CHAPTER 19

PRESSURE

19-1 INTRODUCTION

We live in an environment in which the air in the atmosphere creates pressure around us. We experience changes in pressure when we fly in airplanes or climb mountains. Some people experience changes in pressure when they scuba dive or work in tunnels or caissons. The human body can function within a particular range of pressures, and it is limited in the rate of change it can tolerate. In explosions, there are rapid changes in pressure that can injure people and destroy buildings and other property. There are many products and processes involving elevated pressures where sudden or uncontrolled releases, or both, can cause injury and damage.

19-2 LOW-PRESSURE ENVIRONMENTS

Physics

Low-pressure environments are those that have a pressure less than sea level. (At sea level, standard atmospheric pressure is 760 mmHg or approximately 14.7 lb/in^2). The air around us is composed of oxygen, nitrogen, and small amounts of other gases. Our environment contains approximately 21% oxygen. As we go up in altitude from sea level, the pressure around us decreases (see Table 19.1). However, the gas mixture stays the same. Dalton's law of partial pressure states that the partial pressure, P, of any gas in a mixture (x), is equal to the total pressure, P_{tot}, times the percent of the gas in the mixture:

$$P_x = P_{tot} \times \%\text{gas}x. \qquad (19\text{-}1)$$

For example at sea level, the partial pressure of oxygen P_{O_2} is

$$P_{O_2} = 760 \times 21\% = 160\,\text{mmHg}.$$

At altitudes above sea level, the total pressure is lower than that at sea level. The partial pressure of oxygen is also lower. Table 19-1 lists the pressure at altitudes and depths underwater.

Physiology

The partial pressure of oxygen affects the ability of the blood to transport oxygen throughout the body. The red cells in the blood perform the transport function. They contain hemoglobin, which forms a loose bond with oxygen. When we inhale, the red cells pick up oxygen from the lungs and release it to cells in the body as the blood circulates. During

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TABLE 19-1 Pressures at Altitude and Underwater[a]

Altitude or Depth Below Sea Level (ft)	Total Pressure (mmHg)	Total Pressure (lb/in^2)	Partial Pressure of Oxygen for Standard Gas Mixture in Air (mmHg)
45,000	111	2.15	23.3
40,000	144	2.79	30.2
30,000	223	4.3	46.7
20,000	349	6.8	73.1
15,000	424	8.2	88.8
10,000	523	10.1	110
5,000	632	12.2	132
Sea level	760	14.7	159
100 underwater	3,040	58.8	637
200 underwater	5,320	103	1,115
300 underwater	8,360	162	1,751

[a] Table data assume fresh water and 33 ft of depth is 1 atm.

circulation, the hemoglobin also picks up carbon dioxide, a waste product of cellular metabolism, from the cells. The red cells return to the lungs, release carbon dioxide, and bond with oxygen once again. The carbon dioxide is exhaled.

The percent of the red cells actively bonding with and transporting oxygen is normally approximately 97% at sea level. However with increasing altitude, there is a reduction in the portion of red cells that are effectively transporting oxygen. This is the oxygen dissociation curve shown in Figure 19-1.

The body has some ability to improve oxygen transport at increased altitude by increasing breathing rate and heart rate. These forms of compensation are limited. The body also will produce higher concentrations of red cells in the blood, but this adjustment takes nearly 1 month to occur fully. People who live at high altitudes have a higher density of red cells in the blood than those who live at sea level. Athletes who must perform at high altitude often will train in such an environment for some time to allow the red cell adjustment to occur.

Hazards

Hypoxia is a lack of metabolic oxygen. A reduction in oxygen transport affects cell metabolism. One can express the oxygen deficiency in terms of altitude, saturation of red cells, or partial pressure. The effects are a result of the degree of hypoxia.

One of the first effects exhibited is loss of night vision. There are two kinds of receptor cells in the retina of the eye. One type (cones) senses color; the other type (rods) senses black and white. Rods are most sensitive at low light levels. As one goes up in altitude, the ability to see in low light levels is reduced. This effect begins to appear at approximately 6,000 ft.

As one progresses to higher altitudes, other effects are impaired memory, judgment and coordination, drowsiness, euphoria, syncope (unconsciousness), and death.

As one goes up in altitude, the middle ear vents through the Eustachian tube and pressure in the middle ear that is greater than the surroundings is reduced. When one moves rapidly from altitude to sea level, the surrounding pressure is higher than that in body cavities and venting of the middle ear is more difficult because the opening of the Eustachian

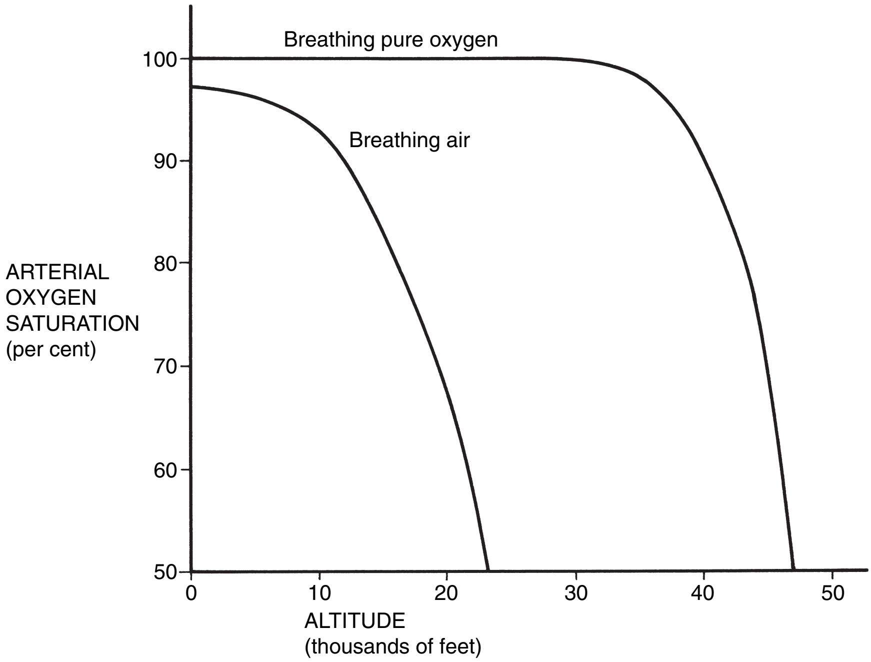

Figure 19-1. The effects of oxygen deficiency caused by low-pressure atmospheres are delayed by increasing the oxygen content of a breathing gas mixture.

tube in the pharynx may seal shut. The increase in atmospheric pressure can create pain in sinuses blocked by mucus.

Controls

The primary objective is to maintain the partial pressure of oxygen near that at sea level. For reduced-pressure environments, one can accomplish this in two ways: increase the total pressure or increase the portion of oxygen in the breathing air.

There is a preferred range of partial pressures of oxygen. The lower limit is equivalent at standard sea level conditions to approximately 16% to 17% oxygen. The body's reaction to high levels of oxygen in air when it is inhaled for extended periods is called oxygen toxicity. At 60% oxygen mixtures at sea level, often the upper limit of recommended oxygen concentrations, people start to cough. At higher concentrations of oxygen, tolerance is reduced further.

Commercial jet aircraft fly at 25,000 to 40,000 ft. At these altitudes, adjustments in breathing air are essential. In most commercial aircraft, the total pressure is increased above that outside the aircraft and there is an emergency oxygen system in the event that cabin pressure is lost.

American manned spacecraft balance the demands for a suitable breathing atmosphere against the structural weight necessary to sustain the pressure difference between inside and outside the spacecraft. A cabin pressure of approximately 260 mmHg with 60% oxygen achieves a desired partial pressure similar to sea level. Higher total pressures require stronger and heavier structural elements for spacecraft flying in pressures that are near zero. Breathing 100% oxygen can extend the oxygen dissociation curve to new limits (see Figure 19-1). However, oxygen toxicity symptoms will appear with extended exposure.

One should also note that increasing the portion of oxygen in an environment elevates the rate of combustion should a fire start.

19-3 HIGH-PRESSURE ENVIRONMENTS

Physics

Pressures above those at sea level are encountered in underwater diving and in certain kinds of construction work. In tunnelling and caisson work, water may seep into the underground work area. So the work area is sometimes sealed and pressurized to minimize the water seepage and to avoid its interference with the work. Workers enter the pressurized area through air locks.

Hyperbaric chambers in which medical activities or other work are performed under elevated atmospheric pressure are other examples of high-pressure environments.

Dalton's law of partial pressure applies to high-pressure environments as well. Pressures under water increase at the rate of 1 atm for every 32 to 33 ft of depth, depending on the density of water. Salt water is slightly more dense than fresh water. Thus, a worker in a pressurized tunnelling project that is 33 ft below the surface is working at a total pressure of approximately 2 atm. Note that the pressure at the surface is already approximately 1 atm and pressure resulting from depth adds to it.

Another important phenomenon for high pressure environments involves Henry's law. This law says that gases will dissolve in fluids that are under pressure. When pressure surrounding the fluid is reduced, the gas escapes, typically forming small bubbles. We observe this when we open carbonated soft drinks that are under pressure.

Hazards

The allowable range of oxygen partial pressures also applies to high-pressure environments. If surface air is pumped under pressure to a diver. The portion of oxygen in the air must be reduced if the diver is more than 65 ft (3 atm) below the surface. Otherwise, the equivalent of the 60% oxygen limit at sea level is exceeded. At significant depths, controlling oxygen content of breathing gases becomes difficult. Limits become very tight. Enriched oxygen mixtures (partial pressures for oxygen above that at sea level) also increase dangers from fire.

Another problem is that of inert gases used in breathing mixtures. At high pressures, nitrogen induces narcotic effects (euphoria, drowsiness, and muscular weakness), called nitrogen narcosis. In deep diving, helium, another inert gas, often replaces nitrogen in breathing gases. Helium does not produce narcotic effects until much higher pressures are reached. However, helium does create communication and heat transfer problems. Speech sounds are at much higher frequencies in a helium atmosphere and convective heat loss increases compared with nitrogen. Contaminant gases in breathing mixtures may add other dangers.

As pressure increases, gas going into solution in the body according to Henry's law is not a problem. However, when someone returns from high-pressure to normal environmental pressure, there are dangers. The family of decompression disorders has various names: decompression sickness, dysbarism, the bends, or caisson's disease. Bubbles or embolisms may form in tissues or in the blood. Bubble formation in tissue frequently occurs in body joints and can be very painful. Bubbles can interrupt blood flow in the heart or lungs if they are large enough.

Controls

Breathing gases supplied to people in high-pressure environments must be well controlled for proper oxygen partial pressures. In addition, contaminant gases and particles from compressor equipment and lubricants may be dangerous and must be removed from breathing mixtures. Carbon monoxide, for example, can be particularly dangerous, because it bonds easily with hemoglobin and prevents red cells from providing adequate oxygen transport.

To prevent nitrogen narcosis, substitute other inert gases when pressures exceed that necessary for nitrogen narcosis onset. Also consider the adverse effects of alternate inert gases.

To prevent decompression sickness, one can either limit the time of high-pressure exposure or control the rate of decompression. Diving tables give information about allowable exposure time at various depths or pressures and the procedures and durations for decompression. Diving tables are based on diving experience. The U.S. Navy diving tables are the most authoritative. (Most other diving tables are derived from Navy tables.) OSHA[1] diving tables give total decompression time for exposures to certain pressures and durations. They also detail how many stages of decompression are needed, the length and pressure of each stage, and the total decompression time after exposures to particular pressures and durations.

There are other controls that are important for work in high-pressure areas and for diving. Divers must be medically qualified and have regular medical examinations. Diving procedures must be planned carefully and followed during predive, dive, and post-dive phases. Equipment must be tested and examined regularly. One must plan for emergencies and practice emergency procedures.

19-4 PRESSURIZED CONTAINERS

There are many kinds of pressurized containers in processes and products, ranging from aerosol cans to inflated tires, water heaters, tanks, compressed gas cylinders, and cookers. In explosions, even buildings and pipes can be pressurized containers. Pipes, pipelines, and process equipment are pressurized containers when they are pressurized to test for leaks and other faults.

Hazards

A container is no stronger than its weakest member, such as a joint, cover, seal, wall, or relief device. Corrosion or physical damage from handling may create a weak point. Containers that have pressurized contents may reach pressures too high for the container, any of its parts, or both. Consequently, the container may leak slowly or suddenly.

The pressure in a container may exceed its limits from exposures or failure of a relief device to function. For example, exposure to sun or some other heat source may increase the pressure in a container. The Boyle-Charles law helps us predict the pressure change:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}, \tag{19-2}$$

where

P is the pressure (absolute),

V is the volume, and

T is the temperature (absolute),

and subscripts define the initial and final conditions.

Example 19-1 Suppose a gas cylinder is pressurized to 2,200 lb/in^2 (gauge) at 70°F. After exposure to direct sun, the temperature increases to 180°F. What is the pressure after exposure?

Because the volume is constant, the final pressure is

$$P_2 = \frac{P_1 T_2}{T_1} = \frac{(2200+15)(180+460)}{(70+460)}$$
$$= 2{,}675\ \mathrm{lb/in^2}\ \text{(absolute)} = 2{,}660\ \mathrm{lb/in^2}\ \text{(gauge)}.$$

A leak in an unrestrained, pressurized container may create sufficient force from the released gas to put the container in motion. A broken valve fitting on a pressurized gas cylinder can send the container in motion like a missile, the momentum of which can send the cylinder through a wall. Similar events occur in overheated and overpressured water heaters.

Leaking material may have dangers inherent to its temperature or toxic or reactive properties. Contact with hot water or high-pressure steam will cause burns. A material may inflict injury if it is a caustic or acid. Inhalation of toxic materials or contact with them may cause harm, depending on the material.

Compressed air in tires, air lines, and equipment may pose fire hazards because of the presence of enriched oxygen. This is particularly true if fuel and sources of heat or sparks are also present.

A sudden release of materials under pressure may produce a shockwave capable of knocking someone down or causing other damage, as noted in Chapter 17. The shockwave may cause materials in its path to strike someone and cause injury and the flying materials may damage other property.

Certain kinds of truck tires and other large tires pose a danger from sudden release of inflating air. This is particularly true for multipiece rims that are inadequately fastened together. If a person is in the path of the rim or other parts that may fly during the release, a serious injury can result.

Controls

Application of Haddon's energy theory (Chapter 9) helps identify controls for pressure release hazards. First, if there is a need for pressure in an application, the amount of pressure should be limited. There are various devices that prevent overpressures. Avoid pressure buildup in containers. For example, do not expose pressurized containers to direct sun or other sources of heat. If pressures are released, controlling the location and direction can prevent injuries to nearby people. The release should be controlled so that hazardous temperatures or materials do not come into contact with people. Releases of steam or other material should be routed to an area where there is little danger. Barriers may help in some cases. For example, tire cages and other tire restraining equipment can prevent some injuries from accidents while inflating truck and other large tires.

Avoid pressures that are not needed and reduce them for certain activities. Equipment should be deenergized and depressurized before working on it. Observe tag out and lock out procedures when servicing pressurized equipment. Train workers about the dangers of pressurized equipment. They must learn how to protect themselves from these dangers.

Normally, aircraft tires are inflated with nitrogen to prevent fire that may otherwise occur if they were inflated with air and heat severely from skids during landing.

Overpressure Devices

There are a number of overpressure devices, each with particular applications. Some devices are suitable for gas and some for steam. Others are suitable for liquids and some for gases, vapors, or liquids. Some require more maintenance and testing than others to ensure that they operate correctly. Some are subject to corrosion, scale buildup, and other problems that could render them inoperative or make them operate poorly. Valves are suitable for relatively clean materials because they must reseat after relieving pressure. Valves minimize loss of material. Rupture discs are better for relieving large volumes and corrosive, dirty, and viscous fluids. Pressure relief devices and components like pipes that direct releases to a safe location must be sized for the flow and type of materials that will be released. The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code gives specifications for installation and certification testing of overpressure devices.

Safety Valves A safety valve is actuated when the upstream pressure exceeds some predetermined value. The valve rapidly opens fully or pops open to relieve the pressure. Safety valves are used for gas, steam, and vapor.

Relief Valves When the upstream pressure exceeds some predetermined level, a relief valve opens in proportion to the amount of overpressure and then closes when the pressure has returned to an acceptable level. Relief valves are used primarily for liquids.

Safety Relief Valves These valves are activated by upstream pressures that exceed some value. The valves are suitable as safety valves or relief valves. They are used in liquid or in gas, steam, or vapor applications.

Frangible Discs Frangible discs or rupture discs are relatively flat metal pieces. Each disc is designed to burst at a particular pressure. They are mounted between two flanges along a vent pipe and they range in size from less than $^1/_2$ in in diameter to approximately 4 ft. Rupture pressures range from a few ounces to very high pressures. Other considerations that may be included in design are the number of pressure cycles and selecting material because of potential corrosion, temperatures in which they are placed, and other factors. Rupture discs generally release large quantities of process material when they fail and perform their function, whereas valves release small quantities. Failure of a disc may produce significant downtime for replacement of the disc, replacement of lost materials, and restart of a process. Some rupture discs are actuated by a quantity of explosive material connected to a sensing device and a detonator control. Frangible discs are used for liquids, gases, steam, or vapor.

Fusible Plugs A fusible plug is a plug made of a metal that will melt at a selected temperature and will relieve a container of pressure. Fusible plugs are used in boilers, compressed gas cylinders, and other pressure vessels. They allow overpressures from fire or other causes of overheating to be vented. A plug may consist entirely of the alloy that will melt or have a high-temperature metal core surrounded by the low-temperature alloy.

Discharge Lines or channels approaching or leaving a pressure relief device must be sized to provide adequate flow of materials. Discharged materials must flow to some location where there is no danger to people because high temperatures and high flow rates may cause injury. High volumes must be discharged to adequately sized holding areas or containers.

Vacuum Failures Pressure reduction can damage containers. For example, tanks can collapse as they are drained. Even if venting is provided, the vent line must provide adequate flow rates to prevent a vacuum from occurring.

Freeze Plugs Another type of pressure relief device is a freeze plug. Water and many water-based liquids expand near the freezing point. A freeze plug will allow the liquid to expand and drain, thereby reducing the likelihood of damage and controlling the location of failure. It may be possible to reduce the risk of damage even further by using antifreeze solutions together with freeze plugs.

Temperature Limit Devices In accordance with Boyles-Charles Law, pressure will increase and decrease in closed containers with temperature changes in contents. Temperature limit sensors and control systems often are used in connection with processes and containers where pressure limits create dangers.

19-5 HIGH-PRESSURE FLUIDS

Gases and liquids under pressure are very common. A few examples are hydraulic lines, compressed air for many purposes, paint sprayers, grease guns, hydraulic and pneumatic tools, spray applicators for agricultural chemicals, water hoses used in fire fighting and landscaping, and fuel injection devices in engines. Gases and liquids under pressure and the lines and hoses used to distribute them have dangers. Pressure testing of pipelines and process equipment can produce explosive releases of gases.

Hazard

Pressurized gases and fluids can cause injury. Major hazards are air and gas injuries, injection injuries, and whipping of lines.

Air and Gas Injuries Getting pressurized gas or air into the viscera can cause injury or can rupture tissues. For example, some people use compressed air to clean parts. If the nozzle of a compressed air line is placed in the mouth with air flowing, the air can inflate and injure tissues.

Injection Injuries Injection injuries occur when a fine stream of gas or fluid enters the body. Fine streams of air, gas, or liquid can penetrate the skin. Medical inoculations with injection guns apply this principle. Fine, high-pressure streams of water (sometimes mixed with abrasive particles) are used to cut stone in excavation projects. A fine stream may look safe because of its size and seem harmless because of the familiarity with water or some other common liquid. However, it can cause serious injection injuries. High-pressure streams of fluids can easily make incisions in skin and other tissue. Injuries from 650 to more than 7,000 lb/in^2 streams are noted in medical literature. Such pressures can be created from equipment operating at much lower pressures. Fluid injected through even a tiny hole in the skin can migrate throughout several layers of tissue and is extremely difficult to remove. If the fluid is toxic or contaminated with infectious microorganisms, amputation often is the only solution. Radical treatments for injection injuries are related to the delay in onset of treatment. Injection injuries typically involve the fingers and hands, but have included the arms, face, and other parts of the body. A gas injected under the skin may create embolisms in the blood stream that can interrupt lung or heart functions if they migrate to these organs.

Whipping of Lines Fluid moving through a nozzle creates reactive forces on the nozzle. If the forces are large enough, they can cause the nozzle and hose to move or whip. If the hose or nozzle strikes someone, it can cause serious injury, and if it strikes something, it can cause damage.

Controls

One control for hazards of compressed air lines is reducing the pressure to a low level. OSHA requires compressed air for cleaning purposes to be 30 lb/in^2 or lower. There are pressure-reducing nozzles that drop line pressure to 30 lb/in^2 or less. Setting pressure regulators on general use air lines to 30 lb/in^2 or less minimizes danger to users.

Controls for reducing the hazards of compressed gas and fluid lines include distance, guarding, and the use of solid lines. Increasing the distance of hydraulic lines from people or body parts reduces the force of released fluid by the time it contacts a person. Leaking hydraulic hoses have caused injection injuries. For example, a line leading to a control box may be within a few inches of an operator's hands. Keeping lines away from hands or fingers can reduce the chance of injury.

Solid lines do not leak as readily as hoses, which develop leaks from vibration, pressure, bending cycles and aging. Where lines must come close to people, solid lines and tight, well-maintained fittings reduce the chances of a leak.

Hose or lines that come near people should have the extra protection of guarding. A shield of metal or other materials that a fluid stream cannot cut easily gives this protection.

People who work around compressed air lines, hydraulic systems and other pressurized fluid and gas equipment should learn about the hazards. They should learn not to place fingers or hands against a fluid stream, and they should learn not to place the stream near anyone else. Protective gloves and clothing may help reduce injection injuries.

When pipelines and process equipment are pressure tested, workers should be clear of potential rupture points along the line. Instruments for reading pressures should not require workers to remain close to pressurized lines. If a compressor and its operators are removed from other crews preparing pipelines for testing, radio communication between crews is essential. Otherwise, one crew may not be aware of what the other is doing. The preparation crew may not be aware of pressure in a line. Department of Transportation regulations and other references give detailed procedures for pressure testing of pipelines transporting hazardous liquids.[2]

EXERCISES

1. A cylinder is filled with nitrogen gas at 70°F to the maximum allowed pressure (2,640 lb/in^2 [gauge]). If it were left in the sun and the contents reached a temperature of 210°F, what would be the resulting pressure in the cylinder?
2. A caisson worker is required to work under water at a depth of 60 ft digging a tunnel under a river. Assuming a 33-ft column of water is equivalent to 1 atm, determine the following:
   (**a**) the pressure for the worker in millimeters of mercury
   (**b**) the partial pressure of oxygen if air is pumped from the surface (assume standard sea level conditions) to the worker
3. In a diving operation, if the upper limit for oxygen at sea level is 40% (where oxygen toxicity starts to appear) and the lower limit is 16% (hypoxia occurs), what is the allowable range for oxygen in the breathing gas mixture (percent of total) when a diver is submerged to 600 ft below sea level?

REVIEW QUESTIONS

1. What is Dalton's law of partial pressure?
2. What effect does low atmospheric pressure and low oxygen partial pressure have on the body?
3. What are the hazards of high altitude?
4. What controls can eliminate or reduce the dangers of high altitude?
5. What is Henry's law?
6. What is the significance of Henry's Law for people who work in high-pressure atmospheres?
7. What are the hazards of high-pressure atmospheres?
8. What controls can reduce the dangers of these hazards?
9. What are alternate terms for dysbarism?
10. Identify three hazards associated with high pressure containers.
11. What controls can eliminate or reduce these hazards?
12. Explain the operating principle for the following overpressure devices:
    (**a**) safety valve
    (**b**) relief valve
    (**c**) safety relief valve
    (**d**) frangible disc
    (**e**) fusible plug
    (**f**) freeze plug
13. When overpressure is released, identify a hazard and control for the release.
14. By what principle of physics are temperature and pressure interrelated?
15. Identify a hazard associated with high pressure

(**a**) hydraulic lines

(**b**) air lines

16. What is a suitable control for each hazard in question 15?

NOTES

1 29 CFR 1926.804.

2 49 CFR 195.300.

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