THE FEASIBILITY OF ADVANCED CONCEPTS IN SUBMARINE LIFE SUPPORT

by

Frederick Morgen Andrew

B.S., Oceanography, The Catholic
University of America
(1980)

SUBMITTED TO THE DEPARTMENT OF OCEAN
ENGINEERING IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN NAVAL ARCITECTURE
AND MARINE ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1989

Contract: N00228-89-G-0350

Signature of Author ______________________
Department of Ocean Engineering
May, 1989

Certified by ______________________
Paul E. Sullivan
Thesis Supervisor

Accepted by ______________________
A. Douglas Carmichael
Chairman
Departmental Graduate Committee
Department of Ocean Engineering

Best
Available
Copy

THE FEASIBILITY OF ADVANCED CONCEPTS IN SUBMARINE LIFE SUPPORT

by

Frederick Morgen Andrew

Submitted to the Department of Ocean Engineering in May, 1989 in partial fulfillment of the requirements for the degree of Master of Science in Naval Arcitecture and Marine Engineering.

Abstract

A methodology is developed for the evaluation of the use of diving technology as the basis for hyperbaric submarine life support with the goal of reducing the structural weight fraction incurred with great operating depth. Atmospheric life support requirements for normobaric and hyperbaric environments are determined with emphasis on human respiration and the physiological effects of pressure.

The first steps of the methodology are applied to three diving technologies in various stages of development in order to evaluate the maximum, practical depth achievable and any additional mission constraints such a life support system would place on the operation of a submarine. The diving technologies are (1) mixed gas, saturation diving, (2) liquid breathing, and (3) extracorporeal membrane oxygenation.

Mixed gas saturation diving has been employed in hyperbaric chamber dives to depths in excess of 2000ft; however, vertical constraint of such a life support system as a result of decompression effects make this system unsuitable for the subject application. Both liquid breathing and extracorporeal membrane oxygenation would eliminate decompression effects; however, below 600ft, treatment for high pressure nervous system would result in a narcotic induced vertical constraint.

Thesis Supervisor: Paul E. Sullivan
Title: Associate Professor, Naval Architecture

Acknowledgements

I wish to thank Professor E. Cravalho and Dr. J. Venegas of the Massachusetts General Hospital, Biomedical Engineering Department for their assisstance and guidance with respect to the biomedical engineering aspects of this thesis. I also wish to thank Dr. D. Ryan of the Massachusetts General Hospital, Pediatric Surgery Department for the opportunity to see the Neonatal Intensive Care Unit and extracorporeal membrane oxygenation in operation and for his thoughts on the applicability of this technology to diving systems.

The Library staff at the Experimental Diving Unit, Panama City, Florida was most helpful in providing information on the SEALAB experiments. Their time and effort in locating, reproducing, and forwarding documents is greatly appreciated.

Professor Peter B. Bennett of the F.G. Hall Environmental Laboratory, Duke University Medical Center is acknowledged for reprints of recent work in liquid breathing and his supportive comments on the worth of this line of research.

I wish to thank Professor Paul E. Sullivan, the thesis supervisor for this thesis, for the opportunity to pursue this line of research, despite its unusual nature, and for his unswerving enthusiasm and support, despite the author's best attempts to make a painful process even more so.

Finally, I wish to thank my wife for her unending confidence and patience.

Table of Contents

List of Tables 6

1 Accessing the Ocean Environment 7

1.1 Motivation 7

1.2 Method 8

1.2.1 non-exposure 8

1.2.2 indirect exposure 10

1.2.3 direct exposure 11

1.3 Current Trends 13

1.4 A Hybrid Approach 14

1.4.1 description 14

1.4.2 methodology for evaluation 15

2 Life Support Requirements 18

2.1 Definitions and Methodology 18

2.2 General Life Support Requirements 20

2.2.1 atmosphere 21

2.2.1.1 respiration 21

2.2.1.2 contaminants 26

2.3 Physiological Considerations in a Hyperbaric Environment 28

2.3.1 decompression effects 30

2.3.2 narcotic effects 32

2.3.3 toxic concentrations 36

2.3.4 high pressure neurological syndrome . 39

2.3.5 communication 41

2.3.6 heat loss 42

2.3.7 mechanical ventilation resistance . . 44

3 Mixed Gas Saturation Diving 46

3.1 Concept 46

3.2 Components 46

3.3 Limitations 49

4 Liquid Breathing 52
4.1 Concept 52
4.2 Liquid Atmospheres: Characteristics and Issues 53
4.3 Components 58
4.4 Limitations 62

5 Extracorporeal Membrane Oxygenation (ECMO) 64
5.1 Concept 64
5.2 Components 65
5.3 Limitations 66

6 Technical Risk 69
6.1 Mixed Gas Saturation 69
6.2 Liquid Breathing 70
6.3 ECMO 72

7 Cultural Risk 73

8 Conclusions 74

List of Tables

Table I Atmospheric components exclusive of water vapor. 21
Table II Overall reactions of human, aerobic respiration. 22
Table III Acceptable concentration ranges for gaseous components of respiration at 1 ATA total pressure. . . 22
Table IV Power, oxygen flux, and carbon dioxide flux associated with various activities. 23
Table V Example of an activity profile.
. . . . 25
Table VI Lipid solubility and relative narcotic potency of some physicochemically inert gases. 34
Table VII Purity standards for diver's breathing air. 36
Table VIII Typical contaminant exposure limits. . . . 37
Table IX Survival time of mice breathing various hyperbarically oxygenated liquids. 54
Table X Pressure tolerance in fluorocarbon breathing rats at various temperatures. 55

List of Figures

Figure 1 Line diagram of a recycling liquid breathing apparatus. 60
Figure 2 Line diagram of an ECMO based breathing apparatus. 67

1 Accessing the Ocean Environment

1.1 Motivation

The ocean environment covers over 75% of the earth's surface and holds a spectrum of resources which impact every aspect of human endeavor. These resources include mineral wealth, energy and food production, research opportunity in virtually every scientific discipline, and a vast quantity of potentially useful space. Further, the oceans offer global communication and large scale transportation of goods. Ecologically, the oceans produce much of the world's supply of atmospheric oxygen and provide climatic mediation on a planetary scale. All of these resources, physical, sociological, and ecological alike, help provide the impetus which draws humanity into the ever-widening study and exploitation of the ocean environment.

The ability to study and exploit the resources of the oceans is dependent upon the ability to enter, survive, and function in the ocean environment. The design, engineering, and analysis of structures and systems which allow groups of individuals to live and work on and in the ocean, is a major task of the ocean engineer. As the degree to which humanity's involvement and dependence upon the ocean environment increases, so does the demand for systems which operate in increasingly hostile environments. One major aspect of this is the expansion of human activities to greater and greater depths.

1.2 Method

All of the methods used for gaining access to the ocean environment fall into one of three categories. The categories are based upon the degree of personnel exposure and adaptation to the environment required by the life support system. For the purposes of this study the environment may be defined as elevated pressure. The three categories are defined as (a) non-exposure, (b) indirect exposure, (c) and direct exposure.

1.2.1 non-exposure

Non-exposure methods encompass surface tended and remote systems. It is interesting to note that this classification includes both the simplest and most sophisticated methods of accessing the ocean environment at depth. There is no special requirement for life support based upon the conditions of the object environment. The life support problem is limited to the sea surface environment.

In their simplest form, these systems consist of a sampling device, a cable, and a winch and davit combination. Sampling devices are placed singly or in series on the cable, lowered to the desired depth, triggered and recovered. Examples of sampling devices include messenger triggered water collection bottles (e.g. Nansen bottles), bottom grabs, camera and strobe combinations, current meters, sonar arrays, and a large variety of specialized sensors. The cable may provide support alone or be combined with rudimentary data and control transmission elements.

The most sophisticated form of the remote/surface methods is the remotely operated vehicle (ROV) which is currently the object of intense engineering development. In essence, the sampling device has been given propulsion and the operators have been given real time sensing and control capability through a video link. In addition the sampling device is often integrated with a manipulator, giving the operators another level of control.

The primary advantage of both forms is the ability to intervene in a hostile environment without exposing the operators to that environment. The primary disadvantage is related to the remoteness of the object environment and the limitations of the equipment.

Sampling devices and ROV's are extremely specialized pieces of equipment each of which is designed for a limited range of functions. The great variety of ROV's tailored to specific tasks attests to this. Employment flexibility and multiple parameter monitoring and control equate to high development and engineering costs, and complex control equipment. Beyond simple monitoring and sampling functions only the most standardized and repetitive tasks represent cost effective employment of the advanced forms of this technology.

1.2.2 indirect exp

Indirect exposure methods encompass vehicles designed to submerge and carry personnel in a one atmosphere or normobaric environment. These methods include submersibles with limited endurance which require some type of surface support, submarines which are capable of long term missions and are self-supporting, and one atmosphere suits.

In all of these methods life support primarily involves the establishment and maintenance of an artificial atmosphere and climate duplicating the surface environment. Personnel are isolated from the elevated pressure of the object environment by a pressure hull. Physiological adaptation of personnel to any aspect of the object environment is not required.

The chief advantage of these methods is the ability to make real time, direct observations of the environment requiring limited facilities for data transmission. Furthermore, relative independence from surface support adds greater flexibility in terms of object destination.

Although direct observation of the object environment is achieved with these systems, manipulation and engineering type tasks beyond simple monitoring and sampling equate to complex and costly engineering. In the case of submersibles and submarines the volumetric cost of such engineering can be particularly critical.

Another disadvantage of indirect exposure systems is the structural cost of maintaining a 1 ATA bubble at operating depth. This cost and the weight fraction it represents increases dramatically with depth.

1.2.3 direct exposure

Direct exposure methods include all forms of intervention in which the operators are exposed to the ambient pressure of the object environment. Examples include diving systems and habitats.

Life support in these methods involves physiological adaptation of the operators to a hyperbaric environment. As a result, life support engineering is most complex and critical. Pressure induced changes in the requirements for life support must be determined and artificial environments devised to meet those requirements. Transition between normobaric and hyperbaric environments also entails significant engineering effort.

The advantages of direct exposure methods are the elimination of the complex engineering and equipment required to conduct remote observation and manipulation of the object environment. Non-repetitive tasks and unique situations can be handled most effectively through direct intervention of operators. Complex engineering operations requiring multiple degree of freedom manipulation and multiple tasks are often more easily accomplished by an on-scene individual. Real time evaluation of and reaction to unforseen events and circumstances is enhanced with the flexibility of an on-scene operator.

The primary disadvantages of direct exposure include the physical and physiological hazards of hyperbaric environments and the transition from hyperbaric environments to the normobaric environment. For surface supported operations, other disadvantages include the cost and complexity of life support systems and the critical nature of failure of these systems. Finally, the effectiveness of these methods is tempered by the normally unproductive time spent in transition.

Truly revolutionary development of direct exposure technologies must be aimed at mitigating and eliminating the difficulties of transition from the hyperbaric environment to the normobaric environment. The effect of such advances would be unconstrained vertical freedom and the elimination of unproductive transition time.

1.3 Current Trends

The increasing physical and physiological hazards associated with the increasing depth of object environments has favored the intensive development of non-exposure and indirect exposure over direct exposure methods. Liability costs for commercial ventures employing individuals in hazardous environments favor the development non-exposure systems. Physiological complications associated with depths in excess of 600 ft and long decompression schedules make the advantages of direct exposure less attractive.

Standardization industry and emphasis on designs with simple, repetitive construction, assembly , and operation tasks suited for automation has provided the background research and technology necessary to support the development of non-exposure methods. The tasks are being designed to minimize the requirement for those qualities which are the advantages of direct exposure methods.

As the technical ability to project human presence, sensory capability, and interaction improves and the equipment which accomplishes that projection becomes smaller and requires less specialized knowledge to operate, the disadvantages of non-exposure methods dwindle. Development of this ability requires advancement in the technologies of multi-channel data processing and transmission. At the least a major portion of enabling technology cluster for development of this ability is fiber optics and digital microprocessing. These technologies are receiving a major influx of academic, industrial, and monetary support.

The foundation for the advancement of direct exposure methods to greater depths is an improved understanding of human response to hyperbaric pressure and artificial atmospheres. At best this is a slowly advancing front of knowledge because of the hazards involved and the safeguards and costs of animal and human experimentation. This reinforces the emphasis on indirect and non-exposure methods of accessing the ocean environment.

1.4 A Hybrid Approach

1.4.1 description

Expanding dependence and interest in the resources of the ocean environment drive requirements for operating depth increasingly higher. There is a price to be paid, however, for operation at deep depths. In the design of submarines structural weight fraction, structural design, and manufacturing complexity are a function of operating depth. As a result deep submergence submarines suffer from low payload weight fraction and high cost.

The high cost of deep submergence may possibly be avoided by stipulating that the internal atmosphere of a submarine be pressurized. Under this stipulation the test depth of a given structural design is increased by the equivalent depth of maximum internal pressurization. Maximum internal pressurization, in turn, is dependent upon the limitations of diving physiology and the ability of the life support system to adapt to changing physiological requirements. In effect, this approach makes the problem of increasing test depth a function of both structure and life support.

1.4.2 methodology for evaluation

To assess the feasibility of this approach to subsea manned engineering, one must first examine the depth limitations of existing and proposed diving technologies. Next, one must apply these diving technologies to a mission requirement with specified test depth, payload, crew size, and duration. This is accomplished by determining the cost (in terms of weight, space, and power) of a diving technology-based life support system designed to support the mission requirement. A careful evaluation of any additional constraints imposed on the mission profile by such a life support system must also be made.

In conjunction with the diving system assessment one must determine the difference in cost between a structure designed to support the mission requirement at the specified operating depth and one designed for operating depth less the maximum depth of the candidate diving system. This structural cost differential may then be compared with life support cost differential consisting of the cost of the diving technology based-life support system less the cost of a conventional life support system. This comparison coupled with the mission profile constraints forms the basis upon which life support augmented operating depth can be evaluated.

This thesis is primarily concerned with the first steps of this process, that is examination of the limitations of several diving systems and the implications and constraints of diving technology-based life support systems. The candidate diving technologies examined include one which represents the current state of the art, one which is the subject of some limited animal experimentation, and one which is based on the practices and developments of biomedical engineering. It is hoped, in the latter two cases, to develop baseline system descriptions using currently available technology. This should focus attention on those areas requiring further development in order to bring these technologies to maturity.

2 Life Support Requirements

2.1 Definitions and Methodology

One goal of any engineering undertaking involving human exposure to a hostile environment is the establishment and maintenance of a stable, benign, artificial environment. This is the definition of life support.

Life support requirements define an acceptable range for each parameter of the immediate environment which affects the ability of the human machine to survive and function effectively. The criticality of a specific environmental parameter is related to the human tolerance to deviation of that parameter from its acceptable range. In general, this tolerance is directly proportional to the magnitude of the deviation.

Maintenance of the artificial environment depends upon any influences which tend to perturb one or more environmental parameters. In general, a perturbing influence can be quantified as a flux associated with an environmental parameter. Examples of perturbing influences include the object environment, human respiration, and all equipment, materials, and processes within the envelope of the artificial environment.

The complexity of the life support problem is a function of the deviation of the object environment from life support requirements and the quantity of perturbing influences. The endurance of the artificial environment is a function of mission duration, crew size, and the magnitude of other perturbing influences. All of these inputs are derived from the mission requirements either directly or as a result of downstream design decisions.

There are at least two approaches to life support engineering. In the first the artificial environment is constrained within the acceptable range of each of the critical environmental parameters. In the second approach, the life support is engineered on the basis of the effect of the object environment on the acceptable range of each of the critical environmental parameters. The former approach equates to life support for indirect exposure methods such as conventional, one atmosphere submarines. The latter approach equates life support for direct exposure methods, diving technology, for example, in which the acceptable range of the environmental parameters is modified by a hyperbaric environment.

Once the approach has been selected, the process of life support engineering begins with the identification of all critical environmental parameters. These are the parameters of the object environment which deviate from life support requirements by a magnitude sufficient to make the mission duration greater than the tolerance to that specific deviation. This is followed by the identification and determination of the magnitude of all perturbing influences for each critical parameter.

Next, the life support system is designed using the acceptable range (unmodified for indirect exposure or modified for direct exposure) of each critical parameter as set-points. The capacity of the design must be sufficient to balance the sum of perturbing influences of each parameter at any time for the duration of the mission. This is to say that the life support system must be capable of developing a flux equal in magnitude and opposite in sign to the sum of the perturbing influences.

The balance of this chapter deals with the quantitative identification of critical environmental parameters, the associated life support requirements, and the perturbing influence of the human machine in a one atmosphere environment and as modified by a hyperbaric environment.

2.2 General Life Support Requirements

2.2.1 atmosphere

2.2.1.1 respiration

The most critical environmental parameters are associated with atmospheric composition. Small deviations of relatively short duration are capable of impairing function and inducing death. Mission requirements in excess of several minutes continuous submergence exceed human tolerance without some provision for an artificial atmosphere.

Table I Atmospheric components exclusive of water vapor.

Component	Volume%	Component	Volume%
Oxygen	20.946	Krypton	<0.001
Carbon dioxide	0.033	Xenon	<0.001
Nitrogen	78.084	Hydrogen	<0.001
Argon	0.934	Methane	<0.001
Neon	0.002	Nitrous oxide	<0.001
Helium	<0.001		

The atmospheric parameters consist of the concentration of each component of the atmosphere. The composition of the planetary atmosphere is given in Table I. [1] The critical components of this mixture are those that take part in aerobic respiration, oxygen (O_2) and carbon dioxide (CO_2) respectively. Nitrogen (N_2) functions as a diluent by virtue of its large concentration. The remaining components are trace constituents and have no direct effect upon human function in the given concentration at one atmosphere absolute pressure (ATA).

The overall chemical reactions which comprise human, aerobic respiration are shown in Table II. [2] Oxygen is consumed while carbon dioxide is produced. The acceptable concentration range for these components is shown in Table III.

Table II Overall reactions of human, aerobic respiration.

Carbohydrate Oxidation	4.0 cal/g
$C_6H_{12}O_6 + 6O_2 \Rightarrow 6CO_2 + 6H_2O$ Glucose	
Fat Oxidation	9.0 cal/g
$C_{57}H_{104}O_6 + 80O_2 \Rightarrow 57CO_2 + 52H_2O$ Triolein	
Protein Oxidation	4.0 cal/g
$2C_3H_7O_2N + 6O_2 \Rightarrow (NH_2)_2CO + 6CO_2 + 6H_2O$ Alanine Urea	

Table III Acceptable concentration ranges for gaseous components of respiration at 1 ATA total pressure.

	O_2	CO_2
Minimum	16%	0%
Maximum	50%	1%

Respiration is the process by which chemical energy is converted to biological energy. The rate at which reactants are consumed and products are produced is dependent upon the rate at which an individual is expending energy (power). From the information in Table II we can determine the oxygen and carbon dioxide flux for various activities. These values, shown in Table IV, are based upon an average diet in which 45% of the energy expended is derived from carbohydrates, 40% from fats, and 15% from proteins. [2]

Table IV Power, oxygen flux, and carbon dioxide flux associated with various activities.

Activity	E' (cal/hr)	O2' (SCF/hr)	CO2' (lb/hr)
sleeping	65	-0.48	0.05
lying awake	77	-0.57	0.06
sitting,rest	100	-0.74	0.08
standing,relaxed	105	-0.78	0.08
dressing	118	-0.88	0.09
typing	140	-1.04	0.11
light exercise	170	-1.27	0.13
walking, slow	200	-1.49	0.16
light industrial activity	240	-1.79	0.19
active exercise	290	-2.16	0.23
severe exercise	450	-3.35	0.35
swimming	500	-3.72	0.39
running	570	-4.24	0.44
very severe exercise	600	-4.47	0.47
walking, fast	650	-4.84	0.50
walking, upstairs	1100	-8.19	0.85

Notes: (1) E' = Power
(2) O2' = oxygen flux
(4) CO2' = carbon dioxide flux
(5) SCF = Surface Cubic Feet (volume of gas at 1 ATA)

The direct relationship between power and the flux of respiration reactants and products is an important tool for sizing the life support system. The primary input to the tool is an individual activity profile. The activity profile consists of a listing of activities weighted by the amount of time the individual engages in that activity. The profile must cover a meaningful, periodic cycle for the individual, such as a day.

Since each of the activities is equivalent to an oxygen and carbon dioxide flux, the flux associated with that activity for a cycle may be calculated by multiplying the weighting factor by the activity flux.

$$F_{(O2)i} = W_i(O_2')_i$$

$$F_{(CO2)i} = W_i(CO_2')_i$$

Where: $F_{(O2)i}$ = Quantity of oxygen consumed during a cycle as a result of activity i.

$F_{(CO2)i}$ = Quantity of carbon dioxide produced during a cycle as a result of activity i.

W_i = Duration of activity i.

$(O_2')_i$ = Oxygen flux associated with activity i.

$(CO_2')_i$ = Carbon dioxide flux associated with activity i.

Summing the weighted fluxes over all of the activities, we obtain oxygen consumption and carbon dioxide consumption for an individual during a single cycle. Dividing these quantities by the duration of the cycle gives us the average flux for an individual for a cycle.

$$F_{(O2)t}/D_c = O_2{}'_{av}$$

$$F_{(CO2)t}/D_c = CO_2{}'_{av}$$

Where: D_c = Duration of a cycle.

$F_{(O2)t}$ = Total oxygen flux for a cycle.

$F_{(CO2)t}$ = Total carbon dioxide flux for a cycle.

$O_2{}'_{av}$ = Average oxygen flux.

$CO_2{}'_{av}$ = Average carbon dioxide flux.

These values represent the average life support load resulting from the respiration of one individual over one cycle. An example of an individual activity profile and the calculation of the average fluxes is shown in Table V.

If the activity profile represents an average for the entire crew, the total respiration load for a mission can be calculated by multiplying the average flux by the number of embarked personnel and the number of cycles in the mission.

To this point we have determined the atmospheric requirements based upon the needs of human respiration. We

Table V Example of an activity profile.

Activity	W (hr/day)	F(O2)i (SCF/day)	F(CO2)i (lb/day)
sleeping	8	-3.87	0.40
sitting, rest	2	-1.49	0.16
standing, relaxed	4	-3.13	0.33
dressing	1	-0.88	0.09
typing	2	-2.08	0.22
light exercise	3	-3.80	0.40
light industrial activity	2	-3.57	0.37
active exercise	2	-4.32	0.45
	24	F(O2)t	F(CO2)t
		-23.14	2.41
		O2'av (SCF/hr)	CO2'av (lb/hr)
		-1.0	0.1

have also developed a tool for determining the flux resulting from human respiration as a function of personnel activity. This tool can be used to determine the average and limiting fluxes, and the total quantities of oxygen and carbon dioxide a life support system must accommodate, given specified crew size and endurance.

2.2.1.2 contaminants

The remainder of the life support problem, with respect to atmospheric composition, concerns the elimination of contaminants resulting from materials and processes within the envelope of the artificial environment. The contaminants take the form of particulate matter, aerosols, and gaseous species. Human tolerance to these contaminants is a function of concentration of the contaminant and the duration of exposure.

A large number of contaminants are hydrocarbons and the products of incomplete combustion. Carbon monoxide is, perhaps, one of the most dangerous of this category since it interrupts the transportation of oxygen throughout the body.

Another large category of contaminants includes petroleum distillates and halogenated hydrocarbons which are used in solvents and refrigeration systems.

Determining the effect of many of these contaminants is difficult as study of low concentration exposure may require decades of exposure duration to elicit results. Elimination of all such contaminants represents the prudent goal of any exercise in life support engineering. Unfortunately, the wide variety of materials and processes used in the construction and operation of ship systems at sea precludes the total elimination of all contaminants.

The quantification of contaminants is specific to the size and mission of the artificial environment. Once the specific contaminants and their flux has been identified the capacity of the equipment required to bring about their elimination is in hand. Currently employed technologies for the elimination of contaminants include (1) activated charcoal filters for the elimination of hydrocarbons, (2) electrostatic dust precipitators for the elimination of particulate matter and aerosols, and (3) catalytic burners for the elimination of the products of incomplete combustion such as carbon monoxide.

In order to present a complete picture of long term life support one must examine each of the following topics in much the same way we have examine the issues of atmosphere:

(1) climate

(2) nutrition

(3) waste management

As the bulk of this thesis is concerned with meeting the atmospheric requirements for human aerobic respiration, these topics are deemed beyond the scope of this thesis.

2.3 Physiological Considerations in a Hyperbaric Environment

To assess the feasibility of the use of diving technologies in submarine life support, one must understand the physiological effects of a hyperbaric environment. The ultimate cause of the majority of these effects can be traced to the compressibility of gases as expressed by Boyle's, Dalton's, and Henry's laws of ideal gases: [3]

1. <u>Boyle's law</u>. At a constant temperature the volume of a perfect gas varies inversely as the pressure.

$$PV = K$$

Where: P = absolute pressure

V = volume

K = constant

2. <u>Dalton's law</u>. In a mixture of gases the pressure exerted by one of those gases (the partial pressure of that gas) is the same as it would exert if it alone occupied the same volume.

$$P_i = F_i P_t$$

Where: P_i = partial pressure of the i^{th} component of the gas mixture

F_i = volume fraction of the i^{th} component of the gas mixture

P_t = absolute pressure of the environment

3. <u>Henry's law</u>. At a constant temperature, the amount of a gas which dissolves in a liquid, with which it is in contact, is proportional to the partial pressure of that gas.

$$C_i = a_i P_i$$

Where: C_i = concentration of i^{th} component of gas mixture dissolved in liquid phase.

a_i = absorption constant of the i^{th} component of the gas mixture in a specified liquid.

P_i = partial pressure of the i^{th} component of the gas mixture

The major implications of these laws , given constant gas mixture composition, are (1) the elevated density of the hyperbaric atmosphere and (2) the elevated concentration of dissolved gases in any liquid phase within the hyperbaric environment. If we model the human body as an air space (respiratory system) in contact with a liquid phase (bodily fluids and tissues), it is evident that an individual in a hyperbaric environment will have an elevated concentration of dissolved gases in bodily fluids and tissues. The actual concentration of dissolved gases in bodily fluids and tissues is a function of gas mixture composition, total pressure, and duration of exposure to the hyperbaric environment.

2.3.1 decompression effects

Decompression is a decrease in environmental pressure. The transition from a hyperbaric environment to a normobaric environment is an example. Decompression involves two pertinent effects based upon the gas laws quoted above. The first is an expansion of the gas mixture within the environment. The second is a decrease in the solubility of the atmospheric components in the fluids and tissues of the body.

The effect of gas expansion is a problem only if the air spaces of the body do not remain open to the environment during decompression. In general the tissue which makes up these air spaces is not capable of withstanding a pressure differential. Unless the air spaces are vented, tissue damage will result. This condition is called barotrauma. The severity of the injury is dependent upon the nature of the tissue affected. [3]

The decrease in solubility of atmospheric components in the fluids and tissues of the body can lead to decompression sickness, the most common form of which is the bends. As the pressure decreases, the solution of dissolved gases in the blood and tissues can become supersaturated. That is, the actual concentration of dissolved gases becomes greater than the solubility of those gases in the blood and tissues. Current decompression theory holds that when the supersaturation, measured in atmospheres, reaches a critical level bubbles will begin to form about gas nuclei. The composition of the bubbles includes all gases in the breathing mixture; however, the major constituent is the diluent, nitrogen in the case of air. The formation of these bubbles and their effect upon the tissues of the body is decompression sickness. [4]

The actual value of this threshold supersaturation is inversely dependent on the size of the gas nuclei. In vitro experimentation has shown that the threshold supersaturation can be increased, delaying the onset of bubble formation, by filtration or repeated exposure to pressure. Both processes effectively eliminate the populations of larger gas nuclei. These results suggest an explanation for the phenomenon of adaptation, decreased susceptibility to decompression sickness with regular exposure to pressure. [4]

In order to avoid decompression sickness the rate of ascent must be controlled so that the level of supersaturation does not exceed the threshold for bubble formation. This allows excess quantities of dissolved gas to leave solution harmlessly at the lungs. Ascent control is accomplished through the use of decompression tables. Inputs to the tables consist of breathing gas composition, bottom time (duration of dive, departure from surface to start of ascent), and maximum depth of dive. The output from the tables is a decompression schedule which prescribes decompression stops in terms of depth and duration.

2.3.2 narcotic effects

The elevated concentrations of inert and trace components of the breathing mixture resulting from exposure to a hyperbaric environment can produce effects not attributed to those components in a normobaric environment. Chief among these is the rapture of the deep or nitrogen narcosis.

Nitrogen narcosis represents the first physiological depth limitation encountered in the development of diving technology. Decompression sickness, although a hazard, did not pose a restriction on depth by affecting the function of the diver at depth.

Early observations in compressed air working environments revealed an anesthetic effect variously described as 'semi-loss of consciousness,' 'slowing of the process of cerebration,'and 'activated functions of the brain.' This effect was eventually attributed to nitrogen, found to be directly related to depth, and subject to a wide variation in individual susceptibility. Subsequent work quantified the effect, revealed additional contributory factors including (1) fatigue, (2) alcohol, (3) anxiety, (4) carbon dioxide concentration, and (5) emotional stability, and described adaptation as a result of repetitive exposure to pressure. [5]

Quantification of the narcotic effect of nitrogen has been based upon many forms of performance tests including physical dexterity, mental/arithmetic agility, reasoning, eye-hand coordination, and combinations of the above. The body of research on the subject holds that the threshold level for the effect is a 3.2 ATA partial pressure of nitrogen, the equivalent of 100 ft of depth, although individual susceptibility can show symptoms of the effect at significantly shallower depths. The effective limiting depth for compressed air diving as a result of nitrogen induced functional impairment is widely held to be 300 ft (8 ATA partial pressure of nitrogen). Studies beyond 300 ft show severe reduction in all categories of performance testing and symptoms normally attributed to psychoactive drugs. [5] [3]

Gases other than nitrogen elicit narcotic response as a function of partial pressure. Relative potency of some gases is shown in Table VI.

Table VI Lipid solubility and relative narcotic potency of some physiochemically inert gases.

Gas	Lipid Solubility	Relative Narcotic Potency
		(least narcotic)
Helium	0.015	4.26
Hydrogen	0.036	1.83
Nitrogen	0.067	1
Argon	0.14	0.43
Krypton	0.43	0.14
Xenon	1.7	0.039
		(most narcotic)

There are many theoretical models which attempt to explain the mechanism of this response. Experimental data shows a strong correlation between lipid solubility and the narcotic potency of gases. In addition, narcotic response, given a constant partial pressure of the anesthetic, is subject to pressure reversal. Increased environmental pressure negates the narcotic response. This supports the view that the mechanism of anesthesia is related to cellular membrane expansion in the central nervous system, since the primary constituent of cellular membranes is lipids. [3] [5]

The method used to avoid the narcotic effect of nitrogen at all depths and access depths beyond 300 ft involves the reduction or replacement of nitrogen in the breathing mixture with a less narcotic gas. This is accomplished by enriching the oxygen content and/or introducing another diluent in the breathing mixture. Although extensive experimentation has been done with each of the gases in Table VI, Helium is almost universally employed in this role. The first operational use of helium occurred during the salvage of the U.S.S. Squalus conducted by the U.S. Navy in 1939. [6]

There is an additional advantage to the use of helium in the breathing mixture which is a result of its relatively small molecular size. Helium diffuses into and out of solution much more rapidly than nitrogen. For long duration dives this implies a reduction in the decompression schedule. This advantage is minimized in short duration dives where rapid diffusion of helium into solution dominates. The reduction in decompression schedule first aroused interest in the use of helium as a diving gas. [3]

2.3.3 toxic concentrations

The presence of contaminants in the breathing mixture is increasingly detrimental with increasing depth. This is due to the hyperbaric concentration of breathing mixture components. In much the same way as nitrogen may be rendered narcotic while maintaining a normal atmospheric percent composition, many contaminants may reach toxic concentration levels while maintaining safe percentage composition for normobaric environments. The solution to this problem is a strict control over diver's air purity. Such control is maintained through diver's breathing air purity standards established by the U.S.

Table VII Purity standards for diver's breathing air.

Oxygen	20-22% by volume
Carbon dioxide	300-500 ppm (0.03-0.05%) by volume
Carbon monoxide	20 ppm maximum
Oil mist and vapor	5 mg/m
Solid and liquid particles	not detectable except as listed above

Navy. The purity standards are shown in Table VII. [3]

In general the standards cover such contaminants as might result from improper handling of compressed gas cylinders or air compressors. Such contaminants include (1) products of incomplete combustion of hydrocarbons, (2) oil mist, (3) oxides of nitrogen, and (4) gaseous hydrocarbons. If diving technology is to be used in conjunction with long term submarine missions the list of contaminants must be expanded to include gaseous and airborne components resulting from industrial and human activity within the artificial environment. Categories of materials which must be considered include (1) petroleum distillates, (2) halogenated hydrocarbons, (3) by-products of human respiration, and (4) various sulfur compounds. [3]

Toxic response is a function of the concentration of the contaminant and duration of exposure. Any listing of contaminant concentration limitations should indicate the duration to which those exposures apply. A partial listing of contaminant concentration limits based upon an 8 hr work day and a 40 hr work week is shown in Table VIII. The table values are based upon exposure in a normobaric environment.

In addition to contaminants one must consider the toxic effects of oxygen. Above a partial pressure of 0.5 ATA chronic oxygen toxicity becomes evident after an exposure period of as little as a few hours. This figure indicates that a atmosphere consisting of compressed air is toxic at a depth of 46 ft. It has already been indicated that the limit to compressed air diving is effectively 300 ft as a result of nitrogen narcosis.

Table VIII Typical contaminant exposure limits.

Substance	8-hr weighted Average Limit (ppm)
Ammonia	50
Carbon dioxide	5000
Carbon monoxide	50
Freon-12	1000
Hydrogen fluoride	3
Nitric oxide	25
Nitrogen Dioxide	5
Ozone	0.1
Phosgene	0.1
Stibene	0.1
Sulfur dioxide	5

The reason for this apparent disparity is the issue of duration of exposure. While 0.5 ATA oxygen is toxic in the long term, short term exposures of up to 2 ATA oxygen can be tolerated by most people without ill effect. Since most dives are of short duration relative to the onset of oxygen toxicity, the higher levels of oxygen concentration resulting from compressed air dives are not a problem. The limitation of 0.5 ATA oxygen is necessary when contemplating long durations at pressure.

In general oxygen toxicity is avoided in long duration hyperbaric exposures by establishing an artificial atmosphere with an oxygen partial pressure near that of a normobaric environment. The balance of pressure to ambient is attained with the designated diluent, which may be nitrogen, helium, or a combination of the two.

2.3.4 high pressure neurological syndrome

The use of helium in breathing mixtures extended the effective range of diving operations below 300 ft by removing the problem of narcosis and shortening decompression times. Estimates based upon the lipid solubility model of inert gas narcosis predicted the onset of helium narcosis and thus limited of helium oxygen dives to 1400 ft. [7]

The 1400 ft prediction broke down in the mid 1960's when personnel participating in hyperbaric chamber dives to 600 ft and beyond began to show symptoms of what was later to be called high pressure nervous syndrome (HPNS). HPNS is characterized by tremors, dizziness, nausea, vomiting, and marked changes in brain waves. The appearance of the symptoms was shown to be related to hydrostatic pressure and rate of compression. Animal studies indicated that the extreme result of HPNS is convulsions. [3]

The first efforts to correct HPNS were based upon reduced compression rates. Over a large number of chamber dives this approach was found to be effective to depths on the order of 1400 ft. Between 1400 and 1800 ft. severely incapacitating HPNS was generally noted. Although greater depths were successfully reached using this approach, the compression rates employed were prohibitively slow and varying degrees of HPNS were induced in the participants. [7]

Further efforts to correct HPNS took advantage of the apparent antagonism between hydrostatic pressure and narcosis. Much of the work in this area was conducted by Peter Bennett, currently the Director of the F.G. Hall Environmental Laboratory, Duke Medical Center. [7]

In essence, gaseous narcotic agents, such as nitrogen, were found to cause an expansion in cellular membranes due to their solubility in lipids. The application of hydrostatic pressure was found to reverse the effects of a specific dosage of a narcotic agent. This evidence supported the model of membrane expansion as the mechanism for narcosis. [5]

Helium, on the other hand, elicited no expansion in cellular membranes. It was reasoned that the symptoms and onset of HPNS might be the result of membrane contraction due to hydrostatic pressure. Following this reasoning, if a sufficient amount of narcotic agent were added to the breathing mixture to exactly counteract the pressure induced membrane contraction, then the net change in membrane area would be zero and both narcosis and HPNS would be eliminated. [7]

Calculations by Bennett indicated that a breathing mixture containing 10% nitrogen would be effective at eliminating HPNS without inducing narcosis. Experiments were conducted using breathing mixtures containing various percentages of nitrogen by a number of investigators. All showed a vast improvement over helium oxygen mixtures. One particular study, the Atlantis series of chamber dives conducted at Duke, culminated in a simulated (hyperbaric chamber) dive to 2250 ft with no symptoms of HPNS. [7]

2.3.5 communication

Communication is degraded by 2 factors in hyperbaric environments. The first is the increase in density of the breathing mixture. It is estimated that a loss of approximately 4% of intelligibility is incurred for each additional 1 ATA increase in pressure as a result of the increased density of the breathing mixture. [3]

The second factor involved in communication degradation is the introduction of helium in the breathing mixture. The characteristics of helium alter the speed of sound in the breathing mixture. This results in an upward shift in frequency and a subjective acceleration of speech, the so-called "Donald Duck effect." [3]

Some adaptation to communication degradation has been noted. Over a period of time intelligibility improves as a result of direct feedback to the individual. Furthermore, equipment based upon three processes is available in various stages of development to help alleviate the effects of helium. The three processes are (1) heterodyning, (2) vocodering, and (3) time-domain processing. Additional work in this area is required to eliminate hyperbaric vocal distortion. [3]

2.3.6 heat loss

Heat loss is expressed in terms of a balance between metabolic heat production (M) and heat dissipation to the environment. Heat dissipation is broken down into four terms, skin convection (C_s), respiratory tract convection (C_r), evaporation (E), and radiative heat transfer to the environment (R). When the magnitudes of the metabolic heat production and the sum of the heat dissipation terms are equal, the body is in thermal equilibrium with the environment and a steady state body temperature is maintained. When the magnitudes are not equal the difference, heat storage (S) results in a rise or fall of body temperature. The terms described above are usually expressed in units of W/m^2. The thermal balance is described by the following equation. [3]

$$M + S = C_s + C_r + E + R$$

Skin convection is a function of the convective conductance of the atmosphere (h_c), the difference between average skin temperature and ambient temperature ($T_s - T_a$), and surface area of the body (A). Respiratory tract convection is a function of breathing mixture density and specific heat capacity, ventilation rate, and the difference between the exhaled breathing mixture temperature and ambient temperature. [3]

Atmospheric convective conductance is an exponential function of environmental pressure (P). [3]

$$h_c = 1.08P^{0.39}$$

The above relationship, the high thermal conductivity of helium relative to nitrogen, and the dependence of respiratory tract convection on breathing mixture density imply an increase in heat dissipation in hyperbaric, helium-rich atmospheres. The only practical way to avoide the increase in heat dissipation is to decrease the temperature gradient that drives the heat transfer. This equates to maintaining a higher ambient temperature in the hyperbaric environment as opposed to the normobaric environment. [3]

2.3.7 mechanical ventilation resistance

The mechanical ventilation resistance, the work of breathing, is the limiting factor to the amount of useful work that can be accomplished in a hyperbaric environment. Resistance to flow is directly proportional to the density of the breathing mixture. Since increasing depth equates to increasing breathing mixture density, the ventilation resistance is directly proportional to depth. [3]

Resistance to flow also increases with velocity of flow. Since the velocity of flow or flow rate is proportional to the activity level of the individual, ventilation resistance increases with activity level. Once the flow becomes turbulent, resistance is related to the square of the velocity of flow. So, at higher activity levels, as the ventilation rate increases, the work required to maintain that ventilation rate increases exponentially. [3]

The effect of breathing mixture composition must be considered. Helium is approximately one seventh the density of air. An 80% helium-20% oxygen breathing mixture is approximately one third the density of air. At any given depth a helium oxygen breathing mixture is proportionately easier to breath than air. Furthermore, the lower density of the helium oxygen breathing mixture delays the transition to turbulent flow to a higher ventilation rate. As a result, the helium oxygen breathing mixture can support higher activity levels than air at a given depth. [3]

3 Mixed Gas Saturation Diving

3.1 Concept

The current state of the art of diving technology is mixed gas saturation diving. It is based upon the concept that at any given depth the amount of dissolved gases in the bodily fluids and tissues will increase until saturation for that depth is achieved. In general, it is assumed that this occurs in approximately 24 hours at depth. Once saturation is achieved the duration at depth can be extended indefinitely without incurring additional decompression time.

The advantage to this concept applies to long term tasks and expeditions. By keeping a diving team at pressure, either in a habitat at the worksite or in a deck decompression chamber on the surface, lengthy decompression after each planned dive may be avoided. A single decompression upon completion of the task the is all that is required.

The concept of mixed gas saturation diving was developed and researched by Captain George F. Bond, MC, USN. His experiments culminated in the U.S. Navy's SEALAB experiments in underwater habitat living.

3.2 Components

The primary component for a saturation life support system is the breathing mixture. It must be tailored to the depth of the object environment in accordance with the information provided in the previous chapter. Oxygen must be provided within the range of 0.2-0.5 ATA to avoid hypoxia and oxygen toxicity. The balance of ambient pressure must be made up of nitrogen, helium, or a combination of the two depending upon depth. Navy requirements stipulate the use of helium below 190 ft. [10] If the object environment is below 600 ft, 10% nitrogen should be included in the breathing mixture in order to preclude HPNS.

A habitat or deck decompression chamber is a closed environment. As such it must conform to the life support requirements in that it have an oxygen supply, a method of eliminating carbon dioxide, and a method of eliminating contaminants. In addition a supply of the diluent in the breathing mixture must be available to use as make-up as needed.

The simplest form of atmosphere regeneration was used in Tektite, a long term, shallow habitat supported jointly by the U.S. Navy, NOAA, and NASA. The habitat was supplied with air from a land based surface support station. The air was continuously fed to the habitat and vented from the habitat. [3] The constant flow effectively maintains oxygen and carbon dioxide within life support requirements; however, this method is not practical for independent operations. The cost in terms of volume of breathing gas is much to great.

Oxygen flux may be maintained independently using bottled gas, chemically derived oxygen such as oxygen candles, or oxygen electrolytically generated from water. Prudent engineering dictates that at least two independent sources of oxygen be available. The system must be capable of providing an average 1 SCF/hr of oxygen for each individual within the artificial environment.

Carbon dioxide flux resulting from human respiration averages 0.1 lb/hr for each individual. Two methods of eliminating this carbon dioxide are available. They are non-regenerative absorbent, such as lithium hydroxide (LiOH), and regenerative absorbent such as monoethanolamine (MEA). The former is the technology generally used in diving. The latter has been developed for use on submarines.

Contaminants are handled by activated charcoal filters, catalytic burners, and dust precipitators. The latter two devices are products of submarine development and are necessitated by the large amount of operating equipment on board submarines.

Monitoring equipment must be capable of determining oxygen partial pressure, carbon dioxide content, and the concentration of the most prevalent contaminants. Carbon monoxide is of particular importance since it is produced in every process that involves combustion.

2.3 Limitations

The problem of safe decompression is the primary limitation to this life support system. Internal pressure must be maintained within excursion limits of the prescribed depth in order to avoid decompression sickness. This translates into either a serious mission constraint or a structural design complication.

If the submarine is designed to be pressure compensating down to saturation depth then we have merely shifted the operating range downward by an amount equivalent to saturation depth. Vertical movement above saturation depth must be very carefully controlled in order to conform with appropriate decompression schedules. Such schedules from significant depths are measured in days. Any event or casualty requiring rapid surfacing without immediately available recompression facilities would be disastrous. Although such facilities can be incorporated into the design in the form of hyperbaric life boats [8], the limited advantage of this approach is outweighed by decompression related mission constraints and risk to personnel.

The decompression related mission constraints can be avoided if the submarine design incorporates the approach utilized in the design of Personnel Transfer Capsules (PTC) for deep diving systems. These systems "store" saturated divers in a Deck Decompression Chamber (DDC) aboard surface craft at the pressure equivalent to saturation depth for the duration of a mission. The PTC is used to transfer divers to and from the worksite as required. [9] [10] [11] In order to fulfill this requirement, the PTC must be designed to withstand internal pressurization to saturation depth while it is still located at the surface.

The analogous approach to submarine design, designing the pressure hull as a pressure vessel rated to withstand internal pressure equivalent to saturation depth, decouples personnel decompression from near-surface operation. This approach renders the pressure hull a structure under tension down to saturation depth and a structure under compression below saturation depth. This is an advantage in that typical hull material performance under tension is better than that under compression due to the absence of buckling modes of failure. Furthermore, the pressure hull is required to withstand only the compressive loading equivalent to the difference between operating depth and saturation depth as opposed to the total compressive loading of operating depth.

Each of these advantages alone simplifies the structural design problem. Taken together they define a structure which must function to resist both internal pressurization and external pressurization. PTC's are, in fact, designed to do this. [9] The requirement to operate in both modes adds complexity to the structural design. For example, any closures, hatches, and hull penetrations must seal in both directions.

It is not intuitively clear that the additional structural complexities associated with this dual mode operation outweigh the advantages of decreased total compressive loading. Such a determination is the grist of detailed engineering analysis and is beyond the scope of this thesis. It is clear that of the two approaches discussed in this section the dual mode operation (in the manner of the PTC) offers the least mission constraints and the greatest operational flexibility. It must be noted that, as in the pressure compensating design, consideration of any situation requiring rapid evacuation necessitates the inclusion of hyperbaric life boats.

4 Liquid Breathing

4.1 Concept

The results of the last chapter indicate that the full advantages of life support augmented operating depth cannot be realized without decoupling decompression effects from variations in ambient pressure. This equates to a diving system which offers the diver freedom from the constraints of decompression schedules. Such a system is required to allow a pressure compensating submarine to maneuver in the vertical plane without risking decompression casualty to embarked personnel. It is also required to avoid the structural design complications of a dual mode operating pressure hull (mode 1: internal pressurization, mode 2: external pressurization). Such a decoupling is not practical in view of the direct relationship between the concentration of dissolved gases in the blood/tissues and the absolute pressure of a gaseous atmosphere.

Decompression effects and pressure related narcosis may be avoided by stipulating an incompressible atmosphere. [12] [13] Such an atmosphere would not be subject to the variation of component concentration with changes in pressure described by the ideal gas laws. If such an atmosphere could be engineered to conform to the life support requirements for hyperbaric environments, a vertically unconstrained diving system would be the result. Assuming that an atmosphere must be fluid, incompressibility can be obtained only with a liquid atmosphere.

The concept of liquid breathing has been the subject of a significant body of research and experimentation since the early 1960's. [3] A large portion of this work has been conducted by Johannes A. Kylstra, most recently of the Duke University Medical Center, Durham, North Carolina. The primary supposition is that as a result of Henry's law a sufficient quantity of oxygen may be dissolved in a liquid to support mammalian respiration. [13] This supposition has been demonstrated on mice, rats, and dogs using various liquids under normobaric and hyperbaric conditions. [12] Furthermore, the contention that liquid breathing confers immunity to decompression sickness has also been demonstrated independently on mice transiting to a normobaric environment from 33 ATA (1089 ft) in 5 seconds and 100 ATA (3300 ft) in 3 seconds. [14] [15]

4.2 Liquid Atmospheres: Characteristics and Issues

A major focus of liquid breathing research has been the physiological reaction to various liquids and optimization of the liquid atmosphere for compatibility with life, and prolonged endurance. As one might imagine, the concept of liquid filled lungs raises several issues which bear upon the solution of the life support problem. These issues include osmotic incompatibility, temperature regulation, mechanical ventilation, oxygen solubility, and carbon dioxide retention.

Osmotic incompatibility occurs when the concentration of dissolved salts in the liquid breathing medium is different than that in the blood. Diffusion and osmosis of solutes and water across the respiratory membrane result in fluid volume and electrolyte imbalances, and tissue damage associated with drowning. [13]

This was demonstrated in early experiments comparing the survival time of mice breathing hyperbarically oxygenated tap water, sea water, and physiologically balanced saline (see Table IX). Physiologically balanced saline provided the greatest survival time. [12]

Table IX Survival time of mice breathing various hyperbarically oxygenated liquids.

Breathing Medium	Survival Time (min)
Tap Water	6
Sea Water	12
Physiological Saline	40

Temperature regulation is an issue with liquid breathing because a significant portion of the heat exchange surface of the body is exposed to a fluid of substantially different heat transfer characteristics than a gaseous atmosphere. Since the circulatory system is the vehicle of heat distribution in the human body [3], the lung is a particularly effective heat exchange surface due to the high level of vascular involvement.

The issue of temperature regulation is readily resolved by externally maintaining the breathing medium at a physiologically compatible temperature. The effect of temperature variation was demonstrated in liquid breathing rats in terms of tolerance to pressure (see Table X). [13]

Table X Pressure tolerance in fluorocarbon breathing rats at various temperatures.

Rectal Temp (deg c)	Pressure Tolerance (ATA)
17	150
21	220
27	220
31	125

The mechanical work of breathing increases exponentially with the density of the breathing medium. In addition the maximum inspiratory flow rate is inversely proportional to the square root of the density of the breathing medium. [3] The density of liquids is on the order of several magnitudes greater than the density of air. As a result, an individual breathing a liquid atmosphere will rapidly reach the limit of endurance. If productive work is to be required of individuals breathing a liquid atmosphere some form of mechanical assistance is required. Forms of mechanical assistance which have been used in animal experimentation include gravity assist [12], and centrifugal pump [16].

Henry's law ensures that a great variety of liquids are suitable for liquid breathing on the basis of oxygen solubility. Optimization of the liquid atmosphere for the highest oxygen solubility is necessary to simplify the task of oxygenating the liquid. Early experiments using water as the liquid atmosphere were hampered with the necessity for high pressure oxygenation. [12] This made initial experimentation with normobaric liquid breathing difficult at best.

Operationally, high pressure oxygenation would preclude near surface operations except under pressure. While this would not be a problem for a hull enclosed system such as a habitat or a submarine, a free swimming diver would be limited to the depth equivalent of oxygen pressurization without the aid of a submerged decompression chamber (SDC) or personnel transfer capsule (PTC). The avoidance of such limitations is the goal of this system.

In 196[illegible] Gollan and Clark first used FX-80, a liquid fluorocarbon, as the basis of a liquid atmosphere for mice. [14] This liquid is immiscible with water, and so does not present osmotic incompatibility. These and subsequent experiments demonstrated sufficient oxygenation at normobaric pressures to support mammalian respiration. [13]

The most severe limitation noted in most liquid breathing experiments is carbon dioxide retention. Carbon dioxide retention manifests itself as respiratory acidosis, decreased blood pH. This is by virtue of the following chemical dissociation.

$$CO_2 + H_2O => H_2CO_3$$

$$H_2CO_3 => H^+ + HCO3^-$$

The physiological reaction to carbon dioxide retention is an increase in ventilation rate. [2] Since the amount of carbon dioxide eliminated from the lungs is directly proportional to the ventilation rate, [13] this would be an effective reaction under normal conditions. Under the conditions of liquid breathing in which ventilation rate is limited by the density of the breathing mixture this response merely adds to a growing case of respiratory distress.

The cause for this carbon dioxide retention is an inadequate solubility of carbon dioxide in the liquid atmosphere. This problem cannot be alleviated by increasing the carbon dioxide partial pressure gradient because the ambient partial pressure of carbon dioxide cannot be decreased below 0 ATA.

The only remaining potential solution for this problem is to somehow enhance the solubility of carbon dioxide in the liquid atmosphere. [13] Attempts to accomplish this were made by using emulsions of carbon dioxide absorbent solutions in the fluorocarbon. [13] The most ambitious of these attempts made use of an emulsion of sodium hydroxide (NaOH) solution in the fluorocarbon FC-80. Various concentrations of NaOH were used with no significant damage to the lung tissue of the subject rats. Significant improvement in the elimination of carbon dioxide was also noted. Based upon the results of these experiments, it was estimated that human respiration could be supported by such a liquid breathing scheme, with only insignificant retention of carbon dioxide, to a level of effort requiring 1.7 SCF/hr oxygen flux. [17] This is roughly equivalent to light industrial activity such as carpentry. [2]

4.3 Components

Recent experiments involving liquid breathing in dogs, conducted at the Duke University Medical Center, Durham, North Carolina, made use of an excellent apparatus to provide liquid ventilation with the fluorocarbon FC-80. [16] The apparatus consists primarily of a sealed tank of oxygenated fluorocarbon, a constant speed centrifugal pump, one "fill" and one "drain" solenoid valve, and a scale which supports and measures the weight of the liquid breathing subject. The apparatus uses a signal from the scale indicating the weight of a single breath of fluorocarbon. The signal controls the opening and closing of the "fill" and "drain" solenoid valves. [16]

The apparatus described above is an example of the current level of the technology of liquid breathing. It must be noted that its purpose is laboratory study of essentially immobile subjects. The apparatus does in fact point out the major hardware limitation to the technology. As in all other studies, the fluorocarbon is not recirculated. That is, the volume of the initial supply of fluorocarbon determines the duration of liquid breathing. No attempt is made to recirculate and re-oxygenate the fluorocarbon for further breathing. What follows is a description of the components required for an individual life support system based upon liquid breathing.

The primary component of any liquid breathing apparatus is the breathing liquid. This consists of an emulsion of a carbon dioxide absorbent in an oxygenated fluorocarbon. The hardware in which this liquid atmosphere is employed is discussed below (see Figure 1).

The oxygenated liquid is supplied from a holding tank. The tank represents a balance between reserve breathing time and available volume. Two liquid reconditioning loops leave the tank. These loops are responsible for maintaining the liquid in the holding tank in a breathable condition.

The loops consist of a pump, with a constant recirculating line for pump cooling, an automatic flow control valve, and a device for modifying a characteristic of the liquid. The automatic flow control valve senses the pertinent characteristic of the liquid in the holding tank and throttles flow to the modifying device. The loops return to the holding tank downstream of the modifying device.

The modifying device in the first loop is an oxygenator. It supplies oxygen to the fluorocarbon so that the concentration of dissolved gases in the holding tank is sufficient for support of human respiration. The modifying device in the second loop is a resistive heating element which maintains the temperature of the fluorocarbon in the holding tank.

The delivery sub-system consists of a line from the holding tank to the ventilation support pump. The ventilation support

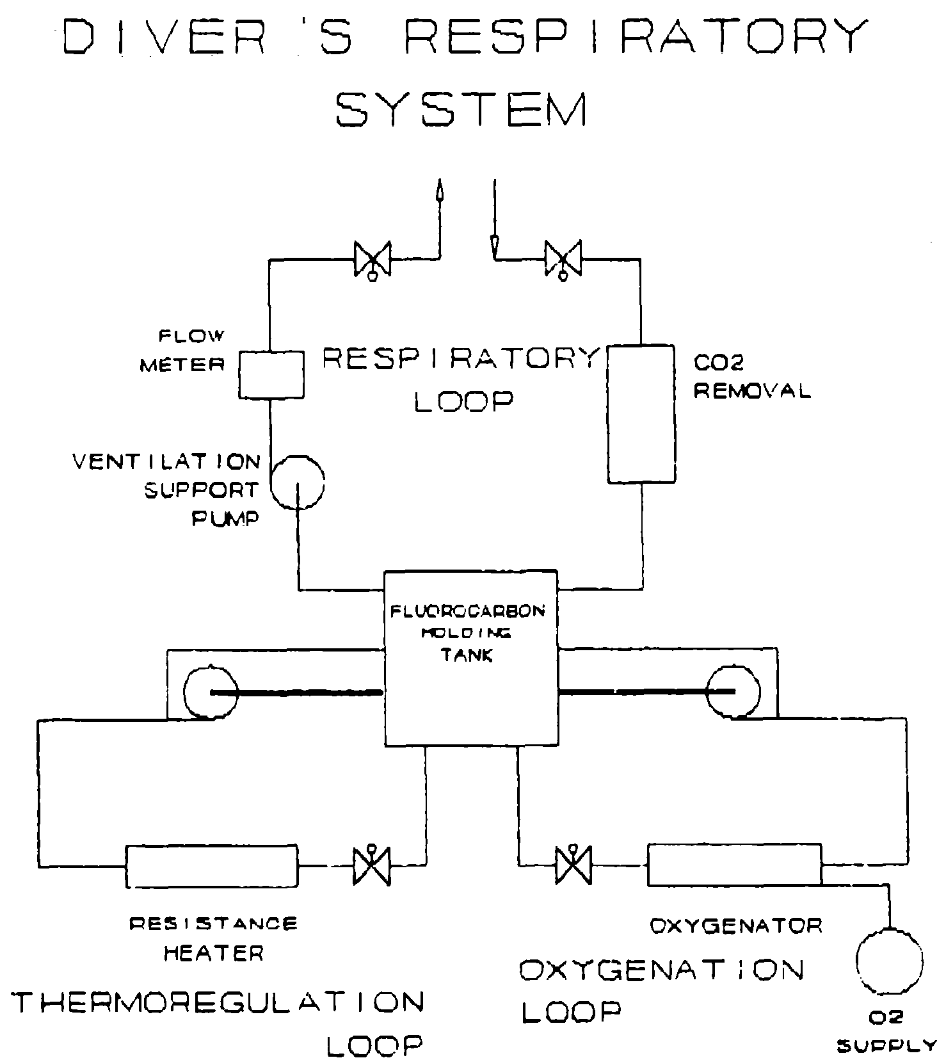

Figure 1 Line diagram of a recycling liquid breathing apparatus.

pump provides positive pressure on demand, supplying breathing liquid to the diver. Flow meters will provide a signal which determines when a sufficient quantity of the liquid has been delivered. At this point an exhaust line will open allowing the diver to exhale the spent liquid. The exhaust line returns the liquid to the holding tank through a device which removes any accumulated carbon dioxide.

4.4 Limitations

Vertical excursions are not constrained by decompression requirements since the partial pressure of dissolved gases in the system is constant; however, HPNS is a function of compression rate and hydrostatic pressure. Experiments conducted on liquid breathing dogs in hyperbaric environments demonstrated that HPNS is not a pharmacological effect of helium but truly a result of pressure. [18] The system must be supplemented by anesthetic administration to achieve depths greater than 600 ft.

The anesthetic must be administered in the form of a drug metered for the desired depth. The 10% nitrogen suggested elsewhere [7] cannot be applied to this system. It implies an increasing concentration with depth which, in turn, implies the need for controlled decompression upon ascent. The drug, on the other hand, places no decompression constraint on ascent and will effectively eliminate HPNS; however, it does place a narcotic constraint on ascent.

The drug must be administered to counteract the pressure at a specific depth. At this depth the narcotic effect of the drug will balance the effect of hydrostatic pressure on the cellular membranes. [5] If that pressure is decreased significantly the narcotic effect will become dominant.

Another limitation of this system is that of level of activity. The limiting factor is carbon dioxide elimination. Exertion beyond the maximum level the system can support will result in retention of carbon dioxide, acid-base imbalance in the blood and the rapid onset of respiratory distress.

5 Extracorporeal Membrane Oxygenation (ECMO)

5.1 Concept

Extracorporeal membrane oxygenation is a development of biomedical engineering. It is a result of the technology which brought about the heart lung machine. The heart lung machine is used during open heart surgery to bypass the heart and circulate and oxygenate the blood. [19]

Extracorporeal membrane oxygenation is used to bypass the lungs of individuals affected by respiratory distress syndrome. In essence an extracorporeal circuit is established in the circulatory system which includes a silicone membrane artificial lung. The artificial lung passes blood along one side of the membrane and oxygen across the other. The oxygen diffuses into the blood and carbon dioxide diffuses into the oxygen mixture. It must be noted that the carbon dioxide elimination is so effective that trace amounts of carbon dioxide must be added to the oxygen in order to avoid upsetting the pH balance of the blood and tissues. [20]

As applied to diving technology and submarine life support this concept involves oxygenating the blood with a liquid containing controlled concentrations of breathing gas components. This is the same approach as was proposed with liquid breathing except that the problems of ventilation are eliminated. The lungs are bypassed with an extracorporeal circuit which includes a silicone membrane lung. Blood passes along one side of the membrane and the oxygenated liquid passes along the other side of the membrane. The resulting transfer of oxygen to the blood and carbon dioxide to the liquid supports the respiration of the individual.

Hydrostatic isolation of the lungs must be accomplished to prevent lung collapse with increasing depth. This may be accomplished by flooding the lungs with a physiologically balanced saline solution and establishing the carbon dioxide level in the bloodstream just below the threshold which triggers the breathing reflex.

5.2 Components

The components of this system are divided into two closed loops (see Figure 2). The first is the loop containing the oxygenated fluorocarbon. Its components are identical to those described in the previous chapter with the exception of the delivery system. The mechanical ventilation support pump is replaced with a variable speed pump controlled by the arterial oxygen partial pressure.

The second loop consists of the ECMO circuit. Blood is drawn from the individual with a cannula placed in a major vein leading directly to the heart. The blood is delivered to a constant displacement roller pump which in turn supplies the blood to the artificial, silicone membrane lung. The blood is then returned to the individual with a cannula placed in a major artery. The ECMO circuit must include a method of introducing heparin to the individual to preclude the formation of blood clots in the ECMO circuit.

The artificial, silicone membrane lung must be sized to support the entire cardiopulmonary load. This load is expressed in terms of blood flow rate. The normal resting load is 5000 ml/min. This can be increased by strenuous activity to 25000 ml/min. [2] A single membrane lung with a surface area of 4.5 m^2 is capable of supporting a flow of approximately 5600 ml/min with complete oxygenation. [20] This means that a full range of activities can be supported with 5 membrane lungs arranged in a parallel circuit.

5.3 Limitations

This system is vertically unconstrained by decompression requirements because the partial pressure of breathing gases is maintained at a constant level, dissolved in the liquid of the first loop. There is a vertical constraint incurred below 600 ft as a result of HPNS.

As with liquid breathing, depths greater than 600 ft require the administration of an anesthetic to eliminate HPNS. The dosage of anesthetic is proportional to the depth and balances narcotic cellular membrane expansion with hydrostatic cellular membrane contraction. Ascent allows the narcotic effect to dominate. For this reason ascent must be timed to coincide with the duration of the dose of anesthetic.

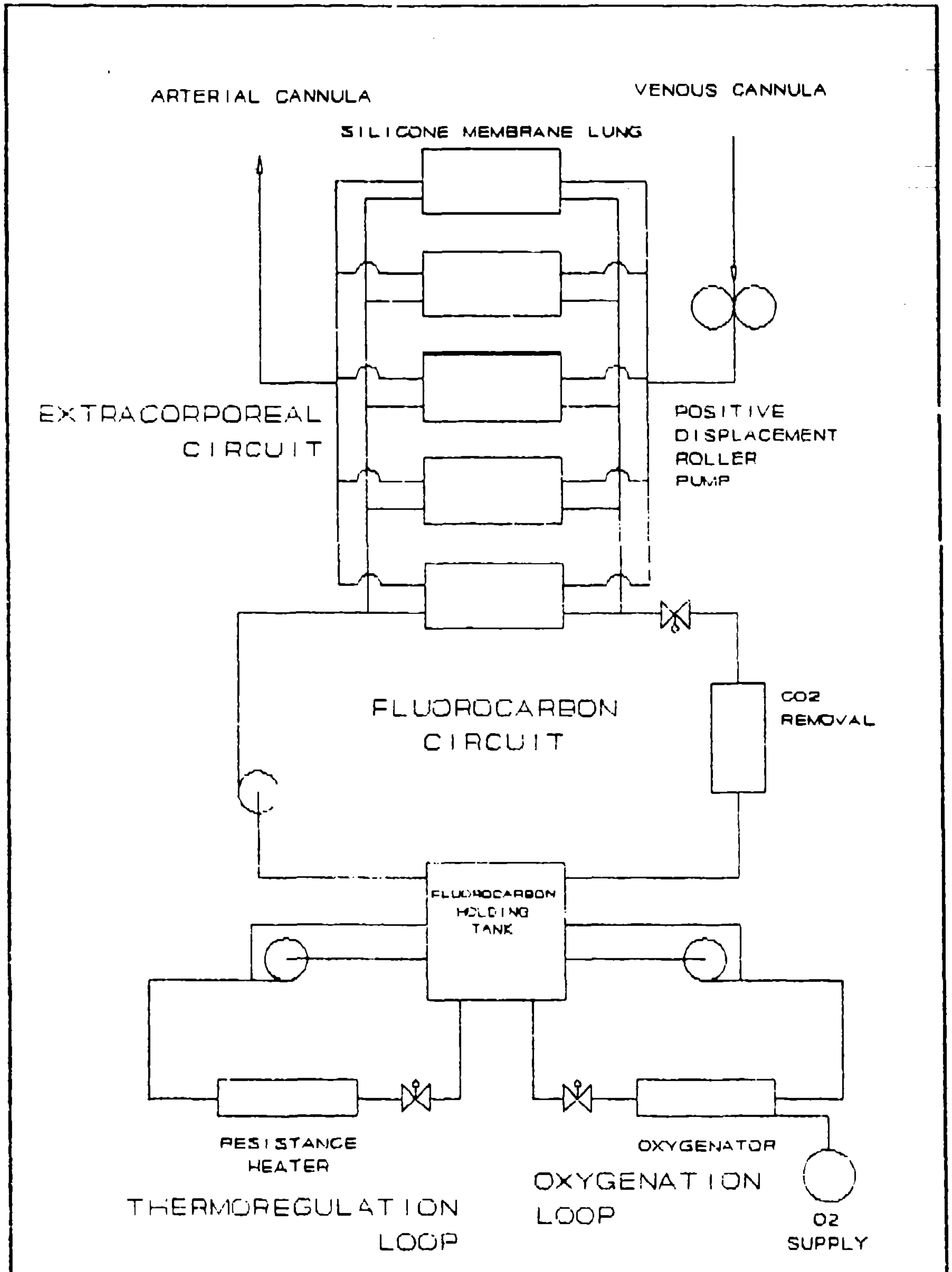

Figure 2 Line diagram of an ECMO-based breathing apparatus.

6 Technical Risk

The technical risk in this approach to submarine design involves the effect of hyperbaric environments on the vast array of equipment employed throughout the submarine. For example, major innovations or alternatives in propulsion technology would be necessary to deal with the changing characteristics of propulsion fluids in response to changing pressure. Evaluation of the sensitivity to pressure and pressure changes of each of the technologies employed in the submarine must be accomplished to truly ga[illegible] the feasibility and effectiveness of this approach.

6.1 Mixed Gas Saturation

Mixed gas saturation diving has undergone extensive development and commercial use primarily in response to applications in the offshore oil industry. These applications and research habitat studies such as SEALAB and Tektite represent the largest source of data available on long term exposure to hyperbaric environments.

The deepest habitat exposure was conducted on the Makai underwater range in Hawaii with the habitat Aegir in 1969. This exposure involved a team of 5 individuals at a depth of 482 ft for a period of 14 days. The longest habitat exposure was conducted in the U.S. Virgin Islands with the habitat Tektite also in 1969. A team of 4 individuals remained at a depth of 42 ft for a period of 59 days. [8] Although a great deal of work has been accomplished at much greater depths [7], these experiments represent the closest approximation of the artificial environment being proposed in this thesis. Unfortunately the depth and exposure durations of these experiments is not sufficient to evaluate saturation techniques for long duration submarine missions.

Habitats in general do not contain the quantity and variety of equipment associated with submarine missions. The quantity and variety of contaminants implied have not been evaluated for tolerance and toxicity. In addition the effectiveness of catalytic burners in hyperbaric environments is not known.

6.2 Liquid Breathing

A major technical risk with respect to the development of liquid breathing is the delivery sub-system. This sub-system must include provision for transition between gas and liquid breathing and must be able to vary delivery with changing oxygen requirements. The most advanced system to date is devised for immobilized animals and is based on a static, preset oxygen load. [16]

Another technical risk involves re-oxygenation of spent fluorocarbon under varying pressures. All studies have been conducted using non-recycling apparatus.[18] [13] A device must be designed which will maintain a reserve quantity of fluorocarbon with the desired concentration of dissolved oxygen. Such a device must involve a gas-liquid interface, and such an interface will experience variations in solubility due pressure variation associated with changing depth. similarly, removal of absorbed carbon dioxide from spent breathing liquid in a closed circuit, recycling application is not yet fully understood. The fact that emulsions of carbon dioxide absorbents in fluorocarbon are the best candidates for breathing liquid makes this technical problem all the more challenging.

For both liquid breathing and ECMO, the peculiar difficulty of narcotic constrained ascent as a result of anesthetic prophylaxis of HPNS makes the feasibility of life support augmented operating depth questionable. An additional 600 ft of operating depth is not insignificant; however, the impact to other systems and the research and developmental costs of these approaches to life support are not justified by a 600 ft increment in operating depth. Steps must be taken to remove this obstacle if this approach is to be fruitful.

Finally and most significantly, the most advanced breathing liquid, an emulsion of sodium hydroxide in FC-80 fluorocarbon, limits the power output of an individual to approximately 22% of an average maximum. Although this is useful, it severely limits the long term applicability. The average power level used for calculating life support requirements is 12.4% of the average maximum. This does not leave a sufficient margin to account for routine excursions in power output. The need for a breathing liquid with improved carbon dioxide solubility is paramount to the further development of this technology.

6.3 ECMO

ECMO represents the greatest technical risk of all the technologies examined. This can be attributed to the fact that the development of ECMO is tied to the maintenance of basal metabolic function alone. Current technology does not have a small enough silicone membrane lung with sufficient surface area to support normal variations in activity level.

Furthermore, the concept involves major surgery to major blood vessels. Redundancies in the way of system failures are difficult to design and system failures in the ECMO loop while in the object environment would almost necessarily be fatal. A significant amount of work in artificial circulatory vessels and connectors is required for an employable system to become feasible. In addition extraordinary measures to guard against infection must be taken, given the nature of employment expected of this system.

Finally, ECMO has been accomplished using a membrane lung with blood on one side of the membrane and oxygen on the other side of the membrane. This application calls for a membrane straddled by blood and oxygenated fluorocarbon. Oxygen transfer and flow restrictions in this scenario are not clearly understood. Study of direct fluorocarbon-blood interface oxygenation have been conducted and bear examination as alternative oxygenators. [19]

7 Cultural Risk

Human extension into hostile environments has always involved shaping the environment to suit human life support requirements. In the most hostile environments this approach has manifested itself as the manufacture of small artificial environments. In a sense this has resulted in a modification of human evolution, downplaying the aspect of physical adaptation.

The technologies examined in this thesis take this modification of evolution one step further, by re-emphasizing physical adaptation as a design tool for the extension of humanity into increasingly hostile environments. In the past such physical adaptation has been accepted as a tool for overcoming handicaps, injuries, and disease, but the intentional modification of healthy human beings elicits is not as clear-cut an ethical issue.

In a similar line of thought, advances in all three of the technologies examined has involved and must involve further animal and human experimentation. Recent public opinion and resultant political sensitivities in these areas render this a significant point for ethical consideration. The perceived gains of such a program must be sufficient to outweigh reluctance generated by recent sentiment. Most importantly, the experimentation which results must be of such a caliber as to totally preclude inhumane treatment cruelty and the appearance of such to any experimental subjects.

8 Conclusions

Life support augmented operating depth requires the development of a vertically unconstrained diving technology. All of the technologies examined herein are vertically constrained. In particular mixed gas saturation diving displays the greatest vertical constraint as a result of decompression effects. This renders that technology infeasible for this application.

All of the technologies examined are capable of providing a safe and stable artificial environment down to 600 ft. Narcotic constrained ascent in liquid breathing and ECMO make greater depths less accessible. This renders these two technologies infeasible for this application without some advance in the prophylactic treatment of HPNS.

Potential application of these technologies to diving and the extension of human activities to greater depths make further study and development a worthwhile pursuit. Sufficient work has been done to indicate that life support systems based on these technologies is feasible.

Finally, the limiting factor to liquid breathing is carbon dioxide elimination. ECMO routinely requires carbon dioxide in the oxygen supply because carbon dioxide elimination as a result of this process is too efficient. This suggests that a marriage of the two technologies may provide the quickest solution to the life support problem at great depth. A significant body of research has been conducted on the removal of carbo dioxide using extracorporeal circuits involving non-major blood vessels.

References

1. Weast R.C., CRC Handbook of Chemistry and Physics, fifty eighth edition, CRC Press, West Palm Beach, Florida (1977-1978).

2. Guyton A.C., Basic Human Physiology: Normal Function and Mechanisms of Disease, second edition, W.B. Saunders, Philadelphia (1977).

3. Shilling, C.W., Werts, M.F., and Schandelmeier, N.R., The Underwater Handbook: a Guide to Physiology and Performance for the Engineer, Plenum Press, New York (1976).

4. Vann, R.D., "Decompression Theory and Applications," The physiology and Medicine of Diving, Third Edition, Balli'ere Tindall, London (1982).

5. Bennett, P.B., "Decompression Theory and Applications," The physiology and Medicine of Diving, Third Edition, Balli'ere Tindall, London (1982).

6. U.S. Navy Diving Manual, Volume I, Air Diving, NAVSEA 0994-LP-001-9020 (1977).

7. Bennett, P.B., "The High Pressure Nervous Syndrome in Man," The physiology and Medicine of Diving, Third Edition, Balli'ere Tindall, London (1982).

8. Haux, G.F., "Under-water Habitats," Subsea Manned Engineering, Bailli'ere Tindall, London (1982).

9. Haux, G.F., "Deep Diving Systems," Subsea Manned Engineering, Bailli'ere Tindall, London (1982).

10. U.S. Navy Diving Manual, Volume II, Mixed-Gas Diving, NAVSEA 0994-LP-001-9020 (1977).

11. Bachrach, A.J., "A Short History of Man in the Sea," The Physiology and Medicine of Diving, Third Edition, Balli'ere Tindall, London (1982).

12. Kylstra, J.A., "Advantages and Limitations of Liquid Breathing," Proceedings of the Third Symposium on Underwater Physiology, Williams and Wilkins, Baltimore (1967).

13. Kylstra, J.A., "Liquid Breathing and Artificial Gills," The Physiology and Medicine of Diving, Third edition, Balli'ere Tindall, London (1982).

14. Gollan, F., Clark, L.C., "Prevention of Bends by Breathing an Organic Liquid," Transactions of the Association of American Physicians, vol. 29 (1967).

15. Kylstra, J.A., Nantz, R., Crowe, J., Wagner, W., Saltzman, H.A., " Hydraulic Compression of Mice to 166 Atmospheres," Science, vol. 158 (1967).

16. Harris, D.J., Coggin, R.R., Roby, J., Feezor, M., Turner, G., and Bennett, P.B., "Liquid Ventilation in Dogs: an Apparatus for Normobaric and Hyperbaric Studies," Special Communications, The American Physiological Society (1983).

17. Matthews, W.H., Kylstra, J.A., " Investigation of a New Breathing Liquid," Underwater Physiology VI, FASEB, Bethesda, Maryland (1978).

18. Harris, D.J., Coggin, R.R., Roby, J., Turner, G., and Bennett, P.B., "EEG and evoked potential changes during gas- and liquid-breathing dives to 1000 msw," Undersea Biomedical Research, Vol. 12, No. 1, March 1985.

19. Skalak, R., Chien, S., Handbook of Bioengineering, McGraw-Hill, New York (1987).

20. Hirschl, R.B., Bartlett, R.H., "Extracorporeal Membrane Oxygenation Support in Cardiorespiratory Failure," Advanced Surgery, vol. 21, pp. 189-212 (1987).