrubber performance was found to be the cross-sectional area of the scrubber bed. The optimum scrub-

ber chamber for the current design is a roughly cylinder shape conforming to the exterior surface of the underlying hard hat with dimensions of approximately 75 mm diameter and 180 mm long. All the design improvements including blending air channels and scrubber intersections into smooth contours and proper choice of scrubber granule size resulted in recirculation flow rate improvements from 37 lpm to 80 lpm, which is our current operational standard.

Current prototypes utilize a commercial NIOSH-approved fiberglass hard hat. The scrubber and air return channels are formed by thermoforming a 1 mm copolyester shell which fits tightly over the hat and is adhesively bonded in place. The aspirator body is currently cast polyester into which a precision brass aspirator jet is accurately positioned. The aspirator is mounted to the shell using adhesive silicone rubber. The hood is fabricated from Teflon FEP (DuPont) film 0.1 mm thick which is cut shape, heat sealed into an approximately cylindrical shape, then adhesively bonded to the brim. The inside surface of the film is treated to allow permanent bonding to the hat and coated with an anti-fog compound to prevent fogging in use. The FEP film is chemically inert, resistant to virtually all chemicals except molten alkali metals or gaseous fluorine, and has excellent impact and tear resistance. The chlorate candles used in the prototype were obtained from Scott Aviation. They have not been optimized in either size or oxygen delivery service time requirements. The connecting hose between the chlorate candle and the aspirator is silicone rubber.

PRELIMINARY TEST RESULTS:

Preliminary tests in our lab using a NIOSH Man Test #4 simulation for a 10 min. service have been uniformly satisfactory. Figure 6 illus-

trates the hood CO₂ concentration as measured at the test subject's mouth using the Beckman LD2 CO₂ analyzer. The tests used treadmill equivalencies (Wang 1966), listed in Table 3, to simulate the different sequential activities required by the NIOSH protocols.

Changes in inspired CO₂ percentages at different work rates are clearly shown. These changes result from the constant recirculation rate the system produces when combined with differing metabolic CO₂ production rates. The highest CO₂ concentration exhaled during this particular test was approximately 4% and the maximum inhaled was 2.2%. This level of CO₂ exposure is well within safety limitations based on previous studies (Dripps 1947, Menn 1970).

SUMMARY:

Research leading to the development of a continuously wearable self contained breathing apparatus incorporated into a protective hard hat is described. Its purpose is to reduce the response time between hazard recognition, and providing respiratory protection thereby increasing survival odds in many emergency situations.

Further work on scrubber temperature and moisture reduction and optimization of the oxygen belt pack are in progress.

ACKNOWLEDGMENT:

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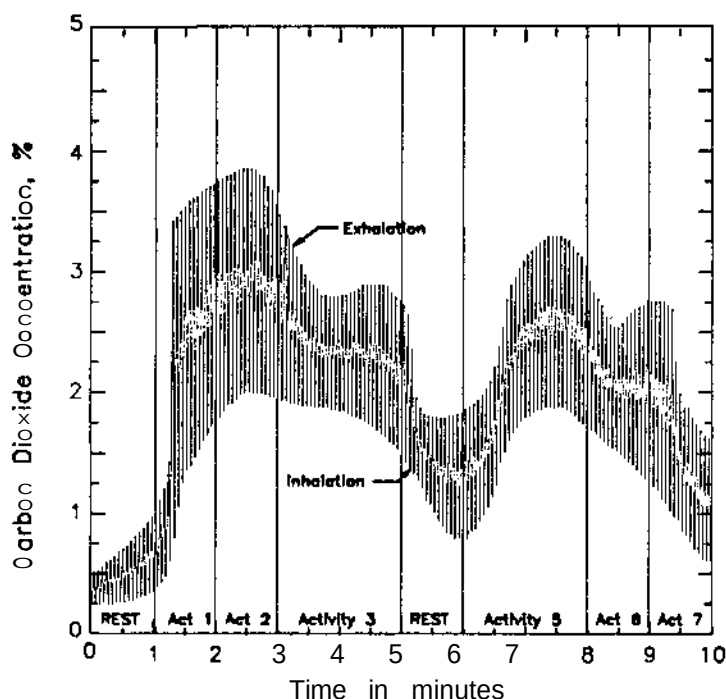
TEXT CITATIONS:

1) Columbo, G.V., E.S. Mills, (1966). Regenerative Separation of Carbon Dioxide via Metallic Oxides. Chem Eng Progress Symp No. 63 89-98, American Inst. of Chemical Engineers.

2) Dripps, R.D., J.H. Comroe, (1947). The Respiratory and Circulatory Response of Normal Man to Inhalation of 7.6 and 10.4 Percent CO₂ with an Comparison of the Maximal Ventilation Produced by Severe Muscular Exercise, Inhalation of CO₂ and Maximum Voluntary Hyperventila-

TABLE 3		
NIOSH Man Test 4 for a 10 Minute Service Time		
Duration of Activity	Description of Activities	Treadmill Equivalent
1 minute	Climb Vertical Treadmill	4.5 mi/hr at a 15° incline
1 minute	Walk 3mi/hr	
30 times in 2 minutes	Pull 20 kg to 5 feet	4.9 mi/hr at a 0° incline
1 minute	Walk 3 mi/hr	
2 minutes	Sampling and Readings	(no activities)
1 minute	Run 6 mi/hr	
1 time in 1 minute	Carries 23 kg Overcast	4.9 mi/hr at a 0° incline

Figure 6
CO₂ Trace from the Simulated Nan Test 4



tion. Am J Physiol 149: 43-51.

3) Harwood, V. (1976). Development of Breathing Device for Emergency Escape. US Navy DTIC # ADA033 959.

4) Kamon, E., b. Thomas, R. Stien, (1975). Steady State Respiratory Responses to Tasks Used in Federal Testing of Self-contained Breathing Apparatus. Am Industrial Hygiene Assoc J, Dec: 886-896.

5) Menn, S.J., R.D. Sinclair, B.E. Welch, (1970). Effect of Inspired PCO₂ up to 30 mmHg on Response of Normal Man to Exercise. J Appl Physiol 28: 663-671.

6) Wang, T.C. (1966). Carbon Dioxide Scribbling Materials in Life Support Equipment. Chemical Engineering Progress Symposium Series No. 63, 14-20, American Institute of Chemical Engineers.