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Oxygen Equipment for Aircraft

RATIONALE

AIR825C is a comprehensive document covering general information on the various types of oxygen equipment and oxygen systems used on aircraft including basic system design information. These requirements and more are covered in greater individual detail by other SAE documents in an AIR825/1 through AIR825/14 document series.

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FOREWORD

Changes in this revision are format/editorial only.

INTRODUCTION

This report has been prepared as a revision of the previous Aerospace Information Report No. 825A dated December 15, 1974, in order to bring that report up to date by including the latest information available on the design and use of aircraft oxygen systems. Accordingly, it supersedes AIR825A. The publication issue is broken down into six (6) sections as follows:

Section I Physiological Oxygen Requirements in Normal and Hypoxic Environments

Section II Gaseous Oxygen and Oxygen Equipment, Introductory

Section III Continuous Flow Oxygen Systems

Section IV Demand and Pressure Demand Oxygen Systems

Section V Liquid Oxygen Systems

Section VI Charts, Tables and Systems Schematics

NOTE: A proposed Section VII on Cabin Pressurization and Rapid Decompression was transferred to SAE Committee AC-9 for incorporation into ARP1270, "Pressurization Control Criteria, Aircraft Cabin."

1. SCOPE:

This report provides information on the design and use of aircraft oxygen systems. It explains the physiological oxygen requirements of the human body in both a normal environment and in an hypoxic environment.

It includes an overview of the continuous flow, demand and pressure demand, and liquid oxygen systems. A basic understanding of how each system operates is then specifically addressed in its own titled section.

The charts, tables, and schematics provide a specific example of a theoretical oxygen system design and the calculations showing how that system would meet the regulations established by the FAR's. A comprehensive overview of the theoretical oxygen requirements of the human body at altitude is also provided.

A detailed list of specifications and standards applicable to aircraft oxygen systems is included.

SECTION I - PHYSIOLOGICAL OXYGEN REQUIREMENTS IN NORMAL AND HYPOXIC ENVIRONMENTS

1. An understanding of at least the elementary facts about respiration is a prerequisite for everyone having responsibilities in connection with oxygen equipment for civilian, military, commercial or general aviation aircraft. Respiration is the process by which a living organism acquires the oxygen necessary for its essential cellular functions (metabolism) and discharges gaseous products of those functions (primarily CO_2). In man this process consists of ventilation (inhalation/exhalation), diffusion of O_2 from lungs to blood (and CO_2 from blood to lungs), circulation of blood between lungs and tissues, and diffusion of O_2 from blood to tissues (and CO_2 from tissues to blood). The following is an introduction to this subject, expressed (insofar as possible) in an easily understood manner. (For reference, see Figure 1 and Table 1.)

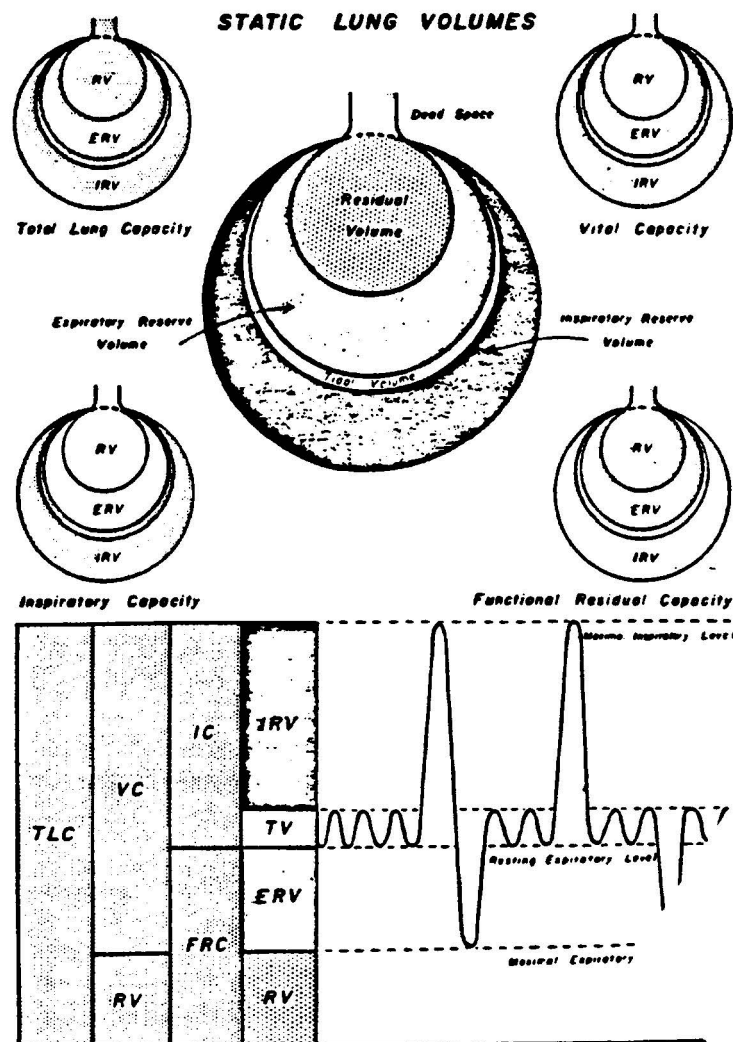
1.1 Definitions and Goals:

Although the work of breathing represents only a small fraction of the total energy expenditure of the body, any additional load imposed upon the physiologic mechanics of breathing by the oxygen equipment will not only disturb the normal breathing patterns but may also cause discomfort and fatigue of the muscles involved in breathing, as well as impose psychological impediment on an almost automatic repetitive physiological function. Every effort must be exerted to minimize impairment of normal breathing.

1.2 Lung Volumes During Breathing:

The quantity of air breathed in one minute is referred to as the minute volume ($\dot{V}$) and is 6-8 Liters in an average healthy normal man at rest. However, respiratory flow is bidirectional within the airways, flowing in (inspiration) and out (expiration) with peak instantaneous flow rates of 20 to 40 liters per minute (LPM) at rest, 80 to 100 LPM in mild exertion. It will increase as exertion and/or anxieties expand peak flow to a maximum of about 500 to 800 LPM (e.g. sneeze or cough). Figure 1 indicates regular evenly spaced respiratory cycles which under normal conditions of respiration is unusual. The normal respiration rate is known as eupnea. Eupnic Respiration is generally irregular in volume, although it may be regular on occasion. There is a normal post expiratory pause following the active-passive cycle of respiration. Ordinarily, inspiration involves an interval of 0.8 seconds, while the expiratory period is 1.2 seconds. Breathing at a rate of 12 times per minute would thus result in a 3 second post expiratory pause. As the respiratory rate increases these three intervals will decrease with the post expiratory pause showing the most marked decrease.

Each breath, in a 70 kg average normal man, has a tidal volume (V_T) (Table 1) of approximately 500 cm^3 (Figure 1) (about $8 \text{ cm}^3/\text{kg}$ body weight), which at a resting frequency of 12 to 16 per minute (R) results in a total ventilation of 6 to 8 liters in one minute. This is a respiratory minute volume ($\dot{V}$). Moderate activity such as walking leisurely requires more than twice the resting ventilation. The capacity of oxygen equipment should be designed to accommodate the transient peak inspiratory flow rates of 20 to 40 LPM (quiet relaxed breathing) but instantaneous flow rates of 500 to 800 LPM during coughing, strenuous exercises, acceleration or anxiety and excitement (associated with aircraft performance failures or misadventures) can occur and should be considered in system design.



—Above: the large central diagram illustrates the four primary lung volumes and approximate magnitude. The outermost line indicates the greatest size to which the lung can expand; the innermost circle (residual volume), the volume that remains after all air has been voluntarily squeezed out of the lungs. Surrounding the central diagram are smaller ones; shaded areas in these represent the four lung capacities. The volume of dead space gas is included in residual volume, functional residual capacity and total lung capacity when these are measured by routine techniques. Below: lung volumes as they appear on a spiographic tracing; shading in vertical bar next to tracing corresponds to that in central diagram above.

Reference: Comroe, J. H., et al., THE LUNG (Second Edition) Chicago: The Year Book Publishers, 1962.

FIGURE 1 - Lung Volumes

TABLE 1 - The Lung Volumes and Capacities

A. VOLUMES - There are four primary volumes which do not overlap (Figure 1):

1. Tidal Volume, or the depth of breathing, is the volume of gas inspired or expired during each respiratory cycle.
2. Inspiratory Reserve Volume (formerly complemental or complementary air minus tidal volume) is the maximal amount of gas that can be inspired from the end-inspiratory position.
3. Expiratory Reserve Volume (formerly reserve or supplemental air) is the maximal volume of gas that can be expired from the end-expiratory level.
4. Residual Volume (formerly residual capacity or residual air) is the volume of gas remaining in the lungs at the end of a maximal expiration.

B. CAPACITIES - There are four capacities, each of which includes two or more of the primary volumes (Figure 1):

1. Total Lung Capacity (formerly total lung volume) is the amount of gas contained in the lung at the end of a maximal inspiration.
 2. Vital Capacity is the maximal volume of gas that can be expelled from the lungs by forceful effort following a maximal inspiration.
 3. Inspiratory Capacity (formerly complemental or complementary air) is the maximal volume of gas that can be inspired from the resting expiratory level.
 4. Functional Residual Capacity (formerly functional residual air, equilibrium capacity or mid-capacity), is the volume of gas remaining in the lungs at the resting expiratory level. The resting end-expiratory position is used here as a base line because it varies less than the end-inspiratory position.
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1.3 Breathing Mechanics:

Active, vigorous inspiratory respiration is accomplished by muscular expansion of the chest rib cage, contraction of the muscular diaphragm and accessory muscles of respiration. Quiet inspiratory breathing is mainly due to lowering of the diaphragm muscle by contraction. More vigorous breathing recruits not only the intercostal muscles but other accessory muscles of respiration (strap muscles of the neck, shoulder girdle, abdominal muscles). The work performed in this phase has to overcome (1) the resistance to air flow in the oronasal passage, larynx, trachea, bronchi and bronchioles; (2) the elastic recoil of the lungs; and (3) inertia of the chest wall, abdominal contents (intestine, liver, spleen, etc.) and the abdominal wall. Subject position (standing, sitting or supine), i.e. gravity, G-forces, and tissue densities, influence the importance of these factors. Expiration during normal breathing on the other hand, does not require active muscular respiratory effort since the elastic forces of the lungs and relaxation of the chest wall suffice to expel the inspired tidal volume. This relaxation of the respiratory muscles reverts the chest volume to the initial resting exhalation position. During positive pressure breathing, the normal pattern is reversed and active effort is required to exhale while mask pressure assists in inflating the lungs during inspiration. It is due to this balance of forces and the cyclic nature of the act of breathing that pressure-demand equipment with "safety pressure" requires the least effort and is at the same time the most economical (physiologically, mechanically and for energy). However, transmural airway pressures above 19 mm Hg (10 in H₂O) are abnormal and tax the recipient physiologically and psychologically. His passive exhalation now must become active and he is required to think in order to forcefully expel his inspiratory air. As soon as he relaxes he is again inflated (inspiration). "Torso Restraint", discussed later, is helpful in this type of "reversed"-abnormal-respiratory cycle.

1.4 Respiratory Air Composition:

At sea level the atmospheric pressure is around 101 kPa (14.7 pounds per square inch), which is equivalent to the pressure exerted by a column of mercury 760 millimeters high (in the earth's gravitational field). One of the laws describing the behavior of mixed gases is the law of partial pressures. This simply means that in any given mixture of gases, such as air, at any given total barometric pressure, the partial pressure exerted by each one of the components in this gas mixture is proportional to the volume percent (%) of each component present. Since air (for practical purposes) consists of about 21% by volume oxygen and 79% by volume nitrogen, oxygen exerts a partial pressure of 21% of 760 mm Hg or 160 mm Hg, and nitrogen 79% of 760 mm Hg or 600 mm Hg. Here the term mm Hg refers to the partial pressure (expressed as the height in millimeters of a column of mercury) exerted by each major part of the two gases composing air. (See Section VI, paragraph 6.8 Composition of the atmosphere, page 77.) A small part of our atmosphere, actually around 1% of the air, consisting of the rare gases -- argon, krypton, xenon, and a few others in trace amounts -- has been included in the nitrogen portion. There is also a varying amount of water vapor in the air giving rise to the humidity. This is expressed in terms of percent of saturation or in millimeters of mercury partial pressure exerted by the water vapor present, at a given temperature. Ordinarily the amount of water vapor in inspired air is extremely small and will detract only slightly from the inspired oxygen component. When calculating oxygen partial pressure in the

1.4 (Continued):

expired or alveolar air, carbon dioxide (normally about 40 mm Hg) and water vapor partial pressure at 37 °C (47 mm Hg) -- (which have been added by the lungs to the total alveolar gas volume) -- must be included as part of the total alveolar pressure. Thus these gases must be subtracted from the breathing barometric or mask pressure prior to calculating alveolar oxygen tensions (mm Hg) from inspired gases (air for example).

1.5 Respiratory Gas Passages:

The air we breathe passes into the trachea or windpipe and from there into the lungs (Figure 2). It undergoes considerable changes in composition as it passes through the trachea, mixes with the gases and water vapor already in the lungs, and is again exhaled. First, the inspired air becomes fully saturated with water vapor at body temperature in the nose (passing by the nasal turbinates) and throat so that the delicate tissue in the lungs will not be damaged by drying. It then mixes with the air already in the lungs that contains carbon dioxide and perhaps small amounts of other gases which, like the rare gases, are of insufficient amounts to be of importance here. Sea level, average figures are given below for a sample of air from the trachea (called tracheal air) and from the lungs (called pulmonary or alveolar air), to show the difference in composition. These are typical values measured in young, healthy, non-smoking, disease free individuals. The proportions of these gases are expressed in millimeters of mercury partial pressure, as well as in percent (%):

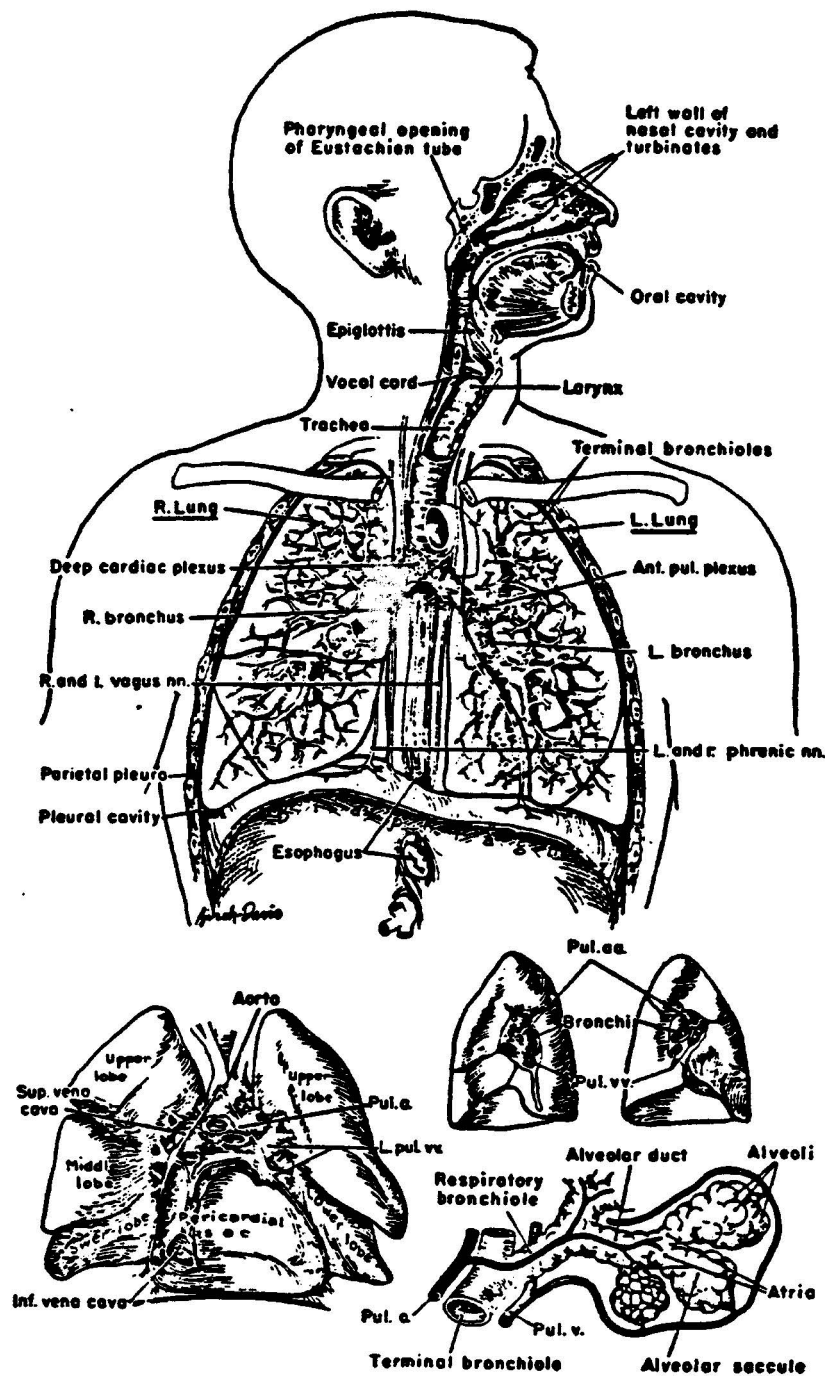
Partial Pressure, mm of Hg (and per cent)

TABLE 2

	Dry Air	Tracheal Air Inspiratory	Alveolar Air (Static) or End Expiratory
Oxygen	160 (21)	149 (19.6)	104 (13.7)
Water Vapor	--	47 (6.2)	47 (6.2)
CO ₂	--	--	40 (5.2)
Nitrogen	600	564	569
TOTAL	760	760	760

1.6 Tracheal Partial Pressures:

For practical purposes the inspiratory tracheal partial pressure is generally used as the criterion of oxygen availability to the body because it can be accurately predicted if the barometric pressure and the fraction of oxygen in the inspired gas are known. The figure 149 mm Hg oxygen partial pressure in the tracheal air is derived from the total pressure, 760 mm Hg, minus 47 mm Hg water vapor pressure (saturated air at body temperature), multiplied by the fraction of oxygen (0.21).



Reference: "Dorland's Illustrated Medical Dictionary," 23rd ed., p 1355, Philadelphia: W. B. Saunders Co., 1957.

FIGURE 2 - The Respiratory System: Man

1.7 Alveolar Partial Pressures:

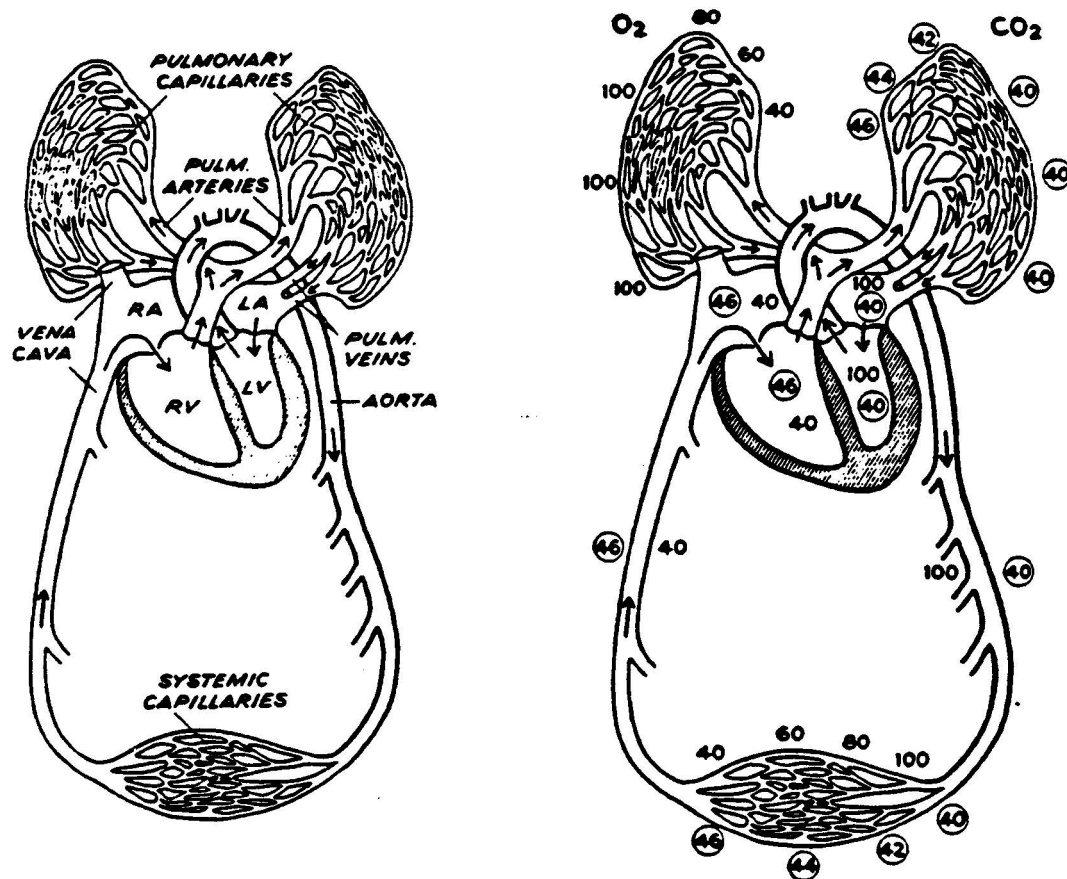
The alveolar partial pressure of oxygen cannot be predicted precisely since it is subject to individual variations in oxygen consumption, pulmonary ventilation and associated pulmonary disease. It must be measured directly from end expired gases by sophisticated instrumentation such as a recording mass spectrometer programmed for expiratory gases.

1.8 Physiologic Oxygen Transport:

Oxygen in the alveoli diffuses through the thin permeable hydrophilic membrane into the capillaries that envelop the alveoli and thence into the red corpuscles where it binds with hemoglobin. The diffusion rate is proportional to the partial pressure of the oxygen present in the alveoli, intracellular fluid and plasma of the blood. The overall amount of oxygen reaching the blood depends upon several additional factors. These include vascular shunting of venous blood to the arterial side of the circulation without re-oxygenation, diffusion barriers to oxygen at the alveolar membrane (silicosis, pneumoconiosis, other causes of pulmonary fibrosis and/or alveolar membrane thickening -- e.g. tobacco smoking), blood flow differences between the top and bottom of the lung because of gravitational effects, non-blood-perfused alveoli, collapsed alveoli (atelectasis), etc.

On their circuit through the body the red cells, at the systemic capillary tissue level (Figure 3), release a portion of their oxygen load to the body tissue for use in the life sustaining processes (metabolism). This release is aided by the oxygen partial pressure gradient (O_2 higher in capillaries, lower in adjacent tissues) and greater acidity (pH effects) in the adjacent tissues due to CO_2 and other metabolic acids.

Many factors can reduce the efficiency of oxygen loading/transport/release by the blood. Among these are anemia, sickle-cell disease, acidosis, some genetic enzyme deficiencies, and various toxic substances (alcohol, carbon monoxide, many drugs, etc.).



-Schematic representation of the pulmonary and systemic circulations. RA=right atrium; LA=left atrium; RV=right ventricle; LV=left ventricle.

-O₂ and CO₂ tensions in pulmonary and systemic blood. Figures in circles are CO₂ tensions; others are O₂ tensions.

FIGURE 3

1.9 Oxygen Partial Pressures Related to Altitude:

As one goes to higher altitude, the total air pressure diminishes and with it the partial pressure of each of the various gases. The percentage relationship of the gases remains unchanged however. The following table shows the approximate oxygen partial pressure (mm Hg) while breathing air at various altitudes:

TABLE 3

	Sea Level	1524 m (5000 ft)	3048 m (10,000 ft)	4267 m (14,000 ft)
Air Oxygen Inspired (dry)	160	132	109	93
Tracheal Oxygen	149	122	100	84
Pulmonary or Alveolar Oxygen	104	82	60	44

Chart II is referenced for altitude and oxygen partial pressures. (See Chart II, pages 91-94.)

It is important to keep in mind that the partial pressure of water vapor at body temperature (37 °C) is 47 mm Hg regardless of altitude. The higher the altitude, the greater is the effect of the water vapor component in decreasing the usable oxygen component.

1.10 Hypoxic Recognition:

Normally, individuals living at sea level may become aware of the effects of altitude at about 1524 m (5000 ft) where the diminishing partial pressure of oxygen results in lessened ability to see at low levels of illumination (night blindness). Decrements in other physiological functions are demonstrable under controlled test conditions at around 1829 or 2438 m (6000 or 8000 ft). Red blood cells are no longer able to acquire a full load of oxygen. However, these altitude effects ebb as the body adjusts and acclimates itself so that after a few days the mild symptoms disappear. Nonetheless most individuals going as high as 3048 m (10,000 ft) will notice definite symptoms of altitude sickness, such as tingling, numbness, tunnel vision and night blindness. These will be particularly evident with exercise. Pilots flying at this altitude or above for any length of time should have oxygen enriched air to breathe in order to maintain the partial pressure of oxygen in the trachea and alveoli sufficient to allow the red cells to take up a nearly normal complement of oxygen.

1.11 Hypoxia:

Mild conditions of oxygen want are called hypoxia -- meaning insufficient oxygen. The symptoms usually increase in severity as time of exposure increases. When the oxygen partial pressure in the lungs falls to 30 mm Hg or less, oxygen supply to the tissues (brain in particular) becomes totally inadequate to maintain consciousness.

1.12 Results of Hypoxia:

Whenever the body tissues fail to receive adequate oxygen from the red blood cells, essential life functions are disrupted. Earliest and most apparent are the severe changes in mental function. Even with minor decreases in oxygen supply (as results from 3048 m (10,000 ft) over a period of time) the brain responds with muddled, confused, uncoordinated thinking, euphoria, and poor judgment. Further decreases in arterial oxygen partial pressure will produce mental symptoms of increasing severity culminating in unconsciousness and death if the oxygen level becomes sufficiently low. Early onset of these altered mental functions, which are not recognized by the individual, represents serious hazard to aircrew, and may be the direct or indirect cause of many accidents, particularly in the "pilot error" category. Even small amounts of alcohol can aggravate and intensify these deleterious effects. For those flying at night it should be noted that there is a moderate loss of night vision at the altitude of 1524 m (5000 ft). Aircrew are recommended to use supplemental oxygen above this altitude during dusk, night flights and night landings.

- 1.12.1 Beards: Airmen who sport beards, mustaches, and/or side burns of the size and type which interfere with mask-to-face-skin contact cannot be adequately protected from hypoxia because of improper mask fit. During inhalation, "inboard" air leakage dilutes the oxygen enriched inspiratory gases. "Safety Pressure" regulator setting will tend to obviate these beard leaks. The presence of a beard will tend to defeat positive pressure ventilation. Consequently, the low tracheal oxygen concentration during aircraft cabin decompression will significantly reduce the airman's time of useful consciousness. In addition a beard can be a fire hazard, especially in oxygen enriched atmospheres. A beard together with smoking is an extreme fire hazard in an oxygen enriched atmosphere and must be prohibited whenever oxygen is in use.

1.13 Chronic Hypoxia and Adaptation:

People living at high altitudes adapt to the lower pressure and thus become acclimatized. For altitudes above 1524 or 1829 m (5000 or 6000 ft) acclimatization requires a few days to two weeks for healthy, young individuals, and longer for older persons or those exposed to higher altitudes. It is important to know that acclimatization to altitude does not take place as a result of flying, even with daily flying, because continuous exposure is required.

1.14 Oxygen Requirements Between Flight Levels 340 and 425:

When one reaches an altitude of 10,363 m (34,000 ft), the standard atmospheric pressure is only 187 mm Hg. Even if 100% oxygen is breathed at this pressure, there will be an oxygen partial pressure of 100 mm Hg or less in the lungs, after allowance is made for the 87 mm Hg partial pressure exerted by the combined water vapor and carbon dioxide. This is the minimum level of alveolar oxygen partial pressure in healthy, non-smoking persons which will provide a full oxygen load to the red cells. To maintain full oxygenation at higher altitudes, more pressure must be applied to the oxygen which is to be inspired. Pressure breathing masks accomplish this by raising the pressure in the lungs above that of the surrounding atmosphere.

1.15 Oxygen Requirements Above Flight Level 425:

As still higher altitudes are reached using pressure breathing, the mask pressure required to maintain full oxygenation of the red blood cells becomes increasingly unbearable because of the increased internal pressure inside the chest. At that point, counterpressure to the chest wall and remainder of the body must be applied to make such breathing pressures tolerable, to maintain balanced unimpeded blood flow and to prevent actual physical damage to the lung tissue. "Partial pressure" and "full pressure" altitude suits provide this counterpressure: the first by direct mechanical containment using inflatable bladders on most visceral and muscular areas of the body, and the second by containing the body in a gas pressurized enclosure. As long as these measures are able to maintain adequate counterpressure, the internal pressure of the oxygen to be breathed can be kept at a level which will ensure adequate oxygenation of the red blood cells and corresponding adequate vital tissue function. With this type of protective equipment, man can continue to function at altitudes where essentially no ambient pressure exists, as in the vacuum of outer space. The airman is able to perform this feat only by carrying the equipment necessary to maintain adequate oxygen pressure within his lungs while external counterpressure is applied to make normal breathing possible. An alternate approach, of course, is to pressurize the cabin at an altitude equivalent to 1829 to 2438 m (6000 to 8000 ft) which diminishes the need for highly specialized oxygen equipment. The great danger then arises from loss of pressurization whereupon severe hypoxia, as well as decompression sickness, will occur. Decompression sickness occurs in a large number of people after a few minutes' exposure to low ambient pressures and is aggravated by exercise as well as by prolonged exposure. (Discussed and expanded later in paragraph 1.17 et. seq.)

- 1.16 The advent of aircraft with pressurized crew and passenger compartments for flying above 4572 m (15,000 ft) altitude introduced the additional hazard of decompression in the event of airframe failure. The speed of the decompression depends on the cabin volume (see ARP1270), the area of the failure orifice (cabin or cockpit window, door or wall area), and the altitude or pressure differential between the cabin and ambient air. From such data it is possible to estimate the area of the leaking orifice for a given cabin volume to decompress from 2438 m to 12,800 m (8000 to 42,000 ft) altitude in a given period of time. Orifice size for ten second decompressions between these altitudes for cabin volumes of 7.5 m^3 (265 ft^3) and 17.8 m^3 (630 ft^3) with compressors inoperable can be computed. The orifice size producing the decompression profile (8000 to 39,000-40,000 ft altitude in ten seconds) for the larger cabin (17.8 m^3) is approximately 25% of the area of a single cabin window. In wide body aircraft with enormous cabin volumes, small leaking orifices permit adequate time to respond to the slowly dropping pressure by supplying supplemental oxygen and initiating a safe rapid aircraft descent. If the rupture or structural failure is large (such as door failure, 1.82 m^2 (20 square ft) area, or bomb damage, etc.) in the wide body aircraft, the effects will be a very rapid to explosive decompression. Rapid decompression is observed in small aircraft decompressing through a single 650 cm^2 (100 in^2) cabin window failure. Experimental data indicate that such failures will produce rapid decompressions of less than a second in smaller volume aircraft, ranging up to 30 seconds in larger volume wide-body aircraft. In the smaller volume aircraft decompressions, many passengers initially breathing air at 8000 ft altitude may lose useful consciousness at flight level 390 to 400 even if successful in donning the presented oxygen mask in less than 3 seconds and inhaling the supplemental oxygen provided.

1.16 (Continued):

To prevent severe hypoxia following decompression to FL550, the crew must breathe 100% oxygen at a positive mask pressure of 40 to 60 mm Hg (21 to 32 in H₂O). Torso restraint vests or chest counterpressure garments enable aircrew to tolerate such high breathing pressures for a short time with little hazard of incapacitation or lung damage. Emergency descent must be initiated as soon as possible following decompression because even these extreme measures provide only limited "get-me-down" protection.

1.17 Decompression Lung Damage:

During very rapid decompressions (less than one second) tears through the lung tissue may occur. This event may occur in some individuals if they hold their breath or close their glottis (as in coughing and some speech) at the instant of decompression. As gas held in the alveoli and airways attempts to expand very rapidly, it can rupture tissues and enter the potential space between the inner chest wall and the lung itself. The trapped gas in the chest cavity collapses the lung, occluding pulmonary blood flow, and preventing oxygenation in the alveoli. Carbon dioxide produced by the body cannot be dissipated, and rapid, severe hypoxia and hypercapnia (elevation of carbon dioxide) result. This condition (asphyxia) can become fatal if not treated quickly.

1.18 Decompression Performance Decrement Prevention:

Despite the rapid availability of 100% oxygen from quick donning masks, crew members in small cabin airplanes experiencing rapid decompression undergo substantial performance decrements due to hypoxia. Alveolar oxygen washout (the oxygen reversal phenomenon) which occurs during such decompressions causes brain deoxygenation unless a high concentration of oxygen is being breathed prior to the decompression. Rapid decompression also accelerates carbon dioxide diffusion into the alveoli, increasing alveolar CO₂ partial pressure which further lowers alveolar oxygen partial pressure. Current experimental data clearly show that moderate or severe performance decrements are virtually inescapable under such circumstances. Therefore, for flights at or above flight level 350, the pilot in control of the small cabin volume aircraft must wear a demand oxygen mask supplied with 100% oxygen or an oxygen-air mixture as determined by a properly functioning dilution regulator. Should cabin pressure altitude exceed flight level 390, this will assure his continued skill and judgment by preventing hypoxia in these excessively low oxygen partial pressures.

The higher the final altitude and the longer the interval between the start of a rapid decompression and the inspiration of 100% oxygen, the greater is the magnitude of the hypoxia. This is minimized by a higher alveolar oxygen partial pressure existing at the start of decompression, and the resulting higher alveolar oxygen partial pressure remaining at the completion of the decompression. Therefore, the partial pressure of the oxygen in the gas breathed by the aircrew in routine flight should approximate breathing air at ground level. However, the equipment required to provide such a cabin pressure at altitude would impose unacceptable weight penalties on aircraft performance and operation. Breathing air at an altitude of 2438 (8000 ft) would provide an alveolar oxygen partial pressure (PAO₂) of 70 mm Hg (assuming alveolar CO₂ pressure of 40 mm Hg), which is the minimum value acceptable for an operating air crew during routine flight. When the crew wears demand oxygen breathing equipment, ground level PAO₂ (109 mm Hg) can be easily provided.

1.18.1 Beards: Beards on operational aircrews usually prevent protective breathing equipment from functioning properly. The inability to provide a tight oxygen mask fit on the bearded face prevents supplying the airman-crew member with suitably oxygen enriched breathing gas to preclude hypoxic decrement in performance. The dilution effect of hypoxic ambient gases to the 100% oxygen mask supply is quickly evident in the decrement of airman operational performance. Adequate protective breathing provisions should, in the event of a loss of cabin pressure, prevent any resultant hypoxia from impairing the performance of aircrew members having essential duties to perform immediately following decompression.

1.19 Aeroembolism:

Rapid decompression experienced with failure of the pressurized aircraft cabin, especially in the smaller aircraft can rapidly lead to aeroembolism (small gas bubbles in the blood vessels). The multiple bubbles found in aeroembolism impair and block blood flow to body parts supplied by the obstructed blood vessel (similar to a vapor lock). If the organ or body parts supplied by the occluded vessel is vital (brain, spinal cord, and/or heart), sudden loss of oxygenated blood perfusion would be rapidly fatal. In other body parts, such as muscle, bone, liver, kidney, spleen, teeth, and joints, disabling pain may well be initiated such that the airman is totally non-functional although still alive. Correction of aeroembolism by rapid recompression is successful if time permits.

1.20 Decompression Sickness:

By definition decompression sickness includes all ailments, excluding hypoxia, associated with barometric pressure changes. Aeroembolism is a form of decompression sickness discussed in 1.19. These ailments manifest themselves as ear pain, sinus blockage and pain, abdominal gas expansion, toothache, bends, chokes, skin sensations or paresthesia, and other neurological symptoms.

Consideration of these effects of barometric changes may be divided into the general topics of trapped gases and evolved gases (see Table 4).

TABLE 4 - Summary of Types, Symptoms, Occurrence and Treatment of Decompression Sickness

Dysbaric Condition	Symptoms	Occurrence	Treatment
Paresthesia (Creeping)	Tingling, itching, cold and warm sensations of skin	During ascent	Descend
The Bends	Pain in and about the joints; possible collapse	During ascent	Descend and refer to flight surgeon
Chokes	Burning sensation beneath sternum; nonproductive cough; sensation of suffocation; collapse	During ascent	Descend and refer to flight surgeon
Aerotitis	Hearing becomes dull; fullness in the ear; pain; severe cases: damage and possible ear drum rupture.	Usually during descent; occurs during ascent when individual has upper respiratory infection or other similar infection.	Swallow, yawn cough. Valsalva ¹ and ascend to higher altitude; spray with vasoconstrictors.
Aerosinusitis (Sinus Pain)	Pain; frontal sinus; pain in forehead; cheek sinus; pain in cheekbones, may be referred to teeth.	During ascent and descent	Level aircraft and descend; vasoconstrictors descend slowly; if occurs on ascent, return to ground level.
Gas Expansion (G I Tract)	Discomfort, pain, interference with respiration severe cases; lowered blood pressure, possible collapse and shock.	During ascent usually above 25,000 feet; in rapid ascent may occur as low as 15,000 feet.	Descend. If marked, level aircraft and massage area. If ineffective, individual should return to ground level.
Aerodontalgia (Toothache)	Pain in the area of the affected tooth.	During ascent (usually between 5 to 10 thousand feet). Occasionally during descent.	Level aircraft and descend. Refer to dentist after flight.

¹ Valsalva's maneuver is an attempt to forcibly exhale with the nose and mouth closed in order to equalize the atmospheric pressure over the middle ear tympanic membrane.

- 1.20.1 Trapped Gases: The gases trapped in the middle ear, sinuses, teeth, and gastrointestinal tract expand or contract (increase or decrease in volume) in accordance with Boyle's Law, which states that the volume of a gas is inversely proportional to the pressure of the gas if the temperature remains constant. This means that as the pressure decreases, as it does when we go to higher altitude, gases expand or increase in volume. Applied to a dry gas, approximate values for increase in volume will be as multiples of the denominator of the fraction of the atmosphere considered. For example, at 1/2 atmosphere (5486 m = 18,000 feet) the volume of a gas will be twice that at sea level: at 1/4 atmosphere (10,363 m = 34,000 feet) the volume will be four times that at sea level. However, in calculating expansion of gases saturated with water vapor (as in the body cavities), the actual increase in volume is greater than that given for dry cases. The following equation will explain how expansion for wet or saturated gases occurs. Let V_1 represent the initial volume; V_2 the final volume at any altitude; P_1 the initial pressure; and P_2 the total pressure at the final altitude concerned. Water vapor exerts a constant pressure of 47 mm Hg in saturated gas at body temperature. You then solve the volume change equation

$$V_2 = \frac{P_1 - 47}{P_2 - 47} (V_1)$$

to calculate the expansion of a wet gas at 5486 m (18,000 feet) from initial conditions at sea level.

$$V_2 = \frac{760 - 47}{380 - 47} (V_1) = 2.14 V_1$$

The gas expansion of 18,000 feet would then be 2.14 times the volume at sea level. This calculation shows that a wet gas will expand slightly more than a dry gas.

- 1.20.1.1 The Ear: Of all the body cavities, the ear can be expected to cause trouble most often in flight. Training in clearing the ears will alleviate most of these conditions. With an infection or inflammation of the naso-pharynx, difficulty may be experienced and the airman or passenger should avoid flying.

The middle ear is a closed cavity except for an opening, called the Eustachian tube, which connects with the nasopharynx. With ascent, decreasing atmospheric pressure results in the expansion of the air trapped in the middle ear and the ear drum bulges slightly. Such pressure is normally equalized by escape of some air out of the Eustachian tube. This escape will be noticeable to the individual by a faint popping sound in the ear as the drum snaps back. Because of the structure of the Eustachian tube, equalization of pressure in the ears on descent is more difficult than on ascent. The opening of the Eustachian tube in the naso-pharynx is similar to a flutter or flap valve and although the air is readily forced out of the middle ear, it is more difficult to force the air back in on descent. A cold or similar infection may cause the opening of the Eustachian tube to become inflamed, thereby blocking the passage of air. Increasing pressure of the atmospheric air pushes the ear drum inward so that a retracted drum results. Continued pressure irritates the membrane and it becomes red, swollen and painful. This interferes with hearing and if the drum is stretched far enough, rupture of the membrane may result. The pressure differential may also affect the inner ear mechanism and produce vertigo.

1.20.1.1 (Continued):

Swallowing, yawning, and stretching the neck all aid in opening the eustachian tube and allowing air to equalize the pressure in the middle ear. If these actions fail, the ValSalva or Frenzel maneuver will often cause equalization to take place. This maneuver consists of closing the mouth, holding the nose shut and gently blowing to force air up the eustachian tube. If the ears are so completely blocked and this procedure does not aid the condition, ascend several hundred feet and try to clear the ears again. The important thing is that the ears be cleared frequently upon descent. If clearing is delayed until pain and discomfort are felt, the task becomes more difficult. Use of nose spray and drops is often beneficial. All sleeping personnel should be awakened upon descent since clearing of the ears is not automatic.

1.20.1.2 The Sinuses: As in the ear, air-filled spaces in the skull usually ventilate freely except in cases of a cold when the membranes become swollen and prevent passage of air from the ducts that open into the nose. Be sure the nose and throat are clear before takeoff and again before letdown. Here again, nose spray or drops may be of great value.

1.20.1.3 Gastrointestinal Tract: Gas taken into or evolved in any part of the gut behaves in accordance with the same laws that affect the ears and sinuses. Gas will escape readily at either end of the alimentary canal but expansion in the rest of the tract may cause pain and discomfort. Trapped gas in the intestine will expand in accordance with Boyle's law and at body temperature this expansion may become severe enough to cause such pain as to bring on shock conditions. The only cure for trapped gas expansion is to descend to a lower altitude. Prevention is more important and care should be taken not to eat or drink foods that are known to cause gas in the digestive tract.

1.20.1.4 Teeth: Pain in the teeth, occurring as a result of exposure to lowered barometric pressures, is called aerodontalgia. Some cases of tooth pain are actually due to pain referred from the sinuses. The mechanism which is responsible is somewhat obscure. Some cases of tooth pain and loss of fillings at altitude are believed to be due to the subjects unconsciously increasing their biting force and grinding their teeth together, particularly during the emotional stress. A pocket of gas trapped under a faulty filling and located very near the tooth pulp cavity might cause tooth pain by expanding and creating pressure on a nerve (pulpitis).

1.20.2 Evolved Tissue Gases: The amount of any gas dissolved in the blood and tissue fluids of the body is directly proportional to the pressure of that gas (Henry's Law). With the decreasing pressure that occurs at altitude such gases come out of solution. These gases are normally transported by the blood passing the alveolar membrane of the lung. The gases come out of solution at the alveolar boundary, pass into the lung, and thence to the outside atmosphere. When one ascends to altitudes above 9144 m (30,000 feet) while breathing air, the fluids of the body release their dissolved gases more rapidly than the blood can carry them off.

Bubbles may also form in the body tissues following rapid decompression. Such bubbles outside the blood vessels, especially in poorly perfused areas such as joints, can produce pain. Recurring decompression exposure can lead to degenerative tissue changes.

1.20.2 (Continued):

Treatment to correct these bubble-produced dysbaric episodes is recompression to one atmospheric pressure. Sometimes, in decompression shock, recompression to 2 to 3 atmospheres is required and will be life saving. Decompression shock results from bubble formation in extravascular (outside the blood vessels) tissues (brain especially) and is resistant to resolution when reexposed to sea level recompression.

Nitrogen bubbles fall into this category, requiring increased pressure (2 to 3 atmospheres) to drive the nitrogen bubbles back into solution. Their evolution in this situation is most likely from fat tissue cells throughout the body where nitrogen is most soluble but only with a very slow solubility time constant.

- 1.20.3 Bends and Chokes: These conditions are brought about by decreasing barometric pressure which results in the release of gases, primarily nitrogen, from the various body fluids and tissues. Bends were first encountered by caisson workers and deep sea divers. The reduction in pressure that occurs when a person comes up to the surface of the water (1 atmosphere pressure) from a depth of 10.3 meters = 33.9 feet (2 atmospheres), is similar to that which occurs when one goes from sea level to 5486 m = 18,000 feet (1/2 atmosphere).

The exact mechanisms that produce the symptoms are not fully understood. It is known that the inert nitrogen is a primary factor and that it is difficult to dispose of the excess gas rapidly, with decrease in pressure favoring its release from solution. This is particularly true of tissues which are poorly supplied with blood vessels and that dissolve large amounts of the gas (i.e., fat tissues). All the gases evolved or released from solution may be disposed of by passing into the blood and then diffusing through the lung alveoli for loss by expiration. The release of gases in excess of what can be readily disposed of in this manner results in the formation of gas bubbles in the tissues and blood stream. The first symptoms rarely occur below 9144 m (30,000 feet) but increase above that level with prolonged exposure. At first there is migratory pain in an extremity or joint. This symptom is associated with the bends. With increased altitude, the pain usually becomes more intense and may lead to vascular changes indicating shock conditions. If despite increasing pain the subject remains at altitude or ascends higher, he will probably eventually collapse.

The best cure for bends is immediate descent to ground level and concurrent treatment with 100 percent oxygen. Perhaps compression therapy may also be employed until all symptoms disappear. Breathing 100 percent oxygen for one-half hour before takeoff and using 100 percent oxygen throughout the flight will aid in preventing the bends by allowing nitrogen dissolved in tissues to be "washed out".

Another symptom of decompression sickness, "the chokes," occurs when escaped gases involve the lung vessels. There is a deep substernal burning, a nonproductive cough arising from deep within the chest, and a sense of suffocation and apprehension. As in bends, descent to lower altitudes (6096 m = 20,000 feet) usually gives relief, but symptoms may persist to ground level and should be treated until they disappear.

1.20.3 (Continued):

Remember that while bends rarely occur below 10,363 m² = (30,000 feet), incidence increases with rapid rate of ascent, prolonged duration at altitude, exercise, age and obesity. Very slow ascent (30 m/min, 100 ft/min) and breathing 100 percent oxygen on the flight will help prevent most symptoms of evolved gases.

1.20.4 Paresthesia and Skin Rashes: Paresthesia (burning or itching sensations) and skin rashes are mild symptoms which occasionally occur and are made worse by exercise and scratching. They are assumed to be due to small gas bubbles in subcutaneous fat or in tissue adjoining nerve endings in the skin.

1.20.5 Flying Following Scuba Diving: Evolved tissue gases (1.20.2) become more medically significant and symptomatic to airmen at hypobaric altitudes following Scuba diving. The National Oceanic and Atmospheric Administration (NOAA) recommend in their diving manual, safety rules for divers who intend to fly as passengers. Any diver who has completed any number of dives on air and decompressed following U.S. Navy standard air decompression tables should wait at sea level breathing air for the computed surface interval that is specified for Group D divers in U.S. Navy Repetitive Diving Table. The aircraft cabin atmosphere must not exceed 8000 feet altitude.

While decompression sickness may, in some rare cases, occur up to 24 hours after exposure to pressure, the vast majority (95 percent) will be evident within 3 hours; one percent will be delayed over 6 hours. It is therefore important that a diver who is flying an aircraft delay his flight for 24 hours to preclude symptoms and signs of decompression sickness.

SECTION II - GASEOUS OXYGEN AND OXYGEN EQUIPMENT, INTRODUCTORY

2. OXYGEN:

Current aircraft breathing oxygen systems may utilize either gaseous or liquid oxygen.

- a. **Gaseous Oxygen:** Gaseous oxygen in the atmosphere is colorless, odorless, and tasteless. It comprises about 21% of normal air by volume and is about 10% heavier than air. Above its critical temperature of -180.4 F (-118 C), oxygen can exist only as a gas regardless of the pressure exerted upon it. Breathing oxygen quality is specified by Military Specification MIL-O-27210.
- b. **Liquid Oxygen:** For information on liquid oxygen, see Section V.

2.1 Oxygen Equipment:

Oxygen equipment to fulfill man's physiological needs in aircraft falls into two general categories, fixed and portable. Fixed equipment is generally provided in those aircraft in which oxygen is frequently required or many passengers are involved. Whether these aircraft have portable equipment in addition depends on FAA requirements for the crew and passengers supply and whether there is a requirement to move from one fixed oxygen station to another.

Cockpit fixed equipment is mounted on the control console or any other convenient location within easy reach. Gauges, indicating instruments, and regulators are placed together and located in the pilot's or co-pilot's normal field of vision so that he can readily see the gauges when in a normal flight position and with minimum interference to his other flight duties.

Portable oxygen equipment consisting of a cylinder of oxygen, a control valve and regulator, and mask are provided for one or more of the crew members where movement of the crew to various stations is involved. Portable equipment is also required for passengers on aircraft not having fixed oxygen installations for first aid use.

- 2.2 Both portable and fixed oxygen equipment can be obtained for continuous flow, demand flow, diluter-demand and pressure-demand types of oxygen systems.

- 2.2.1 **Continuous Flow Equipment:** As its name indicates, continuous flow oxygen equipment provides a continuous flow of oxygen to the mask. There are several types of continuous flow systems ranging from the simplest to more complex systems which afford varying degrees of oxygen economy. At lower altitudes where pure oxygen is not required, air can be added to the mixture of gas delivered into the mask by a controlled means. During inhalation, oxygen flow from the regulator is supplemented by the air which enters through these ports. The amount of air entering the mask depends on the rate of oxygen flow and the rate at which the user inspires. A more complex system would include a gas reservoir in addition to the air ports.

2.2.1 (Continued):

The reservoir is used to collect oxygen during the exhalation phase and permits a much higher inspiratory rate of flow before air dilution takes place. Some systems are designed to collect a fraction of the expired gases for use during the following inspiration. These systems are known as rebreather or economizer circuits. The primary disadvantage of the constant flow system is its inability to adjust itself automatically to various levels of physical exertion of the aircrewman in aircraft. The regulator output for various altitudes can be controlled automatically or by a manual adjustment. This system has been used for many years. It is probably the simplest from a design, cost, weight, and maintenance standpoint and offers reasonable safety for brief periods at altitudes as high as 40,000 ft (12,192 m). For prolonged protection, continuous flow equipment is generally regarded to be adequate up to 25,000 ft (7620 m).

2.2.2 Demand Flow Equipment: Demand flow equipment can be straight demand (a system which delivers pure oxygen) or can be obtained with an air mixing feature (diluter-demand) to conserve oxygen. The distinguishing feature of the demand system is the outlet control valve in the regulator which responds to minute changes in pressure. The slight negative pressure (referenced to ambient) created within the mask at the onset of inspiration opens the valve and permits oxygen flow to pass into the mask until the end of inspiration. At this point the mask pressure has become slightly positive and the valve shuts off the flow. In this manner the demand system operates as the name implies, on demand, supplying flow at the rate required by the user and conserving the oxygen supply during the entire exhalation phase of each breathing cycle.

2.2.3 Pressure-Demand Equipment: Pressure-demand equipment varies from other oxygen equipment previously discussed which provides an oxygen enriched atmosphere for breathing. The technique of increasing the concentration of oxygen can be successfully used up to an altitude of approximately 35,000 ft (10,668 m). Pure oxygen delivered at this altitude will produce the same effect as breathing air at 5000 ft (1524 m). Beyond 35,000 ft (10,668 m), however, it becomes necessary to increase the pressure of the oxygen delivered to the mask in order to provide a 5000-ft (1524 m) equivalent altitude. This is the purpose of the pressure-demand system. Pressure-demand regulators function very much like demand regulators. They can be obtained with or without provisions for air dilution at altitudes below 34,000 ft (10,363 m) where a mixture of air can be tolerated for reasons of economy.

2.2.3 (Continued):

A regulated positive pressure of 100% oxygen is delivered to the outlet and carried to the mask through appropriate tubing and connections. In this manner the lungs are in effect supercharged by the differential pressure between the mask and the surrounding barometric pressure. At lower altitudes the same differential pressure would be more noticeable due to the higher total absolute pressure, but in rarefied atmospheres the total density of the gas even with supercharging is sufficiently low to be tolerable. However, there are disadvantages. The pressure difference is not counterbalanced as would be the case in a pressurized compartment, and this lack of counterbalance does present the possibility of a decrease in cardiac output. In addition, there is an increased effort in breathing. Under normal conditions, the body exerts an effort during inhalation only, and exhalation merely involves relaxing the breathing muscles. During pressure breathing, the reverse is true; exhalation requires effort and inhalation occurs as the muscles relax. Between these two extremes it would seem that a mid-point could be established which would involve less work than either of the extremes. Effortless breathing could then be produced. In actual practice such a condition has not been reached, but in comparing the effort involved in breathing between the demand and the pressure-demand system it can be said that breathing under slight positive pressure is certainly close to effortless. According to Fenn (see paragraph 2.4), there is an intermediate pressure of 3.5 mm Hg where both expiratory and inspiratory work occur; the sum total work, however, is less than the inspiratory work experienced under normal conditions.

As mentioned in paragraph 2.2.2, oxygen flow in straight demand oxygen equipment does not occur until a negative pressure is created by the process of inhalation. The time lag and suction should be minimized between the instant that inhalation commences and new oxygen is forced into the user's mouth. This depends on the length of connecting hose from the regulator, the inside diameter and the number of bends in the hose, the surface condition of its internal bore and the pressure differential required to open the oxygen delivery valve in the regulator. Obviously this lag in response can be reduced by shortening delivery hoses and using regulator designs which possess extremely sensitive valve opening characteristics. It is not always possible to shorten the delivery lines from the regulator to mask, and a regulator with extreme sensitivity will more often than not be unstable in its operation and difficult to maintain. Although not designed primarily for this purpose, the pressure-demand system offers a neat solution to this problem also. In modern oxygen systems the connecting hose problem has been eliminated by using miniature man-mounted demand regulators.

- 2.3 Figure 4 shows a schematic diagram of a typical demand regulator and its associated controlling mechanism. The outlet is connected to the aviator's facepiece. On inhalation, the diaphragm "a" is displaced downward by the differential pressure created across the diaphragm. Appropriate vent holes "b" in the top of the chamber "A" permit a free exchange of air in and out of the chamber as required when the diaphragm is displaced. Through an appropriate valve linkage "c" diaphragm movement is translated into a reduced linear movement of the valve stem, opening the valve "d" which communicates with chamber "C" and allows a controlled flow of oxygen through chamber "B" into the outlet.

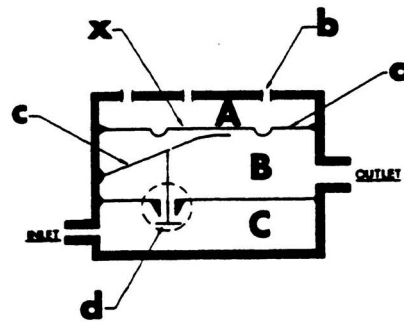


FIGURE 4 - Typical Demand Regulator

2.3 (Continued):

The application of a fixed downward mechanical force at point "X" would have the same effect on the valve as suction applied to the outlet. The pressure of gas developed in chamber "B" will depend on the force applied and the area of the diaphragm. As an example, a force of one pound (4.4 N) applied to point "X" will be distributed equally over the effective area of the diaphragm. An effective area of 5 square inches (32.26 cm²) would, therefore, produce a pneumatic pressure of 0.20 psi (1.4 kN/m²) at the outlet. This example and the pressure resulting would only hold under static conditions as occur during exhalation. In the inspiratory part of the aviator's breathing cycle, however, the pressure developed at the outlet or within the mask will depend on the capacity of the valve and the composite resistance of the entire gas flow passages from the valve to the mask. This method which distinguishes the pressure-demand system from the straight demand system can be used to produce a slight positive pressure within the face mask; the normal lag in regulator response to inhalation is eliminated with gas flow commencing simultaneously at the onset of inhalation. Details of designs vary considerably; however, the principle described is common to all pressure-demand systems. The force applied on the diaphragm is usually accomplished by use of a spring or pneumatic loading. The pressure-demand system, therefore, serves the purpose of producing a flow of oxygen immediately on demand without the attendant lag of the suction demand system. This system is by far more comfortable for breathing and the introduction of positive pressure eliminates all inward leakage of air into the mask and its connecting tubing.

2.4 Bibliography:

Fenn, W. O., Pressure Breathing: Summary of a talk given at a conference held at the Aero Medical Laboratory at Wright Field, October 16, 1945; published in Air Force Technical Report No. 6528, Studies in Respiratory Physiology, prepared by Fenn, Otis and Rahn, August 1951, Wright-Patterson Air Force Base, Ohio, pp. 128-129.

SECTION III - CONTINUOUS FLOW OXYGEN SYSTEMS

3. PRINCIPAL COMPONENTS OF CONTINUOUS FLOW SYSTEM:

This type of system is that by which a continuous flow of gas is metered to each mask through a fixed orifice. Flow is controlled by regulation of the gas pressure. Refer to Figures 15 and 16 in Section VI and paragraph 2.2.1.

The principal components are: (a) Supply system; (b) Distribution system; (c) Dispensing equipment; (d) Sensors, displays and controls.

3.1 Supply System:

This comprises a container or containers for liquid or gaseous oxygen, a contents indicating system, and a means of replenishment. Replenishing of a gaseous supply can be accomplished either by external filling points on the aircraft or by the manual replacement of empty containers with fully-charged units which have been refilled at sites other than on the aircraft.

For a description of liquid oxygen supply systems refer to Section V.

3.1.1 High Pressure Cylinders: These cylinders store gas at 1800 to 2100 psi (12.41 to 14.48 MPa) and are available in a variety of shapes and sizes.

3.1.1.1 Steel Cylinders: Steel cylinders of regular shape with hemispherical ends are commonly in use. Table 18, Section VI, illustrates the weights and dimensions of those cylinders used by commercial carriers. DOT Specification 3AA covers the design and manufacture of regular non-shatterable cylinders. DOT Specification 3HT covers "lightweight" cylinders of the same basic sizes which show a saving in weight of 15 to 30 percent of the weight of the equivalent 3AA type.

Disadvantages of the 3HT type compared with the 3AA type are:

- (a) Lower resistance to shattering.
- (b) Greater susceptibility to damage.
- (c) More stringent service testing is required.
- (d) Limited calendar life.

3.1.2 Low Pressure Cylinders: These cylinders are intended to store gas at 400 to 500 psi (2.76 to 3.45 MPa). They are used mainly in military applications where the smaller energy release on bursting is considered a useful characteristic. For commercial application and use, DOT approved cylinders are available.

Tables 18 through 20, Section VI, illustrates the weights and dimensions of those cylinders widely used by commercial carriers.

3.1.3 Supply Accessories and Components: This section includes items and appurtenances required to provide a complete and workable system. Refer to 3.1.3.1 through 3.1.3.9. The components referred to herein may be optional in some system designs, not applicable or mandatory in others.

3.1.3.1 Gauges: Gaseous systems require pressure gauges as contents indicators. Such gauges may be graduated in psi or contents, i.e., "Full," "Empty." They may be direct or remote reading.

Generally, since an oxygen system requires oxygen lines on the flight deck, a direct reading gauge can be used provided that the lines carry cylinder pressure. If a reducer is installed before the piping reaches the flight deck so that the lines do not carry cylinder pressure, a remote reading indicator is sometimes used with a pressure transmitter.

When the installation allows for the removal of the cylinder for charging off the aircraft, the cylinder valve (see paragraph 3.1.3.6) incorporates a pressure gauge to prevent the re-installation of partly charged or leaking cylinders. If the cylinder can be mounted on the flight deck, a second gauge is unnecessary.

Pressure gauges in liquid systems serve little purpose other than indicating the state of the pressure closing valve. Some contemporary installations have no pressure indication. Contents are measured and indicated electronically. A probe is installed in the top of the container extending down into the liquid. The capacitance of the probe is dependent upon the liquid level; thus a conventional bridge circuit and meter can be used to indicate quantity. (Refer to Section V)

3.1.3.2 Warning Devices: Various devices are used to give warning of low contents:

Liquid content gauges are available with flags or illuminated windows built into the dial. Gaseous pressure gauges may have the lower end of the scale colored red. Audible or visual warning devices are also used to show loss of pressure or flow in gas lines. Devices used are mechanical blinkers or pressure switches used with light.

3.1.3.3 Valves: Line valves are installed at strategic points in the system so as to enable the distribution lines to be isolated for servicing. The valve or valves are located as close to the supply as accessibility requirements will allow so that in the event of a ruptured line as much of the system as possible may be isolated.

- 3.1.3.4 **Check Valves for Crew:** In systems where both crew and passengers draw oxygen from the same supply source, it is mandatory to reserve a quantity of gas for the exclusive use of the crew in F.A.A. certificated aircraft. In multi-container installations, check valves may be used to prevent the container carrying the crew supply from feeding into the passenger system while allowing the crew to draw off the passenger supply when necessary.

In addition, the check valve installation usually provides a means of preventing losses from good cylinders to those which are damaged or leaking.

In single container installations, the normal method of reservation is by use of a line valve to the passenger system. A form of pressure limiting valve may be used which automatically cuts off the passenger supply when the pressure has reduced to a predetermined value.

In liquid oxygen systems the same type of valving applies.

- 3.1.3.5 **Safety Devices:** DOT regulations require that all high pressure cylinders be provided with a safety device to guard against bursting due to excessive pressure. This generally takes the form of a rupture disc incorporated in the cylinder valve.

DOT-3HT cylinders must be equipped with a frangible disc safety relief device, without fusible backing. The rated bursting pressure of the disc shall not exceed 90% of the minimum required test pressure of the cylinders with which the device is used.

A threaded outlet is provided on some designs of cylinder valves so that such a discharge may be piped overboard if desired. Stainless steel lines should be utilized for this overboard piping.

In gaseous filling operations, care must be exercised to avoid accidents, particularly interconnection of high and low pressure systems. Low pressure filling points are of a quite different design from high pressure filling points, and theoretically it is impossible to connect different pressure systems together, provided good control is exercised over ground handling equipment.

In the case of liquid oxygen filler valves, there is no ambiguity about the filling pressure. Both 70 psi (0.48 MPa) and 300 psi (2.07 MPa) systems are filled with the container vented to atmosphere and the pressure in the transfer cart is the only critical factor. A cart pressure of 30 to 40 psig (0.21 to 0.28 MPa) will provide the maximum fill. In addition, the fill valves are either automatic in operation, the system automatically going on "Vent" when the connection is made; or on earlier systems the "Build Up and Vent Valve" and "Fill Valve" are mounted adjacent to each other so that the "Build Up and Vent Valve" handle prevents connection to the "Fill Valve" when the system is on "Build Up."

- 3.1.3.6 **Cylinder Valves:** A variety of cylinder valves are available with pipe threads on the body for screwing into the cylinder neck.

For commercial carrier use, the outlet thread on the side of the valve is a .903-14 Compressed Gas Association No. 540 and an adapter is needed to convert to a standard tube fitting.

The rupture disc outlet mentioned in paragraph 3.1.3.5 can be provided in any desired thread form or capped for inboard discharge.

Modern cylinder valves are available with a "slow-opening" feature. This feature decreases the heat build-up due to adiabatic compression and thus protects downstream non-metallic components from reaching their ignition temperatures.

Automatically opening cylinder valves are also available. Upon installation to system line, the cylinder supply is turned on.

- 3.1.3.7 **Cylinder Gauges:** These are desirable when cylinders are to be recharged away from the aircraft (see paragraph 3.1.3.1) and are incorporated as part of the cylinder valve in most designs.

- 3.1.3.8 **High Pressure Lines:** The diameter of lines is dictated by the mass flow to be carried and the acceptable pressure drop. In multi-cylinder installations the intercylinder lines are of small diameter, 3/16 to 5/16 inch (4.76 to 7.94 mm) O.D. with suitable wall thickness. At least one coil is formed between each cylinder to avoid permanent set occurring during cylinder removal and to prevent load being applied due to relative movement between cylinders under the influence of vibration. Use of high pressure lines should be kept at a minimum.

Various materials are used: copper, copper alloys or stainless steel. With such small diameters, bursting is hardly a problem and the proximity of adjacent cylinders makes it acceptable to rely on the tube end fittings for support of the line.

In the case of main system take-off, the higher flow through a single distribution line fed by multiple cylinders may necessitate a larger diameter. Convenient locations for line supports may not occur with sufficient frequency. In addition, such lines are bound to pass through zones where other equipment is installed and they are subject to damage during servicing.

Aluminum alloy tubing may be quite satisfactory in respect to burst pressure, but stainless steel tubing is commonly used up to the pressure reducer or continuous flow regulator. Sizes in common use are 1/4 inch or 5/16 inch (6.35 or 7.94 mm) O.D. x .028 inch (0.71 mm) wall thickness.

Refer to ARP1532 Oxygen System Installation and Fabrication for further details on tubing practices.

- 3.1.3.9 High Pressure Fittings: The comments of the preceding paragraphs illustrate the considerations dictating the selection of fittings.

Inter-cylinder connections are made with brazed-on nipples and loose coupling nuts (copper and copper alloys) or regular flared or flareless tube fittings with stainless steel.

For the main system take-off, flared or flareless fittings are used.

Usually fittings are of the same material as the lines. Some systems have incorporated mild steel or aluminum alloy fittings with stainless steel lines. However, the aluminum alloy fittings have a wide divergence in electrolytic potential with stainless steel and the cadmium plate necessary on mild steel fittings oxidizes rapidly in contact with the gas, forming a toxic compound. Mild steel fittings also present the possibility of a fire hazard. Loose steel filings or particles dislodged from the inside surface of an oxygen cylinder can travel at fairly high velocities. An impact with a steel fitting could result in an oxygen fire.

Titanium fittings must never be used in oxygen systems because of a possible chemical reaction and resultant fire.

- 3.1.3.10 Fire Safety: The preceding paragraphs illustrate the considerations concerning the selection of components in the system. Fire safety is one other important factor which merits serious consideration. Oxygen by itself is stable and non-flammable. However, it does support and accelerate combustion. Once a fire starts, oxygen will cause adjacent substances to burn rapidly or even explosively. A fire within an oxygen system will require an ignition source to start and fuel to support the combustion.

Fuel accumulation would be best eliminated by the use of compatible materials and by keeping the system clean. Material compatibility may be established by analysis based on test data. However, care must be taken to assure that the test conditions accurately reflect (or exceed in severity) the environment in which the material is to be used and that operational effects are included in the testing procedures.

The other crucial point, elimination of the ignition source, requires controlling temperatures in the system including that of the gas. Oxygen gas temperature tends to increase because of the internal energy changes during compression. This is known as compression heating. The peak temperature of the gas is a function of initial temperature, compression ratio, rate of compression and rate of cooling. In an aircraft oxygen system, the highest temperatures of compression heating will occur at the downstream dead end of the line where the gas is subjected to the highest compression ratio. If heat is developed during the compression at a rate greater than the heat dissipation rate the temperature will increase. If the temperature exceeds the ignition point in oxygen of any combustible material which may be present, rapid chemical decomposition (pyrolysis) and ignition of the chemical matter will take place. This internal fire will contaminate the oxygen with combustion gases and may burn through the system tubing or components to cause an external fire.

3.1.3.10 (Continued):

Compression heating may be minimized by incorporating thermal compensators or heat sinks at the inlet ports of all high pressure control components. The thermal compensator may be constructed in many ways depending on its configuration and application. In any case, it should consist of non-combustible materials having high heat capacity and high thermal conductivity. This heat sink material should be housed in a section of tubing or in a long and narrow container with appropriate fittings to permit installation into the system upstream of and adjacent to any high pressure control components likely to be exposed to compression heating. In practice, the thermal compensator should be designed to absorb and dissipate the heat energy rapidly as it is generated thus minimizing the gas temperature rise during pressurization of the system. The required mass of the heat sink material used in the thermal compensator would depend on the upstream pressure and volume, system flow rate, pressure drop characteristics, etc. Design of the thermal compensator should facilitate its removal for cleaning of accumulated debris. The unit should be designed to preclude shedding of pieces during vibration, flow or servicing.

Such thermal compensators, by precluding gas temperature rising to ignition temperatures during compression, will remove a major potential ignition source within the oxygen system.

3.2 Continuous Flow Distribution System:

The high pressure lines from the supply source continue to either a reducing valve or a regulator.

3.2.1 Regulator: The regulator controls the pressure upstream of the mask orifices.

Basically, all regulators function in a similar manner. Pressure is controlled by controlling the flow through a valve (see Section II).

3.2.1.1 Preset Regulator: Strictly speaking, these are not regulators but simple pressure reducing valves. They reduce the supply pressure to a fixed pressure set for some optimum or maximum altitude. Although they maintain a relatively constant reduced pressure, this reduced pressure will vary slightly as the cylinder pressure or contents are depleted. A control may be incorporated in which an alternative ratio may be selected. They may turn on automatically on reduction of cabin pressure or be turned on manually as required.

3.2.1.2 Manual Regulator: This is the simplest form of regulator in use, consisting of a valve held off its seat by a bellows or diaphragm. A knob adjusts the bellows position, providing a method of setting the required pressure.

A gauge registers pressure downstream and is calibrated in altitude. In operation, the user rotates the knob until the gauge indicates the altitude at which he is flying. The resulting pressure is that calculated to supply the correct oxygen flow through the mask orifice.

Some manual regulators incorporate an on-off valve and a contents indicating pressure gauge.

Such regulators may supply from one to fifty outlets.

- 3.2.1.3 Automatic Regulator: Basically, this type is that in which the knob (see paragraph 3.2.1.2) is replaced by a barometric pressure sensing device which preloads or positions the pressure regulating bellows or diaphragm according to altitude. Thus, once the system has been turned on, line pressure is automatically controlled to the design value for the altitude. Almost any configuration of the altitude/delivery pressure ratio can be provided, but the simplest regulator evolves when the altitude pressure/delivery pressure graph is a straight line.

As with the preset regulator, an automatic or manual turn-on valve, or both, may be provided. Some automatic regulators discharge a small quantity of gas to the atmosphere while they are in operation. This is relatively unimportant when the supply is liquid, but when the supply is gaseous it may not be tolerable.

Automatic regulators are available in various capacity ranges from 1 to 5 outlets to 1 to 200 outlets.

- 3.2.1.4 Single Stage Regulator: Single stage regulators are those which contain one pressure reducing stage. The one valve reduces cylinder or liquid oxygen pressure to that required in the low pressure distribution lines. Some single stage units will not operate above, say, 500 psi (3.45 MPa) inlet pressure, and when used in an 1800 psi (12.41 MPa) system require an upstream pressure reducing valve to be added as part of the system.
- 3.2.1.5 Multi-Stage Regulator: This type regulator has two or more stages of pressure reduction built in. The term "multi-stage" is also applied to regulators constructed with several identical units in parallel as is necessary sometimes to obtain very high flows with tight control of outlet pressure.
- 3.2.1.6 Low Pressure Tubing: Pressure in the distribution lines from the regulators is dependent upon the flow required and the mask or outlet orifice characteristics.

Variations are of the order of zero to 80 psig (0.55 MPa). Mass flow in a large transport aircraft can reach 700 liters per minute, so pressure drop in the lines can be critical. To cater to pressures and flows of this order, the aircraft capable of carrying 150 passengers requires lines of at least 5/16 inch (7.94 mm) I.D. if outlets at the end of the system are to deliver comparable flows with those close to the regulator.

Thus, metallic lines in large low pressure distribution systems are commonly of 3/8 to 1/2 inch (9.52 to 12.7 mm) O.D. x 0.028 inch (0.71 mm) aluminum alloy. In systems for small aircraft of, say, up to 20 passengers, 5/16 inch (7.94 mm) O.D. lines are sufficient.

Where routing is complicated or distribution points are movable, various types of synthetic hose are used. Such hose is selected on the basis of weight and creep characteristics at elevated temperatures.

It should be noted that plastic hoses may weigh slightly more than their equivalent metal counterparts due to the necessarily heavy wall thicknesses. Refer to ARP1532 Oxygen System Installation and Fabrication for further details on tubing practices.