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Administration

Advisory Circular

Subject: Aircraft Operations at Altitudes Above 25,000 Feet Mean Sea Level or Mach Numbers Greater Than .75

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FOREWORD

This advisory circular (AC) alerts pilots transitioning from aircraft with less performance capability to complex, high-performance aircraft that are capable of operating at high altitudes and high airspeeds. In particular, this AC stresses special physiological, equipment, and aerodynamic considerations involved in these kinds of operations. It also provides information to aid pilots in becoming familiar with the basic phenomena associated with high-altitude and high-speed flight.

Title 14 of the Code of Federal Regulations (14 CFR) part 61 prescribes the knowledge and skill requirements for the various airman certificates and ratings, including category, class, and type ratings authorized to be placed thereon. The civil aircraft fleet consists of numerous aircraft capable of high-altitude flight. Certain knowledge elements of high-altitude flight are essential for the pilots of these aircraft. As required by 14 CFR § 61.31, pilots who fly at altitudes at or above FL250 in a pressurized aircraft must receive training in the critical factors relating to safe flight operations under those circumstances. These critical elements include knowledge of the special physiological and/or aerodynamic considerations that should be given to high-performance aircraft operating in the high-altitude environment. High-altitude flight has different effects on the human body than those experienced during lower altitude flight. An aircraft's aerodynamic characteristics displayed in high altitude flight may differ significantly from those experienced when penetrating at a lower altitude. Knowledge of and skill in operating high-performance aircraft will enhance the pilot's ability to easily transition into aircraft capable of high speed, high altitude flight.

It is beyond the scope of this AC to provide a more definitive treatment of this subject. Pilots should recognize that they need greater knowledge and skills for the safe and efficient operation of state-of-the-art turbine and turbocharged powered aircraft. We *strongly* urge pilots to pursue further study from the many excellent textbooks, charts, and other technical reference materials available through industry sources. Pilots will obtain from these sources a detailed understanding of both physiological and aerodynamic factors that relate to the safe and efficient operation of the broad variety of high-altitude aircraft available today and forecast for the future.

/s/ for

John M. Allen
Director, Flight Standards Service

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CHAPTER 1. GENERAL INFORMATION

1-1. PURPOSE. This advisory circular (AC) alerts pilots transitioning from aircraft with less performance capability to complex, high-performance aircraft capable of operating at high altitudes and high airspeeds of the special physiological, equipment, and aerodynamic considerations involved in these kinds of operations. It also provides information to aid pilots in becoming familiar with the basic phenomena associated with high-altitude and high-speed flight.

1-2. CANCELLATION. This AC cancels AC 61-107A, Operations of Aircraft at Altitudes Above 25,000 Feet MSL and/or Mach Numbers (M_{mo}) Greater Than .75, dated January 2, 2003.

1-3. RELATED REGULATIONS. In addition to the training required by Title 14 of the Code of Federal Regulations (14 CFR) part 61, § 61.31(g), pilots of high-altitude aircraft should be familiar with the following regulations.

- Title 14 CFR part 91, § 91.121, Altimeter Settings.
- Section 91.135, Operations in Class A Airspace.
- Section 91.159, VFR Cruising Altitude or Flight Level.
- Section 91.179, IFR Cruising Altitude or Flight Level.
- Section 91.180, Operations Within Airspace Designated as Reduced Vertical Separation Minimum Airspace.
- Section 91.211, Supplemental Oxygen.
- Section 91.215, ATC Transponder and Altitude Reporting Equipment and Use.

1-4. DEFINITIONS.

a. Aspect Ratio. The relationship between the wing chord and the wingspan. A short wingspan and wide wing chord equal a low aspect ratio.

b. Aileron Buzz. A very rapid oscillation of an aileron, at certain critical airspeeds on some aircraft, that does not usually reach large magnitudes nor become dangerous. It is often caused by shock-induced separation of the boundary layer.

c. Aileron Snatch. A violent back and forth movement of the aileron control as airflow changes over the surface.

d. Cabin Altitude. Cabin pressure in terms of equivalent altitude above sea level.

e. Critical Mach Number (M_{cr}). The free stream Mach number (M) at which local sonic flow such as buffet, airflow separation, and shock waves becomes evident. These phenomena occur above M_{cr}, and are as follows:

(1) Subsonic. M below .75.

(2) Transonic. M from .75 to 1.20.

(3) Supersonic. M from 1.20 to 5.0.

(4) Hypersonic. M above 5.0.

f. Drag Divergence. A phenomenon that occurs when an airfoil's drag increases sharply and requires substantial increases in power (thrust) to produce further increases in speed. Do not confuse drag divergence with M_{cr}. The drag increase is due to the unstable formation of shock waves that transform energy into heat and into pressure pulses that act to consume a major portion of the available propulsive energy. Turbulent air may produce an increase in the coefficient of drag.

g. Force. Generally defined as the cause for motion or the cause of change or stoppage of motion. The ocean of air through which an aircraft must fly has both mass and inertia and, thus, is capable of exerting tremendous forces on an aircraft moving through the atmosphere. When all of the above forces are equal, the aircraft is said to be in a state of equilibrium. For instance, when an aircraft is in level, unaccelerated 1.0 G flight, thrust and drag are equal, and lift and gravity (or weight plus aerodynamic downloads on the aircraft) are equal. Forces that act on any aircraft as the result of air resistance, friction, and other factors are:

(1) Thrust. The force required to counteract the forces of drag to move an aircraft in forward flight.

(2) Drag. The force that acts in opposition to thrust.

(3) Lift. The force that sustains the aircraft during flight.

(4) Gravity. The force that acts in opposition to lift.

h. Mach. Named after Ernst Mach, a 19th century Austrian physicist, Mach is the ratio of an aircraft's true speed compared to the local speed of sound at a given time or place.

i. Mach Buffet. The airflow separation behind a shock wave pressure barrier caused by airflow over flight surfaces exceeding the speed of sound.

j. Mach (or Aileron) Buzz. A term used to describe a shock-induced flow separation of the boundary layer air before reaching the ailerons.

k. Mach Meter. An instrument designed to indicate Mach number. Mach-indicating capability is incorporated into the airspeed indicator(s) of current generation turbine-powered aircraft capable of Mach range speeds.

l. Mach Number (M). A decimal number (M) representing the true airspeed (TAS) relationship to the local speed of sound (e.g., TAS 75 percent (.75 M) of the speed of sound where 100 percent of the speed of sound is represented as Mach 1 (1.0 M)). The local speed of sound varies with changes in temperature.

m. Mach Speed. The ratio or percentage of the TAS to the speed of sound (e.g., 1,120 feet (ft) per second (ft/s) (660 knots (kts)) at mean sea level (MSL)), represented by a Mach number.

n. Mach Tuck. The result of an aft shift in the center of pressure causing a nosedown pitching moment.

o. Maximum Operating Limit Speed (M_{MO}) in Mach. An airplane's maximum certificated Mach number. Any excursion past M_{MO}, whether intentional or accidental, may cause induced flow separation of boundary layer air over the ailerons and elevators of an airplane and result in a loss of control surface authority and/or control surface buzz or snatch.

p. Maximum Operating Limit Speed (V_{MO}) Expressed in Knots Calibrated Airspeed (KCAS). An airplane's maximum operating limit speed. Exceeding V_{MO} may cause aerodynamic flutter and G-load limitations to become critical during dive recovery. Structural design integrity is not predictable at velocities greater than V_{MO}.

q. Q-Corner or Coffin Corner. A term used to describe operations at high altitudes where low IAS yield high TAS (as indicated by Mach number) at high angles of attack (AOA). The high AOA results in flow separation, which causes buffet. Turning maneuvers at these altitudes increase the AOA and result in stability deterioration with a decrease in control effectiveness. The relationship of stall speed to the M_{cr} narrows to a point where sudden increases in AOA, roll rates, and/or disturbances (e.g., clear air turbulence) cause the limits of the airspeed envelope to be exceeded. Coffin corner exists in the upper portion of the maneuvering envelope for a given gross weight and G-force.

r. Service Ceiling. The maximum height above MSL at which an airplane can maintain a rate of climb of 100 ft per minute (ft/min) under normal conditions.

1-5. RELATED READING MATERIAL. The following documents provide additional information related to the subject of this AC.

- Airplane Flying Handbook (FAA-H-8083-3).
- Glider Flying Handbook (FAA-H-8083-13).
- Pilot's Handbook of Aeronautical Knowledge (FAA-H-8083-25).
- Aeronautical Information Manual (AIM).
- Airplane Upset Recovery Training Aid.

1-6. WARNING, CAUTION, AND NOTE. This document uses "Warning," "Caution," and "Note" throughout to highlight different levels of importance of information provided. The list below defines them in order of decreasing severity or importance.

a. Warning. Explanatory information about an operating procedure, practice, condition, etc., that may result in injury or death if not carefully observed or followed.

b. Caution. Explanatory information about an operating procedure, practice, or condition, etc., that may result in damage to equipment if not carefully observed or followed.

c. Note. Explanatory information about an operating procedure, practice, or condition, etc.

1-7. BACKGROUND. On September 17, 1982, the National Transportation Safety Board (NTSB) issued a series of safety recommendations that included, among other things, the establishment of a minimum training curriculum for use at pilot schools covering pilots' initial transition into General Aviation (GA) turbojet airplanes. Aerodynamics and physiological aspects of high-performance aircraft operating at high altitudes were among the subjects recommended for inclusion in this training curriculum. These recommendations were the result of an NTSB review of a series of fatal accidents that the NTSB believed to involve a lack of flightcrew knowledge and proficiency in GA turbojet airplanes operating in a high-altitude environment. Although the near-total destruction of physical evidence and the absence of installed flight recorders have inhibited investigators' abilities to pinpoint the circumstances that led to these accidents, the NTSB is concerned that a lack of flightcrew knowledge and proficiency in the subject matter of this AC contributed to either the initial loss of control, or the inability to regain control of the aircraft, or both. A requirement has been added to part 61 for high-altitude training of pilots who transition to any pressurized airplane that has a service ceiling or maximum operating altitude, whichever is lower, above 25,000 ft MSL. Recommended training in high altitude operations that would meet the requirements of this regulation can be found in Chapter 2. We are updating this AC to include strong emphasis on hypoxia awareness, time of useful consciousness, and recovery.

1-8. DISCUSSION.

a. Knowledge and Skill Requirements. Title 14 CFR Part 61 prescribes the knowledge and skill requirements for the various airman certificates and ratings, including category, class, and type ratings authorized to be placed thereon. The civil aircraft fleet consists of numerous aircraft capable of high-altitude flight. Certain knowledge elements of high-altitude flight are essential for the pilots of these aircraft. Pilots who fly in this realm of flight must receive training in the critical factors relating to safe flight operations at high altitudes. These critical elements include knowledge of the special physiological and/or aerodynamic considerations, which should be given to high-performance aircraft operating in the high-altitude environment. High-altitude flight has different effects on the human body than those experienced in lower altitude flight. The aircraft's aerodynamic characteristics in high-altitude flight may differ significantly from those in lower altitude flight.

b. Training and Review. Pilots who are not familiar with operations in the high-altitude and high-speed environment are encouraged to obtain thorough and comprehensive training. This should include a checkout in complex high-performance aircraft before engaging in extensive high-speed flight, particularly at high altitudes. The training should enable the pilot to become thoroughly familiar with aircraft performance charts, aircraft systems and procedures. The pilot should also review the more critical elements of high-altitude flight planning and operations. The aircraft checkout should enable the pilot to demonstrate a comprehensive knowledge of the aircraft performance charts, systems, emergency procedures, and operating limitations, along with a high degree of proficiency in performing all flight maneuvers and in-flight emergency procedures. Knowledge of and skill in high-performance aircraft will enhance the pilot's ability to transition to operating aircraft in the high-speed and high-altitude flight environment.

CHAPTER 2. RECOMMENDATIONS FOR HIGH-ALTITUDE TRAINING

2-1. PURPOSE. This chapter presents an outline for recommended high-altitude training that meets the requirements of § 61.31(g). The actual training, which may be derived from this outline, should include both ground and flight training in high-altitude operations. Upon completion of the ground and flight training, the flight instructor who conducted the training should certify that he or she gave training in high-altitude operations by providing an endorsement in the pilot's logbook or training record. A sample high-altitude endorsement is available in the current edition of AC 61-65, Certification: Pilots and Flight and Ground Instructors.

a. Training Applicability. Note that § 61.31(g) applies only to pilots who fly pressurized airplanes with a service ceiling or maximum operating altitude above 25,000 ft MSL, whichever is lower. But we highly recommend it for all pilots who fly at altitudes above 10,000 ft MSL.

> **NOTE: All pressurized aircraft have a specified maximum operating altitude above which they must not operate. This maximum operating altitude is determined by flight, structural, powerplant, functional, or equipment characteristics. An airplane's maximum operating altitude is limited to 25,000 ft MSL or lower, unless certain airworthiness standards are met. Maximum operating altitudes and service ceilings are specified in the Airplane Flight Manual (AFM).**

b. Aircraft Applicability. The training outlined in this chapter is designed primarily for single-engine and light twin-engine airplanes that fly at high altitudes, but that do not require type ratings. The training should be incorporated into all training courses for aircraft that fly above 25,000 ft MSL if the pilot has not already received training in high-altitude flight. The training in this chapter is intended mainly for reciprocating engine and turboprop aircraft. Therefore, it does not encompass high-speed flight factors such as acceleration, G-forces, Mach, and turbine systems. You can find information on high-speed flight in Chapter 3.

2-2. OUTLINE. This training covers the minimum information needed by pilots to operate safely at high altitudes. We encourage pilots to seek additional information specific to their operation.

a. Ground Training.

(1) The High-Altitude Flight Environment.

(2) Weather.

- The atmosphere.
- Winds and wind shear.
- Clear air turbulence.
- Clouds and thunderstorms.
- Icing.

(3) Flight Planning and Navigation.

- Flight planning.
- Weather charts.
- Navigation.
- Navigational Aids (NAVAID).

(4) Physiological Training.

- Physics of the atmosphere.
- Respiration.
- Trapped gas.
- Physiological problems at increased altitudes.
- Decompression in pressurized aircraft.
- Altitude chamber (optional).
- Physiology of flight video library.

(5) High-Altitude Systems and Components.

- Turbochargers.
- Oxygen and oxygen equipment.
- Pressurization systems.
- High-altitude components.

(6) Aerodynamics and Performance Factors.

- Air density.
- Knots true air speed (KTAS).

(7) Emergencies.

- Decompression.
- Turbocharger failure or malfunction.
- Vapor lock.
- In-flight fire.
- Flight through thunderstorm activity or severe turbulence.

b. Flight Training.

(1) Preflight Briefing.

(2) Preflight Planning.

- Weather briefing and considerations.
- Course plotting.
- AFM/POH review.
- Flight plan.

(3) Preflight Inspection.

- Inspection/setup of oxygen system—verify quantity and proper switch position.
- Functional test of the oxygen system to include communications.

(4) Runup, Takeoff, and Initial Climb.

(5) Climb to High Altitude and Normal Cruise Operations While Operating Above 25,000 ft MSL.

(6) Simulated Emergencies.

- Simulated rapid decompression.
- Emergency descent.

(7) Planned Descents.

(8) Shutdown Procedures.

(9) Postflight Discussion.

2-3. GROUND TRAINING. Ground training should cover all aspects of high-altitude flight, including the flight environment, physiological aspects of high-altitude flight, and the need for the immediate donning of oxygen masks following activation of cabin altitude warning. Training should also address high-altitude systems and equipment, aerodynamics and performance, and high-altitude emergencies. The ground training should include the history and causes of some past accidents and incidents involving the topics included in subparagraph 2-2a. Accident reports are available from the NTSB and some aviation organizations.

2-4. THE HIGH-ALTITUDE FLIGHT ENVIRONMENT. Section 61.31(g) considers all flight operations conducted above 25,000 ft MSL to be high altitude. However, the high-altitude environment itself begins below 25,000 ft MSL. For example, flight levels (FL) are used at and above 18,000 ft MSL (e.g., FL 180) to indicate levels of constant atmospheric pressure in relation to a reference datum of 29.92 inches of mercury (inHg). Certain airspace designations and Federal Aviation Administration (FAA) requirements become effective at different altitudes. Pilots must be familiar with these elements before operating in each realm of flight. Pilots of high-altitude aircraft are subject to two principal types of airspace at altitudes above 10,000 ft MSL. These are Class E airspace, which extends from the surface up to FL 180, and Class A airspace, which extends from FL 180 to FL 600.

2-5. WEATHER. Pilots should be aware of and recognize the meteorological phenomena associated with high altitudes and the effects of these phenomena on flight.

a. The Atmosphere.

(1) Composition. The atmosphere is a mixture of gases in constant motion, composed of approximately 78 percent nitrogen, 21 percent oxygen, and 1 percent other gases. The atmosphere constantly absorbs and releases water vapor, which causes changes in weather. There are three levels of the atmosphere where high-altitude flight may occur. The first is the troposphere, which can extend from sea level to approximately FL 350 around the poles and up to FL 650 around the equator. The next is the tropopause, which is a thin layer at the top of the troposphere that traps water vapor in the lower level. The highest is the stratosphere, which extends from the tropopause to approximately 22 miles (mi). The stratosphere is characterized by lack of moisture and a constant temperature of -55 °Celsius (°C), while the temperature in the troposphere decreases at a rate of 2 °C per 1,000 ft. Condensation trails, or contrails, are common in the upper levels of the troposphere and in the stratosphere. Aircraft flying in clear, cold, humid air generate these cloud-like streamers formed by the addition of water vapor from aircraft exhaust gases to the atmosphere, causing saturation or supersaturation of the air. Contrails can also form aerodynamically by the pressure reduction around airfoils, engine nacelles, and propellers cooling the air to saturation.

(2) Atmospheric Density. Atmospheric density in the troposphere decreases gradually with altitude, decreasing to 50 percent of its sea-level value at 18,000 ft MSL. This means that at FL 180 the same volume of air contains only one-half the oxygen molecules as at sea level. Because the human body requires a certain amount of oxygen for survival, aircraft that fly at high altitudes must be equipped with some means of creating an artificial atmosphere, such as cabin pressurization.

b. Winds and Wind Shear.

(1) Jet Stream. The jet stream is a narrow band of high-altitude winds, near or in the tropopause, that results from large temperature contrasts over a short distance (typically along fronts), creating large pressure gradients aloft. The jet stream usually travels in an easterly direction between 50 and 200 kts. The speed of the jet stream is greater in the winter than in the summer months because of greater temperature differences. It generally drops more rapidly on the polar side than on the equatorial side.

(2) Polar Front Jet Stream. In the midlatitudes, the polar front jet stream is found in association with the polar front. This jet stream has a variable path, sometimes flowing almost due north and south. Because of its meandering path, the polar front jet stream is not found on most circulation charts. One almost permanent jet is a westerly jet found over the subtropics at latitude 25° about 8 mi (42,200 ft) above the surface. Low-pressure systems usually form to the south of the jet stream and move northward until they become occluded lows that move north of the jet stream.

c. Wind Shear. Horizontal wind shear and turbulence are frequently found on the northern side of the jet stream. Horizontal wind changes of 40 kts within 150 nautical miles

(NM) or vertical wind shear of 6 kts or greater per 1,000 ft usually indicate moderate to severe turbulence and should be avoided.

d. Clear Air Turbulence (CAT). CAT is a meteorological phenomenon associated with high-altitude winds. This high-level turbulence occurs where no clouds are present and can take place at any altitude (normally higher than 15,000 ft above ground level (AGL)), although it usually develops in or near the jet stream where there is a rapid change in temperature. CAT is generally stronger on the polar side of the jet and greatest during the winter months. Causes of CAT are wind shear, convection currents, mountain waves, strong low pressures aloft, or other obstructions to normal wind flow. CAT is difficult to forecast because it gives no visual warning of its presence and winds can carry it far from its point of origin. Pilot Weather Reports (PIREP) are one of the best methods of receiving timely and accurate reports on icing and turbulence at high altitudes.

e. Clouds and Thunderstorms. Cirrus and cirriform clouds are high-altitude clouds composed of ice crystals. Cirrus clouds are found in stable air above 30,000 ft MSL in patches or narrow bands. Cirriform clouds, such as the white clouds in long bands against a blue background known as cirrostratus clouds, generally indicate some type of system below. Cirrostratus clouds form in stable air as a result of shallow convection currents and also may produce light turbulence. Clouds with extensive vertical development (e.g., towering cumulus and cumulonimbus clouds) indicate a deep layer of unstable air and contain moderate to heavy turbulence with icing. The bases of these clouds are found at altitudes associated with low to middle clouds but their tops can extend up to 60,000 ft MSL or more.

NOTE: Cumulonimbus clouds are thunderstorm clouds that present a particularly severe hazard that pilots should circumnavigate. Hazards associated with cumulonimbus clouds include embedded thunderstorms, severe or extreme turbulence, lightning, icing, and dangerously strong winds and updrafts.

f. Icing. Icing at high altitudes is not as common or extreme as it can be at low altitudes. When it does occur, the rate of accumulation at high altitudes is generally slower than at low altitudes. Rime ice is generally more common at high altitudes than clear ice, although clear ice is possible. Despite the composition of cirrus clouds, severe icing is generally not a problem although it can occur in some detached cirrus. It is more common in tops of tall cumulus buildups, anvils, and over mountainous regions.

2-6. FLIGHT PLANNING AND NAVIGATION.

a. Flight Planning.

(1) Operational Considerations. Careful flight planning is critical to safe high-altitude flight. Pilots must consider pressurization system settings, particularly on takeoff, climb, and descent to assure operation in accordance with the manufacturer’s recommendations. They must also consider fuel management, reporting points, weather briefings, direction of flight, airplane performance charts, aircraft systems, and procedures, high-speed winds aloft, and oxygen duration charts. When possible, additional oxygen should be provided to allow for emergency situations. Breathing rates increase under stress and extra oxygen could be necessary.

(2) Altitude Considerations. Flight planning should take into consideration factors associated with altitudes that pilots will transit while climbing to or descending from the high altitudes (e.g., airspeed limitations below 10,000 ft MSL, airspace, and minimum altitudes). Westward flights should generally be made away from the jet stream to avoid the strong headwind, and eastward flights should be made in the jet stream when possible to increase ground speed. Ground speed checks are particularly important in high-altitude flight. If fuel runs low because of headwinds or poor flight planning, a decision to fly to an alternate airport should be made as early as possible to allow time to replan descents and advise air traffic control (ATC).

b. Knowledge of Aircraft. Complete familiarity with the aircraft systems and limitations is extremely important. For example, many high-altitude airplanes feed from only one fuel tank at a time. If this is the case, it is important to know the fuel consumption rate to know when to change tanks. This knowledge should be made part of the preflight planning and should have its accuracy confirmed regularly during the flight.

c. Gradual Descents. Pilots should plan gradual descents from high altitudes in advance to prevent excessive engine cooling and provide passenger comfort. They should comply with the manufacturer’s recommendations found in the AFM, especially regarding descent power settings, to avoid stress on the engines. Although most jets can descend rapidly at idle power, light twin airplanes require some power to avoid excessive engine cooling, cold shock, and metal fatigue. ATC does not always take aircraft type into consideration when issuing descent instructions. It is the pilot’s responsibility to fly the airplane in the safest manner possible. Cabin rates of descent are particularly important and should generally not exceed 500 or 600 ft/min. Before landing, cabin pressure should be equal to ambient pressure or inner ear injury can result. If delays occur en route, pilots should adjust descents.

d. Weather Charts. Before beginning a high-altitude flight, pilots should consult all weather charts, including those designed for low levels. High-altitude flight allows a pilot to over-fly most adverse weather, but pilots must consider low altitude weather for arrival, departure, and en route emergencies that require an immediate diversion.

e. Types of Weather Charts. Weather charts that provide information on high-altitude weather include:

- Constant pressure charts provide information on pressure systems, temperature, winds, and temperature/dewpoint spread at the 850 millibar (mb), 700 mb, 500 mb, 300 mb, and 200 mb levels (the five charts are issued every 12 hours).
- Prognostic charts, which provide forecast winds, temperature, and expected movement of weather over the 6-hour valid time of the chart.
- Observed tropopause charts, which provide jet stream, turbulence, and temperature/wind/pressure reports at the tropopause over each station.
- Tropopause wind prognostic charts, which are helpful in determining jet stream patterns and the presence of CAT and wind shear.

- Tropopause height vertical wind shear charts, which are helpful in determining jet stream patterns and the presence of CAT and wind shear. Dashed lines indicate wind shear.

f. Navigation. Specific charts are available for flight at FL 180 and above. En route high-altitude charts delineate the jet route system, which consists of routes established from FL 180 up to and including FL 450. The very high frequency Omnidirectional Range (VOR) airways established below FL 180 found on low-altitude charts must not be used at FL 180 and above. High-altitude jet routes are an independent matrix of airways, and pilots must possess the appropriate en route high-altitude charts before transitioning to the FLs.

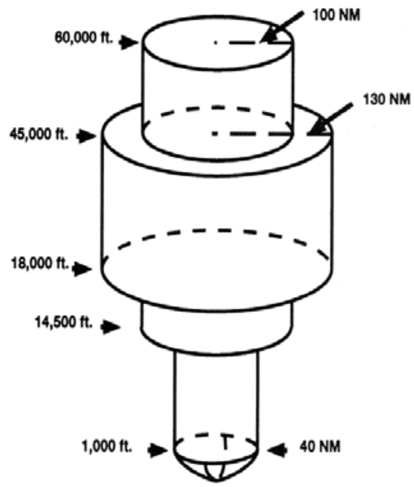
(1) Jet Routes. Jet routes in the United States are predicated solely on VOR or VHF Omnidirectional Range Collocated and Tactical Air Navigational (VORTAC) navigation facilities, except in Alaska where some are based on low/medium frequency NAVAIDs. All jet routes are identified by the letter "J" followed by the airway number.

(2) Q-Routes. The U.S. and Canada use "Q" as a designator for RNAV routes. Q-routes routes are designed for RNAV or RNP capable aircraft. One benefit of this system is that aircraft with RNAV or RNP capability can fly safely along closely spaced parallel flight paths on high density routes, which eases airspace congestion.

(3) Reporting Points. Designated reporting points must be used by flights using the jet route unless otherwise advised by ATC. Pilots may conduct flights above FL 450 on a point-to-point basis, using the facilities depicted on the en route high-altitude chart as navigational guidance. Area Navigation (RNAV) routes, using either random or fixed waypoints, are also used for direct navigation at high altitudes. These routes are based on RNAV capability between waypoints defined in terms of latitude/longitude coordinates, degree-distance fixes, or offsets from established routes or airways at a specified distance and direction. Radar monitoring by ATC is required on all random RNAV routes.

g. NAVAIDS. VOR, distance measuring equipment (DME), and TACAN depicted on high-altitude charts are designated as Class H NAVAIDs, signifying that their standard service volume is from 1,000 ft AGL up to and including 14,500 ft AGL at radial distances out to 40 NM; from 14,500 ft AGL up to and including 60,000 ft AGL at radial distances out to 100 NM; and from 18,000 ft AGL up to and including 45,000 ft AGL at radial distances out to 130 NM. See Figure 2-1, Standard High-Altitude Service Volume, for an illustration of the high-altitude service volume. Ranges of non-directional beacon (NDB) service volumes are the same at all altitudes.

FIGURE 2-1. STANDARD HIGH-ALTITUDE SERVICE VOLUME

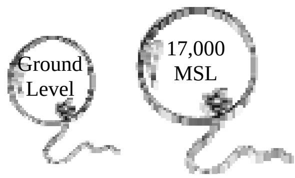


2-7. PHYSIOLOGICAL TRAINING. To ensure safe flights at high altitudes, pilots of high-altitude aircraft must understand the physiological effects of high-altitude flight and the effect of hypoxia on an individual's ability to perform complex tasks in a changing environment. Additional physiological training information, including locations and application procedures for attending an altitude chamber, can be found in paragraph 2-8. Although not required, altitude chamber training is highly recommended for all pilots.

a. Physics of the Atmosphere. The combined weight, or force, of all gases in the atmosphere at any given point gives us our atmospheric pressure. As you ascend from sea level, the atmospheric pressure will correspondingly drop. As atmospheric pressure drops, the air becomes less dense. The primary reason for this phenomenon lies in the kinetic nature of atoms and molecules. Molecules, especially those of a gas, are in a constant state of motion. As pressure around the molecules is reduced, the molecules will travel further apart. This explains why air becomes less dense as altitude increases, and accounts for gas expansion. Since air is a mixture of gases, it is subject to the laws that govern all gases. Table 2-1, Gas Laws and Their Effect on the Human Body, explains the effects of reduced barometric pressure and its interplay on the human body.

TABLE 2-1. GAS LAWS AND THEIR EFFECT ON THE HUMAN BODY

GAS LAW	EXPLANATION	AVIATION APPLICATION
Graham's Law *Law of gaseous diffusion*	A gas will diffuse from an area of high concentration to an area of low concentration.	*TRANSFER OF GAS IN BODY* This law explains the transfer of gases between the atmosphere and the lungs, the lungs and the blood, and the blood and the cell.

GAS LAW	EXPLANATION	AVIATION APPLICATION
Boyle's Law $\frac{P1}{P2} = \frac{V2}{V1}$  	A volume of a gas is inversely proportional to the pressure to which it is subjected with the temperature remaining constant.	*TRAPPED GAS* This law explains how pressure change allows the gas to expand and contract in body cavities (ears, sinuses, and gastrointestinal (GI) tract) with increasing and decreasing altitude.
Dalton's Law PT=P1+P2+…PN	The total pressure of a mixture of gas is equal to the sum of the partial pressure of each gas in the mixture.	*HYPOXIA* This law explains how ascent to altitude reduces the total atmospheric pressure, thus reducing each of the partial pressures associated with the total atmospheric pressure.
Henry's Law $\frac{P1}{P2} = \frac{A1}{A2}$  	The amount of gas dissolved in solution varies directly with the pressure of that gas over the solution.	*DECOMPRESSION SICKNESS* This law explains why nitrogen in the body comes out of solution forming bubbles that cause decompression sickness. As altitude increases, pressure decreases and nitrogen will attempt to leave the body and equalize with the surrounding environment. If pressure change is too rapid, the excess nitrogen may form a bubble(s).
Charles' Law $\frac{V1}{V2} = \frac{T1}{T2}$	The pressure of a gas is directly proportional to its temperature.	This gas law has no physiological bearing since body temperature is a constant 98.6°F.

b. Respiration. When we are exposed to a high altitude environment, our ability to obtain and utilize oxygen is dramatically affected. External respiration is the exchange of gases between the lungs and the surrounding atmosphere. With each breath (about half a liter of air), we inhale 2.79×10^{21} oxygen molecules.

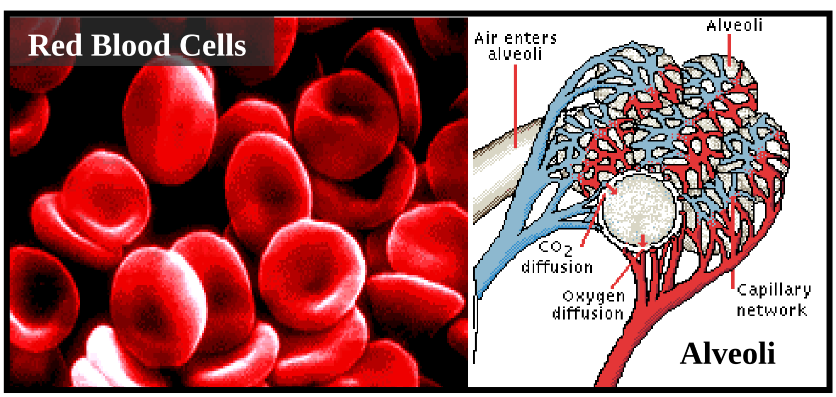
(1) Partial Pressure of Oxygen. The partial pressure of oxygen is approximately 20 percent of the total atmospheric pressure. At sea level, this would be about 152 millimeters of mercury (mmHg) of pressure (20 percent of the total atmospheric pressure of 760 mmHg). When a breath is drawn into the lungs, one would expect the partial pressure of oxygen to remain at

152 mmHg. However, the lungs contain other gases that exert a constant pressure (water vapor at 47 mmHg and carbon dioxide at 40 mmHg). These gases tend to displace part of the oxygen, reducing the partial pressure of oxygen at the air sac (alveoli) level to 102 mmHg.

(2) Oxygen and Carbon Dioxide Diffusion in the Blood. Oxygen and carbon dioxide move into and out of the blood in the lungs in accordance with Graham's Law, which states: "An area of high gaseous pressure will exert force towards an area of low gaseous pressure." This will cause gases to move back and forth across a gas permeable membrane (such as the air sacs). At sea level, the high partial pressure of oxygen (102 mmHg) diffuses through the air sac wall and into the blood (see Figure 2-2, Blood Cells and Alveoli). This in turn raises the partial pressure of oxygen in venous blood (blood that has left the cells and therefore is low in oxygen) from 40 mmHg to 102 mmHg. At the same time this is happening, the high pressure of carbon dioxide (approximately 47 mmHg) in the blood will cause some of the carbon dioxide to diffuse into the air sacs where carbon dioxide pressure is a constant 40 mmHg. This principle also applies to internal respiration (the exchange of gases from the blood to the cells). The high partial pressure of oxygen in arterial blood causes the oxygen to move from the blood into the cells. Due to cellular metabolism, the high partial pressure of carbon dioxide in the cell will cause it to diffuse into the blood for transport to the lungs.

(3) Atmospheric Areas and Normal Body Function. The human body functions normally in the atmospheric area extending from sea level to 12,000 ft MSL. In this range, brain oxygen saturation is at a level that allows for normal functioning. Optimal functioning is 96 percent saturation. At 12,000 ft MSL, brain oxygen saturation is approximately 87 percent, which begins to approach a level that could affect human performance. Although oxygen is not required below on 12,500 ft MSL when operating in accordance with part 91, we recommend its use when flying unpressurized above 10,000 ft MSL during the day and above 5,000 ft MSL at night when the eyes become more sensitive to oxygen deprivation.

FIGURE 2-2. BLOOD CELLS AND ALVEOLI



c. Trapped Gas. Gases readily expand with any decrease in pressure. Gas expands in accordance with Boyle's Law, which states: "A volume of a gas is inversely proportional to the pressure to which it is subjected, temperature remaining constant." From this law it is apparent that if you reduce the pressure, as you ascend to altitude, gases increase in volume and then decrease in volume on descent.

(1) The human body has several cavities that contain varying amounts of gas. Most of these cavities have an opening that will allow the gas to enter and escape. If the opening is reduced in size or closed, then the gas is trapped. Once trapped, it is still subject to gas expansion and compression in accordance with Boyle's Law. The result of having changes in gas volume within these cavities without equalization will usually be pain. Table 2-2, Trapped Gas Issues, gives examples of body areas that may be affected by trapped gas during the specified phases of flight.

(2) Table 2-3, In-Flight Treatment of Trapped Gas Emergencies, gives the recommended procedures for in-flight treatment of trapped gas emergencies.

TABLE 2-2. TRAPPED GAS ISSUES

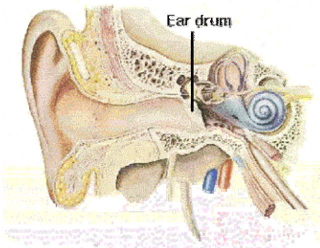
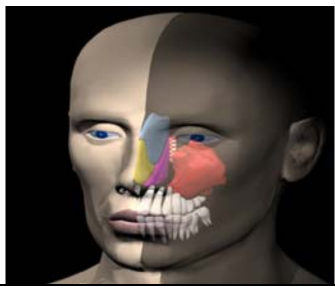
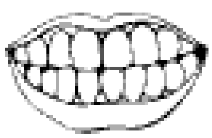
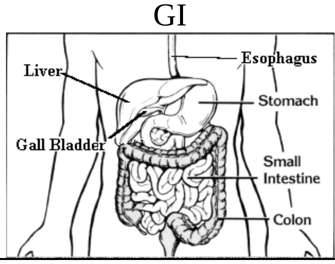
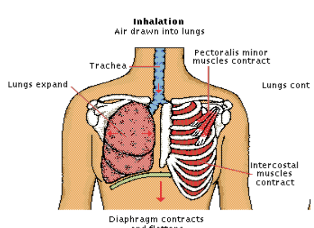
BODY AREA	**PROBLEM PHASE OF FLIGHT**	**PHYSIOLOGY**
MIDDLE EAR  	DESCENT	On ascent, the air and pressure of expanding gases will escape via the eustachian tube. The base of each eustachian tube is collapsed, which acts as a one-way valve to allow gases and liquids to escape and not travel up to the middle ear. On descent, the gas is naturally trapped. Because of the increasing pressure on descent, this pressure will need to be equalized or an ear block will result.
SINUSES 	DESCENT or ASCENT (rare)	The maxillary sinuses that sit under the cheekbones and the frontals that lie under the eyebrows have an unobstructed opening that will allow gas to enter and escape. In the event of an upper respiratory infection (URI), the openings will be swollen and possibly closed allowing no route for the gas and pressure to equalize, resulting in a sinus block.
TEETH 	ASCENT	A tooth block is very rare. They can occur if you have had a recent cavity filling. If there is any airspace trapped between the filling and the pulp of the tooth, it will expand on ascent and cause pain.
GI  	ASCENT	The GI tract will always contain a varying amount of gas. This gas is usually a result of the digestion process and can escape by either flatulation or belching. If the gas expands, as in unpressurized flight to altitude, and is not allowed to escape, it could result in pain and possible syncope (fainting).
LUNGS  	DECOMPRESSION	Gas in the lungs will normally enter and escape via the trachea. If the breath is held during a rapid increase in altitude, the gas within the lungs will expand in accordance with Boyle's Law, but have no pathway to escape. This could cause possible lung damage.

TABLE 2-3. IN-FLIGHT TREATMENT OF TRAPPED GAS EMERGENCIES

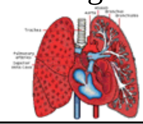
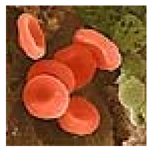
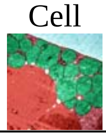
AILMENT	SYMPTOMS	TREATMENT
Ear Block	Can start out as a full feeling that will progress to pain. Pain increases with descent. Can also cause vertigo.	• Level off from descent. • Try ear-clearing maneuvers such as valsalva, aviators jaw jut, yawn, or swallow. • Ascend and try ear-clearing again. • If there is no relief, land A.S.A.P.
Sinus Block	Intense pain under the cheekbones and in the upper teeth (maxillary). Intense pain under eyebrows and in corner of the eyes (frontal).	• Level off from descent. • Try the valsalva maneuver. • Ascend and try sinus-clearing again. • If there is no relief, land A.S.A.P.
Tooth Block	A pain in a single tooth where the pain increases with a corresponding increase in altitude.	• Level off from ascent. • If there is no relief, land A.S.A.P. and see a dentist.
GI Tract	Progressively increasing pain in the abdominal area with a corresponding increase in altitude.	• Try to pass the gas through flatulating or belching. • If there is no relief, immediate descent.

d. Physiological Problems at Increased Altitudes.

(1) Hypoxia. Hypoxia is a state of oxygen deficiency in the blood, tissues, and cells sufficient to cause an impairment of body functions. Anything that impedes the arrival or utilization of oxygen to the cell places the body in a hypoxic state. All cells require oxygen to function. The central nervous system (made up of the brain and spinal cord) demands a great deal of oxygen (approximately 20 percent of all oxygen that you inhale feeds the brain). If the oxygen supply to the body is reduced, the brain will be one of the first organs to be affected, with the higher reasoning portions of the brain showing degraded function first. This means that judgment and cognitive skills diminish from the very start. There are many conditions that can interrupt the normal flow of oxygen to the cells. Table 2-4, Hypoxia Types, describes the various levels at which hypoxia can occur:

(2) Hyperventilation. Hyperventilation is defined as an increase in the rate and depth of breathing that exchanges gas in the lung beyond the volumes necessary to maintain normal levels of oxygen and carbon dioxide. Hyperventilation will result in disturbances in the acid-base balance in the blood, and eventually the brain as the levels of carbon dioxide in the lungs fall. The signs and symptoms of hyperventilation are easily confused with those of hypoxic hypoxia. Because hyperventilation occurs as an carly adaptive mechanism to hypoxia at altitude, it becomes even more difficult to differentiate between the two conditions. Symptoms perceived by an aviator who is hyperventilation include dizziness, lightheadedness, tingling, numbness, visual disturbances, and loss of coordination. The treatment of hyperventilation requires a voluntary reduction in the rate and depth of ventilation. Because hypoxia and hyperventilation are so similar and both can incapacitate so quickly, the recommended treatment procedures for aviators is to correct both problems simultaneously: (1) administer 100% oxygen under pressure; (2) reduce the rate and depth of breathing: (3) check the oxygen equipment to ensure proper functioning: and (4) descend to a lower altitude where hypoxia is unlikely to occur.

TABLE 2-4. HYPOXIA TYPES

Common Name	Location of Impediment	Explanation
Hypoxic (Altitude) Hypoxia	Lungs 	Any condition that interrupts the flow of O_2 into the lungs. This is the type of hypoxia encountered at altitude due to the reduction of the partial pressure of O_2.
Hypemic Hypoxia	Blood 	Any condition that interferes with the ability of the blood to carry oxygen, such as: • Anemia. • Bleeding. • Carbon monoxide poisoning. • Smoking. • Certain prescription drugs.
Stagnant Hypoxia	Blood Transport 	Any situation that interferes with the normal circulation of the blood arriving to the cells. Heart failure, shock, and positive G-forces will bring about this condition.
Histotoxic Hypoxia	Cell 	Any condition that interferes with the normal utilization of O_2 in the cell. Alcohol, narcotics, and cyanide all can interfere with the cell's ability to use the oxygen in support of metabolism.

(a) Hypoxic (Altitude) Hypoxia. The cause of this type of hypoxia is an insufficient partial pressure of oxygen in the inhaled air resulting from reduced oxygen pressure in the atmosphere at altitude. Altitude hypoxia poses *the greatest potential physiological hazard* to a flightcrew member *when at altitude*. Supplemental oxygen will combat hypoxic hypoxia within seconds. Check your oxygen systems periodically to ensure an adequate supply of oxygen and that the system is functioning properly. Perform this check frequently with increasing altitude. If supplemental oxygen is not available, initiate an emergency descent to an altitude below 10,000 ft MSL.

> **WARNING:**
>
> If hypoxia is suspected, immediately don oxygen mask and breathe 100 percent oxygen slowly. Descend to a safe altitude. If supplemental oxygen is not available, initiate an emergency descent to an altitude below 10,000 ft MSL. If symptoms persist, land as soon as possible.

(b) Hypemic Hypoxia. This type of hypoxia is defined as a reduction in the oxygen-carrying capacity of the blood. Hypemic hypoxia is caused by a reduction in circulating red blood cells (anemia) or contamination of blood with gases other than oxygen.

1. The most common cause is smoking, but carbon monoxide poisoning due to a leak in the exhaust system for the engine is also a consideration. Pilots should take into consideration the effect of smoking on altitude tolerance when determining appropriate cabin pressures. If heavy smokers are among the crew or passengers, a lower cabin altitude should be set because physiologic altitudes for smokers are generally much higher than actual altitudes. For example, a smoker's physiological altitude at sea level is approximately 7,000 ft MSL. Twenty thousand ft actual altitude for a nonsmoker would be equivalent to a physiological altitude of 22,000 ft MSL for a smoker. The smoker is thus more susceptible to hypoxia at lower altitudes than the nonsmoker.

2. Hypemic hypoxia is corrected by locating and eliminating the source of the contaminating gases. A careful preflight of heating systems and exhaust manifold equipment is mandatory. If symptoms persist, ventilate the cabin, land as soon as possible, and seek medical attention, because the symptoms may be indicative of carbon monoxide poisoning.

WARNING:

If hypoxia is suspected, immediately don oxygen mask and breathe 100 percent oxygen slowly. Descend to a safe altitude. If supplemental oxygen is not available, initiate an emergency descent to an altitude below 10,000 ft MSL. If symptoms persist, land as soon as possible.

(c) Stagnant Hypoxia. This is a less common form of hypoxia. It is due to inadequate blood flow to the tissues. Causes include heart failure, shock, prolonged positive pressure breathing, and excessive G-forces.

WARNING:

If hypoxia is suspected, immediately don oxygen mask and breathe 100 percent oxygen slowly. Descend to a safe altitude. If supplemental oxygen is not available, initiate an emergency descent to an altitude below 10,000 ft MSL. If symptoms persist, land as soon as possible.

(d) Histotoxic Hypoxia. This is the inability of the body's cells to use oxygen because of impaired cellular respiration. Alcohol or drug use can cause this type of hypoxia. The only method of avoiding this type of hypoxia is to abstain, before flight, from alcohol or drugs that are not approved by a flight surgeon or an Aviation Medical Examiner (AME).

WARNING:

If hypoxia is suspected, immediately don oxygen mask and breathe 100 percent oxygen slowly. Descend to a safe altitude. If supplemental oxygen is not available, initiate an emergency descent to an altitude below 10,000 ft MSL. If symptoms persist, land as soon as possible.

(e) Hypoxia Signs and Symptoms.

1. Signs of hypoxia can be detected in an individual by an observer. Signs aren't a very effective tool for hypoxic individuals to use to recognize hypoxia in themselves. Symptoms of hypoxia are the sensations a person can detect while in a hypoxic state. Personal symptoms of hypoxia are as individual as the person experiencing them. A group of people who are hypoxic will, a majority of the time, get the same symptoms. However, the symptoms will appear in a different order and in varying intensities. The greatest benefit in hypoxia training in an altitude chamber is that the order and the intensity of your symptoms will usually remain constant over the years. Therefore, familiarity with one's own hypoxia "signature" will facilitate the recognition of a hypoxic state during flight. Table 2-5, Common Hypoxia Signs and Symptoms, lists some of the more common signs and symptoms of hypoxia.

TABLE 2-5. COMMON HYPOXIA SIGNS AND SYMPTOMS

SIGNS	SYMPTOMS
Rapid Breathing Cyanosis (bluing effect of the skin) Poor Coordination Lethargy Executing Poor Judgment Sweating Trembling Myoclonic (Muscle) Spasms	Air Hunger Fatigue Nausea Headache Dizziness Hot and Cold flashes Tingling Visual Impairment Euphoria

2. Of the listed symptoms, visual impairment is probably the least reliable. Your visual field will be affected, but at such a slow rate that it could go unnoticed. Generally, symptoms will appear before unconsciousness occurs. Except for possible headache and nausea, there are no other uncomfortable symptoms. Of all the symptoms, euphoria (a false sense of well-being) is probably the most dangerous. Furthermore, in most cases, hypoxia onset is very insidious. Any preoccupation with flying duties could be enough of a distraction to allow the hypoxia to progress beyond the point of self-help.

WARNING:

A common misconception among pilots is that it is easy to recognize the symptoms of hypoxia and to take corrective action before becoming seriously impaired. While this concept may be appealing in theory, it is both misleading and dangerous for crewmembers.

3. While other significant effects of hypoxia usually do not occur in a healthy pilot in an un-pressurized aircraft below 12,000 ft MSL, there is no assurance that this will always be the case. Furthermore, the altitude range of impairment due to hypoxia is best described as a continuum; there is no definitive altitude at which the effects of hypoxia begin or end. To mitigate the risk associated with these variations, if hypoxia is suspected, a descent to altitudes below 10,000 ft MSL is recommended.

(f) Preventative Measures Against Hypoxia.

1. A common technique for aviators to monitor themselves for hypoxia is the use of finger pulse oximeters that report the degree of hemoglobin oxygen saturation as a percent. This value is useful in predicting the partial pressure of oxygen available to drive oxygen into the cells.

CAUTION:

The FAA cautions against relying on pulse oximeters as the sole indicator of hypoxia because:

- Waiting for the percent oxygen saturation levels reported by the pulse oximeter to fall before taking action may result in a level of hypoxia sufficient to cause impairment.
- Hemoglobin oxygen saturation in blood passing through the finger may not reflect true oxygen availability to the brain because of reductions in brain blood flow resulting from hyperventilation (a response to hypoxia).

2. The following are recommended actions to reduce the chance of hypoxia.

- Fly at an altitude where oxygen is not required.
- Fly in a pressurized cabin.
- Fly in accordance with current regulations in reference to the use of supplemental oxygen.

NOTE: The FAA recommends that on any unpressurized flight to or above 10,000 ft in the day, or above 5000 ft at night, supplemental oxygen should be used.

(g) Treatment for Hypoxia. Hypoxia, under most situations, will be insidious in its onset, which gives it its dangerous nature. Because of the rapid breathing associated with hypoxia, you must slow your breathing rate to prevent hyperventilation. Recognition and the immediate execution of emergency procedures for decompression are the most important factors that dictate the crew’s ability to survive. If hypoxia is suspected, immediately don an oxygen mask and breathe 100 percent oxygen slowly. Descend to a safe altitude. Once hypoxia is detected and 100 percent oxygen is administered, recovery usually occurs in a matter of seconds. If supplemental oxygen is not available, initiate an emergency descent to an altitude below 10,000 ft MSL. If symptoms persist, land as soon as possible. The common emergency procedures follow in Table 2-6, Common Emergency Procedures for Hypoxia.

TABLE 2-6. COMMON EMERGENCY PROCEDURES FOR HYPOXIA

DON MASK	In 5 seconds or less. Check for flow. Breathe 100 percent oxygen
DESCEND	Preferably below 10,000 ft.
LAND A.S.A.P	At nearest suitable installation where appropriate medical help can be found.

e. Decompression in Pressurized Aircraft. Even though there are numerous advantages to pressurized flight, there will always be one major disadvantage—possible loss of pressurization.

(1) Rate of decompression. Factors that dictate how fast an aircraft will decompress are:

(a) Size of Opening. With all other factors equal, the larger the opening, the faster the pressure will travel out of the aircraft.

(b) Size of Cabin. With all other factors equal, the smaller the cabin, the faster the pressure will depart.

(c) Pressure Differential. With all other factors equal, greater pressure differential means slower decompression.

(d) Pressure Ratio. When cabin pressurization is lost, aircraft compressors will continue to operate. The rate at which the compressed air comes in dictates how fast pressure is lost.

(e) Altitude. Higher altitude results in a faster decompression due to less resistance to the air leaving the aircraft.

(2) Phenomena Associated with Decompressions. These decompression phenomena are very common to rapid and explosive decompressions. However, during a slow decompression, the phenomena below may not be evident. Furthermore, the insidious nature of hypoxia and depression of mental function decreases the ability to recognize the emergency and undertake appropriate recovery procedures. For this reason, *slow decompressions are the most dangerous***,** and the aviator must always be on guard against this insidious threat.

(a) Noise. Noise can come from a leaky door seal, a window departing, a breech of structural integrity, or from the aircraft's alarm system.

(b) Fog. On smaller airframes (Learjets, Citations, Falcons) the fog could fill the aircraft.

(c) Flying Debris, Dust, and Dirt. If there is a large opening, anything not secured down will move towards the opening. These items could cause injury.

(d) Wind Blast. The loss of pressure in the aircraft may be felt by crew and passengers as a wind blast.

(e) Cooler Temperatures. When the pressure (air) departs the cabin, the temperature will drop.

(f) Gas Expansion. As the gas expands with decreasing pressure, it will be most noticeable in the ears and gastro-intestinal (GI) tract of the body.

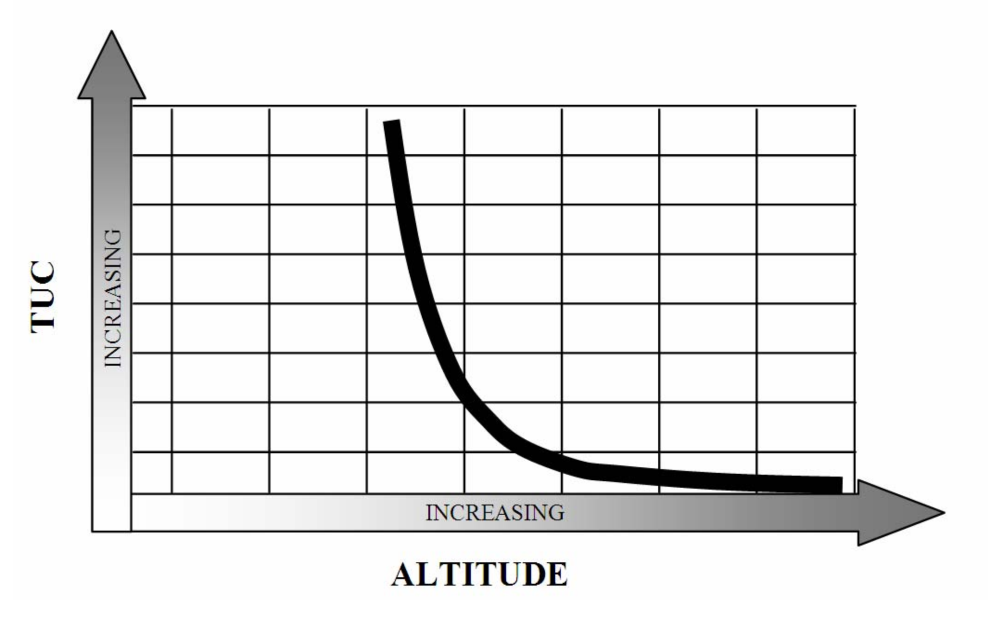
WARNING:
Slow decompression *is as dangerous as or more dangerous than* a rapid or explosive decompression.

(3) Time of Useful Consciousness (TUC) or Effective Performance Time (EPT). This is the period of time from interruption of the oxygen supply, or exposure to an oxygen-poor environment, to the time when an individual is no longer capable of taking proper corrective and protective action. The faster the rate of ascent, the worse the impairment and the faster it happens. TUC also decreases with increasing altitude. Figure 2-3, Times of Useful Consciousness versus Altitude, shows the trend of TUC as a function of altitude. However, slow decompression ***is as dangerous as or more dangerous than*** a rapid decompression. By its nature, a rapid decompression commands attention. In contrast, a slow decompression may go unnoticed and the resultant hypoxia may be unrecognized by the pilot.

WARNING:

The TUC *does not* mean the onset of unconsciousness. Impaired performance *may be immediate. Prompt use of 100 percent oxygen is critical.*

FIGURE 2-3. TIMES OF USEFUL CONSCIOUSNESS VERSUS ALTITUDE



ALTITUDE	TUC/EPT	Following Rapid Decompression
18,000	20–30 min	10–15 min
22,000	10 min	5–6 min
25,000	3–5 min	1.5–2.5 min
28,000	2.5–3 min	1–1.5 min
30,000	1–2 min	30 s–1 min
35,000	30 s–1 min	15–30 s
40,000	15–20 s	Nominal
43,000	9–12 s	Nominal
50,000	9–12 s	Nominal

NOTE: The above times are to be used as averages only and are based on an individual at rest. Physical activity at altitude, fatigue, self-imposed stress, and individual variation will make the times vary.

(a) Factors Affecting Hypoxia Recognition and TUC: Slow Decompression and Rapid or Explosive Decompression. Rapid loss of aircraft pressurization dramatically reduces TUC. As a general rule, it can be assumed that the TUC following decompression to altitudes between 25,000 ft and 43,000 ft will be reduced by 50 percent. Above 43,000 ft, the TUC is reduced to the time it takes for the blood to circulate from the lung to the brain, plus any reserve oxygen stored in the brain. This is approximately 9–12 s from the start of a rapid decompression to the loss of functional capability. In some cases, hypoxia exposure can lead to a shock type reaction that could further reduce the TUC. In any case, the potential for impairment begins almost immediately. For this reason, the donning of the oxygen mask should be practiced from time to time.

(b) Other Factors that Determine TUC.

1. TUC decreases with:

(aa) Rate of ascent. The faster you ascend to altitude, the shorter your EPT/TUC becomes.

(bb) Rate of decompression. Rapid decompression decreases the TUC by at least 50 percent.

(cc) Physical activity at altitude. Any physical activity will reduce your EPT/TUC. For example, if you did 10 deep knee bends at 25,000 ft with your oxygen mask off, your EPT/TUC would be reduced by 50 percent.

(dd) Fatigue. If you enter the cockpit in a fatigued state, you are less resistant to hypoxia.

(ee) Diet. The brain feeds exclusively from glucose (blood sugar), so if your glucose is low, as in hypoglycemia, you are more prone to hypoxia.

(ff) Alcohol. Alcohol brings about its own form of hypoxia. When altitude is coupled with alcohol, you are a strong candidate for a hypoxic episode.

(gg) Medications. Some drugs, including over-the-counter medications, will cause cells not to utilize oxygen properly and therefore will make you less altitude resistant.

(hh) Other factors. Smoking, poor physical condition, and illness also decrease the TUC.

2. Impairment increases with:

- Increasing altitude.
- Increasing difficulty and complexity of the task.
- New tasks compared to learned, practiced tasks.

(4) Altitude-Induced Decompression Sickness (DCS). According to Henry's Law, when the partial pressure of a gas over a liquid is decreased, the amount of gas dissolved in that liquid will also decrease. One of the best practical demonstrations of this law is offered by opening a soft drink. When the cap is removed from the bottle, gas is heard escaping and bubbles can be seen forming in the soda. This is carbon dioxide gas coming out of solution as a result of sudden exposure to a lower partial pressure of carbon dioxide in the environment.

(a) Nitrogen Absorption. One of the more dangerous problems an aviator may face is the threat of DCS (nitrogen bubbles in body fluids and tissues) at high altitudes. Nitrogen we breathe is taken into the lungs at a pressure of 608 mmHg (80 percent of the total atmospheric pressure 760 mmHg at sea level). The nitrogen is then distributed throughout the body by the circulatory system and stored at a pressure of about 608 mm. At sea level, the nitrogen pressure inside the body and outside of the body is in equilibrium. When atmospheric pressure is reduced as a result of ascent, the equilibrium is upset. This results in nitrogen leaving the body by passing from the cells, to the blood, and then out through the respiratory system. If the nitrogen is forced to leave the solution too rapidly because of a large partial pressure difference, bubbles may form, causing a variety of signs and symptoms. The symptoms result from the location of the bubbles. These evolving and expanding gases in the body are known as DCS. There are two groups.

1. Trapped Gas. Expanding or contracting gas in certain body cavities during altitude changes can result in abdominal pain, toothache, or pain in ears and sinuses if the person is unable to equalize the pressure changes. Above 25,000 ft MSL, distention can produce particularly severe GI pain.

2. Evolved Gas. When the pressure on the body drops sufficiently, nitrogen comes out of solution and forms bubbles, which can have adverse effects on some body tissues. See Table 2-7, Types of Evolved Gas Decompression Sickness. Fatty tissue contains more nitrogen than other tissue, thus making overweight people more susceptible to evolved gas DCS.

TABLE 2-7. TYPES OF EVOLVED GAS DECOMPRESSION SICKNESS

DCS Type	Bubble Location	Signs & Symptoms (Clinical Manifestations)
Bends	Mostly large joints of the body (shoulders, elbows, wrists, hips, knees, ankles)	Localized deep pain, ranging from mild (a "niggle") to excruciating. Sometimes a dull ache, but rarely a sharp pain. Active or passive motion of the joint aggravates the pain. Pain can occur at altitude, during the descent, or many hours later. The pain gradually becomes more severe, can become incapacitating, and can even result in collapse.
Neurologic	Brain	Confusion or memory loss. Headache. Spots in visual field (scotoma), tunnel vision, double vision (diplopia), or blurry vision. Unexplained extreme fatigue or behavior changes. Seizures, dizziness, vertigo, nausea, vomiting, and unconsciousness may occur.
	Spinal Cord	Abnormal sensations such as numbness, burning, stinging, and tingling around the lower chest and back. Symptoms may spread from the feet up and may be accompanied by ascending weakness or paralysis. Girdling abdominal or chest pain.
	Peripheral Nerves	Urinary and rectal incontinence. Abnormal sensations such as numbness, burning, stinging, and tingling (paresthesia). Muscle weakness or twitching.
Chokes	Lungs	Burning deep chest pain (under the sternum). Pain is aggravated by breathing. Dry constant cough. Possible cyanosis (a bluish color of the skin, nail beds, and the mucous membranes due to insufficient oxygen in the blood). Shortness of breath (dyspnea), sensation of suffocation, progressively shallower breathing, and, if a descent is not made immediately, collapse and unconsciousness.
Skin Manifestations	Skin	Itching usually around the ears, face, neck, arms, and upper torso. Sensation of tiny insects crawling over skin (formication). Mottled or marbled skin usually around the shoulders, upper chest, and abdomen, accompanied by itching. Swelling of the skin, accompanied by tiny scar-like skin depressions (pitting edema).

(b) Risk Trends. Most cases of altitude DCS occur among individuals exposed to altitudes of 25,000 ft or higher. A United States Air Force (USAF) study of altitude DCS cases reported that only 13 percent occurred below 25,000 ft. The risk of developing altitude DCS increases with altitude and time of exposure.

(c) Predisposing Factors.

1. Repetitive Exposures. Repetitive exposures to altitudes above 18,000 ft within a short period of time (few hours) also increase the risk of developing altitude DCS.

2. Rate of Ascent. The faster the rate of ascent to altitude, the greater the risk of developing altitude DCS. An individual exposed to a rapid decompression (high rate of ascent) above 18,000 ft has a greater risk of altitude DCS than being exposed to the same altitude at a lower rate of ascent.

3. Time at Altitude. The longer the duration of the exposure to altitudes of 18,000 ft and above, the greater the risk of altitude DCS. Time at altitude has been shown to be the strongest predictor of DCS.

4. Age. There are some reports indicating a higher risk of DCS with increasing age.

5. Previous Injury. There is some indication that recent joint or limb injuries may predispose individuals to developing "the bends."

6. Ambient Temperature. Exposure to very cold ambient temperatures may increase the risk of altitude DCS.

7. Body Type. A person who has a high body fat content may be at greater risk of altitude DCS, as nitrogen is stored in greater amounts in fat tissues.

8. Exercise. When a person is physically active while flying at altitudes above 18,000 ft, there is greater risk of altitude DCS.

9. Alcohol Consumption. The after-effects of alcohol consumption, such as dehydration, increase susceptibility to DCS.

(d) Self-Contained Underwater Breathing Apparatus (SCUBA) Diving Before Flying. SCUBA diving requires breathing air under high pressure. Under these conditions, there is a significant increase in the amount of nitrogen dissolved in the body (body nitrogen saturation). The deeper the SCUBA dive, the greater the body nitrogen saturation. Following SCUBA diving, if not enough time is allowed to eliminate the excess nitrogen stored in the body, altitude DCS can occur during exposure to altitudes as low as 5,000 ft or less. After SCUBA diving, a person who flies in an aircraft to a pressure altitude of 8,000 ft MSL would experience the same effects as a non-diver flying unpressurized at 40,000 ft MSL.

1. The recommended waiting period before going to flight altitudes up to 8,000 ft MSL is at least:

- Twelve hours after non-decompression stop diving (diving that does not require a controlled ascent), and
- Twenty-four hours after decompression stop diving (diving that requires a controlled ascent).

2. For flight altitudes above 8,000 ft MSL, the recommended wait time is at least 24 hours after any SCUBA diving. (See AIM paragraph 8-1-2, subparagraph d2.)

(5) What to Do If You Suspect DCS in Flight.

(a) Put on your oxygen mask immediately and switch the regulator to 100 percent oxygen.

(b) Begin an emergency descent and land as soon as possible. Even if the symptoms disappear during descent, you should still land and seek medical evaluation while continuing to breathe oxygen.

(c) If one of your symptoms is joint pain, keep the affected area still; do not try to work pain out by moving the joint around.

(6) Medical Treatment. A mild case of "the bends" may disappear during descent from high altitude. However, it still requires medical evaluation. If the signs and symptoms persist during descent or reappear at ground level, it may be necessary to receive hyperbaric oxygen treatment immediately. This involves 100 percent oxygen delivered in a high-pressure chamber.

WARNING:

Neurological DCS, "the chokes," and skin manifestations (mottled or marbled skin lesions) are very serious and potentially fatal if untreated.

(7) Things to Remember about DCS.

(a) Altitude DCS is a potential risk every time you fly in an unpressurized aircraft above 18,000 ft, and at lower altitudes if you SCUBA dive prior to the flight.

(b) Be familiar with the signs and symptoms of altitude DCS and monitor all aircraft occupants, including yourself, any time you fly an unpressurized aircraft above 18,000 ft.

(c) Avoid unnecessary strenuous physical activity prior to flying an unpressurized aircraft above 18,000 ft and for 24 hours after the flight.

(d) Even if you are flying a pressurized aircraft, altitude DCS can occur as a result of sudden loss of cabin pressure (in-flight rapid decompression).

(e) Following exposure to an in-flight rapid decompression, do not fly for at least 24 hours. In the meantime, remain vigilant for the possible onset of delayed symptoms or signs of altitude DCS. If you experience delayed symptoms or signs of altitude DCS, seek medical attention immediately.

(f) Keep in mind that breathing 100 percent oxygen during flight (ascent, en route, descent) without oxygen pre-breathing prior to take off, does not prevent the occurrence of altitude DCS.

(g) Do not ignore any symptoms or signs that go away during the descent. In fact, this could confirm that you are actually suffering altitude DCS.

(h) Any case of altitude DCS should be medically evaluated as soon as possible, even if symptoms are mild or disappear on descent.

(i) If there is any indication that you may have experienced altitude DCS, do not fly again until you are cleared to do so by a physician familiar with and experienced with treatment of DCS. For questions about your continued eligibility for your airman medical certificate contact an FAA medical officer or your AME.

(j) Allow at least 24 hours to elapse between SCUBA diving or hypobaric (altitude) chamber exposure and flying.

(k) Be prepared for a future emergency by familiarizing yourself with the availability of hyperbaric chambers in your area of operations. However, keep in mind that not all of the available hyperbaric treatment facilities have personnel qualified to handle altitude DCS emergencies. To obtain information on location of hyperbaric treatment facilities capable of handling altitude DCS emergencies, call the Diver's Alert Network at 919-684-9111.

f. Vision Deterioration. Vision has a tendency to deteriorate with altitude; smoking worsens this effect. A reversal of light distribution at high altitudes (bright clouds below the airplane and darker, blue sky above) can cause a glare inside the cockpit. Glare effects and deteriorated vision are enhanced at night when the body becomes more susceptible to hypoxia and can occur at altitudes as low as 5,000 ft MSL. In addition, the empty visual field caused by cloudless, blue skies during the day can cause inaccuracies when judging the speed, size, and distance of other aircraft. We recommend sunglasses to minimize the intensity of the sun's ultraviolet rays at high altitudes.

2-8. FAA PHYSIOLOGICAL TRAINING. There are no specific requirements in 14 CFR part 91 or 125 for physiological training. However, § 61.31(g), requires the high-altitude training outlined in this AC. Also, 14 CFR parts 121 and 135 require flightcrew members that serve in operations above 25,000 ft MSL to receive training in specified subjects of aviation physiology. None of the regulations include altitude chamber training. Although most of the subject material normally covered in physiological training concerns problems associated with reduced atmospheric pressure at high-flight altitudes, it covers other equally important subjects as well. Such subjects of aviation physiology as vision, disorientation, physical fitness, stress, and survival affect flight safety and are normally present in a good training program.

a. FAA Civil Aerospace Medical Institute (CAMI) Aviation Physiology Course. CAMI offers a 1 day aviation physiology course for FAA flightcrews, civil aviation pilots, and FAA AMEs. In addition to the basic academic contents, this course offers practical demonstrations of rapid decompression (8,000 to 18,000 ft MSL) and hypoxia (25,000 ft MSL) in a hypobaric chamber. Additionally, the course features a practical demonstration of spatial disorientation in a spatial disorientation demonstrator.

(1) Requirements. Persons who wish to take this training must be at least 18 years of age, hold a current FAA Airman Medical Certificate, and not have a cold or any other significant health problem when enrolling for the course.

NOTE: Anyone can attend the training regardless of whether they are a pilot or not. However, trainees still must obtain a minimum of a Class III medical certificate in order to participate in the altitude chamber training.

(2) Scheduling. CAMI's Airman Education Programs obtains a list of training dates from each base that are available to anyone interested in the training. Call 405-954-4837 to access these dates. Scheduling a training slot requires the following information:

- Full name,
- Date of birth,
- Name of organization (if applicable),
- Mailing address,
- Daytime phone number,
- Aircrew position or non-aircrew position, and
- All applicants that are not U.S. citizens must provide additional information (Security Clearance Request) found at http://www.faa.gov/pilots/training/airman_education/media/SecurityClearanceRequest.doc.

(3) Submitting an Application. CAMI will mail a notification letter to you. The applicant should take the notification letter, along with a current medical certificate, to the training facility the day of the training. For more information see the CAMI Web site at www.faa.gov.

b. Physiology of Flight Video Library. The FAA has developed a series of educational programs developed to address human factors hazards of high-altitude flight. You may view these videos at www.faa.gov/about/office_org/headquarters_offices/avs/offices/aam/med_pilots/pf_videos.

c. Airplane Upset Recovery. The FAA has developed a training aid on upset recovery and high-altitude operations. You can obtain the training aid at http://www.faa.gov/about/office_org/headquarters_offices/avs/offices/afs/afs200/branches/afs210/training_aids.

2-9. HIGH-ALTITUDE SYSTEMS AND EQUIPMENT. Several systems and equipment are unique to aircraft that fly at high altitudes, and pilots should be familiar with their operation before using them. Before any flight, a pilot should be familiar with all the systems on the aircraft to be flown.

a. Turbochargers. Most light piston engine airplanes that fly above 25,000 ft MSL are turbocharged. Turbochargers compress air in the carburetor or cylinder intake by using exhaust gases from an engine-driven turbine wheel. The increased air density provides greater power and improved performance. Turbocharged engines are particularly temperature-sensitive.

Manufacturers often recommend increasing the fuel flow during climbs to prevent overheating. It is also important to cool the engine after landing. Allow the engine to idle for approximately 1 minute before shutting it down. This permits engine oil to flow through the system, cooling the engine while simultaneously cooling and lubricating the turbocharger. Light aircraft use one of two types of turbocharger systems.

(1) Normalized System. The first is the normalized system, which allows the engine to develop sea level pressure from approximately 29 inches of manifold pressure up to a critical altitude (generally between 14,000 to 16,000 ft MSL).

(2) Supercharger System. The second is the supercharger system, which is driven by the engine through a gear train at one, two, or variable speeds. It is a more powerful system that allows the engine to develop higher than sea level pressure (up to 60 in of manifold pressure) up to a critical altitude. To prevent overboosting at altitudes below the critical altitude, a waste gate is installed in the turbocompressor system to release unnecessary gases. The waste gate is a damper-like device that controls the amount of exhaust that strikes the turbine rotor. As the waste gate closes with altitude, it sends more gases through the turbine compressor, causing the rotor to spin faster. This allows the engine to function as if it were maintaining sea level or, in the case of a supercharger, above sea level manifold pressure. The three principal types of waste gate operations are manual, fixed, and automatic.

(a) Manual Waste Gate. Manual waste gate systems are common in older aircraft, but have been discontinued due to the additional burden on the pilot. Waste gates were often left closed on takeoff, resulting in an overboost that could harm the engine.

(b) Fixed Waste Gate. Fixed waste gates pose less of a burden on the pilot, but the pilot must still be careful not to overboost the engine, especially on takeoff, initial climb, and on cold days when the air is especially dense. This type of waste gate remains in the same position during all engine operations, but it splits the exhaust flow, allowing only partial exhaust access to the turbine. The pilot simply controls manifold pressure with smooth, slow application of the throttle to control against overboost. If overboost does occur, a relief valve on the intake manifold protects the engine from damage. This is not a favorable system due to fluctuations in manifold pressure and limited additional power from the restricted control over the exhaust flow. In addition, the compressor can produce excessive pressure and cause overheating.

(c) Automatic Waste Gate. Automatic waste gates operate on internal pressure. When internal pressure builds towards an overboost, the waste gate opens to relieve pressure, keeping the engine within normal operating limits regardless of the air density.

1. The pressure-reference automatic waste gate system maintains the manifold pressure set by the throttle. Engine oil pressure moves the waste gate to maintain the appropriate manifold pressure, thus reducing the pilot's workload and eliminating the possibility of overboost. If the airplane engine is started and followed by an immediate takeoff, cold oil may cause a higher-than-intended manifold pressure. Allow the oil to warm up and circulate throughout the system before takeoff.

2. Compressor discharge air controls the density-reference waste gate system. A density controller holds a given density of air by automatically adjusting manifold pressure as airspeed, ambient pressure, temperature, altitude, and other variables change.

b. Oxygen and Oxygen Equipment. Most high-altitude airplanes come equipped with some type of fixed oxygen installation. If the airplane does not have a fixed installation, portable oxygen equipment must be readily accessible during flight. The portable equipment usually consists of a container, regulator, mask outlet, and pressure gauge. A typical 22-cubic ft portable container will contain enough oxygen for approximately 1.5 hours at 18,000 ft MSL for four people. Aircraft oxygen is usually stored in high-pressure system containers of 1,800 to 2,200 pounds per square inch (psi). The container should be fastened securely in the aircraft before flight. When the ambient temperature surrounding an oxygen cylinder decreases, pressure within that cylinder will decrease because pressure varies directly with temperature if the volume of a gas remains constant. A drop in indicated pressure on a supplemental oxygen cylinder can be an indication that the oxygen supply has merely compacted (not necessarily a leak). High-pressure oxygen containers should be marked with the psi tolerance (i.e., 1,800 psi) before filling the container to that pressure. Only oxygen that meets or exceeds the Society of Automotive Engineers International (SAE) Aerospace Standard AS8010 (as revised), *Aviator's Breathing Oxygen Purity Standard*, should be used. To assure safety, periodic inspection and servicing should take place by a certified maintenance provide found at some fixed base operations and terminal complexes.

(1) Regulator and Mask Systems. Regulators and masks work on continuous flow, diluter demand, or pressure demand systems.

(a) Continuous Flow System. The continuous flow system supplies oxygen at a rate that may be controlled automatically or by the user. The mask is designed so the oxygen can be diluted with ambient air by allowing the user to exhale around the facepiece, and comes with a rebreather bag, which allows the individual to reuse part of the exhaled oxygen. Pilot masks sometimes allow greater oxygen flow than passengers' masks, so it is important that pilots use the masks indicated for them. Although certificated up to 41,000 ft MSL, system capabilities require very careful attention when using continuous flow oxygen systems above 25,000 ft MSL.

(b) Diluter Demand and Pressure Demand Systems. Diluter demand and pressure demand systems supply oxygen only when the user inhales through the mask. An automix lever allows the regulators to automatically mix cabin air and oxygen or supply 100 percent oxygen, depending on the altitude. The demand mask provides a tight seal over the face to prevent dilution with outside air and can be used safely up to 40,000 ft MSL. Pilots who fly at those altitudes should not have beards and mustaches because air can easily seep in through the border of the mask. Pressure demand regulators also create airtight and oxygen-tight seals, but they also provide a positive pressure application of oxygen to the mask facepiece, which allows the user's lungs to be pressurized with oxygen. This feature makes pressure demand regulators safe at altitudes above 40,000 ft MSL.

(2) Increased Fire Risk. Pilots should be aware of the increased danger of fire when using oxygen. Materials that are nearly fireproof in ordinary air may be susceptible to burning in oxygen. Oils and greases may catch fire if exposed to oxygen and, therefore, cannot be used for sealing the valves and fittings of oxygen equipment. Smoking during the use of any kind of oxygen equipment must also be strictly forbidden.

(3) Equipment Inspection. A certified maintenance provider must inspect the aircraft system, and a DOT approved facility must hydrostatic test the oxygen bottles, before use. Before each flight, the pilot should thoroughly inspect and test all oxygen equipment. The inspection should be accomplished with clean hands and should include a visual inspection of the mask and tubing for tears, cracks, or deterioration. The regulator should also be checked for valve and lever condition and positions. Also be sure to check the oxygen quantity as well as the location and function of oxygen pressure gauges, flow indicators, and connections. The mask should be donned and the system tested. After any oxygen use, verify that all components and valves are shut off.

c. Pressurization Systems. Cabin pressurization is the compression of air in the aircraft cabin in order to maintain a cabin altitude lower than the actual flight altitude. Because of the ever-present possibility of decompression, the aircraft still requires supplemental oxygen. Pressurized aircraft meeting specific requirements of 14 CFR part 23 or 25 have cabin altitude warning systems, which activate at a cabin altitude of 10,000 ft. Pressurized aircraft meeting the more stringent requirements of part 25 have automatic passenger oxygen mask-dispensing devices that activate before exceeding 15,000 ft cabin altitude. It should be noted that some aircraft require that the flightcrew disable the automatic passenger oxygen mask-dispensing devices prior to landing at airports over 10,000 ft MSL to prevent inadvertent deployment when the cabin depressurizes at landing. The system is then re-armed after departure.

(1) Pressure Control. Turbine aircraft use a steady supply of engine bleed air for cabin pressurization. In the case of most pressurized light aircraft, the air supply is sent to the cabin from the turbocharger’s compressor or from an engine-driven pneumatic pump. In any case, an outflow valve regulates the flow of compressed air out of the cabin, which keeps the pressure constant by releasing excess pressure into the atmosphere. The cabin altitude selection can be manual, or if available, electronic. A gauge that indicates the pressure difference between the cabin and ambient altitudes helps the pilot to monitor the cabin altitude. A manually set backup control automatically controls the rate of change between these two pressures.

(2) Pressure Differentials. Each pressurized aircraft has a determined maximum pressure differential, which is the maximum differential between cabin and ambient altitudes that the pressurized section of the aircraft can support. The pilot must be familiar with these limitations, as well as the manifold pressure settings recommended for various pressure differentials. Some aircraft have a negative pressure relief valve to equalize pressure in the event of a sudden decompression or rapid descent to prevent the cabin pressure from becoming higher than the ambient pressure. Reducing exposure to low barometric pressure lowers the occurrence of decompression sickness and eliminates the need for an oxygen mask as a full-time oxygen source above certain altitudes. Many airplanes are equipped with automatic visual and aural warning systems that indicate an unintentional loss of pressure.

d. High-Altitude Components. Thin air at high altitudes has created a need for specialized aircraft components that are adapted to this environment.

(1) Magnetos. Thin air at high altitudes makes the unpressurized magneto susceptible to crossfiring. Therefore, we recommend the use of pressurized magnetos. Sealed caps and plugs that keep the electrodes contained within the body compose the high-tension pressurized system. A pressure line extends directly from the turbodischarger to the magneto. Pressurized magnetos perform better at high altitudes where low pressure and cold atmosphere have a detrimental effect on electrical conductivity. Avoid flight above 14,000 ft MSL with an unpressurized magneto because of its higher susceptibility to arcing.

(2) Vacuum Pump. Another airplane component recommended for flight at high altitudes is the dry vacuum pump. Engine-driven wet vacuum pumps cannot create a sufficient vacuum to drive the gyros in the low air density found at high altitudes. Furthermore, oil contamination from the wet pump system, which uses engine oil for lubrication and cooling, can ruin gyros and rubber deicing boots. Dry vacuum pumps are lightweight, self-lubricating systems that eliminate oil contamination and cooling problems. These pumps can power either a vacuum or pressure pneumatic system, allowing them to drive the gyros, deice boots, and pressurize the door seals.

2-10. AERODYNAMICS AND PERFORMANCE FACTORS. Thinner air at high altitudes has a significant impact on an airplane's flying characteristics because surface control effects, lift, thrust, drag, and horsepower are all functions of air density.

a. Aircraft Controls. The reduced weight of air moving over control surfaces at high altitudes decreases their effectiveness. As the airplane approaches its absolute altitude, the controls feel sluggish, making altitude and heading difficult to maintain. For this reason, most airplanes that fly at above 25,000 ft MSL are equipped with an autopilot.

b. Horsepower. The engine uses a determined weight of air to produce an identified amount of horsepower through internal combustion. For a given decrease of air density, horsepower decreases at a higher rate, which is approximately 1.3 times that of the corresponding decrease in air density.

c. Speed and Velocity. For an airplane to maintain unaccelerated level flight, drag and thrust must be equal. Because density is always greater at sea level, the velocity at altitude given the same AOA will be greater than at sea level, although the IAS will not change. Therefore, an airplane's TAS increases with altitude while its IAS remains constant. In addition, an airplane's rate of climb will decrease with altitude.

2-11. EMERGENCIES AND IRREGULARITIES AT HIGH ALTITUDES. All emergency procedures in the AFM should be reviewed before flying any airplane, and be readily accessible during every flight. A description follows of some of the most significant high-altitude emergencies and remedial action for each.

a. Decompression.

(1) Causes and Results. Decompression is the inability of the aircraft's pressurization system to maintain its designed pressure schedule. Decompression can be caused by a malfunction of the system itself or structural damage to the aircraft. A rapid decompression will often result in cabin fog because of the rapid drop in temperature and the change in relative humidity. A decompression will also affect the human body. Air will escape from the lungs through the nose and mouth because of a sudden lower pressure outside of the lungs. Differential air pressure on either side of the eardrum should clear automatically. Exposure to wind blast and extremely cold temperatures are other hazards the human body may face with decompression.

(2) Cabin Volume and Decompression Rates. Decompression of a small cabin volume pressurized aircraft is more critical than a large one, given the same size hole or conditions, primarily because of the difference in cabin volumes. Table 2-8, Aircraft Cabin Volume Ratios, is a comparison of cabin volume ratios between several large transport airplanes and some of the more popular GA turbojet airplanes in current use. Table 2-8 also shows that, under the same conditions, a typical small, pressurized aircraft can decompress on the order of 10 to 200 times faster than large aircraft. The B-747/Learjet comparison is an extreme example in that the human response, TUC, and the protective equipment necessary are the same. Actual decompression times are difficult to calculate due to many variables involved (e.g., the type of failure, differential pressure, cabin volume, etc.). However, it is more probable that the crew of the small aircraft will have less time in which to take lifesaving actions.

TABLE 2-8. AIRCRAFT CABIN VOLUME RATIOS

Aircraft Type	Cabin Volumes in Cubic Ft	Ratio
DC-9 vs CE-650	5,840 vs 576	10:1
B-737 vs LR-55	8,010 vs 502	16:1
B-727 vs NA-265	9,045 vs 430	21:1
L-1011 vs G-1159	35,000 vs 1,850	19:1
B-747 vs Learjet	59,000 vs 265	223:1

Data Source: Physiological Considerations and Limitations in the High-altitude Operation of Small Volume Pressurized Aircraft. E. B. McFadden and D. de Steigner, Federal Aviation Administration (FAA) Civil Aeromedical Institute (CAMI).

(3) Types of Decompression.

(a) Explosive Decompression. A change in cabin pressure faster than the lungs can decompress. Most authorities consider any decompression that occurs in less than 0.5 seconds as explosive and potentially dangerous. This type of decompression is more likely to occur in small volume pressurized aircraft than in large pressurized aircraft and often results in lung damage. To avoid potentially dangerous flying debris in the event of an explosive decompression, properly secure all loose items such as baggage and oxygen cylinders.

(b) Rapid Decompression. A change in cabin pressure where the lungs can decompress faster than the cabin. The risk of lung damage is significantly lower in this decompression compared to an explosive decompression.

(c) Gradual or Slow Decompression. A gradual or slow decompression is dangerous because it may not be detected. Automatic visual and aural warning systems generally provide an indication of a slow decompression.

(4) Recovery. Recovery from all types of decompression is similar. Regardless of the type of decompression, recognition of the decompression, awareness of cabin altitude/cabin pressurization warning systems, or recognition of hypoxia symptoms are essential for a safe recovery.

> **WARNING:**
>
> If hypoxia is suspected, immediately don oxygen mask and breathe 100 percent oxygen slowly. Descend to a safe altitude. If supplemental oxygen is not available, initiate an emergency descent to an altitude below 10,000 ft MSL. If symptoms persist, land as soon as possible.

(a) Oxygen. Because hypoxia can drive an increase in respiration as a reaction to make up for a lack of oxygen, you should carefully control your breathing rate and depth. The excessive rate and depth of respiration (hyperventilation) can cause symptoms similar to hypoxia. To recover from hypoxia, breathe 100 percent oxygen; it will not worsen hyperventilation. Thus, for either hypoxia or hyperventilation, the recovery procedures are the same—breathe 100 percent oxygen and slow the breathing rate. In some cases, particularly recovery from an extreme hypoxia exposure, the administration of 100 percent oxygen can cause an apparent increase in severity of symptoms lasting for 15–60 seconds. Even if this reaction occurs, the recovery procedures remain as described above. Breathe 100 percent oxygen and breathe slowly.

(b) Descent. Although top priority in such a situation is reaching a safe altitude, pilots should be aware that cold-shock in piston engines can result from a high-altitude rapid descent, causing cracked cylinders or other engine damage. The time allowed to make a recovery to a safe altitude before loss of useful consciousness is, of course, much less with an explosive decompression than with a gradual decompression.

b. Turbocharger Failure or Malfunction. Increased oil temperature, decreased oil pressure, and a drop in manifold pressure could indicate a turbocharger malfunction or a partial or complete turbocharger failure. The consequences of such a malfunction or failure are twofold. The airplane may not be capable of sustaining altitude without the additional power supplied by the turbocharged system. The loss in altitude in itself would not create a significant problem, weather and terrain permitting, but you must notify ATC of the descent.

> **CAUTION:**
>
> Loss of cabin pressurization can occur if the pressurization system is dependent on the turbocharger compressor. Careful monitoring of pressurization levels is essential during the descent to avoid the onset of hypoxia from a slow decompression.

c. Vapor Lock. Another potential problem associated with turbochargers is fuel vaporization. Engine-driven pumps that pull fuel into the intake manifold are susceptible to vapor lock at high altitudes. Most high-altitude aircraft are equipped with tank-mounted boost pumps to feed fuel to the engine-driven pump under positive pressure. These pumps should be turned on if fuel starvation occurs as a result of vapor lock.

d. In-Flight Fire. Because of the highly combustible composition of oxygen, if a fire breaks out during a flight at high altitude, pilots should initiate an immediate descent to an altitude that does not require oxygen. Follow the procedures in the AFM.

e. Flight Through Thunderstorm Activity or Known Severe Turbulence. When pilots anticipate flight through severe turbulence and/or it is unavoidable, we recommend the following procedure:

CAUTION:

Flight through thunderstorm activity or known severe turbulence should be avoided, if possible.

(1) Airspeed. Airspeed is critical for any type of turbulent air penetration. Use the AFM-recommended turbulence penetration target speed or, if unknown, fly an airspeed below maneuvering speed. Use of high airspeeds can result in structural damage and injury to passengers and crewmembers. Severe gusts may cause large and rapid variations in IAS. Do not chase airspeed.

(2) Altitude. Penetration should be at an altitude that provides adequate maneuvering margins in case severe turbulence is encountered to avoid the potential for catastrophic upset.

(3) Autopilot. If severe turbulence is penetrated with the autopilot on, the altitude hold mode should be off. If the autopilot has a pitch hold mode, it should be engaged. The autopilot pitch hold mode can usually maintain pitch more successfully than a pilot under stress. With the autopilot off, the yaw damper should be engaged. Controllability of the aircraft in turbulence becomes more difficult with the yaw damper off. Rudder controls should be centered before engaging the yaw damper.

(4) Lightning. When flight through a thunderstorm cannot be avoided, turn up the intensity of panel and cabin lights so lightning does not cause temporary blindness. White lighting in the cockpit is better than red lighting during thunderstorms.

(5) Attitude and Heading. Keep wings level and maintain the desired pitch attitude and approximate heading. Do not attempt to turn around and fly out of the storm because the speed associated with thunderstorms usually makes such attempts unsuccessful. Use smooth, moderate control movements to resist changes in attitude. If large attitude changes occur, avoid abrupt or large control inputs. Avoid, as much as possible, use of the stabilizer trim in controlling pitch attitudes. Do not chase altitude.

2-12. FLIGHT TRAINING. Flight training required to comply with § 61.31(g) may be conducted in a simulator that meets the requirements of part 121, § 121.407 or a high-altitude airplane. The simulator should be representative of an airplane that has a service ceiling or maximum operating altitude, whichever is lower, above 25,000 ft MSL. The training should consist of as many flights as necessary to cover the following procedures and maneuvers. If an airplane is being used, each flight should consist of a preflight briefing, flight planning, a preflight inspection, demonstrations by the instructor of certain maneuvers or procedures when necessary, and a postflight briefing and discussion.

a. Preflight Briefing. The instructor should verbally cover the material that will be introduced during the flight. If more than one flight is required, previous flights should be reviewed at this time. The preflight briefing is a good time to go over any questions the trainee may have regarding operations at high altitudes or about the aircraft. The instructor should encourage questions by the trainee during all portions of the flight training.

b. Preflight Planning. Complete a thorough flight plan for a predetermined route. The flight plan should include a complete weather briefing. Contact a Flight Service Station (FSS) (1-800-WX-BRIEF) or use one of the various internet-based services such as Direct User Access Terminal System (DUATS) to obtain a weather briefing. Determine the altitude for the flight using winds, pilot reports, the freezing level, and other meteorological information obtained from the briefing to determine the best altitude for the flight. Retain the information to aid in subsequent calculations made during flight.

(1) Course Plotting. Plot the course on a high-altitude navigation chart, noting the appropriate jet routes and required reporting points on a navigation log. Low-altitude charts should be available for planning departures and arrivals to comply with airspace and airspeed requirements. Identify and note alternate airports.

(2) AFM. Review the AFM with particular attention to Weight and Balance (W&B), performance charts, and emergency procedures. Calculate oxygen requirements, airspeeds, groundspeeds, time en route, and fuel burn using the AFM and weather data, when applicable. Plan fuel management and descents at this time. The AFM should be readily accessible in the cabin in the event of an emergency.

(3) Flight Planning. Complete a flight plan using appropriate jet routes from the en route high-altitude chart. File the flight plan with the nearest FSS, ATC facility, or with one of the online services, such as DUATS.

c. Preflight Inspection. The aircraft checklist should be followed carefully. Particular attention should be given to the aircraft's fuselage, windshields, window panels, and canopies to identify any cracks or damage that could rupture under the stress of cabin pressurization. The inspection should also include a thorough examination of the aircraft oxygen equipment, including available supply, an operational check of the system, and assurance that supplemental oxygen is in a readily accessible location.

- Preflight the oxygen equipment so that the system is ready for use upon donning the mask.
- Demonstrate crew communications using the oxygen equipment, both between crewmembers (if more than one required pilot) and with ATC.

d. Runup, Takeoff, and Initial Climb. Follow the procedures in the AFM, particularly the manufacturer's recommended power settings and airspeeds, to avoid overboosting the engine. Standard callout procedures are highly recommended and should be used for each phase of flight where the airplane crew consists of more than one crewmember.

e. Climb to High Altitude and Normal Cruise Operations While Operating Above 25,000 ft MSL. Perform the transition from low to high altitude repeatedly to assure familiarity with appropriate procedures. Specific oxygen requirements should be met when climbing above 12,500 ft MSL and pressurization should be adjusted with altitude. When passing through FL 180, the altimeter should be set to 29.92 inHg and left untouched until descending below that altitude. Comply with reporting points, and also with appropriate altitude selection for direction of flight. Throughout the entire climb and cruise above 25,000 ft MSL, emphasis should be given to monitoring cabin pressurization.

f. Simulated Emergencies. Training should include at least one simulated rapid decompression and emergency descent. Do not actually depressurize the airplane for this or any other training. Actual decompression of an airplane can be extremely dangerous and should never be done intentionally for training purposes. Simulate the decompression by donning the oxygen masks, turning on the oxygen controls, configuring the airplane for an emergency descent, and performing the emergency descent as soon as possible. Coordinate with ATC in advance of any practice emergency descent. Do not vacate any assigned altitude without clearance.

g. Descents. Gradual descents from altitude should be practiced to provide passenger comfort and compliance with procedures for transitioning out of the high-altitude realm of flight. Follow the airplane manufacturer’s recommendations with regard to descent power settings to avoid stress on the engine and excessive cooling. Particular emphasis should be given to cabin pressurization and procedures for equalizing cabin and ambient pressures before landing. Emphasis should also be given to changing to low-altitude charts when transitioning through FL 180, obtaining altimeter settings below FL 180, and complying with airspace and airspeed restrictions at appropriate altitudes.

h. Engine Shutdown. Allow the turbocharged engine to cool for at least 1 minute and assure that all shutdown procedures in the AFM are followed. Before exiting the airplane, always check that all oxygen equipment and oxygen valves have been turned off or placed in the position recommended by the manufacturer.

i. Postflight Discussion. The instructor should review the flight and answer any questions the trainee may have. If additional flights are necessary to ensure thorough understanding of high-altitude operations, preview the material for the next flight during the postflight discussion.

CHAPTER 3. MACH FLIGHT AT HIGH ALTITUDES

3-1. PURPOSE. To present certain factors involved in the high-speed flight environment at high altitudes. It is the lack of understanding of many of these factors involving the laws of aerodynamics, performance, and Mach speeds that has produced a somewhat higher accident rate in some types of turbojet aircraft.

3-2. CRITICAL ASPECTS OF MACH FLIGHT. In recent years, a number of corporate jet airplanes have experienced catastrophic loss of control during high-altitude/high-speed flight. A significant causal factor in these accidents may well have been a lack of knowledge by the pilot regarding critical aspects of high-altitude Mach flight. Maximum operating altitudes of some General Aviation (GA) turbojet airplanes now reach 51,000 ft mean sea level (MSL). These types of accidents will become less common as pilots gain experience and also learn to respect the more critical aspects of high-altitude, high-speed flight. It is imperative to have a thorough knowledge of their specific make and model of aircraft and its unique limitations.

a. Mach. From the pilot's viewpoint, Mach is the ratio of the aircraft's traffic advisory system (TAS) to the local speed of sound. At sea level, on a standard day (59 °F)/15 °C), the speed of sound equals approximately 660 knots (kts) or 1,120 feet per second (ft/s). Mach 0.75 at sea level is equivalent to a TAS of approximately 498 kts (0.75 x 660 kts) or 840 ft/s. The temperature of the atmosphere normally decreases with an increase in altitude. The speed of sound is directly related only to temperature. The result is a decrease in the speed of sound up to about 36,000 ft mean sea level.

b. Airspeed Limitations. The sleek design of some turbojet airplanes has caused some operators to ignore critical airspeed and Mach limitations. There are known cases in which corporate turbojet airplanes have been modified by disabling the airspeed and Mach warning systems to permit intentional excursions beyond the FAA-certificated maximum operating limit speed (V_{MO}/M_{MO}) limit for the specific airplane. Such action may critically jeopardize the safety of the airplane by setting the stage for potentially hazardous occurrences. The compulsion to go faster may result in the onset of aerodynamic flutter, excessive G-loading in maneuvering, and induced flow separation over the ailerons and elevators. This may be closely followed by the physical loss of a control surface, an aileron buzz or snatch, coupled with yet another dangerous phenomenon called Mach tuck, leading to catastrophic loss of the airplane and the persons onboard.

(1) Mach Tuck. Mach tuck is caused principally by two basic factors:

(a) Flow Separation. Shock wave-induced flow separation, which normally begins near the wing root, causes a decrease in the down wash velocity over the elevator, and produces a tendency for the aircraft to nose down.

(b) Center of Pressure Movement. The center of pressure moves aft. This tends to unbalance the equilibrium of the aircraft in relation to its center of gravity (CG) in subsonic flight. The airplane's CG is now farther ahead of the aircraft's aerodynamic center than it was in slower flight. This dramatically increases the tendency of the airplane to pitch more nose-down.

(2) Pressure Disturbances. Pressure disturbances in the air caused by an airfoil in high-altitude, high-speed flight result from molecular collisions. These molecular collisions are the result of air that moves over an airfoil faster than the air it is overtaking can dissipate. When the disturbance reaches a point at which its propagation achieves the local speed of sound, Mach 1 is attained. One hundred percent of the speed of sound at MSL with a temperature of 15 °C is 760 statute miles (sm) or 660 nautical miles (NM) per hour. This speed is affected by temperature of the atmosphere at altitude. Thus, optimum thrust fuel and range considerations are significant factors in the design of most GA turbine-powered airplanes that cruise at some percentage of Mach 1.

(3) Mach Compensating Device. Most turbojet airplanes capable of operating in the Mach speed ranges are designed with some form of trim and autopilot Mach compensating device (stick puller) to alert the pilot to inadvertent excursions beyond its certificated M_{MO}. If for any reason there is a malfunction that requires disabling the stick puller, the aircraft must be operated at speeds well below $M_{MO,}$ as prescribed in the applicable AFM procedures for the aircraft.

CAUTION:

The stick puller should never be disabled
during normal flight operations in the aircraft.

(4) Coffin Corner. An airplane's indicated airspeed (IAS) decreases in relation to TAS as altitude increases. As the IAS decreases with altitude, it approaches the airspeed for the low-speed buffet boundary where pre-stall buffet occurs for the airplane at a load factor of 1.0 G. The point where high-speed Mach, IAS, and low-speed buffet boundary IAS merge is the airplane's absolute or aerodynamic ceiling. Once an aircraft has reached its aerodynamic ceiling, which is higher than the altitude limit stipulated in the AFM, the aircraft can neither be made to go faster without activating the design stick puller at Mach limit nor can it be made to go slower without activating the stick shaker or pusher. This critical area of the aircraft's flight envelope is known as coffin corner.

(5) Mach Buffet. Mach buffet occurs as a result of supersonic airflow on the wing. Stall buffet occurs at angles of attack that produce airflow disturbances (burbling) over the upper surface of the wing, which decreases AOA lift. As density altitude increases, the AOA that is required to produce an airflow disturbance over the top of the wing is reduced until a density altitude is reached where Mach buffet and stall buffet converge (described in subparagraph 3-2b(4) as coffin corner). When this phenomenon is encountered, serious consequences may result, causing loss of control of the aircraft.

(6) Mach Buffet Limits. Increasing either gross weight or load factor (G factor) will increase the low-speed buffet and decrease Mach buffet speeds. A typical turbojet airplane flying at 51,000 ft MSL altitude at 1.0 G may encounter Mach buffet slightly above the airplane's M_{MO} (0.82 Mach) and low-speed buffet at 0.60 Mach. However, only 1.4 G (an increase of only 0.4 G) may bring on buffet at the optimum speed of 0.73 Mach and any change in airspeed, bank angle, or gust loading may reduce this straight and level flight 1.4 G protection to no protection.

Consequently, a maximum cruising flight altitude must be selected that will allow sufficient buffet margin for the maneuvering necessary and for gust conditions likely to be encountered. Therefore, it is important for pilots to be familiar with the use of charts showing cruise maneuvering and buffet limits. Flightcrews operating airplanes at high speeds must be adequately trained to operate them safely. This training cannot be complete until pilots are thoroughly educated in the critical aspect of aerodynamic factors pertinent to Mach flight at high altitudes.

3-3. AIRCRAFT AERODYNAMICS AND PERFORMANCE. Pilots who operate aircraft at high speeds and high altitudes are concerned with the forces affecting aircraft performance caused by the interaction of air on the aircraft. With an understanding of these forces, the pilot will have a sound basis for predicting how the aircraft will respond to control inputs. The importance of these aerodynamic forces and their direct application to performance and execution of aircraft maneuvers and procedures at altitude will be evident. The basic aerodynamics definitions that apply to high-altitude flight are contained in paragraph 1-4.

a. Wing Design.

(1) Induced Lift. The wing of an airplane is an airfoil or aircraft surface designed to obtain the desired reaction from the air through which it moves. The profile of an aircraft wing is an excellent example of an efficient airfoil. The difference in curvature between the upper and lower surfaces of the wing generates a lifting force. Air passing over the upper wing surface moves at a higher velocity than the air passing beneath the wing because of the greater distance it must travel over the upper surface. This increased velocity results in a decrease in pressure on the upper surface. The pressure differential created between the upper and lower surfaces of the wing lifts the wing upward in the direction of the lowered pressure. This lifting force is known as induced lift. Induced lift may be increased, within limits, by:

- Increasing the AOA of the wing or changing the shape of the airfoil; changing the geometry (e.g., aspect ratio).
- Increasing the wing area.
- Increasing the free-stream velocity.
- A change in air density.

(2) Critical Mach Number (M_{CR}). The pilot may have only varying degrees of control over these factors. Thus, the pilot must keep in mind that an aircraft will obey the laws of physics just as precisely at its high-speed limits as it does during a slower routine flight. So, regardless of wing shape or design, Mach range flight requires precise control of a high volume of potential energy without exceeding the critical Mach number (M_{CR}). The M_{CR} is important to high-speed aerodynamics because it is the speed at which the flow of air over a portion of a specific airfoil design reaches Mach 1. This results in the formation of a shock wave and drag divergence.

(3) Wing Sweep. Sweeping the wings of an airplane is one method used by aircraft designers to delay the adverse effects of high Mach flight and bring about economical cruise with an increase in the M_{CR}. Sweep allows a faster airfoil speed before critical Mach is reached when compared to an equal straight wing. This occurs because the airflow now travels over a different cross-section (camber) of the airfoil. This new cross-section has less effective camber, which results in a reduced acceleration of airflow over the wing, thus allowing a higher speed before critical Mach is reached. Sweep may be designed either forward or rearward; the overall effect is the same. However, rearward sweep appears to be somewhat more desirable, since it has presented fewer problems to manufacturers of models of GA aircraft in terms of unwanted design side effects. In effect, the wing is flying slower than the airspeed indicator indicates and, similarly, it is developing less drag than the airspeed indicator would suggest. Since less drag is being developed for a given IAS, less thrust is required to sustain the aircraft at cruise flight.

(a) There is a penalty, however, on the low speed end of the spectrum. A swept-wing airplane has a higher landing/stall speed when compared with a similar straight-wing aircraft. This means higher touchdown speed, longer runway requirements, and more tire and brake wear as opposed to a straight-wing design. A well-stabilized approach with precise control of critical "V" speeds is necessary. Swept-wing drag curves are approximately the reverse of the lift curves. A rapid increase in drag component may be expected with an increase of AOA with the amount being directly related to the degree of sweep or reduction of aspect ratio.

(b) The extension of trailing edge flaps and leading edge devices may, in effect, further reduce the aspect ratio of the swept wing by increasing the wing chord. This interplay of forces should be well understood by the pilot of the swept-wing aircraft. Raising the nose of the aircraft to compensate for a mild undershoot during a landing approach at normal approach speeds will produce little lift and may instead lead to a rapid decay in airspeed, reducing the margin of safety.

(4) High-Speed Laminar Airflow Airfoil. Another method of increasing the M_{CR} of an aircraft wing is through the use of a high-speed laminar airflow airfoil in which a small leading edge radius is combined with a reduced thickness ratio. This type of wing design is more tapered with its maximum thickness further aft, thus distributing pressures and boundary layer air more evenly along the chord of the wing. This tends to reduce the local flow velocities at high Mach numbers and improve aircraft control qualities.

(5) Vortex Generators and Boundary Layer Energizers. Several modern straight-wing, turbojet aircraft use another design method to delay the onset of Mach buzz and obtain a higher M_{MO}. These aircraft sometimes incorporate the use of both vortex generators and small triangular upper wing strips as boundary layer energizers. Both systems seem to work equally well, although the boundary layer energizers generally produce less drag. Vortex generators are small vanes affixed to the upper wing surface, extending in height approximately 1 to 2 in. This arrangement permits these vanes to protrude through the boundary layer air. The vortex generators deflect the higher energy airstream downward over the trailing edge of the wing and accelerate the boundary layer aft of the shock wave. This tends to delay shock-induced flow separation of the boundary layer air, which causes aileron buzz, and thus permits a higher M_{MO}.

(6) Lift Characteristics Related to Swept Wings. The lift characteristics of straight-wing and swept-wing airplanes related to changes in AOA are more favorable for swept-wing airplanes. An increase in the AOA of the straight-wing airplane produces a substantial and constantly increasing lift vector up to its maximum coefficient of lift and, soon thereafter, flow separation (stall) occurs with a rapid deterioration of lift. By contrast, the swept wing produces a much more gradual buildup of lift with no well-defined maximum coefficient, the ability to fly well beyond this point, and no pronounced stall break.

(7) Airflow and Airspeed. Regardless of the method used to increase the critical Mach number, airflow over the wing is normally smooth. However, as airspeed increases, the smooth flow becomes disturbed. The speed at which this disturbance is encountered will be determined by the shape of the wing and the degree of sweep. When the aircraft accelerates, the airflow over the surface of the wing also accelerates until, at some point on the wing, it becomes sonic. The aircraft March number at which this occurs is the M_{CR} for that wing.

b. Jet Engine Efficiency.

(1) Fuel Economy. The efficiency of the jet engine at high altitudes is the primary reason for operating in the high-altitude environment. The specific fuel consumption of jet engines decreases as the outside air temperature decreases for constant revolutions per minute (rpm) and TAS. Thus, by flying at a high altitude, the pilot is able to operate at flight levels where fuel economy is best and with the most advantageous cruise speed. For efficiency, jet aircraft are typically operated at high altitudes where cruise is usually very close to rpm or exhaust gas temperature limits. At high altitudes, little excess thrust may be available for maneuvering. Therefore, it is often impossible for the jet aircraft to climb and turn simultaneously, and all maneuvering must be accomplished within the limits of available thrust and without sacrificing stability and controllability.

(2) Compressibility. Compressibility also is a significant factor in high-altitude flight. The low temperatures that make jet engines more efficient at high altitudes also decrease the speed of sound. Thus, for a given TAS, the Mach number will be significantly higher at high altitude than at sea level. This compressibility effect, due to supersonic airflow, will be encountered at slower indicated speeds at high altitude than at low altitude.

c. Controllability Factors.

(1) Static Stability. Static stability is the inherent flight characteristic of an aircraft to return to equilibrium after being disturbed by an unbalanced force or movement.

(2) Controllability. Controllability is the ability of an aircraft to respond positively to control surface displacement and to achieve the desired condition of flight.

(3) Air Density. At high-flight altitudes, aircraft stability and control may be greatly reduced. Thus, while high-altitude flight may result in high TAS and high Mach numbers, calibrated airspeed is much slower because of reduced air density. This reduction in density means that the AOA must be increased to maintain the same coefficient of lift with increased altitude. Consequently, jet aircraft operating at high altitudes and high Mach numbers may simultaneously experience problems associated with slow-speed flight such as Dutch roll, adverse yaw, and stall. In addition, the reduced air density reduces aerodynamic damping, overall stability, and control of the aircraft in flight. Swept-wing and airfoil design alone, with boundary layer energizers such as the vortex generators described earlier, has reduced the hazardous effect of the problems described below. However, these problems are still encountered to some extent by the modern turbojet airplane in high-altitude flight.

(a) Dutch Roll. Dutch roll is a coupled oscillation in roll and yaw that becomes objectionable when roll, or lateral stability, is reduced in comparison with yaw or directional stability. A stability augmentation system is required to be installed on the aircraft to dampen the Dutch roll tendency when it is determined to be objectionable, or when it adversely affects control stability requirements for certification. The yaw damper is a gyro-operated autocontrol system installed to provide rudder input and aid in canceling out yaw tendencies such as those in Dutch roll.

(b) Adverse Yaw. Adverse yaw is a phenomenon in which the airplane heading changes in a direction opposite to that commanded by a roll control input. It is the result of unequal lift and drag characteristics of the down-going and up-going wings. The phenomena are alleviated by tailoring the control design by use of spoilers, yaw dampers, and interconnected rudder and aileron systems.

(4) Results of Supersonic Flow. Supersonic flow over the wing is responsible for:

(a) Shock Waves. The formation of shock waves on the wing, which results in drag rise.

(b) Aft Shift. An aft shift in the center of lift resulting in a nosedown pitching moment called Mach tuck.

(c) Airflow Separation. Airflow separation behind the shock waves resulting in Mach buffet.

(5) G-Force and Safety Margins. In general, this discussion has been confined to normal level, unaccelerated 1.0 G-flight, when rotating or maneuvering about the pitch axis; however, acceleration of G-forces can occur while maintaining a constant airspeed. As G-forces increase, both the aircraft's aerodynamic weight and AOA increase.

(a) Maneuvering Flight G-Loading. The margin over low-speed stall buffet decreases, as well as the margin below Mach buffet, because of the increased velocity of the air over the wing resulting from the higher AOA. This, in effect, could lower the aerodynamic ceiling for a given gross weight.

(b) Non-Maneuvering Flight G-Loading. Increased G-loading can also occur in non-maneuvering flight because of atmospheric turbulence or the lack of fine-touch skill by the pilot. Pilots flying at high altitudes in areas where turbulence may be expected must carefully consider acceptable safety margins necessary to accommodate the sudden and unexpected vertical accelerations that may be encountered with little or no warning. How wide is the safety margin between low-speed and high-speed buffet boundaries for an altitude and weight in a 30 bank? The answer may be easily determined by reference to the Cruise Maneuver/Buffet Limit Chart for a particular aircraft. For example, in a typical jet aircraft, the 1.0 G buffet-free margin at FL 350 is 135 kts; at FL 450, this speed is reduced to a mere 26 kts. Thus, the safety margin in airspeed spread diminishes rapidly as the aircraft climbs and leaves little room for safety in the event of an air turbulence encounter or accidental thunderstorm penetration.

(6) Thunderstorm Penetration. If a thunderstorm cannot be avoided, follow high-altitude thunderstorm penetration procedures and avoid over-action of thrust levers. When excessive airspeed buildup occurs, pilots may wish to use speed brakes. The use of aerodynamic speed brakes, when they are part of the lateral control system, may change the roll rate any time there is a lateral control input.

(7) Information. For detailed information concerning the operation of specific turbojet aircraft, refer to the aircraft's Airplane Flight Manual (AFM).