OXYGEN

1. Introduction

Molecular oxygen [7782-44-7], O_2, is a gaseous element constituting 20.946% (1) of the earth's atmosphere. Oxygen is essential to respiration and life in animals and is formed as a waste product by most forms of vegetation. Oxygen supports the combustion of fuels that supply heat, light, and power and enters into oxidative combination with many materials. The speed of reaction and effectiveness of combination increase with oxygen concentrations greater than that of air. Industry has established a 99.5% purity for the majority of commercial product, although a significant fraction of oxygen is also produced in the 90–93% purity range.

The discovery of oxygen, the development of a clear understanding of the nature of air, and a knowledge of the role of oxygen in combustion and in life processes were historically important scientific achievements. In the 1770s, air and ethers were studied by such scientists as Cavendish, Priestley, and Scheele. Both Scheele and Priestley independently prepared oxygen. Whereas Scheele's work remained unpublished until after his death, Priestley was able to relate his discovery directly to Lavoisier in 1775.

Lavoisier checked Priestley's work and recognizing that air contains mainly two gases, named one vital air and the other azote (nitrogen), the latter not supporting life. Later, vital air became oxygen, from the ability to form acids: *ox*, ie, sharp (taste) and *gen*, to form. In 1777, Lavoisier developed the theory of combustion. His ideas became widely established and were firmly fixed by his textbook, *La Traité Elémentaire de Chemie* (2).

After the discovery of oxygen, Cavendish, who had been the first to make a thorough study of hydrogen in 1766, sparked hydrogen with air and oxygen, thereby producing and proving the nature of water (qv). Cavendish also sparked the mixture of oxygen and air to form nitric oxide and nitrogen dioxide, which was absorbed in aqueous alkali. He also burned the excess oxygen with sulfur, and the resultant sulfur dioxide was absorbed in alkali.

For well over 100 years after its discovery and initial preparation, oxygen was made either chemically or by the electrolysis of water. Early in the twentieth century, Linde and Claude introduced processes for the liquefaction and distillation of air that have since grown into a mature and highly competitive industry. In 1991, over 13.4×10^9 m^3 (4.7×10^{11} ft^3) of oxygen was produced in the United States. About 70×10^9 m^3 (24.7×10^{11} ft^3) was produced worldwide.

Oxygen in combination with hydrogen forms the waters of the earth's surface (89 wt % O_2). In combination with metals and nonmetals oxygen is contained in well over 98% of rocks, entering into a very large number of known minerals as well as a vast array of organic compounds. Together, free and combined oxygen constitute 46.6% (3) of the mass of the earth's crust, making it the most abundant element. In the Earth's geological beginning the atmosphere probably contained little or no oxygen. The subsequent emergence of free molecular oxygen into the atmosphere may have arisen because of dissociation of water by high energy rays from the sun and cosmic rays in the upper atmosphere, followed by differential escape of hydrogen into space (4). The detection by the Apollo 16 moon flight, in April 1972, of a massive cloud of atomic hydrogen enveloping the earth and extending to ca 64,360 km, supports this view. Another thesis explains the emergence of oxygen through evolution of the process of photosynthesis (5,6). Thus, chlorophyll, using the radiant energy of sunlight, converted water and carbon dioxide taken from the atmosphere into a very large number of compounds that are the substance of vegetation. During photosynthesis, oxygen is produced and released into the atmosphere.

In nature, oxygen occurs in three stable isotopic species: oxygen-16 [14797-70-7],^{16}O, 99.76%; oxygen-17 [13968-48-4], 0.038%; and oxygen-18 [14797-71-8], 0.20% (7). Commercial fractional distillation of water produces concentrations of ^{18}O as high as 99.98%; ^{17}O concentrations up to 55% are also produced. The ^{18}O isotope has been used to trace mechanisms of organic reactions.

2. Physical Properties

Gaseous oxygen is colorless, odorless, and tasteless. When cooled to 90.188 K it becomes a pale blue liquid, slightly more dense than water. On further cooling, it becomes a blue solid. The blue color probably results from a small equilibrium concentration of associated oxygen molecules. The liquid becomes colorless when passed through a bed of carefully activated silica gel, presumably because the associated molecules are removed. The color returns after some hours of standing. Oxygen is moderately soluble in water (see Table 1).

Selected physical properties are listed in Table 2.

The oxygen molecule is paramagnetic, having a magnetic moment in accord with two unpaired electrons. The gases with which oxygen is normally associated are diamagnetic. Thus the oxygen content of a mixture of gases can be determined using simple instruments that measure the magnetic properties of the gas.

3. Chemical Properties

Oxygen reacts with all other elements except the light, rare gases helium, neon, and argon (13). The reactants usually must be activated by heating before the reaction proceeds at appreciable rates, and if the final union releases more than enough energy to activate subsequent portions of both reactants, the overall process may be self-sustaining. The process is known as combustion when light and heat are evolved. For certain elements, such as the alkali metals rubidium and cesium, activation energy provided at room temperatures is sufficient, and chemical reactions become spontaneous upon contact. Other metals such as finely powdered iron and nickel may be made pyrophoric by careful preparation and reduction of surface oxides. These then ignite spontaneously upon contact with the oxygen in air and continue to react with the evolution of light and heat. Such reactions may be explosive.

The design of all oxygen piping and containment systems must follow specific criteria to ensure that the containment or piping itself does not ignite and subsequently burn in the oxygen. One design criterion (5) limits the velocity of the oxygen in steel pipes so that any foreign material present cannot impact the pipe with sufficient energy to ignite, and in turn ignite the pipe. Oils and other foreign materials may react vigorously with oxygen, which in turn may ignite the oxygen piping or containment systems. All piping components must be thoroughly cleaned (14) to prevent this problem from occurring (see PIPING SYSTEMS).

Most materials must be heated to some particular temperature, called the ignition temperature, to initiate combustion. However, in the presence of moisture, combination reactions with oxygen frequently slowly occur, even at ordinary temperatures. Some examples are found in the respiration of organisms, the rusting and corrosion of metals, the decay of wood, and the hardening of linseed oil. On the other hand, extreme temperatures can be reached, for example, by burning acetylene in the presence of oxygen. The process of cutting iron involves burning away the iron with pure oxygen after the ignition point has been reached by heating with an oxygen–acetylene torch. Whereas noble metals can be oxidized only at very high temperatures, oxides are often formed through an alternative route.

Oxygen usually exhibits a valence of −2 in combination with other chemical elements to form compounds such as oxides. Most elements combine with oxygen, which is highly electronegative, in more than one ratio because of the variety of valences exhibited by the other element, or because of the existence of complicated molecular structures. An extended discussion of oxides is available in the literature (13).

When fuels such as petroleum (qv), natural gas (see GAS, NATURAL), or coal (qv) burn with an excess of oxygen, either as air or pure O_2, the products are heat, carbon dioxide (qv), and water (qv), plus nitrogen oxides, etc, if air is used. When the amount of oxygen is limited, however, the reaction produces a mixture of carbon monoxide and hydrogen, also known as synthesis gas or syngas. This important gaseous mixture reduces iron (qv) ore to pig iron in a blast furnace. It also serves as the precursor from which methanol (qv) may be synthesized or as a raw material to provide hydrogen for ammonia (qv) synthesis. At lower temperatures, frequently in the presence of catalysts, oxygen reacts with organic chemicals to give oxygenated hydrocarbons.

Animal metabolism is based on the reactions of oxygen and organic compounds containing carbon, hydrogen, oxygen, and nitrogen and other heteroatoms. Enzymes catalyze these biochemical oxidations, which are accomplished at about 30–40°C and frequently proceed stepwise to produce specific changes in carbohydrates (qv), fats, and proteins (qv).

Oxidation rate is controlled in part by the area available for oxygen contact, eg, iron filings rust far faster than does a solid piece of iron. Violent or explosive reactions take place when combustible, finely divided, and suspended dusts or powders are ignited, as in grain elevators, coal mines, or in a manufacturing plant. These dangerous reactions may be mitigated by controlling the amount of dust or excluding air (oxygen) by dilution with sufficient inert gas (see POWDERS, HANDLING, DISPERSION OF POWERS IN LIQUIDS). On some metals, such as aluminum, the oxide surface film is adherent and continuous and thus prevents further access of oxygen to the unoxidized metal. Finely divided or thin sheets of aluminum, however, may be explosive in liquid oxygen (15,16).

4. Manufacture

Commercial oxygen, both gaseous and liquid, at about 99.5% purity is produced by cryogenic distillation in air separation plants. In these plants the air is cleaned, dried, compressed, and refrigerated until it partially liquefies at about 80 K (see CRYOGENIC TECHNOLOGY). The air is then distilled into its components (see Table 3). Commercial gaseous oxygen at about 90–93% purity is produced from air by vacuum swing adsorption (VSA) processes (see ADSORPTION, GAS SEPARATION). The VSA method is the fastest growth portion of oxygen production.

Air was first liquefied and oxygen subsequently separated about 1900. Technologies introduced after World War II substantially improved the air separation process for high purity oxygen production. In the 1960s the production of high volume, low cost oxygen for the manufacture of chemicals and petrochemicals, and especially for the basic oxygen process (BOP) for the manufacture of steel (qv), provided a distinct advantage. Since about 1980 a number of further improvements have occurred in the cryogenic air separation process resulting in significant efficiency, productivity, and reliability gains. The most modern cryogenic plants operate at thermodynamic efficiencies in the vicinity of 35%, a number significantly higher than for other industrial processes, such as petroleum refining.

Process improvements include (*1*) improved energy transfer in heat exchangers via improved thermal design of the main heat exchangers; (*2*) more complex heat integration yielding more optimal distillation column performance; (*3*) improved expander–compressor efficiencies; (*4*) reduced pressure drops within distillation columns via improved distillation tray design and the use of packing in place of trays; (*5*) use of down-flow reboilers; (*6*) use of high (up to ca 3100 kPa (450 psi)) pressure operating cycles; and (*7*) improved front-end purification equipment requiring less energy to reactivate (17,18).

Process improvements have been combined into a number of operating cycles. The choice of which cycle to use depends on a number of factors, including the ratio of oxygen:nitrogen produced; the ratio of liquid oxygen:nitrogen vs gaseous oxygen:nitrogen produced; and the final pressure required of the gaseous oxygen and nitrogen.

Improvements in instrumentation and automatic controls, especially the introduction of digital, ie, computerized, control systems, have provided significant gains in personnel productivity as well as in the ability to optimize process parameters to maintain peak efficiencies (see also PROCESS CONTROL). The standardization of (especially) smaller cryogenic air separation plants has further reduced design and construction costs. These types of plants often operate unattended. Even moderately large plants may be unattended during certain periods of operation.

The principal impurity in 99.5% oxygen is argon because of the closeness of the boiling points. There was a high demand for argon in the 1990s so that the oxygen is further refined (via distillation) to recover the argon. As a result, oxygen purity often rises to 99.8%. This additional refining has also influenced the selection of operating cycles (see also HELIUM GROUP GASES).

4.1. Cryogenic Separation. In the cryogenic air separation process, the ambient intake air is compressed and the moisture and carbon dioxide removed, either by cooling the air or by adsorption systems. In the former, the moisture and carbon dioxide are deposited as both liquid and ice, including solid carbon dioxide. These deposits are sublimed or removed in a second step after switching (reversing) the flows of air and waste nitrogen, thus warming the deposits. In the adsorption method, water, carbon dioxide, and trace impurities, eg, hydrocarbons (qv), are removed by zeolite and silica gel-type adsorbents. The adsorbent bed is regenerated on a periodic basis, typically by flushing with a hot waste oxygen–nitrogen stream while the main air flow is diverted to a second bed. This adsorption process for removal of moisture and carbon dioxide has similarities to the vacuum swing adsorption process for the production of oxygen. The choice of processing technique, ie, reversing exchangers or adsorption, depends on the total output of pure oxygen and nitrogen expected from the unit as well as the size of the unit, but adsorption has largely become the method of choice in newer plants.

Many of the trace impurities within the incoming air are either frozen out and trapped in the reversing exchangers or are removed together with the moisture and carbon dioxide by adsorption. All modern plants also include silica-gel adsorbers in the oxygen-rich liquid circuit as well as in the guard circuit used to control any accumulation of undesirable materials in the oxygen pool of the oxygen distillation column (see ADSORPTION, LIQUID SEPARATION). Silica gel is particularly effective in removing acetylene, which in early plants was responsible for initiating explosions of itself or other hydrocarbons concentrated in the liquid oxygen.

After compression and removal of impurities, the air is cooled in heat exchangers and expanded to low pressure through a turbine, to recover energy, or through a valve. Liquid air, which forms at about 80 K, is separated via a distillation column (19). The column as well as the heat exchangers and the associated piping are placed within a cold box, which is packed with insulation to minimize heat transfer (qv) between streams and to protect the system from the ambient air external to the cold box.

4.2. Adsorptive Separation. A noncryogenic air separation process, which is increasingly employed for small- to moderate-scale oxygen production units, is based on the adsorption of nitrogen (but not oxygen) onto zeolites (see ADSORPTION, GAS SEPARATION) (20). This batch process, known as vacuum swing adsorption (VSA), typically uses two identical switching beds, each containing two strata. The first stratum removes water and carbon dioxide; the second adsorbs nitrogen from the flowing air. In the two-bed system, while unit one is on-stream adsorbing first water and carbon dioxide and then nitrogen from the air, unit two is being evacuated to remove the previously adsorbed nitrogen. The product oxygen is substantially unaffected. After a certain period, the second bed is brought into sequential use, while the first is evacuated, etc. Depending on the operating cycle chosen, the product may be up to about 93% oxygen. The balance is nitrogen and argon. Moisture and carbon dioxide residuals are in the low ppm range. The oxygen is produced at about 24 kPa (3.5 psig) and must be compressed if the oxygen is required at higher pressures. The flow of the oxygen is unsteady but the use of a surge tank or a compressor can even out the oxygen flow.

VSA plants range from small hospital units to very large units producing as much as 229,000 m^3/d (8.0×10^6 ft^3/d). Fully assembled units in moderate sizes can be transported readily. Energy costs of larger units approach the equivalent cryogenic unit. The VSA plant can be started quickly and readily shut down. The largest use for the 90–93% purity, low pressure product is for oxygen enrichment in combustion furnaces. Oxygen may also be produced by pressure swing adsorption (PSA) units. Sales of PSA units, however, are normally for very small applications.

Another noncryogenic technique for oxygen production involves the electrolysis of water. This technique is used only to an insignificant extent. However, if the use of Hydrogen Energy (qv) grows significantly, hydrogen (qv) production via electrolysis could also grow; concomitantly, relatively large quantities of oxygen would be coproduced.

5. Production, Pipelines, and Shipping

5.1. Production. Oxygen production facilities for relatively large users generally fall into one of three categories: (*1*) a captive plant on the oxygen user's property owned and operated by the user; (*2*) a plant owned and operated by an industrial gas company that is on or adjacent to the oxygen user's property (on-site facility), where a long-term contract for the supply of oxygen usually exists between the industrial gas company and the oxygen user; and (*3*) a plant owned and operated by an industrial gas company that supplies oxygen to several users. In the first two cases, the gaseous oxygen is generally supplied to the user site via a pipe. In the last instance gaseous oxygen is carried via a pipeline having branches to the individual industrial users. The pipeline and the central production facility are typically owned by the same industrial gas company.

If an industrial gas company owns the plant, nitrogen may also be supplied to users via additional pipelines. Liquid oxygen, liquid nitrogen, or liquid argon that can be delivered by truck to smaller users or to other industrial gas plants may also be produced. Alternatively, the liquid product could be stored on-site as a backup supply in case the air separation plant is not operating. In this last instance, the liquid oxygen is vaporized and placed in the gaseous oxygen pipeline.

Some oxygen production facilities are built solely to supply liquid oxygen, and generally liquid nitrogen and liquid argon, via truck to generally smaller customers. These plants typically use a process cycle optimized for total liquid production.

In the U.S. air separation industry, the size of a plant is specified by the design capacity for oxygen production which is usually measured in metric tons per day. Air separation plants built in the 1950s favored sizes ranging from 50 t/d (37,500 m^3/d) to 100 t/d (75,000 m^3/d). In the 1960s, many facilities built were more than double that size, and a few air separation units (ASUs) were on an order of 1000 t/d (7.5×105 m^3/d) and even larger. By the end of the 1970s, ASUs rated at 2000 t/d were being completed worldwide. Since that time, however, significant increases in unit capacities have not occurred. The most spectacular assemblage is the six 2000 t/d plants built by L'Air Liquide of France for the SASOL-II coal liquefaction complex in South Africa.

Oxygen is a commodity sold either as a gas under pressure or a very low temperature liquid close to its boiling point. Because of the expense of the containers required, it cannot be stored in more than modest amounts nor can it be shipped profitably more than a few hundred kilometers. Liquid oxygen storage facilities are limited to volumes on the order of 4000 m^3.

5.2. Pipelines. Gas by pipeline is the least expensive way to manufacture and supply oxygen. The energy of refrigeration is recovered by the heat exchangers at the point where ambient-temperature gas exits and ambient-temperature air enters the plant. There is no loss by evaporation, and the costs of truck delivery are eliminated. Between 80 and 90% of all oxygen is transported in gas pipelines. Typical pipeline pressures are up to about 3450 kPa (500 psi) and diameters are usually within the range of 10–30 cm. In certain heavily industrialized areas, multiair separation plants–multicustomer oxygen–pipeline networks or complexes exist (see PIPELINES).

Oxygen pipelines exist extensively in the Gulf Coast and in the southern Lake Michigan areas of the United States. Pipelines covering hundreds of kilometers and linking 10 or more oxygen-producing plants with 24 or more users are among the largest oxygen networks. Oxygen pipelines also exist in Europe as well as in the Pacific Rim (Asian) countries.

5.3. Shipping. Merchant oxygen gas and liquid is transported to the smaller oxygen users by tube (gas) or cryogenic tank (liquid) trailers and railroad car (liquid). Cryogenic liquid tanks or customer stations of appropriate sizes are permanently installed on the premises of large- and small-volume merchant users, including most hospitals. A liquid oxygen tank or customer station may be found outside nearly every hospital.

Liquid storage tanks at customer sites, trailers, and railroad cars are constructed to minimize the inevitable boiloff of the liquid. Generally the liquid oxygen is contained within a tank inside of another tank. The annular space between the tanks is evacuated and filled with a semisolid insulator. Using proper design of the vacuum-jacketed systems, the boiloff rates can be very low. For logistic and economic reasons, liquid oxygen is usually not hauled by truck more than about 800 km, although it can be hauled for longer distances based on acceptable boiloff rates. Liquid oxygen may also be transported for relatively short (usually up to about 400 m) distances via a vacuum-jacketed pipeline system.

If relatively large amounts of liquid oxygen are needed in one location, such as for a rocket launch where the liquid oxygen is one of the propellants, trucks and rail cars are the only practical means of transport. In some cases specially designed barges can also be used.

For users of small merchant quantities, liquid oxygen may be transferred at a distribution station to portable cryogenic containers holding as little as 148 L of oxygen, equivalent to 127 m^3 of oxygen gas. These containers can deliver either gas or liquid. The distributor also has facilities for vaporizing liquid and filling the familiar high pressure oxygen gas cylinders that are widely used, eg, by welders and medical personnel. Liquid distribution stations are equipped with a vaporizer that is heated by ambient air, electrically, or by steam to provide gas under pressure. Unlike liquid nitrogen, very little oxygen is used directly as the liquid for low temperature purposes.

About 80–90% of oxygen that is produced in the United States is distributed by pipeline. Merchant oxygen, distributed in high pressure cylinders and high pressure tube trailers, accounts for only about 1%. The method of shipping the balance of the oxygen, produced as a liquid, is one of at least four possible means. The liquid O_2 may be stored at an air separation plant site then revaporized and placed in a pipeline, hauled by tank truck (or rail car) to customers as merchant liquid oxygen, hauled by tank truck to other air separation plants for eventual distribution, or hauled by tank truck to industrial gas distribution centers where it is vaporized and placed in high pressure cylinders and high pressure tube trailers.

6. Economic Aspects

Total primary production of oxygen in the United States for 2003 was $697{,}741 \times 10^6$ ft^3 of which $505{,}217 \times 10^6$ ft^3 was produced cryogenically on site and pipeline. Total shipped was $611{,}529 \times 10^6$ ft^3. The value was \$$998{,}680 \times 10^3$. Liquid produced for merchant shipment was $108{,}250 \times 10^6$ ft^3. A total of $103{,}070 \times 10^6$ ft^3 was shipped worth \$$232{,}137 \times 10^3$. Other shipments or uses totaled $28{,}391 \times 10^6$ ft^3 (21).

Value of oxygen shipments from selected states for the 1997 and 2002 are listed in Table 4. Product class shipments are those that are economically significant and whose production is geographically dispersed (22).

7. Specifications and Analysis

7.1. Grades.

Twelve oxygen grades are defined by the Gas Specification Committee of the Compressed Gas Association (CGA) (23), 10 of which are given in Table 5. The contaminants identified relate to possible residues from the atmosphere as well as particulates or fibers that may have been contributed by the manufacturing process or the distribution system. In addition, government agencies and certain commercial users have developed specifications for individual needs (24). In most cases, these specifications closely parallel the CGA grades.

In general, the products from a given cryogenic air separation unit (ASU) controlled by automatic instruments, sometimes using computer programming, are consistent in quality and contaminants (Table 5). The principal inert constituent in oxygen is argon, which is present because the small difference in boiling points ($\Delta t = 2.90$ K), puts undue demand on the bulk distillation process, (see Table 3). Argon, together with small traces of inert krypton and xenon, slightly dilutes the oxygen and is objectionable in uses where residual gases could interfere, eg, in some electronic processes. Nitrogen may be present, but in smaller quantities than argon. Methane (bp $= 111.60$ K) and higher hydrocarbons, as well as krypton and xenon, have boiling points higher than oxygen and accumulate in the oxygen liquid.

To improve oxygen purity much above 99.6%, the 99.5% product is redistilled, sometimes after catalytic oxidation of hydrocarbons (methane) followed by removal of the resulting produced carbon dioxide and moisture. Redistillation reduces not only argon and nitrogen but also the traces of krypton and xenon, providing a first step in the recovery of these two gases. The demand for argon has caused many newer (cryogenic) ASUs to be designed to remove most of the argon directly within the ASU, resulting in oxygen purity typically exceeding 99.8%.

The highest purity ($\geq$99.99%) oxygen is obtained through further refinement. At 99.99% the impurities total only 100 ppm. This grade of oxygen is used in the manufacture of electronic components, Fiber Optics (qv), etc, or for gas chromatograph calibration or research applications.

VSA-produced oxygen typically has a purity of 90–93%. The balance is nitrogen, argon, moisture, carbon dioxide, and small amounts of other gases.

Grade A. Types I and II both represent the requirements of the USP XX (25). The USP tests arose from original formal oxygen specifications made necessary by the low purity and certain contaminants, particularly CO and CO_2, contributed by early chemical and cryogenic manufacturing methods. Containers marked Oxygen-USP must also indicate whether or not the gas has been produced by the air liquefaction process (see also FINE CHEMICALS, PRODUCTION).

Grades B and C. Type I B and C and Type II Grade C are typical of pipeline and merchant gas and liquid. These are used for steel refining and synthetic chemical manufacturing, which together account for most oxygen consumption. Water, the only contaminant specified, could freeze out in Type II and cause gas transfer problems as well as chemical manufacturing difficulties.

Grade C, Type II is typical of liquid oxygen used as a rocket propellant oxidizer. Particulate content is limited because of the critical clearances found in mechanical parts of the rocket engine. In addition to water, acetylene and methane are limited because, on long standing, oxygen evaporation could cause concentration of these combustible contaminants to reach hazardous levels.

Other Grades. Type I and II, Grade D are typical of oxygen purities required for aviators' oxygen masks. The limitation on odor is obvious. Limits are placed on particulates in the liquid as well as on light hydrocarbons, oxides of nitrogen, nitrous oxide, and halogenated solvents. Grade E, Type I typifies oxygen used for purging and pressurizing rocket engines. It may also be specified for more critical merchant uses. Grade F is typical of the oxygen purity required for Fuel Cells (qv) on space vehicles. In addition, increasing amounts of this grade of oxygen are used in research and fabrication of semiconductors, fiber optics, and similar applications.

7.2. Analysis. *Oxygen.* Assay as minimum percentage contained is determined readily by absorption in a suitable oxygen reagent contained in a volumetric apparatus of the Orsat type, particularly the simplified version of the Hempel pipet (26), which is traditionally used in the oxygen industry. When 100 cm^3 gas is drawn into the pipet, the unabsorbed inert constituents may be measured directly on a calibrated limb. Modern oxygen plants continuously monitor purity on an instrument of the thermal conductivity or paramagnetic type. These instruments must be calibrated against known standards.

Inert Gases. For oxygen of the highest purity or where grade specifications require limitations, the individual impurities are determined and the sum subtracted from 100%. The main inert constituent is argon, with lesser amounts of nitrogen, methane plus other hydrocarbons, carbon oxides, krypton, and xenon. These gases may be separated and their concentration can be estimated using a gas chromatograph or a quadrupole mass spectrometer.

Odor. Odor is excluded in military applications and in the four grades specified for human breathing. The gas is tested by smelling a flowing stream or by smelling a beaker from which a liquid sample has just evaporated. Oxygen that is produced in modern ASUs employing turbine compressors or nonlubricated piston machines is odorless.

Water. Oxygen, gas or liquid, exiting the cryogenic ASU contains little or no water. To verify the dryness of gases, electrical hygrometers having scales graduated in parts per million are commercially available. These instruments include a number of models based on the direct amperometric method (27) on the piezoelectric sorption detector. Dew point, the temperature at which frost or condensed water first forms, continues to be a specification. The dew point of dry gases is usually obtained by conversion from the scale reading of the instruments, using the data given in Table 6 (28).

Total Hydrocarbon Content. The THC includes the methane combined in air, plus traces of other light hydrocarbons that are present in the atmosphere and escape removal during the production process. In the typical oxygen sample, methane usually constitutes more than 90% of total hydrocarbons. The rest may be ethane, ethylene, acetylene, propane, propylene, and butanes. Any oil aerosol produced in lubricated piston compressor plants is also included here.

A flame-ionization, total hydrocarbon analyzer determines the THC, and the total carbon content is calculated as methane. Other methods include catalytic combustion to carbon dioxide, which may be determined by a sensitive infrared detector of the nondispersive type. Hydrocarbons other than methane and acetylene are present only in minute quantities and generally are inert in most applications.

Acetylene has a low solubility in liquid oxygen. Excessive concentrations can lead to separation of solid acetylene and produce accumulations that, once initiated, can decompose violently, detonating other oxidizable materials. Acetylene is monitored routinely when individual hydrocarbons are determined by gas chromatography, but one of the wet classical methods may be more convenient. These use the unique reaction of acetylene with Ilosvay's reagent (monovalent copper solution). The resulting brick-red copper acetylide may be estimated colorimetrically or volumetrically with good sensitivity (29).

8. Health and Safety Factors

Hazards associated with the use of oxygen derive from the facts that the cryogenic liquid is very cold and increases in volume enormously when it vaporizes, that combustion rates accelerate with oxygen concentrations above 21%, and that the gas is transported and dispensed in high pressure cylinders. Liquid oxygen and other cryogenic liquids can inflict severe damage on human tissues.

Protective gloves, garments, and face shields are imperative, and detailed advance instruction in procedures for use are essential before any activity involving liquid oxygen is undertaken (14,30-33). At ambient pressure, the volume of a given quantity of liquid oxygen increases 860 times during the change from the boiling liquid to the gas at ambient temperatures. Hence, if a sample of liquid oxygen is confined to its original volume, a pressure of 87.2 MPa (12,640 psi) develops, bursting all but the strongest containers. Safety considerations demand that any volume where liquid could be trapped must be provided with pressure-relief valves or a bursting disk.

When oxygen from either gas or liquid sources is brought into the presence of oxidizable materials, mixtures ranging from combustible to explosive may result. Oxidizable materials include oils and greases, fingerprints, paint, plastics, rubber materials, carbon, asphalt, wood, clothing, and hair. Some solid materials are porous, eg, wood, clothing, some plastics, asphalt, and charcoal, and may absorb considerable quantities of oxygen. If these are subsequently ignited by an ignition source, very fast combustion or an explosive reaction may ensue. Up to about 1940, sawdust and liquid oxygen were ingredients of some commercial explosives. An ignition source can be as simple as a mechanical impact. Tragic accidents have occurred in which the clothing of workers in confined areas became saturated with oxygen, either accidentally in the oxygen-rich atmosphere or deliberately when the worker dusted himself with an oxygen hose. Ignition of the oxygen-saturated clothing produces an intense flash fire. In oxygen-rich atmospheres, the human body burns vigorously.

Steel cylinders containing any gas under pressure in excess of 173 kPa (25 psig) are covered by U.S. Department of Transportation (DOT) regulations. When these cylinders are moved, the valve cap must be properly secured. In storage and use, the cylinders must be chained or otherwise fastened. If it is excessively shocked, a high pressure cylinder may fracture or shatter. Equipment used in conjunction with oxygen must be kept scrupulously clean. When gas pressures are increased rapidly in the presence of contaminants, the heat of compression in an oxygen atmosphere may be high enough to ignite combustible materials.

Hazards are associated with atmospheres containing either excessive concentrations of oxygen or deficient concentrations of oxygen (33).Even a slight increase in oxygen content of air above the normal 21% greatly increases the oxidation or burning rate (34). Accidents and fatalities frequently occur in confined spaces where free access of air into the space is restricted or there is significant in-leakage of inert gases, eg, nitrogen. As a result, an oxygen-deficient atmosphere develops. The atmosphere in any confined space should be monitored.

9. Uses

There are relatively few substitutes for oxygen in most of its uses. Oxygen cannot be reclaimed commercially or recycled except via the atmosphere. The spectacular increase of oxygen production since World War II has in a very large measure occurred because of availability and its usefulness in steelmaking (see STEEL) and in chemicals and petrochemicals production, high temperature production furnaces, water purification, and hazardous waste destruction. The largest uses of oxygen in the United States are steel, chemicals, metal welding and cutting, coal gasification, nonferrous metals, petroleum refining, and health.

The practical and economic advantages of the use of oxygen and oxygen-enriched air over air alone, across a number of industries, typically fall into one or more of the following categories. (*1*) Higher combustion or flame or reaction temperatures and shorter flames, yielding faster reactions at nominal reaction temperatures. Typical maximum flame temperatures using oxygen can be as high as 3033 K (5000°F), whereas for air maximum flame temperatures are usually lower by more than 555 K (1000°F). In many applications, higher temperatures permit faster melting or processing. In some processes the desired product or result may not even be achieved at the lower temperatures obtained using air. (*2*) Less waste energy in the gas or vent flue gas. To recover energy, flue gas is often heat-exchanged down to as low a temperature as is practical, but at the end of the heat-exchange process, the residual heat content retained in the flue gas represents a loss of energy. When the nitrogen is removed, the flue gas flow is reduced by about 75%, providing a distinct energy advantage. (*3*) Reduced volume of flue gas or vent gas to treat. When gases must be treated to remove pollutants, reduced volume (no nitrogen) means that the treating devices, eg, scrubber, baghouse, or electrostatic precipitator, may be much smaller in volume and the pollutant to be removed much more concentrated. In some cases lower quality, lower cost fuels or feedstocks may be used because the pollutants may be more easily removed from the flue gas or vent gas. (*4*) Reduced emissions of nitrogen oxides. The elimination of nitrogen from the combustion or process air often results in a significant reduction in the formation of nitrogen oxides such as NO, NO_2, and N_2O. (*5*) The desired product is easier to remove at the end of the process. The reduction or removal of nitrogen from the feed translates to a higher concentration of product in the plant streams and an easier separation to recover the product. (*6*) Economics of air compression. When oxygen or air is required at high, eg, >13,800 kPa (2,000 psi), pressure for a process, but only the oxygen reacts, it may be more economical to separate the air initially and only supply the oxygen at high pressure, saving the cost of compressing the nitrogen. (*7*) Nitrogen in the product is undesirable, yet cannot be removed economically.

9.1. Steelmaking. Large amounts of oxygen are used in almost all aspects of the steelmaking process, largely to oxidize the principal contaminants, eg, carbon, phosphorus, and silicon.

The largest use of oxygen for steelmaking is in the basic oxygen process (BOP), also called the basic oxygen furnace (BOF). This process consumes about 75% of all of the oxygen used in the steel industry. Oxygen is added to the molten pig iron via a lance, and the impurities are largely removed via gasification or by the formation of slag. About 0.08 metric tons of oxygen is required for each metric ton of steel produced by the BOF, utilizing advantages (*1–3*), and (*7*) outlined. Oxygen is being increasingly used to enrich the hot blast in blast furnaces. Consumption of O_2 of up to 0.10 t/t of pig iron are common.

Electric furnaces, often operated by mini-mills, account for over 35% of steel production. These furnaces operate mostly on scrap steel and produce a wide range of steels, up to high grade stainless steels. Oxygen use, via injection into the molten bath, increases the efficiency of the furnace via advantages (*3*) and (*7*). The argon–oxygen-decarburizing (AOD) process for refining stainless steel involves blowing argon–oxygen mixtures into a special AOD vessel. This process follows the electric funance via advantages (*3*) and (*7*).

Oxygen is also utilized in a variety of other applications within the steelmaking industry. For example, it is used to reheat furnaces, using oxygen or oxygen enrichment; and to reheat steel more quickly, requiring less fuel gas (advantages *1–4*). Also, oxygen scarfing or skimming removes surface defects from steel billets (advantage *1*); ladle preheating using fuel and oxygen or oxygen enrichment utilizes advantages (*1*), (*3*), and (*4*). A method for cutting steel with oxygen has been reported (35).

9.2. Nonferrous Metallurgy.

In nonferrous metallurgy, oxygen enrichment of the fuel–air flame in reverberatory smelting furnaces and oxygen use in autogeneous smelting save money and time in the smelting of Copper (qv), Lead (qv), antimony, and zinc. A rapidly growing use for oxygen involves flame enrichment in flash smelters for copper and nickel production from sulfide ores. The addition of oxygen increases productivity, improves sulfur recovery in the form of sulfuric acid, and provides for easier control of emissions via advantages (*1–4*).

Uranium *in situ* leaching is a more recent development in which an oxidative–complexing solution recovers uranium from low grade, deep-lying deposits that may be water-saturated. Oxygen is finding increased use in gold recovery. Oxygen is used to prepare the less desirable sulfide-based gold ores for refining because of advantage (*1*).

Oxygen, often the VSA-produced 90–93% purity, is beginning to be used for the recycling of aluminum because of advantages (*1–4*).

9.3. Other Furnace Temperature Applications.

Oxygen-enriched combustion within glass (qv) furnaces for fiber glass, bottle glass, and float glass is developing a newer use for oxygen. Oxygen-enriched combustion within cement (qv) kilns and brick kilns is also developing (advantages *1–4*). VSA-produced oxygen in the 90–93% purity is often adequate for many of these applications.

9.4. Chemical Processing.

The use of oxygen in large-volume chemical and petrochemical manufacture is well-established as a result of advantages (*3*) and (*4*). Most oxidation reactions are catalytic; many begin with a feedstock initially made catalytically from methane or natural gas.

Syngas is a basic feedstock in the chemical and petrochemical industry and consists of carbon monoxide and hydrogen. Syngas is generally made via partial oxidation by mixing oxygen, natural gas, and steam and passing the mixture over a catalyst (advantages *1* and *5*). The hydrogen of syngas may be separated from the carbon monoxide and the carbon monoxide combined with steam and a catalyst to make additional hydrogen as well as carbon dioxide. When the hydrogen is again separated, the resulting two streams of hydrogen represent the main commercial source of hydrogen. This hydrogen is widely used to make ammonia, to hydrotreat petroleum, and for metallurgical applications.

Partial oxidation of natural gas or a fuel oil using oxygen may be used to form acetylene, ethylene (qv) and propylene (qv). The ethylene in turn may be partially oxidized to form ethylene oxide (qv) via advantages (*1*) and (*5*). A few of the other chemicals produced using oxygen because of advantages (*1*) and

(*5*) are vinyl acetate, vinyl chloride, perchloroethylene, acetaldehyde (qv), formaldehyde (qv), phthalic anhydride, phenol (qv), alcohols, nitric acid (qv), and acrylic acid.

Partial oxidation of coal to form either synthetic fuel, syngas, or synthetic natural gas represents a potential use of oxygen (see FUELS, SYNTHETIC, GASEOUS FUELS). Programs designed to demonstrate these technologies from coal and other solid fuels are being driven primarily by environmental benefits. Advantages (*1*), (*2*), and (*5*) come into play. Oxygen is also used in a growing number of applications within Petroleum (qv) refineries including oxygen enrichment of air used to regenerate fluidized catalytic cracking (FCC) catalysts and improving sulfur recovery via the Claus process (36).

9.5. Other Industrial Uses. In the pulp (qv) and paper (qv) industries, oxygen is needed to make lime used to prepare or reconstitute white liquor. Oxygen is added to the air–fuel primary burner to enhance the intensity of the flame. The increased heat raises the lime production capacity (advantage *1*). Additional benefits are obtained from fuel savings, improved lime reactivity, and control of sulfur odor (37) (advantages *1* and *3*). Oxygen is also used for black liquor and white liquor oxidation. Many pulp and paper applications of oxygen are driven by environmental requirements (advantage *3*). Oxygen may also be used to delignify and bleach wood chips, increasing the quality and yield of the pulp. The result is lower material costs and the use of an inherently nonpolluting process (advantage *3*).

Oxygen, when introduced into fish-farming ponds and pools, particularly trout pools, enables these fish to increase their food intake and hence grow more rapidly (see AQUACULTURE CHEMICALS). Fermentation operations are accelerated by sparging with oxygen (see AERATION, BIOTECHNOLOGY; FERMENTATION).

Oxygen is used to treat municipal wastewater and wastewater from the pulp and paper industry (see AERATION, WATER TREATMENT; WASTES, INDUSTRIAL; Water, Sources and Quality Issues). Many of these water applications can use VSA-produced oxygen (advantage *1*). Demonstration and development programs are in place that use oxygen to oxidize sludge from municipal waste and burn hazardous wastes and used tires (advantages *1–4*). A direct oxygen injection method for groundwater remediation has been reported (38). The system reduces a contaminated subterranean body of water with a plurality of spaced injection sites.

9.6. Medical Applications. The maintenance of arterial blood oxygen at a partial pressure close to the normal level of 13.3 kPa (100 mm Hg) is fundamental to all uses of oxygen in medical and life support. At saturation, each 100 mL of arterial blood holds 19 vol % oxygen. Of this, 0.3 mL are in solution in the plasma; the remainder is chemically bound as oxyhemoglobin. If the hemoglobin is below normal, ie, <14.89 g/100 mL, less oxygen is carried. As blood flows around the body under normal metabolic conditions, 100 mL of blood gives 5 mL of oxygen to the tissue, then returns to the lungs as venous blood carrying a basic 14 mL O_2. Oxygen in solution is 0.13 mL/100 mL blood and the rest is present as reduced hemoglobin. If 100% oxygen is inhaled instead of air, the 0.3 mL oxygen in solution increases to 2 mL and the amount of oxygen taken up by the hemoglobin may be increased (39). Higher concentrations of oxygen are valuable in case of severe anemia and other, similar disorders.

Modern hospitals include a built-in system from which oxygen is conducted to convenient bedside locations and into operating rooms. The supply point is usually an outdoor cryogenic container from which liquid oxygen is withdrawn and vaporized automatically as needed. Modern anesthesia routinely uses oxygen as a component of the gaseous mixture, thereby ensuring an adequate supply for life support and maintaining the diluting effects of gaseous anesthetics.

Oxygen is supplied quite routinely to patients suffering impaired respiratory function as well as in other situations where oxygen is deemed to be useful. The pure oxygen, with humidification, is delivered via a simple double tube (cannula) to a point just inside the nostrils where the 99.5% gas blends with the room air (21% O_2), and is inhaled. The concentration of oxygen that reaches the lungs thus depends on the rate and volume of air inhaled and on the exit flow of oxygen from the cannula, usually one to six L/min.

The use of oxygen in pediatric incubators is an important factor in increasing the survival rate of premature infants who develop cyanosis. However, the use of oxygen is associated with risk of developing the visual defect known as retrolental fibroplasia (40). A careful monitoring of arterial blood oxygen partial pressure is important.

In the past, hyperbaric oxygenation as a medical procedure has received considerable attention. In this treatment the patient is given pure oxygen and may be placed in a pressurized chamber. In effect, the patient may thus receive $\geq$400 kPa ($\geq$4 atm) of pure oxygen. Beneficial results in cases of carbon monoxide poisoning, gangrene, severe burns, and other difficulties are often achieved as a result of this treatment.

Oxygen inhalators are used as a first-aid measure for a long list of emergencies, including heart attacks and suffocation, and as a result are carried routinely by rescue squads. Oxygen–helium mixtures have proved beneficial in asthmatic attacks, because these permit more rapid flow of gas into congested areas of the respiratory system.

9.7. Life-Support Applications. Exploration of outer space by humans has focused considerable attention on maximum as well as minimum limits in the oxygen content of life-support atmospheres. Above the earth, both the atmospheric pressure and the partial pressure of oxygen decrease rapidly. The oxygen content of air remains constant at 20.946% to an altitude of ca 20 km, after which it decreases rapidly (1).

Human evolution has taken place close to sea level, and humans are physiologically adjusted to the absolute partial pressure of the oxygen at that point, namely 21.2 kPa (159.2 mm Hg), ie, 20.946% of 101.325 kPa (760 mm Hg). However, humans may become acclimatized to life and work at altitudes as high as 2500–4000 m. At the 3000-m level, the atmospheric pressure drops to 70 kPa (523 mm Hg) and the oxygen partial pressure to 14.61 kPa (110 mm Hg), only slightly above the 13.73 kPa (102.9 mm Hg) for the normal oxygen pressure in alveolar air. To compensate, the individual is forced to breathe much more rapidly to increase the ratio of new air to old in the lung mixture.

In passenger aircraft flying at higher altitudes, the cabin is customarily pressurized to an elevation equivalent to ca 2300 m, where the oxygen partial pressure is 16.13 kPa (121 mm Hg), which is equivalent to a sea-level concentration of approximately 16% oxygen. With passengers at rest no discomfort is observed. To provide for an emergency in which the oxygen partial pressure drops dangerously, for example at 11.5 km oxygen partial pressure is 4.46 kPa (4.4% O_2) vs 21.22 kPa (20.95% O_2) sea level equivalents, oxygen masks are provided for each passenger. Hence, using pure oxygen as a supplement, normal physiological exchange continues despite loss of cabin pressure. However, above 11.5 km even pure oxygen is insufficient and the plane is forced to descend.

Where cabin pressure cannot be maintained, as in military aircraft, supplemental oxygen must be provided by mask, and somewhat higher oxygen partial pressures are the rule. The U.S. Air Force has established 56.7 kPa (425 mm Hg) as the maximum oxygen partial pressure supplied to aviators. Exposure to higher partial pressures for more than a few hours leads to pneumonia, difficulties in the central nervous system, and other complications. Similarly, the lower practical limit in military practice has been established at about 16.7 kPa (125 mm Hg). The astronaut's space suit is pressurized with pure oxygen to 34.5 kPa (259 mm Hg), equivalent to 34% oxygen at earth's surface (see OXYGEN-GENERATION SYSTEM).

Life-support atmospheres supplied in underwater operations require even more careful control. The dangers of excessive pressures of nitrogen and other inert gases are well known. When oxygen is present in excessive amounts and the period of exposure is long, toxic effects develop. The problem thus becomes one of choosing the gas mixture that simultaneously provides mechanical support and becomes the carrier and diluent for the oxygen (41). The borderline incidence of pulmonary toxicity is considered to be 60.8 kPa (456 mm Hg) of oxygen, a <5% reduction in vital capacity for resting humans inhaling pure oxygen continuously in excess of 750 h (40). At 50.66 kPa (380 mm Hg), 50% oxygen at sea level, tolerance times are infinite. Concentrations of oxygen above 284 kPa (2.8 atm) cause difficulties in the central nervous system within a few hours (42).

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Table 1. **Oxygen Solubility in Water**

Temperature, °C	Aqueous solubility of O_2 at STP, L/L
0	0.0489
5	0.0429
10	0.0380
15	0.0342
20	0.0310
25	0.0283
30	0.0261
40	0.0231
50	0.0209
60	0.0195
70	0.0183
80	0.0176
90	0.0172
100	0.0170

Table 2. **Physical Properties of Oxygen**[a]

Property	Value
triple point	
temperature, K	54.359 ± 0.002
pressure, Pa[b]	146.4
density, g/L	
gas	0.0108
liquid	1306.5
solid	1300
boiling point, at 101.3 kPa, K	90.188
density, g/L	
gas	4.470
liquid	1141.1
melting point, K	54.22
critical point	
temperature, K	154.581
pressure, MPa[c]	5.043
density, g/L	436.1
gas, at 101.3 kPa	
density, g/L	
at 0°C	1.42908
at 21°C	1.327
heat capacity, J/(mol·K)[d]	
C_p, at 25°C	29.40
C_p, at 26°C	1.396
dielectric constant at 20°C	1.0004947
n_{D}°	1.0002639
viscosity at 25°C, μPa·s(=cP × 10^{-3})	20.639
thermal conductivity, at 0°C, mW/(m·K)	2.448
sound velocity, at 0°C, m/s	317.3
liquid	
heat capacity, sat liq, J/(mol·K)[d]	54.317
heat of vaporization, J/mol[d]	6820
viscosity, μPa·s(=cP × 10^{-3})	189.4
thermal conductivity, mW/(m·K)	149.87
sound velocity, at 87 K, m/s	904.6
surface tension, at 87 K, N/m	13.85×10^{-7}
volume ratio, gas at 21°C to liquid at bp	859.9
solid	
heat of sublimation, J/mol[d]	8204.1
heat capacity, J/(mol·K)[d]	46.40
heat of fusion, J/(mol)[d]	444.5

[a] Refs. (8–12).

[b] To convert Pa to mm Hg, multiply by 0.0075.

[c] To convert MPa to psi, multiply by 145.

[d] To convert joule to cal, divide by 4.184.

Table 3. **Gaseous Composition of Air**[a]

Constituent[b]	Vol %	Boiling point, K
	Fixed components	
nitrogen	78.084 ± 0.004	77.36
oxygen	20.946 ± 0.002	90.18
argon	0.934 ± 0.001	87.28
carbon dioxide	0.033 ± 0.003	
neon	$(1.821 \pm 0.004) \times 10^{-3}$	27.09
helium	$(5.239 \pm 0.05) \times 10^{-4}$	4.215
krypton	$(1.14 \pm 0.01) \times 10^{-4}$	119.81
xenon	$(8.7 \pm 0.1) \times 10^{-6}$	165.04
hydrogen	ca 5×10^{-5}	20.27
	Impurities[d]	
water	0.1–2.8	
methane	1.5×10^{-4}	
carbon monoxide	$(6–100) \times 10^{-6}$	
sulfur dioxide	0.1 to 1.0	
nitrous oxide	5×10^{-5}	
ozone	$(1–10) \times 10^{-6}$	
nitrogen dioxide	$(5–200) \times 10^{-8}$	
radon	6×10^{-18}	
nitric oxide	[e]	

[a] Refs. (1,11), and 12.

[b] Composition of dry air is constant to an altitude of 20 km.

[c] Sublimation temperature. Liquid CO_2 does not exist at 101 kPa (1 atm).

[d] In ambient air, including dusts, pollen, and local pollutants.

[e] Trace amounts.

Table 4. **Product (Oxygen) Class Shipments for Selected U.S. States: 2002 and 1997**[a]

NAICS product class code	Product class and geographic area	Value of product shipments $\$ \times 10^3$
United States	2002	807,573
	1997	993,637
California	2002	55,642
	1997	46,329
Illinois	2002	21,625
	1997	32,148
New York	2002	14,601
	1997	19,348
Ohio	2002	97,448
	1997	81,801
Pennsylvania	2002	27,027
	1997	36,014
Texas	2002	113,194
	1997	221,781
Washington	2002	13,753
	1997	15,353
West Virginia	2002	21,973
	1997	

[a] Ref. 22.

Table 5. **Compressed Gas Association, Oxygen Commodity Specifications**[a]

Limiting characteristics	Type I, gas grades[b]						Type II, liquid grades[b]			
	A	B	C	D	E	F	A	B	C	D
O_2, min %	99.0[c]	99.5	99.5	99.5	99.6	99.995	99.0[c]	99.5	99.5	99.5
inert	[d]			100[d]			[d]			[d]
water			50	6.6	8	1.0		6.6	26.3	6.6
dewpoint, °C			−48.1	−63.1	−62.2	−76.1		−63.3	−53.1	−63.3
THC, as methane[e]					50	1.0			67.7	
methane				50						25
ethane and other hydrocarbons[f]				6						3
ethylene				0.4						0.2
acetylene				0.1		0.05			0.62	0.05
carbon dioxide	300			10		1.0	300			5
carbon monoxide	10					1.0	10			
nitrous oxide				4		0.1				2
halogenated refrigerants				2						1
solvents				0.2						0.1
other by infrared				0.2						0.1
permanent particulates									<1.0 mg/L	

[a] Ref. 23.

[b] Minimum contained oxygen and maximum contaminant levels where specified for the several grades of oxygen. Contaminants given in volumes per million (vpm). Low purity oxygen (93%) has not been included.

[c] USP grade.

[d] Material has no odor.

[e] THC = total hydrocarbon content.

[f] As ethane.

Table 6. **Moisture: Dew Point Conversion**[a]**, Water Vapor per Total Mixture Volume**[b]

	Moisture content	
Dew point, °C	Volume, ppm	mg/mL
−78.9	0.65	0.49
−76.1	1.02	0.76
−73.3	1.57	1.17
−70.5	2.4	1.79
−67.8	3.6	2.7
−65.0	5.4	4.0
−62.2	7.9	5.9
−59.4	11.6	8.6
−56.7	16.7	12.5
−53.9	24.0	17.9
−51.1	34.0	25
−48.3	48.0	36
−45.6	67.0	50

[a] Ref. 29.

[b] Table applies equally to air, argon, nitrogen, helium, hydrogen, and neon.