

SUBMARINE AIR TREATMENT

Revision: September 12, 2001

Learning Objectives:

1. Describe how oxygen is produced on submarines with the following processes: electrochemical oxygen generator and oxygen candle furnace.
2. Describe how carbon monoxide is removed from the submarine atmosphere with the following processes; LiOH absorbers and CO-H₂ burner.
3. Describe how carbon dioxide is removed from the submarine atmosphere using the CO₂ scrubber.
4. Describe how H₂ is removed from the submarine atmosphere using the CO-H₂ burner.
5. Discuss the impact of submarine atmospheric pressure changes with respect to the following biologically essential and/or sensitive gases; oxygen, carbon monoxide, and carbon dioxide.
6. Describe the use of activated carbon for the removal of odors and other noxious gases.

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Life in a Confined Space in a Hostile Environment

(A story to set the stage)¹

Welcome to my 1-atmosphere diving bell. We will be making a hypothetical observation dive to 300 feet (91.4-m) beneath the ocean's surface to survey the wreckage of the *Andrea Doria*. You will notice that this capsule, although only eight feet (2.4-m) in diameter, contains most of the comforts of home. The atmosphere inside this capsule is indistinguishable from the air we breathe on the surface, thanks to an environmental control system, which continually monitors and adjusts the temperature and humidity.

We have just reached our destination when for some unexplained reason we suffer a complete shutdown of our main power supply and primary life support systems! It appears that we have become entangled in some type of obstacle on the bottom and severed our power cable, which connects us to the surface. Please don't panic!

Auxiliary battery power is presently supplying eerie, low intensity lighting in our sealed compartment. These batteries should last for at least 48 hours. It is at least some consolation to know that our capsule has ½-inch (1.3-cm) thick walls, and is constructed of high-yield strength steel. The bell will keep us from being crushed by the outside pressures, which are over 10 times those inside (thumb rule: pressure increases 1 atmosphere for every 33 feet of depth in seawater).

Our initial concern is to our supply of oxygen. Presently, our bodies are consuming approximately 0.3-0.5 liters per minute of oxygen gas to support our resting metabolic functions. This oxygen is being taken from the capsule atmosphere. If not replenished, the oxygen content in this atmosphere will slowly decrease from its initial value of approximately 21% by volume. If the oxygen content is allowed to drop to 16%, we will begin experiencing labored breathing, confusion, and finally unconsciousness. Even if we can't replenish this atmosphere with fresh oxygen, at the rate at which we are consuming oxygen we should have nearly 6 hours before these symptoms become noticeable, and up to 13 hours before we are unconscious. We fortunately brought along an additional supply of oxygen to extend these times by 12 hours. But, by all means, please stay calm, as increased anxiety will only increase our oxygen consumption rates.

Even of more concern is the buildup of carbon dioxide, which our environmental sensors are detecting. Since we no longer have power to operate the ventilation fans in our capsule, the air from our atmosphere is no longer being forced through the carbon dioxide absorption system, which we have on board. The carbon dioxide, which our bodies are generating through normal metabolism, is being dumped into our capsule environment. As in the case of oxygen, our bodies are tolerant of only a slight variation in the carbon dioxide content in the air, which we breathe. Even though we can tolerate short exposures at carbon dioxide levels of up to 3%-4%, we will begin experiencing respiratory discomfort, a feeling of air hunger, and perhaps dizziness and nausea when breathing only 1%-2% carbon dioxide for extended durations; at 6%, we will be on the brink of unconscious. Based on our present rates of carbon dioxide generation, our capsule environment is predicted to reach 2% levels

¹ Nuckols et al., (1996)

of CO₂ in approximately 3 hours and 6% in slightly over 6 hours. Don't be surprised though if you experience a headache and reduced sensory perceptions (hearing, seeing, etc) before these times are reached. Again, steady yourself; further anxiety will only speed up the timetable.

You say that it is getting cold? Unfortunately, the capsule is not insulated. Without the electrical heating system, which was more than adequate when power was available, the temperature inside the capsule quickly reaches the surrounding water temperature of about 40° F (4.4° C). We need to try to stay as warm as possible, since any shivering will only increase our oxygen consumption and carbon dioxide generation rates.

One way that we can re-warm the cabin atmosphere and ward off the extremely uncomfortable consequences of being cold is to pressurize the bell with our emergency gas banks. By increasing the cabin pressure, we immediately feel a renewed warmth, not unlike the rise in temperature that we see when inflating an automobile tire. If done in stages, we may have a chance to offset the continual heat loss from the bell to the surrounding water, and maintain a tolerable cabin temperature until rescue is made.

But, alas, the increase in cabin pressure offers only momentary relief from the extreme cold. The lack of insulation and immense heat sink provided by the ocean quickly dissipates the increased temperature to that of the ambient water temperature. In addition, the increased cabin pressure has caused even further problems. The physiological responses of our bodies to the levels of carbon dioxide in the cabin are increased proportionately to increases in pressure.

An environment at 10 atmospheres of pressure having only 0.5% carbon dioxide will be as toxic to our bodies as when we breathe 5% carbon dioxide at surface pressure (1 atm). The consequences of breathing these toxic levels will only occur sooner as we pressurize the diving bell!

Finally, the unwise, albeit desperate, act of pressurizing our cabin may have eliminated our last safe means of escape. By exposing our bodies to an increased pressure, we have built up a decompression debt, like the deep-sea divers. The inert gases in our atmosphere are slowly dissolving into our bodies. Once our capsule is rescued and brought back to the surface, catastrophic results await our bodies when the hatch is opened unless we undergo a slow decompression. In rapid decompression, dissolved gases come out of solution too rapidly, causing bubbles to form in our body tissues and blood. Like a diver experiencing decompression sickness, our symptoms will be pain in the joints, nausea, dizziness, possibly paralysis or even death. But of course slow decompression will be impossible since our oxygen supply is being depleted and our atmosphere is being contaminated with carbon dioxide. A re-supply of electrical power appears to be our only hope!

1. Submarine Atmosphere Characteristics

Within a submarine, the atmospheric control system assumes importance equal to the propulsion, weapons, and navigation systems. An efficient and reliable system insures the health and safety of the crew and prevents damage to the ship's machinery from atmospheric contaminants. To accomplish these goals, the atmospheric control system maintains air in the submerged submarine at a composition that is close to that of clean surface air. The equipment used to measure and maintain this air quality is based on applications of principles taught in general chemistry.

In order to create an atmosphere close to that of clean surface air; we must establish the composition of clean dry air shown in Table 1. Variations to this normal composition occur in nature, due to the presence of water vapor, dust, pollen, and particulate matter.

Table 1 – Composition of Clean Dry Air²

Component	Symbol	Specific Gravity	Volume %	Partial Pressure (Torr)
Nitrogen	N ₂	0.967	78.09	593
Oxygen	O ₂	1.105	20.95	159
Argon	Ar	1.38	0.93	7
Carbon Dioxide	CO ₂	1.53	0.03	1

GENERAL NOTES:

(1) Data is for standard dry air weighing 0.075 lbs·ft⁻³ (1.2 kg·m⁻³) at 70°F (21°C) and at a barometric pressure of 29.92 in. of mercury (760 Torr).

(2) The table omits very minute quantities of other gases (neon, helium, methane, krypton, nitrous oxide, hydrogen, xenon, and ozone) with a combined total of 28 ppm.

(3) The composition shown will vary slightly because of the presence of a small percentage of water vapor normally present. Thus, clean air at 50 percent relative humidity will have an oxygen content of approximately 20.5 percent.

(4) Specific gravity data is based on reference of air having a specific gravity of 1.000.

The atmosphere in a submarine differs from that in nature in three important respects:

- greater variability in the oxygen and carbon dioxide content;
- the presence of a wide range of organic and inorganic contaminants and;
- the potential problem associated with the toxicity of certain substances (see below).

The last two categories are significant since the volume of air in the submarine is limited and there is no place for “the wind to carry the toxic gases away.” More than fifty

² *Technical Manual for Nuclear Powered Submarine Atmosphere Control Manual*, (1992)

chemicals, including such reactive materials as HF, CO, NO₂, and O₃, were found to be present in measurable quantities in atmospheres measured on board operating submarines. Tracing the sources of some forty of these contaminants indicated they came from smoking, sanitary tanks, battery gassing, lubricants, paints, adhesives, cooking, engine exhaust, electric arcing, refrigerants, fuel oils, and, frustratingly, as products from the atmosphere purification systems when improper materials were released in the closed atmosphere of the submarine. The remainder are suspected to be from cigarette smoke although they have not been quantitatively verified.

Even the least reactive and toxic of these compounds is neither pleasant nor necessarily safe to breath for long periods. The more toxic components represent a real threat even on a short-term basis. The effect of any substance to which a person might be exposed depends on:

- a) length of exposure,
- b) concentration,
- c) solubility or *permeability* in tissue and body fluids, and
- d) type of gas or toxic medium.

2. Medical/Toxicological Considerations

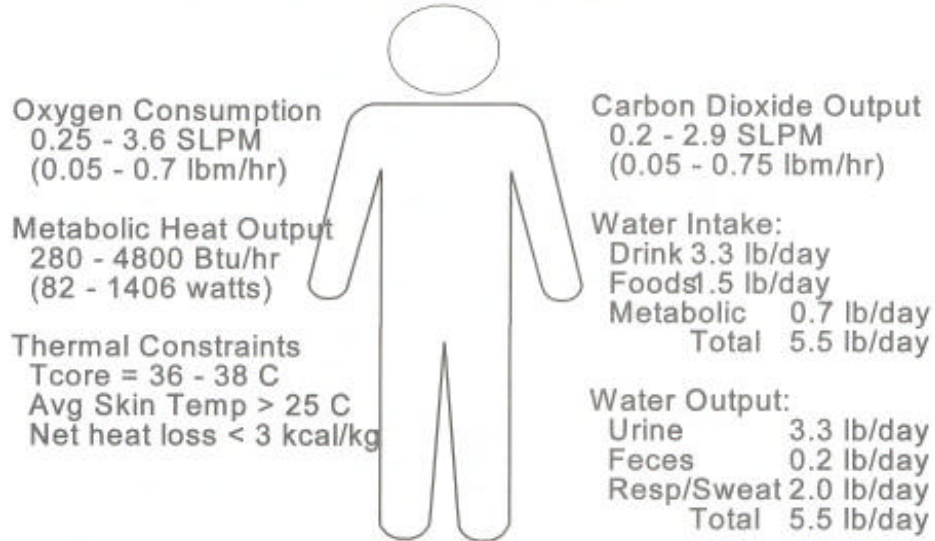
Let's begin with a simple description of the human respiratory process. Air taken into the lungs reaches very small dead-end spaces called *alveoli*. These tiny sacs have extremely thin walls filled with *capillaries* (very fine blood vessels). The total alveoli provide a large surface area through which gases pass into the capillaries' blood and, hence, into the general blood stream. As a result, the gases establish almost immediate equilibrium with the blood: both oxygen in and carbon dioxide out. In the red blood cells, oxygen unites chemically with *hemoglobin* to form a relatively weak chemical bond. When the red blood cell has been carried to regions of the circulatory system remote from the lungs, the oxygen is freed and consumed by the cells at that point. The blood, returning to the lungs, carries CO₂ and other waste products back to the lungs for expulsion. Figure 1 is a material balance for the average submarine crewmember.

Under ordinary conditions, the respiratory rate is about 15 breaths/minute, or about 20 SCFH (standard cubic feet per hour of air as shown in Table 1) per person. Air intake is only about 0.02 ft³ per breath (SCFB), only a small fraction of the total lung capacity. A raised level of activity requires energy, which creates a larger demand for oxygen. This need is met by both greater rate of breathing and greater volume per breath. At a minimum, the human body must absorb sufficient oxygen to support the biochemical activity of the brain and other vital organs.

As a reflection of the equilibrium constant for such absorption, it is the partial pressure of the oxygen (P_{O_2}) in the atmosphere that determines how much oxygen is carried in a unit of blood. In normal, healthy individuals, *arterial* blood has above 90% of its holding capacity for oxygen when P_{O_2} is 110 Torr or higher (Sea Level, $P_{O_2} = 160$ Torr). Oxygen levels in submarine atmospheres at 110 Torr or higher will insure against *hypoxia* (see section 3).

Life Support Considerations

A Delicate Balance



Notes: SLPM – standard liters per minute
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Figure 1 – Submarine Material Balance

Deployed submarine atmospheres undergo fluctuations of P_{O_2} and P_B (Barometric Pressure). Such fluctuations must be controlled to insure adequate life support for the crew. Although the partial pressure of oxygen is the critical factor physiologically, the % of oxygen is more critical in propagation of oxygen-supported fire where the inert gasses interfere with the mechanism of burning. The safe operating zone, or boundary conditions, for a submarine (Submarine Atmosphere Zone) is defined by the ranges:

$$P_{O_2} = 119 \text{ to } 160 \text{ Torr}$$

$$P_B = 700 \text{ to } 810 \text{ Torr}$$

$$\% O_2 = 17.0 \text{ to } 21.0 \%$$

This corresponds to a range for P_{O_2} from roughly sea level to the level maintained in a commercial aircraft cabin or a point similar to the atmospheric conditions in Bogota, Columbia at 9000 feet above sea level. The P_B levels are more restrictive and the normal atmosphere for Denver, Colorado at an altitude of 1 mile would be outside of the Submarine Atmosphere Zone.

3. Physiological Problems

Important acute problems that may arise from improper atmospheric conditions are:

a) Hypoxia – Insufficient delivery of O_2 to the body is the result of atmospheres with low P_{O_2} . Symptoms vary with P_{O_2} level and can include: impaired night vision, heavy breathing, impaired judgment, dizziness, slow thinking, impaired muscular coordination, unconsciousness, and death.

b) Decompression Sickness – This malady is due to the formation of gas bubbles in the body due to gases such as nitrogen coming out of solution in body fluids. It results from an excessive reduction in ambient pressure (P_b).

c) Oxygen Poisoning – Lung injury results from P_{O_2} values over 380 Torr, and generally with excessive P_b as well. Oxygen poisoning is a possible problem for aviators with an improper gas mixes in their oxygen masks, however, it is not likely in a submarine, but it is not impossible.

d) Carbon Dioxide Buildup – Most of the CO_2 produced in a submarine results from respiration. An average person produces about 0.83 SCFH. An increase in activity raises the CO_2 partial pressure in the blood, which stimulates rapid respiration. Exposures to atmospheres with high P_{CO_2} have the same effect as hypoxia. Symptoms can range from increased respiration, through mild discomfort, to dizziness, stupor, unconsciousness, and death. Both concentration and exposure time to CO_2 are important. Acute symptoms arise from sustained exposure at high concentration and are the result of upsetting pH and the biochemical balances related to O_2 and CO_2 . Increased CO_2 will cause impairment and danger before reduced P_{O_2} will have an effect in contained, untreated atmospheres.

e) Carbon Monoxide Buildup – The *affinity* of CO for hemoglobin is about 210 times that of oxygen. As a consequence, relatively low concentrations of CO lead to deprivation of oxygen carriers in the blood. Toxic exposure causes tissues to be deprived of oxygen although the P_{O_2} is adequate.

f) Excess Refrigerants – Halocarbons such as dichlorodifluoromethane, CCl_2F_2 , a commercial refrigerant known as R-12 and dichlorodifluoroethene, $CClF_2CClF_2$, a commercial refrigerant known as R-114, can act as simple asphyxiants, causing dizziness at low concentration and death at high concentrations. Products of the thermal decomposition of these materials can be highly corrosive and toxic, e.g., HCl and HF.

g) Excess Hydrocarbons – Aromatic and aliphatic hydrocarbons appear in trace amounts from a number of sources, including paints and thinners, fuels, lubricants, sealing compounds, solvents, adhesives, etc. The *aliphatic compounds*, as a class, are considered relatively non-toxic in trace amounts; but high levels show an impact on liver function. *Aromatics* are generally more dangerous because they do enter into the metabolism of

various organs and irritate the skin and mucous membranes. Although most of the exposure will be from respiration, some of these materials penetrate the skin.

h) Excess Ozone – Ozone is produced by any spark that passes through an oxygen-containing atmosphere. Electric motors and the electrostatic precipitators used to remove particles from the air are the major producers on a submarine. Ozone is highly irritating to all mucous membranes and can cause skin and eye irritation, respiratory irritation, and may produce coma at concentrations above 1-ppm. It also causes cracking of natural rubber products such as hoses, gaskets, seals, etc.

i) Excess Hydrogen – Although hydrogen does not offer significant physiological risk, it is highly flammable and explosive if the P_{H_2} rises above 4%. It is generated by battery charging and is a product of electrolytic oxygen generators. The oxygen bled to the atmosphere may contain as high as 1% hydrogen, which is then significantly diluted by the nitrogen in the ship.

4. Classification of Materials by Biological Effect

Some of the major categories used by the Navy for toxic materials are based on the biological effects that they have on the exposed organism. Some examples are presented here with the primary source listed.

a) Irritants – These are characterized by corrosive action when in contact with moist or mucus surfaces.

1) Respiratory Tract or Eyes (NH_3 , SO_2 , HCl , HF , NO_2 , N_2O , Freon) Sources include smoking, sanitary tanks, refrigerants, product of $CO-H_2$ burners when other hydrocarbons react.

2) Upper Respiratory Tract, and Lungs (O_3 , Cl_2 , those in “1” above) Sources include electric arcs in machinery, salt water in batteries, sterilizing solutions and bleaches.

3) Air Sacs/Terminal Respiratory Passages in Lungs. Sources include tobacco mists and dusts, aerosols of many things.

b). Asphyxiants – These interfere with oxidative metabolism.

1) Inerts – These displace the oxygen in the air being breathed. (CO_2 , N_2 , hydrocarbon vapors, Freons and other refrigerants) The quantity required to be effective is typically larger than that usually found in submarine atmospheres but these do represent a very real threat to personnel working in closed spaces. There are several fatalities a year in which the death was caused by entering a closed space where oxygen had been displaced by some other gas.

2) Chemical Asphyxiants – These are toxic agents, which interfere with the normal transport of oxygen by the blood. (HCN , H_2S , and CO) CO is the biggest threat since it comes from smoking, cooking, engine exhaust, and missile launch systems (See abatement effort below).

c) Anesthetics and Narcotics – These are depressants acting on the central nervous system and are generally reversible. Their effect depends on their partial pressure in the blood. (grain alcohol, hydrocarbons, methyl chloroform) Sources include solvents used in cleaning systems, fuels and lubricants, and adhesives.

d) Systemic Poisons – These are materials, which react irreversibly with specific organs and hinder the function of that organ.

1) General Muscle Effect – These inhibit normal muscle function or interfere with transport properties; especially in the liver. (Freons and other halocarbons) Sources include cleaning solvents and refrigerants.

2) Damage to the Blood Forming System – These generally target the *bone-marrow*. (benzene and other aromatic hydrocarbons) Sources include paints, fuels, solvents, lubricating oils.

3) Nerve Poisons (methanol, phosgene) Sources include cleaners and cigarette smoke.

4) Toxic Metals – These interfere with enzyme function and other protein related activity. (Hg, Cd, Pd, Se) Sources include products of wear of batteries and various alloys. These can be especially dangerous if they are found in organic molecules.

5) Toxic Anions – These compete for important biological reactants. (sulfides and fluorides, in particular). Sources include metal impurities in various materials.

For these and other contaminants, there are specific limits described by Navy regulations so they are monitored frequently while the submarine is under way.

5. Atmospheric Control Systems

The most effective way of reducing or eliminating toxic contaminants is the control at the source of the material. However, equipment for the removal of contaminants, and for the supply of oxygen to maintain proper atmospheric conditions, is standard on all Navy submarines.

5.1 Oxygen Supply Systems

Oxygen may be replenished while submerged by *electrolytic oxygen generators* (EOGs), stored oxygen, or oxygen candle furnaces. Most nuclear submarines are equipped with EOG systems, but many classes carry other oxygen systems as back up. The EOG can supply oxygen indefinitely; the other systems are limited by storage capacity.

5.1.1 Electrochemical Oxygen Generator

The production of oxygen is accomplished by the electrolysis of water. Direct current is passed through a KOH solution, which electrolyzes the water to H₂ and O₂. The water has been treated by an ion exchange system to eliminate other electrolytes. Sixteen electrolytic cells at about 1000 amps are required to produce 120 SCFH of O₂ (sufficient for 120 men) at

pressures up to 3000 psig. The gases are removed from the cells and distributed (O₂) or disposed of (H₂). Hydrogen is discharged overboard.

5.1.2 Solid Polymer Oxygen Generator

A new generation oxygen generator has been developed to advance the technology of safe and reliable oxygen production. The Oxygen Generating Plant (OGP) produces breathing oxygen through water electrolysis using a Solid Polymer Electrolyte (SPE) cell. This method of producing oxygen requires no free acids or caustic liquids. The OGP offers the following advantages over current units.

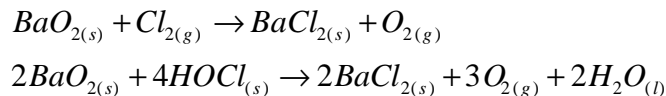
- a) Eliminates caustic electrolyte (KOH) and asbestos which is used as an insulator. The catalyst impregnated plastic diaphragm serves as both the electrolyte and separator.
- b) Microprocessor controlled. The OGP requires only 15 minutes to go through a shutdown, purge, and restart to full operation compared to the 6 hours required by the EOGs.
- c) Operates at low pressure. Although capable of operating at pressures between 300 and 3000 psi, the normal mode of operation will be at low pressure (500-600 psi) once the oxygen banks are charged.
- d) Reduced inventory of combustible gases. At equal pressure the hydrogen side contents of the OGP are one-tenth of the EOG. Lower normal operating temperatures bring further H₂ reductions.
- e) Maximum output – 225 SCFH of O₂. A 50% increase over EOG capacity, which permits providing the entire crew O₂ needs with only one OGP.
- f) Discharges pure oxygen products. Provides essentially pure O₂ compared to EOG contamination of 0.5 to 1.0 % H₂ contamination.

5.1.3 Oxygen Candle Furnace

The *chlorate candle* is a mixture of sodium chlorate, iron, a small amount of barium peroxide, and a fibrous binding material. The basic process in burning the "candle" is the thermal decomposition of the chlorate:



The iron (about 5% by weight) combines with some of the oxygen and produces enough heat to sustain the reaction. The barium peroxide is added to remove undesirable chlorine products including free chlorine and hypochlorite:



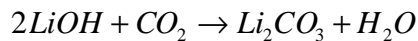
Each candle burns near 400°F for 45 - 60 minutes, and produces approximately 115 SCF of O₂ at 0.5 psig. The smoke and salt also produced must be separated by filtration. The stored candles represent a significant fire hazard since they are self-sustaining in oxygen. Resupply needs also limits their use to emergency back up.

5.2 Carbon Dioxide Removal

CO₂ is removed from submarine atmospheres by means that are classified as *regenerative* or *non-regenerative* depending on whether the absorbent can be recycled at sea.

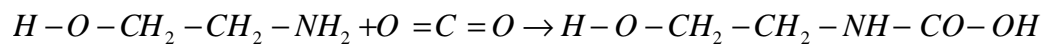
5.2.1 *LiOH absorbers*

These are a non-regenerative means for removing CO₂ from the gas stream passed through canisters holding the LiOH. Since this is the lowest formula weight strong base, it sets the theoretical standard for such ability at 29 lbs. of CO₂ absorbed per 31.5 lb. canister. Actual performance is approximately 28 lbs. In operation it can keep atmospheric CO₂ below 2% at 1 atm total pressure and does not require power for operation although it is used with a fan when possible.



5.2.2 *CO₂ Scrubbers*

These are regenerative systems which utilize aqueous solutions of 25 - 30 wt.% (4-5 M) monoethanolamine (MEA), NH₂CH₂CH₂OH. The absorption process is a *Lewis acid-base* reaction:



The reaction is reversed by heat or by exposure of the product to an atmosphere with low P_{CO_2} . The air to be treated enters the *exchange tower* at 80°F and 75% relative humidity (RH). It is blown through woven stainless steel packing over which the MEA solution is flowing. Between 70 and 90% of the CO₂ is removed by this one pass through. The air is passed through a filter to entrap droplets of the MEA solution and the air returns to the sub at about 75° and 100% RH.

The MEA solution is recycled over the stainless steel screens with a portion of it withdrawn on each pass. This material is passed through a column packed with glass rings and heated to drive off the CO₂ under pressure. The "cleaned" MEA is returned to the absorption cycle. The CO₂ is cooled, compressed, and discharged overboard.

Some problems with the system include the *carry-over* of MEA and ammonia, created when the MEA slowly breaks down during the stripping phase, into the submarine's atmosphere with the cleaned air. The decomposition of MEA is also catalyzed by the presence of metal ions so *chelating agents* are added to limit this degradation. Even with filtering, some physiologically significant material escapes into the sub.

5.3 Air Purification

5.3.1 CO-H₂ Burner

This is used to remove CO, H₂, hydrocarbons, and other contaminants by oxidizing them to CO₂ and H₂O. The system draws preheated air through a CuO/MnO₂ catalyst bed at about 600° F. The product gases are cooled and passed through a bed of Li₂CO₃ to remove any acidic gases (like HCl from destruction of refrigerants). LiOH is a minor component of the catalyst as well, so some of the acids are removed at that stage. In the final stage, the air is passed through activated charcoal, a simple *absorber*. The catalyst can be used indefinitely, if not abused, and it does not require much additional fuel once it has reached operating temperature.

5.3.2 Activated Carbon

Charcoal can be prepared from any carbonaceous material and is activated by the use of controlled heating, such as with steam. The heat removes all material from the capillaries, which cannot be carbonized. Activated charcoal differs from charcoal in that activation increases the vapor adsorption capability of charcoal. For submarine service, the activated coconut shell charcoal is generally referred to as activated carbon.

The behavior of activated carbon in removing contaminant gases is a complex phenomenon involving capillary attraction and adsorption. Adsorption is the dominant factor for organic compounds, particularly hydrocarbons.

Activated carbon is commonly used for odor removal in washroom, water closet, and sanitary tanks. In addition, galley systems and CO₂ removal plants utilize charcoal systems for hydrocarbon removal.

6. Emergency Air

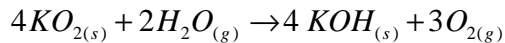
6.1 Emergency Air Breathing (EAB) System

This system is used when there is a fire with the development of smoke, CO, CO₂, or when there is the detection of a toxic component. The EAB system simply allows for direct connection of full-face masks for each crew member into the ship's clean, high pressure air banks. Masks, hoses and pressure reduction gear are part of the EAB system.

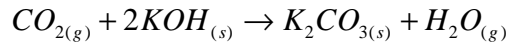
6.2 Oxygen Breathing Apparatus (OBA)

This system is a self-contained unit that is worn by each person. It can generate approximately a 60 minutes supply of oxygen and removes exhaled CO₂. This system functions by the decomposition of *potassium superoxide*, KO₂.

The reaction is initiated by water vapor exhaled by the wearer:



The KOH from this reaction, (and from water vapor interacting with K_2O , removes the CO_2 from the air in an acid-base reaction:



The system allows for rebreathing since only each breath uses a fraction of the O_2 .

6.3 SCBA – Scott Air Packs

Scott air pack is the most common self-contained breathing apparatus, which is essentially the same system as SCUBA but designed for the air environment. These systems offer portable, rechargeable breathing systems, which may serve as a replacement for OBAs.

7. Atmospheric Monitoring

The closed atmosphere in a submarine requires frequent monitoring to maintain the quality of the air. This monitoring allows detection of potentially hazardous substances as well as adjustment of the air composition. Routine analysis is conducted in several compartments before submerging and as often as three times an hour while submerged. Unusual circumstances, such as a fire, require sampling as frequently as every 15 minutes.

A number of modern instrumental techniques are used to provide quantitative assessment of these vital characteristics.

a) Infrared spectrophotometry for CO . The CO molecule undergoes vibration at a characteristic frequency in the infrared (IR) region. The amount of CO in the atmosphere is obtained by measuring the effects of IR absorption by CO at this frequency.

b) Thermal conductivity for H_2 . The uniquely small size of the hydrogen molecule accounts for its very high thermal conductivity, or ability to conduct heat. In a mixture with much larger gases, changes of H_2 content can be conveniently and simply measured by changes in the thermal conductivity of the gas stream.

c) Photoionization detection of total hydrocarbons in a trace gas analyzer (TGA). In this technique, a beam of high energy (ultraviolet) photons causes hydrocarbon molecules, both aromatic and aliphatic, to lose electrons, resulting in an ion current as a measure of hydrocarbon content. The energy of the photons is too low to ionize nitrogen, the major component of the submarine atmosphere.

d) Paramagnetic detection of O_2 and NO . Substances with unpaired electrons, such as O_2 and NO , are attracted into a magnetic field. The magnetic field used in this detector is non-uniform, allowing the torque on a sensing element in the field to change when

paramagnetic gases alter the magnetic forces. The motion of the sensing element is used as a measure of the concentration of such substances in a gas stream.

e) Mass spectrometry for quantifying a variety of contaminants. In this technique, gas molecules are ionized by an electron beam, followed by sorting of the different ions in a magnetic field. Because the ions are separated in the magnetic field, mass spectrometry allows the individual measurement of virtually all components in the submarine atmosphere. This technique is particularly powerful because it gives both the identity and amount of atmospheric components in a single automated measurement. Aboard submarines, this technique is called CAMS (Central Atmosphere Monitoring System).

Some qualitative testing is also done using *Draeger tubes*. These are glass tubes containing reagents, which change color upon reaction with specific components in the submarine atmosphere. The color can be examined *photometrically* as well, giving a semi-quantitative result. These devices work well for acetone, ammonia, carbon monoxide, carbon dioxide, chlorine, hydrogen chloride, nitrogen dioxide, sulfur dioxide, ozone, and several other compounds.

The Central Atmosphere Monitoring System (CAMS MK II) is a single unit housing a mass spectrometer to analyze for H₂, O₂, CO₂, Freon 12, 114, 134a, aliphatic hydrocarbons, and aromatic hydrocarbons and an infrared detector to analyze for CO. This unit provided continuous indication and alarm and is installed on all modern U.S. submarines.

8. Conclusion

Our diving bell suffered a loss of electrical power due to a short circuit in the electrical supply panel on the diving tender support ship. Repairs were made within about six hours and power was restored. Although the crew suffered from headache and fatigue from the low oxygen and high carbon dioxide conditions, restoration of the atmosphere control system allowed for their recovery without any permanent physiological damage.

Not unlike the diving bell scenario, submarine air monitoring, treatment and control strike a delicate balance between the submarine's available power, resources, and ability to ventilate. Submarines remain a national asset only if they remain undetected and snorkeling greatly increases their chance of detection. Operations under the ice greatly limit the ability to rely on snorkeling as an emergency backup, so systems must be designed, constructed, and maintained to the most stringent of standards in order to preserve the well being of the crew.

9. References

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