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The Proceedings of the 1976 Divers' Gas Purity Symposium is composed of papers prepared by the speakers at the Symposium. These papers, submitted by the authors discuss the results of the authors most current work in the fields of diving, engineering, medicine, and science as it relates to divers' breathing gas. The Supplement to this Proceedings contains a paper by M. V. Roloff and A. P. D'Addario of the Naval Medical Research Institute, Bethesda, Maryland.

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FOREWORD

The 1976 Divers' Gas Symposium is the third in a triennial series begun in 1970, sponsored by the U. S. Navy Supervisor of Diving upon recommendation by the Chief of Naval Operations.

The Symposium, as before, will provide a forum for current researchers in the fields of diving, engineering, medicine and science to discuss the results of their most current work as it relates to divers' breathing gas. The papers have been prepared in advance for these proceedings so that all participants may develop questions and discussion after each author has presented his work. All papers were submitted as camera-ready copy by the individual authors, and any questions not answered during the course of the discussions should be addressed to them.

The Office of the Supervisor of Diving expresses its appreciation to authors and program participants, whose efforts are constantly improving the state of the art of diving.

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RATIONALE FOR BREATHING GAS REQUIREMENTS OF THE NIOSH RECOMMENDED STANDARD FOR COMMERCIAL DIVING

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Abstract

A recommended standard for diving produced under contract for NIOSH includes many breathing gas limits. Breathing gas should not contain more than 10 ppm CO, 500 ppm CO_2, or 5 mg/m^3 oil mist, according to traditional experience. Oxygen is limited to 1.6 atm PO_2 for one hour, or 1 atm for 24 hours, more than stated U.S. Navy limits but consistent with Navy practice. Nitrogen in mixed gas is limited to 5.4 atm, consistent with air diving experience. Chamber CO_2 should not exceed 11.4 mmHg, and PO_2 in long dives should not exceed 0.5 atm. Oxygen should be kept below 25% for fire safety. The Standard also protects divers by requirements for adequate gas flow to breathing equipment (4.5 acfm), minimal work of breathing (0.17 kg-m/liter), and specifications for compressors, filters and maintenance, gas reserves, and mask breathing systems.

TABLE I. BREATHING GAS LIMITS

Carbon monoxide	10 ppm
Carbon dioxide	500 ppm or 7.6 mmHg, whichever is lesser
Oil mist	5 mg/m^3
Odor	no pronounced odor

This section is directed primarily at compressed air supplied by a low-pressure compressor, but covers mixed-gas diving as well.

Carbon monoxide

Tolerable levels for carbon monoxide exposure have gradually crept downward over the years (2). The value of 10 ppm agrees with the Compressed Gas Association's current recommendations for "E" grade air--the minimum grade CGA approves for diving--but is on the safe side. For most diving operations the actual CO value should be moot; even 10 ppm is too much, as it indicates a compressor drawing in exhaust or in need of maintenance. An exception to this would be where diving is being conducted in a polluted area--the Standard would require purification. A case can be made for allowing higher levels for short exposures, but we felt such a rule might open Pandora's Box.

The principal toxicity mechanism for carbon monoxide is its displacement of oxygen from hemoglobin, forming COHb. This reaction depends on duration of exposure as well as level. With COHb as an end point, CO acts as a function of partial pressure, and consequently its action will be multiplied at increased pressures. Where oxygen also increases with pressure, as in air diving, the CO/O_2 ratio is the determining factor for the formation of COHb(2), independent of depth. Since this rule applies to mixtures other than air, the 10 ppm level provides adequate safety whereas 20 ppm might not at pressures of 10 or more atm.

No specific provision covers CO in the saturation dive; commercial experience has not shown it to be a problem under normal operating conditions.

Carbon dioxide

Carbon dioxide has always been a problem in diving, primarily because it is generated by the diver and builds up when

breathing equipment--or the diver's lung--is not sufficiently well ventilated. This fact alone is justification for a rule requiring as low a CO_2 as can reasonably be achieved. But also, CO_2 acts synergistically with nitrogen and oxygen, increasing both narcosis and oxygen toxicity. The maximum of 500 ppm is in the range of normal ambient air, but CO_2 is an easy gas to control in a gas supply, easy to measure and easy to remove. The presence of CO_2 in a compressor output may indicate compressor malfunction, and certainly suggests that the carbon monoxide level be checked.

From a physiological point of view, rather large amounts of CO_2 can be breathed without effect and even without detection, where ventilation is not otherwise impeded. Long-term studies (3) show levels as high as 30 mmHg (about 4% or 40,000 ppm!) cause adaptive physiological responses but involve little performance decrement and are no risk to safety or health. CO_2 acts as a function of partial pressure.

Oil mist

The level of 5 mg/m^3 of condensed hydrocarbons ("oil mist") is a traditional one, based presumably on "complaint-and-nuisance" factors but nonetheless well accepted [4,5]. Values of 100 mg/m^3 will cause lung damage in animals, but only after months of exposure.

The 5 mg/m^3 level is not an easy one to meet; it will require filtration equipment.

Other contaminants

Standards for other possible contaminants are not included. These could be acetylene, methane, sulphur dioxide, oxides of nitrogen, halogenated compounds, etc. Many of these are innocuous, some are not, but none are commonly found in diver's breathing gas. To include these in a standard would impose a requirement for analysis that would be totally inconsistent with the safety which would be achieved. Further, the trace contaminants which do pose a toxic threat all have pronounced odors and would be most unlikely to pass undetected. Operational rules will tend to minimize this type of contamination.

Oxygen limits

A dose-response approach is used to regulate exposure to oxygen, according to the following maximum values:

TABLE II. OXYGEN LIMITS

PO_2 maximum, atm	Time, hours
1.6	1.0
1.5	1.5
1.4	2
1.3	3
1.2	5
1.1	8
1.0	12

These values are higher than those listed in the U.S. Navy Diving Manual (NAVSHIPS 0994-001-9010) as normal exposure limits. This decision was made with great deliberation, based on the logic that reducing the allowable oxygen exposure would certainly reduce the safety of decompression from deep, short-duration diving, and that the added oxygen safety would not be worth it. It must be remembered that the Navy does not do deep, short-duration diving at all. Also, the manual limits are backed up by substantially longer "exceptional exposure" limits, a concept not possible in a standard.

TABLE III. U.S. NAVY OXYGEN LIMITS

Time, hours	Normal maximum PO_2, atm	Exceptional PO_2, atm
30	1.6	2.0
40	1.5	1.9
60	1.3	1.8
120	1.1	1.5
240	1.0	1.3

Also,the Navy allows normal exposures using closed oxygen rigs of 1.76 atm for 75 minutes, and calls for oxygen breathing during decompression (not working) of 2.5 atm (but, for never more than 18 minutes). The U.S. Navy Diving Gas Manual (NAVSHIPS 0994-003-7010, 1971) contains an oxygen exposure chart which our standard does not violate.

Long-duration oxygen exposures are limited to 0.5 atm, a value found in thousands of hours of commercial exposure to be safe. During saturation decompression it is necessary to raise oxygen levels, and again the safety added to the decompression is, we believe, more important overall than the reduction of the possibility of oxygen toxicity.

Oxygen exposures during decompression from deep short-duration dives not uncommonly causes pulmonary symptoms. A clean method of regulating this, again without increasing decompression risk, is not known. A start, we feel, is to require that employers at least keep track of their oxygen exposures. This can be done with the UPTD logging method of the University of Pennsylvania,[6] or equivalent. Tables which cause pulmonary toxicity must be modified or discarded. In due course appropriate UPTD values should become known.

Nitrogen limits

In mixed-gas diving, the amount of nitrogen in the mix is limited to 5.4 atm. This value will not inhibit any reasonable operation (it is equivalent to about 190 fsw) but will assure that the unacclimated diver is given a tolerable dose of nitrogen. Shallow NOAA-OPS-type nitrogen saturation-excursion diving where divers can adapt to high levels of nitrogen (7) is not so limited.

Operational procedures

In addition to the specific purity standards given above, the Standard imposes many additional rules which will improve the divers' breathing gas situation. These include such things as:

A requirement for periodic checks of compressors to see that the purity standards are being met (every 500 hours or six months, whichever comes first). Compressors must have running-time meters.

Compressors and supply regulators must be able to supply gas adequately to all breathing equipment which may be on line.

Compressors must have intake filters, water separators, and be equipped with interstage coolers where appropriate. Oil-lubricated compressors must have oil-mist filters.

Free-flow helmets must have a flow of 4.5 acfm (or must show by tests that a lesser flow is adequate); demand regulators must also meet this flow requirement.

Breathing apparatus must meet minimum work-of-breathing requirements, no more than 0.17 kg-m/liter of ventilation[8]. These rules will tend to minimize problems of CO_2 accumulation as a result of inadequate ventilation.

Semi-closed and closed breathing apparatus must have low oxygen alarms.

Chlorinated hydrocarbon solvents must not be used for cleaning breathing systems. This especially excludes the use of trichloroethylene.

Hoses must be capped when not in use, and must be purged before use.

Chamber gas limits

The CO_2 limit in a chamber is set at 11.4 mmHg, or 1-1/2% sea level equivalent, at all depths. The method of maintaining this value is optional; ventilation and flow rates of scrubbers are specified, according to Navy experience. Some method of CO_2 removal must be available where a compartment is occupied long enough to bring the CO_2 level up to 8 mmHg.

Oxygen in chambers must be kept below 25% by volume, either by means of an overboard dump breathing system or ventilation backed up by analysis. This limit is set for fire safety purposes only. It is itself a compromise, since even the 21% oxygen in air poses a significant fire threat at several atmospheres pressure. To reduce O_2 much below 25% by ventilation with air is difficult if O_2 is being introduced continuously into the chamber, and brings with it other problems such as noise.

All chambers and compartments must have oxygen analysis, except those relying solely on ventilation with air for atmosphere control. Bells are required to have a backup method of O_2 analysis, as well as some CO_2 analysis capability.

Provision for mixing of gases added to a chamber must be provided. Toilets must not vent continuously into a chamber.

Mask breathing systems

All occupied chambers or compartments must have a mask breathing system armed with an appropriate breathing gas at all times. This is to provide a means of breathing in event of fire or when chamber contents for some reason become unbreatheable. Example: Abort of a saturation dive involving decompression to sea level with a mixture of 2 or 3% oxygen.

An oxygen breathing system is an obvious necessity where much decompression is involved.

Gas reserves

The Standard requires that an operator have at the dive site twice the amount of gas needed for a given dive. This

value of 2X is an arbitrary choice in line with operational practice.

At least two sources of breathing gas must be available for a lockout or surface-supplied diver. An additional compressor running throughout the dive is acceptable, or a storage bank twice as large as needed to handle the dive and anticipated decompression. The diver-carried reserve must be good for 5 minutes, or twice the time needed to reach safety or additional gas.

A bell lockout diver must have 15 minutes working time in event of loss of the bell umbilical. This is enough time to allow the diver to attempt to untangle a fouled bell, and this amount can be carried on existing bells. A bell also shall have enough oxygen and CO_2 absorbent for 24 hours for occupants at rest. Lockout submersibles are treated like bells in most cases, but for them reserve life support requirements are 72 hours, since a submersible may be harder to locate and retrieve.

Treatment mixtures

Mixtures needed for treatment of decompression sickness must be on hand. The amount of pre-mixed gas should be sufficient for one hour of treatment at maximum depth. Adequate for most treatments, this amount is not enough for all possible situations. It will give a skilled crew enough time to mix additional gas if needed. Enough air and oxygen for any U.S. Navy treatment table should be available during surface-supplied diving.

Conclusion

The Standard proposes a series of exposure limits and operational procedures which, if followed, should substantially improve the safety and health of divers. The rules are intended to be realistic, and in most cases will not differ much from present safety practices of responsible operators. Safety does not mean zero risk, it means acceptable risk. The Standard attempts to protect divers, but still hopes to permit the full advantage of the tolerance and adaptability of man to be used on the job.

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GAS ANALYSIS REQUIREMENTS TO REACH DEPTHS IN EXCESS OF 1800 FEET

By

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ABSTRACT

To allow manned exploration of the ocean floor, it is necessary to provide a safe breathable mixture at elevated pressures. A critical requirement in providing such a mixture is the ability to detect and measure all important atmospheric constituents. The term "important atmospheric constitutents" can become quite extensive when you have a fixed volume for dilution of trace contaminants. The usual components which are monitored, their detection limits at greater depths, and the abilities of present gas analysis instruments for meeting these requirements are covered. Discussion of other contaminants to be evaluated are outlined, such as the 400 or more compounds generated by man himself and the off-gasing of hundreds from polymeric materials of equipment. The OSHA threshold limit values for these components adjusted for pressure are used to establish detection requirements for each component. This presentation uncovers several areas where additional research should be directed.

INTRODUCTION

Man has lived for many years on the surface of earth with little thought to the gaseous environment of his world. Nature very efficiently has purified this breathing mixture and adjusted the chemical content to meet man's requirements. Man has now come to a point in time where he has the need to duplicate such a process, thus allowing him to tap the ocean's wealth of resources. To allow manned exploration of the ocean floor, it is necessary to provide a safe breathable mixture at elevated pressures. A critical requirement in providing such a mixture is the ability to detect and measure all important atmospheric constitutents.

IMPORTANT ATMOSPHERIC CONSTITUENTS

The term "important atmospheric constituents" can become quite extensive when you have a fixed volume for dilution of trace contaminants. This problem is highlighted by the high pressure involved and the fact that the body generally responds to the partial pressure of the contaminants while most of our analytical instruments respond to molar composition.

The gas analysis of a closed system such as that of the OSF (Ocean Simulation Facility) poses two main problems. One is what components must be detected. The second problem is at what concentration need they be measured. The list of components can be so varied and changeable, with the introduction of any new apparatus into the closed high pressure system, that the sensitivity and limited capability of a single component gas analysis instrument commonly used at shallow depth may fail to protect the health and well-being of the occupants in the hyperbaric environment.

The usual components which must be monitored are listed in Table 1, together with their concentration at related depths. These components are monitored at hyperbaric facilities which work at depths up to 1000 feet. The detection limits of present instruments are not sufficient for greater depths. The physiological limits of these components are set by their solubility in body fluids and are a function of partial pressure; however, most of the analytical instruments respond to percentage composition.

DISCUSSION

The first component, oxygen, not only has an upper limit set by the toxic effect on the central nervous system, but also a lower limit (reference 1) due to oxygen deficiency as displayed in Figure 1. Exceeding either of these two limits to any great extent could result in death to our diver. At 2000 feet the desired oxygen content is .34 percent. An O_2 composition change of .47 percent above or .08 percent below the desired content, a span of .55 percent, would have a very adverse effect on our diver. Going to 3000 feet of depth, the safe oxygen content total span range is only .37 percent wide. Not only does this call for accurate, dependable gas analysis, but also has the requirement of good gas standards plus the knowledge of handling such standards (reference 2).

Nitrogen should not present any gas analysis problem since it has only an upper limit, which is within the percentage range, set by the first symptoms of nitrogen narcosis.

Hydrogen, a possible substitute for helium for depths beyond 200 feet, appears to be non-toxic at atmospheric pressure. The long-term effects of hydrogen on the double carbon bonds, hydrogenation, of body tissues at high partial pressure has not been explored, so any limits set by this consideration are not known. The known limits are set by combustibility of hydrogen-oxygen mixtures. This explosive danger limits the permissible oxygen content to 6 percent (reference 3); such concentrations should present no great analysis problem.

Table 1. Common Gaseous Constituents in a Manned Hyperbaric Environment

Constituent	Normal Concentration at Various Depths		
	0 Feet	2000 Feet	3000 Feet
Oxygen	21%	.34%	.22%
Nitrogen	0-80%	1.3%	.87%
Hydrogen	1 ppm	0-99.6%	0-99.7%
Helium	0-80%	0-99%	0-99.7%
Carbon Monoxide*	21 ppm	.3 ppm	.2 ppm
Carbon Dioxide	400 ppm	6.4 ppm	4.2 ppm
Hydrocarbons (Total)**	25 ppm	.4 ppm	.26 ppm
Krypton, Neon	20 ppm	20 ppm***	20 ppm***
Argon	1%	161 ppm	105 ppm

*Based on a constant CO - O_2 ratio of 1 ppm CO for each percent of O_2 (see reference 1).

**As methane equivalents.

***Based on neon content of helium.

Helium is an inert gas that should present no analysis problem from the ppm range on up into the percentage range by either gas chromatograph, mass spectrometer, or the Frost apparatus (reference 6).

Carbon monoxide (CO) is a colorless, odorless, and toxic gas that combines with the hemoglobin in the blood, thus reducing the body's capacity for oxygen transport. The upper limit is dependent upon the oxygen content of the breathable gas. At 2000 feet of depth, it will be a few tenths of a part per million and will present detection problems. This calls for detection capabilities beyond the standard infrared (IR) units. It would also be desirable to have 10 times the detection capability to measure developing trends. This requirement clearly exceeds the present state-of-the-art for IR analyzers. Urgent developmental work needs to be done in this area to assure diver safety. Several approaches are possible but they all call for utilization of very complex equipment; CO could be catalytically converted to CH_4 and then detected with a chromatograph using a

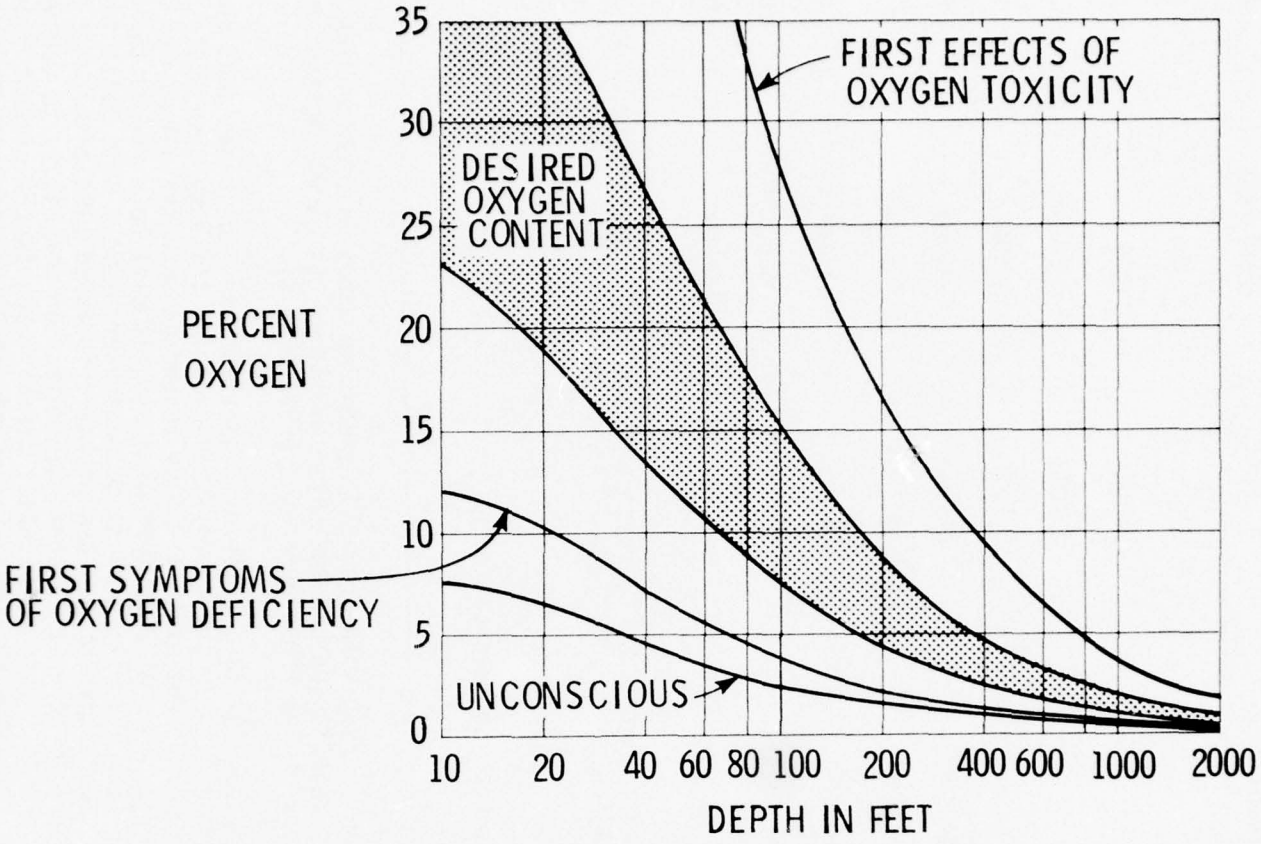

FIGURE 1. EFFECT OF OXYGEN IN BREATHING MIXTURES AS A FUNCTION OF DEPTH

hydrogen flame detector. Another approach could be the use of concentration methods (reference 5) which, if set up correctly, would give rapid results by the use of a chromatograph or mass spectrometer. The limits of each instrument must be considered in the design of such a system. If chromatography is used then the separation and sensitivity of CO in high concentration of other gases presents a problem. The choice of detection is probably limited to either helium ionization or hydrogen flame ionization, which adds complexity to the system. The mass spectrometer calls for a resolution of one part in 6000 to separate CO at a mass of 28.0104 from N_2 at a mass of 28.014, and this is beyond the capability of most instruments. The breakdown pattern would allow N_2 analysis; however, the breakdown pattern of CO would only be helpful if there were no other large sources of carbon or oxygen. Sensitivity for CO needs to be increased to .02 ppm to allow detection of developing trends. Increased sensitivity would also be desirable to allow for a greater margin of error.

The toxic effects of carbon dioxide relate to the exposure time and partial pressure. There are instruments, IR, electrochemical, and others, that detect CO_2 to the levels desired. However, such instruments do not allow detection of developing trends at maximum depth. A sensitivity of .4 ppm would be desirable.

The detection of total hydrocarbons using a hydrocarbon flame type detector can meet current requirements. The use of such a detector in conjunction with a chromatograph column will allow the separation and identification of each component of the mixture.

The inert gases neon, argon, krypton, and xenon are considered non-toxic; however, argon, krypton, and xenon exhibit narcotic effects which are directly related to the gases increasing molecular weight. The detection and separation of the inert gases can be made using chromatographic methods (references 4 and 5). Increased sensitivity can be obtained by the use of a helium ionization type detector. The chromatographic separation of argon from oxygen can be obtained by the use of subambient temperatures.

The above components of Table 1 represent the past concept in gas analysis. However, with the long time duration of a 2000-foot saturation dive with limited gas dilution volumes, we must extend our gas analysis to include other components which would be present and could prove harmful if their concentration approaches the threshold limit. Because of the large number of these components, we cannot have a single-purpose instrument for each. Therefore, it is necessary to use more complex instruments such as gas chromatograph, mass spectrometer, GC-MS combination, IR, and others. The interpretation of such data and the nonroutine type setup calls for individuals who have more than just surface knowledge of these subjects. They must have a detailed knowledge of gas chromatography column characteristics and arrangements, plus operational knowledge of mass spectrometer with a sound base of chemistry for MS and GC-MS data interpretation. Such analysis will never become routine because the introduction of any new item of equipment to such chamber complexes could change completely the analytical requirements.

SOURCE OF TRACE CONTAMINANTS AND ALLOWABLE LIMITS

Let's take a look at some of the other contaminants which we may encounter. The first source of such contaminants that come to mind is man himself. It may even be that man's metabolism and physiology may be related to some of these unidentified components in trace amounts. The adverse effects of others may be cumulative. We may even encounter minor psychological problems related to the presence of some of these trace components which could affect the cooperativeness of our diver. Will our array of scrubbers and absorbents effectively remove these components? We do not know, but the first step in finding out would be to have the analytical capability to identify these components.

What are some of these components that we should look for? An insight into the vast number of components that may show up in our system is illustrated by Weber, who, following a literature search, compiled a list of 400 compounds that may be encountered as effluents from man (references 7 through 14). Some of these materials are produced during time of high physical exercise, others in the presence of unusual ambient atmospheres (references 15 and 16). Table 2 lists components for which threshold limit values (TLV) could be obtained. Other components for which the TLVs have not been determined may also be quite harmful. Such lists should not be considered complete since improvement in analytical methods will vastly increase the number of constituents uncovered. There is also the question of whether the threshold limit values should be considered valid for hyperbaric chambers. By definition, it is the upper limit to which a worker can be exposed for 8 hours, 5 days a week without adverse effects. The effects of a 24-hour day, 7 days a week are not covered. All current values are for 1 atmosphere of pressure. If the components undergo a solubility interaction with the body fluids, they become a partial pressure function and consequently, adjustments must be made for pressures in excess of 1 atmosphere.

With no change in the partial pressure of a given gas, an increase in the total pressure results in a decreased ppm limit for that gas.

Such threshold limit values adjusted for pressure are also listed in Table 2. A look at these adjusted values reveals a concentration of such low values that detection by direct measure would be impossible with present instruments. Rapid concentration methods for groups or individual components must be developed. Although much research is needed in this area, NCSL (Naval Coastal Systems Laboratory) has the necessary instruments to do many of these analyses if they are applied in a nonroutine type operation tailored to each individual analysis.

In addition to Table 2, there are other products that can be generated by the interaction of these components with the fixed atmospheric gases. This can occur whenever a sufficient source of energy is introduced into the chamber. This energy could be thermal, radiation, or photo in nature. The introduction of certain catalytic materials could allow some of these reactions to occur at ambient temperatures. As an example, the operation of CO/H_2 burners can cause changes which should be monitored. Freons used in refrigeration systems and chlorinated hydrocarbons used as

Table 2. Threshold Limit Values for the Effluents of Man

Component	TLV in PPM	TLV at 2000 Feet Water Depth in PPM
Acetaldehyde	200	3.25
Acetic acid	10	0.16
Acetic anhydride	5	0.08
Acetone	1000	16.3
Acetonitrile	40	2.4
Acetylene	*	-
Acrolein	0.1	0.002
Allyl alcohol	2	0.03
Ammonia	25	0.4
Amyl acetate	100	1.6
Benzene	10	.16
Benzyl chloride	1	0.02
Bromine	0.1	0.002
Butyl acetate	200	3.25
Carbon dioxide	5000	81.3
Carbon disulfide	20	0.3
Carbon monoxide	50	0.81
Chlorine	1	0.02
Chlorobenzene	75	1.3
Chloroprene	25	0.4
Cyclopropane	400	6.5
Diazomethane	0.2	0.003
Dichloroethylene	200	3.25
Ethyl acetate	400	6.5
Ethyl alcohol	1000	16.3
Ethylamine	10	0.16
Ethyl bromide	200	3.25
Ethyl chloride	1000	16.3
Ethylene chlorohydrin	5	0.08
Ethylene chloride	1000	16.3
Ethylene diamine	10	0.16
Ethylene oxide	50	0.8
Fluorine	0.1	0.002
Formaldehyde	2	0.03
Formic acid	5	0.08
Hydrogen bromide	3	0.05
Hydrogen chloride	5	0.08
Hydrogen cyanide	10	0.16
Iodine	0.1	0.002
Isopropyl acetate	250	4.1
Isopropyl alcohol	400	6.5
Isopropyl amine	5	0.08
Methyl chloride	100	1.6
Methyl ethyl ketone	200	3.2

Table 2. Threshold Limit Values for the Effluents of Man (Cont'd)

Component	TLV in PPM	TLV at 2000 Feet Water Depth in PPM
Methyl formate	100	1.6
Methyl iodine	5	0.08
Methyl isocyanate	0.02	0.0003
Methyl mercaptan	0.5	0.008
Nitric oxide	25	0.4
Nitrobenzene	1	0.02
Nitrogen dioxide	5	0.08
Nitromethane	100	1.6
Phenol	5	0.08
Propyl acetate	200	3.25
Propyl alcohol	200	3.25
Propylene oxide	100	1.6
Pyridine	5	0.08
Sulfer dioxide	5	0.08
Toluene	100	1.6
Toluidine	5	0.08
Vinyl chloride	1	.016

cleaning solvents may be only partially decomposed in the CO/H_2 burners. The intermediate decomposition products may be extremely toxic. Another source of contamination is that caused by bacteria from man which have been known to alter synthetic materials, converting them into new substances. Bacterial action on the surface of the skin produces valeris and butyric acid, which, along with other skin secretions, have an adverse effect on synthetic rubber and other polymeric materials.

In addition to the byproducts of man, other components could be introduced into the closed environment from equipment being evaluated. The testing of diving equipment which contains polymeric materials could result in the off-gasing of toxic materials.

Table 3 lists many of the solvents commonly used in rubber and the break-down products of rubber along with their TLVs at 1 atmosphere and at 2000 feet. The additives used in rubber and plastic manufacturing are in the hundreds. The particular application of these additives may vary with each manufacturer, thus, it would be almost impossible to know the precise content.

In view of the scope of the problem, we should make every effort to assure a safe breathable mixture. At today's state-of-the-art in gas analysis, it is impossible to provide a high degree of protection for our divers. We go to great detail to assure that chamber material and construction procedures are certifiable. After all, a ruptured pipe or chamber could not only hurt

Table 3. Threshold Limit Values for Compounds Associated with Rubber Products

Compound	TLV in PPM	TLV at 2000-Foot Depth in PPM
Acrylonitrile	20	.32
Aniline	5	0.08
Benzene	10	.16
Benzidine	*	*
Beta-Naphthylamine	*	*
Butadiene	1000	16.3
Carbon dioxide	5000	81.3
Carbon monoxide	50	0.81
Carbon tetrachloride	10	.16
Chloroform	25	.4
Chloroprene	25	0.4
Coal tar pitch volatiles	0.2 mg/m^3	-
Cresols	5	0.08
Cyclohexane	300	4.9
Decahydronaphthalene	190	3.1
Ditertiarybutylhydroxytoluene	C*	C*
Ethylene dichloride	50	.8
Hydrogen cyanide	10	0.16
Hydrogen sulfide	10	0.16
Isoprene	C*	C*
Methylchloroform	350	5.7
Methylmercaptan	10	0.16
Methylcyclohexane	500	8.1
n-Heptane	500	8.1
n-Hexane	500	8.1
n-Octane	500	8.1
n-Pentane	1000	16.3
Naptha	100	1.6
Naptha (petroleum)	100	1.6
Phenyl-Beta-Naphthylamine	*	*
Styrene	100	1.6
Sulfur dioxide	5	0.08
Sulfur monochloride	1	0.02
Tetrachloroethane (1122)	5	.08
Tetrahydronaphthalene	-	-
Thiram	5 mg/m^3	-
Toluene	200	3.2
Toluene diisocyanate	0.02	0.0003
Trichloroethylene	100	1.6
Trichlorotrifluoroethane	1000	16.3
Turpentine (oil)	100	1.6
Vinyl chloride	1	.016
Xylene	100	1.6

C* TLV value not established but solvent is known to be toxic only in relatively high concentrations.

*Substances known to be occupational carcinogens without an assigned TLV.

the divers on the inside, but personnel external to the chambers could also be affected. Should not certification also warrant certain analytical capabilities to assure a safe, breathable mixture for our divers on a land-based hyperbaric facility? If we are going to have problems, this is where they should be detected rather than wait until we actually have saturated divers on the ocean floor or until statistics show that dives at 2000 feet shorten man's life span by X number of years due to cumulative effects of trace contaminants. Surely, this calls for more than O_2, CO_2, and CO indicators. Not only do we have requirements for highly sophisticated equipment, but trained personnel to work out the required procedures to handle such analyses. Such a task force cannot be generated overnight. It takes planning and cooperation to obtain such skills. We now have an insight into the requirements; what are we going to do about it?

CONCLUSIONS

Long duration toxicological studies under pressure have not been performed. One cannot make the assumption that all components undergo a partial pressure interaction with the body; however, any error made in this assumption may be offset by the fact that TLVs are based on an 8-hour day, 5 days a week, where saturation exposure is a continuous 24-hour day exposure. Such exposures under pressure could alter life patterns or have adverse long range health effects. We should not repeat a process which history has shown to be wrong. There are many illustrations to show that we should proceed with caution. Examples of a few of these are the use of carbon tetrachloride as a cleaning agent, bone necrosis seen in tunnel work and deep sea divers, and the effects of radium and thorium exposures among watch face painters.

One can also find many examples related to the components listed in Tables 2 and 3. Ethyl acetate, considered to be one of the less toxic solvents, has been reported by Lehmann and Flury (reference 18) to be the cause of death to a tank painter. There have been more than 140 deaths from benzene poisoning before 1959 (reference 19). Leukemia has been reported to frequently develop several years after discontinuance of exposure to benzene (reference 20).

Exposure to many of the components listed in Tables 2 and 3 have documented cases of irreversible damage to the heart, liver, kidneys, and nervous system.

Our needs for hyperbaric threshold limit values are urgent; however, such toxicologic data will not be available in the foreseeable future. Until such information becomes available, we should keep track of these trace components to minimize the effects on future saturation divers.

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SYNTHETIC MICROLUBRICATION OF RECIPROCATING COMPRESSORS

A Route to Gas Purity and Safer Conditions

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ABSTRACT

In the early 1960's, a program was initiated to develop microlubrication systems for reciprocating compressors. The initial systems were designed for chemical processing compressors utilizing chemically inert fluorinated silicone oils. The objectives of the program were to minimize contamination of the process gas streams and reduce maintenance.

By the late 1960's, the microlubrication was extended to air compressors to eliminate fire hazards and minimize oil and carbon deposits in compressed air systems, for example, for instrument use. Because of the extremely high price of fluorinated silicone oils, and because they will not adequately lubricate aluminum pistons often found in air compressors, other silicone/synthetic oils were developed in the early 1970's. Work is under way in developing systems for breathing air compressors.

With microlubrication of a non-lube air compressor, it has been possible to increase ring life from four months to greater than two-and-one-half years by feeding only one pint per year of silicone oil to the cylinder. This calculates to be an oil contamination level of only 0.0005 milligrams per liter of air, well below the tentative standard of 0.020 milligrams per liter for breathing air.

This paper covers the design of the microlube systems to reduce the synthetic oil fed to the compressor cylinders (in some cases reduced by 98%), the descriptions and properties of the various oil blends now being used, and field performance including service with a 3000 psi compressor for scuba diving air.

INTRODUCTION

Several problems are associated with lubrication of reciprocating compressor cylinders. With the most common approach -- standard force feed lubricators and conventional petroleum oils -- the extreme conditions in the cylinders can cause oil breakdown resulting in carbon and sludge build-up in the cylinders and elsewhere in the compressed gas system. Also, the lubricators which come with the compressors are usually designed to deliver excessive amounts of oil, causing a compressed gas contamination problem. Fires and occasionally an explosion can occur, particularly in air compressor service.

The other extreme -- eliminating all lubricating oil and equipping the compressors with self-lubricating piston rings and rider or wear bands -- can create valve corrosion and excessive ring wear. In some cases, the piston rings and wear bands have been known to wear out in a month or less.

A third approach -- microlubrication -- provides accurate metering of the minimum amount of oil required for adequate lubrication of the compressor cylinder walls. In this mode of operation, it is important to use a lubricator designed to feed small amounts of oil and an oil which will not break down in contact with the hot gases in the cylinder. Also, the oil should be non-volatile, resist thinning, and have good film retention in order to minimize the oil usage.

EARLY DEVELOPMENT - PROCESS COMPRESSORS

Contamination of the process gas streams resulting in reactor catalyst poisoning, coupled with high maintenance, costly production downtime and safety hazards, prompted the initial synthetic lube system development program at a major chemical company. The objectives of the program were two-fold:

1. To come up with a suitable oil for cylinder lubrication of reciprocating compressors which would resist solvent "washing" action, chemical breakdown, the thinning effect, and thermal degradation when in contact with chlorinated solvent vapors and acidic gases at elevated temperatures to 450°F. Also, the oil was to have sufficient film retention to allow reducing feed rates below the contamination level that would cause catalyst poisoning.

2. To come up with a force feed lubricator capable of accurately feeding the minimum amount of oil required for adequate lubrication of the compressor cylinder walls.

Physical properties and lab screening tests lead to the selection of a fluorinated silicone oil for the initial evaluation. Lube performance in production compressors correlated well with the lab tests and the results proved to be favorable (1),(2),(3),(4).

The force feed mechanical lubricators of these process compressors consisted of small (1/4" dia.) plunger pumping units mounted in an oil reservoir. There was a single pumping unit with sight feed for each point of lubrication (Figure 1). The lubricator shaft was connected to the compressor drive and geared down to a speed of 15 RPM or fifteen strokes per minute for the pumping unit plungers. The plunger stroke length could be adjusted to deliver a minimum of 0.001 cubic inches of oil per stroke. With this lubricator arrangement, the minimum oil feed to a compressor cylinder, even with only one lube point, was about twenty pints per month. This oil feed rate could not be tolerated with the high price of fluorinated silicone oil ($20.00 per pint) and, also, the oil contamination level was too high. For a 9" diameter piston with a 9" stroke length, running at 360 RPM, double acting, the gas stream contained about 4 ppm of oil, more than enough to cause rapid catalyst poisoning.

To reduce the oil to the compressor cylinders for these early installations, the lubricator shaft was geared down to a speed of 3 RPM and the plunger diameter reduced to 3/16". This produced a ten-fold reduction in the amount of oil fed to the cylinders. For a 9" x 9" x 360 RPM cylinder with one lube point, the oil rate could then be minimized at two pints per month and the oil contamination level at 0.4 ppm, a tolerable level with respect to the catalyst. The oil costs were still about $40.00 per month for a 9" x 9" compressor, but the savings were $175.00 per month in reduced compressor maintenance costs. These cost savings did not include savings in reduced catalyst poisoning and reduced production downtime.

For these early installations, in all cases the compressors were lubricated construction with iron cylinders, pistons, piston rings, and rod packings.

NATURAL GAS COMPRESSORS

The favorable results with synthetic cylinder lubrication of process compressors using very small amounts of fluorinated silicone oil led to an evaluation at a natural gas supply and storage company in 1969. This company had previously initiated a program of Teflon conversion in an effort to reduce the amount of lubrication required with consequent reduction of oil carry-over into the pipeline system. The results with reducing the amount of conventional hydrocarbon oil varied with compressor station location and with individual compressor units within one station. At one station, Teflon operated satisfactorily with no lubrication. At other locations, the Teflon materials lasted only five hundred hours without lubrication and two thousand hours (three months) with 25% of the normal amount of hydrocarbon oil still being applied to the cylinders(5). There is no one explanation to account for these variations.

One of the compressors experiencing high Teflon wear (two thousand hours life with reduced hydrocarbon oil usage) was picked for the fluorinated silicone evaluation (6). This compressor was a 1,000 HP unit with three 9" diameter horizontal pistons by 17" stroke length used to boost the gas pressure from 300 to 900 psig. There was a lube point on the top of each cylinder and on each rod seal -- a total of six lube points. All three pistons were equipped with Teflon rider or wear bands. New piston rings were installed using a different material on each piston: Teflon, bronze, and Bakelite. All three packings were Teflon with bronze back-up rings.

To minimize the amount of fluorinated silicone fed to each lube point, four of the six plunger pumping units were removed from the existing lubricator reservoir. The remaining two pumping units were used to feed oil to a divider block unit (Figure 2). The majority of the oil (90% to 95%) was returned to the reservoir and the rest divided equally between the six lube points on the compressor. A 900 psi back pressure balancing valve was installed in the oil return line to the atmospheric reservoir to maintain this line under pressure and thus prevent "short circuiting" all of the oil back to the reservoir. With this lubricator arrangement, it was possible to maintain a feed rate of only one-half pint per lube point per month. This amounted to a total of three pints per month to the six lube points on the compressor. This feed rate was only 2% of the normal amount of hydrocarbon oil fed.

The cylinders were inspected at five hundred and one thousand hours and showed no signs of excessive wear. At six thousand hours, the pistons were pulled and the rider bands and piston rings measured. Ring wear was acceptable for all material combinations (greater than 17,000 hours projected life) with only 0.003" wear for the Bakelite rings. This evaluation demonstrated that an adequate lube film was provided at silicone lube rates of only about one pint per 160 x 10^6 square feet of swept compressor cylinder surface.

AIR COMPRESSORS

Favorable results with microlubrication of process and natural gas compressors led to an investigation of the use of this technology for air compressor cylinder lubrication.

The initial evaluation involved a 9" x 9" reciprocating unit, all iron construction, single stage compression from atmospheric to 100 psi(7). Because of the high compression ratio, the air discharge temperature averaged 375°F. This high operating temperature caused hydrocarbon oil breakdown and carbon formation on the valves and pistons resulting in frequent fires and possible detonations. Again, fluorinated silicone oil was chosen for this evaluation program because of previous good experience in process and natural gas compressors and because of its fire-resistant properties. The flash point for this fluorinated silicone is above 500°F, the fire point 620°F, and the autoignition 890°F or higher. Use of this oil eliminated the fires and greatly reduced deposits on the valves which resulted in extended inspection and maintenance intervals.

Because carbon build-up and fires are fairly common problems with conventional petroleum lubricated air compressors, interest in synthetic lubricants for air compressor lubrication has been growing. Several synthetic lubricants have been under evaluation(8). Phosphate esters are used primarily because of their excellent fire-resistant properties. Their autoignition is about 1100°F. Phosphate esters, however, have poor software compatibility (attack rubbers, paints, and plastics) and they are not particularly stable with heat and moisture in the air. They also thin out and run off the cylinder walls of a reciprocating compressor at the elevated operating temperatures, which rules out their use for microlubrication. At least one explosion has been reported with excessive amounts of phosphate ester oil in a compressed air system(9).

Organic esters (diesters and polyolesters) are used for jet engine lubrication and are the most widely applied of all the synthetics today. They have improved fire-resistance, lower volatility, and better oxidation and thermal stability than conventional hydrocarbons. There have been some good reports on their use for reciprocating air compressor cylinder lubrication. At least one organic ester supplier, however, recommends checking software compatibilities as they will attack certain elastomers. There is little or no experience using these lubricants for microlubrication of air compressors. Reportedly, reductions in organic ester feed rates of 50% the conventional hydrocarbon oil rates are possible, but not nearly the ten-to fifty-fold reductions required for microlubrication. Because data shows the organic esters to be considerably more volatile than silicones, microlubrication development is continuing using the silicone lubricant family or blends of silicones and other synthetics.

One of the earlier air compressor applications involved a couple of fairly large two-stage air compressors producing plant air at 110 psig discharge pressure. The first stage piston was 22" in diameter and was made of aluminum. The second stage was 13-1/2" in diameter and was made of cast iron. The cylinders and piston rings in both stages were cast iron. The stroke length for the pistons was 10" and the speed, 450 RPM. Since fluorinated silicones are not acceptable for lubrication of aluminum, an alkylmethylsilicone blend was chosen as it is an excellent lubricant for aluminum and other hard-to lubricate metals and even superior to conventional hydrocarbon oil as demonstrated by the wear test results below:

4-BALL WEAR TEST

20 kg load, 167°F, 600 RPM

Materials	Alkylmethylsilicone Wear Scar (mm)	SAE 30 Petroleum Lube Wear Scar (mm)
Steel vs Aluminum	0.41	1.12
Aluminum vs Aluminum	0.89	2.69

The alkylmethylsilicone blend has a flash point above 500°F, a fire point above 600°F, and has thermal and oxidative stability at temperatures to 350°F, well above the 285°F operating tem-

perature for these compressors. In addition to reduction of carbon formation and improved fire protection, microlubrication with a stable oil was chosen to eliminate carbon monoxide formation and reduce the level of oil contamination as the air was occasionally used for breathing. It was determined that a total of 250 ml per day (approximately one-half pint per day) of this oil was adequate to lubricate both cylinders of these compressors. The majority of this oil is knocked out in the aftercooler as it is non-volatile, but even if all the oil were carried through in the airstream, the oil contamination level calculates to be 0.004 milligrams of oil per liter of air, which is well below the tentative standard of 0.020 milligrams per liter for breathing air (10).

Since these first two air compressors on alkylmethylsilicones, many other lubricated construction air compressors (metal rings) have been operating successfully utilizing alkylmethylsilicone/synthetic blends for cylinder microlubrication. These installations include 500 psi three-stage sootblower air compressors in electrical generation plants; several 100 psi plant air compressors of various sizes up to 34-1/2" diameter pistons; 50 psi, 28" diameter single stage glass blower air compressors in glass container plants; and 250 psi two-stage instrument air compressors in gas transmission stations.

At the gas transmission stations, each two-stage 250 psi instrument air compressor has a mechanical liquid trap in the discharge line to remove oil and water, followed by a single refrigerated filter to remove the remaining moisture. With hydrocarbons, the filter rapidly became saturated with oil carryover and the filter element had to be replaced in less than six months. There have been no filter problems or contaminates in the instruments since conversion to silicone microlubrication. In March, 1976, a filter which had been in service with microlubrication for a year was inspected and the filter element found to be clean and with no signs of oil contamination.

For compressed air applications where it is desirable to eliminate all oil contamination of the air stream, the trend is to convert compressor cylinders to non-lube construction (Teflon rings and wear bands). Under conditions of heavy loads, high operating temperatures, and continuous service, Teflon wear can be excessive, resulting in servicing of the compressors to replace rings and wear bands every three to six months. For these situations, silicone microlubrication is being investigated with an emphasis on feeding the very minimum oil to improve ring life, and for some of these applications, a

dimethylsilicone oil is being evaluated. Although dimethylsilicones are poor metal lubricants, they are excellent lubricants for Teflon, other plastics, and rubbers. Besides having low volatility (less than 0.5% weight loss after twenty-four hours at 302°F, good fire resistance (545°F flash point, 645°F fire point, and 810°F autoignition), excellent thermal and oxidation resistance (no breakdown or gel formation after 2,000 hours in an air oven at 400°F), very flat viscosity-temperature curve (Figure 3, Viscosity Comparison, Dimethylsilicone vs Hydrocarbon Oil), these silicones have very low toxicity and are used in cosmetics, skin creams, and food processing applications. Studies recently completed show that dimethylsilicones not only have a very low order of toxicity, but should also have minimal environmental effects (11).

For the non-lube air compressor application, where it is desirable to feed extremely small amounts of silicone oil, other means of applying the lubricant are under study. One method involves miniature pneumatically operated lube pumps which have a stroke length adjustment to deliver between 0.0002 to 0.002 cu. in. of oil per stroke or lube interval. The lube interval is controlled by a timer-air valve. With a four-minute lube interval, one of these lube pumps can meter as low as one pint per year of oil to a lube point on the compressor. Several of these miniature lube pumps can be mounted together and make use of a common lube reservoir and a common timer-air valve unit. Figure 4 shows a two-lube pump feed system.

Another means of feeding minute amounts of silicone oil to a non-lube compressor cylinder is with replaceable self-actuating automatic lubricators (Figure 5). Seating of the activating screw forces the activating pellet into the electrolyte. Galvanic action generates gas, expanding the bladder which pushes against the piston seal. Movement of the piston seal gradually discharges the lubricant from the reservoir at a relatively constant rate. When spent, the lubricator unit is replaced with a new one. One plant reports excellent results using these lubricators on 7" x 9" x 270 RPM single-stage double-acting non-lube compressors delivering air at 95 to 100 psi. These compressors have now gone two-and-one-half years without replacing Teflon rings or rider bands. Prior to silicone microlubrication, rings and rider bands wore out every three to four months. Two of these lubricators are used to feed oil to the compressor air suction. Each lubricator meters only one-fourth pint of oil over the course of the six months' lubricator life for a total oil feed to the compressor

of one pint per year. This calculates to be only one pint per 250 x 10^6 square feet of swept compressor cylinder surface and only about 0.0005 milligram of oil contaminate per liter of air if all of the silicone ends up in the compressed air stream.

Objectionable odors prompted an analysis showing impurities in compressed air used for scuba diving. This, in turn, led to a request a couple of years ago to develop a new compressor oil for this application. The compressor is a small three-stage reciprocator compressing the air to 3000 psi. Even though the compressor is equipped with special cooling, the third stage air discharge temperature exceeds 212°F.

Since the cylinders of this three-stage compressor are lubricated by a splash system using crankcase oil and there is therefore no absolute control over the amount of oil carryover, it was decided that using a USP (US Pharmacopoeia) grade mineral base oil which meets the requirements of FDA 121.1146 and is suitable for internal and medicinal applications would be the safest approach. Previous experience has shown that this oil, which is processed to be completely saturated, is quite stable chemically but is a poor lubricant. Rather than using chemical additives to improve the properties, small additions of pure silicones which have a low order of toxicity are added to the USP mineral oil to improve the lubricity (Figure 6) and the lube film strength and to act as a defoamant, thus minimizing oil carryover into the compressed air stream.

Results to date look very promising for this three-stage scuba diving air compressor application (12). There have been no oil losses and the air driers are free of oil carryover. Air samples have been analyzed using a highly sensitive Perkin Elmer IR Grating Spectrometer, Model No. 467, and there were no detectable contaminates in the compressed air stream.

More field experience and analysis work are planned to further substantiate the present excellent results using this oil for this application.

CONCLUSIONS

Silicone/synthetic microlubrication of compressors is showing great promise in reducing maintenance costs, eliminating fire hazards, and providing cleaner air for applications where good quality air is important, i.e. instrumentation and breathing air. Further field work and analyses are under way to assure the safest quality breathing air from compressors using silicone/synthetic microlubrication systems.

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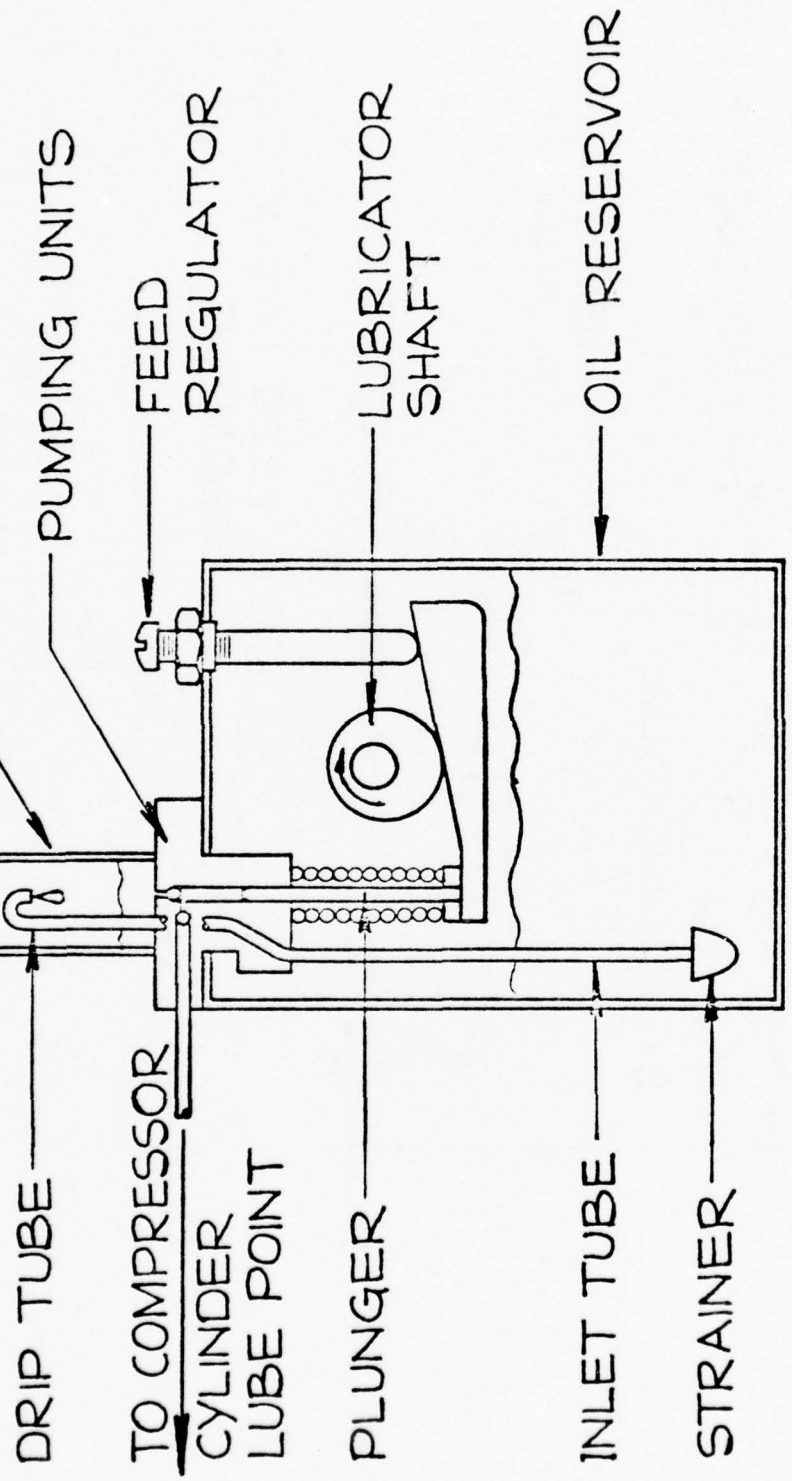
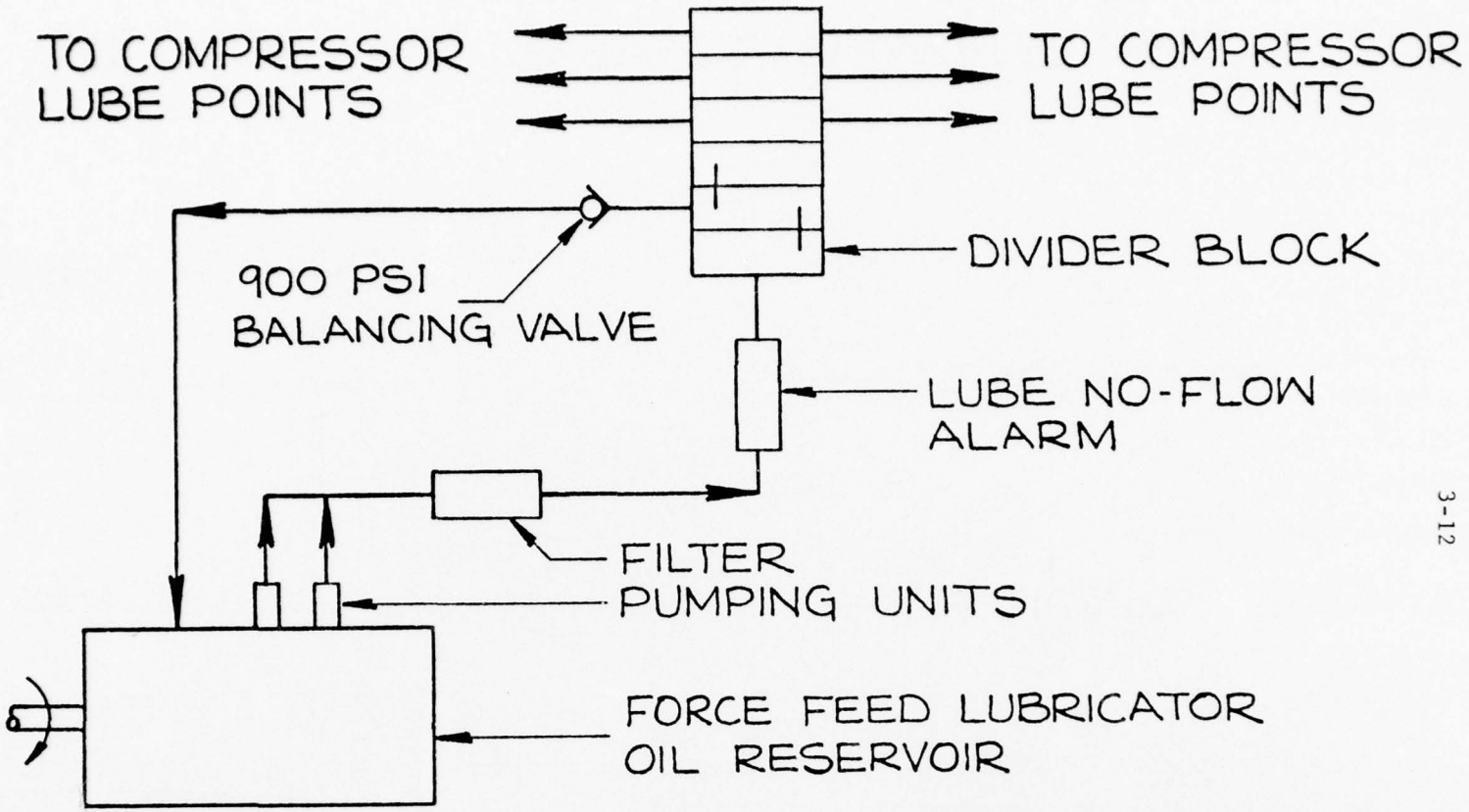
(12) Degrow, T., Seaquatics, Inc., Private Communications, 1975-1976.



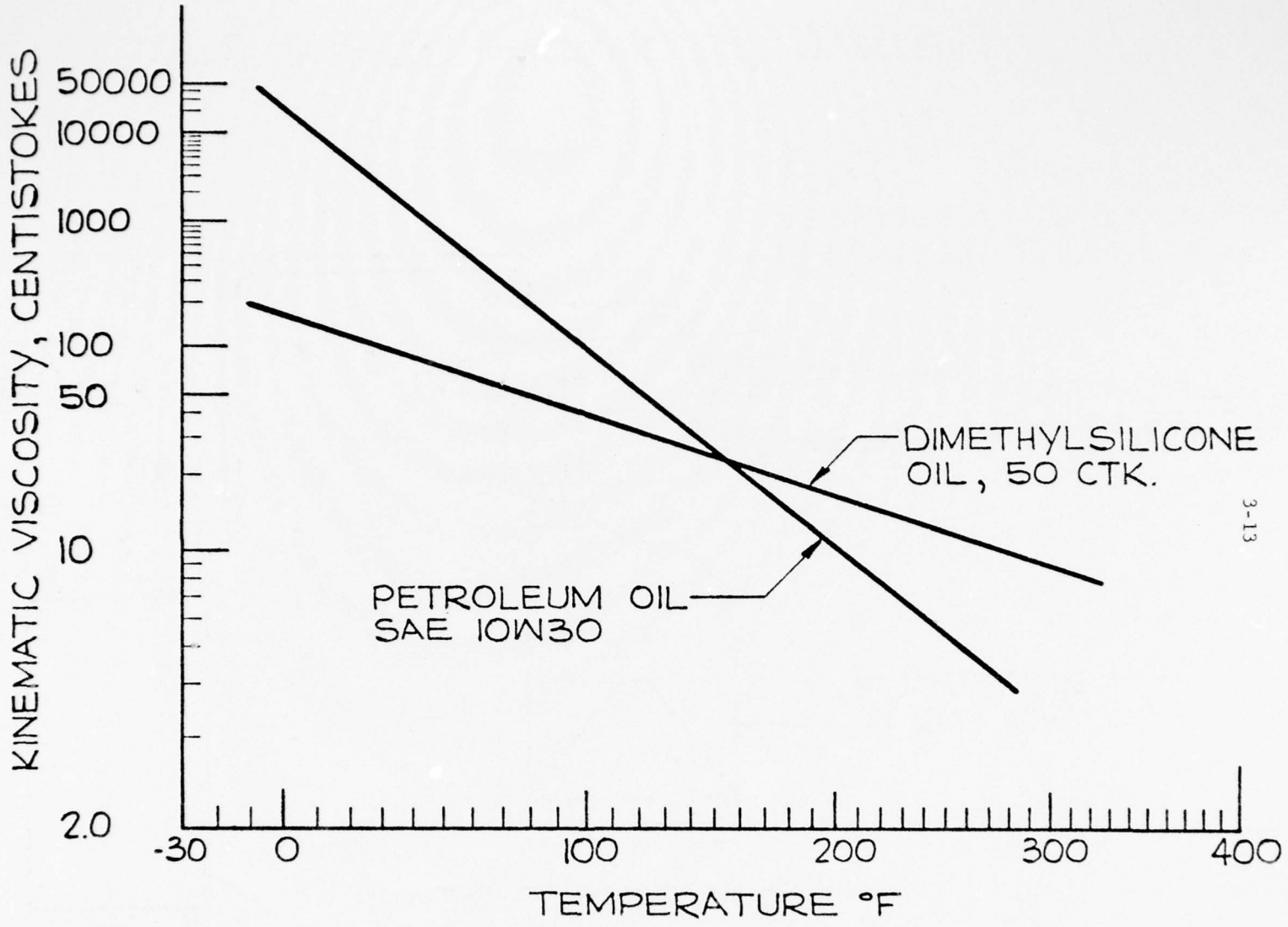
TYPICAL FORCE FEED LUBRICATOR WITH SINGLE PLUNGER PUMPING UNIT

FIGURE 1



MECHANICAL MICROLUBE SYSTEM

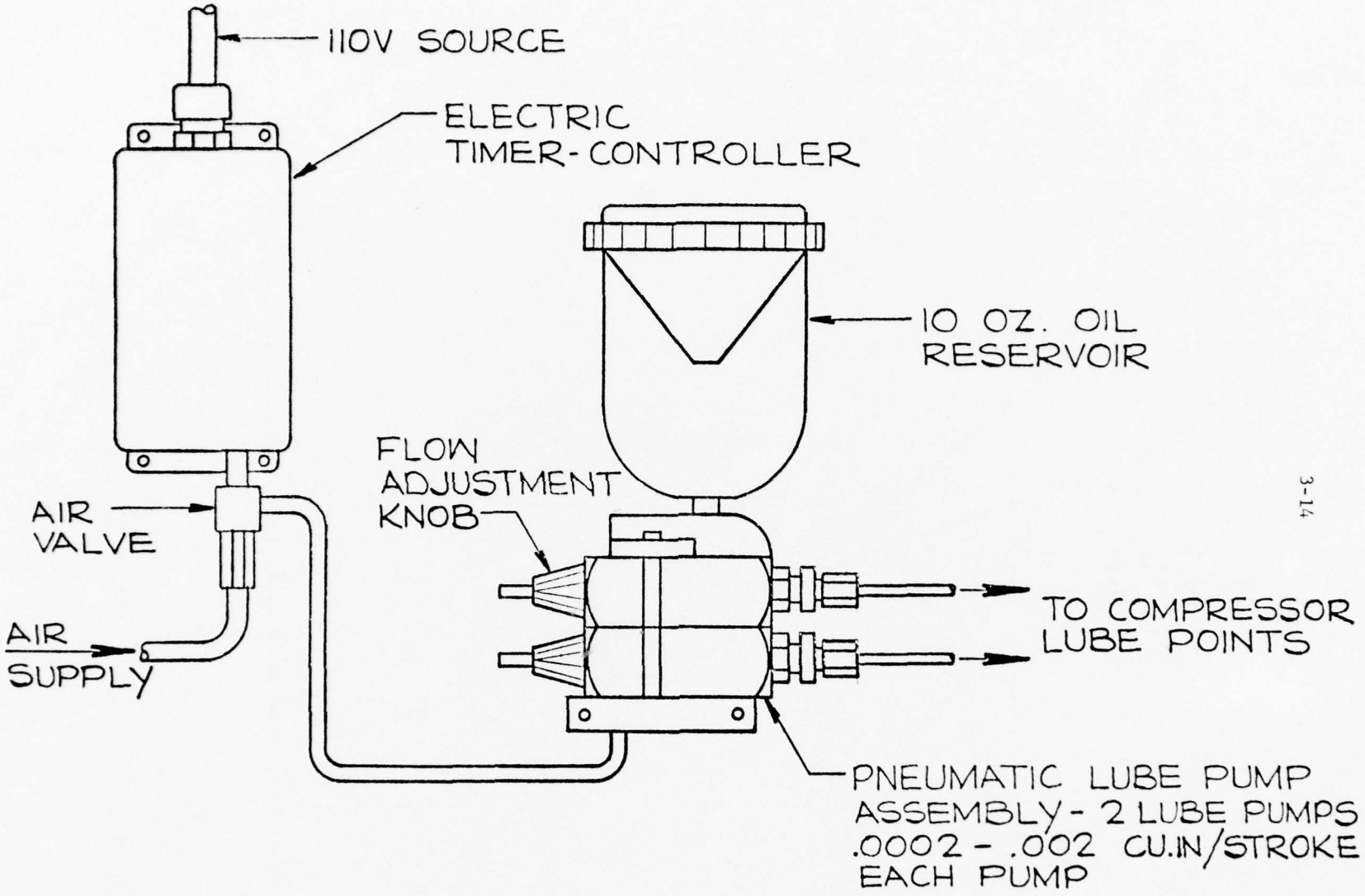
FIGURE 2



VISCOSITY COMPARISON

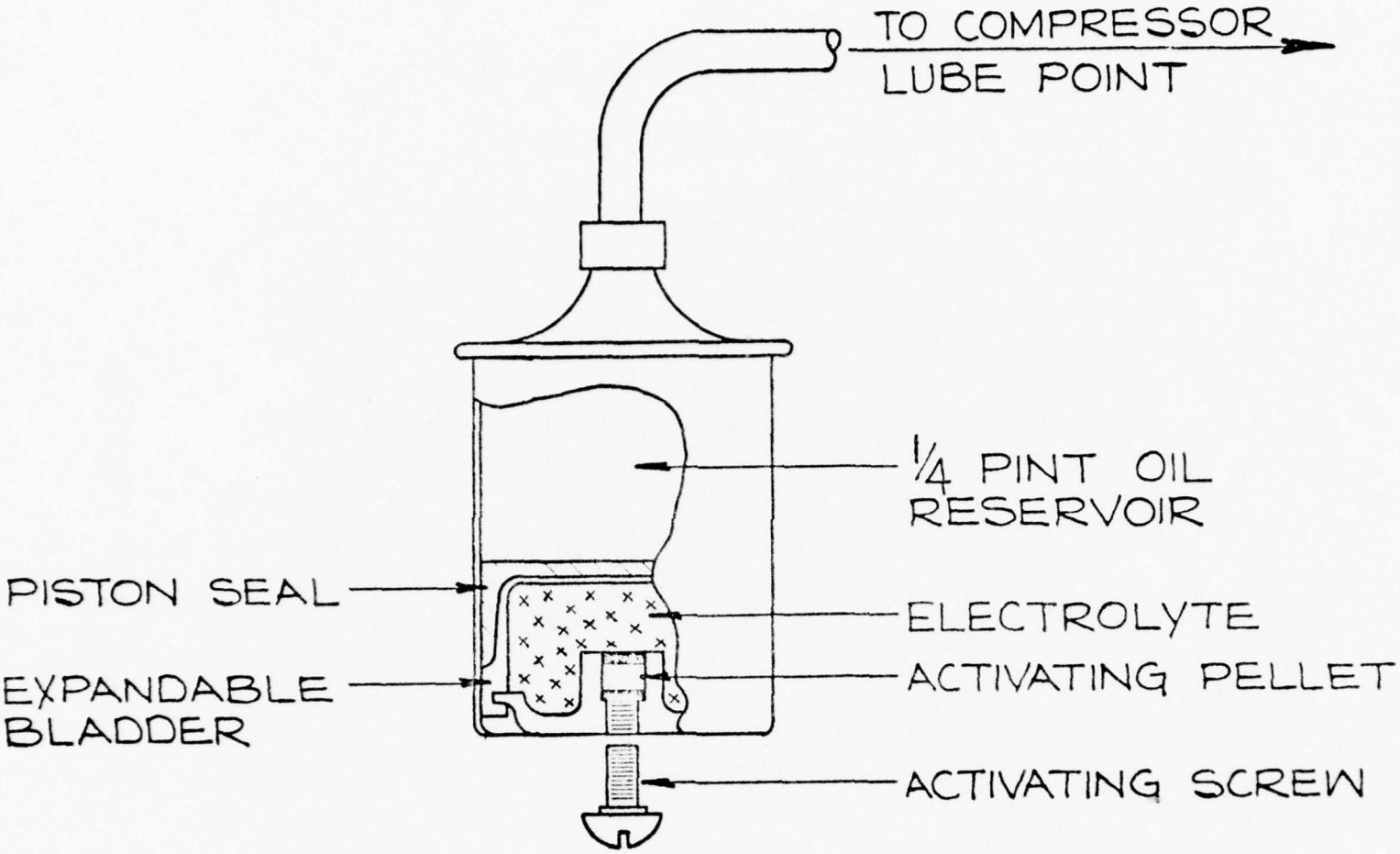
DIMETHYLSILICONE vs HYDROCARBON OIL

FIGURE 3



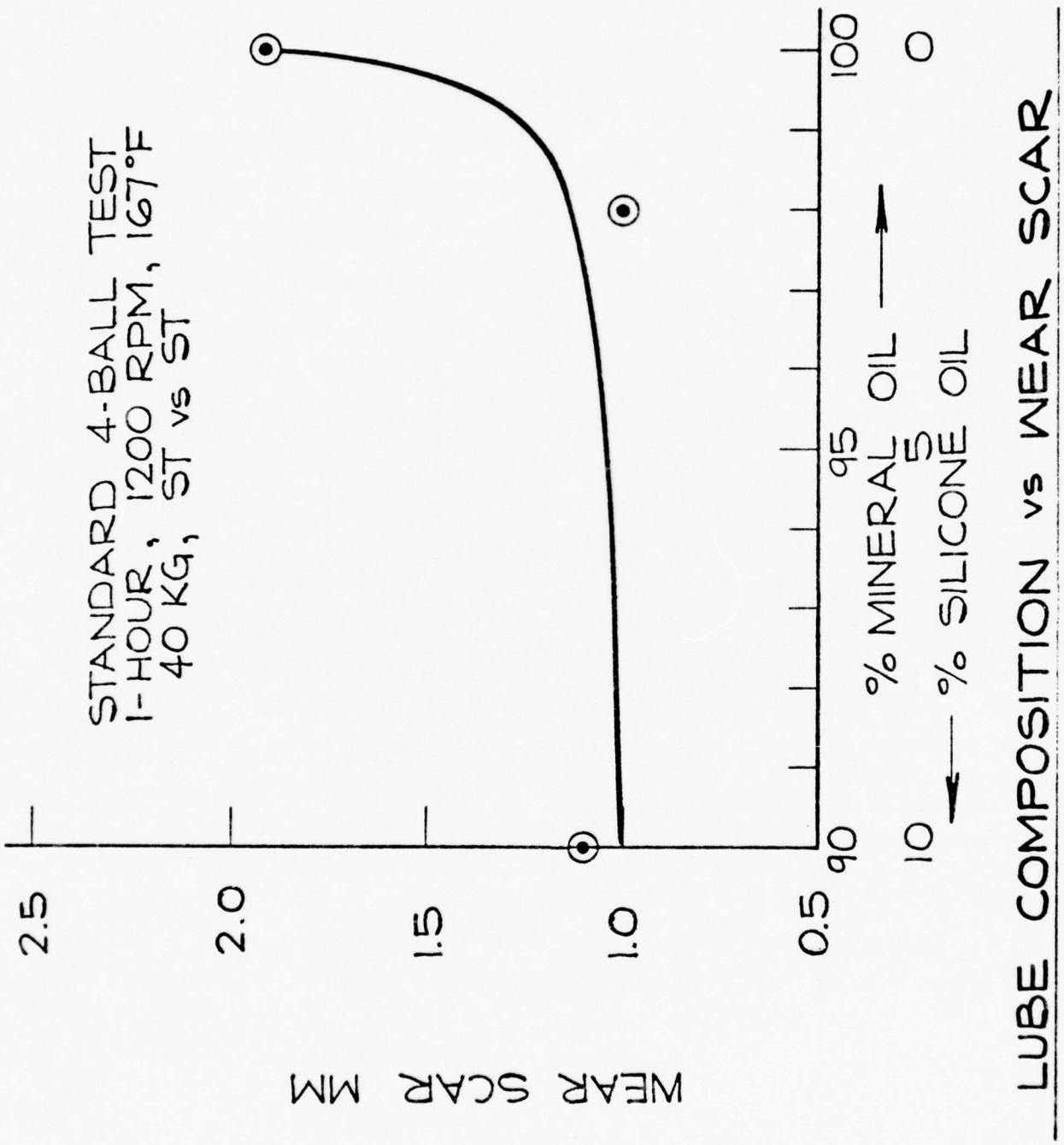
PNEUMATIC MICROLUBE SYSTEM

FIGURE 4



SELF-ACTUATING AUTOMATIC MICROLUBRICATOR

FIGURE 5



LUBE COMPOSITION vs WEAR SCAR

FIGURE 6

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FUNDAMENTALS OF RESPIRATORY AIR PROCESSING

by

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ABSTRACT

The proposed paper covers the essential aspects involved in respiratory air processing. It delves into the exacting cleanliness procedures that must be implemented by the manufacturer and the ultimate user and the cleanliness control that must be exercised during installation and throughout the life of the system, with special emphasis on periods of operation and maintenance.

The paper describes the three stages of the air purification process (compression, purification, and storage), and includes an analysis and discussion of the type of system that is required to process respiratory air safely and economically to the ultra high purity levels that must be achieved when supplying air to human lungs.

INTRODUCTION

Consider the following points: What constitutes a well-designed air purification system? What basic features should we look for? What can be done to assure the delivery of ultra pure respiratory air?

To start with, I am sure we are all aware that there is no such thing as a "breathing air" compressor. Ordinary air today contains dust, soot, hydrocarbons, and other impurities (such as CO) in varying degrees. Due to a particular set of circumstances, one or more of these contaminants may be present in such high concentrations as to constitute a health hazard. We must never forget for a moment that lungs are lungs, regardless of whether they are in a man who is working in a coal mine, boiler room, grain elevator, tar pit, or foundry, or fighting a raging fire in a smoke-filled chemically toxic plastics plant. Assuming an "ideal" compressor--one that will not add contaminants during compression--the air it delivers will be no better than the air it took in. However, all the contaminants initially present in the atmospheric air are now present in the compressed air in highly concentrated form. Hence not even the best compressor by itself can deliver air that is safe to put in a person's lungs. Many compressors are equipped with filters and called "breathing air" compressors. A filter will only remove solid particles and suspended liquids. It will not remove oil vapors, gaseous hydrocarbons, and toxic gases. Therefore, a compressor equipped with a filter is <u>not</u> a "breathing air" compressor. It must be used in conjunction with a purification unit.

Purification is an overall process, consisting of three stages, which are compression, purification, and storage. Compression not only permits storing the air in a reduced space; but, more important, prepares it for the second stage: purification, which is the removal of <u>all</u> harmful matter. Filtration is one of the stages of the purification process, but filtration alone is <u>not</u> purification. It must, therefore, be concluded that compression and purification are separate steps of a process, and neither one alone can produce acceptable respiratory air - air that is pure enough to put into people's lungs intentionally. Let us take an in-depth look at the three processing steps.

STEP ONE - COMPRESSION

Compression makes it possible to store air in a reduced space; but even more importantly, it prepares the air for the second step in purification, which is accomplished by "squeezing out" the contaminants. The higher the pressure, the more contaminants are squeezed out - as in wringing out a wet sponge. The most economical pressure for processing air to ultra high purity levels is in the pressure range of 3800 to 3500 PSI. For this reason, it is important that the compressor have a maximum pressure rating of no less than 3000 PSI. The compressor should be equipped with an intake filter, automatic start-stop pressure switch, high air temperature shutdown switch, low oil level shutdown switch, and pressure gauges. It should also have following each stage, condensate traps (preferably with automatic drain system) intercooler or after-cooler, and safety valves. A timer and solenoid should also be used to activate dumping of the third- and fourth-stage after-coolers at timed intervals (approximately every 30 minutes) while the compressor is running.

The choice of the compressor itself is all-important. We hear a good deal today concerning oil-free compressors, some of which use Teflon piston rings, and diaphragms, to name a few. There is no doubt that all of these non-lubricated compressors rightfully belong in the industrial world. However, it is when they are misapplied that problems develop. We must constantly ask ourselves what is the application? What is the need we wish to fill? Extremely high temperatures created by friction cause Teflon to outgas at approximately +450°F. This outgassing produces carbon, carbon monoxide, and other harmful toxic gases. A diaphragm is highly expensive initially and, because of its general design (which is basically a series of thin partitions bonded together), is vulnerable to breaking when exposed to the rigors of continuous flexing and unflexing under high-pressure and high-temperature conditions. Water-lubricated compressors are very expensive to maintain since they require large quantities of deionized water.

Another problem is that of leaky seals, which will cause water to be pumped into the purification system. The best choice, therefore, from a standpoint of long compressor life and low-cost maintenance is an oil-lubricated compressor. After all,

if there were an acceptable substitute for an oil lubricant for high-friction, high-temperature engines, we would use it in automobiles. A non-detergent mineral oil should be used for the break-in period, after which it should be replaced with Anderol 500 which is a synthetic, and most ideally suited for this type of application.

Once the choice of a compressor has been made, careful consideration should be given as to the location in which it will be installed. If the compressor intake pipe is to be inside the building, the area should be well removed from all possible sources of contamination, such as motor vehicle exhausts, furnaces, smoke, fumes, sewers, and such operations as sandblasting, painting, and welding. Furthermore, the intake pipe itself should be 8 feet or higher above floor level and at least one size larger than the compressor intake port. When running the intake pipe outdoors, it should be equipped with a filter to stop solid particles; and it should be hooded to keep out windblown dirt and rain, insects, etc. You don't have to take out what you don't put in!!

STEP TWO - PURIFICATION

Purification, the second step of the air process, is the removal of all harmful matter. What matter is harmful depends upon the end usage of the product. In the case of compressed air for human respiration, purification is an overall process which consists of filtering out solid particles, removing all liquid contaminants (water and oil), removing vaporized and gaseous contaminants (water and oil vapors, gaseous hydrocarbons, noxious gases) to established levels, and eliminating all unpleasant odors. Anything less is NOT purification. It is important to note that while filtration is a necessary phase of purification, filtration alone is not sufficient. Filtration alone will NOT make air safe for breathing purposes.

The only means of accomplishing the required degree of purification efficiently is through mechanical separation and adsorption under pressure. As has been pointed out, a pressure of no less than 2800 PSI is mandatory for economical processing to the specified purity level. It is not possible, with any degree of practicality to purify low pressure "plant" air.

Maximum flow through a purification system should not exceed 20 standard cubic feet per minute (SCFM). The rate of flow at which air passes through a system is known as "dwell time," which is a most important factor in achieving maximum contaminant removal.

Thus, a respiratory air purification unit must include all the equipment necessary to achieve total purification of the compressed air so that it at least meets the already-mentioned minimum air quality levels. Primarily, the unit must consist of a mechanical device to remove liquid water and oil and to filter solid particles to at least 10 microns (nominal), a device for removal of water and oil vapors and noxious gases, and a device for removal of odors. A dewpoint of at least -80°F should be maintained, as the greatest problem in relation to the processing of compressed respiratory air is moisture. Excessive moisture encountered during the air purification process can cause the contaminants that have been adsorbed to flush downstream, causing contamination of the entire system. In addition, moisture causes the formation of scale that is extremely harmful to the inside of air receivers, and to control valves and regulators. Other devices that should be a part of any purification system are those that will eliminate obnoxious odors and that will convert deadly carbon monoxide to carbon dioxide, which can be tolerated without ill effect in much higher concentration than CO.

To safeguard efficient performance, the unit should also have inlet and outlet shutoff valves, a back pressure valve, a bleed valve, and a pressure gauge. To ensure operating safety, a relief valve must be included, as well as some type of visual and/or audible alarm that will signal the need for operator attention. Highly desirable also is an automatic drain system for waste liquids, and a second gauge for indicating pressure upstream of the purification unit (at the compressor outlet).

A question might be raised at this point regarding the need, or even the desirability, of all this equipment. It is, of course, a fallacy to maintain that the more accessories a unit has the better it is or the safer it is. Everyone will agree that each item must make its own specific contribution to the overall operation; if it does not, it should not be included. Conversely, it would be foolish indeed to attempt to do without

any item which DOES play a part in ensuring operating safety or the quality of the output air. One does not gamble with human lives!

STEP THREE - STORAGE

Once compressed and purified, the air is generally stored in a large stationary receiver or cascade system, from which it can be withdrawn as needed - usually to fill portable compressed air cylinders. Proper storage, the last stage of the process, makes an important contribution to the overall result.

Stationary air receivers (or accumulators) are classified as "unfired pressure vessels" and must conform to the ASME Code for Unfired Pressure Vessels, which specifies a 4-to-1 safety factor. ICC or DOT cylinders do NOT meet the requirements of the Code. The receiver should be equipped with a pressure gauge and with a valve that meets the CGA code for Standard Cylinder Valve Outlet Connections for Human Respiration.

It is important to bear in mind that receivers or cascade bottles should be used for the storage of purified air ONLY. They should never be filled with unpurified air directly from the compressor. Air receivers that are filled with contaminated air gradually become pitted and corroded causing the cylinder to become sufficiently weakened, reducing the safety factor which existed when the cylinder was new. In addition, rust and scale can find its way downstream causing malfunction of control valves, regulators, etc.

When, rather than store the processed air, it is necessary to pipe it to the point of usage (as in a hospital or industrial plant), the purified air can be regulated to a convenient pressure for transmission through existing lines--if these are compatible with respiratory air. Depending on the length of the lines, it may be necessary to install one or more secondary single-unit purifiers in order to maintain air purity.

GENERAL REQUIREMENTS

Performance and safety requirements of the equipment which comprises the compression, purification, and storage stages of the air process have already been set forth. However, it is equally important that attendant hardware be of a quality and type compatible with the intended usage and that plumbing and electrical connections be performed in accordance with national and local codes by competent technicians who are thoroughly experienced in their respective fields. A bad tube flare or an improper bend can cause serious problems. The same can be said of a deficient electrical system which can, in addition, invalidate fire insurance.

For these reasons, it is important that correct size wire be used and that the compressor's motor be protected by a circuit breaker or fuse with a capacity at least three times the motor's amperage rating.

Similarly, inlet and discharge lines should be of the proper size so as not to restrict flow at any point. Inlet piping should be one size larger than the diameter of the compressor inlet port; lines should be braced at 16-inch intervals and should preferably be no longer than 10 feet. Drain lines, if extended more than 3 feet, should also be stepped up one size so as not to restrict the exit of waste matter.

On the downstream side, only clean stainless steel tubing (not copper or iron) or non-toxic, non-shedding hose (no longer than 36 inches) should be used. All tubing and hose must be of the correct pressure rating and should be securely anchored or restrained about every 16 inches to prevent a "whipping" action in the event of rupture and to minimize vibration which may loosen fittings.

Good operating practices and the highest possible standards of cleanliness should be observed throughout all phases of the air processing function. Leak-checking should be a continuing practice and should be done with an inert leak detector, such as Sherlock Five-Second Leak Detector. Soapsuds, for example, should <u>NEVER</u> be used.

Contaminants can enter a pressurized system through loose connections or even through minute pinholes in vessels or tubing. If there is any reason even to suspect that any portion of the processing system has become contaminated, that portion and everything downstream must be completely disassembled and thoroughly cleaned. Whenever a system is dismantled to provide periodic maintenance, all threaded areas, and O-rings should be lightly lubricated with an inert lubricant. Inert means that it is deficient in active properties that could contaminate the system.

If I have done my job, then it should be crystal clear to you that the most important factor of all is that pure air processing equipment should be selected <u>not</u> on the basis of <u>low initial price</u> but on the basis of <u>low ultimate cost</u>. The following items should be thoroughly investigated before a final decision is reached as to what type of equipment to procure.

1. Does the initial price include all the components that are necessary to make up a complete and efficient package?

2. How many cubic feet of air can be processed on a set of cartridges and to what purity levels? (This should always be designated. Test Reports conducted by an independent test laboratory should be insisted upon.)

3. What is the longevity of the equipment? What are the maintenance costs involved? Is cartridge changing fast and simple?

4. How long has the manufacturer been in business?

The above questions should be asked by the prospective buyer and he should insist on getting bona fide answers. Pure air processing equipment is a life support system that is going to sustain the recipient in a toxic or oxygen-deficient atmosphere. The procurement of the right kind of equipment could make the difference between life and death, and to undertake such a major purchase in the same manner as the purchase of a box of nuts and bolts seems ludicrous.

In closing, let me say I hope that I have been at least partly successful in conveying to you that an air processing unit is not just a piece of hardware. Rather, it is a means of obtaining a desired end product--which in this instance is pure, safe, breathable air. This cannot be accomplished by a compressor equipped with a filter (as distinguished from a purification unit) or by attempting to purify low pressure plant air. The air processing function involves the correct selection, installation, operation, and maintenance of an integrated unit that will compress atmospheric air, purify it under pressure, and store the purified air ready for usage.

COMPRESSOR-PRODUCED GAS CONTAMINANTS

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ABSTRACT

Oil lubricated compressors operated under normal conditions can deliver acceptable air for breathing. However, with time or lack of proper maintenance, two things are likely to happen. Ring wear will permit increased quantities of oil to enter the air stream. Secondly, valve malfunction, leakage or failure will result in an excessive compression ratio in one or more of the stages. The high compression ratio can cause "dieselizing" of the oil to occur, producing potentially lethal quantities of carbon monoxide. Further, most filter systems often used on breathing air compressors effectively remove oil and odors but do not remove carbon monoxide.

Consideration is given to air or gas purity as affected by compressor-generated heat in situations where increased heating may occur due to minor but common types of compressor malfunctions. Comparative evaluation of oil lubricants as well as oil free compressors used to pump breathing gases and "state of the art" of non-lubricated compressors are discussed.

INTRODUCTION

Piston type air compressors have been used to supply breathing air to divers since the turn of the century. For most underwater work air compressors delivering 50 to 250 psi by hose to the diver have met the need. The invention of air supplied self contained underwater breathing apparatus (SCUBA) in 1943 brought forth a new requirement. To carry sufficient air on the diver's back, it must be compressed and stored at high pressures. Storage tanks in use today are rated at 1800 to 4500 psi pressures. Compressors designed to deliver these higher pressures are necessarily more complex, and the number of failure modes is correspondingly increased.

Because both military and civil objectives require tasks increasingly achieved by the use of diving, equipment safety and reliability has come under close scrutiny. Identification of areas of concern and consideration of new design criteria will result in greater safety and will prove cost effective due to lower insurance rates and reasonable safety laws by legislators.

This paper discusses situations in which toxic gases, in particular carbon monoxide, are formed by compressors used to provide diver's air.

All compressors which use oil to lubricate the compressor pistons can generate carbon monoxide as a result of a malfunction, misuse, or poor condition. Further, malfunctions that result in carbon monoxide production can occur suddenly or intermittently and without visible change in the compressor's operation. Non lubricated or oil free compressors eliminate the problem.

While oil lubricated compressors are used extensively to provide both high and low pressure breathing air for diving, there are very few, if any, documented cases of diver fatalities directly attributed to compressor generated carbon monoxide. However, the possibility exists and, in fact, appears likely in older or poorly maintained compressors.

Diving accident data to date is not sufficient to determine the extent of this problem. John McNaiff, Director of the National Underwater Accident Data Center at the University of Rhode Island states that very few accident reports are on file in which air analysis was done. Analysis equipment to determine carbon monoxide content of the blood or a gas sample has been available to laboratory pathologists for only the past year or two.

Most diving fatalities are attributed to drowning caused by in-

adequacy of the diver, his training or his equipment. The circumstances leading to drowning are more evasive. Without an air analysis and blood test for carbon monoxide, the possibility of carbon monoxide poisoning incapacitating the diver, or causing unconsciousness, followed by drowning, cannot be ruled out. Carbon monoxide is a subtle poison; it has no odor, taste or color. It often causes blackout without warning, although sometimes unconsciousness is proceeded by a feeling of well being, headache, nausea or dizziness. There is disagreement among medical experts both as to the mechanism of poisoning and the point at which incompacitation occurs at the surface condition; the effects when complicated by cold and pressure are even less known. A growing awareness of the possible problem is causing organizations, such as the National Underwater Accident Data Center, to obtain air analysis and blood tests in diving accidents where possible. Consequently, the extent of the problem will be better known within the next few years.

CRITERIA FOR CARBON MONOXIDE FORMATION

Two conditions must be present to cause carbon monoxide formation in a compressor:

The presence of oil in the compression cylinder
and
Sufficiently high temperature to cause the oil to react (burn) with the air in the cylinder

Oil lubricated compressors always have oil present on the cylinder walls. In designing oil lubricated breathing air compressors, consideration is given to keeping the presence of oil to a minimum and keeping air and cylinder temperatures low. Because of the rapid rate of compression, compressor air temperature approximates that of adiabatic compression of an ideal gas, as given by the formula:

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{K-1}{K}}$$

where

T_2 = discharge temperature (absolute)

T_1 = inlet temperature (absolute)

P_2 = discharge pressure (absolute)

P_1 = inlet pressure (absolute)

K = ratio of specific heats (1.4 for air)

Figure 1 shows compression cylinder discharge temperature vs compression ratio (P_2/ P_1) for air with an inlet temperature of 120°F, based on the above formula. Also shown are the typical temperature ranges where oils will ignite and burn as well as a range of typical compressor compression ratios. For example, a three stage compressor delivering 3000 psi will have a minimum C.R. (compression ratio) of 5.85 to 1, in practice it may be somewhat higher, in the range of 6.5 to 7. By comparison, a minimum C.R. to achieve auto-ignition is about 10 to 1.

It is evident that with good design and normal conditions, auto ignition temperatures are not reached. However, a variety of malfunctions can create ignition temperatures. These include:

a) Restriction of the compressor intake

This could result from a clogged or dirty inlet filter, a kinked inlet hose, undersized or extended inlet piping or other restriction at the compressor suction. The compressor is then required to pump air from lower than ambient pressure. Because of fixed compressor geometry and cylinder size, reduced inlet pressure proportionately reduces interstage pressures. Consequently, the final compressor stage has to make up the difference with a proportionately higher C.R. If, for example, the inlet pressure is reduced by 50%, the final stage C.R. will double, resulting in high temperatures and auto-ignition.

b) Interstage leaks

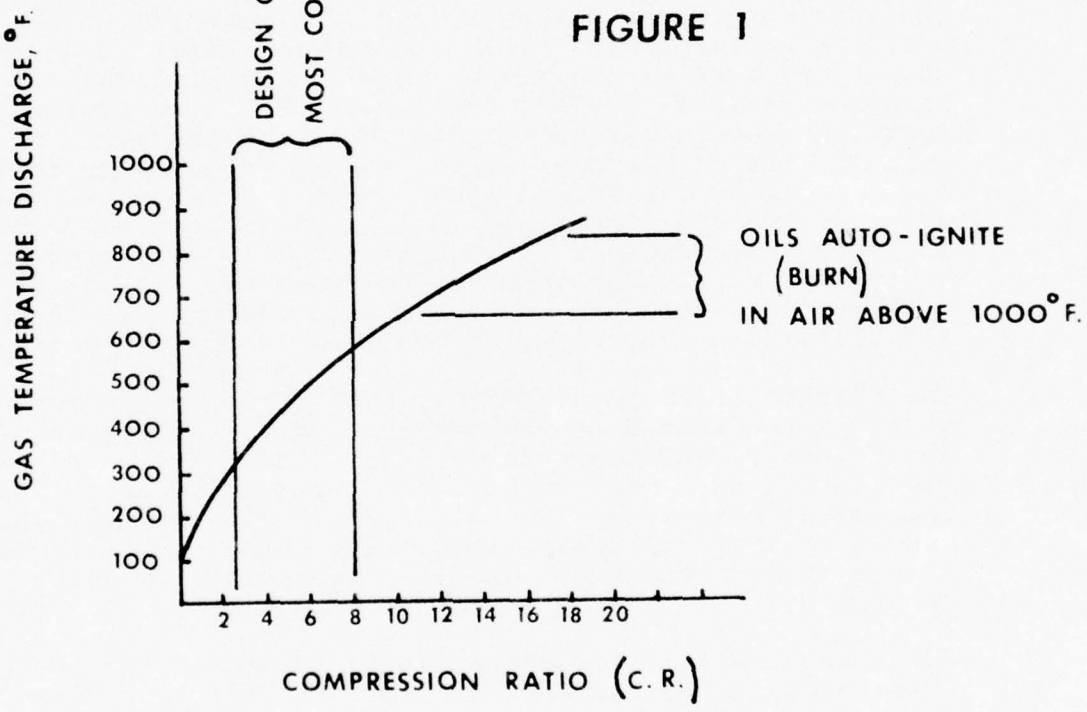
Leaks from interstage piping, vibration loosened fittings, head gaskets, or excessive piston blow-by, will result in reduced pressure available to the final compression stage and proportionately higher final stage C.R.

c) Compressor valve leakage or failure

Poor operation of the first stage valves can result in reduced pressure to following stages and a nearly proportionately higher C.R. in the final stage. Failure of valves in the following stages imposes a higher discharge pressure and C.R. on the next lower stage. Relief valves between all stages will prevent a hazardous condition resulting from valve failure with exception of valve failure in the first

COMPRESSOR GAS TEMPERATURE V.S. COMPRESSION RATIO

FIGURE 1



stage. First stage valve failure will result in a reduced pressure to each stage throughout the compressor, except at the final discharge outlet.

d) General overheating

Operation of the compressor outside of its design can directly or indirectly be the cause of CO production. High ambient temperature with marginal cooling fin area can result in excessive cylinder temperature. An inoperative cooling fan, loss of cooling water, blocked cooling air passages or inadequate cooling between stages of the air being compressed can also result in auto-ignition temperatures.

LUBRICANTS AND THEIR EFFECT ON AIR PURITY

Oil lubricated compressors always have some oil on the cylinder walls in contact with the air being compressed. Under normal operation, some of the oil mixes with the air. The oil itself is not a serious problem. Any number of filter systems will effectively remove oil vapors and odors. In the event of filter failure, the oil vapors can be readily detected by smell or taste and remedial action taken. When the filter is operating properly and the compressor is not, sufficient temperatures can be reached to decompose or ignite the oil, resulting in serious toxins, primarily carbon monoxide. However, the normal recognizable indicators of compressor malfunctions, taste and odor, are filtered out by even the most simple filter system.

The flashpoint is more commonly considered in the selection of oils. It is defined as the temperature of the liquid oil at which sufficient vapors are given off to flash when a flame is applied. It is a measure of the volatility of the oil and not thermal stability. A more volatile oil (lower flash point) will result in more oil vapors in the air being pumped, however, it is not an indication of the oil's resistance to carbon monoxide production.

Perhaps the most important property to consider in compressor lubricants is the auto-ignition point. This is defined as the temperature at which oil, mixed with air, will burn without the aid of an ignition source. Usually, this temperature is slightly lower in high pressure air than in air at ambient pressure. Specification sheets normally show auto-ignition temperatures at ambient pressure.

Numerous other properties are significant in selection of compressor lubricants such as viscosity, viscosity index, lubricity, oxidation resistance and pour point, however, these are given minor consideration here since our primary concern is thermal stability and resistance to ignition.

Figure 2 shows a number of lubricants reviewed as possible candidates for breathing air compressors. The classes of lubricants listed include all acceptable possibilities.

Following the table is a brief discussion of the individual lubricants.

a) Mineral oils

Mineral oils are the most widely used compressor lubricants. They are economical and the most common of lubricating oils. They are the base stock for automotive oils as well as compressor oils in general use with the exception of the newer synthetic oils. Certain fundamental rules exist for mineral oils by which thermal stability can be characterized. In straight-chain hydrocarbons, short alkyl chain lengths ordinarily produce high thermal stability. As chain length increases, as in the Pennsylvania paraffin oils, thermal stability decreases. Simple aromatic structures are more thermally stable than straight-chain compounds. Despite these variations, auto-ignition temperatures of different mineral oils varies only slightly.

b) Vegetable oils

Vegetable oils, such as castor oil, have been used to a limited extent in breathing air compressors. The reasoning is that lung tissues will more readily absorb inspired vegetable oil vapor. This is of little real advantage since oil vapors are easily filtered from the air. The real problem of thermal degradation exists equally with mineral and vegetable oil. Also, the low oxidation resistance of these oils result in gum and sludge formation.

c) Ester-base oils

Synthetic ester base oils have been in use in aircraft and other special applications for over 30 years and are excellent lubricants. Compared to mineral oils, they have superior lubricity, viscosity index, oxidation resistance and thermal stability. Recently, they have become widely distributed for automotive and compressor lubricants. Auto

COMPRESSOR CYLINDER
LUBRICANT DATA

LUBRICANT OR CLASS	AUTO IGNITION POINT	FLASH POINT	LUBRICITY	MANUFACTURER OR DISTRIBUTOR	TYPICAL COST PER GAL.
MINERAL OIL	650 – 750	400 – 550		BRAY OIL CO.	$4
VEGETABLE OILS	650 – 750	400 – 650	POOR TO FAIR		$10
ESTER BASE	700 – 800	450 – 550	VERY GOOD	BRAY OIL CO.	$20
SILICONES	700 – 800	500 – 600	POOR TO FAIR	DOW CORNING	$40
HALOCARBONS	——	——	GOOD	DUPONT	$1000
POLYPHENYL ETHER	1100 – 1150		GOOD	MONSANTO CO.	$400
SILANES	900 +	——	——	——	——
SOAP SOLUTION	650 – 750	——	POOR	——	——

FIGURE 2

ignition temperature is only slightly above mineral oils so the advantage in preventing carbon monoxide production is marginal.

d) Silicone oils

Silicone oils have somewhat more thermal stability than either mineral or ester based oils. However, they have auto-ignition temperatures comparable to ester oils. The poor lubricating properties of the pure silicone oils prevent their general use in machinery. Silicones have been blended with additives to improve lubrication but these products are questionable as far as toxicity is concerned.

e) Halocarbon oils

These chlorinated and/or fluorinated oils have had limited use in oxygen compressors where their complete non-flammability is a singular advantage. Decomposition into various other halocarbon components can occur at temperatures above 500°F. Since these components can potentially be extremely toxic, the manufacturers recommend that halocarbon oils not be used in breathing air compressors.

f) Polyphenyl ether oils

With auto-ignition points above 1000°F and thermal stability in excess of 800°F, these are the only oils the author has found that could offer a solution to possible oil ignition in compressors. The oils require a compression ratio of 46 to 1 to ignite. The molecular structure consists of aromatic rings linked by oxygen molecules, oxygen links inherently provide high thermal stability. Monsanto manufactures a five ring polymer (05124). Cost is high (in the neighborhood of $400.00 per gallon). A second disadvantage of the five ring polymer is its pour point of +40°F preventing its use below 40 or 50°F. Monsanto previously manufactured a four ring polyphenyl ether polymer with a more reasonable pour point of +10°F, however, this product is no longer in production. The author has successfully used the four ring polymer in small portable compressors where minimal oil consumption reduced the cost disadvantage.

g) Silanes oils

Silanes differ from silicone oils in that they are not a polymer, but a single silicone atom surrounded by aromatic or alkyl radicals. They closely follow the polyphenyl ether

oils in high temperature stability and, in general, have adequate properties for a lubricant. With high thermal stability, particularly associated with the aromatic radical silane, this material is a possible candidate for a "safe" compressor lubricant. The author currently knows of no one that produces these compounds in a suitable lubricant form. As with the polyphenyls, manufacturing cost appears to be excessive.

h) Soap solutions

Soaps and detergents are organic compounds and, in general, have somewhat less thermal stability than oils. Consequently, they are subject to auto-ignition in a compressor. In view of this as well as their generally poorer lubricating properties, they are seldom used.

TESTS AND DATA

A number of simple tests were run to determine when carbon monoxide might be formed in a compressor. The first series of tests used an older, surplus 1000 psi, 0.8 SCFM unit of the type occasionally adopted to filling SCUBA tanks. The compressor passed oil at a rate of about 1 or 2 oz. per hour. Such oil usage rates are not uncommon for worn compressors. It was determined, most of the oil entered the air in the 1st stage, thus the air/oil mix entered the second stage. Figure 3 shows when evidence of auto-ignition occurred. At the onset of auto ignition, occasional "knocking" could be heard as well as a sudden, extreme increase in carbon monoxide. At other times, substantial quantities of carbon monoxide were produced without any noticeable change in compressor operation. Also shown are test conditions involving lower compression ratios where smaller amounts of carbon monoxide were formed, probably due to general thermal breakdown of the oil rather than ignition and burning. The internal compressor cylinder wall temperature was estimated at 200°F. Three oils were tested as follows:

a) Test oil #1 - mineral oil

A medical grade mineral oil of approximately SAE #20 weight, flash point 460°F was used. This is a compressor oil sold by Cornelius Co. (Stewart Warner) for use in small, portable compressors. It can be considered representative of compressor grade mineral oils.

b) Test oil #2 - synthetic oil, ester base

A specially purified neopentyl polyol ester, trade name Brayco 899G, meeting MIL L23699 (2) was used. It has an approximate viscosity of SAE #20 and 500°F flash point. It is comparable to the newer synthetic compressor oils on the market.

c) Test oil #3 - synthetic oil, polyphenyl ether base

A four ring polyphenyl ether polymer, formerly marketed by Monsanto as MCS 210. Approximate viscosity is SAE #20, flash point 510°F, auto-ignition point 1150°F. It is not currently manufactured.

It is evident from Figure 3 that serious problems with carbon monoxide production do not occur until a critical "ignition" temperature occurs. When this temperature occurs in a compressor which passes excessive oil, carbon monoxide levels that will cause death within minutes, are suddenly produced.

The second series of tests were done using a compressor in new condition, and of a cross head design (compression cylinders separate from the crankcase) so oil feed rates to the cylinders could be controlled. The compressor was a water cooled model. A low oil feed rate to the cylinders was used, sufficient to maintain adequate cylinder lubrication, employing a mineral base compressor oil. Under normal running conditions, the compressor generated no carbon monoxide. When flow of cooling water was decreased, allowing cylinders and interstage temperatures to rise to about 200°F, carbon monoxide production reached 30 PPM.

Cooling water was restored and interstage pressure was then decreased by loosening a fitting. Carbon monoxide production jumped to 60 PPM when the compressor ratio reached about 11 to 1. Figure 4 shows the graph produced by an on-line CO analyzer. The importance of maintenance of oil lubricated compressors is evident from the above test series. CO production from the new compressor would have also generated disasterous quantities of carbon monoxide if the oil feed rate had been greater.

PHYSIOLOGICAL EFFECT OF CARBON MONOXIDE

The red blood cell's normal function is to carry oxygen throughout the body. Carbon monoxide has a high affinity for the red blood cells, approximately 200 times as great as oxygen. Thus, the mechanism of carbon monoxide poisoning is simply combining with the red blood cells and preventing their availability to

TEST DATA

CARBON MONOXIDE PRODUCTION
WITH WORN COMPRESSOR
USING OIL LUBRICATION

	INLET PRESSURE	OUTLET PRESSURE	COMPRESSION RATIO	CO IN AIR	NOTES
TEST OIL 1 (MINERAL)	165 PSI	1900 PSI	10.6	>2000 PPM	ONSET OF IGNITION (CO BEYOND INSTRUMENT SCALE)
TEST OIL 2 (ESTER BASE)	165 PSI	2100 PSI	11.7	>2000 PPM	ONSET OF IGNITION (CO BEYOND INSTRUMENT SCALE)
TEST OIL 3 (POLYPHENYL ETHER	80 TO 200 PSI	3000 PSI	32 MAX	0-20 PPM	COULD NOT CAUSE IGNITION
TEST OIL 1	165 PSI	1700 PSI	9.5	30-60 PPM	NO IGNITION
TEST OIL 1	165 PSI	1500 PSI	8.3	0-10 PPM	NO IGNITION

FIGURE 3

TEST GRAPH

CARBON MONOXIDE PRODUCTION
WITH NEW COMPRESSOR
USING OIL LUBRICATION

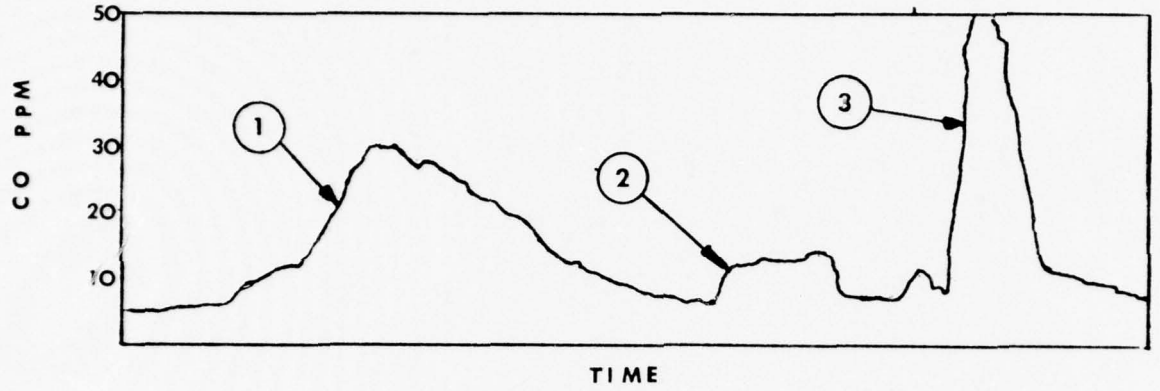


FIGURE 4

1 CARBON MONOXIDE INCREASE DUE TO RESTRICTED COOLING WATER SUPPLY

2 CARBON MONOXIDE INCREASE DUE TO DIRTY INLET FILTER

3 CARBON MONOXIDE INCREASE DUE TO INTERSTAGE FITTING LEAKS

carry oxygen. Carbon monoxide is a colorless, odorless, tasteless, non-irritating gas. Characteristic symptoms are headache, mental dullness, and physical distress. Unfortunately, these are common symptoms and often disregarded. Unconsciousness follows. In some cases, unconsciousness occurs without other noticeable symptoms.

Figure 5 shows effects of breathing various concentrations of carbon monoxide on blood saturation level. Symptoms, in turn, are related to per cent blood saturation as noted on the right side of the graph. For normal industrial exposure, the threshold limit was established by the American Conference of Government Hygienists in 1958 at 100 PPM. This was later reduced to 50 PPM.

For diving applications, the U.S. Navy Diving Manual states that 20 PPM is an upper limit for non-decompression diving and 10 PPM for decompression diving. In a given air sample, partial pressure of carbon monoxide will increase proportionately with total pressure. It is postulated that the effect of carbon monoxide will increase with depth according to the partial pressure increase. Little hard evidence supports this, however, an event in the U.S. Navy's Sea Lab II experiments tends to prove it. The crew of Sea Lab II complained of bad headaches. Gas analysis indicated 25 PPM carbon monoxide. Since Sea Lab II was under seven atmospheres total pressure, this should have the effect of 175 PPM on the surface. Considering the exposure time of several hours and referring to Figure 5, the physiological effects correspond. When the carbon monoxide was reduced, the headaches ceased. Even at standard atmospheric conditions, there is considerable disagreement among pathologists regarding physiological effects of carbon monoxide. Some think mental and physical conditions of the individual is impaired before any noticeable symptoms, such as a headache, occur. There is, however, little disagreement that extreme environmental conditions, such as cold or fatigue, may obscure symptoms preceding serious physical or mental hardships.

SAFEGUARDS TO PREVENT COMPRESSOR PRODUCED CARBON MONOXIDE IN OIL LUBRICATED COMPRESSORS

a) Compressor maintenance

A new or well maintained oil lubricated compressor will not produce carbon monoxide. Unfortunately, as the compressor wears, the two prerequisites to carbon monoxide production can occur, namely increased oil passage and increased compression ratios resulting from one of the numerous mal-

EFFECTS OF CARBON MONOXIDE [13]

ON HUMAN BEINGS AT SEA LEVEL 14.7 PSIA

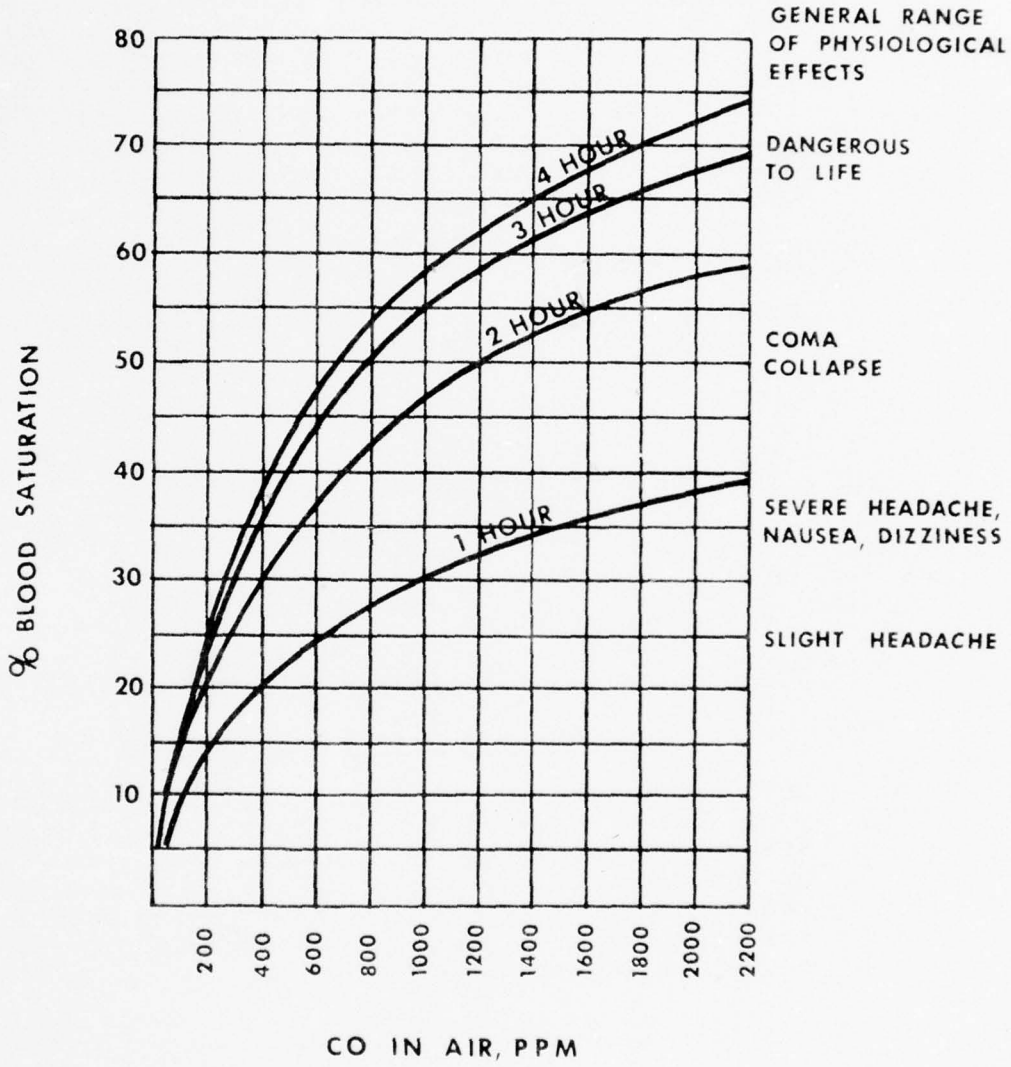


FIGURE 5

functions mentioned above. Thus, compressor maintenance is particularly important if air of breathing quality is required.

b) Use of correct oils

The extremely heat stable oils, such as the polyphenyl ethers, are not currently available for economic reasons (Figure 2). Therefore, it is adviseable to use the oil recommended by the compressor manufacturer. Although these may not eliminate the possibility of auto-ignition and carbon monoxide production, they are generally better than most oils, possessing higher than average flash points and low volitility. Frequent visual inspection of compressor valves, particularly in the final compression stage, may disclose discoloration or carbon deposits .... a sure sign that CO has been produced.

c) Use of filters

Compressors generally utilize one or a combination of the following filter materials:

Mechanical water/oil separator

Silica Gel

Activated Alumina

Activated Charcoal

Molecular Sieve TM

Purifil TM

These materials effectively remove odors, oil and water.

None will remove carbon monoxide.

The only effective means of removing carbon monoxide is via a catalytic agent that oxidizes the carbon monoxide to relatively harmless carbon dioxide. Hopcalite TM manufactured by MSA Corp. is one such catalyst. To function, the catalyst requires extremely dry air, thus drying filters, containing the better drying agents, such as molecular sieve, must necessarily preceed it.

Failure of the dryer to function will cause moisture to poison the catalyst.

Various companies manufacture completed filter assemblies. To assure proper operation, understanding of and maintenance of the filter system is required.

d) Analyzing the air

Several companies manufacture carbon monoxide analyzers. One effective type consists of a hand held aspirator with disposable analyzer tubes. The unit operates by drawing the gas sample through the tube which contains a chemical. Carbon monoxide produces a stain in the chemical. The length of stain denotes amount of carbon monoxide. Effective range of most kits is 10 to 2000 PPM which is well suited for checking diving air. The kits cost around $100.00 and the tube, good for one test, about $1.00. This testing method, as a minimum, is strongly recommended when using oil lubricated compressors or when the air source is questionable. It is important to remember that air sampling should be accomplished at operating points considering highest ambient temperature, maximum pressure, and full ratio capacity.

More sophisticated electronic carbon monoxide analyzers have recently been developed utilizing the fuel cell principle. They are well suited as on-line or spot check analyzers, have minimal operating cost and cost around $1,000.00 or more. Since oil lubricated compressors can generate carbon monoxide intermittently due to such malfunctions as a temporarily stuck valve, dirty inlet filter, or fouled heat exchanger surfaces, the advantage of continuous on-line analysis is clear.

e) Other on-site checks

Numerous visual on-site checks can be made to help insure proper compressor operation and pure air. The operator should insure that the compressor is adequately cooled, the intake is sufficient distance from engine exhausts and other contaminate sources, and that interstage pressures are within the range recommended by the compressor manufacturer.

USE OF NON-LUBRICATED COMPRESSORS

The use of non-lubricated compressors eliminate the presence of oil in the cylinders, thus completely eliminating the possibility of carbon monoxide production, regardless of compressor condition, maintenance or age. Proper in-field maintenance and precautions necessarily associated with oil lubricated compressors,

as outlined above, are beyond the control of the manufacturer. Use of other than specified oils, inadequate compressor and filter maintenance, and lack of air analysis often occur in diving operations. Thus, only non-lubricated compressors can effectively eliminate the danger of compressor produced contaminants in diving.

Non-lubricated compressors utilize composites of Teflon™ (TFE) and fillers such as powdered bronze as ring and seal material. These materials, operating against polished metal cylinder liners, give excellent life. Operating at 100 to 150 psi, wear is not measurable after 1000 hours when proper design is used. Until recently, (within the last 4-5 years), the Teflon composite seals gave very poor service life when used at high pressures. Recent developments have resulted in reasonable seal life (several hundred hours) at 2000 to 3000 psi. Some compressors now utilize this seal design and have become viable candidates for high pressure uncontaminated breathing air.

SUMMARY

The intent of this paper is to generate an awareness regarding the use of oil lubricated compressors for divers' breathing air and to consider their ability, under some conditions, to produce toxins. These toxins, particularly carbon monoxide, can be produced without noticeable changes in the operation of the compressor. Further, carbon monoxide production can occur intermittently for brief periods or lengthy periods of time which may not be detected by periodic analysis. Most filters utilized on diving compressors are capable of removing oil vapor and odors but not carbon monoxide. Only special catalytic filters will remove carbon monoxide. A search for possible "safe" lubricating oils that would eliminate the possibility of carbon monoxide production was not fruitful. The eventual use of non-lubricated compressors for all breathing air/gas service is advocated, as this approach completely eliminates the possibility of compressor produced toxins.

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THE PROTECTIVE TREATMENT OF HIGH PRESSURE GAS SYSTEMS

Development and Application of the PCP System

M.A. McMahon - A.M.I.C.S.T.

Abstract

This paper gives a general description of a protective coating system which has been developed to provide a corrosion prevention treatment for the interior surfaces of high pressure gas cylinders, hyperbaric chambers and deep diving systems.

It details some of the problems involved in providing corrosion-free, non-toxic, particle-free gas storage facilities for life support systems.

The problems of satisfactory surface preparation and cylinder cleaning are discussed and details given of the PCP System materials which were developed to meet the very stringent service requirements laid down by the Royal Navy.

Results are given of the development work and testing carried out in association with the Royal Navy Physiological Laboratory and the Ministry of Defence Procurement Executive.

Details are given of the production methods devised for the use of this system in the protective treatment of cylinders, chambers and offshore hardware and finally the important features of the system are discussed with particular reference to Diving and Offshore applications.

The Problem of Providing Clean Gas Systems

In recent years a general awareness has developed among diving specialists in both the Naval and Commercial spheres, that on grounds of health, safety, efficiency and economics, steps need to be taken to provide clean corrosion-free gas storage facilities for all types of diving equipment and systems.

It surely makes good sense, on both technical and financial grounds, that equipment should provide as clean a gas supply as possible, hence the normal traditional reliance on the extensive use of separators, filters and driers to remove water, oil and particulate matter from compressed gases before they are passed into the cylinders of storage tanks from which Divers will draw their supplies.

In practice, however, most compressors and gas systems suffer from the introduction of water, oil and dirt into the system. The normal method of cleaning the gas is to use a series of water separators and filters of the regenerable type, such as activated alumina, charcoal, molecular sieve or silica gel; but these cause their own problems by producing fine particulates which require still more filtration.

For high pressure air and gas systems, whose purpose is to provide breathing gases through a variety of pressure regulators and controllers, it is necessary to remove virtually all particles larger than 10-15 microns. Filtration systems that can remove all particles below this size are extremely expensive, bulky and cause a high pressure drop adversely affecting the performance of the system.

Diving procedures require the provision of adequate gas storage facilities so that sufficient gas of the right quality is always available for use - this means banks of high pressure cylinders which must be to the same standard of cleanliness as the rest of the system. It is clearly expensive and wasteful to go through the process of cleaning, drying and filtering gases only to pass them into dirty, rusty cylinders so that when the gas is required at the prescribed quality it is necessary to be totally dependant upon further expensive filtration. Filters should only be present to safeguard against any dirt entering the system, not against the system manufacturing its own dirt from rusty cylinders!

Recent examination of two Scuba Cylinders which had been in service only a couple of years with a company diving in the North Sea revealed $2\frac{1}{2}$ ounces of rust, scale, sludge and dirt - sufficient in fact to half fill a paper coffee cup, I certainly would not like to have breathed from those cylinders and I don't think you would either.

It is in fact impossible to fully assess the danger to the health of Divers caused by the lack of system cleanliness but in view of the increasing amount of "health and safety at work" legislation which is now in force and which is being extended to cover offshore and diving activities, it is clear that every aspect of diver health and safety is being looked at closely by Government inspectors and there are official moves being made to encourage the use of cleaner systems and equipment.

There are also other dangers however, unless gas systems are kept scrupulously clean, some water, oil and particulates will get through into the cylinders causing surface corrosion, pitting and the detachment of metallic particles from the interior surfaces. At such high pressures rust particles can cause valves to jam and metal particles projected through small valve orifices at high velocity can impinge on other metal surfaces with the risk of explosion and fire.

The typical corrosion pattern exhibited on cylinder interiors shows a relatively clean area at the top end with corrosion streaks developing down the sides and fairly extensive pitting at the bottom end caused by the corrosive action of condensates which form small electrochemical cells leading to the removal of metal.

Pitting is usually a slow process at first; the small size of pits and the small amounts of metal dissolved make detection difficult in the early stages, but because pits tend to be self-generating their development tends to accelerate and can cause unexpected failures. Extensive pitting corrosion has been the cause of failure in many types of industrial pressure systems.

How then can the interiors of cylinders be cleaned and protected to provide a safe virtually inert surface that would complete a truly "clean" gas system?

Royal Navy Developments

In 1973 this was the problem which had been facing the Royal Navy Physiological Laboratory for almost ten years and which had severely hampered their research programme into deep diving, submarine escape and rescue.

They tried, without success, various methods of cleaning cylinders including rumbling, chemical cleaning and shotblasting, plus a vast variety of treatments and coatings such as dipping, chemical treatments, plating processes and many types of synthetic paints and coatings, including such materials as vinyl zinc chromate and epoxy coatings.

Our organisation had supplied some material to provide chemical resistance against goat urine in small medical test chambers and this gave such good protection that scientists from the Physiological Laboratory, together with engineers from Portsmouth Dockyard and the Ministry of Defence at Bath, approached us to see if we could find a solution to the problem of the internal treatment of gas cylinders and chambers.

We isolated three main problems and a host of smaller ones!

First. How to prepare the surface properly and ensure that the selected method of surface preparation would give a really clean metal surface ready for coating?

Second. What type of coating system to use in order to satisfy the highly complex and conflicting requirements imposed by the service conditions?

Third. How to successfully apply the selected coating materials, through a two inch hole at each end of the cylinder?

The main parameters laid down by the Navy for an acceptable coating were:-

a. Any coating system applied to cylinder interiors must be non-inflammable and must not ignite in high pressure air at high temperatures.

b. The system must be resistant to condensates containing salts, oil and water.

c. The system must be non-toxic.

d. The system must not absorb gases or moisture.

e. The system must withstand working pressure of 4000 psi.

f. The system must withstand vacuum conditions.

g. The system must be unaffected by extremes of temperature.

h. The coatings must not strip, flake, dust or blister in service.

i. The system must prevent corrosion even on a rough or already pitted surface.

j. The system must withstand the effects of steam cleaning, hot water and degreasing solutions.

k. The system should be suitable for service in as wide a range of gases as possible.

l. It should be possible to remove the coating system entirely should this ever become necessary.

Quite a formidable list of requirements I think you will agree!

By the end of three months however we had finalised our development work on the coating materials which we believed would form an acceptable system.

This PCP System, as we later called it, consisted of a multi coat treatment with each material in the system designed to perform a specific job. The basis of the system was a unique combined Primer/Metal Treatment material, which penetrated and passivated the metal surface giving an exceptionally high adhesion factor and containing back-up corrosion inhibitors. Over this was applied an Intermediate coat of a hybrid epoxy-urethane material containing insoluble pigments as a barrier layer against salt water. The system was then completed by the application of three coats of a finishing grade epoxy-polyurethane material which had outstanding resistance to chemical and physical attack. All the materials used were approved by the Royal Navy Physiological Laboratory and the Admiralty Materials Laboratory.

Having produced what we felt sure was a suitable system, we then approached the problem of how to prepare the interior surfaces of cylinders and apply the coatings through the very small holes available.

Suffice it to say for the moment, that our experience in the field of surface preparation convinced us that blast cleaning with a manufactured abrasive or grit was the fastest, most economical and most efficient method of preparing the surface.

Unfortunately however, there was no suitable equipment available from the normal commercial suppliers of blasting nozzles, which would fit through the holes in the cylinder ends properly, would successfully clean all the interior surface to the required standard and would survive the effects of blasting in such an enclosed space.

After a series of experiments we designed and produced our own special lances and nozzles which did go into the cylinders, did blast at the correct angles to ensure cleanliness of all the interior to the required standard, (which was SA3 or white metal finish) and which successfully withstood the conditions and gave a useful working life at reasonable cost.

Similarly on the application of the coatings, we designed a special applicator which was used to apply a measured quantity of material to the interior, ensuring that each coat was to the correct film thickness and coverage.

This is where we have to draw a temporary veil of secrecy over the proceedings because the equipment finally developed is the subject of patent applications which have been filed but, because of pressure of work at the Patent Office, have not yet received the final seal of approval.

The Test Programme

An initial test programme was set up which involved the treatment of eight high pressure cylinders of 9.1 cu.ft. size. These cylinders are six feet long by 20 inches in diameter and weigh $\frac{1}{2}$ ton each. They were put on test at the Royal Navy Physiological Laboratory and subjected to cycles of charging and discharging to simulate two years' normal working life.

Visual examinations were made of the coated interiors and cylinders were filled and tested with various gases over a period of some six months.

Air samples were taken for particulate analysis, toxicity tests were carried out, temperature ranges were checked, a full vacuum was applied, tests were made with salt water, cold fresh water and hot water and the coated cylinders were even hydrostatically tested to 6000 psi.

Table 1 shows random examples taken from over 800 charge/discharge cycles. It particularly shows that the extremes of temperature involved have no effect on the coating system and there was no loss of adhesion of the coatings in any of these tests.

TABLE 1

Charge or Discharge	Pressure P.S.I.	Duration	Temperature Start	Finish
All charged	0-4000	6 mins.	15°C	29°-30°C
Discharge 1.	4000-0	40 mins.	17.5°C	0°C
Discharge 2.	4000-0	40 mins.	23°C	3°C
Discharge 3.	4000-2000	13 mins.	18°C	8°C
Discharge 4.	4000-0	40 mins.	20°C	1°C
Discharge 5.	4000-2000	13 mins.	18.5°C	9°C
Discharge 6.	4000-2000	10 mins.	22°C	11°C

Maximum temperature recorded on 800 charges: + 30°C
Minimum temperature recorded on 800 discharges: -3°C.

In the complete range of tests the coating system withstood pressures of 4000 psi in air and gases, 6000 psi in water (hydrostatic test) plus the application of a full vacuum for 48 hours. There were only two small adhesion failures in all these tests and these were without doubt attributable to undercured areas where coatings had been applied too thickly. If the coatings are applied too thickly solvent becomes trapped and absorbs gas which is released by pressure cycling and forms blisters leading to delamination. Subsequent controlled film thickness tests on over 100 large cylinders have confirmed this.

Two of the original test cylinders have now been standing charged with helium for two years and are reported to be still in excellent condition.

Although the human nose could detect a very faint solvent odour from the test cylinders, the instruments used to determine out-gassing from the coatings showed no reading whatsoever, and no trace of toxic substances could be found. When the cylinders were later used in a hyperbaric system, the gases were reported to be odour and taint-free. Since these early tests our curing methods have been vastly improved so that we can now produce cylinders which are completely odour-free when they leave our factory.

Inflammability tests on the coating materials showed that in HP air no problems were detected but, in HP oxygen there was apparently a risk of ignition as shown in table 2.

TABLE 2

H.P. Air at 130 bar (g)	
Chemitec Primer	- No ignition in 6 tests up to 400°C.
Chemiseal Finishing Grade	- No ignition in 6 tests up to 400°C.
H.P. Oxygen at 130 bar (g)	
Chemitec Primer	- One ignition in 6 tests up to 400°C. Ignition temperature 335°C.
Chemiseal Finishing Grade	- One ignition in 6 tests up to 400°C. Ignition temperature 325°C.

It was felt however that the test method used for inflammability was rather suspect and new equipment has recently been ordered to check these findings for HP Oxygen.

In practice we understand that cylinders coated with our system have been successfully used with oxy-helium mixtures containing up to 40% oxygen enrichment. The problem of providing a suitable treatment for pure oxygen is still being investigated.

The final tests carried out by the Royal Navy on the original eight cylinders consisted of six air sample particle counts taken on HP air drawn from the bank of coated cylinders which had been placed in a dried and filtered system of normal usage. As table 3 shows the results were good and there was no detectable particulate contamination from the interal surfaces of the cylinders, indeed it was suggested that the small amounts of contamination recorded probably came from the piping and filter systems.

TABLE 3

Bottle No.	P.S.I. Pressure	Volume Sampled	Contamination level per cu.ft. in microns			
			15-30	10-15	5-10	1-5
No. 53	3200	150 ft.3	.4	1.86	7.46	32.40
No. 54	3100	150 ft.3	.37	1.40	7.46	48.50
No. 55	3100	150 ft.3	.66	1.53	11.20	70.81
No. 56	3100	150 ft.3	.69	2.33	5.60	63.46
Panel 1 Supply	3700	150 ft.3	.46	2.04	9.47	53.69
No. 55 Drain	2900	150 ft.3	.37	1.18	7.89	64.74

The Production Programme

As a result of these successful trials a contract was placed with us by the Ministry of Defence for the complete treatment of 100 x 9.1 cu.ft. high pressure cylinders for the Royal Navy Physiological Laboratory plus three hyperbaric chambers in the experimental high pressure section, which are used for deep diving research.

Further practical refinements in our production and quality control methods were made during 1975 with the result that a Ministry of Defence specification has now been issued approving the use of this coating system for high pressure cylinders in service with shore establishments and all surface warships. Negotiations with the authorities are shortly expected to be finalised with the issue of a similar directive giving approval for the treatment of cylinders used in submarines.

Our factory has now been geared up to cope with a large variety of types and sizes of cylinders so that we are able to undertake all stages of work from initial inspection through steam cleaning, hydrostatic testing, blast cleaning, vacuum cleaning, coating application and curing, right through to final inspection and despatch. All coating work and curing is carried out in "clean room" conditions in a paint shop which is fully air-conditioned with temperature and humidity control. We operate our own rigorous quality control procedures and of course are subject to regular inspection visits from our local Ministry of Defence inspector.

The spin-off from Navy work this year has become considerable, with cylinders, recompression chambers, diving bells, habitats, complete saturation diving systems and submersibles now being treated for the Offshore industry.

The important features of the coating system which make it particularly suitable for the protective treatment of diving and offshore hardware are as follows:-

1. The coating system is unaffected by condensates containing salt, oil and water.

2. When cured, the coating system is non-toxic, there is no out-gasing of solvents.

3. The coating is virtually impervious and does not absorb gases under pressure.

4. The coating system applied to cylinder interiors is non-inflammable and will not ignite in high pressure air at high temperatures.

5. The coating is elastic and flexible enough to withstand the expansion of cylinders during pressurisation to a working gas pressure of 4000 psi and hydrostatic testing to a pressure of 6000 psi. There is no loss of adhesion on pressurisation or decompression.

6. The coating system withstands the extremes of temperature during compression up to full working pressure and subsequent decompression on discharge.

7. The coating system also withstands application of a full vacuum without loss of adhesion.

8. The coating system does not blister, flake or dust under service conditions.

9. The coating system prevents corrosion of the internal service of cylinders even though the surface may be thoroughly wetted and dried at regular or irregular intervals by condensates and gases.

10. The cylinder interiors can be cleaned by the use of steam cleaning or hot water and mild detergent or degreasing solvents without damaging the internal coatings.

11. The coating system has so far proved suitable for service with high pressure air, nitrogen, oxy-helium mixtures with 40% oxygen enrichment, pure helium and hydrogen.

12. It is possible to remove the coating system by a special process should this ever be found necessary.

You will no doubt agree that these features fulfill to a very high degree the original requirements laid down by the Royal Navy for a cylinder protective treatment.

A further new development in recent months has been a method of blast cleaning and coating the interiors of gas cylinders and Scuba cylinders which have only a single small hole of between 1 inch and $\frac{1}{2}$ inch diameter in the end. This has again meant the design and construction of special tools and equipment to permit batches of cylinders to be treated on a regular production basis, for example 400 Scuba Cylinders are currently in work for a well known European diving company.

All in all both laboratory tests and field experience are daily confirming the high performance characteristics of this coating system and proving that the useful life of high pressure gas cylinders and systems can be extended with measurable improvements in system cleanliness, operational efficiency, plus diver health and safety.

BREATHING DYNAMICS OF A DIVING HELMET WITH A NECK SEAL

by

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INTRODUCTION

One of the most useful items of breathing apparatus is the lightweight diver's helmet. Replacing the traditional deep-sea diving helmet, with its attendant bulky dress and heavy weights, the lightweight helmet permits greater mobility than formerly attainable. The increased mobility is possible because the helmet is nearly neutrally buoyant without requiring extra weight to make it so. Thus, the diver may dress in almost any suit that he chooses, don his helmet, and go to work.

The water is kept out of the helmet by a neck dam, a flexible sleeve of elastic material that is pulled over the diver's head and fits snugly around his neck, preventing the entry of water into the helmet.

The helmet is equipped with two valves, an inlet valve for admitting gas at the rate desired by the diver, and an exhaust valve that vents gas from the helmet. Although operation of the neck-seal equipped helmet is superficially similar to operation of the standard deep-sea rig, it is not identical, although it has been so treated in some analyses.

It is the purpose of this paper to provide a mathematical description of the dynamics of breathing within a neck-seal helmet, and to identify those characteristics of the apparatus that affect its design and use.

SYSTEM DESCRIPTION

The system is composed of the helmet, which encloses the diver's head, the inlet valve which the diver uses to admit gas, the neck seal that provides compliance and keeps out water, and the exhaust valve which controls the pressure within the helmet.

The Helmet

The helmet is a shell that surrounds the diver's head, containing the bubble of gas from which the diver breathes. Its construction will vary widely, as may be seen from observation of the many different types of helmets on the market. The typical helmet will have a faceplate in front and will be constructed of metal or fiberglass, with weight added as necessary to make the helmet neutrally buoyant. Helmets will vary in ventilation efficiency depending on the internal ducting of the gases as they pass by the diver's nose and mouth, but this will not affect internal helmet pressure. Our sole concern, for this analysis, will be with the fact that the helmet is the chassis upon which the inlet valve, neck dam, and exhaust valve are mounted.

Inlet Valve

Gas is admitted to the helmet through the inlet valve. By opening it to varying positions, the diver can regulate the flow of gas to any level he desires up to the limit of the supply system. Normally the diver will keep the inlet flow adjusted to less than maximum flow capacity, and will change the adjustment infrequently. In this analysis it will be considered that the flow of incoming gas is constant during respiration.

Neck Seal

The neck seal keeps water out of the helmet. It consists of two parts, neck ring and neck dam. The neck ring is a rigid ring that mates to the base of the helmet, while the neck dam is a flexible rubber sleeve, attached to the neck ring, that fits snugly around the diver's neck. In donning the apparatus, the neck ring is pulled over the diver's head until the elastic neck dam seats comfortably around the diver's neck. Then the helmet is joined to the neck ring, completing the sealing operation.

Normal procedure is for the neck dam to assume a convex bulge in the direction of the diver's shoulders, although some prefer to wear it convex upwards. In this analysis, the direction of orientation will not be considered significant.

Pressure within the helmet will be that at the depth of the neck dam, since the neck dam is resilient and, in this analysis, may be considered simply as a perfectly flexible overlay on a free water surface. Pressure may thus be indicated by the depth of the neck dam relative to a fixed point. The fixed point will be considered to be the top of the helmet.

Exhaust Valve

The exhaust valve is the principal means for controlling pressure within the helmet. Originally conceived as a buoyancy control for hard-hat divers, its general construction in many cases is similar to that of the standard deep-sea rig. The valve is usually an adjustable spring-loaded pressure relief valve. Operating over a fairly narrow band of pressure, it remains closed until the pressure reaches some adjusted lower limit, h_o. Then, as pressure increases, the valve opens more and more until it is fully open. Its operation may be seen in Figure 1.

In this analysis flow through the valve is considered linear with differential pressure.

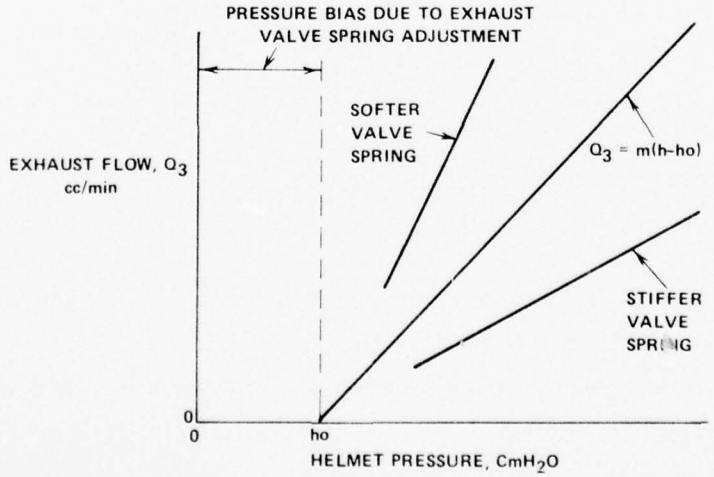


FIGURE 1. EXHAUST VALVE CHARACTERISTICS

The Diver

The final component of the system is the diver. In our analysis he will be simply an air pump, and the only items of interest to us will be his breathing methods and his neck size.

Flow and Pressure Relationships

The theoretical relationship between internal helmet pressure and the various gas flows may be established by derivation. Figure 2 is a schematic view of the helmet and its components.

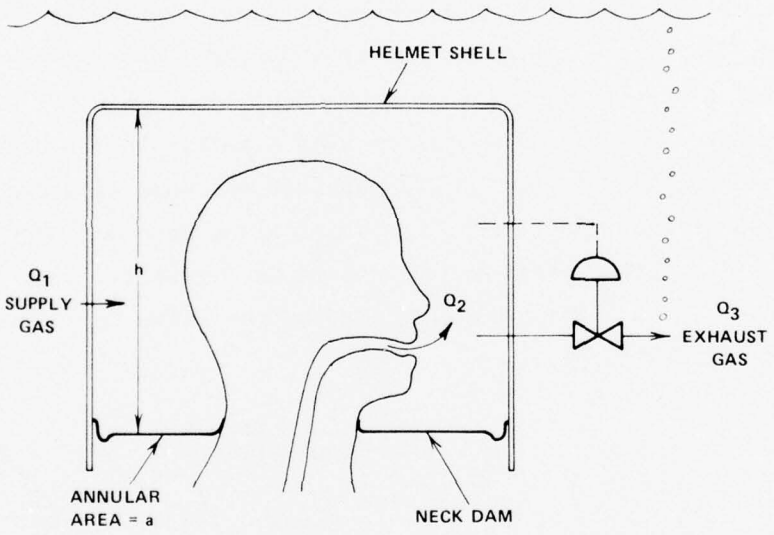


FIGURE 2. HELMET SCHEMATIC

Flows and pressures, at any constant depth, are found as follows:

Supply flow to diver = Q_1, cc/min.

Q_1 will be considered as invariant in this analysis.

Respiration flow = $Q_2 = \pi(RMV)\sin \omega t$, cc/min.

where

$\omega = 2\pi N$

RMV = respiratory minute volume, cc/min.

N = respiratory rate, breaths/min.

t = time, minutes.

Exhaust flow = $Q_3 = m(h-h_o)$, cc/min.

where

h = helmet pressure, cm H_2O relative to ambient pressure at top of helmet

m = valve opening rate, cc/min/cm H_2O

h_o = pressure bias due to bias spring, cc/min.

Area of neck dam = a, cm^2. This is the annular area between the diver's neck and the ring supporting the outer edge of the neck dam.

Helmet Volume = V, cc

Now, considering flow to be incompressible (because pressure changes are very small relative to ambient), we can say:

$$\text{Volume change per unit time} = \frac{dV}{dt} = a\frac{dh}{dt} = Q_1 + Q_2 - Q_3 \qquad (1)$$

Substituting, we obtain the basic differential equation of the system:

$$\frac{dh}{dt} + \frac{m}{a}h = \frac{Q_1 + mh_o}{a} + \frac{\pi(RMV)}{a}\sin \omega t \qquad (2)$$

If we make the following substitutions:

let $C_1 = \frac{m}{a}$

$C_2 = \frac{Q_1 + mh_o}{a}$

$C_3 = \frac{\pi(RMV)}{a}$

then (2) reduces to:

$$\frac{dh}{dt} + C_1 h = C_2 + C_3 \sin \omega t \tag{3}$$

The complete solution to (3) may be found by conventional means to be:

$$h = b\, e^{-C_1 t} + \frac{C_2}{C_1} + \frac{C_3}{\sqrt{C_1^2 + \omega^2}} \sin (\omega t - \beta) \tag{4}$$

where

$$\beta = \tan^{-1} \left(\frac{\omega}{C_1}\right)$$

and b may be found from system boundary conditions.
When (4) is expressed in original notation:

$$h = b\, e^{-\frac{m}{a}t} + \frac{Q_1 + mh_o}{m} + \frac{\pi(RMV)}{\sqrt{m^2 + (2\pi Na)^2}} \sin \left(2\pi Nt - \tan^{-1} \frac{2\pi Na}{m}\right) \tag{5}$$

Equation (5) completely describes the response of the system. It is composed of three terms. The first is a rapidly-decaying exponential, of little interest to us. The second term represents the mean value of the helmet pressure, and the third is the sinusoidal variation due to respiration. Let us put some realistic numbers into equation (4) and see what happens:

Neck seal area: A typical neck reing has an inside diameter of 22.5 cm. If we have a diver with a round neck of 16 inches circumference, the annular space between neck and ring will have an area of 266 square centimeters, or:

$$a = 266 \text{ cm}^2$$

Exhaust Valve: The exhaust valve is closed when h_o = 20 cm and flows 14 ACFM when h = 30 cm.

Since exhaust flow, $Q_3 = m(h - h_o)$, substitution yields

$$m = 39620 \text{ cc/min/cm } H_2O$$

Supply Flow: Assume that the supply flow is 6 ACFM. Then:

$$Q_1 = 169800 \text{ cc/min}$$

Respiration: Assume that the diver is breathing at 2 liters per breath, 36 breaths per minute. Then:

$$N = 36$$
$$RMV = 2\ (36)(1000) = 72000 \text{ cc/min}$$

Substitution in (5) yields the solution for the assumed realistic values:

$$h = b\ e^{-148.9t} + 24.3 + 3.05 \sin (226.2t - .99)_{rad}$$

Since, for any remotely realistic initial conditions the first term virtually disappears in a few seconds, we have a steady-state variation in h of 6.1 cm, centered around a mean value of 24.3 cm. Movement of the neck dam lags behind respiration by about 1/4 second.

Of particular interest to the helmet designer are the second and third terms of equation (5). The second term defines the average pressure in the helmet and the third term defines the amoumt of pressure variation to be expected due to respiration.

Average Helmet Pressure

Since average helmet pressure is defined by the second term of equation (5):

$$h \text{ average} = \frac{Q_1 + mh_o}{m} \qquad (6)$$

It is seen that average helmet pressure is affected by:

(1) Inlet flow to the helmet

(2) Exhaust valve opening rate

(3) Initial exhaust valve pressure setting.

If it is desired to keep the average helmet pressure reasonably constant during the dive, it is necessary to vary the pressure setting (h_o) on the exhaust valve inversely with inlet flow, since the diver can do nothing about his neck dam area.

Variation of Helmet Pressure

Helmet pressure variation is defined by the coefficient of the third term of equation (5):

$$\text{h variable} = \frac{\pi(RMV)}{\sqrt{m^2 + (2\pi Na)^2}}$$

Variation is thus affected by:

(1) Diver breathing rate and minute volume

(2) Exhaust valve opening rate

(3) Neck seal annular area.

The components that most affect helmet pressure have been seen to be the exhaust valve and the neck seal. Of the two, the neck seal presents the least problem because there are physical limitations that govern its size and movement, and thus reduce the range of choice open to the designer.

Neck Seal Geometry

A look at Figure 3 reveals some important geometrical properties of the neck seal. The upper portion of Figure 3 shows the neck seal at its two extremes of travel, in which it encloses a roughing toroidal volume. In the foregoing analysis, the seal has been assumed to exist as a plane. The lower portion of Figure 3 shows the same seal deformed in the planar mode. Thus, for our previous example of a seal of 22.5 cm diameter on a diver with a 16-inch neck, we see that toroidal seal expansion permits a pressure range of 7.5 cm H_2O, while the planar seal allows only a 4.37 cm range.

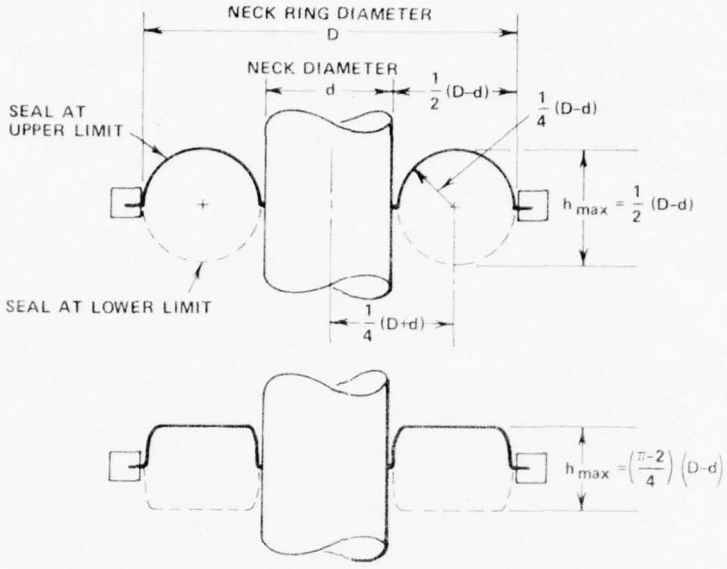


FIGURE 3. NECK SEAL GEOMETRY

In reality, because the diver's neck is not always coaxial with the seal plane axis, and because the seal material is not perfectly flexible, the seal will not behave exactly like either case.

Proper Inflation of the Neck Seal

If pressure in the helmet is regulated at too high a level, the neck seal will distend downward, remaining taut due to excessive internal pressure. Too little helmet pressure, on the other hand, will result in the seal bulging upward toward the diver's head.

To take maximum advantage of the compliance of the neck seal, the mean helmet pressure should be that which keeps the seal in the mid-position, while the pressure excursions due to breathing should not cause the seal to distend beyond its limits. If the seal does over- or under-inflate, an increase in pressure, and thus respiratory work, will be seen.

As an illustration of this, refer to Figure 4. It is a plot of respiratory work vs. helmet pressure, at constant supply flow and breathing rate, for a neck seal helmet recently developed at Battelle. It can be seen that there is a narrow mean pressure range where respiratory work is minimum. Outside this range, respiratory work increases with either greater or less mean helmet pressure.

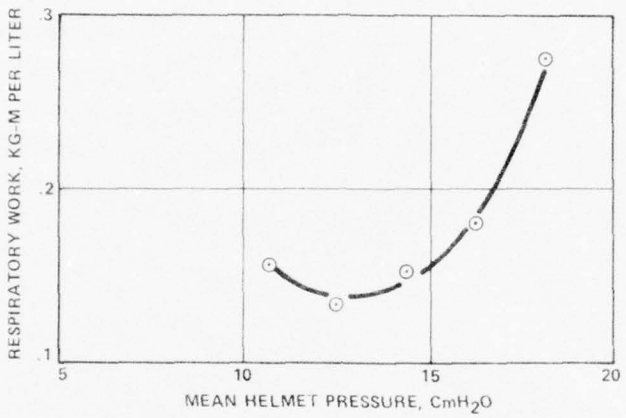


FIGURE 4. RESPIRATORY WORK VS. MEAN HELMET PRESSURE FOR ONE NECK SEAL HELMET

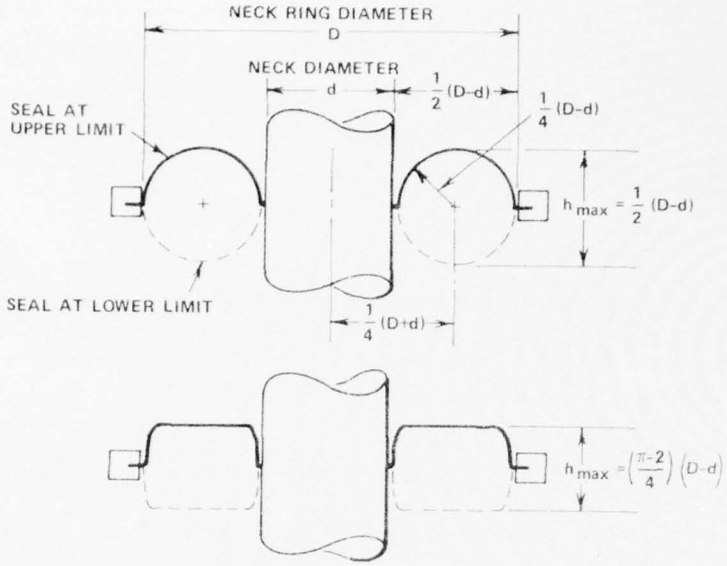
Exhaust Valve Characteristics

If no neck seal was present to absorb peak flows, the exhaust valve would have to be capable of exhausting the sum of the inlet flow and the peak exhalation flow. Indeed, it is prudent to design it thus, for if the neck seal is over-inflated it can go taut just when flexibility is needed, forcing the exhaust valve to behave as if the system was rigid.

The exhaust valve, then, should have the following characteristics:

(1) Capacity to exceed the sum of inlet flow and peak exhalation flow.

(2) Opening rate high enough to permit the valve to operate within the capability of the neck seal to move.



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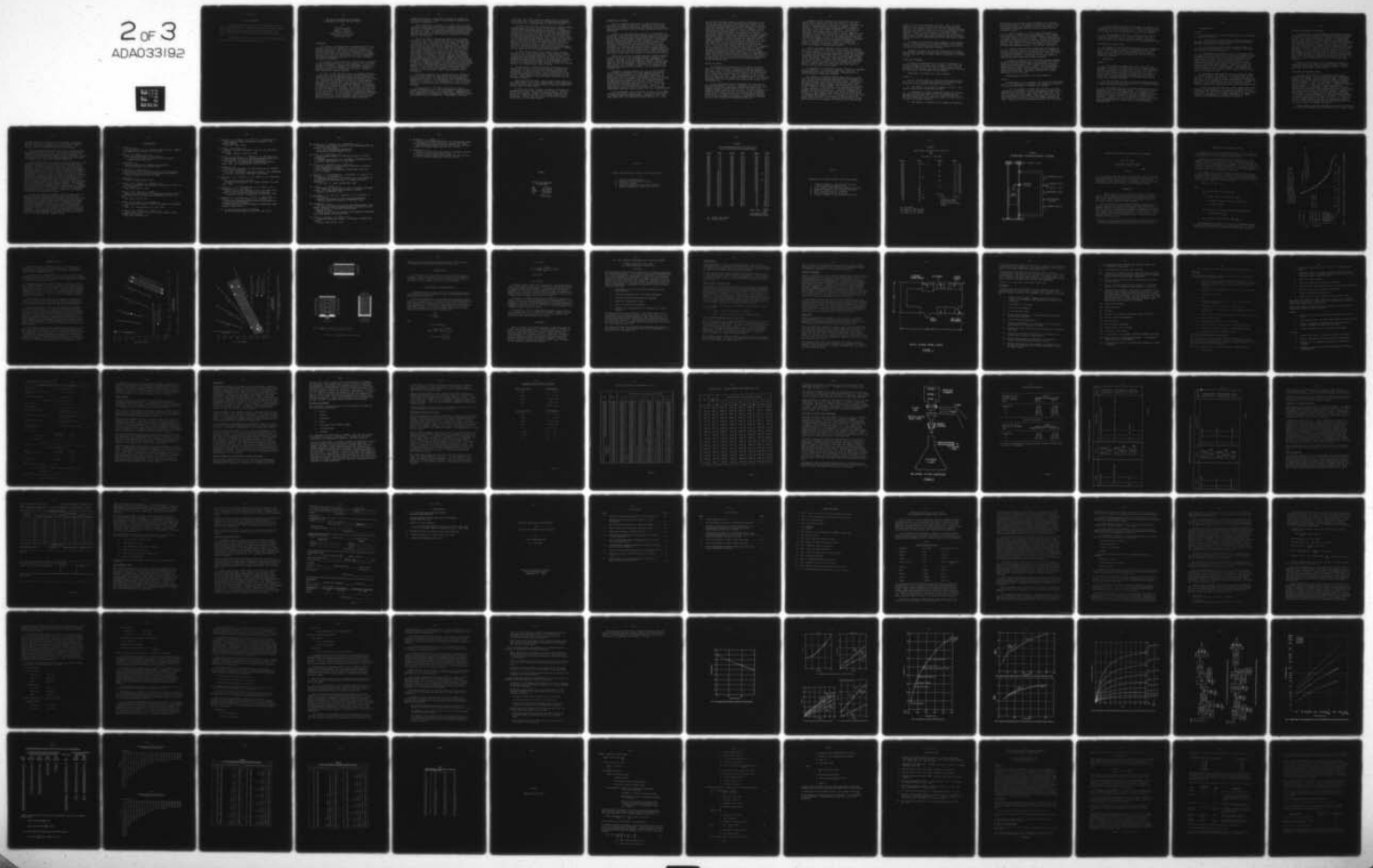

Use of the Formulas

While the formulas are accurate for the assumed conditions, it must be remembered that those conditions do not, in reality, exist. Divers do not breathe sinusoidally, rubber is not perfectly flexible, valve characteristics may not be linear and Murphy's Law applies in its usual way.

Nevertheless, the formulas are a place to start the design process, and it is the author's hope that they will be of help.

THE USE OF NON-EXPLOSIVE MIXTURES OF HYDROGEN AND OXYGEN FOR DEEP DIVING

by

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BACKGROUND:

The effects of hydrogen-oxygen breathing mixtures on animals initially was examined in 1789 by Lavosier (1) who placed guinea pigs in bell jars containing a mixture of hydrogen and oxygen. The initial concentration of oxygen was "in nearly the same proportion in volume which exists between life-giving air and nitrogen gas in the atmosphere." The animals apparently survived 8 to 10 hours, probably succumbing to asphyxia.

One hundred forty-eight years elapsed before a hydrogen-oxygen breathing mixture again was examined, (2) this time by Case and Haldane. These workers breathed a mixture of hydrogen, nitrogen and oxygen in a hyperbaric chamber at an ambient pressure of 10 atmospheres for up to 6 minutes. They reported no adverse reaction.

In 1943, in part because of the anticipated difficulty in obtaining helium, Arne Zetterstrom of the Swedish Navy suggested the use of hydrogen-oxygen breathing mixtures as an alternative to helium-oxygen breathing mixtures for diving (3). Zetterstrom developed a method of cracking ammonia catalytically, resulting in a gas mixture containing 75% hydrogen, 25% nitrogen and unchanged ammonia. By removing the ammonia and adding 4% oxygen he arrived at a breathable mixture containing 72% hydrogen, 24% nitrogen and 4% oxygen. In 1943 he conducted 2 successful dives on this mixture to 40 and 100 meters. He also conducted 2 additional dives to 70 and 160 meters on a 2-gas mixture containing 96% hydrogen and 4% oxygen (4). On the 160-meter dive he lost his life when one of the two winch operators raising his platform hauled him directly to the surface without observing

decompression stops. Since upon reaching the surface he still was breathing 4% oxygen he succumbed to hypoxia and probably airembolism (5).

The Swedish Navy continued for a short time after that accident to study the feasibility of hydrogen-oxygen diving under the encouragement of Engineer Commodor Ture Zetterstrom, the father of Arne. A laboratory explosion related to testing the safe limits of hydrogen-oxygen mixtures apparently greatly influenced the Swedish Navy to discontinue further work in this area (5).

After the rather unfortunate experiences in Sweden, interest in the use of hydrogen-oxygen as a breathing gas lay dormant until 1966 when Brauer (6) began to study the possible effects of hydrogen on various mammals. His work, principally on mice and monkeys, suggested that hydrogen might have less narcotic or convulsive effect than helium at the same pressure (7) (8) (9) (10) (11) (12), but the full scope of biological effects were not conclusively determined. His work did, however, lead him to conclude that molecular hydrogen is not toxic and is less narcotic than helium. As a result of these favorable results from short exposures with small animals, Brauer and his French co-workers attempted to carry out a human dive to 300 meters. Because of a number of problems on this dive he did not shift to the use of hydrogen-oxygen. He did, however, raise further question as to the possible narcotic effect of helium which Bennett (13) and others (14) had reported appearing below 800 feet. The terms "Helium Tremors," and later "High Pressure Nervous Syndrome" (HPNS), were applied to this phenomenon.

From these observations it appeared that at depths of 1000 feet divers might be approaching the limits at which helium could be used. In view of the clearly anesthetic properties of Xenon at one atmosphere (21), and the narcotic effect of nitrogen at 6 to 7 atmospheres, it came as little surprise to many workers that helium might cause a similar response.

The appearance of the HPNS caused Fife in 1967 to develop the capability to work with hydrogen-oxygen mixtures involving animal studies in the laboratory. Independently, Edel, supported by a commercial diving company began to study the possible use of hydrogen as a replacement for helium

in diving. The diving company financed several early man dives under Edel, beginning with hydrogen-oxygen exposures of 10 minutes at a simulated depth of 200 feet (Photo 1).

In 1968, Fife and Edel joined efforts to conduct several extended deep saturation dives on dogs using hydrogen-oxygen and helium-oxygen breathing mixtures. It consisted of one dive to 300 feet during which the dog was exposed to hydrogen for 12 hours; one dive to 1000 feet involving 24 hours of hydrogen exposure; and one dive to 1000 feet with an identical exposure to helium. The results of these dives will be discussed in more detail below. Work also continued on man dives of gradually increasing hydrogen exposure. This series ended in 1969 with exposures of up to 2 hours duration. One of us (W.P.F.) took a 1½-hour-200-foot hydrogen exposure, followed 8 days later by a 2-hour exposure. No ill effects were noted from the hydrogen, although in some dives the divers experienced mild bends.

In 1969, French workers (16) obtained some alarming results in their work with rabbits. They exposed a number of animals to a simulated depth of 944 feet (29 bars). As a precaution they accomplished this by lowering the animal chamber from pontoons to a depth of 6 meters under the ocean. The EEG's of these animals began to show abnormal trends within 2-3 hours; within 7½ hours there was electrical silence. Further, all animals died within 20 hours.

Further work by Fructus and Naquet was carried out on baboons (Papio papio) at simulated depths of between 300-675 meters. Of the 8 baboons used, all demonstrated abnormal EEG patterns and 4 died. Most troubling of all was the reported presence of brain abscesses in several of the animals. These abnormal EEG's and brain abscesses will be discussed presently.

Upon completion of their initial work on dogs, Edel and Fife again began to work more independently, Fife emphasizing deep diving with dogs, rats and mice, while Edel carried out another series of man studies.

In 1976, Fife began a series of studies to develop man decompression tables for hydrogen-oxygen diving. Working jointly with Mezzino, tables now have been developed and tested to a depth of 300 feet, with bottom times of up to 30 minutes. Interim 300-foot tables of up to 45 minutes bottom time now are being tested.

USEFULNESS OF HYDROX:

The first question which must be raised involves the usefulness of hydrox for diving. Although we do not view this gas as a complete replacement for helium, its use has several theoretical as well as already demonstrated practical advantages.

Firstly, in some countries there is no local source of helium gas. Such countries are dependent upon the good graces of the few countries with natural helium sources such as the United States, Netherlands, Canada and Africa. The problem may not be quite as simple as this, however, since in this country federal subsidies for helium production are decreasing. Further, this country wastes helium at a rate in excess of 1 billion cubic feet per year. One authority estimates that our present sources may be virtually gone by the year 2000 (17), and the present cost of approximately $35 per cylinder of helium most certainly will climb. It would, therefore, appear useful to search for another breathing gas.

Until now, the cost of hydrox placed it beyond economic feasibility since it was considerably more expensive than heliox. The cost of one cylinder was $64, purchased in quantity from the one known commercial source. On the other hand, we now have developed a rapid and safe mixing method which permits us to produce a cylinder of 3% oxygen in 97% hydrogen for about $20 per cylinder. We will discuss this method later.

Secondly, although hydrogen has not yet been studied sufficiently to determine if it can improve the speed or safety or decompression, such would appear possible. It seems clear that with dogs, decompression from 1000-foot saturation dives is different with hydrogen than with helium. We have not yet attempted to work out an optimum hydrox decompression table for such dives but a table which is satisfactory for hydrox requires 57.3 hours. This table does not call for breathing pure oxygen (Table 2). We would expect that the addition of another gas in the decompression repertoire would enhance the rate of decompression.

A third possible value of hydrox is that it has a lower viscosity and density than heliox. This becomes significant at greater depths as demonstrated by Dougherty (24). His work showed that the maximum breathing capacity of a diver

at 200 feet breathing hydrox is improved approximately 40% over heliox, and 141% over compressed air. While a diver at shallow depth performing at a modest work level may not find the 40% improvement particularly important, it may become very important at high work levels. Further, as the diver moves to greater depths it seems clear that the increased breathing resistance will become work limiting. At this point, hydrox may become a necessity. One must raise the possibility that at some depth hydrox would become necesary. The precise depth at which this would be the case is not known. Lambertsen and his workers (18) exposed divers to a simulated depth of 1200 feet breathing a mixture of helium, neon and oxygen in which the breathing resistance was equivalent to breathing helium-oxygen at a depth of 5000 feet. This work would suggest that man may be able to perform low to medium work at these depths using heliox. However, at these depths the 40% increase in breathing capacity afforded by hydrox may become important. Since it seems clear that breathing resistance will limit the maximum diving depth long before absolute pressure begins to cause damage at the tissue level, it may be that hydrox will be essential to permit man to function effectively at deeper depths (below 4000-5000 feet).

SAFETY OF HYDROX:

In considering the possible use of hydrox for diving, the first question which is raised concerns the safety of this gas. This first was considered by Case and Haldane (2) who reported that a mixture of 97% H_2 and 3% O_2 was entirely safe. They also reported that 68.7% H_2 and 31.3% air also was safe from explosion. Better documented recent work by Dorr and Schreiner (19) places the safety limit at 5.2% oxygen, although it has been reported that Russian work lowers this value somewhat.

In our laboratory we have considered that the work by Dorr and Schreiner is reliable. However, we as well as most others working with hydrox have arbitrarily limited the maximum allowable oxygen level to 3.5%. This has given us an adequate safety margin as well as leeway in our procedures since in both animal and man diving we are able to descend comfortably to a depth of 200 FSW, (7 atmospheres absolute) at which time 3% oxygen provides an oxygen partial pressure equal to that found at one atmosphere with air.

Perhaps the best indication of the safety with which hydrox can be used may be seen from Figure 1. We have carried out in excess of 4,560 hours of animal and human exposure to hydrogen-oxygen mixtures in chambers without accident. These range from simulated dives to depths of 200 feet of sea water (FSW) to 1000 FSW. Total times of individual dives range from 5 hours to over 5 days in duration. It should be noted that in all but about 20 hours of hydrox diving we have elected to flood the chamber with the hydrox mixture. So far, in the human dives we have delivered the hydrox by mask with overboard dumping of exhaled gas. On the human dives the chambers have contained 3% oxygen with nitrogen. We are, however, technicially ready to conduct a manned saturation dive to 300 feet in which the chamber is flooded with hydrox.

Since a 3% oxygen-hydrogen mixture cannot be ignited even with a spark (19), mixtures of this ratio are referred to as non-explosive. In our view, the main hazard is created by leaks or faulty operating procedures. Leaks are prevented by preliminary testing of the entire facility with helium at a pressure greater than that to be used with hydrox. Each valve, connection, fitting, window, door, hose and regulator is tested for leaks. Further, as the chamber is compressed the same thorough testing is carried out each 100 feet of depth. Finally, while on bottom the same leak check is carried out at least every 4 hours.

In addition to the physical testing for leaks, a hydrogen warning detector is in constant operation. This unit is activated by less than 0.1% hydrogen. Exhausted gas is passed through a flash-back arrestor.

The question of hydrogen embrittlement must be raised since it has been reported by Michaud and his colleagues (26) that chamber failure occurred from this cause. Studies conducted on various types of metals suggest that while hydrogen embrittlement could, indeed, be a threat under some circumstances, the embrittlement varies greatly with diffrent alloys. Further, it is lessened by the presence of oxygen in the quantities we employ (26). Since the hydrogen in our chambers always contains oxygen, it perhaps is important to examine in a more quantitative manner the effects of oxygen on hydrogen embrittlement (27) In one type of stainless steel it was shown that when the hydrogen contained 150 ppm of oxygen there was only a 7.5% reduction in strength. Further, when these data were graphed, the reduction in strength was

shown to be a semi logarithmic function. Thus, by extrapolation, when oxygen levels reach 500 ppm, the strength appears to be reduced by only 0.1% from its original strength. This must be viewed in light of the fact that hydrogen causes different amounts of embrittlement in different alloys. However, of the different alloys tested in the above cited work, the particular alloy just discussed (CW 301 stainless) showed much greater embrittlement than did the other 3 alloys tested.

It should be realized that the hydrogen in our chambers always contains oxygen in far greater amounts than 500 ppm. In fact, we would never expect with our present facility to have less than about 1000 ppm of oxygen.

Finally, we cannot fail to call attention to the many high pressure hydrogen cylinders which have been in constant use for many years with little cause for alarm due to cylinder failure.

OPERATING PROCEDURE:

It must be remembered that at no time can hydrogen be placed in contact with more than 3% oxygen. This rule can be observed and still permit both animals and man to shift between air and hydrox. This may be illustrated by reviewing our compression and decompression procedures.

Compression Procedures for Animal Chambers:

Figure 2:

The CO_2 scrubber motor is operated continuously during the entire dive to assure that there are no pockets of gas which fail to equilibrate during shifting of gas.

1. The chamber is closed with animals in place. The chamber contains 21% oxygen-79% nitrogen.

2. Compression is begun using pure helium or nitrogen. Upon reaching 200 feet depth (7 ATA) the oxygen partial pressure is essentially the same as at ground level but it now constitutes only 3% of the total gases. At this time it is safe to introduce hydrogen.

3. The chamber is flushed with 3% oxygen-97% hydrogen.

This permits the nitrogen and helium gases to be removed, leaving only hydrox. The amount of hydrox gas used in this flush depends upon the internal volume of the chamber and the amount of residual nitrogen and helium which can be allowed to remain.

4. If the chamber is to be further compressed to a greater depth it is done with pure hydrogen. This assures that upon reaching the desired depth the partial pressure of oxygen will be essentially normal. During pressurization, the oxygen percentage will, of course, continue to decrease although the chamber maintains the same partial pressure of oxygen. The pause at each 100 foot depth for leak checks also promotes adequate mixing of the chamber atmosphere.

5. As the animal utilizes oxygen from the chamber it must be replaced. However, to avoid creating an explosive mixture or re-introducing an undesired inert gas, the oxygen is replaced by adding 3% oxygen as hydrox. It usually is possible to establish a slow bleed-in of hydrox which is just sufficient to replenish oxygen consumed.

It should be apparent that the carbon dioxide produced by the animal must be removed. If not removed, the animal would die from buildup of carbon dioxide even before the oxygen depletion would kill it. There are many standard techniques for carbon dioxide removal. As a precaution we employ induction-type, or sealed explosion-proof blower motors with soda-sorb. Soda-lime, baralyme or lithium hydroxide also may be used.

Decompression Procedures for Animal Chambers:

Figure 3.

Decompression is not precisely the reverse of compression since it is necessary to introduce a non-combustible mixture of inert gas and oxygen to replace the hydrogen.

1. If the chamber is deeper than 200 feet, it is decompressed in accordance with the pre-planned schedule until reaching 200 feet depth. Since the chamber may have less than 3% oxygen when the ascent begins (at 1000 feet it will have approximately 0.6% oxygen), the oxygen level must be raised so that it reaches 3% when the chamber reaches 200 feet. This is done by flushing periodically with 3% hydrox.

2. Upon reaching 200 feet the chamber is flushed with 3% oxygen and helium replacing the hydrogen with helium while maintaining the safe 3% oxygen level. Again, the quantity of heliox employed will depend upon the size of the chamber.

3. The chamber finally may be brought to the surface with the heliox mixture, or it may be flushed with air. Since the chamber no longer contains hydrogen, the oxygen may be raised to any level required by the decompression table.

PROCEDURES FOR HUMAN DIVES:

As a matter of economy and convenience in our laboratory, the man chamber is not flooded with hydrox during a hydrox dive. It is flooded with a non-combustible gas mixture containing an oxygen level sufficient to sustain life in event of a mask failure, but never above 3%. It is accomplished as follows:

Compression:

Figure 4.

1. The chamber is compressed to 100 feet with pure nitrogen. The diver then dons a mask with overboard exhaust and begins to breathe 10% oxygen-90% helium. The chamber is further compressed on nitrogen until reaching 200 feet. At that time the chamber contains 3% oxygen and 97% nitrogen. It will sustain life although experience has shown that a sudden shift from helium-oxygen to nitrogen-oxygen creates significant nitrogen narcosis.

2. Upon reaching 200 feet the diver's breathing mixture is shifted to 3% oxygen-helium to purge the 10% oxygen mixture. It then is shifted to 3% hydrox.

3. The chamber then may be further compressed with pure nitrogen to the planned bottom depth. If the dive is to be below 300 feet it is recommended that the chamber be compressed with helium since below 300 feet a sudden shift from breathing helium or hydrogen to breathing nitrogen may be dangerous. Further, if the bottom depth is much greater than 300 feet, decompression time becomes so extended that it is quite exhausting for the diver to use a mask throughout decompression.

Decompression:

Figure 5.

For human dives, gas shifting during ascent is precisely the reverse of descent.

1. If the diver is deeper than 200 feet he ascends to 200 feet using the pre-planned decompression profile while breathing the appropriate gas mixture.

2. Upon reaching 200 feet the breathing mixture is shifted to 3% oxygen-helium to purge the hydrox. The diver then shifts to 10% oxygen-helium.

3. Decompression proceeds, employing pre-mixed ratios of helium or nitrogen and oxygen. Care is exercised to avoid a sudden shift from helium to nitrogen deeper than 80 feet since there have been several instances of permanent ear damage when such shifts took place at 100 feet. It is important to remember that the chamber contains no more than 3% oxygen when ascent begins. Thus, by the time the chamber reaches 160 feet flushing with air must begin to avoid hypoxia in event of mask failure. The chamber must have 21% oxygen by the time the diver removes his mask which often is at about 60 feet.

An experimental decompression table is shown in Figure 5. As may be seen, this table is for a hydrox dive to 300 feet for a 30 minute bottom time. It will be noted that at 100 feet a shift is made to 50/50 helium-oxygen. We consider this table to be experimental and are continuing to modify it. However, it has been developed in such a way as to lend itself to operational diving with little further modification.

It also will be noted that this table employs deep stops. Our work in decompression (20) strongly indicates that gas bubbles may be created by an uninterrupted ascent of as little as 20 FSW. The use of very deep stops appears to reduce the instance of decompression sickness and results in divers feeling less fatigued upon reaching the surface.

EFFECTS OF HYDROGEN ON THE BODY:

Initially there was considerable speculation concerning the possible adverse effects of breathing molecular hydrogen. It ranged from predictions that it would cause detrimental shifts in the body pH (acid-base balance), to suggestions that it would serve as a highly reducing environment which could disturb body metabolism. None of these dire predictions has been substantiated. Of more serious nature, however, were the observations of Michaud and his associates (16) (21) referred to earlier. Again, we have failed to confirm these findings. We have discovered no brain abscesses in any of our animals, and we find that they are able to carry out 5-day saturation dives and return to the surface in good health. The longest exposures we have carried out have been on mice which have survived over 30 days at a depth of 270 feet. On dogs it has been approximately 3½ days, and on man about 6 hours.

We have found, however, that temperature control is essential during deep hydrox saturation diving. Failure to provide sufficient external heat may result in loss of body heat and the death of the animal.

THE MIXING OF HYDROGEN-OXYGEN

A number of methods have been proposed for mixing hydrogen and oxygen. Case and Haldane simply introduced oxygen into a rubber bag containing hydrogen. Others have proposed causing the oxygen to diffuse through a membrane into the hydrogen. Edel (24) developed a complex method whereby oxygen is slowly injected into a cylinder of hydrogen at high pressure. Although his last system worked successfully, it suffers from several problems. Firstly, there is the possibility that hydrogen may diffuse back into the oxygen line creating an explosive mixture. Secondly, if there should be an explosion in the hydrogen cylinder due to temporary uneven distribution of the introduced oxygen, the cylinder could not contain the explosion. Thirdly, this technique employs helium to purge all lines. As a result, the final hydrox mixture contains an appreciable amount of helium. Under most circumstances this helium does not significantly affect the hydrox usefulness.

Still another technique employed by at least one group is to introduce the hydrogen at low pressure into a heavy, strong

cylinder and then slowly bleed in the oxygen. The mixing pressure is kept low enough so that the cylinder would be able to contain any explosion which might occur. After mixing, the gas is boosted to the desired pressure.

We have developed two techniques, both of which are now the property of the U.S. Navy. One employs an electrolytic technique in which controlled current flow determines the ratio at which hydrogen and oxygen gases are produced. Mixing takes place as the two gases ascend through the electrolyte. The hydrox then is dried and further compressed.

The second technique is the one currently employed in our laboratory (Figure 6). This works on the principle that if oxygen is introduced at a slow rate into a swiftly moving turbulent stream of hydrogen, mixing will be so rapid that there will not be a sufficient volume containing an explosive mixture to sustain an explosion. We have tested this concept by attempting to ignite such a stream with a spark (at one atmosphere). As can be seen in Figure 6, it only is necessary to continue injecting oxygen until the desired level is obtained. This requires about 20 minutes, following which the hydrox can be transferred into a storage cylinder. We have, of course, added a few other features to our operational unit for convenience and more precise control. For example, we use a differential pressure gauge to permit us to maintain the oxygen inlet line precisely 100 pounds above the pressure in the mixing tower. This assures us that we can precisely control the rate of oxygen inflow. There are a few other refinements too tedious to mention.

In the past year some interest has been shown over the possibility that molecular hydrogen under high partial pressure may cause regression of certain types of cancer (25). This was based on the observation that skin lesions on mice appeared to be improved after 7 days' exposure to hydrogen at a depth equivalent to 240 feet. This observation still is being studied and several other types of malignancies are being reviewed. We are guarded in our optimism for this treatment. We are of the opinion that hyperbaric hydrogen probably is not a panacea for cancer, but may be of some use in certain types, probably in conjunction with other treatments. This requires much further study.

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FIGURE 1

Total Time Exposure
To Hydrogen

Man	29 hours
Dog	605 hours
Mouse	3,912 hours
Rat	36 hours
	4,562 hours

Figure 2

Chamber Compression for Animal Dives Using Hydrox

1. Start CO_2 Scrubber Motor;
2. Compress to 200 FSW with Helium;
3. Flush with Hydrox;
4. Descend to Operating Depth with Hydrogen;
5. Replace Metabolized Oxygen with Hydrox.

FIGURE 3

Dog Decompression Table for Saturation
Dive to 1000 FSW on Hydrogen-Oxygen

Depth	Time	Depth	Time	Depth		Time
980	1.0	600	24.0	300		43.0
960	1.0	590	26.0	290		45.0
940	1.0	680	25.0	280		45.0
920	1.0	570	26.0	270		47.0
900	1.0	560	27.0	260		48.0
880	1.0	550	26.0	250		49.0
860	1.0	540	27.0	240		50.0
840	1.0	530	28.0	230		52.0
820	1.0	520	28.0	220		54.0
810	6.0	510	29.0	210		55.0
800	19.0	500	29.0	200	(a)	57.0
790	20.0	490	29.0	190		59.0
780	20.0	480	30.0	180		61.0
770	20.0	470	31.0	170		63.0
760	20.0	460	31.0	160	(b)	38.0
750	20.0	450	31.0	150		41.0
740	21.0	440	32.0	140		43.0
730	21.0	430	33.0	130		47.0
720	21.0	420	34.0	120		50.0
710	21.0	410	34.0	110		54.0
700	22.0	400	34.0	100		59.0
690	22.0	390	36.0	90		64.0
680	22.0	380	36.0	80		69.0
670	23.0	370	37.0	70		76.0
660	23.0	360	38.0	60		84.0
650	23.0	350	38.0	50		92.0
640	23.0	340	40.0	40		103.0
630	24.0	330	40.0	30		115.0
620	24.0	320	41.0	20		129.0
610	25.0	310	42.0	10		149.0
				Total Time		3439.0 min

(including travel time between stops)

(a) Flush with heliox
(b) Flush with air

Figure 4

Compression for Manned Chamber Dives Using Hydrox

1. Compress Chamber to 100 FSW with Nitrogen (Diver Breathing Chamber Air);
2. Shift Diver to Mask with 10% Oxygen in Helium;
3. Compress Chamber to 200 FSW with Nigrogen;
4. Shift Breathing Gas to 3% Heliox;
5. Shift Breathing Gas to 3% Hydrox;
6. Compress Chamber to 300 FSW with Nitrogen.

FIGURE 5

TAMU Hydrox Decompression Table #5

MAN

30 minutes - 300 feet

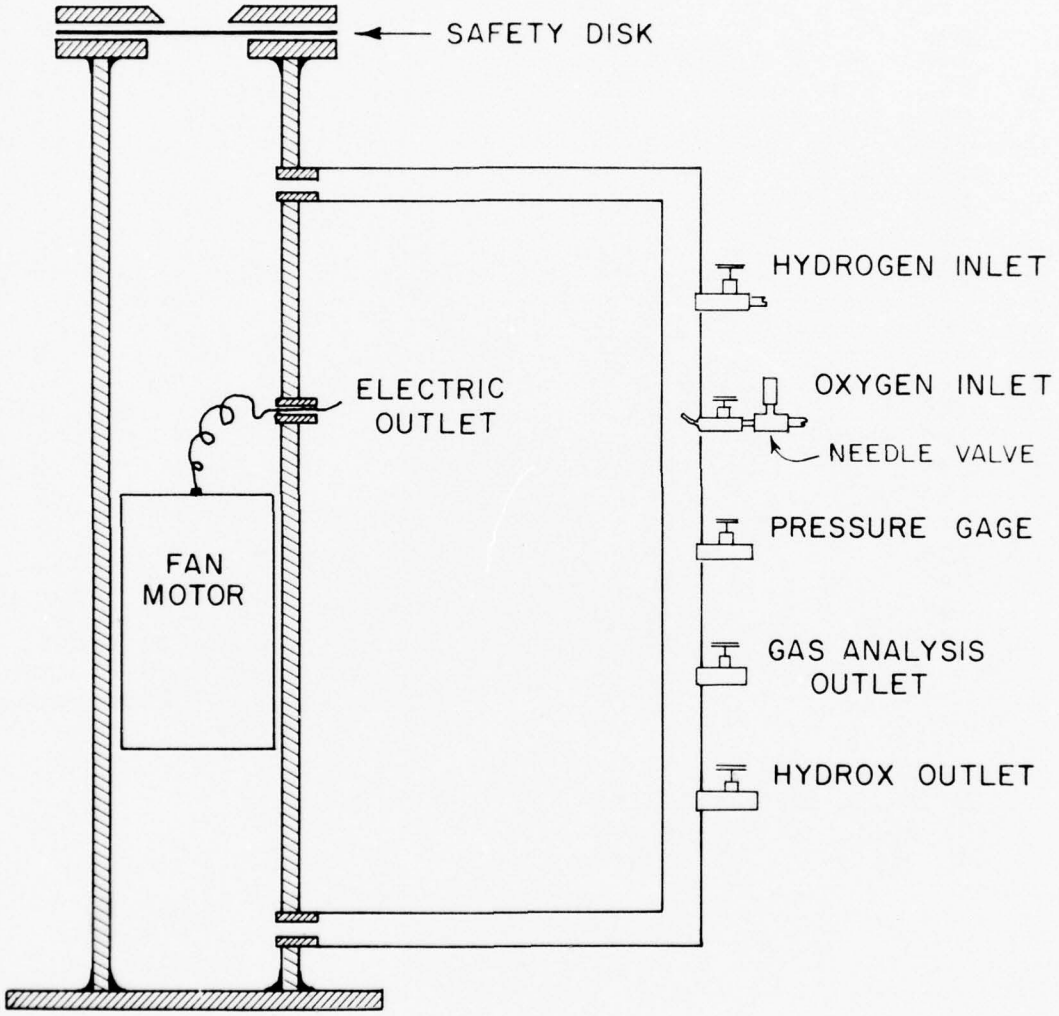
Depth	Time	Depth	Time
300'	30 min. (a)	60'	12 - O_2
280	1	50	7 - O_2
260	1		5 - air
250	2		4 - O_2
240	2	40	15 - O_2
230	2		5 - air
220	4		1 - O_2
210	4	30	18 - O_2
200	3 (b)		5 - air
190	2		6 - O_2
180	6	20	13 - O_2
170	6		5 - air
160	5		17 - O_2
150	9	10	2 - O_2
140	10		5 - air
130	12		20 - O_2
120	14		5 - air
110	18		10 - O_2
100	9 (c)	Surface	____
90	10	Total	320 min.
80	8 (d)		
70	10		

including ascent time (one minute travel time between stops)

(a) 3% hydrox
(b) shift to 10% heliox
(c) shift to 50% heliox
(d) shift to 50% nitrox

FIGURE 6

HYDROGEN–OXYGEN MIXING SYSTEM



SOME DESIGN CONSIDERATIONS FOR HYPERBARIC CO_2 SCRUBBERS

by

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ABSTRACT

This paper discusses important factors relative to the design of hyperbaric CO_2 scrubbers. Methods of predicting scrubber bed life and calculating required flowrate are presented. The importance of scrubber bed orientation for cold chamber operation is suggested. Much of the information for the paper is based on actual tests in hyperbaric chambers.

INTRODUCTION

Adequate CO_2 removal is a necessity for any diver's hyperbaric chamber. For air chambers, purging can be used to remove CO_2; however, for deep diving where helium-oxygen is used, a CO_2 scrubber is generally used. These scrubbers typically consist of a small blower which forces gas through a bed of chemically absorbent material.

Several variables including pressure, temperature, humidity, gas composition, residence time, chemical absorbent efficiency, and canister geometry affect the performance of the scrubbers. Relatively little information is available for designing CO_2 scrubbers for hyperbaric environments. In this paper, test data have been correlated to show the effect of temperature, humidity, and scrubber bed orientation. All tests referred to in this paper used Sodasorb[1] for the absorbent material. The effects of other variables are also discussed.

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[1] Sodasorb is a registered trade name for the CO_2 absorbent material manufactured by Dewey and Almy Chemical Division of W. R. Grace and Co.

CHAMBER DEPTH AND SCRUBBER EFFICIENCY

Chamber depth affects the CO_2 absorbing efficiency of the chemical absorbent where efficiency is defined as the percentage of CO_2 removed from the gas mixture as it passes through the absorbent bed.

Studies by the Naval Research Laboratory in Washington, D. C. have shown the efficiency to be a function of the gas density. Preliminary findings from their studies are shown in Figure 1. It should be noted that the data are for a fixed temperature and humidity. Testing at 600 feet with Sodasorb as the chemical absorbent indicates that this efficiency remains relatively constant for approximately 80 percent of the useful absorbent life after which there is a rapid decrease in efficiency.

The scrubber efficiency must be known in order to determine the required gas flowrate to maintain an acceptably low CO_2 level in the chamber where the maximum allowable level is considered to be 0.5 percent surface equivalent. The required gas flowrate to be circulated through the scrubber can be calculated from the following relationship:

$$\dot{M}_{CO_2} = Q(e)\ (L_{CO_2})\ \rho_{CO_2} \quad . \tag{1}$$

where

$\dot{M}_{CO_2}$ = mass flowrate of CO_2 input, $\frac{lb}{hr}$

Q = volume flowrate of processed gas, $\frac{ft^3}{hr}$

e = absorptive efficiency, ratio of CO_2 removed to CO_2 entering, $\frac{ft^3}{ft^3}$

L_{CO_2} = design level of CO_2 in chamber at specified depth (volume fraction), $\frac{ft^3}{ft^3}$

ρ_{CO_2} = density of CO_2 at specified depth, $\frac{lb}{ft^3}$.

The relationship in Equation (1) is based on an equilibrium condition of removing the same amount of CO_2 that is being generated. It is interesting to note that the chamber volume does not affect required flowrate.

Note: This information is from Encl (1) of NRL ltr 6130-222:DDW:cmc Ser 3567, May 1970 by Stanley T. Gadomski and Dale D. Williams of the Naval Research Laboratory in Washington, D.C.

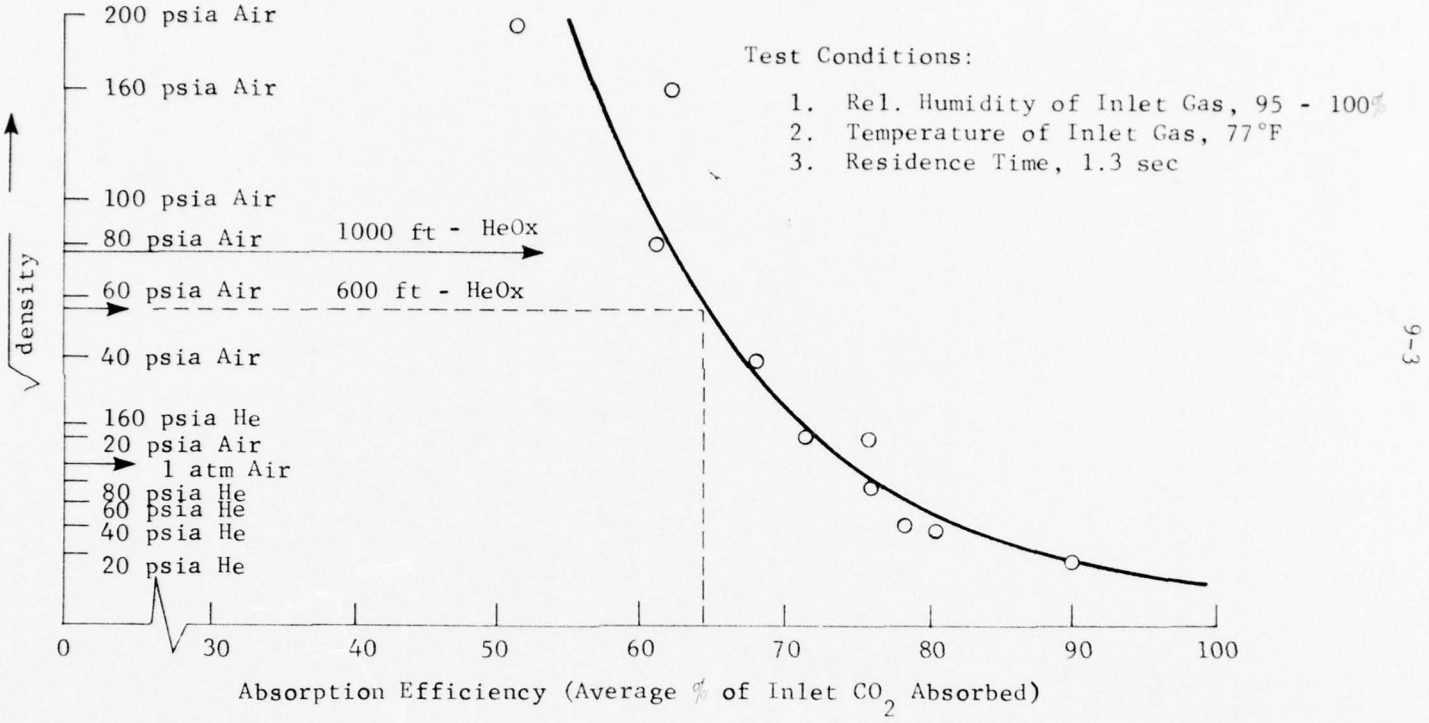


FIGURE 1. EFFECT OF GAS DENSITY (PRESSURE) ON CO_2 ABSORPTION EFFICIENCY FOR SODASORB

ABSORBENT BED LIFE

The maximum theoretical absorbing capacity of an absorbent such as Sodasorb is 0.41 pounds of CO_2 per pound of absorbent. This becomes a good yardstick in comparing test data. Bed life can be presented as a ratio of actual life/theoretical life.

An important factor in specifying bed life is the criteria for determining when useful life has ended. For this purpose that time is considered to be when the scrubber can no longer maintain the atmosphere below 0.5 percent by volume surface equivalent of CO_2.

Based on actual tests with three different CO_2 scrubbers, data have been correlated and presented as Figures 2 and 3. It was found more useful to present the data for vertical scrubber beds on one graph, and horizontal and annular beds on another. Figure 4 shows the three scrubber bed configurations. From Figures 2 and 3, it can be seen that well designed scrubbers under favorable conditions of high humidity and 90°F temperature can perform very efficiently. Fortunately these are conditions normally found in diving chambers.

Figure 2 shows a drastic reduction in performance if the gas is dry; hence, the gas should not be heated before it enters the scrubber bed. While no elevated temperature tests were made on the horizontal and annular bed scrubbers, the same reduction in performance can be expected.

There is a significant trend in the cold temperature performance of the different bed geometries. For chamber temperatures of 40 to 50°F, there is a 20 percent reduction in performance for the vertical scrubber bed, and for the horizontal and annular scrubbers, an 80 percent reduction. The number of tests are too limited to be conclusive; however, they do suggest the distinct possibility of temperature related performance. Further testing would be desirable to substantiate this probability. The added advantage of vertical scrubbers over horizontal or annular scrubbers can be a significant factor if chamber temperatures of 40 to 50° are considered, such as would be the case with a personnel transfer capsule (PTC) heating failure.

Bed oriendation appears to have a pronounced effect on bed life at the lower temperatures and may be due to the way moisture accumulates in the bed. Water vapor is an essential element for the chemical reaction between the Sodasorb and the CO_2. Also free water is produced in the reaction. In all three bed orientations (Figure 4), excess moisture will accumulate at the bottom of the absorbent bed unless the humidity is low, then the moisture will evaporate. Only in the vertical type canister will the flow be forced to go through the high moisture area; the added moisture then

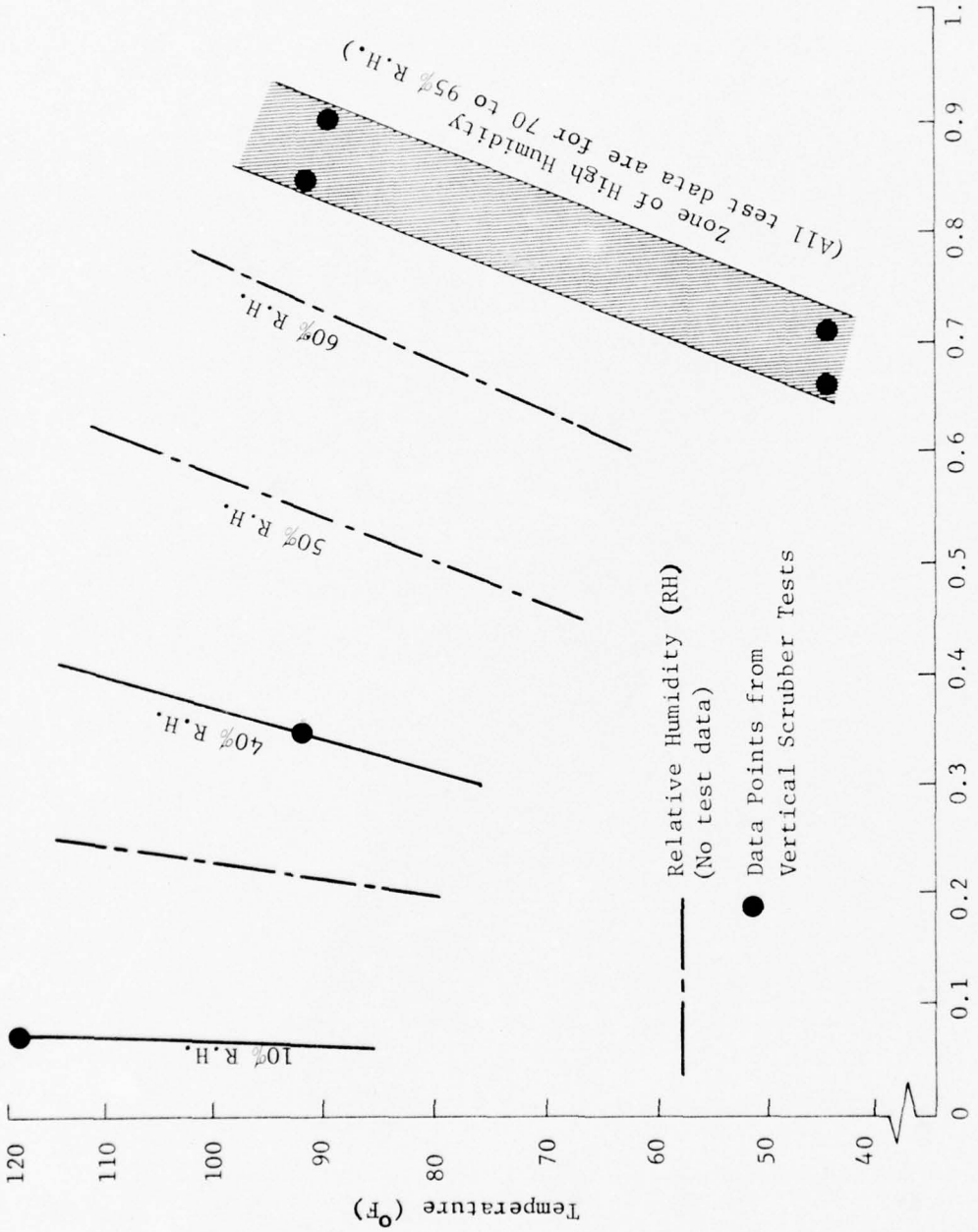


FIGURE 2. PERFORMANCE OF VERTICAL SCRUBBER BED USING SODASORB AT 600 FEET

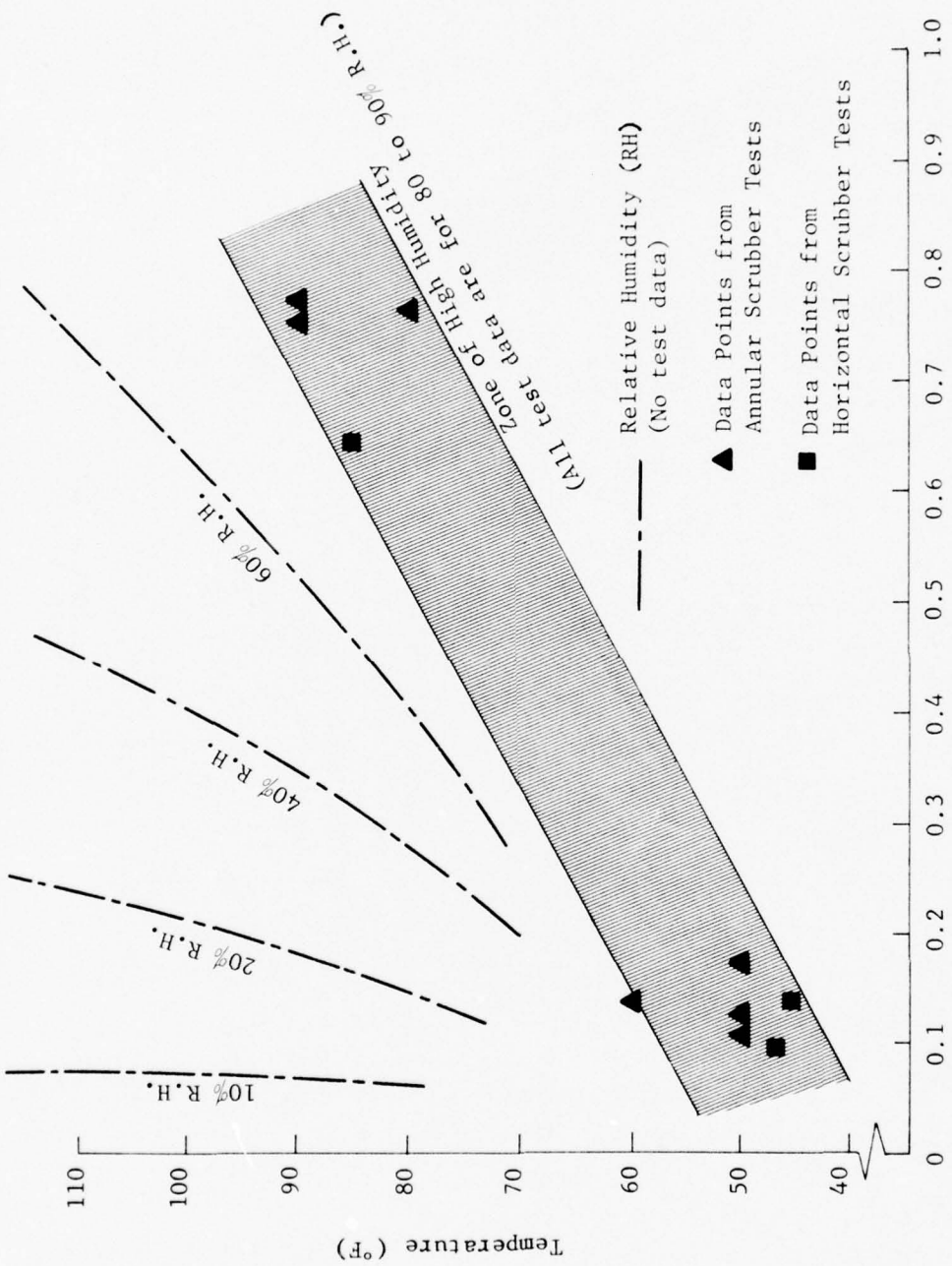
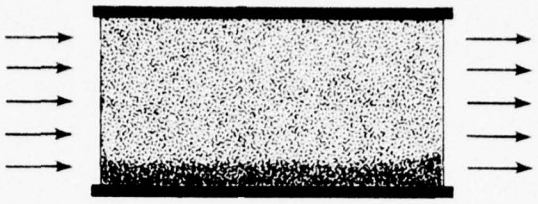
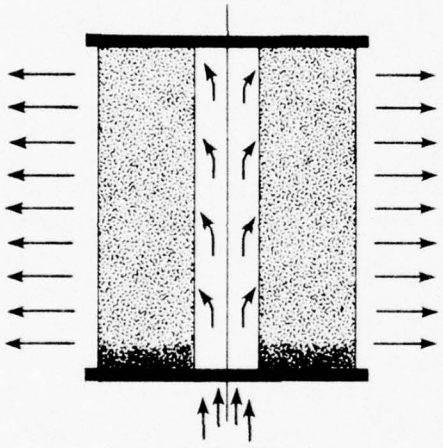


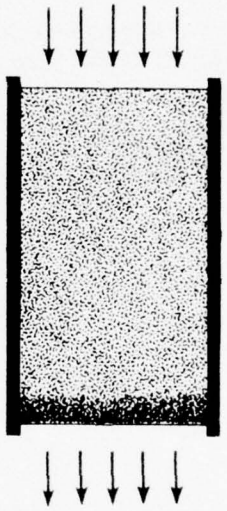
FIGURE 3. PERFORMANCE OF A HORIZONTAL AND AN ANNULAR SCRUBBER BED USING SODASORB AT 600 FEET



Horizontal Bed



Annular Bed



Vertical Bed

NOTE: Shaded area indicates accumulated moisture.
Arrows represent direction of gas flow.

FIGURE 4. CO_2 SCRUBBER BED CONFIGURATIONS

appears to be the only reason for the longer life of the vertical bed at low temperature compared to the horizontal and annular type.

RESIDENCE TIME

The residence time is the time the gas is exposed to the absorbent material. In general, residence times of 1 second or more have been used in scrubber designs. However, tests have shown that residence times can vary from 1 to 0.1 second and still have an operating system.

CASE HISTORY OF A SCRUBBER ANALYSIS

A scrubber with annular construction and a Sodasorb absorbent bed volume of 1100 cubic inches was designed for use in a deep diving PTC having an operating depth of 850 feet.

If the PTC atmosphere was to be maintained below the maximum allowable CO_2 level of 0.5 percent surface equivalent, the specified design level would have to be considerably less; it was assumed in this case to be 0.39 percent. Further, it was assumed that the CO_2 produced by four divers would be 0.458 pounds per hour. So, knowing the assumed values and the operating depth of 26.7 atmospheres the required scrubber flowrate could be calculated from Equation (1) which has been rewritten here:

$$Q = \frac{\dot{M}_{CO_2}}{e\ (L_{CO_2})\ \rho}$$

where

$e = 0.62$ from Figure 1

$$L_{CO_2} = \frac{0.39}{26.7} \times \frac{1}{100} \frac{ft^3 \text{ of } CO_2}{ft^3 \text{ of mix}}$$

$$\rho = 0.11 \times 26.7 \frac{\text{lb of } CO_2}{ft^3 \text{ of } CO_2}$$

$$Q = \frac{0.458}{0.62\ (\frac{0.39}{26.7} \times \frac{1}{100})\ (0.11 \times 26.7)}$$

$$= 1722\ ft^3/hr$$

or

$$= 28.7\ ft^3/min\ .$$

The volume of the canister is 1100 cubic inches. The density of Sodasorb is 0.0317 pounds per cubic inch. Therefore, the canister will hold an estimated 34.9 pounds of CO_2 absorbent. The maximum amount of CO_2 that can be absorbed is 14.3 pounds (34.9 lb of absorbent x 0.41 lb of CO_2/lb of absorbent = 14.3 lb of CO_2). Assuming that the absorbent could remove the maximum theoretical amount of CO_2 at the specified production rate of 0.458 pounds per hour the scrubber bed would last 31.3 hours.

From Figure 3 for 90°F and high humidity at 600 feet of seawater the ratio of actual life to maximum theoretical life is approximately 0.75. The difference in performance between 600 and 850 feet is not anticipated to be significant. Therefore, for the PTC operating at design depth the predicted scrubber life would be 31.3 hr x 0.75 or 23.5 hr. In actual testing of the scrubber the useful life was 23.7 hours.

For operation at 45°F in a high humidity atmosphere a ratio of actual life to maximum life of 0.15 is obtained from Figure 3. Therefore the predicted life at 45°F is 31.3 hr x 0.15 or 4.7 hr. The scrubber's useful life was 2.9 hours measured during actual testing.

CONCLUSION

Many factors affect CO_2 scrubber performance of which temperature and moisture are the most significant. As would be expected in a chemical reaction, increased temperature results in increased performance. This is only true if sufficient moisture is available. Moisture is available through humidity in the atmosphere and in the scrubber bed. The moisture in the bed appears to be better utilized with gas flow in the vertical direction particularly during cold temperature operation. Additional testing is required to better understand the combined effects of temperature and humidity on hyperbaric CO_2 scrubbers.

U.S. NAVY CLEANING PROCEDURES FOR DIVING GAS SYSTEMS

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Abstract

This discussion deals with the importance of cleaning procedures for diving gas systems. The cleaning technician's responsibility in cleaning systems and components on man-rated diving systems, along with calibration and analysis is basic to the safety and success of any diving operation. Personnel assigned to operate and maintain the clean room and perform the functions associated with it must have prior schooling and/or on-the-job-training in cleaning procedures. Knowledge and experience in the following areas is desirable:

1. Maintenance of the clean room for operations and certification.
2. Cleaning techniques for valves and components.
3. In-place cleaning techniques for systems.
4. Tests for cleanliness levels.
5. Tests for functional operation.
6. Removal and reinstallation of components in cleaned systems.

Equipment must meet the standards of the cleanliness levels of the systems to be cleaned and must include the facilities to perform the required sample analysis. The clean room is a restricted area with access limited to those personnel assigned for qualified reasons. A restricted area access list is posted on the entry door. Clean room garments are required before entry into the clean room air lock.

The clean room must be maintained and inspected periodically. It must qualify to the class 100,000 clean room requirements prior to the start of the operation.

INTRODUCTION

It is imperative to clean a hyperbaric diving system and its component parts to eliminate any contaminants that may be directly or indirectly hazardous to the personnel inside or that may cause failures in equipment supporting those personnel.

In the past 15 years, the U.S. Navy has suffered numerous fires in its hyperbaric chambers and their sub-systems. Two of these will be discussed: the U.S. Navy Experimental Diving Unit fire, 16 February 1965 and U.S.S. Ortolan, ASR-22, explosion and fire, 3 June 1974.

NEDU Fire-16 February 1965

The conclusion of the board of inquiry was that the $C0_2$ scrubber-filter (Type AN 6236-3, conforming to Mil-Spec # MIL-F-5504B for Filters and Filter Elements, Fluid Pressure, Hydraulic Micronic Type) was one contributing cause of the fire. All filters under Mil-F-5504B are required to be tested using a petroleum base hydraulic fluid, but there is no requirement to clean them after testing. In a test conducted by the U.S. Navy Research Laboratory on an identical filter element, hydro-carbons were found in the form of a middle distillate petroleum product. In this case, the three elements necessary for combustion were present:

1. Fuel - the paper filter element and the fluid in which it was tested.

2. Oxygen - 28% 0_2 atmosphere in chamber.

3. Heat - electric motor running on starting phase.

U.S.S. Ortolan, ASR-22, Fire 3 June 1974

The last U.S. Navy fire or explosion-related accident that occurred in a hyperbaric system was the U.S.S. Ortolan, ASR-22 fire and explosion on 3 June 1974. The board of inquiry concluded that a piece of particulate matter lodged in the suction head check valve of the portside oxygen transfer pump, a Corblin diaphragm compressor. As the valve worked, the particle got hotter and eventually ignited in the high oxygen atmosphere. Again all three components of combustion were present.

The probable cause of both accidents was the presence of contaminants in the system. At NEDU, the contaminants were hydrocarbons; on the Ortolan they were particulates.

Removal of these contaminants from the diving systems significantly reduces the possibility of accidents, equipment damage and danger to personnel in and around the system.

CLEANING STANDARD

Prior to 1975, the U.S. Navy had no one publication that contained cleaning procedures to cover diving systems. Each unit of the diving community, in conjunction with its overhaul facility, assembled the cleaning procedure for its system from numerous Mil-Specs, Fed-Specs, Shipyard-Specs and best practice policies. This resulted in a wide variety of interpretations throughout the diving community. In 1975, the Naval Sea Systems Command (NAVSEA) assembled a standard set of rules in a publication entitled NAVSEA 0994-016-6010; "Cleaning Procedures For ASR-21 and 22 DDS". Although it was only intended to apply to the deep diving systems on ASR-21 and 22, this instruction has been used as a basic reference from which local cleaning instructions for other Navy deep diving systems have been derived.

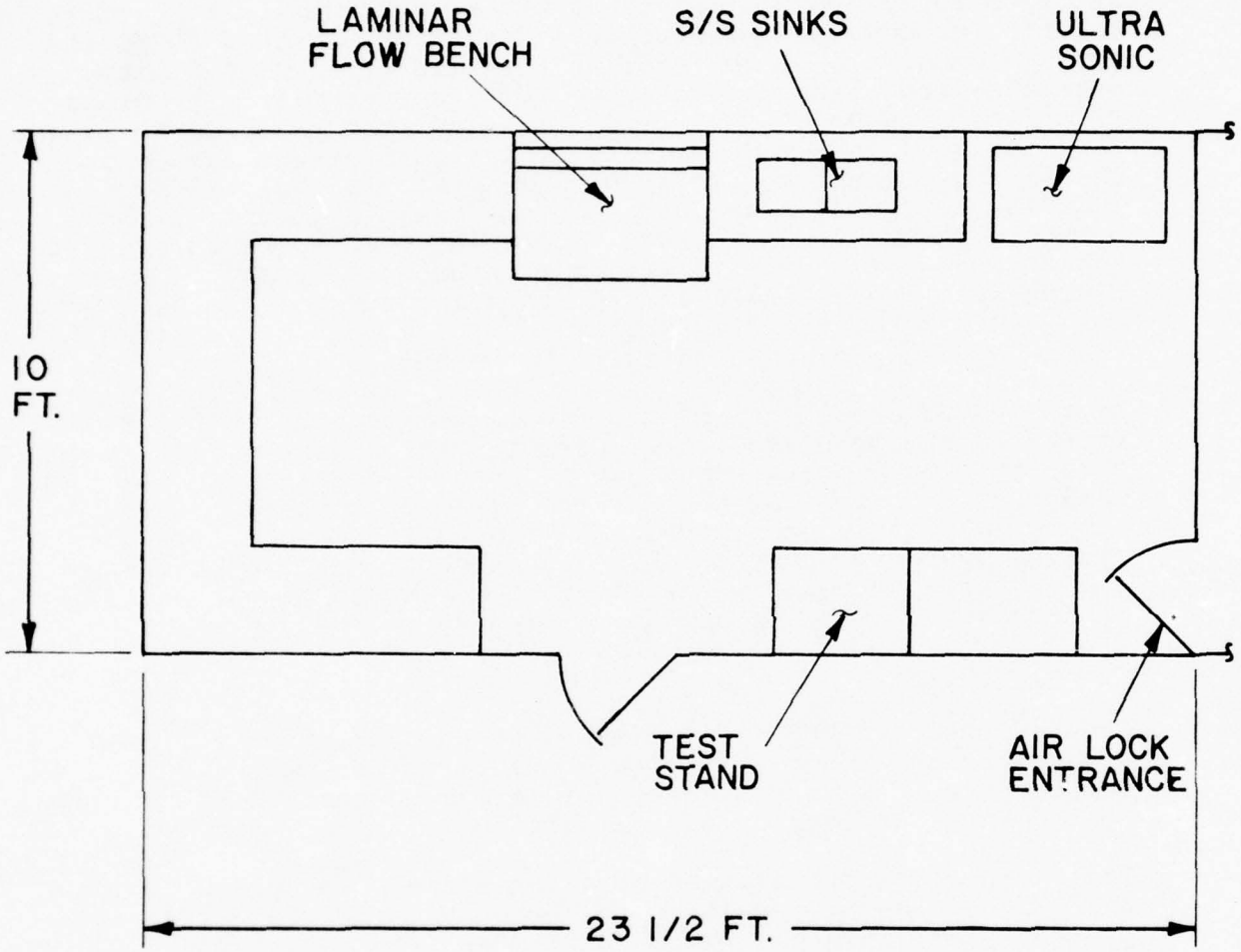
In the NAVSEA Publication, the clean room technician can find the basic equipment and materials which a class 100,000 cleaning facility should contain and how it should operate. It gives the standards for cleaning the various types of components and systems, procedures for removal and reinstallation of components in cleaned systems, gauge calibration methods, sampling techniques and analysis, etc. Now the clean room technician has at his fingertips, all the information he needs to operate.

CLEAN ROOM

Federal Standard 209 (B) defines a clean room as an enclosed area employing control over particulate matter in the air. Temperature, humidity and pressure are also controlled but only to the extent required for the particular application.

There are different classes of clean rooms. The class designation specifies the density of airborne particulate matter. The U.S. Navy Experimental Diving Unit maintains a class 100,000 clean room to clean the systems and components of the Ocean Simulation Facility (OSF). Class 100,000 means that the total number of particulates 0.5 micron and larger is less than 100,000 per cubic foot or the total number 5.0 microns and larger is less than 700 per cubic foot.

Cleanliness levels in a clean room may vary within the room. Separate areas for different levels are not required if a work station can be maintained at a higher standard than required for the work being performed.



NEDU CLEAN ROOM LAYOUT

FIGURE 1

The air supply associated with the room is capable of maintaining a positive static pressure of 0.05 inches of water gage (approximately 0.002 psig) above the surrounding areas.

Clean rooms can be laminar or non-laminar flow facilities. In a laminar flow room the air flow through the room is uniform with no turbulance. The NEDU clean room is a non-laminar type. However a laminar flow bench which maintains a uniform flow over the work surface is installed and utilized for reassembly.

Figure 1 is a plan view of the NEDU clean room.

EQUIPMENT:

A clean room must be equipped to enable achieving the cleanliness levels of the systems to be cleaned and to perform the required sample analysis. The equipment that should be available is:

1. Spools, blind flanges, jumpers and hose required to connect sub assemblies and components for testing and cleaning.

2. A pH meter 0 - 14 range.

3. A freon leak detector.

4. An ultraviolet light.

5. A dew point indicator - to determine moisture after drying piping systems.

6. A Contamination Analysis Kit.

7. Binocular microscope - 10-100 power to visually count particulates of 5 microns or larger.

8. Microscope light, high intensity variable on an adjustable arm.

9. Vacuum oven capable of holding 29" Hg vacuum and of generating up to 200°C temperatures.

10. Vacuum pump capable of drawing 25" of mercury for drawing samples through millipore filter.

11. Vacuum pump with fail-safe capable of drawing 29" of mercury for operating vacuum ovens and drawing vacuum on sample bombs.

12. A comparator tester with 0-160, 0-600, 0-5000, and 0-10,000 psi test gauges.

13. A thermoconductivity gas leak detector.

14. A supply of fittings, various types and sizes, individually bagged and cleaned to specifications to expedite cleaning and testing of other components.

15. Plastic bag sealer iron with a heat range for Nylon C and Aclar 33C.

16. Miran I Infrared Fixed Filter Analyzer - 3.4 micron resolution - to determine hydrocarbons in solutions.

17. Automatic Gage Cleaner - this piece of equipment is of the type which allows the cleaning technician to clean the gage without continuously monitoring the cleaning process while in progress. The basic operation is that the cleaner draws a vacuum and then cycles to allow the bourdon tube to fill with filtered PCA grade freon. This cycle occurs every 10-12 seconds.

18. Pyrex filter holder.

19. Filtering flask.

20. Forceps.

21. 142 mm filter holder, with filter pads (5 micron).

22. Solvent filtering dispenser.

23. Filter discs.

24. Two adjustable wrenches.

25. High pressure filter holder.

26. Stainless steel trays.

27. An assortment of glassware (funnels, beakers, bottles).

28. Model 400 Total Hydrocarbon Analyzer - to determine hydrocarbons in a gas sample.

29. Millipore filter set - to filter test samples of cleaning blanks.

30. Ultrasonic cleaner, twin tanks, 60 gallon capacity.

MATERIALS

The following consummable materials and supplies are necessary to sustain cleaning operations:

1. Clean dry air, filtered to 25 microns absolute, and dried to a dew point of -40°F, or a supply of nitrogen, Type II, Class I, Grade A, filtered to 25 microns absolute.

2. Anhydrous trisodiumphosphate (TSP) $Na_3 PO_4$, technical grade.

3. Non-ionic detergent.

4. Tape

5. Cleaning solvent (Freon PCA) - pure and filtered to 25 microns absolute.

6. Containment bags of Nylon C or Aclar 33C.

7. Filter cloth for clean rags - to be disposed of after each use.

8. Helium, Type I, Grade A, filtered to 25 microns absolute.

9. Approved lubricants.

10. pH indication paper - 5.0 - 8.0 range.

11. Grade "B" water - filtered to 25 microns absolute.

12. Carbon tetrachloride (CCl_4), spectrographic grade.

13. Isopropyl alcohol, laboratory grade.

CLEAN ROOM MAINTENANCE AND INSPECTION

The clean room must be cleaned and inspected daily. Cleaning must be done at the beginning of each day in accordance with the daily cleaning requirements and a check off sheet (Figure 2) must be signed by the person responsible.

The daily cleaning routine should consist of the following:

1. Vacuum rooms.

2. Damp mop floors with Grade "B" water or detergent and water.

3. Wash work benches, counters and table tops with clean lint-free cloth or synthetic sponge dampened with liquid detergent and/or Grade "B" water.

4. Remove all waste material.

5. Clean and inspect all equipment and tools.

6. Perform black light inspection of clean room and equipment.

7. Perform a particulate count on atmosphere.

8. Record temperature and humidity.

9. Check water for pH, resistivity and particle count.

The clean room supervisor must approve the check list in order to begin daily operations. These lists are retained as a permanent record for sustaining certification.

Weekly and monthly inspection and maintenance is also required and should consist of the following:

Weekly:

1. Vacuum front side of pre-filter on Laminar flow clean bench.

2. Wipe down ceilings and lights with clean lint-free cloth.

3. Dampen a synthetic sponge with filtered (5.0 micron nominal) alcohol and wipe down all walls.

4. Perform a particle count on Laminar flow bench.

Monthly:

1. Inspect and repair or replace equipment as needed.

2. Wash or replace pre-filters on Laminar flow bench.

3. Inspect or, if necessary, replace air conditioning filters.

4. Examine all HEPA filters for damage and/or excessive contamination.

CLEAN ROOM CLEANING CHECK SHEET Date _____

CHANGE ROOM AIR LOCK - Daily Inspection

Wipe Floors	_____	Wipe Ledges	_____
Examine Door Frames and Closures	_____	Check Uniforms	_____
Check Air Pressure	_____	Vacuum Room	_____

CLEAN ROOM - Daily Inspection

Wipe Counter	_____	Vacuum Room	_____
Wipe Ledges	_____	Examine Oven Interior	_____
Wipe Braces and Legs	_____	Inspect Tools, Blacklight and Wipe	_____
Inspect Sealers for Dirt	_____	Examine Microscope and Test Equipment	_____
Blacklight Counters	_____	Examine Door Frames and Closures	_____
Examine Sinks for Contamination	_____	Check Gage Test Stand	_____
Wipe Floors	_____		

	Acceptable	Actual
Temperature	72° ± 5°F	_____
Humidity	40% ± 10%	_____

Signature _____

WATER/AIR ANALYSIS

	Acceptable	Actual
WATER		
Maximum Particle	25 - over	_____
pH	6 - 8	_____
Resistivity	500,000	_____
AIR		
5 microns or larger	700	_____

Action taken if actual exceeds acceptable limits:

Signature _____

Room is hereby certified for operation

Signature Supervisor _____

Figure 2

In addition each time a solvent source container is changed, the clean room solvents must be checked to determine whether they meet the requirements of the applicable specification. The gas supply to the area is checked weekly or whenever the source is changed to assure that the gas meets the cleanliness requirements. Checks are made on the Grade "B" water supply for pH and resistivity at least once a day and when the tank is changed.

ENTRY CONTROL

The clean room is a restricted area with access limited to personnel assigned to the area. A restricted area access list is posted on the entry door. Exceptions may be made, but instructions about rules and regulations for clean room operations must be understood prior to entry into the restricted area.

Entry into the clean room is through an airlock. Before entering the air lock, all personnel must change into clean room garments, including coveralls, head coverings, booties (clean room shoes), gloves, and in some circumstances, a face mask.

The clean room uniform must not touch the floor. All clean room garments are stored in the change room area in plastic bags or on hangers provided. Clean room clothing is changed twice weekly or more often if it becomes soiled. Torn or damaged clothing is replaced. Contaminated clothing is stored in large plastic bags in the change room area until removed for processing. The garments may be laundered in a standard automatic washer with normal detergents provided they are done alone to avoid lint pick-up.

No personal effects may be carried into the restricted area with the exception of eye glasses and hearing aids. Smoking, eating, and gum chewing are prohibited at all times in the cleaning areas. Cabinets, work benches and other furniture have fixed positions and may not be moved without permission. Preliminary washing of hands and face must be done outside the clean room.

Personnel must meet personal health and work standards of cleanliness. Personnel who are sunburned or have skin irritation to the extent that shedding of the skin is evident may not enter the clean room. Personnel with respiratory ailments are not allowed in the clean room. Daily bathing and frequent hand washing is a must along with proper care of the hair to avoid dandruff. The technician must shave daily, keep fingernails clean and trimmed and always wear specified clothing. Ball point pens are used for writing and work is always done on bare table surfaces whenever possible to avoid contact with cloth or paper.

OPERATIONS

Before any component is brought into the clean room it must be disassembled, if necessary, and pre-cleaned. This initial preparation of components is coordinated with clean room personnel to minimize storage problems. When components are received, all packaging is removed. Tape residue is removed with the appropriate solvent. Polyethylene or nylon wraps remain on parts or openings if the wraps are determined to be clean. Loose paint or rust is removed by chemical means prior to entry into the pre-clean lock. Loose dust is removed with a high pressure gas purge. All appurtenances not necessary to the operation or testing are removed (i.e. brackets, panels, tags, supports). Solvents and/or detergents are used to insure reasonable cleanliness and their use is followed by rinsing. Any special tools required are treated in the same manner as the component.

Once pre-cleaned, the components must be inspected with a bright light to check for any visible contaminants. The parts are then transferred into the clean room through the air lock in stainless steel or aluminum trays. These trays must be clean and in good repair. Any manuals or assembly drawings to be transferred with the components must be enclosed in polyethylene.

In the clean room the components are cleaned, rinsed and dried according to the specification required for that type of material and then, if necessary, reassembled on the laminar flow bench.

When the laminar flow bench is to be used, the technician turns on the air supply at least 10 minutes before beginning work on the clean project. All necessary equipment, tools and parts are arranged in such a manner that the parts being worked on receive the first air discharged from the HEPA filters. The technician must consider the relation of all body movements to fallout contamination. He works downstream from the part being worked on as much as possible. All containers are stored to one side or downstream from the part. Open dishes containing parts and work fixtures are placed in unobstructed clean airflow positions. At the end of the work day, all parts, tools, and non-essential equipment are removed from the work station and placed in storage. The cleaned component is sealed to prevent recontamination before installation into the system.

QUALITY CONTROL OF CLEANLINESS OUTSIDE CLEAN ROOM

The cleaning technician must maintain specific standards when removing components from systems that are exposed to external contamination. Replacing a component in a clean system is an

arduous task. When re-entry into a clean system is necessary, the technician must ensure that he does not further complicate the problem by contaminating the component when it is removed. Contamination is minimized by rigging a polyethylene tent around the area in which the work is to be done. The area inside the tent is cleaned to reduce the chances of contamination. Filtered air at a positive pressure is supplied to the tent by a blower. Care is taken to bag the openings from which the component is removed, in the event that a clean component is not being reinstalled immediately. Since the technician and his clothing must be clean he wears disposable white coveralls and headgear.

CLEANING PROCEDURES

Many different components make up a diving system but they can be categorized as follows:

1. Piping
2. Valves
3. Regulators
4. Gages
5. Compressors and transfer pumps
6. Storage flasks
7. Chambers

All components have one thing in common: they must be cleaned to eliminate any type of contaminant. However, the cleaning procedures vary depending on material, size and location.

Cleaning is performed on in-place systems and components separate from the system. Each case presents different problems. In a complex like NEDU's Ocean Simulation Facility (OSF), which is spread throughout a three story building, the distances that heated cleaning solutions must be pumped to in-place systems are so great that it is difficult to maintain proper temperatures of the solutions. Yet, removal of most of the piping and components requires a large expenditure of time and effort. The technician must decide on a case by case basis the most efficient method of cleaning the system. Control consoles in the OSF are particularly difficult to clean as they must be completely dissembled and the components cleaned separately.

In any case, all valves, flow fuses, check valves, regulators, etc. are removed. If the system is to be cleaned in place these items are replaced with spools and the system cleaned in the smallest sections possible.

There are some instances when cleaning particular components is beyond the capability of the cleaning technician. Such is the situation with the carbon steel storage flasks at the OSF. There are a total of 76 flasks with a floodable volume of nearly 80 cubic feet each. They lie in a horizontal position stacked three high in cradles. Cleaning is performed by commercial firms on a contract basis.

In the following sections, cleaning procedures for several of the different types of components are discussed.

CLEANING OF PIPING AND TUBING

The first step in the cleaning of piping or tubing is the determination of cleaning solution flow rate, internal surface area and volume. Flow rates are obtained from Table 1 which lists the required rates for different size piping and tubing. Internal surface areas, necessary in the calculation of particulate density, are given in Tables 2 and 3. The volume of the pipe is required so that the volume of cleaning solution to be used can be computed. A minimum of 20 times the volume of the system being cleaned must be used.

The technician prepares pipe for cleaning by attaching spools and jumpers when necessary. The systems are cleaned in the smallest segments possible. A flowmeter is attached to the discharge side of the pipe section to measure flow rate, or, if a flowmeter is not available, the filling of a container of known volume is timed. The technician then prepares a solution of 2 lbs TSP per 5 gallons of Grade "B" water and heats it to 125°F + 5°F. He takes a 1 liter sample of the unused solution as a blank. The cleaning solution is circulated through the pipe for 30 minutes at the calculated rates. At the conclusion of the flushing operation, the technician takes a 1 liter final sample for hydrocarbon analysis.

The technician flushes the pipe with Grade "B" water at 140°F until the effluent shows a pH of 6.0 - 8.0 and the shake test shows no visible trace of detergent. He also takes a 1 liter sample for the particulate analysis. The pipe is then dried by purging it with nitrogen until a -40°F dew point reading is reached.

FLOWRATES FOR CLEANING SOLUTIONS

Tube Size (O.D.)	GPM Flowrate
1/4"	1 ± 1/4
3/8"	2 ± 1/4
1/2"	3 3/4 ± 1/4
3/4"	6 3/4 ± 1/2
1"	12 1/2 ± 1/2

Pipe Size (IPS)	GPM Flowrate
1/4"	2 ± 1/4
3/8"	3 ± 1/4
1/2"	5 1/2 ± 1/2
3/4"	9 1/2 ± 1/2
1"	15 1/2 ± 1
1 1/4"	23 ± 1
1 1/2"	35 ± 1
2"	50 ± 3

Table 1

PIPE INSIDE SURFACE AREA CHART (sq. ft.)

IPS	Wall	Surface Area for Specified Lengths					
		1 ft.	2 ft.	3 ft.	4 ft.	5 ft.	10 ft.
1/4"	.042	.1117	.2234	.3351	.4468	.5585	1.1170
1/4"	.065	.1004	.2008	.3012	.4016	.5020	1.0040
1/4"	.072	.0970	.1940	.2910	.3880	.4850	.9700
1/4"	.088	.0892	.1784	.2676	.3568	.4460	.8920
1/4"	.120	.0735	.1470	.2205	.2940	.3675	.7350
1/4"	.134	.0666	.1332	.1998	.2664	.3330	.6660
3/8"	.049	.1414	.2828	.4242	.5656	.7070	1.4140
3/8"	.065	.1335	.2670	.4005	.5340	.6675	1.3350
3/8"	.072	.1301	.2602	.3903	.5204	.6506	1.3010
3/8"	.095	.1188	.2376	.3564	.4753	.5940	1.1880
3/8"	.134	.0997	.1994	.2991	.3988	.4985	.9970
3/8"	.148	.0928	.1856	.2784	.3712	.4640	.9280
1/2"	.065	.1740	.3480	.5220	.6960	.8700	1.7400
1/2"	.109	.1524	.3048	.4572	.6069	.7620	1.5240
1/2"	.120	.1470	.2940	.4410	.5880	.7350	1.4700
1/2"	.203	.1063	.2126	.3189	.4252	.5315	1.0630
3/4"	.065	.2245	.4490	.6735	.8980	1.1225	2.2450
3/4"	.083	.2166	.4332	.6498	.8664	1.0830	2.1660
3/4"	.113	.2019	.4038	.6057	.8076	1.0095	2.0190
3/4"	.148	.1848	.3696	.5544	.7392	.9240	1.8480
3/4"	.238	.1406	.2812	.4218	.5624	.7030	1.4060
1"	.065	.2904	.5808	.8712	1.1616	1.4520	2.9040
1"	.095	.2757	.5514	.8271	1.1028	1.3785	2.7570
1"	.120	.2634	.5268	.7902	1.0536	1.3170	2.6340
1"	.180	.2340	.4680	.7020	.9360	1.1700	2.3400
1"	.300	.1752	.3504	.5256	.7008	.8760	1.7520
1 1/2"	.072	.4303	.8606	1.2909	1.7212	2.1515	4.3030
1 1/2"	.109	.4122	.8244	1.2366	1.6488	2.0610	4.1220
1 1/2"	.145	.3946	.7892	1.1838	1.5784	1.9730	3.9460
1 1/2"	.180	.3774	.7548	1.1322	1.5096	1.8870	3.7740
1 1/2"	.250	.3431	.6862	1.0293	1.3724	1.7155	3.4310
2"	.083	.5414	1.0828	1.6242	2.1656	2.7070	3.4140
2"	.120	.5232	1.0464	1.5696	2.0928	2.6160	5.2320
2"	.154	.5066	1.0132	1.5198	2.0264	2.5330	5.0660
2"	.220	.4742	.9484	1.4226	1.8968	2.3710	4.7420
2"	.340	.4142	.8284	1.2426	1.6568	2.0710	4.1420

Table 2

RIGID TUBING - INSIDE SURFACE AREA CHART (sq. ft.)

O.D.	Wall thk.	Surface Area for Specified Lengths					
		1 ft.	2 ft.	3 ft.	4 ft.	5 ft.	6 ft.
.125	.020	.0222	.0445	.0667	.0890	.1112	.2225
.250	.020	.0549	.1099	.1649	.2199	.2748	.5497
.250	.035	.0471	.0942	.1413	.1884	.2355	.4717
.375	.028	.0835	.1670	.2505	.3341	.4176	.8351
.375	.035	.0798	.1597	.2395	.3194	.3992	.7985
.375	.049	.0725	.1450	.2175	.2900	.3626	.7251
.500	.035	.1126	.2251	.3377	.4503	.5629	1.1257
.500	.065	.0968	.1937	.2906	.3874	.4843	.9685
.750	.049	.1707	.3414	.5121	.6828	.8535	1.7069
.750	.095	.1466	.2932	.4398	.5864	.7330	1.4660
1.000	.035	.2435	.4870	.7304	.9739	1.2174	2.4347
1.000	.049	.2361	.4723	.7084	.9446	1.1807	2.3614
1.000	.065	.2277	.4555	.6833	.9111	1.1388	2.2777
1.000	.095	.2116	.4232	.6348	.8464	1.0580	2.1160
1.250	.035	.3089	.6178	.9368	1.2357	1.5446	3.0892
1.250	.049	.3016	.6032	.9480	1.2064	1.5080	3.0159
1.250	.065	.2932	.5864	.8796	1.1728	1.4660	2.9321

Table 3

Particulate analysis is performed using the millipore filter apparatus shown in Figure 3. Allowable particle populations are given in Table 4.

The technician analyzes the used and unused cleaning solutions. The maximum allowable hydrocarbon concentration is 1.0 ppm pickup. If this limit is exceeded, the procedure is repeated. The unused cleaning solution must contain less than 1.0 ppm hydrocarbons.

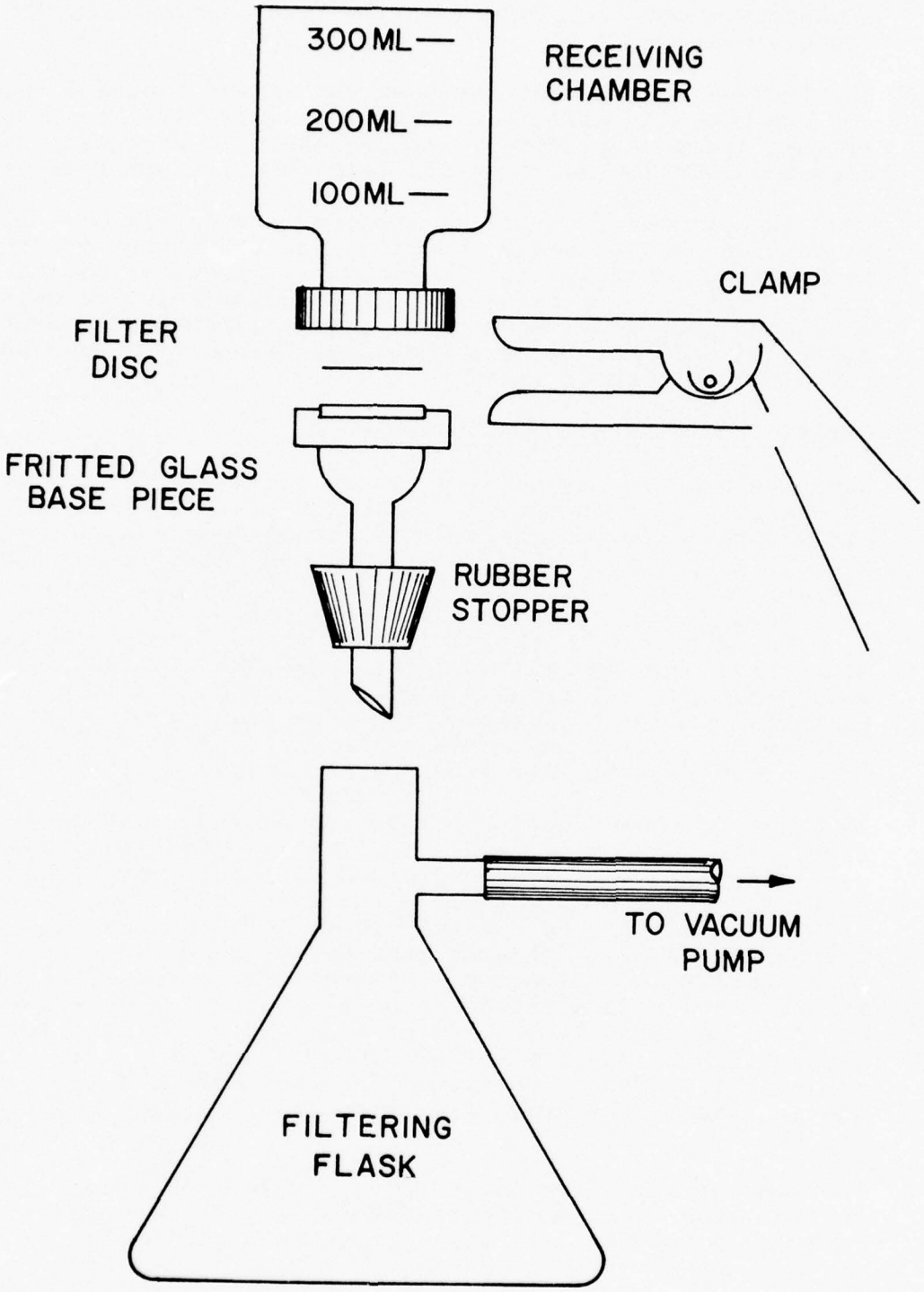
Upon completion of cleaning, rinsing, and drying of the pipe, the technician caps or seals the pipe ends to protect it from contamination. Metallic or plastic caps, plugs, or blanks are used for sealing the openings. Tape is used to hold the caps or blanks in place. The pipe segment is tagged "cleaned per NAVSEA 0994-016-6010" and the date and Component Cleanliness Data Sheet serial number are included.

CLEANING OF VALVES AND REGULATORS

When the cleaning technician cannot certify a valve or regulator as Grade "A" oxygen service clean, it must be cleaned. It is disassembled down to the smallest components possible and all visible contaminants removed. Each component is scrubbed with the appropriate solution to remove rust, paint, tape, flue, oil or grease. Soft goods-seats, seals, etc. - are removed and cleaned according to the procedure in the following section. After pre-cleaning the components are examined for visible contaminants under a bright light. The presence of visible contaminants is cause for repeating the pre-cleaning process. After passing the visual inspection, the parts are transferred into the clean room in stainless steel or aluminum trays.

In order to clean small openings and passages not accessible by hand, the ultrasonic cleaner is used for cleaning valves and regulators. A solution of 2 pounds TSP for every 5 gallons of Grade "B" water is prepared in the tank and heated to 160°F. A 1000 ml sample of the solution is taken as a reference blank. The parts are placed in the tank and cleaned for 10-30 minutes, when another 1000 ml blank is taken. The components are rinsed with filtered (25 micron) Grade "B" water at 140°F until no traces of the cleaning solution are present and the rinse water reaches a pH of 6.0 to 8.0. A 500 ml sample of Grade "B" water that is run over or through the critical areas that come in contact with gas is taken. The areas are taken from charts similar to Tables 5 and 6.

The samples taken are marked and analyzed for hydrocarbons and particulates. The millipore method is used for particulate count. Failure to meet the specifications means recleaning.



MILLIPORE FILTER APPARATUS

FIGURE 3

PARTICLE POPULATION

Maximum Particle Population per Sq. Ft. Surface Area	Micron System Cleanliness Level	
	Oxygen Heliox	Helium Air
Unlimited	0-49	0-149
10	50-70	150-230
3	71-95	231-320
2	96-125	321-410
1	126-150	411-500
0	151 & Up	501 & Up

Particle Population

Maximum Population Per Sq. Ft. Surface Area	Micron Fiber * Length Limits	
	Oxygen, Heliox	Helium, Air
Unlimited	0-49	0-149
10	50-150	150-500
1	151-300	501-1000
0	301 & Up	1001 & Up

* A fiber is defined as a particle whose length-to-width ratio is 10 to 1 or greater.

Table 4

SURFACE AREA OF VARIOUS VALVE COMPONENTS

Item	Size	Description	Area ft^2
Valve Body	1/4" ips	CPV All Models Angle or Straight	0.11
	3/8" ips		0.16
	1/2" ips		0.20
	3/4" ips		0.26
	1" ips		0.41
	1 1/4" ips		0.58
	2" ips		0.91
Valve Cartridge Assy	1/4" ips	CPV All Models Incl - Seat, Disc, & Bonnet	0.08
	3/8" ips		0.13
	1/2" ips		0.15
	3/4" ips		0.22
	1" ips		0.28
	1 1/4" ips		0.36
	1 1/2" ips		0.44
	2" ips		0.52
Valve Disc	3/4" ips	CPV - All Models	0.06
	1" ips		0.09
	1 1/4" ips		0.13
	1 1/2" ips		0.16
	2" ips		0.20

Table 5

SURFACE AREA OF VARIOUS VALVE COMPONENTS (Cont)

Item	Size	Description	Area ft^2
Valve Bonnet	1/4" ips	CPV - All Models	0.02
	3/8" ips		0.03
	1/2" ips		0.04
	3/4" ips		0.06
	1" ips		0.07
	1 1/4" ips		0.09
	1 1/2" ips		0.10
	2" ips		0.12
Valve Seat	1/4" ips	CPV - All Models	0.04
	3/8" ips		0.06
	1/2" ips		0.07
	3/4" ips		0.09
	1" ips		0.12
	1 1/4" ips		0.15
	1 1/2" ips		0.18
	2" ips		0.20
Valve Disc	1/4" ips	CPV - All Models	0.02
	3/8" ips		0.03
	1/2" ips		0.04

Table 6

After analysis, the components are blown dry with filtered (10 micron) nitrogen. If there are passages that are not visible, as in regulators, the part is dried in the vacuum oven at 125°F.

Reassembly is accomplished on the laminar flow bench and then the valve is sealed in at least 2 Alcar 33C or Nylon C bags and the bag marked "cleaned per NAVSEA 0994-016-6010".

CLEANING OF O-RINGS AND SEALS

The cleaning of soft goods used in valves, regulators, and other components varies according to the material involved. The different compounds that make up these O-rings and soft goods can be destroyed if the wrong cleaning solution is used. For example, a trisodium-phosphate solution would not be used on Kel-F, Viton, teflon or ethylene-propylene. This solution would attack and destroy the working life of these compounds.

O-rings and seals made of Kel-F are cleaned for 3 minutes in a filtered PCA Freon solution. They must be wiped clean with a lint-free rag which has been soaked in PCA Freon to remove dirt and matter. Viton and ethylene-propylene base compounds are cleaned with filtered isopropyl alcohol for 10 minutes; then wiped with a lint free rag soaked in isopropyl alcohol to free any dirt or foreign matter. In both cases, the soft goods are rinsed with new filtered freon or alcohol and blown dry with filtered air. They are then examined under ultraviolet light for hydrocarbons. If they meet the cleaning specs, they are rinsed with filtered Grade "B" water from which a 500 ml sample is taken for particulate analysis. If contaminants are found, the procedure is repeated. When certified clean, they are placed in vacuum ovens at 125°F and 29" mercury vacuum.

When O-rings and seals are visually dry, they can be installed into their respective components or sealed in bags for further use.

GAGE CALIBRATION

The cleaning technician is also responsible for gage calibration. Pressure gages calibrated to read depth in feet of sea water are especially important in diving. Since almost all gage testers are graduated in pounds per square inch, conversions are needed. An appropriate number of points should be checked depending on the scale of the gage and the increments available with the tester. At each increment of pressure, the actual reading of the gage being tested should be recorded, together with the true depth

GAGE CALIBRATION DATA SHEET			GAGE DESIGNATOR OR SERIAL NO.		
DATE	GAGE MFG./MODEL NO.	DIAL SIZE	RANGE	INCREMENTS	SYSTEM

CALIBRATION DATE

ACTUAL PRESSURE	GAGE READING					
	RUN 1		RUN 2		RUN 3	
	PRESS	DEPRESS	PRESS	DEPRESS	PRESS	DEPRESS

CERTIFICATION

CALIBRATION METHOD	MEDIUM	DATA SHEET NO.	DRYNESS (°F)

REMARKS

ALL RESULTS REVIEWED AND FOUND TO BE ACCEPTABLE

SIGNATURE (CLEAN ROOM SUPERVISOR)	DATE	BADGE NO.

REFERENCES:

Figure 4

that corresponds to the pressure. In testing a gage, it is desirable to run more than one test (or at least to note readings both with increasing and decreasing steps of pressure) to check the consistency of errors. A gage that shows larger or variable errors, or one that sticks excessively, should be repaired or surveyed.

An attempt may be made to adjust a gage according to Article 87-17 of NAVSHIPS Technical Manual. If this is not done or is not wholly successful, a calibration curve (graph) or table must be prepared to indicate the relationship between true depths and gage readings. If the deviations are within 5 feet of true depth and vary less than 2 feet in a 50 foot change of depth, 50 foot increments must be used in the calibration table. If the deviations are greater than this, 10 foot increments must be used. (In such a case, readjustment, repair, or replacement of the gage is actually preferable).

The calibration table should be affixed to the inside of the gage face glass. It should include this information:

1. Identification of depth gage
2. True depths in feet
3. Corresponding actual gage readings
4. Name of ship or activity
5. Initials of individual responsible
6. Date of calibration

A gage calibration data sheet (Figure 4) is also completed and retained.

GAS TIGHTNESS TESTS

Gas tightness tests are conducted on components and sub-systems that are of new manufacture or have been dis-assembled for modification or cleaning. If the system, such as a diver's gas manifold, is sufficiently small, the technician can remove the unit as a whole and take it to the clean facility where it is disassembled, rough cleaned, final cleaned and reassembled. Then it is pressurized to operating pressure with a test medium and checked for leaks using a helium leak detector. In this way, the technician can check each fitting and joint to see if it will hold the desired pressure and gas without a pressure drop. This test requires the technician to monitor pressure and temperature at designated intervals for a determined period of time set up in the gas tightness test procedure.

The test medium for helium and heliox systems is helium and for oxygen and air systems the test medium is either nitrogen with a 10% (by pressure) helium trace, or pure helium. Testing gas is always filtered to prevent contamination of the system or component tested.

Functional tests are run on valves and components after cleaning as well as on systems after removal and reinstallation of components. These tests vary according to the system but do include a leak test at operational pressure with the gas to be used in that system unless other requirements are specified by separate test procedure.

Any proof testing (1 1/2 x operating) as specified by separate test procedure is done with water (hydrostatic) pressure for safety.

COMPONENT CLEANLINESS DATA

It is imperative that the cleaning technician keep a complete written record of all cleaning, analysis and testing of parts and components. These records are retained in order to sustain certification of the system. The Component Cleanliness Data Sheet is completed for each item cleaned and tested. All other information pertaining to the cleaning and/or testing of a particular item is attached to the written record. This information includes, but is not limited to, outside laboratory reports, gage calibration charts, vendor data, etc. A sample Data Sheet is shown in Figure 5.

Certain items which require cleaning and testing and which are not actually part of the diving system, may also require traceable certification. In these cases, a Component Cleanliness Data Sheet must be completed. Items of this sort may include test gages, pumps, bulk gas supplies, bulk cleaning solutions (such as Freon PCA), etc.

It is also possible that certain data and results will apply to more than one Data Sheet. For example, it is possible that a sample for gaseous contaminants will be taken by sampling an entire system. This system consists of numerous items, each having its own Data Sheet. To ensure complete documentation, the technician must reference the results of the gaseous contamination analysis on each affected Data Sheet. The Component Cleanliness Data Sheets must be filled out as the cleaning/testing is being done and not after the fact. A unique serial number is assigned to each Data Sheet. These numbers are logged and assigned by the clean room personnel in order to provide for complete traceability. A complete set of data sheets are maintained and controlled by the clean room supervisor. A log book is also kept showing issuance of serial numbers and date of issuance.

COMPONENT CLEANLINESS DATA SHEET SERIAL NO.

U.S. NAVY EXPERIMENTAL DIVING UNIT DATE:

SYSTEM DESIGNATOR:

DESCRIPTION

HYDROSTATIC TEST

DATE _____ REQUIRED PRESSURE _____

TEST PRESSURE _____ LENGTH OF TIME _____

TEST GAGE NO. _____

CALIBRATION DATE _____

TECHNICIAN _____

PARTICULATE ANALYSIS

DATE _____ SAMPLE SIZE _____ SURFACE AREA _____

PARTICLES		FIBERS	
SIZE	_____	SIZE	_____
ALLOWED	_____	ALLOWED	_____
ACTUAL	_____	ACTUAL	_____

TECHNICIAN _____

HYDROCARBON TEST

DATE _____ CLEANING PROCESS TSP / PCA VENDOR CLEANED _____

TEST TSP EXTRACTION _____ SAMPLE SIZE _____ ML

FREON RINSE _____ SQ. FT. AREA _____

IR SCAN

BLANK AT 3.42 _____ HYDROCARBON PPM _____ ULTRA VIOLET

SAMPLE _____ INSPECTION _____

DIFFERENCE

TECHNICIAN _____

GAS SAMPLE

DATE _____ SYSTEM HOLD PRESSURE _____ TIME HELD _____

TYPE OF GAS _____

CONTAMINATE	ALL FREONS	HYDROCARBONS	CHLORINATED COMPOUNDS
ALLOWED	5. PPM	2.8 PPM	1.0 PPM
ACTUAL	_____	_____	_____

TECHNICIAN _____

Figure 5

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Compressor Application in Diving Systems

and

Its Operation to Enhance Divers' Air Purity

by

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TERMS USED IN TEXT

1. ACFM - actual cubic feet per minute independent of pressure
2. ARS - U.S. Navy designation for offshore salvage ship type
3. BTU - British Thermal Unit
4. CFM - cubic feet per minute
5. °F - Fahrenheit
   °R - Rankine
6. Flow pressure - pressure required to maintain a given flow
7. FPM - feet per minute
8. FSW - Feet of depth in terms of sea water
9. PSI - pounds per square inch (lbs_f per $in.^2$)
10. psia - pounds per square inch absolute
11. psid - pounds per square inch drop
12. psig - pounds per square inch at gauge pressure
13. Qair - sensible heat BTU/hr
14. Qwater - sensible and latent heat BTU/hr.
15. SCF - standard cubic feet @ 70°F 14.7 psia
16. SCFM - standard cubic feet per minute @ 70°F 14.7 psia
17. ΔP - difference between two pressures (i.e., $P_1 - P_2 = \Delta P$)

COMPRESSOR APPLICATION IN DIVING SYSTEMS AND ITS OPERATION TO ENHANCE DIVERS' AIR PURITY

A diving system, contrary to conventional training and application, does not originate at the diving station where the hoses are connected. It does originate at the source of the breathing media, which is normally the earth's atmosphere, and some natural gas wells in the Southwest U.S.A. These locations are the primary sources of air, oxygen and helium used to support diving. The oxygen and helium are separated cryogenically from their respective sources and are, as a result, high purity components when so extracted.

It is recognized that the atmosphere contains all of the gas components that have been used in all diving breathing mixtures, and all could be obtained from the atmosphere by cryogenic processing. The following table lists normal atmospheric components and their boiling temperatures at one atmosphere.

Table 1

Gaseous Components of Air

Component	% by volume	Boiling Point @ 1 atm.
Nitrogen	78.09	-317.8° F
Oxygen	20.99	-320.36° F
Argon	0.94	-297.4° F
Carbon Dioxide	0.03	-109.4° F *sublimation temp.
Hydrogen	0.01	-423.0° F
Neon	0.00123	-410.9° F
Helium	0.0004	-452.1° F
Krypton	0.00005	-244.0° F
Xenon	0.000006	-162.6° F

The variance in boiling points permits separation of these components from the atmosphere; in fact, the USN has for nearly 25 years been separating breathing oxygen from the atmosphere using shipboard installed cryogenic systems. These cryogenic systems utilize air compressors similar to those used to support diving systems, wherein the operation of these compressors is controlled by the process to provide nearly pure air to the air separator unit. These operating conditions could easily be transferred to divers' air supply systems to enhance the purity of air supplied by their compressors.

The principal requisite in the operation of these plants is their inherent control of the compressor discharge pressure at, or nearly at, the

design operating pressure of the compressor. This single requisite, with routine drainage of condensate traps, eliminates the migration of nearly all but gaseous contaminants into the air separation plant. Furthermore, recognizing that moisture and compressor lubricants make up virtually all of the contaminants that are not in a gaseous state, these can be essentially eliminated through collection in condensate traps and routine draining of these traps. The most appropriate method of effectively draining these traps was discovered during the operation of a helium refrigeration system which cooled test specimens to a temperature of 20° R(-440° F).[1] There was no condensate in this system but there was lubricating oil carry-over. To eliminate this, the traps were routinely drained through needle valves every four hours during the operating cycle, which varied between 15 to 25 days. Both the oxygen-producing and the helium refrigeration systems operated continuously 24 hours per day for up to one month per cycle.

These are severe operating conditions for any compressor, and the requisite gas purity in both cases greatly exceeds that prescribed for diver's breathing, implying that appropriate system control and meticulous operational maintenance procedures will assure breathing quality air from systems that utilize reciprocating compressors. It is important to recognize that the outlet pressure of the compressors used in the cryogenic systems was inherently controlled in their application. This may or may not be the case where air for diving is obtained from ship's service air compressors. If it is not controlled, it then becomes the responsibility of the diving supervisor to effect control by making certain that the compressor outlet pressure exceeds the required diving station pressure at all times. This implies that the compressor's rated capacity must exceed the required flow and that its operating pressure be greater than the requisite diving station pressure, or the actual flow delivered to the diver will be inadequate.

This leads us to the axiomatic premise that you cannot get 100 SCFM out of a 50 SCFM compressor, implying that you must know what the intended application of your compressed air system is prior to selecting the air compressor to support planned diving operations. Conversely, you must restrict the application of an air compressor to diving operations which it can adequately support. To determine application of a compressor the required flow, which varies with diving appratus and depth of the operation, must be determined.

Table 2 lists the individual requirements in SCFM for all current diving equipment including treatment chamber application. Multiplying these values by the anticipated number of participants will provide the required flow for the projected operation. Provisions for supporting the stand-by diver must be included.

These requirements must be correlated with the available compressed air supply, which may be an air compressor or a stored high pressure compressed air bank.

Some compressors are rated and have a capacity stamped on their nameplates, for example, 100 SCFM at 3000 psig. This implies that the compressor will provide a compressed air flow of 100 SCFM when the air entering the intake is at 70°F with a relative humidity (RH) of 36%, a total pressure of

14.70 psig and a density of 0.0750 lbs./ft.^{3} when the rating procedure conforms to that prescribed by the "Compressed Air and Gas Institute" (CA&GI).[2]

The inlet conditions would be modified to a temperature of 60°F if the rated flow is in conformance with the rating procedure defined by The American Society of Mechanical Engineers (ASME).[2]

The inlet conditions would be altered to 122°F 50% RH at atmospheric conditions when USN specifications[3,4,5] are applied.

The actual capacity of the compressors, if dry air at 70°F enters the intake, would be nearly comparable for CA&GI and ASME criteria but would be significantly greater when applying USN criteria.

It is known that the capacity of a positive displacement air compressor may be affected by the variations of the following:

- Speed (revolutions per minute)
- Downstream pressure
- Inter- and aftercooling
- Staging

Additional variations caused by inlet air conditions include the following:

- Atmospheric pressure
- Intake ambient air temperature
- Relative humidity

In addition, intake ducting, which is used to obtain air from the weather, will adversely affect the capacity; minimally when well designed and significantly if poorly designed, or not designed at all.

In order to satisfy both the supplier and the user that a compressor will provide a specified capacity at a designated operating pressure, extensive and well defined rating procedures have been established and are normally invoked by specification requirements.

It is now evident that a positive displacement compressor is, within limits, a variable flow machine, and the flow rate will range between the displacement of the first stage and a capacity comensurate with existing intake conditions when operating at its rated pressure.

Measured flow obtained from a nominal 50 CFM two-stage compressor during operation on an ARS ranged from approximately 80 SCFM near zero pressure to approximately 50 SCFM at its operating pressure of 150 psig. These measurements were not corrected to standard conditions, and the measuring apparatus was not specifically calibrated, so therefore, the measured flow is specified

as approximate SCFM. The nature of the variation in flow rate relative to outlet pressure is plotted in Figure 1, and extrapolated to the displacement which was 78.1 CFM at zero psig.

This clearly establishes that a positive displacement piston type compressor is a variable flow machine, but it must be recognized that operating the compressor at pressures well below its operating pressure to gain capacity is undesirable, particularly where the air is to be used for breathing.

Pressure itself does not imply adequacy of the support system, particularly when it can be shown that the content of a single 90 SCF SCUBA cylinder charged to 3,000 psig will not maintain the specified flow rate to the MK 12 apparatus at 190 FSW for a duration of two minutes, if the diving station pressure requirements are maintained. A fundamental tenet for the application of compressors in diving systems is that pressure, in excess of flow pressure, can only exist when the supply (compressor capacity) equals or exceeds that used or exhausted. This clearly indicates that with a compressor providing 4 SCFM to a system supplying 3 SCFM, the system pressure will increase. Conversely, with a compressor system providing 3 SCFM to a system supplying 4 SCFM, the system pressure will decrease until the supply equals the 3 SCFM compressor capacity. This is an extremely basic example, but of utmost significance if the air processing inherent in compressed air systems is to enhance the quality of the breathing air supplied.

The former tenet will permit, and indeed enhance, the quality of the air supplied for breathing, whereas the converse of the tenet will not only permit, but enhance, the migration of the condensation with its attendant lube oil emulsification towards the diving apparatus.

The selection of a compressor for application in a diving system should be based on the premise that its capacity is adequate to accommodate the projected diving operations, and that it will operate at a pressure sufficient to maintain the requisite diving station flow pressure.

Diving outfits supplied to fleet activities, in general, have uniform lengths of hose and hose diameter. Limited application of flow-monitoring instrumentation exists in these systems. The maintenance of pressure at the diving station provides the only indication that adequate flow is available. Using widely accepted compressible flow criteria and the general criteria developed by Colebrook[6] for determination of the ΔP in the hose, pressure versus depth criteria for existing apparatus have been computed. The results are as shown in Figures 2, 3 and 4.

These pressure requirements, together with the flow rates obtained from Table 2, will define the minimum capacity and pressure to be provided from the diver's air compressor system. For example, if three divers (two working, one stand-by) are going to perform an operation at 190 feet, the pressure and flow when using MK 5 apparatus will be:

From Table 2:
Flow capacity required: 3 X 40.5 = 121.5 SCFM

From Figure 2:
The diving station pressure required @ 190 feet is 170 psig.

This pressure implies the lower set pressure of the compressor shall be no less than 170 psig, or if a 200 psig 150 SCFM compressor is selected, the operating ΔP will be 30 psig. Normally, a compressor equipped with start-stop controls should not start more than five times in one hour. This provides criteria for sizing the air receiver. The minimum receiver capacity must be sized for the compressor to operate between 170 and 200 psig. The compressor capacity exceeds the flow requirements by 28.5 SCFM and the depletion rate is 121.5 SCFM. The cyclic operation between 170 and 200 psig may be determined as shown below:

Assuming 100 ft.^{3} receiver volume, the available capacity between 200 and 170 is:

$$100 \frac{(200-170)}{14.7} = 204.08 \text{ SCF/ft.}^3$$

The depletion rate is: 121.5 SCFM.

The replenishment is: (150 - 121.5) = 28.5 SCFM

Depletion time is: $\frac{204.08}{121.5} = 1.68$ minutes.

Time to replenishment is: $\frac{204.08}{28.5} = 7.16$ minutes.

One cycle = 1.68 + 7.16 = 8.84 minutes or $\frac{60}{8.84} = 6.78$ cycles per hour.

A 100 ft.^{3} receiver would limit cycling as shown. A receiver one-half this size would double the cycles, etc.

Receivers are normally sized to limit temperature rise in the electrical components due to frequent starting and stopping of the compressor, and it would be desirable to increase the receiver size in the example to limit the start-stop cycles to 10 minutes. Another option to prevent start-stop of the motor is to apply load-unload controls on the compressor. These controls unload the compressor when the upper limit is reached, and load the compressor when the lower limit is reached without stopping the motor, thus reducing the high electrical system heat loads associated with starting and stopping a compressor motor.

Another consideration in selecting the compressor is that the compressor have adequate staging to limit the temperature rise in the air being compressed. In general, all compressors used to support diving operations should be staged if they are to be used to supply the spectrum of permissible diving operations. A singular reason for staging compressors is to minimize the temperature rise which will approach levels as shown in Figure 5. It depicts not only the temperature increase at normal compression ratios for compressors, but includes the temperature increase associated with some internal combustion engines to provide a reasonable frame of reference. This indicates that compressors are relatively low temperature machines when in comparison with

conventional internal combustion and compression-fired diesel engines. Recognizing that the heat capacity of air is relatively low, the size of appropriately designed inter- and aftercoolers can be relatively small when they are water to air coolers.

The specific horsepower required to compress air is shown in Figures 6 and 7 for single and multi-stage compression. In general, with the prevailing concern about expenditure of energy, it is not prudent to compress air to levels exceeding the maximum pressure required, but there are exceptions to this rule that are applicable in diving support systems. Some specific ones are the use of stored air to pressurize recompression/decompression chambers and to support the MK 1 diving apparatus. Use of stored air to support the former precludes the need for excessive compressor capacities to meet the pressurization requirements. For the latter, stored air systems inherently supply well processed air without condensation or emulsions, thus precluding the possibility of inhaling these contaminants. One additional advantage in using stored air to support MK 1 apparatus is the ability to monitor consumption and availability by observing the stored bank pressure during the diving operations. The relatively low average consumption rates predicted for this apparatus further reinforce the desirability of using stored high pressure air.

The flow rates considered excessive are those associated with chamber pressurization, which were established as follows:

Chamber volumes

Two Lock Aluminum

Outer Lock	64.9 $ft.^3$
Inner Lock	136.3 $ft.^3$
TOTAL	201.2 $ft.^3$

Two Lock Steel

Outer Lock	147.2 $ft.^3$
Inner Lock	335.6 $ft.^3$
TOTAL	482.8 $ft.^3$

For SUR-D Pressurization - to 50 feet @ 60 FPM

Aluminum Chamber

Outer Lock	117.7 SCFM
Inner Lock	247.3 SCFM

Steel Chamber

Outer Lock	267.0 SCFM
Inner Lock	608.7 SCFM

These flow rates are based on the following:

1 atm = 33.075 FSW

Pressurization Rate 60 FPM

Therefore the required flow rate is: $\frac{60}{33.075} \times V$

where V is the volume of the lock to be pressurized in cubic feet.

These computations are presented to establish a method of approximating pressurization flow requirements. Other analytical methods will be included in an appendix section following the presentation, so as not to encumber the presentation with equations, dimensions and theory. Continuing the application of stored gas, it is imperative that the scope and extent of application be clearly determined, and that the banks be sized accordingly.

The physical size of high pressure air banks can be established once the scope of application of available diving equipment is postulated. To accomplish this, tables defining total air requirements to support a diver performing specified diving would be invaluable. Tables 3, 4, 5 and 6 providing total air usage for divers using MK 1 apparatus (2 ACFM) and MK 5 or MK 12 apparatus (6 ACFM) have been developed for which decompression is required, and similarly, for dives where no decompression is required. Comparable tables were previously developed for application of the treatment tables. They are published in the USN Recompression Chamber Operator's Handbook.[7]

These requirements provide the total quantity of air required to perform a diving operation or treatment table as currently defined.

The application of these data to establish stored compressed air requirements will permit adequate projections of the size and capacity of high pressure air banks necessary to perform the treatment or diving operations, as the case may be. Table 7 is provided to demonstrate unit storage capacity as a function of pressure utilizing real gas properties.[8]

It is a reasonable approximation to assume that 200 SCF of air are stored in each cubic foot of storage volume pressurized to 3,000 psig. The availability of this stored air will be reduced by the residual pressure to support diving operations required to maintain the requisite diving station pressure. In addition to this, the thermodynamics of pressure vessels must be considered in that constant volume expansion will significantly reduce the temperature of air remaining in the pressure vessel and consequently increase the quantity remaining at the minimal pressure needed to supply the required flow.

It is evident that the rate of change in the air temperature is related to both the expulsion flow rate and the heat transfer into the pressure vessel, implying that when the supply source contains several gas flasks, as many as possible should be placed "onstream" consistent with the flow requirements and emergency supply requisites for stand-by diver utilization.

Using the data provided and simple analytical procedures described, it is possible to postulate and design a diver's support system that will provide the necessary flow and pressure to effectively support normal diving operations. The compressor selected must be capable of providing all steady or continuous flow requirements that will exist during the diving operations while maintaining a system pressure greater than the required diving station diving pressure. The capacity of a selected low pressure air compressor (300 psig or less) must always equal or exceed the highest continuous flow requirement or alternatively, the availability of high pressure stored air combined with the capacity of a high pressure air compressor will provide the necessary flow throughout the profiled diving operations.

When using low pressure compressed air, the compressor capacity, presuming adequate pressure is provided, becomes the only parameter needed to define adequacy. Determining the capability of a high pressure stored air system necessitates analyses of available stored air capacity and the simultaneous application of the compressor.

After the definition of the system requirements are established, compressor selection can proceed. In general, compressors with two stages or more are required, and normally the following criteria should be adhered to when the divers' air purity is a consideration:

- Two stages for pressures up to 300 psig
- Three stages for pressures up to 2,400 psig
- Four stages for pressures up to 4,500 psig.

Adhering to these requirements will limit the air temperature in each stage and enhance the processing of the compressed air.

All divers' air compressors should be equipped with inter- and aftercoolers, preferably air to water, and the operating pressure range should be minimized, so as to be consistent with the intended application.

The heat load of air entering an intercooler or aftercooler of an air compressor must accommodate the sensible heat of both the air and moisture contained therein and latent heat of vaporization of the moisture condensed. When air saturated at 95°F enters a two stage air compressor with a compression ratio of 2.33 to 1, the first stage heat load will be for each cubic foot of air that is compressed:

Sensible heat

$Q_{air} = 151.606$ BTU/hr

$Q_{water} = 10.000$ BTU/hr

Latent heat

Q water 88.009 BTU/hr Total 209.696 BTU/hr

The second stage heat load will be:

Sensible heat

Q air = 151.606 BTU/hr

Q water = 4.197 BTU/hr

Latent heat

Q water 36.552 BTU/hr Total 192.355 BTU/hr.

If additional stages were added, both the water sensible and latent heat requirements would continue to diminish. The example indicates, additionally, why the air compressor should be operated at or near its rated pressure. Otherwise, a significant imbalance in heat exchanger requisites will occur. This will permit uncondensed moisture to enter the storage volume and/or diving apparatus with the likelihood of condensation occurring there.

The desirability of obtaining intake air from the weather is evident, particularly when understanding that typical engine room environmental conditions are 122°F and 50% RH. When provisions are made to obtain the intake air from the weather, careful design of the ducting is paramount to preclude undue loss in compressor capacity. Bushway[9] defines a procedure for so doing.

When the system has been adequately designed and installed, the operation of the system will then become very significant in maintaining the desired air quality.

Few, if any, compressed air systems containing adequately sized compressors with sufficient staging, inter- and aftercooling and adequate intake ducting will fail to provide air quality consistent with current divers' breathing air standards,[10] when their operation is controlled.

This control must limit pressure excursions through a very narrow pressure range near their rating pressures to effect condensation at designated sites such as the condensate traps located downstream of each intercooler and aftercooler. Forcing this condensation, which the compressor systems are designed to do, further enhances the potential purity of the compressed air supply in that particulates consisting primarily of oil mists form the nuclei for condensation, much like silver iodide used in cloud seeding; thus simultaneously eliminating the compressor lube oil carry-over. Most of the moisture will be condensed in an adequately designed, first-stage intercooler with the quantity condensed in subsequent inter- and aftercoolers diminishing.

The possibility that appropriate heat transfer characteristics exist in inter- and aftercoolers operating outside their normal narrow design pressure range is remote, so when the operating pressure is significantly below

the design pressure, the uncondensed moisture will enter subsequent inter- and aftercoolers which would not be designed to accommodate the higher heat load associated with this condensation.

The condensation of atmospheric moisture, where the air is saturated at the temperature specified, is shown in Figure 8 by indicating the moisture remaining, with perfect cooling during pressurization to 100 psi. That existing prior to compression is shown in the index at the left of the graph in Figure 8.

The sensible heat of the air to cool it and the quantity that would be condensed if pressurized to 3,000 psig is shown in the truncated scale to the right of the graph in Figure 8.

To assure proper operation of a staged compressor, the observation and logging of these pressures is warranted. These pressures will ordinarily provide evidence that the compressor is performing properly, and deviation from the norm should prompt immediate investigation to ascertain the abnormality. The foregoing is based on a balanced compression ratio which may or may not exist in the compressor applied. Nevertheless, the principles are the same even though the observed pressures may differ. Figure 11 indicates the pressures that will exist in each stage of a balanced compression ratio compressor relative to the outlet pressure.

When variations from these pressures are observed, it generally indicates a malfunction of the compressor values and corrective maintenance must be undertaken to rectify the malfunction.

As an example, assuming the second-stage pressure is greater than that specified, and the third stage is below that defined, this implies the third stage inlet valve is leaking. Similarly, diagnoses exist for each of the stage's valves, and when no immediate maintenance procedures are implemented the temperature of the air compressed in the second stage will be inordinately high and could conceivably approach lubricant decomposition temperature (i.e., formation of carbon monoxide).

Maintaining operating logs and performing both routine and corrective maintenance is essential where air compressors are used to supply divers' breathing air.

In summary, the authors have attempted to define the application of oil lubricated compressors in diving air support systems. When a system designer selects a compressor for use in a diving system, the following criteria should be applied:

- The compressor discharge pressure must equal or exceed the flow pressure requirements at the diving station given in Figures 2, 3, and 4.
- The compressor capacity must be sized to exceed the diving equipment requirements listed in Table 2.
- Low pressure receivers and high pressure storage banks must be sized to accommodate an appropriate cyclic rate of compressor operation and to accommodate intermittent flow requirements which exceed the compressor capacity.

- Inter- and aftercooler heat capacity requirements must be balanced to assure proper condensation. (Note: If moisture is not eliminated at the first-stage intercooler, then the diver's air hose will likely become the aftercooler.)

- Needle valve drains on condensate traps, interstage pressure gauges and compressor hour meters should be installed on each compressor used for diving system support.

Once the diving system has been installed, it is extremely important to operate the compressor by the following guidelines:

- Ensure the compressor is operated at or near its design pressure by either maintaining the required flow pressure at the diving station or otherwise restricting the diving operation to within the capacity of the compressor.

- Limit the operating pressure range to the upper 20% of the full range (i.e., 125 psig to 150 psig for a compressor rated pressure of 150 psig).

- Establish a routine condensate trap drainage schedule (the authors recommend trap drainage at four hour intervals of operating time).

- Establish a log for recording interstage pressures in consonance with condensate trap drainage schedule.

Unless compressors installed in diving systems are properly applied and operated, the following hazards will exist for the diver:

- The quality of the compressed air delivered to the diver is degraded. The moisture content is increased and migration of oil-water emulsion to the diver is imminent.

- Insufficient pressure and/or flow to meet requirements of diving equipment at respective full depth capability will result in the following limitations:

  - The number of divers will be limited by the flow capacity.

  - The diving depth will be limited by the flow pressure.

  - Limitations will be placed on operational use of the diving system due to inadequacy of the system support capability.

- Excessive wear on the compressor due to being operated below (40% of full range) rated pressure is as follows:

  - Lubrication drops below design efficiency when condensation is not being removed in design location, from the preceding stage.

  - Piston ring blow-by of oil-water emulsion will accumulate in the crankcase of the compressor.

When compressors installed for use in diving systems are applied and operated in accordance with the foregoing guidance, the result will be an adequate support capability for the intended diving mission plus enhanced air quality of the compressed air delivered to the diver.

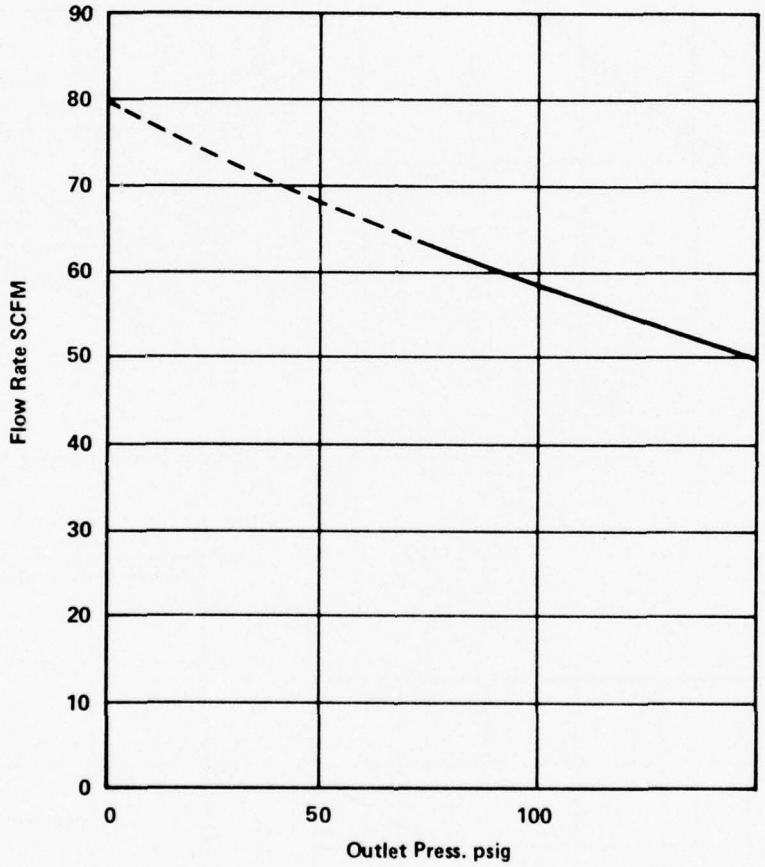

Fig. 1 150 psig-2 Stage Compressor Capacity vs Outlet Pressure

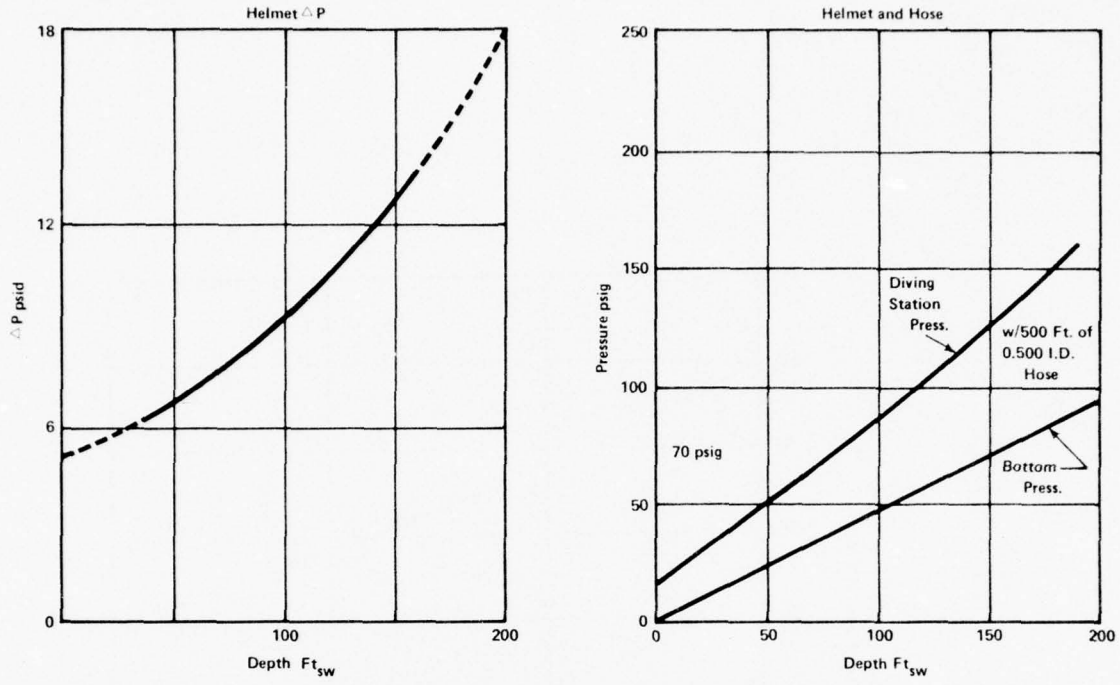

Fig. 2 USN MK 5 Apparatus Diving Station Pressure vs Depth Requirements

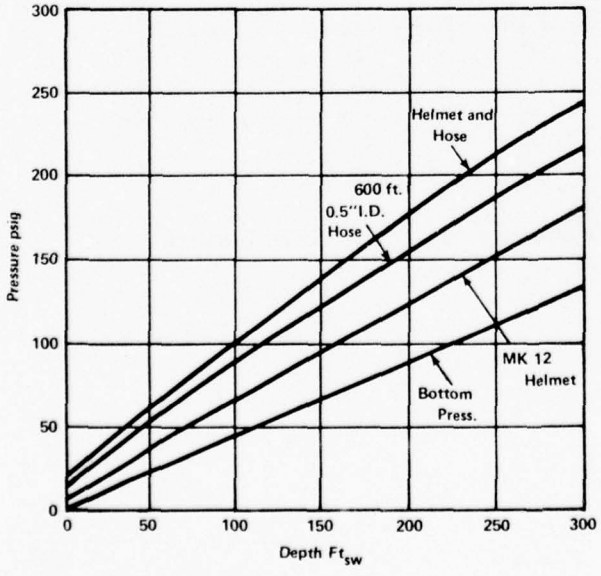

Fig. 3 MK 12 Diving Station Pressure vs Depth Requirements

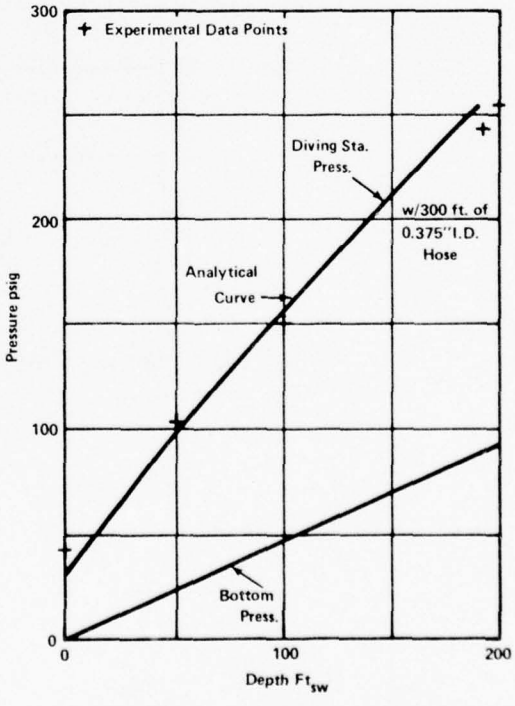

Fig. 4 USN MK 1 Apparatus Diving Station Pressure vs Depth

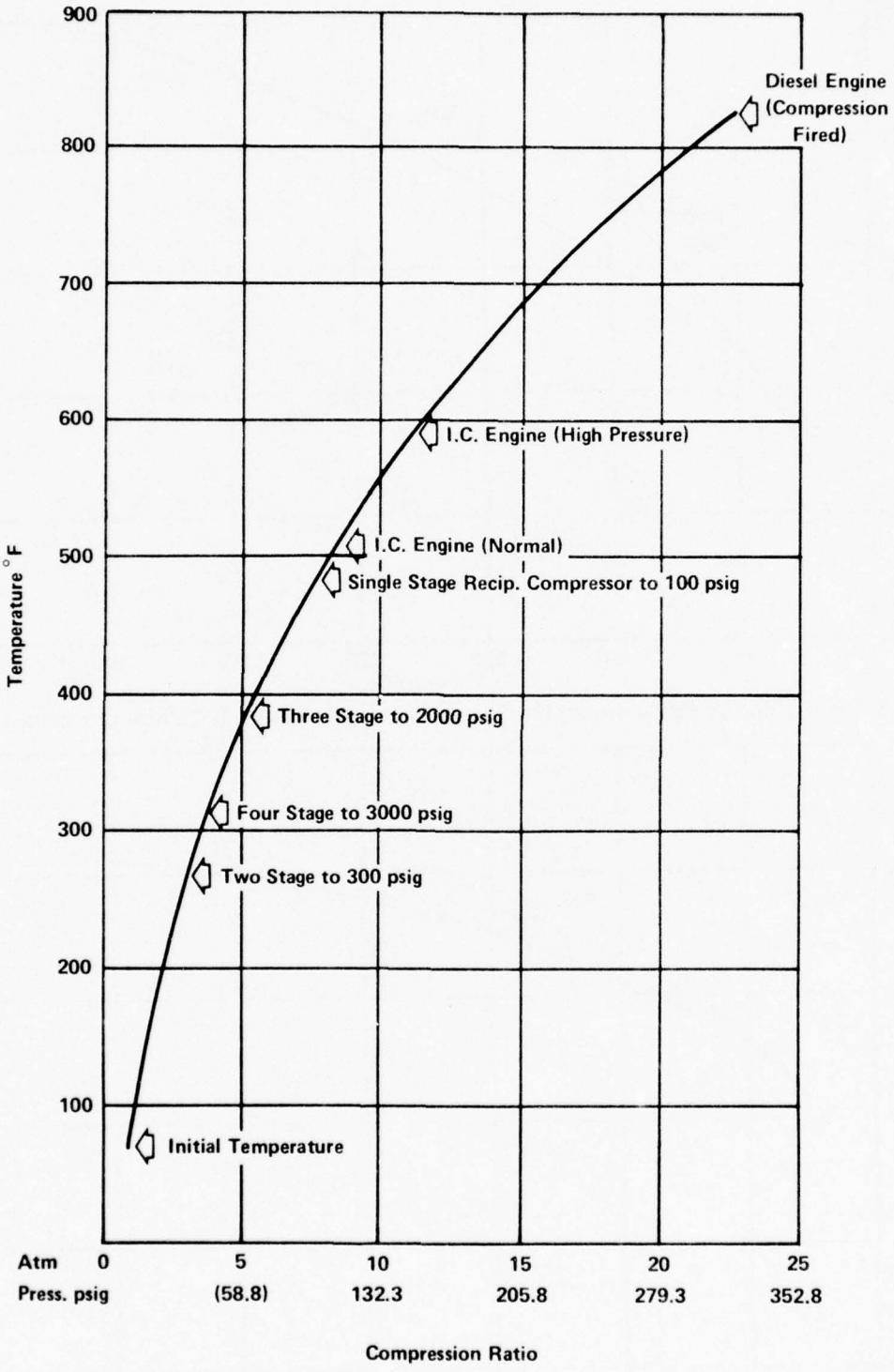

Fig. 5 Temperature Increase vs Compression Ratio

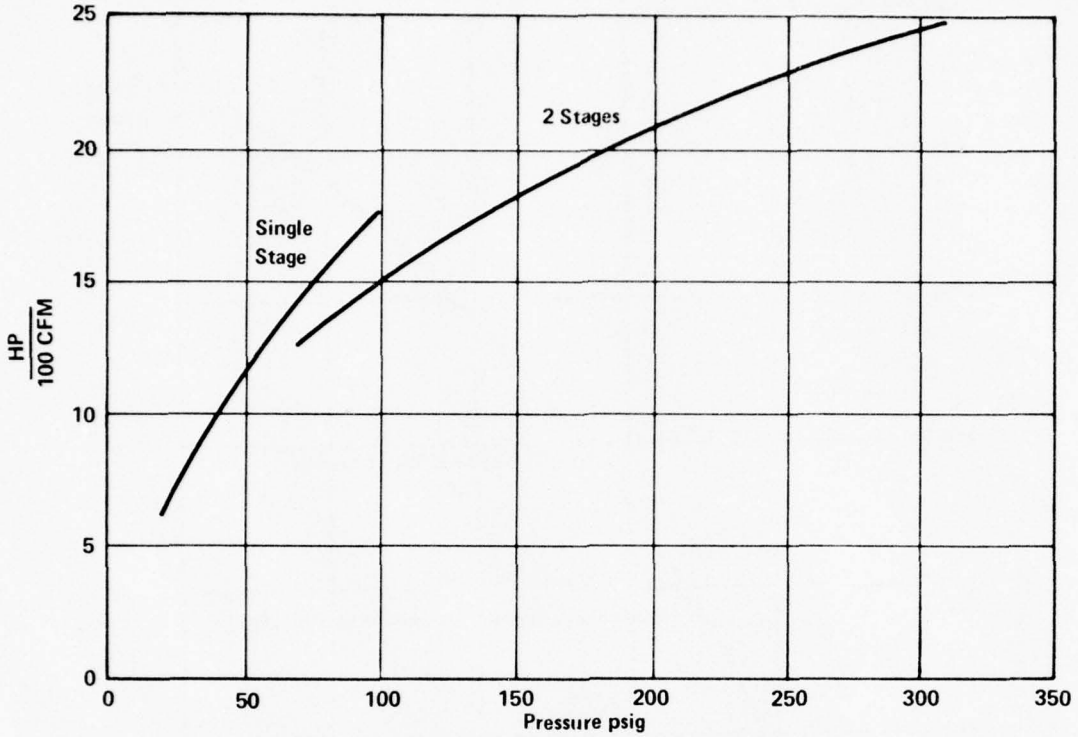

Fig. 6 Specific Energy Requirement for Compression of Air Single & 2 Stage Compressor

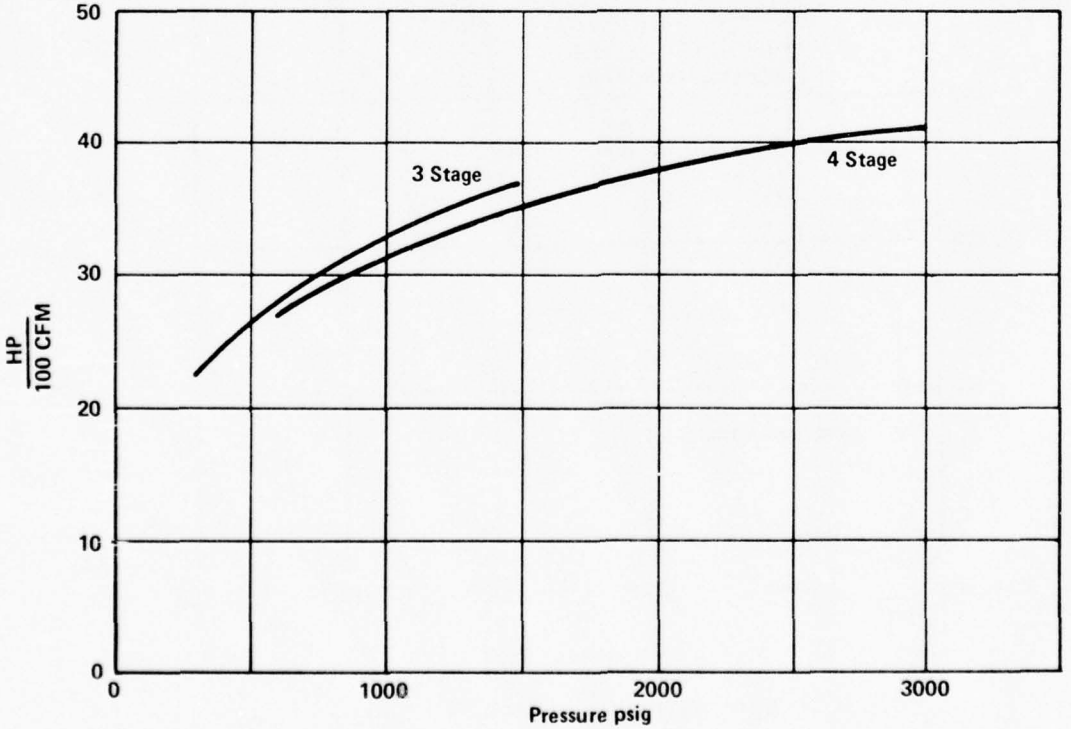

Fig. 7 Specific Energy Requirement for Compression of Air 3 Stage & 4 Stage Compressor

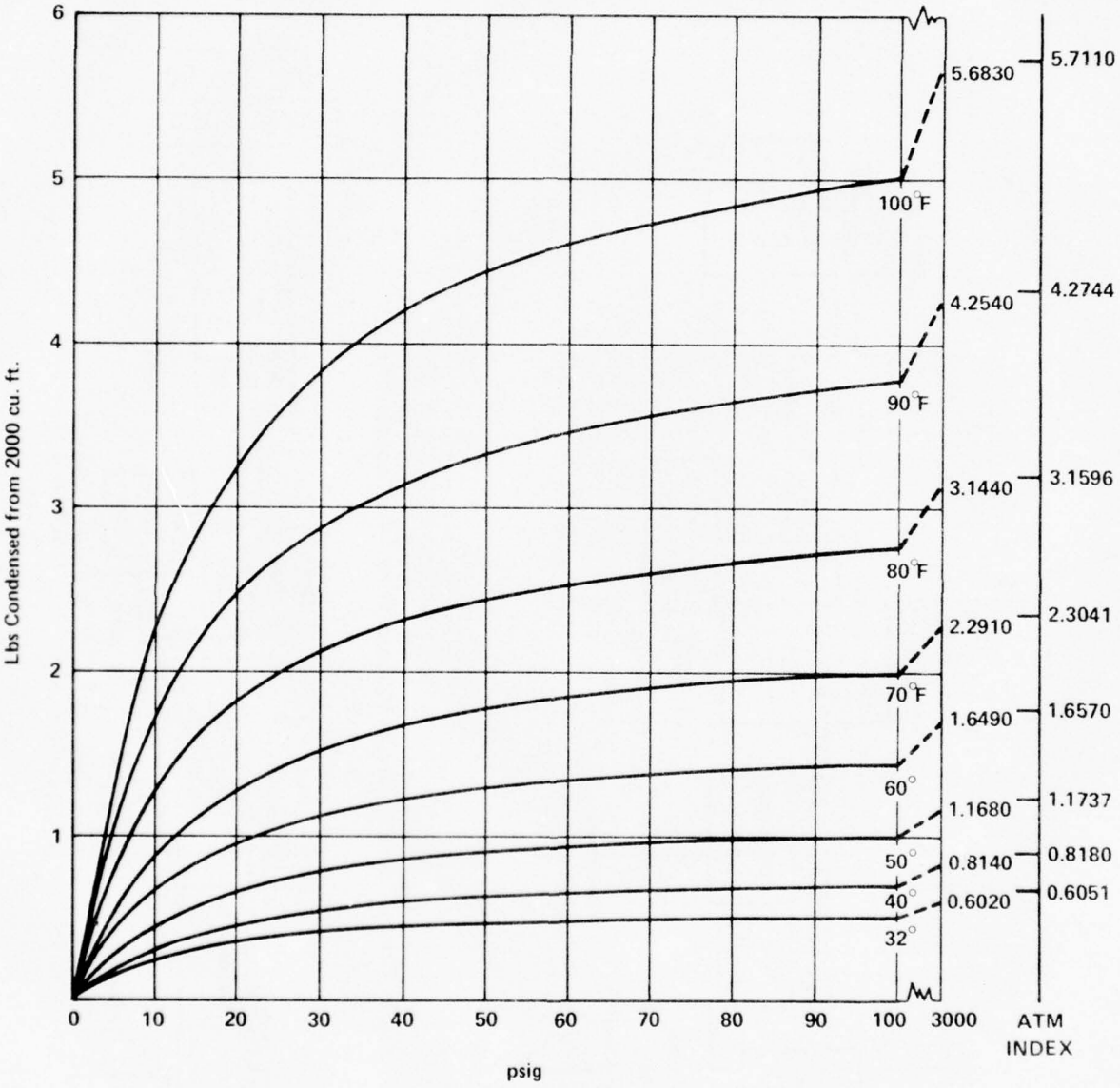

Fig. 8 Condensation of Atmospheric Moisture vs Pressure for Various Saturated Intake Conditions

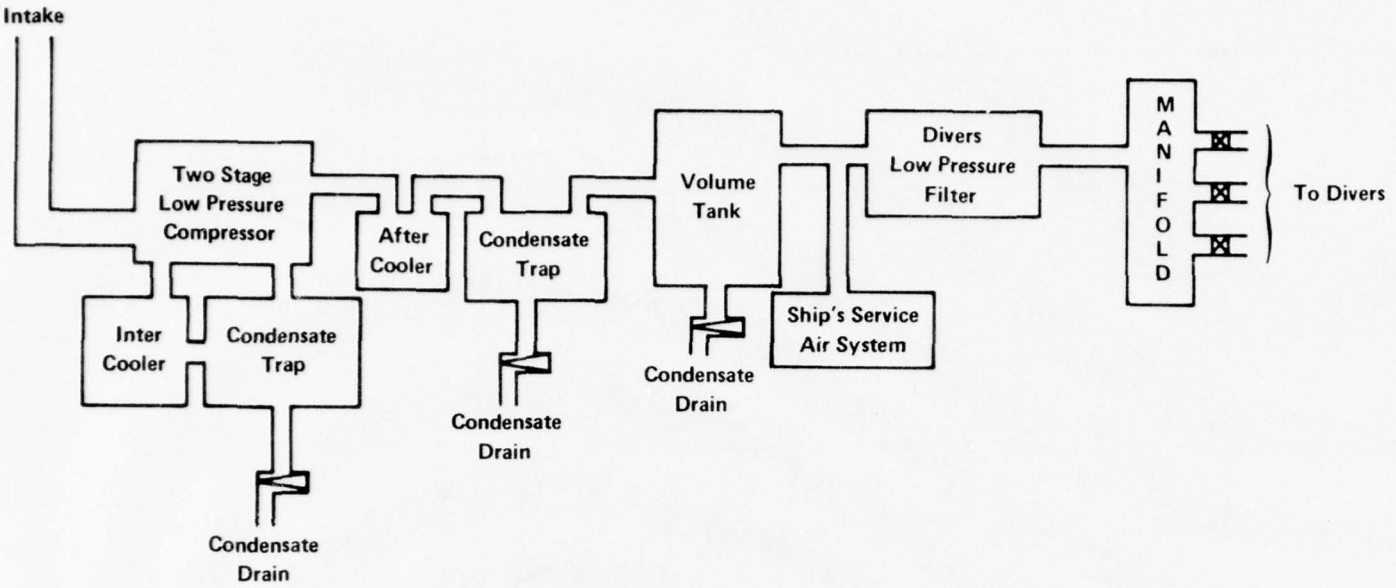

Fig. 9 Typical Low Pressure (0-300 psig) Divers' Air Support System

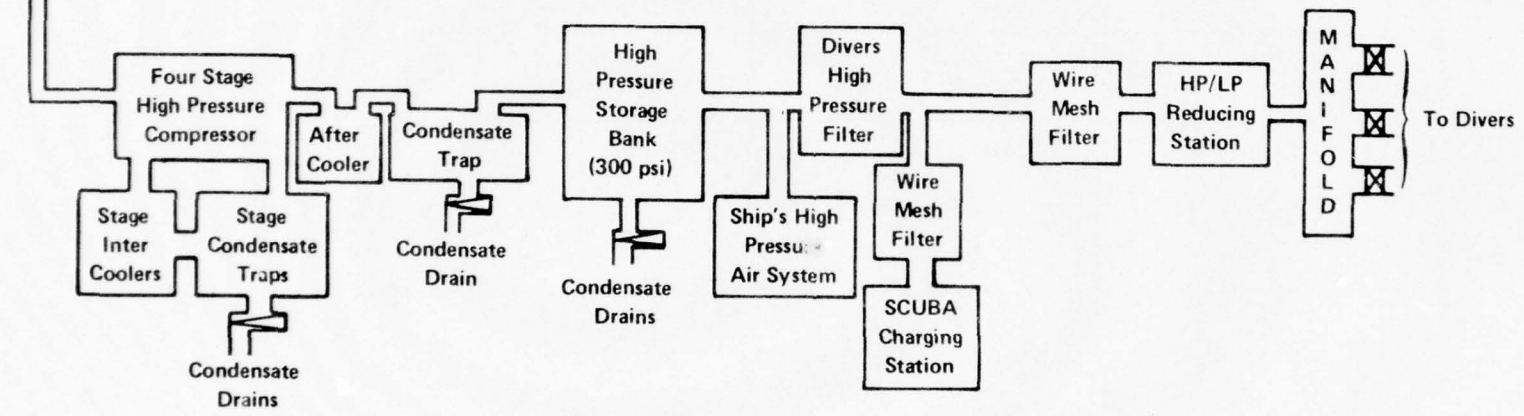

Fig. 10 Typical High Pressure (0-3000 psig) Divers' Air Support System

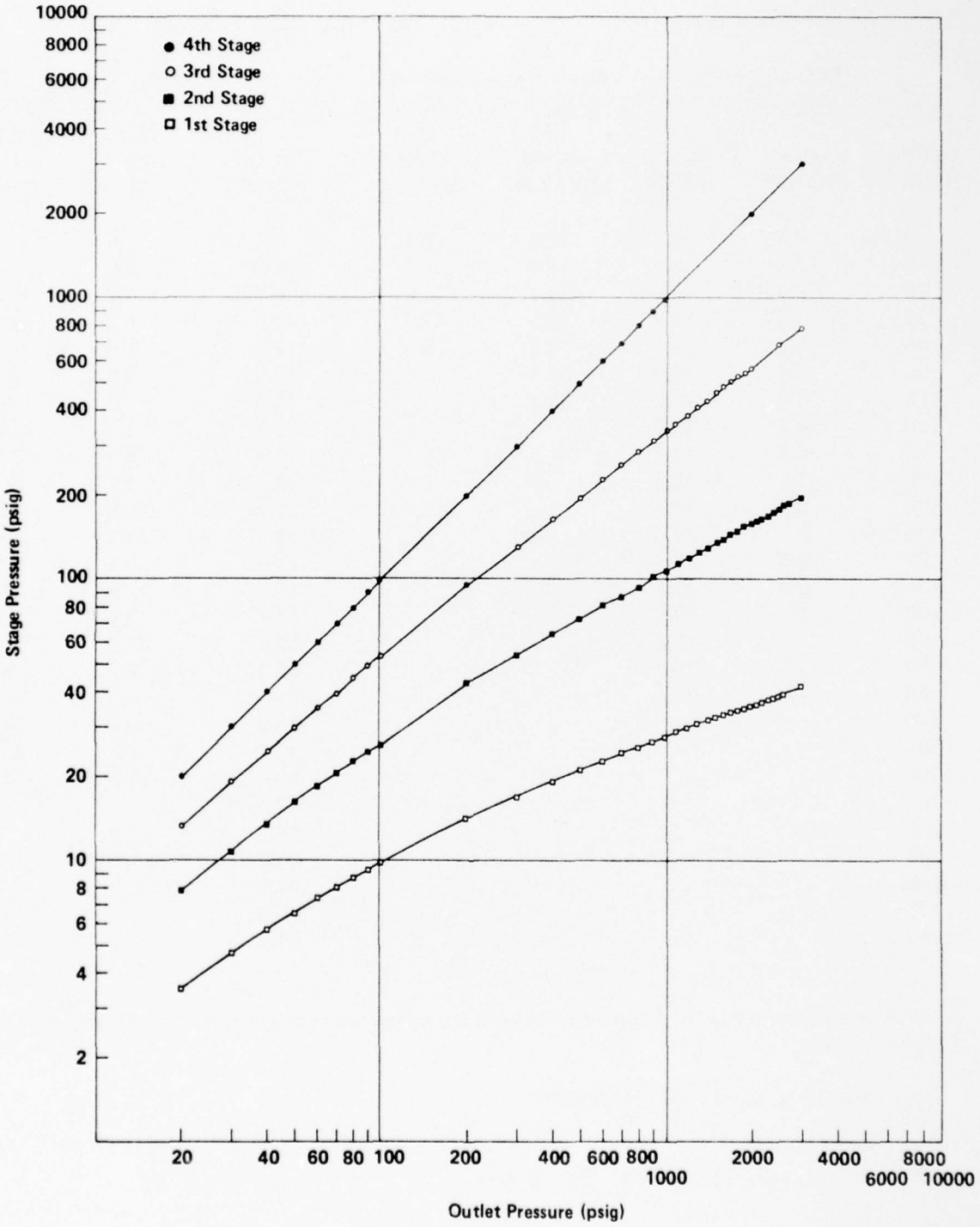

Fig. 11 Stage Pressure vs Discharge Pressure for a Four Stage Balanced Compression Ratio Machine

TABLE 2

ACFM REQUIREMENTS CORRELATED TO SCFM RATING OF COMPRESSOR

	RECOMPRESSION CHAMBER REQUIREMENTS					DIVING REQUIREMENTS	
	AIR TREATMENT		OXYGEN TREATMENT		VENT. APP.	DEMAND APP.	
DEPTH (FSW)	2 ACFM/ PATIENT	4 ACFM TENDER	12.5 ACFM/ PATIENT	25 ACFM TENDER	6 ACFM	2.46 ACFM (MEAN)	6.66 ACFM (PEAK)
0	2.1	4.1	12.6	25.1	6.1	2.6	6.7
10	2.7	5.3	16.3	32.6	7.9	3.4	8.7
20	3.3	6.5	20.1	40.2	9.7	4.2	10.7
30	3.9	7.7	23.9	47.7	11.5	5.0	12.7
40	4.5	8.9	27.7	55.3	13.3	5.8	14.8
50	5.1	10.1	31.4		15.1	6.5	16.8
60	5.7	11.3	35.2		16.9	7.3	18.8
70	6.3	12.5			18.7	8.1	20.8
80	6.9	13.7			20.6	8.9	22.8
90	7.5	14.9			22.4	9.7	24.8
100	8.1	16.1			24.2	10.5	26.8
110	8.7	17.4			26.0	11.3	28.8
120	9.3	18.6			27.8	12.1	30.9
130	9.9	19.8			29.6	12.9	32.9
140	10.5	21.0			31.4	13.6	34.9
150	11.1	22.2			33.3	14.4	36.9
160	11.7	23.4			35.1	15.2	38.9
165	12.0	24.0			—	—	—
170					36.9	16.0	40.9
180					38.7	16.8	42.9
190					40.5	17.6	44.9
200					42.3		
210					44.1		
220					46.0		
230					47.8		
240					49.6		
250					51.4		

AFCM is a volumetric flow of 1 cubic foot per minute independent of pressure. This is correlated to SCFM as follows:

Sea water density 64.0 $\frac{\text{lbs.}}{\text{ft}^3}$ @40°F

Pressure per foot of depth $\frac{64}{144} = 0.4444$

Assume a 30° temperature differential between surface and diver depth.

Then SCFM = $\frac{530}{500}$ (ACFM X .4444D + 14.7)/14.7

TABLE 3

COMPRESSED AIR REQUIRED FOR NO DECOMPRESSION DIVES – SCF –
FOR SPECIFIED BOTTOM TIME VS. DEPTH OF DIVE FOR MK 1,
DEMAND APPARATUS (ONE DIVER AT 2 ACFM)

DEPTH FSW ↓ / BOTTOM TIME MINUTES →	0	5	10	15	20	25	30	40	50	60	80	100	120	140	160	180	200	220	240	260	280	300
10		14	28	41	55	69	83	110	138	166	221	276	331	387	442	497	552	607	663	718	773	828
20		17	35	51	69	85	103	137	171	205	273	341	409	477	545	613	681	749	817	885	954	1022
30		20	42	61	83	101	123	164	204	245	325	406	487	568	649	730	811	891	972	1053	1134	1215
40		23	49	70	96	117	143	189	236	283	377	470	564	658	751	845	939					
50		27	56	80	109	133	163	216	269	322	362	535										
60		30	64	89	123	149	183	243	302	362												
70		33	71	99	137	165	203	269	335													
80		36	78	109	151	181	223	296														
90		39	87	118	166	197	245															
100		52	94	137	180	222																
110		56	102	148	193																	
120		61	110	159																		
130		66	119																			
140		70	126																			
150		76																				
160		81																				
170		86																				
180		92																				
190		97																				

TABLE 4

COMPRESSED AIR REQUIRED FOR NO DECOMPRESSION DIVES – SCF –
FOR SPECIFIED BOTTOM TIME VS. DEPTH OF DIVE FOR MK V, MK 12
VENTILATED APPARATUS (ONE DIVER AT 6 ACFM)

DEPTH FSW ↓ / BOTTOM TIME MINUTES →	0	5	10	15	20	25	30	40	50	60	80	100	120	140	160	180	200	220	240	260	280	300
10		41	84	124	167	207	249	332	415	498	664	829	995	1161	1326	1492	1658	1823	1989	2155	2320	2486
20		51	105	153	207	255	309	411	513	615	819	1024	1228	1432	1636	1840	2044	2248	2452	2656	2861	3065
30		61	126	182	248	303	369	490	611	733	975	1218	1460	1703	1946	2188	2431	2673	2916	3158	3401	3643
40		70	148	211	288	351	429	569	710	850	1131	1412	1693	1974	2255	2536	2817					
50		80	169	240	328	399	488	648	808	967	1287	1606										
60		89	191	268	370	447	549	728	907	1086												
70		99	213	297	411	495	610	808	1006													
80		109	236	326	454	544	671	889														
90		118	260	355	496	592	733															
100		155	283	411	539	667																
110		169	306	444	581																	
120		183	330	477																		
130		198	356																			
140		212	379																			
150		228																				
160		244																				
170		259																				
180		276																				
190		292																				

TABLE 5

SCF OF AIR REQUIRED AT 2 ACFM TO SUPPORT ONE DIVER

DEPTH FT SW	BOTTOM TIME MIN	SCF USED BOTTOM	SCF USED DECOMPRESSION STOPS 50 FT	40 FT	30 FT	20 FT	10 FT	SCF ASCENT	SCF TOTAL
40	200	937					0	2	939
	210	984					6	2	991
	230	1077					19	2	1099
	250	1171					30	2	1204
	270	1265					41	2	1308
	300	1405					52	2	1460
50	100	532					0	3	536
	110	586					8	3	597
	120	639					14	3	656
	140	745					28	3	776
	160	852					58	3	913
	180	958					80	3	1042
	200	1065					97	3	1165
	220	1171					110	3	1285
	240	1278					130	3	1411
60	60	358					0	4	362
	70	418					6	4	427
	80	477					19	4	501
	100	597					39	4	639
	120	716					72	4	792
	140	835					108	4	947
	160	955					133	4	1091
	180	1074					155	4	1233
	200	1193				3	191	4	1391
70	50	330					0	5	335
	60	396					22	5	424
	70	462					39	5	506
	80	529					50	5	583
	90	595					64	5	663
	100	661					91	5	757
	110	727				7	113	5	852
	120	793				14	130	5	941
	130	859				20	144	5	1028
	140	925				27	155	5	1112
	150	991				31	168	5	1195
	160	1057				44	199	5	1305
	170	1123				65	218	5	1411
80	40	290					0	6	296
	50	362					28	6	396
	60	435					47	6	488
	70	507					64	6	577
	80	580				7	86	6	678
	90	652				24	108	6	790
	100	725				37	127	6	895
	110	797				44	146	6	994
	120	870				58	155	6	1088
	130	942				65	174	6	1187
	140	1015				88	191	6	1300
	150	1087				109	213	6	1415
90	30	237					0	8	244
	40	316					19	8	342
	50	394					50	8	452
	60	473					69	8	550
	70	552				24	83	8	666
	80	631				44	110	8	793
	90	710				61	133	8	911
	100	789				71	149	8	1017
	110	868				82	168	8	1125
	120	947				109	188	8	1251
	130	1026			20	122	204	8	1380
100	25	213					0	9	222
	30	256					8	9	273
	40	341					41	9	391
	50	426				7	66	9	508
	60	512				31	77	9	629
	70	597				58	108	9	771
	80	682				78	133	9	902
	90	768			12	78	157	9	1024
	100	853			28	78	182	9	1151
	110	938			40	116	199	9	1302
	120	1024			49	139	215	9	1436
110	20	183					0	10	194
	25	229					8	10	248
	30	275					19	10	305
	40	367				7	58	10	442
	50	459				27	72	10	568
	60	550				61	99	10	721
	70	642			4	78	157	10	892
	80	734			28	78	157	10	1008
	90	825			49	102	177	10	1163
	100	917			61	126	199	10	1313

DEPTH FT SW	BOTTOM TIME MIN	SCF USED BOTTOM	SCF USED DECOMPRESSION STOPS 50 FT	40 FT	30 FT	20 FT	10 FT	SCF ASCENT	SCF TOTAL
120	15	147					0	12	159
	20	196					6	12	214
	25	245					17	12	274
	30	294					39	12	345
	40	392				17	69	12	490
	50	491				51	86	12	639
	60	589			8	75	124	12	808
	70	687			36	78	152	12	965
	80	785			61	92	174	12	1123
	90	883			77	126	204	12	1302
	100	981			93	153	221	12	1460
130	10	105					0	14	118
	15	157					3	14	173
	20	209					11	14	234
	25	261					28	14	303
	30	314				10	50	14	387
	40	418				34	69	14	535
	50	523			12	71	102	14	722
	60	627			36	78	149	14	899
	70	732			65	82	168	14	1060
	80	836		14	77	119	199	14	1259
	90	941		37	77	153	221	14	1443
140	10	111					0	15	126
	15	166					6	15	187
	20	222					17	15	254
	25	277				7	39	15	338
	30	333				17	58	15	423
	40	444			8	54	72	15	593
	50	555			24	82	121	15	797
	60	666			65	78	155	15	979
	70	777		19	77	109	188	15	1184
	80	887		47	93	139	218	15	1400
150	5	59					0	17	76
	10	117					3	17	137
	15	176					8	17	202
	20	235				7	19	17	278
	25	293				14	47	17	371
	30	352				27	66	17	463
	40	469			20	65	91	17	663
	50	587			49	78	141	17	872
	60	704		14	77	88	171	17	1072
	70	821		52	77	133	207	17	1307
	80	939	5	80	77	170	232	17	1520
160	5	62					0	19	81
	10	124					3	19	146
	15	186				3	11	19	219
	20	248				10	30	19	307
	25	309				24	55	19	408
	30	371			8	37	91	19	478
	40	495			28	78	108	19	729
	50	619		9	65	78	152	19	942
	60	743		42	77	112	191	19	1184
	70	866	5	80	89	150	221	19	1430
170	5	65					0	21	87
	10	130					6	21	157
	15	195				7	14	21	237
	20	260				14	41	21	337
	25	325			8	24	64	21	442
	30	390			16	44	72	21	544
	40	521		5	40	78	124	21	790
	50	651		23	73	78	168	21	1015
	60	781	11	70	89	126	204	21	1302
	70	911	43	80	77	173	237	21	1543
180	5	68					0	24	92
	10	137					8	24	169
	15	205				10	17	24	255
	20	273			4	17	47	24	365
	25	341			12	34	66	24	478
	30	410			24	58	75	24	590
	40	546		14	57	78	138	24	857
	50	683	11	42	77	102	179	24	1118
	60	819	27	75	77	150	224	24	1395
190	5	71					0	26	97
	10	143				3	8	26	181
	15	214				14	19	26	273
	20	286			8	20	55	26	396
	25	357			20	37	69	26	510
	30	429		5	32	65	88	26	645
	40	572		37	57	78	152	26	922
	50	715	21	61	89	112	199	26	1223
	60	858	53	80	77	170	232	26	1496

TABLE 6

SCF OF AIR REQUIRED AT 6 ACFM TO SUPPORT ONE DIVER

DEPTH FT SW	BOTTOM TIME MIN	SCF USED BOTTOM	SCF USED DECOMPRESSION STOPS 50 FT	40 FT	30 FT	20 FT	10 FT	SCF ASCENT	SCF TOTAL
40	200	2810					0	7	2817
	210	2951					17	7	2974
	230	3232					58	7	3297
	250	3513					91	7	3611
	270	3794					124	7	3925
	300	4215					157	7	4380
50	100	1597					0	9	1607
	110	1757					25	9	1791
	120	1917					41	9	1968
	140	2236					83	9	2329
	160	2556					174	9	2739
	180	2875					240	9	3125
	200	3195					290	9	3494
	220	3514					331	9	3855
	240	3834					389	9	4232
60	60	1074					0	12	1086
	70	1253					17	12	1282
	80	1432					58	12	1502
	100	1790					116	12	1918
	120	2148					215	12	2375
	140	2506					323	12	2841
	160	2864					398	12	3273
	180	3222					464	12	3698
	200	3579				10	572	12	4173
70	50	991					0	15	1006
	60	1189					66	15	1271
	70	1387					116	15	1519
	80	1586					149	15	1750
	90	1784					191	15	1990
	100	1982					273	15	2271
	110	2180				20	340	15	2556
	120	2378				41	389	15	2824
	130	2577				61	431	15	3084
	140	2775				82	464	15	3336
	150	2973				92	505	15	3585
	160	3171				133	596	15	3916
	170	3369				194	654	15	4233
80	40	870					0	19	888
	50	1087					83	19	1189
	60	1305					141	19	1464
	70	1522					191	19	1731
	80	1739				20	257	19	2035
	90	1957				71	323	19	2370
	100	2174				112	381	19	2686
	110	2392				133	439	19	2982
	120	2609				173	464	19	3265
	130	2827				194	522	19	3561
	140	3044				265	572	19	3900
	150	3261				327	638	19	4245
90	30	710					0	23	733
	40	947					58	23	1027
	50	1183					149	23	1355
	60	1420					207	23	1650
	70	1657				71	248	23	1999
	80	1893				133	331	23	2380
	90	2130				184	398	23	2734
	100	2367				214	447	23	3051
	110	2603				245	505	23	3376
	120	2840				327	563	23	3752
	130	3077			61	367	613	23	4140
100	25	640					0	27	666
	30	768					25	27	819
	40	1024					124	27	1174
	50	1279				20	199	27	1525
	60	1535				92	232	27	1886
	70	1791				173	323	27	2314
	80	2047				235	398	27	2706
	90	2303			36	235	472	27	3073
	100	2559			85	235	547	27	3452
	110	2815			121	347	596	27	3906
	120	3071			146	418	646	27	4307
110	20	550					0	31	581
	25	688					25	31	744
	30	825					58	31	914
	40	1100				20	174	31	1326
	50	1376				82	215	31	1704
	60	1651				184	298	31	2164
	70	1926			12	235	472	31	2676
	80	2201			85	235	472	31	3024
	90	2476			146	306	530	31	3489
	100	2751			182	378	596	31	3938
120	15	992					0	36	427
	20	589					17	36	641
	25	736					50	36	821
	30	883					116	36	1035
	40	1177				51	207	36	1471
	50	1472				153	257	36	1917
	60	1766			24	225	373	36	2423
	70	2060			109	235	456	36	2896
	80	2355			182	276	522	36	3370
	90	2649			230	378	613	36	3906
	100	2943			279	459	663	36	4380
130	10	314					0	41	354
	15	470					8	41	520
	20	627					33	41	701
	25	784					83	41	908
	30	941				31	149	41	1161
	40	1254				102	207	41	1604
	50	1568			36	214	306	41	2166
	60	1881			109	235	431	41	2697
	70	2195			194	245	505	41	3180
	80	2509		42	230	357	596	41	3776
	90	2822		112	230	459	663	41	4328
140	10	333					0	46	379
	15	499					17	46	562
	20	666					50	46	762
	25	832				20	116	46	1015
	30	998				51	174	46	1270
	40	1331			24	163	215	46	1780
	50	1664			73	245	364	46	2392
	60	1997			194	235	464	46	2936
	70	2330		56	230	327	563	46	3552
	80	2662		141	279	418	654	46	4201
150	5	176					0	52	228
	10	352					8	52	412
	15	528					25	52	605
	20	704				20	58	52	834
	25	880				41	141	52	1114
	30	1056				82	199	52	1388
	40	1408			61	194	273	52	1988
	50	1760			146	235	422	52	2615
	60	2112		42	230	265	514	52	3216
	70	2464		155	230	398	621	52	3920
	80	2816	16	239	230	510	696	52	4560
160	5	186					0	58	244
	10	371					8	58	438
	15	557				10	33	58	658
	20	743				31	91	58	922
	25	928				71	166	58	1223
	30	1114			24	112	124	58	1433
	40	1485			85	235	323	58	2186
	50	1856		28	194	235	456	58	2827
	60	2228		126	230	337	572	58	3551
	70	2599	16	239	267	449	663	58	4290
170	5	195					0	64	260
	10	390					17	64	471
	15	586				20	41	64	712
	20	781				41	124	64	1010
	25	976			24	71	191	64	1327
	30	1171			49	133	215	64	1632
	40	1562		14	121	235	373	64	2369
	50	1952		70	218	235	505	64	3045
	60	2343	32	211	267	378	613	64	3907
	70	2733	128	239	230	520	712	64	4628
180	5	205					0	71	276
	10	410					25	71	506
	15	615				31	50	71	766
	20	819			12	51	141	71	1094
	25	1024			36	102	199	71	1433
	30	1229			73	173	224	71	1770
	40	1639		42	170	235	414	71	2571
	50	2049	32	126	230	306	538	71	3353
	60	2458	80	225	230	449	671	71	4184
190	5	214					0	78	292
	10	429				10	25	78	542
	15	643				41	58	78	820
	20	858			24	61	166	78	1187
	25	1072			61	112	207	78	1530
	30	1287		14	97	194	265	78	1935
	40	1716		112	170	235	456	78	2766
	50	2145	64	183	267	337	596	78	3669
	60	2574	160	239	230	510	696	78	4487

TABLE 7

STORED COMPRESSED AIR AVAILABLE (SCF/ft^3) vs OPERATIONAL PRESSURE RANGE 500 TO 4500 PSIG

PSIG	50°F	70°F	90°F
500	0	0	0
600	6.4	4.5	2.8
700	13.7	11.5	9.5
800	21	18.4	16.1
900	28.3	25.4	22.7
1000	35.6	32.3	29.3
1100	42.9	39.2	35.9
1200	50.2	46.1	42.5
1300	57.4	53	49
1400	64.6	59.8	55.5
1500	71.8	66.6	62
1600	79	73.4	68.4
1700	86	80.1	74.8
1800	93.1	86.8	81.1
1900	100.1	93.4	87.4
2000	107	99.9	93.7
2100	113.8	106.4	99.8
2200	120.5	112.8	105.9
2300	127.2	119.1	112
2400	133.8	125.4	117.9
2500	140.3	131.6	123.8
2600	146.7	137.7	129.7
2700	153	143.7	135.4
2800	159.3	149.6	141.1
2900	165.4	155.5	146.7
3000	171.4	161.3	152.2
3100	177.4	167	157.7
3200	183.2	172.6	163.1
3300	189	178.1	168.4
3400	194.6	183.5	173.6
3500	200.2	188.8	178.7
3600	205.6	194.1	183.8
3700	211	199.3	188.8
3800	216.2	204.3	193.7
3900	221.4	209.3	198.5
4000	226.5	214.3	203.3
4100	231.5	219.1	208
4200	236.4	223.9	212.6
4300	241.2	228.6	217.2
4400	246	233.2	221.6
4500	250.6	237.7	226.1

Appendix

Explanatory Calculations

Table 2 Analysis to obtain Table 2

Seawater density 64.0 $\frac{\text{lbs}}{\text{ft}^3}$

Pressure per foot of depth

$\frac{64.0}{144} D = 0.4444 D$

Recommended flow rates

Chamber 2 ACFM per patient

4 ACFM per tender

12.5 ACFM per patient breathing oxygen

25.0 ACFM per tender breathing oxygen

Diving Apparatus 6 ACFM for each diver and tender using Mk 5, Mk 12 Apparatus

4.5 ACFM for J. Brown at depths of 90 feet

60 LPM-RMV when using Mk 1 apparatus equivalent to $\sim$ 2.2 ACFM

Peak Flow is the maximum instantaneous rate occurring during breathing conforming to 2 sinisoidal pattern. The maxima is π x RMV or $\sim$ 188 LPM

All these flows are volumetric and must be maintained independent of depth; therefore the correlation between SCFM and ACFM requires both depth pressure parameter and a nominal temperature correction:

$$\text{ACFM} \times \frac{(0.4444D + 14.7)}{14.7} \times \frac{530}{500} = \text{SCFM at the surface}$$

This correlation is used throughout the presentation.

To establish pressure requirements at the diver's station, the losses due to fiction in the hose must be considered. A 400-foot length of hose was used in the following isothermal equation to find pressure losses. The 1st stage pressure regulator was assumed to be set at 120 psi over bottom pressure.

$$P_1^2 - P_2^2 = \frac{W^2 RT}{g A^2} \left[2 \log_e \frac{V_2}{V_1} + f \frac{L}{d} \right] \qquad (3)$$

P_1 = Diver Station Pressure, psi A

P_2 = KMB 2nd Stage Pressure, psi A

T = Water Temperature, °R

W = Weight Flow, lb/sec

A = Cross sectional Hose Area, ft^2

g = Gravity, 32.2 ft/sec^2

R = Univ. Gas Constant, $\frac{ft\ lb}{lb\ °R}$ (53.34 air)

V_1 = Velocity of Air at Diver Sta, ft/sec

V_2 = Velocity of Air at 1st Stage, ft/sec

f = Friction Factor, dim'l

L = Length of Hose, ft

d = Diameter of Hose, ft

The friction factor f is expressed in the Colebrook equation,

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left[\frac{\varepsilon}{3.7d} + \frac{2.51}{R_E \sqrt{f}} \right] \tag{4}$$

f = Friction Factor, dim'l

d = Diameter of Hose, ft

ε = Roughness Coeff, dim'l

R_E = Reynolds Number, dim'l

where $R_E = \frac{Vd}{v}$ (5)

V = Velocity of Air ft/sec

d = Hose Diameter ft

v = Kinematic Viscosity, ft^2/sec

and, $v = 10 - \left(\frac{P}{102} + 3.638 \right)$ (6)

v = Kinematic Viscosity, ft^2/sec

P = Air Pressure, PSIG

The velocities (V, and V_2) may be expressed as,

$$V = \frac{W}{\rho a} \tag{7}$$

V = Velocity of Air at Respective Sta., ft/sec

ρ = Density of Air at Respective Sta, lbm/ft^3

A = Area, ft^2

W = Mass Flow, lb/sec

where,

$\rho = \frac{P}{RT}$ (for one ft^3 of gas)

P = Pressure, PSF (Absolute)

R = Univ Gas Constant $\frac{ft}{°R}$ (53.34 arr)

T = Temp °R

A program has been written employing these relationships to determine pressure losses in the hose and thus defining the diver station pressure.

In solving Eqn 3 for the pressure losses, it was assumed that $\log \frac{V2}{V1}$ was insignificant in finding the pressure difference. An investigation of this expression at various depths has shown this to be a valid assumption.

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THE TOXICITY OF CARBON MONOXIDE UNDER PRESSURE AND CONSIDERATIONS FOR STANDARD SETTING

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ABSTRACT:

Theoretical considerations regarding the toxicity of carbon monoxide (CO) to man, both at one atmosphere and at elevated pressures is explored. The literature on the subject is reviewed, particularly the low level toxic effects of CO. It is concluded that: (1) for all practical purposes, in the present range of diving to 350 meters, the toxicity of CO per se, does not increase with depth, but is a function of the carboxyhemoglobin (COHb) level in the blood which is determined by the ratio of Pco to Po_2; (2) the demonstration of physiological impairment at COHb levels less than 5% is dependent on specific methodologies of acute transient state exposures neither representative nor extrapolatable to the diving situation. Suggestions to establish CO levels at 10 parts per million (ppm) for air diving or 10 ppm surface equivalent carbon monoxide (SECO) for gas diving are medically unjustified and technologically unreasonable. A CO level of 20 ppm in air diving corresponding to 3.3% COHb at equilibrium or 20 ppm SECO in gas diving is medically quite adequate as a maximum level of CO exposure. A formula is given for the proper calculation of the SECO level taking into consideration the Po_2 level in gas diving.

INTRODUCTION:

Carbon monoxide and its toxicity under pressure is of great concern to the diver and the diving community and of special interest in a year when OSHA is about to promulgate diving standards. The following questions are often raised:

1. Does the toxicity of carbon monoxide increase under pressure?

2. What are the acceptable levels of carbon monoxide exposure under pressure?

3. How does one go about calculating the surface equivalent toxicity of carbon monoxide under pressure?

TOXICITY OF CARBON MONOXIDE:

Carbon monoxide exerts its effect at three, and possibly four levels in the human body.

1. The most important reaction is the combination of CO with hemoglobin (Hb) to form carboxyhemoglobin (COHb) according to the equation:

$$CO + Hb \rightleftharpoons COHb$$

Hemoglobin is the principal transport vehicle for O_2 in the body:

$$O_2 + Hb \rightleftharpoons O_2Hb$$

Thus, oxygen and CO are in competition for hemoglobin. However, the affinity of CO for Hb is well established at physiologic pH and temperature as being approximately 210 times that of oxygen. The concentration of COHb is a function of the partial pressure of CO (Pco) and Po_2 according to the equation:

$$\frac{(COHb)}{(O_2Hb)} = M \times \frac{Pco}{Po_2}$$

where (COHb) and O_2Hb) are the concentrations of COHb and O_2Hb (usually expressed as percent saturation), and M is the affinity constant (210).

CO exerts its toxic effect on hemoglobin by: (a) displacement of O_2 from hemoglobin in arterial blood; (b) shifting of the oxygen dissociation curve to the left resulting in oxygen not being released as readily at the tissue level. Thus, inactivation of say 10% of one's hemoglobin with CO causes a greater tissue hypoxia than 10% anemia.

2. CO combines with myoglobin(Mb) in the muscles to form carboxymyoglobin (COMb). Myoglobin may function as a reservoir for O_2 in the muscle. This accounts for the great muscle fatigue seen in significant CO exposures.

3. Cytochrome oxidases are hemeproteins that also entertain a competitive reaction between O_2 and CO for themselves. However, evidence suggests that interactions between CO and cytochrome oxidases are of minor significance when compared to the effects of CO on hemoglobin.

4. There have been suggestions in the literature that CO may exert a direct toxic effect on the central nervous system that is unrealted to the COHb level. However, at this time there is no evidence to support this.

The level of COHb is the most important factor and the one and only common denominator to which the toxicity of CO can be related. Due to the endogenous production of CO in the body, there is a normal background level of COHb of approximately 0.5%. For any given exposure to CO, about 80% is bound to Hb as COHb, about 20% is bound to myoglobin in the muscles as COMb and an estimated 1% is bound to the cytochrome oxidases. About 12 hours is the time for a given level of CO to equilibrate with the hemeproteins. At saturation, the following formula has been proposed by Goldsmith and Landlaw[1] as the best representation of experimental data for continuous exposures to CO of less than 100 ppm:

$$\% \text{ COHb} = 0.16 \times \text{CO in ppm}$$

Thus, after a 12 hour or equilibrium exposure to CO, the following is obtained:

Continuous Exposure Level of CO in ppm	% COHb in Blood
50 ppm	8.4%
40 ppm	6.7%
30 ppm	5.0%
20 ppm	3.3%
10 ppm	1.7%
(non-smoker)	0.5%

Back and Cominguez[2] studied the toxicity of CO in well trained monkeys and concluded that the stimulus response pattern was not altered by levels of COHb that are clearly detrimental to humans. It does not seem reasonable, therefore, to extrapolate the results of animal experiments to any possible human tolerance for CO.

Data and results of human exposure to CO at first, appears quite conflicting:

AUTHOR	EXPOSURE (ppm x time)	COHb %	TEST/RESULT
Forbes[3]	____ x ____	30%	Simulated car driving/No effect
Schulte[4]	____ x ____	20.4%	16 physiological & psychological tests/Considered that an effect should be detectable at COHb levels of 2-3%
Grudzinska[5]	100 x ____	7-10%	EEG/Flat low voltage frequencies with scanty alpha rhythm ($P < 0.01$)
Bear & Wertheim[6]	50 x 90 min.	Estimated 2.5%	Impairment of temporal discrimination/Demonstrated at statistically significant level
Steward, et al[7]	1-100 ppm x 8 hours	11-13%	Time estimation, hand-reaction test/No detectable change
Mikulka, et al[8]	50 & 125 x 3 hours	2.98 & 6.64%	Time estimation tracking task & vestibular function/No effect

The above studies employed important methodologic differences:

1. Different methods for testing time estimation.

2. Both the Steward and the Mikulka studies were in a group setting where elements of competition and other stimuli were present as opposed to:

3. The Beard and Wertheim study where individuals were tested in an isolated booth for 4 hours where boredom and fatigue may well have added to the effect of CO.

Despite the apparent discrepancies in results, each of the results must be considered to be highly specific to the method and conditions of testing. However, extrapolation of the results to other areas must be restricted. In particular, the present author questions the validity of acutely exposing men to high concentrations of CO for short periods of time and drawing the conclusion that this bolus is equivalent to a given COHb level. If, instead of exposing men to 50 ppm for 90 minutes, as in the Beard and Wertheim paper, and equating this exposure to 2.5% COHb (not measured) one were to approach 2.5% COHb via a 12 hour equilibrium with 15.5 ppm, it is questionable whether the impairment of temporal discrimination seen above and related to a 2.5% COHb level would be observed.

Beard and Grandstaff[9] in acute exposure of 7 subjects demonstrated consistent impairment of visual performance. However, COHb levels were estimated from expired air samples. At each CO concentration, there was a rapid recovery in performance subsequent to the exposure and test results returned to normal more quickly than did the CO concentrations in the expired air.

These kind of results point out this author's concern when an attempt is made to relate a given impairment to a given COHb level when that level is the estimated transient state result of a high CO concentration, short time exposure.

SOURCES OF CARBON MONOXIDE AND IMPLICATION TO DIVING:

There are 5 sources of carbon monoxide of concern to diving:

1. Smoking. Carbon monoxide occurs in high concentration in cigarette smoke, 20,000 ppm, and the average concentration inhaled is 400-500 ppm. A study by Goldsmith[10] revealed the following:

SMOKING HABITS	MEDIAN % COHB LEVEL	CO EXPIRED PPM
Light smoker (less than ½ pack/day)	3.8	17.1
Moderate smoker (more than ½ pack/day and less than 2 packs/day)	5.9	27.5
Heavy smoker (2 packs or more/day)	6.9	32.4

The above data is presented to point out the fact that a smoking diver already has his blood polluted with a level of COHb that exceeds what he would acquire if he were exposed to air containing 20 ppm CO for 12 hours.

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2. Incomplete combustion of organic materials such as occurs in the internal combustion engine and various industrial processes is an ubiquitous source of CO. This results in contamination of the atmosphere, either locally as results from being in the down wind proximity to an internal combustion engine or as a general rise in the level of carbon monoxide pollutants in the atmosphere as occurs around our major cities and ports. The level of CO in the atmosphere varies from a low of 25 ppb to values as high as 81 ppm in Los Angeles. There are 17 cities in America[11] that have CO levels in excess of 10 ppm 50% of the time over a one year average. The atmosphere is thus a source of CO of concern to diving as this contaminated air may be compressed and supplied to divers. Moreover, the level of CO in air that may be compressed for air diving may exceed proposed standards. Thus, the grave need to promulgate reasonable standards that will take these factors into consideration is evident.

3. Compressors, either air or mixed gas booster compressors, may be a source of carbon monoxide contamination, both to air and mixed gas.

4. Dry welding processes in underwater welding habitats will severely contaminate the inert atmosphere in which the diver is welding. Normally the diver is on a BIBS and he certainly is not breathing the carbon monoxide contaminated inert welding atmosphere. However, the integrity of the system cannot always be guaranteed. For example, the diver/welder may unknowingly break the seal on his mask and inhale the welding atmosphere that may have an actual carbon monoxide content in the hundreds of parts per million at depth.

5. The diver himself is a source of carbon monoxide. Endogenous production of carbon monoxide from the human body as a by-product of heme catabolism is a contaminant in the closed life support system of a saturation complex. The present author has observed CO levels in diving saturation complexes ranging from undetectable levels to actual 4.1 ppm at 100 meters and Po_2 of 0.395 ATA. This is an approximate surface equivalent toxicity of 23.9 ppm. However, in the non-welding saturation diving complex, endogenous production and accumulation of CO is not a problem as the oxidation and odor removal chemicals in the environmental control system also keep the CO at a low level.

FACTORS TO BE TAKEN INTO CONSIDERATION REGARDING THE TOXICITY OF CO UNDER PRESSURE:

1. There is no evidence in the literature that CO acts directly on nervous system tissue, and in particular there is no evidence that a direct toxic effect on tissue is enhanced by increased partial pressure of CO.

2. The diffusivity of CO in another gas is decreased with increasing density. There are suggestions in the ligerature[12,13] that in the depth range of 500 to 600 meters there could be an inhibition of endogenous CO washout from the lungs resulting in an increased background COHb level

while in saturation. However, this has not been well established and further work is necessary at these depths. In the present commercial and military diving range of 0-350 meters, there is no evidence that accumulation of endogenously produced CO, and thus COHb, is a problem due to inadequate washout at the alveolar level.

3. Should the affinity constant of CO for hemoglobin increase with pressure, this would result in an increased level of COHb. However, the work of Rodkey, et al[14] detected no change in the affinity constant of CO for Hb down to 21.4 ATA and thus to the equivalent depth of 215 meters can be regarded as constant.

4. The one and only real concern is the % level of COHb in the blood. For an equilibrium time of 12 hours, the % COHb is a function of the ratio Pco/Po_2.

AIR DIVING:

In air diving, the ratio of Pco/Po_2 remains constant with increasing depth. Thus, focusing on the maximum value attainable, i.e. the equilibrium value, the % COHb does not increase with depth for the entire depth range of air diving. The toxicity of 20 ppm CO in air at 70 meters is no greater than at the surface. 30 ppm CO in air results in a measured equilibrium value of 5% COHb.

As attempts to demonstrate physiological impairment for values less than 5% COHb are questionable as to both technique and applicability for purposes of promulgating legal standards 30 ppm CO in air, corresponding to an equilibrium value of about 5% COHb, would be medically acceptable; 20 ppm CO in air corresponding to about 3.3% COHb is totally adequate; and 10 ppm CO in air corresponding to an equilibrium value of about 1.7% COHb is medically unjustified.

As a matter of perspective, 17 U. S. cities have recorded 50% of the time, over a one year period, CO levels greater than 10 ppm. Also, the average light cigarette smoker will have a COHb level of 3.8% and the extreme heavy smoker will have 18% COHb[15].

As the above COHb levels of 5%, 3.3% and 1.7% are equilibrium values attainable after about 12 hours exposure to the corresponding CO levels, these COHb levels, despite their medical acceptability, would seldom be attained for most air diving at the respective CO levels.

Any standard, and especially those promulgated as law, must consider what is medically sound with what is technologically and economically feasible.

Thus, for air diving, a standard requiring 10 ppm CO as the upper limit is not medically justified and should be denounced. 20 ppm CO in air meets all of the criteria. It is more than medically adequate for air diving.

Technologically, it is not unreasonable to require all air compressors to meet this standard and the atmosphere in most locations in essentially all U. S. cities and ports will be able to meet this level.

MIXED GAS DIVING:

In mixed gas diving, in general, and particularly in saturation diving, where for the most part the Po_2 is maintained at a level set between 0.3-0.6 ATA, the Pco will increase with depth for a given CO level expressed as ppm. However, the objective of gas standard setting is the same as for air, to maintain the COHb level within acceptable limits, i.e. less than 5% COHb. As the % COHb is for all practical purposes a function of only the ratio Pco/Po_2, it is a very simple matter to set a standard in which the Pco is maintained as a set fraction of the Po_2. A Pco of 1/10,000 the Po_2 is recommended as the standard for all mixed gas and saturation diving. This corresponds to 20 ppm in air diving and is the proposed standard set forth for consideration by the European Undersea Biomedical Society at a recent meeting in Newcastle upon Tyne, England.

However, as most CO is measured as ppm and not as partial pressure, a surface equivalent CO level in ppm can be set at 20 ppm SECO provided it is calculated taking into consideration the Po_2 according to the following formula of this author:

$$\text{SECO in ppm} = \frac{\text{actual CO in ppm at depth} \times \text{depth in ATA} \times 0.21}{Po_2 \text{ ATA}}$$

It should be noted that all three recommended standards for the maximum permissible level of CO in diving are identical. 20 ppm CO in air is the same as 20 ppm SECO in air at any depth which is the same as 20 ppm SECO in gas at any depth which corresponds to a Pco of 1/10,000 the Po_2 level as regards the resulting % COHb at equilibrium. The aforementioned recommended levels for CO would keep the level of COHb in the blood at 3.3% or less.

SUMMARY:

1. As far as can be ascertained from the literature, the low level toxicity of CO is strictly a function of the COHb level in the blood and the resultant tissue hypoxia, whether at one atmosphere or at increased pressure. Thus, within the present-day range of diving there is no evidence to suggest that the toxicity of CO increases with pressure other than that which is manifested through increased COHb levels at constant Po_2.

2. The affinity of CO for Hb as measured is constant to 21.4 ATA.

3. There is no evidence to suggest that CO has a direct effect on nervous tissue, let alone that such a hypothesized effect is enhanced by pressure.

4. As the stimulus response pattern in some higher animals is not altered by levels of COHb that are clearly detrimental to humans, it is not reasonable to extrapolate the results of animal experiments to any possible human tolerance to CO.

5. Only equilibrium steady state values of COHb should be considered for standard setting. Thus, a standard that results in some maximum equilibrium value of less than 5% COHb is medically recommended.

6. A CO level of 10 ppm in air or a SECO of 10 ppm in mixed gas is medically not justified.

7. A CO level of 20 ppm CO in air diving or 20 ppm SECO (Pco of 1/10,000 Po_2) in mixed gas and saturation diving is medically quite adequate, technologically reasonable, and is recommended as the appropriate level for future standards.

8. The surface equivalent (SE) CO level expressed in SE ppm must be calculated taking into consideration the Po_2 according to the formula:

$$\text{SECO in ppm} = \frac{\text{actual CO in ppm x depth in ATA x 0.21}}{Po_2}$$

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NEW SHIPBOARD COMPRESSORS

by

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NEW SHIPBOARD COMPRESSORS

Shipboard compressors have changed little over the past 40 years. A typical destroyer has long had two-stage reciprocating-piston compressors for 125 psi low-pressure (LP) air and four-stage units for 3000 psi high-pressure (HP) air. Pistons and cylinders were oil lubricated by crankcase splash on LP machines or with direct oil injection on HP compressors. As exceptions, about 10 years ago, aircraft carriers began getting large capacity centrifugal compressors to support large air requirements for servicing aircraft. Also beginning about two years ago, submarines began to receive water-ring type rotary LP air compressors. (Actually, some 80 psi water-ring compressors had previously been used with submarine O_2 generators and as aircraft carrier combustion control air compressors.)

As long as 15 years ago the WWII vintage compressor machinery was recognized as a major maintenance problem. The service record of compressors bought even through the 1960's was poor - especially HP compressors where 500 hours between major overhauls was considered very good. More likely, these compressors would require major servicing every 200 hours. The high maintenance problems were generally lubrication related. Too little oil resulted in high wear and even scuffing of rings and cylinders. Too much oil to the cylinders accelerated carbon buildup on valves and ring grooves. In addition, water carried over from undrained interstage moisture separators interfered with oil lubrication as did air blowby past leaky piston rings. Even when these compressors were operated under laboratory conditions it

was difficult to achieve more than 500 hours between ring change outs and probably replacement of one or more cylinder liners.

While the high maintenance requirements were lamented, the concern for possible air/oil fires in submarine 4500 psi air systems evoked even more concern. These factors combined to create an environment within the Navy's engineering community receptive to the concept of an oil-free compressor.

It was fully recognized by those associated with the undertaking that significant technological advances would be required. Many on the periphery of the project, including the then current Navy compressor suppliers, doubted the project could be successfully completed. However, in due course, the design and materials puzzle fell into place until on 7 February 1969 a drastically modified Worthington five-stage compressor with oil-free cylinders completed a 1000 hour, 5000 psi run at DTNSRDC and was shortly thereafter installed aboard USS INDEPENDENCE (CV-62) on O_2N_2 plant service, where it remains to this date. On the basis of meeting certain longevity goals on compressors in the laboratory and aboard INDEPENDENCE, NAVSEC proceeded to write purchase specifications.

Implicit in the ability to build a reliable five-stage oil-free 3000 psi compressor is the ability to build a reliable two-stage oil-free 125 psi compressor. It was on the rationale that the technology already existed that the Navy decided to buy LP oil-free compressors without a specific LP compressor R&D effort.

Performance-type contracts were written which included requirements for corrosion-resistant materials in certain areas and emphasized designs that provided good maintainability and low vibration. Also required were

extensive first-article demonstration testing; 1000 hours for LP compressors and 2000 hours for HP compressors.

The compressor replacement program was aimed at the surface fleet including combatant and underway replenishment ships. At the same time oil-free compressors were being written into requirements for new construction surface ships and submarines. The first procurements occurred in June 1971 and as can be seen in Table I, approximately 774 compressors are currently under contract or have already been delivered.

TABLE I

Oil-Free Compressor Procurements

Contractor	No. of Units	Begin Delivery
	Low Pressure Compressors	
Ingersoll-Rand	116	6/75
Worthington	105	6/74
Worthington	101	---
Worthington	112	4/76
Worthington	136	4/76
Worthington	105	---
	High Pressure Compressors	
Ingersoll-Rand	7-30 cfh	6/75
Ingersoll-Rand	23-30 cfh	10/75
Ingersoll-Rand	22-20 cfh	6/74
Worthington	11-20 cfh	10/76
Worthington	22-20 cfh	6/77
Ingersoll-Rand	14-20 cfh	6/78

In addition, oil-free compressors have been specified and have or are being purchased by the shipbuilders for virtually every new class of surface ship and submarine. In addition to keeping oil away from the compression cylinders, the new compressor specifications emphasized extending the time between overhauls, ensuring accessibility for maintenance and providing automated operation. A brief description of some of the salient points of these compressors may be useful in highlighting some of the quality features of these compressors. Figure (1) shows a cross-sectional view of the new shipboard oil-free high pressure air compressor built by the Ingersoll-Rand Company. This unit is rated at 20 cfh at 3000 psi. Basically, the new designs use a conventionally lubricated crankcase to drive the oil-free pistons. A full frame distance or spacer section separates the lubricated and nonlubricated portion of the compressor and high efficiency oil scraper rings located at the bottom of the distance piece seal against the piston rods and prevent oil from leaving the crankcase. No portion of the piston rod which enters the lubricated crankcase enters the oil-free air-cylinder area.

Internally, corrosion resistant materials are used throughout, both to prevent corrosion and provide long wear life in the oil-free environment. Typically, low-pressure cylinder liners (to 150 psi) are constructed of hardened 400 series stainless steel or dense hard chromium plate on a corrosion resistant base material. Higher pressure cylinder liners may use either the hard chromium plating or a "Malcomized" type 17-4 PH stainless steel for long life and wear resistance. Piston rods

have typically been made of hardened 400 series stainless steel in order to be compatible with fluorocarbon air-packing seals.

To provide a minimum of 6000 hours on low-pressure components, bronze-particle-filled fluorocarbon is used for the low-pressure seal, rider, and packing rings. Bronze wire and glass fiber filled fluorocarbon, used in the higher pressure piston ring and sleeve seal pistons, provide in excess of 2000 hours for the high pressure stages. Other self-lubricating materials such as carbon graphite and polyimide are used as bearing surfaces for piston members and valve guides to prevent metal-metal rubbing contact and ensure long life in these units.

All other components and ancillary equipment in contact with the product air such as the piping, coolers, moisture separators, cylinder heads, valves, etc., are fabricated from corrosion resistant materials such as bronze, copper-nickel, monel or stainless steel to promote reliable service in the shipboard environment. Other features incorporated into the design of these units include low piston speeds, thermostatically controlled freshwater cylinder cooling systems, and high efficiency interstage moisture separators between each stage of compression. Furthermore, automatic condensate drain systems and drain-system monitors are used to prevent condensate carryover into the cylinders. This feature, combined with a new 10-point enunciating temperature monitor on the HP machines, and the other compressor safety devices allow these units to operate virtually unattended.

Maintenance has been enhanced by making all cylinder valves individually accessible without disturbing air piping or other components. Additionally, all cylinders are accessible without removing any ancillary apparatus such as coolers or separators or disturbing more than one

other stage of compression. Finally each new design unit has undergone a rigorous 1000 or 2000 hour qualification test to prove that the advanced design features required in the purchase specifications have been satisfactorily demonstrated.

Even with several hundred of the presently contracted oil-free reciprocating-piston compressors still to be delivered, an even more advanced new-generation LP compressor has completed laboratory development and is considered ready for fleet service. The new compressor is the water-flooded helical-screw concept. Figure (2) illustrates the concept of a water-flooded helical-screw compressor. Compression occurs in the moving pocket formed by the advancing action of the screw-thread rotors. Water is sprayed into the compression volume to absorb the heat of compression and also to reduce air leakage across screw-thread sealing boundaries. Although compression takes place in a water spray environment, the outboard ends of each rotor are carried in oil-lubricated rolling-contact bearings well separated from the compression housing. The rotors are timed with precision gears to prevent rotor-to-rotor contact. Materials for the rotors and housing have been selected to avoid several types of corrosion which may occur in a water environment and also provide adequate strength.

The principal advantages of the screw compressor are its small size and its excellent reliability.

A screw compressor package presents a reduction in size and weight of over 50%. As an example, a water-cooled 30 hp oil-free screw compressor package including motor and motor controller weighs only 1500 pounds, while a comparable piston compressor weighs between 3000 and 5000

pounds. The savings are even more important if it is remembered that because of its low vibration characteristics the screw compressor does not require a stiff subbase and can be mounted on any deck that can support the weight of the compressor.

The reliability characteristics of the water-flooded screw compressor have shown to be outstanding in over 15,000 hours of compressor operation at a Navy laboratory and 2000 hours during the manufacturer's first-article test. These compressors should be capable of well over 10,000 hours of unattended operation with no maintenance except the infrequent checking of lubricating oil to the bearing/gear lubrication system and the scheduled maintenance required by the drive motor and heat exchanger. Comparing the operating characteristics of the Ingersoll-Rand water-flooded screw compressor to their oil-free reciprocating piston unit shows a slightly lower airborne noise level, a substantially lower structureborne noise level, and a 8% higher fully-loaded power consumption for a 30 hp unit. The screw compressor delivers air at about 25° F above cooling (sea) water temperature without using an aftercooler. The intimacy of the product air and the circulating freshwater yields approximately isothermal compression. In fact, with very cold seawater to the freshwater cooler, the temperature of the discharge air can be lower than that of the inlet air.

The use of water necessitates the proper selection of materials of construction to avoid serious corrosion problems. Experience to date indicates that corrosion of compressor parts should not be a life-limiting factor with water-flooded helical-screw compressors. The use of water within the compressor does,however,require the system to be drained

prior to periods of inactivity if freezing conditions are anticipated.

The small size of the compressor coupled with the high reliability discussed below makes modular replacement very attractive using a rotatable pool concept. Compressors which require repair could be shipped to a central repair facility, or to the manufacturer's plant, where repairs can be accomplished by trained personnel. A complete spare compressor could be stocked by a field activity in less space (and probably as cheaply) as a set of spare parts for a reciprocating-piston compressor.

Finally, the oil-free screw compressor, with its weight, space and reliability advantages offers a more than 20% reduction in initial cost, and an estimated 50% reduction in life-cycle costs when compared to reciprocating-piston compressors of the same capacity and performance.

The implications and possible benefits of the new compressors to diving operations must be established by the diving community. However, a careful review of the materials used in these new compressors indicates that it is unlikely that any contaminants harmful to divers will be added to the air during compression. Therefore, if breathable air is taken into the compressor suction, it will also be breathable at the discharge connection.

INGERSOLL-RAND 5 STAGE OIL-FREE AIR COMPRESSOR

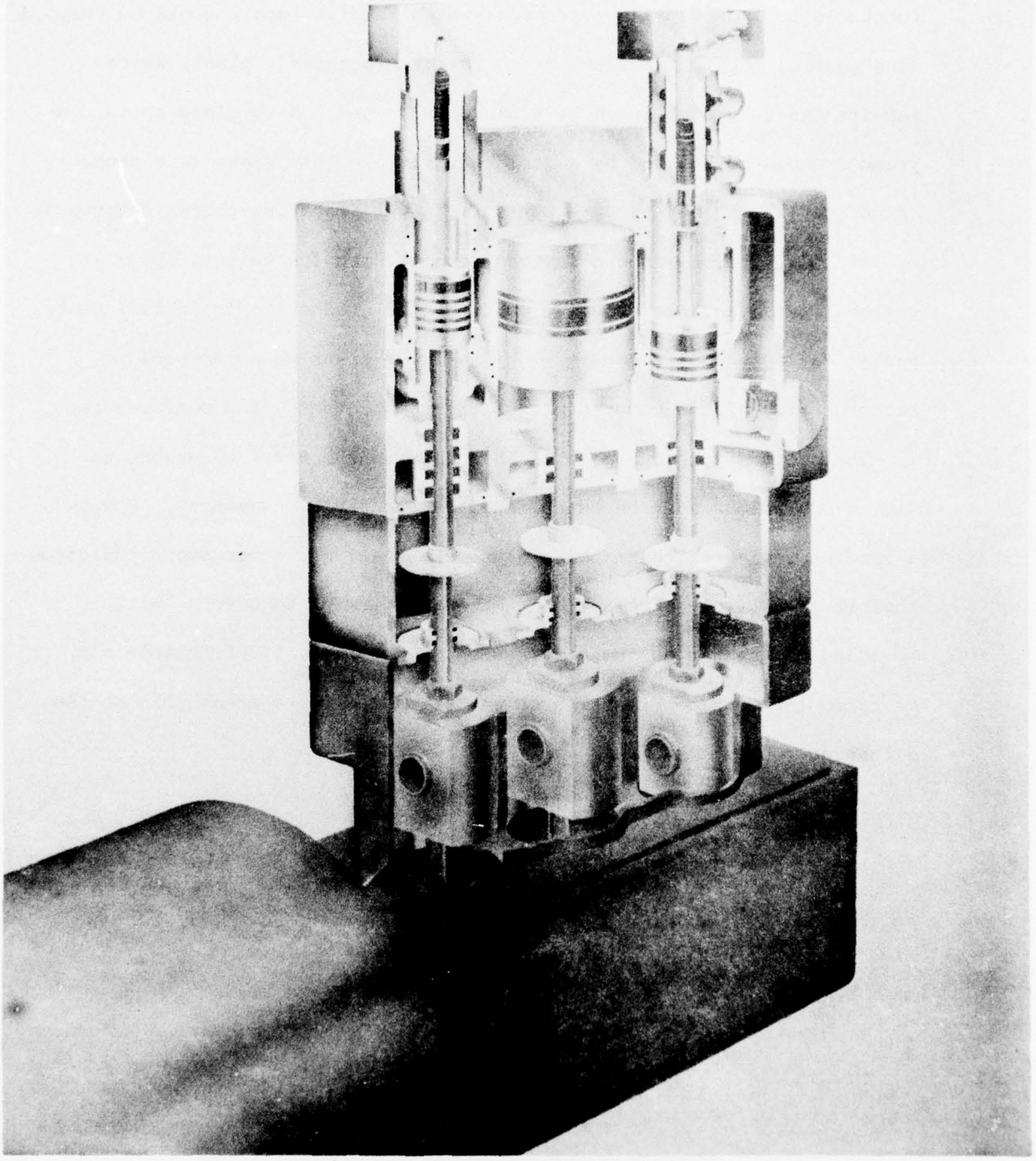

FIGURE 1

TWIN-SCREW COMPRESSOR

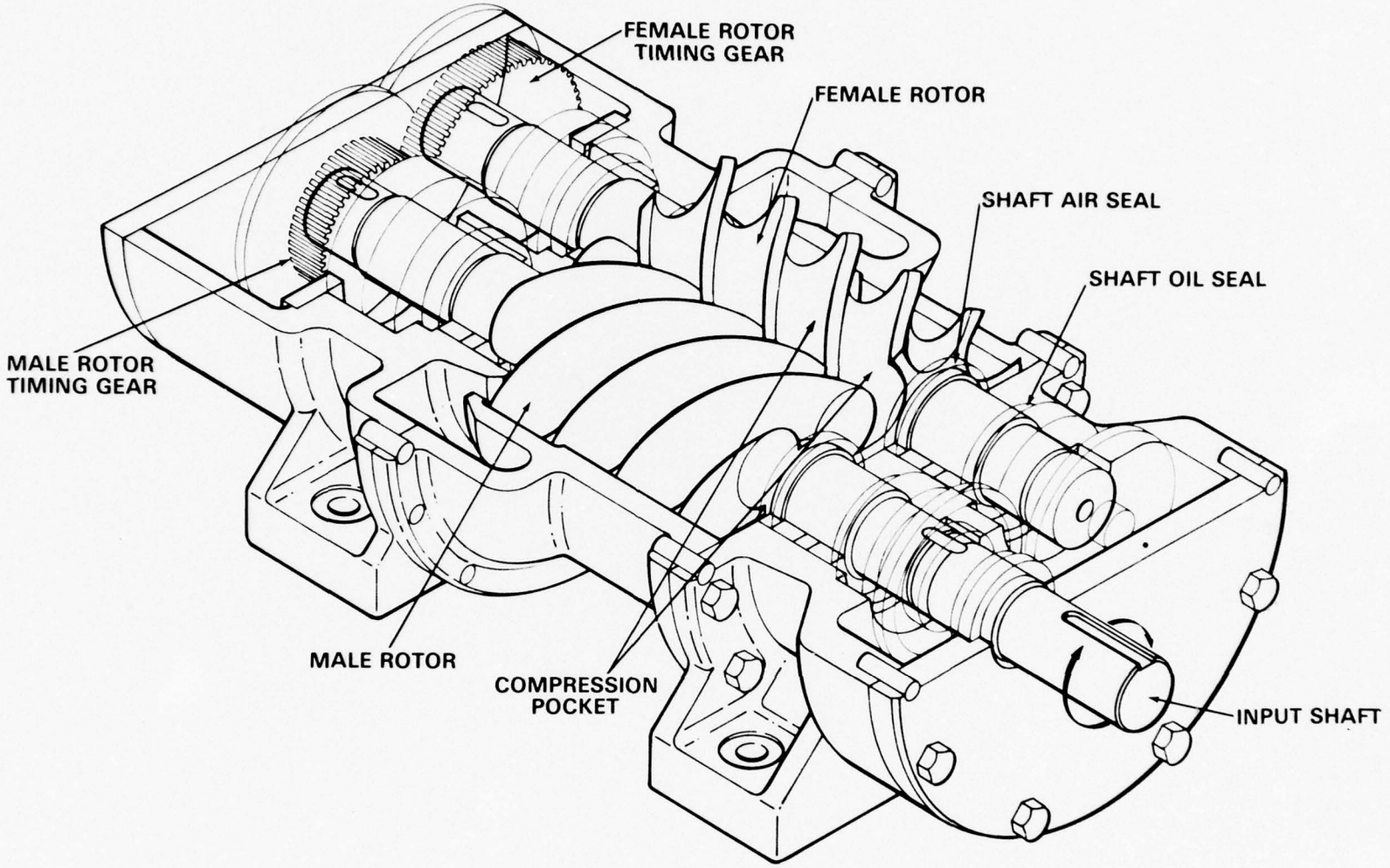

Figure 2

LIFE SUPPORT AIR SAMPLING EQUIPMENT

by

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ABSTRACT

New equipment for obtaining meaningful air samples from compressed air supplies has been developed and is in current use on a number of sampling programs. The system employs a method that lowers the pressure of both HP and LP air supplies to less than three atmospheres absolute pressure, which, in turn, reduces the size and weight of the equipment and containers needed to obtain the samples. The equipment is safe and readily transportable by any mode of transportation including U.S. priority mail and United Parcel Service. Results of 174 diver's air samples taken earlier this year show that about 11% of the air supplies tested were out-of-spec on CO and/or Oil Mist and particulates and that the average off-spec concentration seems dangerously high. A substantial fraction were off on CO_2, but the average off-spec concentration was only 20% high. All air quality problems facing the diving community cannot be identified and controlled by air sampling programs alone. Running time meters, air capacity checks, good maintenance and record keeping, and more are needed to assure that life support air of consistently high quality is delivered to the diver.

1.0 INTRODUCTION

In 1973, a friend and former associate of ours gave a paper before the Divers' Gas Purity Symposium entitled "Sampling and Analysis Methods to Test Breathable Air." The system that Colin Thomas described was basically very well engineered and had an exceedingly wide range of capabilities. It consisted of a filter in a high pressure holder, in series with a high pressure sample bottle, which was connected to a low pressure flow measuring section via a pressure reducing valve. The unit also had a high pressure relief valve and two high pressure ball valves which were used to isolate the sample bottle from the rest of the system when the sampling period was complete. That system was a definite step forward, but it had some disadvantages. It was heavy, expensive to own and expensive to ship; relative to what the diving community perceived were its needs and its ability to pay the bills. The community's perception of its needs were solely to satisfy the requirements of the diving manual, which were (and are) to obtain periodic samples from its compressors and meet a specification on CO, CO_2, O_2 and particulates including oil mist. Last year we undertook an in-house project to develop a system which could be economically employed on a routine sampling program, but which would not sacrifice flexibility.

The first and best idea was to reduce the pressure ahead of the filter instead of downstream of the sample bottle. This reduces weight and hardware costs, and opens up new transportation modes. The next was to convert to all GC and combine several analytical steps for gas analysis, which reduces the volume of air sample needed as well as analytical costs. Finally, the method of obtaining a flow through a sealable sample bottle which is only open on one end, provided a basic gas sampling method with broad applicability.

Our objective in this paper is to describe the equipment in its present form, discuss how it is being used in air sampling programs, what some of the results have been, and indicate that some other air quality control tools are needed if the goal of consistent high quality life support air for diving is to be met.

2.0 DESCRIPTION OF EQUIPMENT

2.1 Basic System

The basic system is presented in Exhibit 1. It consists of an input fitting, in this case a scuba fitting, a particulate filter and holder, a flow measuring section, a gas transfer fitting, a gas sample container, and a muffler for noise control. Exhibit 2 shows a cutaway section which helps illustrate how the system works. Expanding air is introduced at the scuba fitting and passes through the particulate filter into the flow measuring section. A slight back pressure (typically 5-15 psig) created by the orifice is measured by the pressure gage. This back pressure enables us to force air into the gas sample bottle via the air transfer fitting, as well as accurately measure the flow rate of air through the system. The muffler has a thermometer attached to it so that the air flow rate measured can be corrected to standard conditions.

The air transfer fitting has a cupped end to receive the sample bottle. As shown, when the sample bottle is inserted into the fitting, two hypodermic needles attached to the fitting penetrate the septum through an opening in the cap. The septum effects a temporary gas tight seal. The center needle allows air from the flow section to enter the center chamber of the sample bottle and the off-center needle permits air from the outer chamber of the sample bottle to vent to the atmosphere. During the taking of an air sample, air is permitted to flow through the bottle a sufficient length of time to completely purge the tube of its previous contents. The inner chamber of the sample tube is equipped with a float to indicate that the necessary minimum flow rate is obtained. Exhibit 3 shows the glass sample bottles with the sampling cap and the metal foil lined shipping cap, which provides a more permanent seal while the sample is returned to our laboratory for analysis. Exhibit 4 gives a closer view of the air transfer fitting.

2.2 Auxiliary Equipment

As a consequence of taking samples at reduced pressure, the air velocities are many times higher than in high pressure sampling equipment. We have found that with a 47mm filter, flow rates greater than 10 acfm can cause condensed hydrocarbons to be removed from the filter and at greater than 15 acfm the filter can be disintegrated by the air stream if it is loaded with solid particulates. Thus, for flow rates above 8 acfm, we use the deep sea divers fitting, the flow expansion section, and the 90mm filter holder shown in Exhibits 5 and 6 to reduce the air velocity through the filter. As in the basic unit, all the sections are provided with quick lock mechanisms to facilitate easy assembly and disassembly.

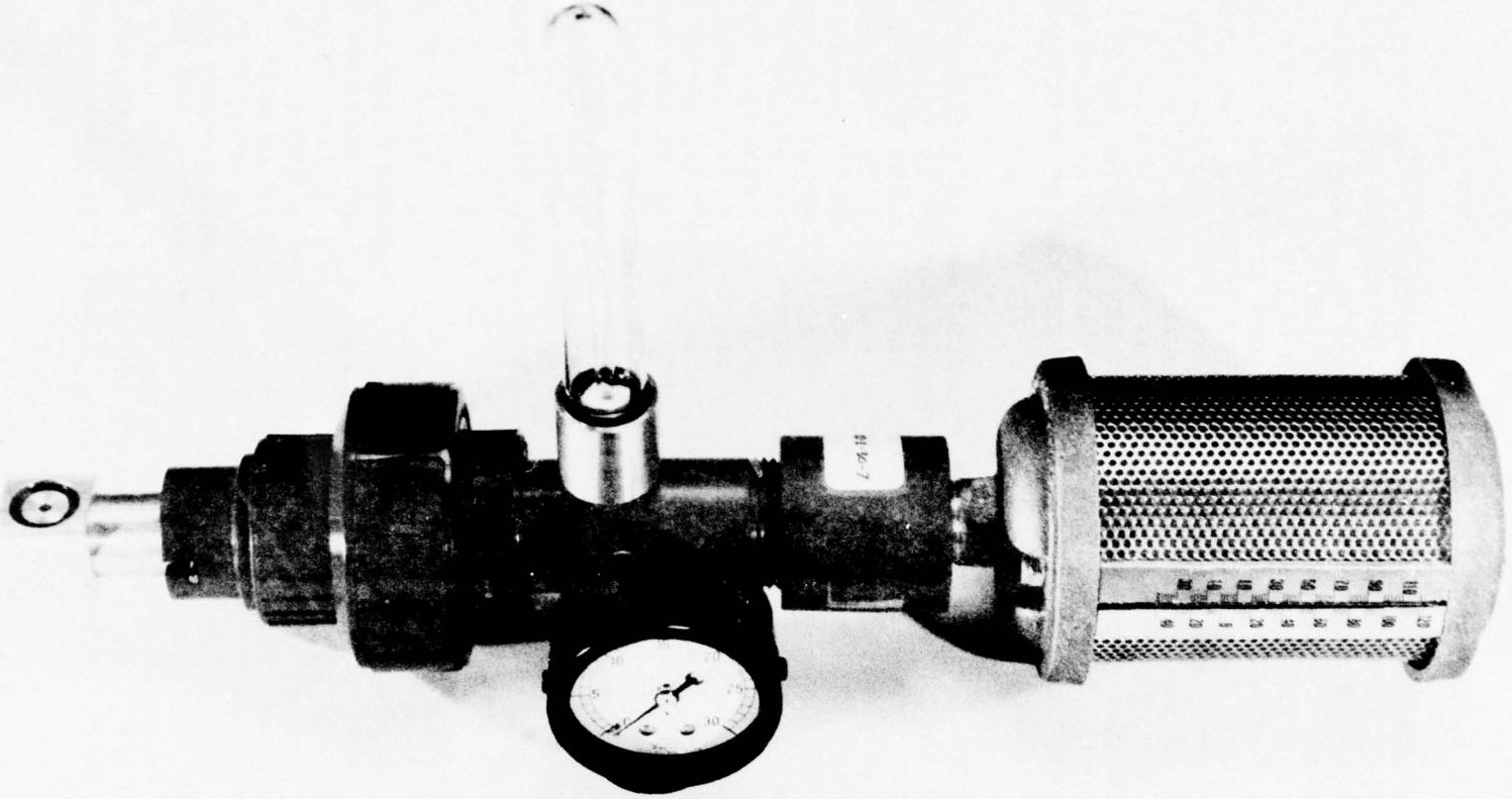

EXHIBIT 1
HP AIR SAMPLING SYSTEM

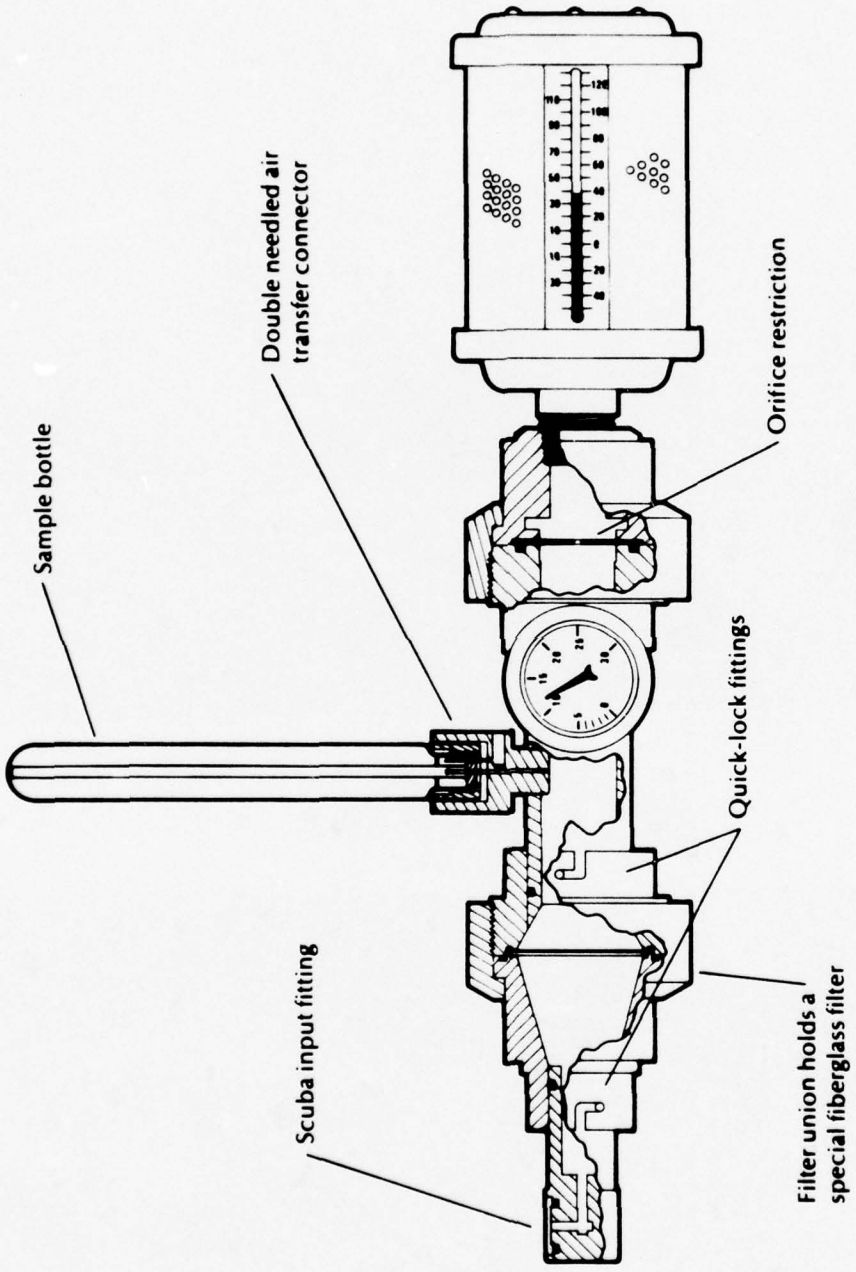

EXHIBIT 2
HP AIR SAMPLING SYSTEM--CUTAWAY

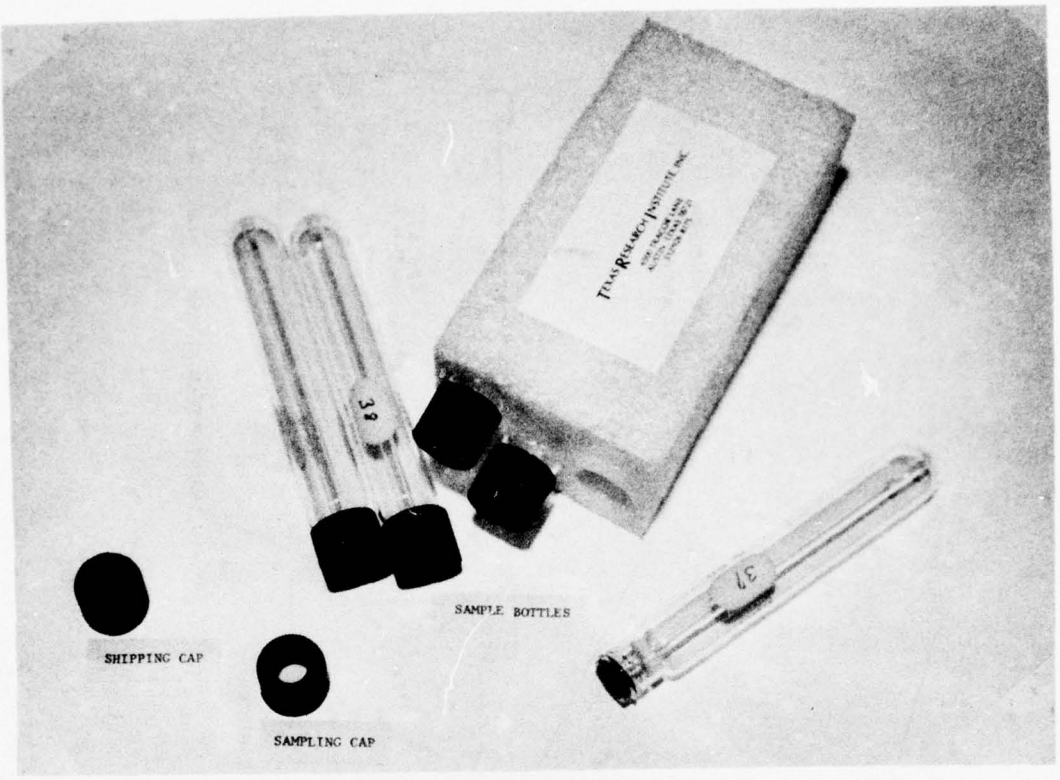

EXHIBIT 3
SAMPLE BOTTLES

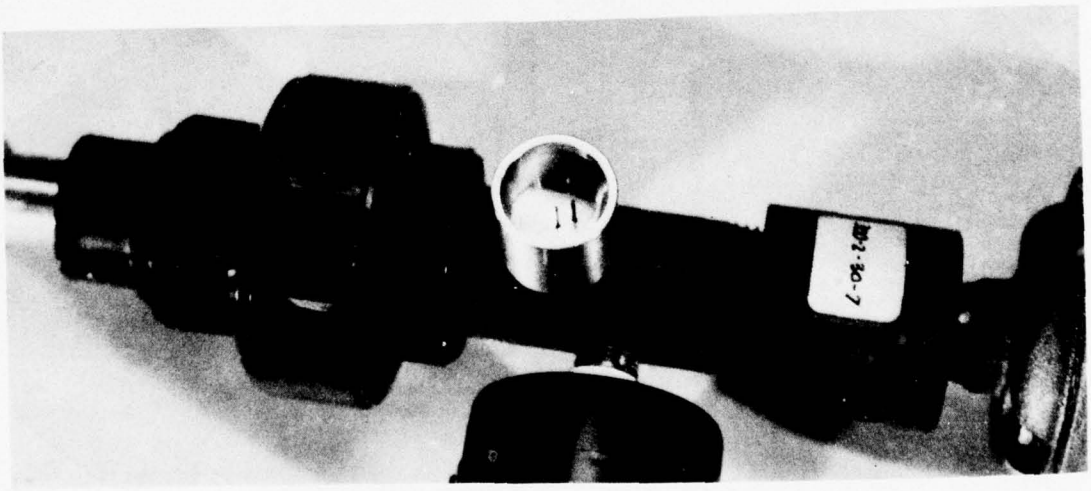

EXHIBIT 4
AIR TRANSFER FITTING

EXHIBIT 5
LP AIR SAMPLING SYSTEM

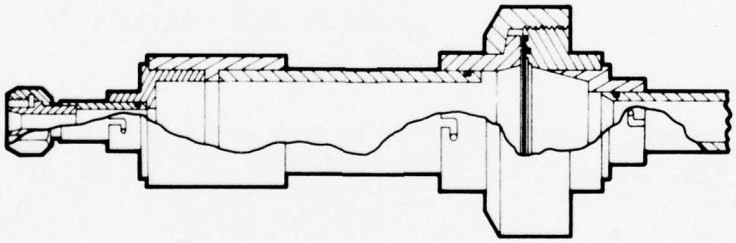

EXHIBIT 6
FLOW EXPANDER CUTAWAY

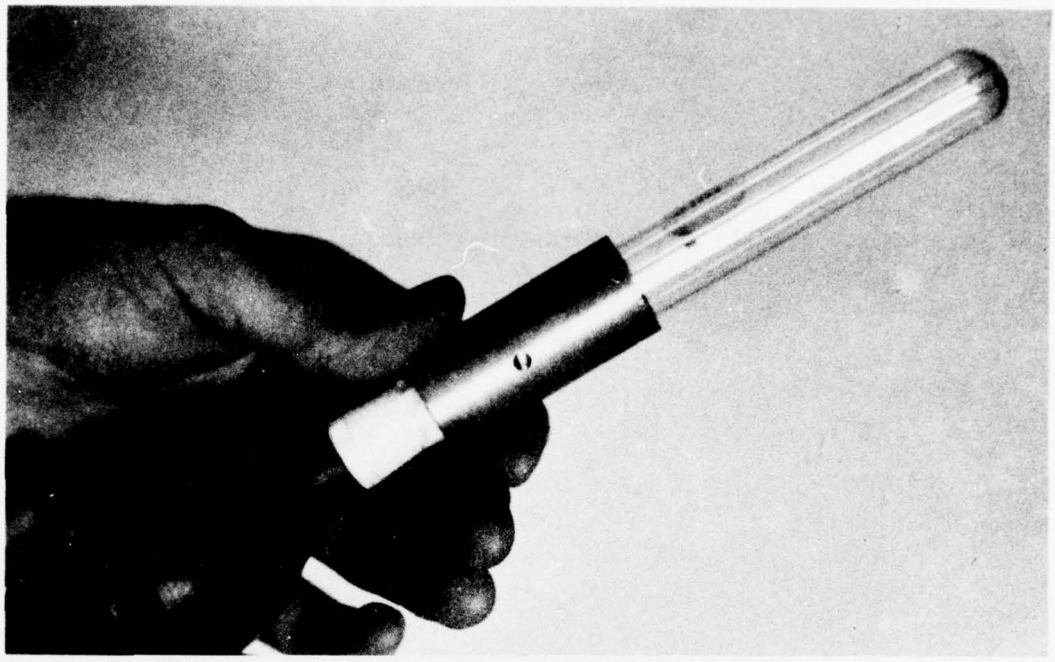

EXHIBIT 7
AMBIENT AIR SAMPLER

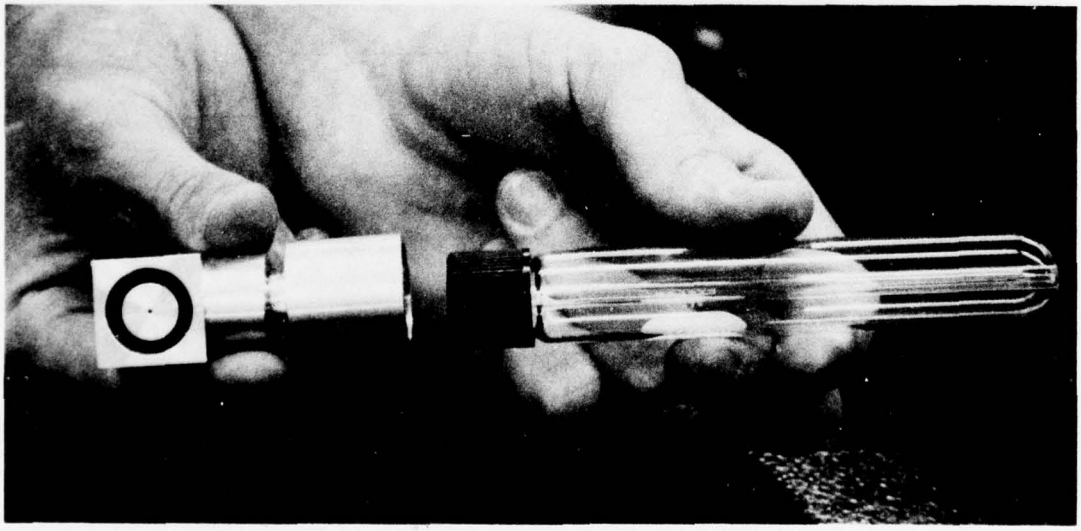

EXHIBIT 8
MINI SAMPLER

In order to provide data for helping to diagnose the origin of an out-of-spec air sample, the ambient air sampler shown in Exhibit 7 is used. We recommend that a sample of air be taken at the compressor intake at the same time the compressor discharge air is sampled. The ambient air transfer fitting is similar to the one that fits on the flow section, except that the center needle is connected to the side port and the air is drawn through the bottle by the rubber vacuum bulb at less than atmospheric pressure. Each pump of the bulb pulls about 50ml of air through the 25ml sample bottle and 8 or 10 pumps is sufficient to obtain a good sample. To minimize the vacuum inside the sample bottle, the bottle is not removed from the sampling device until the float indicates that flow has ceased.

Occasionally, a sample of air without a companion particulate sample is needed. An example of this is when re-checking an air supply known to be out-of-spec only in one or more of the gaseous contaminants. The miniature sampling device we developed for such a need is shown in Exhibit 8. The flow into the sample bottle is limited by the orifice which you can see in the photograph and a vent opening in the side of the scuba fitting which is not visable in the photograph. The orifice and side vent are sized for sampling HP sources, but can also be used for LP sources, by partially blocking the side vent to develop enough pressure to force air through the sample bottle via the needles in the air transfer fitting.

2.3 Safety Features

A number of safety features have been incorporated into the sampling equipment which make it possible to undertake sampling and testing tasks on a wide range of air supplies without fear of damage to the sampling equipment or to personnel.

Control of pressure in the sampling equipment is achieved by a combination of appropriately sized inlet and outlet flow restrictions. The flows through both the inlet and outlet restrictions of the flow section and the inlet and outlet needles of the air transfer fitting are governed by equations of the type:

$$q = 690\ Y C\ d_1^{\,2} \sqrt{\frac{\Delta P P_1}{T_1}} \qquad (1)$$

where
- q = flow rate in scfm
- Y = expansion factor
- C = flow coefficient
- d_1 = nozzle or orifice diameter in inches
- ΔP = pressure drop across the orifice or nozzle, psi
- P_1 = upstream pressure, psia
- T = upstream temperature, ^{o}R

Under steady state conditions the inlet and exit flow rates are equal. Thus

$$Y_1 C_1 d_1^2 \sqrt{\frac{(P_1 - P_2) P_1}{T_1}} = Y_2 C_2 d_2^2 \sqrt{\frac{(\Delta P) P_2}{T_2}} \qquad (2)$$

where subscript ^{1} refers to conditions at or upstream of the inlet restriction. Subscript ^{2} refers to conditions at or upstream of the exit restriction, and ΔP is the pressure drop across the exit restriction.

The input fittings to both the HP and LP versions of the sampling system have restrictions which at high pressures limit the flow rate through the fittings to sonic velocity. This means that at high upstream pressure the flow rate through the fitting depends only on the upstream pressure and temperature. The orifice at the exit end of the sampling system is sized to accommodate the flow at the maximum upstream pressure anticipated without permitting damage to the sampling equipment. With an upstream pressure of 3000 psi, the scuba fitting will pass 25 scfm and with an upstream pressure of 250 psi the deep sea diver's fitting will pass 80 scfm. The companion downstream orifice sizes of .200 and .375 for HP and LP sampling respectively will create a maximum flow section pressure of 30 psig.

The relationship between the diameters or the inlet restriction and the outlet orifice is given approximately by

$$\left(\frac{d_1}{d_2}\right)^2 = K \sqrt{\frac{\Delta P P_2}{P_1}} \qquad (3)$$

where B is barometric pressure and K is a factor combining flow parameters and temperatures for the inlet and outlet openings. The predicted value for K is 1.07 based on published data for nozzles and square edged orifices with corner taps, and assumed isothermal throttling. Experimentally we find that a K of about 1.2 more accurately describes the sampling system. The difference is due primarily to the method of measuring ΔP.

The system is designed such that inadvertent use of an orifice smaller than recommended for the air supply being tested will not be dangerous to personnel. For example, the use of the .200 orifice in place of a .375 orifice will create a pressure in the flow section of about 120 psig if the full 80 scfm is passed by the inlet fitting. This is well within the pressure holding capability of the system, although the gage may suffer some internal damage. The most restrictive orifice plate that is currently supplied with this equipment has a .115 diameter opening, and is recommended for use only on low capacity HP sources. However, because of potential hazards of misuse, the small orifice contains three small rupture diaphragms which provide pressure relief starting at 60 psig.

In sizing the inlet and exhaust needles for the air transfer fitting, equation (2) can be simplified to

$$\left(\frac{d_1}{d_2}\right)^2 = \frac{\sqrt{\Delta P P_2}}{(P_1 - P_2)P_1} \qquad (4)$$

since the parameters of flow for each needle are practically the same. The needle sizes were selected to limit the pressure in the sample bottle to less than 10 psig for a flow section pressure of 30 psig.

While the glass sample bottles have been pressurized to several hundred psi without fracture, due to the possibility of an accidental drop of the bottle, we prefer to eliminate high velocity fragments by limiting the internal pressure of the bottle. Should the exhaust needle become clogged during the taking of a sample, or should an inadvertent overpressurization of the sampling system occur, a second safety feature is provided by the elastomeric septum. Between 17 and 20 psi with the sampling cap in place, the septum will deform, overcoming the restraint of the cap and permit air to escape. With the cap removed, the internal pressure needed to force the septum out of the neck of the bottle is about 10 psig.

2.4 Transportability

One of the biggest problems with previous equipment for taking air samples was transportability. The U.S. Postal Service will not accept pressurized air cylinders for priority mail. Air freight carriers will accept them provided that the proper label is affixed to the outer container, and the appropriate shipper's certifications are submitted. However, air freight is expensive and lacks reliability for other than direct flights. Therefore, if a local laboratory equipped to do the job were not available, the periodic sampling requirement was difficult to meet.

Exhibits 9, 10, and 11 show several kit styles that have been in use for the recent NAVSEA Shipyard and Ship Survey of diver's life support air supplies as well as our continuing commercial programs. Exhibit 12 presents typical round-trip priority mail and United Parcel Service shipping costs to various geographical points from our laboratory. The highest listed cost for zone 8 (Hawaii or Puerto Rico) on a per sample basis is $4.20, which is almost an order of magnitude lower than our previous experience with the heavier metal equipment.

EXHIBIT 9
2HP KIT

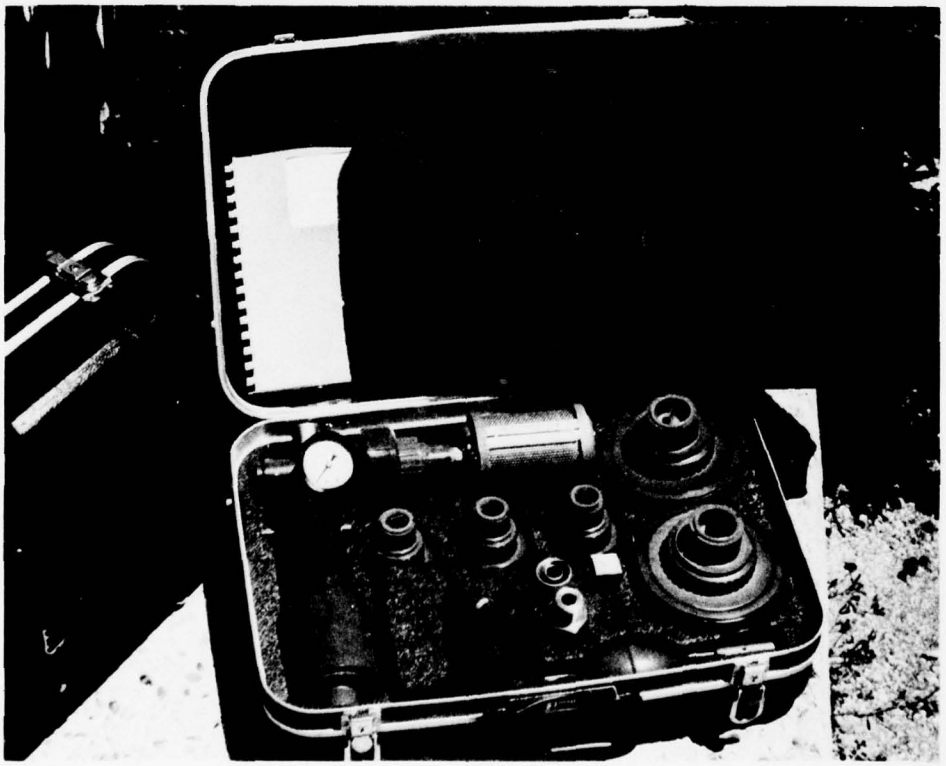

EXHIBIT 10
3HP 2LP KIT

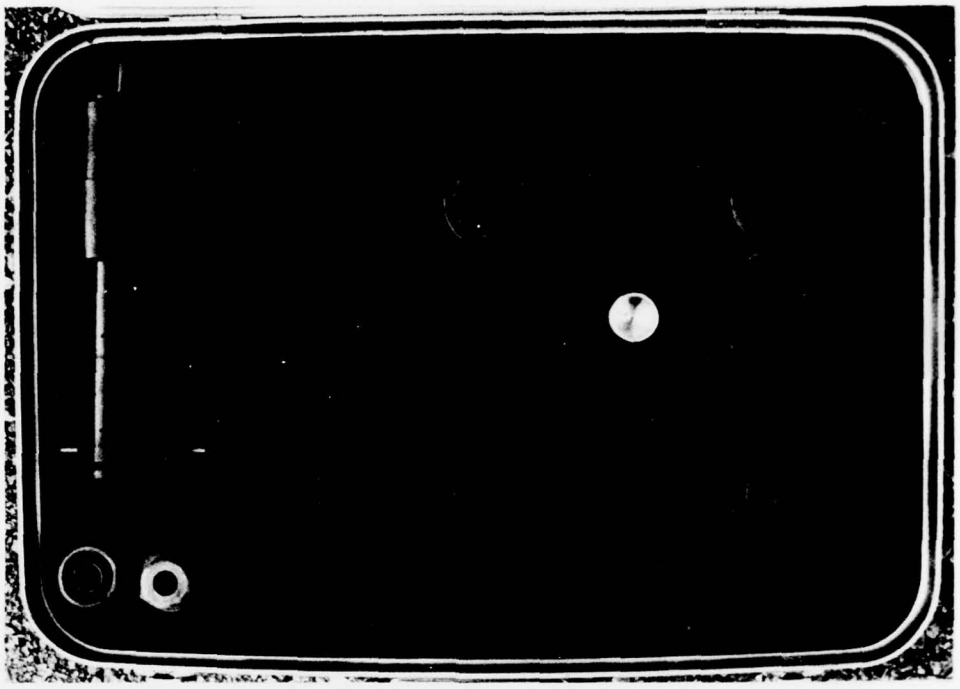

EXHIBIT 11
4LPXE KIT

TRANSPORTATION COSTS FOR SAMPLING EQUIPMENT

Zone	Locations	Kit Size	UPS Round Trip	Priority Mail Round Trip	UPS Out-Priority Mail Back
6	Norfolk	2HP	$2.80	$ 7.12	$ 4.96
	Los Angeles	3HP-2LP	7.14	17.20	12.17
7	Groton	2HF	3.20	7.76	5.48
	San Francisco	3HP-2LP	8.50	19.04	13.77
8	Puerto Rico	2HP	N/A	8.40	N/A
	Hawaii	3HP-2LP	N/A	20.88	N/A

EXHIBIT 12

ANALYSIS OF RESULTS ON LIFE SUPPORT AIR SAMPLING PROGRAMS

	Number of Samples	CO >3 ppm	CO >10 ppm	CO highest	CO_2 >500 ppm	CO_2 >1000 ppm	CH_4 >4 ppm	THC >10 ppm	THC >25 ppm	THC highest	Oil Mist and Particulates >1 $\frac{mg}{sm^3}$	Oil Mist and Particulates >5 $\frac{mg}{sm^3}$	Oil Mist and Particulates highest
Commercial Diver's Air	45	11.1%	4.4%	110ppm	17.8%	0	0	37.8%	4.4%	41ppm	6.7%	2.2%	75 $\frac{mg}{sm^3}$
Ambient Air	44	6.8%	4.5%	510ppm	18.2%	4.5%	4.5%	47.7%	11.4%	36ppm	--	--	--
Naval Shipyards Diver's Air	34	11.8%	5.9%	67ppm	0	0	0	15.2%	3.0%	32ppm	35.4%	5.9%	230 $\frac{mg}{sm^3}$
Ambient Air	25	12.0%	8.0%	58ppm	0	0	0	12.0%	0	18ppm	--	--	--
Naval Ships Diver's Air	79	1.3%	1.3%	85ppm	5.1%	0	0	5.1%	0	9ppm	20.3%	6.3%	73 $\frac{mg}{sm^3}$
Ambient Air	27	0	0	3ppm	29.6%	0	0	7.4%	0	13ppm	--	--	--
UDT & SEAL Teams Diver's Air	16	50.0%	25.0%	142ppm	0	0	0	6.3%	0	11ppm	37.5%	25.0%	20 $\frac{mg}{sm^3}$
Ambient Air	14	35.7%	14.3%	88ppm	0	0	0	0	0	10ppm	--	--	--

EXHIBIT 13

3.0 APPLICATIONS AND DISCUSSION

3.1 Air Sampling

One hundred seventy-four samples from life support air systems have been collected over the first 7½ months of this year using the sampling equipment (or prototypes thereof) described. These samples have been obtained by military personnel; various survey teams made up of NAVSEA civilian, NAVSEA contractor and Navy laboratory personnel; dive shop owners; diving contractors; firefighters and by personnel from TRI's laboratory. Thus, a large number of individuals as well as a wide variety of HP and LP compressors are represented in the information presented in Exhibit 13. Most of the data analyzed were for a single sample from each air supply and most air supplies were for diving. Air samples were generally taken at the diver's manifold or at the scuba charging station. There are several interesting features that can be noted from the tabulation presented. First of all there is a fairly high degree of correlation between gaseous contamination in diver's air and that in ambient air samples. Furthermore, each of the categories of air supplies seems to have distinct chemical characteristics which are related to their respective environments. For example, commercial air supplies which are often in shopping centers have a very high percentage of samples with greater than 500ppm CO_2. This is due to inside intakes, large numbers of people and recirculating air conditioning systems. Compressors located in stock rooms with minimal air circulation probably run hotter and may breathe in self generated gaseous hydrocarbons. Yet the commercial air supplies score best on oil mist and particulates. Is this because of the filtration equipment they use or because they keep back pressures up? If it is filtration equipment, then the elements are not being changed frequently enough to keep gaseous hydrocarbons under control.

The difference between Naval Ships and Naval Shipyards is in carbon monoxide and total hydrocarbons. The lower gaseous contamination level for the ships is probably because of fewer engine driven compressors and less of an industrial type atmosphere. Both ship and shipyard compressed air supplies get lower marks for liquid and solid particulates than the commercial sources. As a slight digression we would like to mention that at this laboratory we take a liberal interpretation of the diving manual specification on oil mist and particulates. A sample is called out only if the combined total of oil mist and other particulate matter exceeds 5mg per standard cubic meter of air.

Although there are only 16 samples listed for the UDT and SEAL Teams, an additional 21 samples analyzed between mid-August and mid-October show the same trend. Those little portable HP

SUMMARY OF OFF-SPEC
AIR RESULTS

Category	% Off-Spec	Average Off-Spec Concentration
CO	5.2%	61 ppm
Particulates	6.9%	40 $\frac{mg}{}$
CO or Particulates	10.9%	
CO_2	6.3%	601 ppm
CO, CO_2 or particulates	16.7%	

EXHIBIT 14

compressors have a problem. Where does one put the intake, how long should it be, and also where are those back pressure controls called for at the last meeting of this symposium three years ago?

Exhibit 14 summarizes the results on off-spec air samples out of the total population of 174 diver's air samples. While 5.2% were out on CO and 6.9% were out on particulates, a few were out on both; so that 10.9% were out on one or the other. It may be significant that although 89% of the air samples have less than 5mg/sm^3 particulates and less than 10ppm carbon monoxide the 11% out-of-spec have average contamination levels that seem dangerously high.

The results on CO_2 suggest that further consideration be given to the specification limit of 500ppm set by the Navy Diving Manual. The average off-spec CO_2 is only 20% over the limit compared to 500% and 700% for CO and particulates respectively. Is the danger of an extra 100 ppm CO_2 commensurate with the cost of re-sampling when it can be shown that too many people were standing around the intake? Should an inside installation be required to have an outside intake which gives the operator even less control over or awareness of other possible air contamination?

3.2 Life Support Air Quality Control

While the air sampling and analysis programs have succeeded in focusing attention on some of the problems in air quality for divers, there are some other tools that have demonstrated or potential value. Running time meters, thermometers and pressure gages are relatively inexpensive, and if used in conjunction with good record keeping, will alert the compressor operator of changes in the mechanical condition of his compressor. Periodic air capacity measurements have value also. It has been our experience that compressors which have suffered a significant loss of capacity deliver a much larger than normal amount of oil to the receiver. Whether or not oil mist is carried on to the diver's manifold or scuba charging station depends on factors such as receiver size, air temperature, time, and relative elevations of the system components. In order to have a useful number with which to compare successive flow capacity checks, especially those made in different seasons of the year, it is necessary to correct the flow rate at constant delivery pressure (steady state) for moisture condensed in intercoolers and in the receiver and for inlet conditions. If these correction factors are not applied, the apparent capacity of a compressor can easily be 5% higher or lower than the true capacity.

Dependable in-line monitors for oil mist and carbon monoxide would be useful for the less reliable air supplies but should not take the place of better training programs or maintenance budgets. As more data become available, we will be applying mathematical tools to the analysis of both the positive and the negative results, and how they correlate with installation, maintenance and operating history.

Air quality control is a worthwhile goal which cannot be achieved by air sampling and analysis alone, although a routine air sampling program is an important tool. The key to consistently high quality life support air as you will hear again at this meeting is the properly designed, constructed, installed, maintained, and operated air compressor. What the compressor operator should have is a basic understanding of his equipment, and practical tools to keep him informed of the most probable condition of his system.

4.0 ACKNOWLEDGEMENTS

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SOME SPECIFIC CASE HISTORIES OF U. S. NAVY BREATHING GAS SYSTEMS CONTAMINATION

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ABSTRACT

A brief look at specific contamination cases which have been encountered in U. S. Navy breathing gas systems. Both particulate and gaseous contamination is discussed. The sources of the contaminants, analysis methods, corrective action and background information is presented. Some overall reasons for these problems are given along with some potential solutions.

INTRODUCTION

During the past few years, Dahlgren Laboratory of the Naval Surface Weapons Center has been directed by the Supervisor of Diving to maintain a fast response sample and analytical capability for divers' breathing gas. This capability is utilized to provide answers to specific contamination problems when normal analysis indicates a problem with a gas source, but does not actually define the problem. For instance, unknown contaminants are often found. This Laboratory maintains a full gas analysis capability as well as the means for determining origins of particulate contaminants. Once the source of contamination has been found, then corrective action can be recommended.

In the performance of this work, several interesting cases of contaminated systems have been found. Reasons for the occurrence of these contaminants, the analytical methods used for their determination, and corrective actions taken are given in the following pages.

CASE I: AIR AND OXYGEN SYSTEMS CONTAMINATED WITH CUPRIC CITRATE

Divers, while conducting chamber qualifications on a Navy submarine rescue ship (ASR) were enveloped in a green fog. A medical attendant in the chamber became ill and required treatment in sick bay where it was discovered that he had copper poisoning. In an effort to determine where the green powder originated, several valves in the thick wall copper system were removed and disassembled. A heavy buildup of bluish-green powder was noticed in these valve bodies. The powder was removed and the system flushed with air. After cleaning and flushing, the system apparently remained clean for only a few weeks when the powder was again noticed. Dahlgren Laboratory was asked to sample the air system, determine the contaminant and, if possible, the cause of the contamination. Gaseous as well as particulate samples were obtained from the various ship's air systems. Several valves were disassembled and the bluish-green powder which had collected there was scraped into sample vials. These samples were returned to Dahlgren Laboratory for analysis. No contaminants were found in the gaseous samples.

Analysis of the bluish-green powder was accomplished by infra-red spectrophotometry. Several copper compounds were synthesized and analyzed on the infra-red spectrophotometer. These analyses showed that the bluish-green powder in the air system was cupric citrate. Dahlgren Laboratory was asked to recommend a way to use the system which would not require expensive recleaning of the entire system.

Installation of particulate filters at each point of use was recommended. This recommendation was implemented and the filters successfully prevented cupric citrate contamination from reaching the user.

It was later determined that the cupric citrate contamination was caused by a system flush which took place during a scheduled shipyard overhaul. An ammonium citrate solution was used to flush the helium, oxygen and air systems. This was followed by a water flush and then dried with nitrogen. The buildup of cupric citrate was evidently caused by some of the citrate solution being left in low lying sections of the piping. The chemical reaction between the copper system and the citrate solution formed the cupric citrate. Over a year later a similar problem became evident in the pure oxygen system. This was corrected by removing the system components and flushing with hot water. Samples were taken and the system was shown to be clean.

In this case, the contamination was actually caused by the ammonium citrate flush which was used to remove other copper compound deposits. The copper system was bright and shiny for a while, until the bluish-green powder started growing. Then a means had to be found to prevent that material from reaching the user without causing further damage to the system.

CASE II: HIGH HYDROCARBON CONTENT IN HIGH PRESSURE AIR FLASKS

After shipyard overhaul, divers on a submarine rescue ship noticed that the divers' air had a very strong offensive odor. The odor was first noticed when they were filling and flushing the high pressure air flasks. The odor seemed to originate in the high pressure air flasks.

Another laboratory went to the ship with a portable gas analyzer. A high total hydrocarbon (THC) content was found in air from most of the banks of air flasks. The portable instrument was able to provide a quantitative but not a qualitative analysis.

Dahlgren Laboratory was asked to obtain air from this system and provide qualitative analysis of the air. While samples were being obtained from these flasks, the overhaul work package documentation was being reviewed to ascertain the source of the contamination. The most likely sources were the primer and/or coating used on the interior of the flasks after they were cleaned. A list of the components in the primer and coating was obtained. Standard concentrations of the hydrocarbons contained in these coatings were made and retention times in a Flame Ionization Detector (FID) equipped gas chromotograph were determined.

Air samples from the flasks were returned to Dahlgren Laboratory for analysis. These analyses determined that the air from the flasks contained methyl isobutyl ketone (MIBK) up to 17 ppm and toluene up to 9 ppm. The THC content was as high as 163 ppm expressed as methane.

The U. S. Navy Bureau of Medicine (BUMED) was consulted to provide the allowable limits of these contaminates; 1 ppm of either was suggested.

The flasks were flushed with air over a period of several weeks. The level of contamination was low when the flasks were first charged but built up again within a few days. Heat was applied to the flasks in an attempt to speed the off gassing and that was also unsuccessful. Air which stayed in the flasks longer than a few days eventually reached a level higher than the BUMED limits. These procedures were repeated several times with the same results.

After these procedures failed, two banks of these flasks were removed from the ship and the coatings were mechanically removed. The flasks were replaced, recharged, and air samples were again taken. The analysis of these last samples showed no trace of MIBK or toluene.

In this case, the contamination was placed into the flasks in the form of a primer and coating. The only way this system could be used to support diving activities was to remove the contaminant. In this case, the flasks finally had to be physically removed and cleaned.

CASE III: CARBON MONOXIDE FROM PORTABLE COMPRESSORS

There have been frequent reports of unacceptable levels of carbon monoxide (CO) in SCUBA tanks charged by gasoline engine driven, portable, high pressure air compressors. Reported contamination sometimes exceeded 100 ppm of CO compared to an acceptable limit of 20 ppm*. The Supervisor of Diving directed Dahlgren Laboratory to establish a test program to determine the cause of the high CO. During the course of these tests, SCUBA tanks were charged 78 times while several variables were monitored. At the beginning of the tests, it was thought that some mechanical defect of the compressor was responsible for the CO contamination.

In the early tests at Dahlgren, the compressors were operated with no particular test plan in mind except to see if the CO contamination could be reproduced. The compressors were set up in a logical orientation with the intake hose stretched upwind of the compressor and the exhaust directed downwind. The first few SCUBA charges produced clean air of less than 10 ppm. However, on the fourth test, one of our relatively inexperienced personnel was instructed to charge SCUBA tanks in the same manner as the previous three. He managed to produce 115 ppm in the SCUBA tank. It was later determined that the compressor had been oriented such that the exhaust was directed upwind into a very light breeze with the compressor inlet hose extended downwind. The operator was further cautioned about improper wind orientation and three more SCUBA tanks were charged with no evidence of CO contamination. The eighth test resulted in 40 ppm CO. This time the compressor was set up in the ideal orientation to the prevailing wind but the wind had shifted to the reverse direction while the SCUBA tank was charged. We began to get suspicious of a major role in the CO problems being played by wind orientation.

While visually checking the compressor, excess oil was noticed in the intake of the compressor. Effects of excess oil in the intake were tested by adding significant quantities of oil to the intake while charging SCUBA tanks. No increase in CO was noticed in these tanks. It was concluded that excess oil in the intake had no effect on the CO level. No detectable CO could be found unless exhaust gases actually entered the compressor inlet.

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*At the time, 20 ppm of carbon monoxide was acceptable.

We did find that compressor design contributed to CO contamination in one area. The particular compressor model tested utilizes a 14 ft. plastic inlet hose which is connected to the compressor inlet at a metal cap which covers the intake valve area. This cap was not sealed to the compressor and some of the surrounding air was being drawn into the compressor through the unsealed interface. The air at the compressor can be either clean or contaminated with exhaust gases, depending on wind conditions and orientation. It is not always easy to keep engine exhaust away from the compressor, particularly when the wind is reversing or near calm. In these conditions, the exhaust may never leave the area of the compressor. We recommended that all intake leaks be positively secured by means such as gaskets and clamps to eliminate this potential problem. After numerous confirming tests, it was concluded that operator error was responsible for the CO contamination which was reported from the fleet.

In this case, the primary cause of contamination was compressor orientation. Proper orientation of the compressor exhaust with the intake hose and wind direction will prevent carbon monoxide from entering the compressor.

DISCUSSION

In summation, it is believed that if the personnel responsible for operation and maintenance of diving systems were more cognizant of approved methods for the performance of these tasks, then less contamination such as discussed here would be encountered.

The Supervisor of Diving has initiated a Navy-wide surface supported diving equipment survey. The survey will indicate areas of weakness in the Navy's diving capability and point the way for improvements to all aspects of Navy diving, the main interest here being gas quality and gas system maintenance.

Another program presently being discussed by the Supervisor of Diving and Dahlgren Laboratory is a comprehensive review of divers' breathing gas system cleaning procedures. The object being to simplify, clarify, and remove ambiguities in the present directives.

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CARBON MONOXIDE INDUCED ALTERATIONS IN PULMONARY ALVEOLAR MACROPHAGES AT AMBIENT AND ELEVATED PRESSURES

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Paper not available at time of printing, but it will be distributed at the Symposium.