CHAPTER 4

The Atmosphere

Since the study of flight engineering involves interpretation of charts which convey conditions of the atmosphere at various flight levels and temperatures, the flight engineer should know something about the characteristics of the atmosphere. A brief discussion of weather, cloud formation, and effects of air masses and fronts is included. This information helps the flight engineer to "read" the horizon, interpret conditions indicated by cloud formations, and assists the pilot in plotting his cruise accordingly. Also included in this chapter is a discussion of how standard atmosphere charts for various altitudes and flight conditions have been established by ICAO (International Civil Aviation Organization) and accepted by the National Advisory Committee for Aeronautics. These charts, known as ICAO charts, are built around a theoretical standard condition known as the ICAO Day.

THE CANOPY OF AIR*

In spite of all his hard-won knowledge of the physical world, man continues to regard himself as a self-sufficient being, dominating the surface of the earth. Never does he picture himself as a creature dwelling fishlike at the bottom of a sea of atmosphere, doomed and helpless without the life-giving medium into which he is cast.

Yet he lives at the bottom of a sea of air hundreds of miles deep, where he subsists as precariously as a marine organism in its natural element of water. Raise him a few miles from the bottom of his sea and he suffers severe internal pressures and becomes unconscious, or dies. Man cannot say that he lives on top of the world—but only between two layers of it.

Without atmosphere, no plant or animal could exist. Without the atmosphere, there would be no weather, winds, clouds, or rain; no beautiful sunsets or dawns; there would be no fire and no sound. Vegetation could not grow nor birds fly. Aircraft could not fly either, and an organized knowledge of flight engineering, atmospheric characteristics, and cloud formations would be unnecessary.

Besides all this, the atmosphere also serves as a protective canopy that shields the earth and its inhabitants from the intolerable violence of the sun. At night the atmosphere imprisons the heat of day and prevents its escape into space. Without atmosphere, the temperature of the earth would be about 230° F by day and a —300° at night. In addition, the atmosphere catches and consumes hundreds of millions of meteors which fall into it each day.

The medium through which man moves is a mixture of many gases, but five predominate, either in quantity or in importance. They are:

Nitrogen	78%
Oxygen	21%
Argon	about .93%
Water vapor	.41 to 4%
Carbon dioxide	.03%

Also included are:

Helium	.0005%
Hydrogen	.00005%

The origin of these gases of the air is still a mystery. Of all the planets in range of our vision,

* Portions of this chapter and several illustrations are taken from *The World We Live In; Part IV, The Canopy of Air*, by Lincola Barnett (Life Magazine, June 8, 1953, Time Inc.). Used with permission of the publisher.

only Mars appears to have an atmosphere somewhat similar to ours, containing a small amount of water vapor and some traces of oxygen. None of these important life giving gases has been detected in the spectrum of the thick clouds overhanging Venus. The atmospheres enveloping Jupiter and Saturn seem to be composed largely of hydrogen, helium, methane (marsh gas), and ammonia. Mercury, like the moon, may have no atmosphere at all.

Thus, you see that our atmosphere presents a queer situation—the elements which largely compose our atmosphere are rare in other parts of the solar system, and those most common in other parts of the solar system are relatively scarce in our atmosphere. However, if all the parts of the universe were created out of the same elemental cloud of cosmic gas, we are to assume that all planets and sun and stars are composed of the same elements enveloped with the same gases. Yet the earth's atmosphere contains only .00005 per cent of free hydrogen and .0005 per cent helium. What became of all the hydrogen and helium that may have been present in large quantities?

It is thought that after the larger parts of the universe—the planets, the stars, the sun—had been formed, the free helium and hydrogen were evaporated by solar radiation and gathered in by the sun. Other quantities of gases remained locked in chemical combination in other planets. These reacted internally and slowly bubbled forth from crags and volcanoes of the shrinking, cooling planets. On the earth, these gases belched forth from springs, volcanoes, folding rocks, and settling marshes, and little by little fed and enriched the sparse air until the dark sky brightened and turned blue.

One of these emissions of gases was our critical, free oxygen. This life-giving element did not emit from crags or volcanoes, but it is believed to have been created by an immensely slow process parallel to the evolution of plant life, for plants are the earth's chief manufacturers of oxygen. At first, however, oxygen was produced in very small quantities, but as plants developed from the primitive to the more complex, the process quickened.

THE ANATOMY OF THE AIR

Air is a complex and ever-varying mixture. Its ingredients vary from place to place and from day to day. Besides the gases mentioned before, it contains quantities of foreign matter such as pollen, dust, bacteria, soot, volcanic ash, spores, and dust from outer space.

Although the composition of the air remains quite constant from sea level up to its highest reaches, its density diminishes rapidly with altitude. Six miles up, for example, it is too thin to support respiration and 12 miles up there is not enough oxygen to keep a candle burning. At some point several hundred miles above the earth, some gas particles spray out into space; some, dragged by gravity, fall back into the ocean of air below; others never return but travel like satellites around the earth; and still others, like hydrogen and helium, escape forever from the earth's gravitational field.

The topmost layer may be thought of, therefore, not as the smooth surface of a placid sea, but as a nebulous veil or mist rising over jets of innumerable mountains. Physicists disagree as to the boundaries of the outer fringes of the atmosphere. Some think it begins 240 miles above the earth and extends to 400 miles; others place its lower edge at 600 miles and its upper boundary at 6000 miles.

Besides the quantitative differences, certain curious unconformities appear at various levels. For example, in the layer between 12 and 30 miles up (see chart) solar ultraviolet radiation reacts with oxygen molecules to produce a thin curtain of ozone. This ozone then filters out a small portion of the sun's lethal ultraviolet rays, allowing only enough to come through to give man sunburn, kill bacteria, and prevent rickets. At 40 to 65 miles up, most of the oxygen molecules begin to break down under solar radiation into free atoms, and to form the incomplete hydroxyl molecule, (OH) from water vapor. Also in this region all the atoms become ionized.

Perhaps one of the greatest surprises produced by studies of the atmosphere is that the temperature does not decrease uniformly with increasing altitude. As shown in the chart, it gets steadily colder up to a height of about 7 miles where the rate of temperature change slows down abruptly and remains almost constant up to about 15 miles. Then the temperature begins to rise up to a peak value at about 30 miles, and drops again at the 55-mile level to about the temperature exhibited in the layer between 7 and 15 miles. Thereafter it climbs steadily, reaching about 2000° F at a

height of approximately 300 miles. So from the 40-mile level upward, a man or any other living creature in space, without protective cover of the atmosphere, would be roasted on the sunny side of the earth and frozen on the other side.

Note, in figure 4-1, that for ease in formulating rules and standards, the atmosphere is divided into layers or levels. Transition through these layers is gradual as they are without sharply defined boundaries. However, one boundary, the tropopause, is defined as existing between the first and second layers. The tropopause is defined as the point in the atmosphere at which the decrease in temperature with increasing altitude abruptly ceases—between the troposphere and the stratosphere. In the illustration, note the three atmospheric layers are troposphere, stratosphere and ionsphere. Exosphere, a fourth layer, is not shown. The upper portion of the stratosphere is often called the chemosphere or ozonosphere. The exosphere is also known as the mesosphere.

Troposphere

The *troposphere* extends from the earth's surface to about 36,000 feet at middle latitudes, but varies from 28,000 feet at the poles to about 54,000 feet at the equator. The troposphere is characterized by large changes in temperature and humidity, and by generally turbulent conditions. Of the total weight of the atmosphere, approximately ¾ of it is within the troposphere. The temperature and absolute pressure in the troposphere steadily decrease with increasing altitude to a point where the temperature is approximately −69.7° F and the pressure is about 6.9 inches Hg on a standard day.

Nearly all cloud formations are within the troposphere. Water vapor is generally found from sea level up to approximately 32,000 feet. The exact amount of water vapor that is contained in the air depends on the temperature and whether the air is, or recently has been, over large bodies of water. Because of these ever-changing currents and the varying moisture content of the atmosphere, clouds form and precipitation takes place. This is followed by evaporation and the never-ending cycle continues. These characteristics, plus geographical considerations, make our local weather and climate. They directly affect flight operations, military maneuvers, and everyday life.

Tropopause

There is a uniform temperature drop with an increase in altitude up to a certain point. The point at which the temperature drop stops marks the boundary called the *tropopause* (tropo + pause—to cease). See the chart, *Characteristics of the Earth's Atmosphere,* figure 4-1. The tropopause is not considered a region but rather an imaginary plane dividing the troposphere and the stratosphere.

Stratosphere

The *stratosphere* (stratos—stratified layers + sphere) extends from the tropopause to an average altitude of 20 miles. It is expected that most highspeed aircraft flight and certain missile operations will take place in the stratosphere. It is doubtful whether air-breathing jet engines, such as the turbo-jet and ram-jet, will be able to operate efficiently at higher altitudes. One of the notable characteristics of the stratosphere is that there is almost a total absence of weather phenomena. There is smoother flight in most cases, but with high winds.

Chemosphere

The *chemosphere* (chemical + sphere) lies between the 20-mile layer and the 50-mile layer. In the upper regions, the molecules of oxygen begin to break down under solar radiation into free atoms and to form the incomplete hydroxyl molecule (OH) from water vapor. In this region, most of the atoms become ionized (electrically charged) and a concentration of ozone is produced when an electric spark is passed through the air.

Ionosphere

The *ionosphere* (ionize + sphere) ranges from the 50-mile level to the 250-mile level. Basically, this layer is characterized by the presence of ions and free electrons, and the ionization seems to increase with altitude and in successive layers. Little is known about the characterics of the ionosphere, but it is believed that many electrical phenomena occur in this layer. There is a comparatively high-temperature region at the base of the ionosphere caused by a concentration of ozone which absorbs solar ultraviolet radiation. This same ultraviolet radiation causes ionization

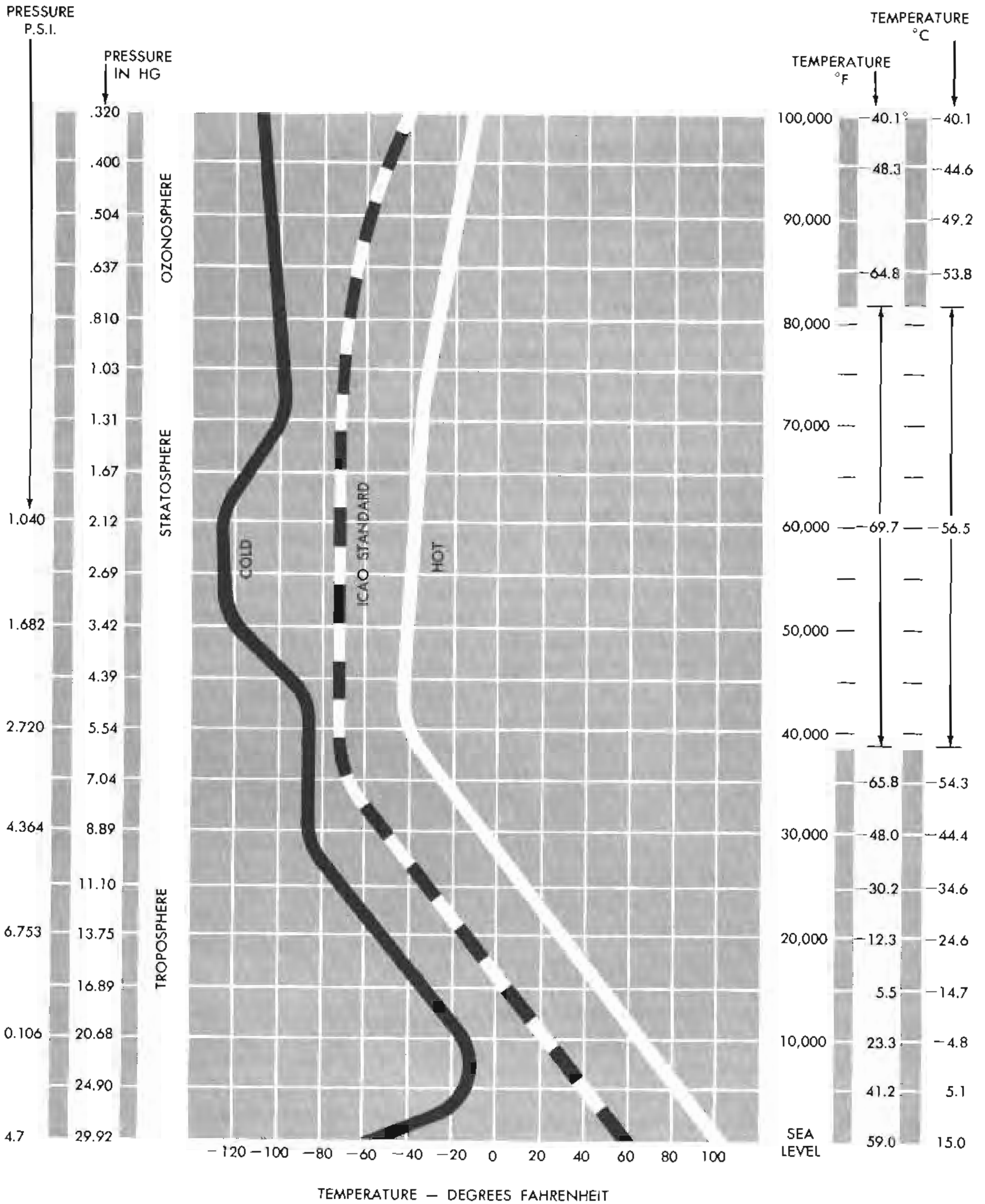

Figure 4-1. Characteristics of Earth's Atmosphere

of some of the few molecules of air at this altitude. Thus it is in this region that the D, E, F_1, and F_2 layers are found, each of which reflects radio signals of various frequencies.

Exosphere

The outermost layer of the atmosphere is the mesosphere (connecting—sphere) which is sometimes referred to as the *exosphere.* The upper limit of the mesosphere is arbitrarily fixed at 1000 miles from the earth's surface. In this layer propagation of sound is believed to be impossible due to the lack of molecular substance. For all practical purposes, the mesosphere is interplanetary space, and currents influence the weather across the face of the earth, for whenever the air aloft warps upward to form a great wave crest or ridge, there is probably a related high pressure area somewhere on the earth below. On the other hand, when the air aloft sinks into a valley or trough, a low pressure area is revealed on the earth below.

High Pressure Area

A *high pressure area (high)* is a mass of air, the pressure of which is higher than that of surrounding air. Because of the higher pressure in the center, there is a pressure difference directed outward in all directions. This pressure difference, called pressure gradient, is the basic factor in causing air to move (wind). As the heavier, stacked-up air moves downward and spirals outward, it causes winds to spiral outward and thus to blow from the high pressure area. As the air moves downward and outward, it becomes warmer with a greater capacity to hold moisture. Thus, the weather in a high is generally characterized by clear skies, sunshine, and pleasant, dry air.

Low Pressure Area

A *low pressure area (low)* is a region where the pressure is lower than that of surrounding air masses. The pressure gradient is now directed towards the center of the low and the air moves in and rises. As it rises, it is cooled and is made to give up some of the moisture it bears. Thus lows bring with them fog, rain, or other types of bad weather.

As the earth spins on its axis, the highs and lows are made to move slowly from west to east, particularly in the temperate zone. In the United States, for example, they pass from a southwesterly to a northeasterly direction, bringing with them the rain, the clouds, the sunshine and the storms. Occasionally an air mass is disrupted in its movement by another one moving in a different direction. This sets up a disturbance which may range from a rain-giving warm front to a thunderstorm or even a tornado. These disturbances are better known to pilots and engineers as *fronts.*

Frontal Systems

Meteorologists recognize four kinds of fronts—*cold, warm, occluded, and stationary.* A cold front, figure 4-2, occurs when a swift-moving cold air mass overtakes warm air and forces it aloft,

Figure 4-2. Cold Front

Courtesy Time Incorporated

Courtesy Time Incorporated

Figure 4-3. Warm Front

often causing violent winds and thunderstorms. The turbulence is usually brief, however, and very localized. A warm front, figure 4-3, evolves when a warm mass slowly overtakes and slides over a cooler one. It may cover large areas, often several states, or even whole sections of the country. It is accompanied by dreary, rainy weather, which may persist for days. An occluded front develops when a cold front overtakes a warm front and lifts it completely off the ground so that the line of contact between them is aloft. It brings characteristic features of both the cold and warm front disturbances. Once in a while, a cold or a warm front simply stands still. In such cases the front is known as a stationary front, and the weather remains fixed until the front moves on.

All these movements of air masses are indicated by clouds and their movements. Humidity (moisture) in the air forms into clouds when a warmer mass of air is cooled. The density and shape of the cloud indicate the abruptness and severity of the temperature change. Thus, by watching the clouds, one can estimate the movement of the air masses. Occasionally, a fast-moving current may sweep along at an upper level with no indication that it may be there. The presence of such a current, known best to flyers as the jet stream, is the subject of intense study in an effort to predict and utilize its value in preflight planning.

The Wandering Winds

The most conspicuous property of the air is its mobility. By nature, the molecules of air are free and unfettered, not tightly bound as in solids, nor linked loosely as in liquids. This mobility of the atmosphere, as shown in figure 4-4, manifests itself both in flow of local winds and in a vast, orderly system of air movements that appear to govern weather conditions around the globe. The greater winds of the earth are impelled by two great forces—the heat of the sun and the rotation of the earth on its axis.

In this process, the sun is the heat source for the "engine" that drives the winds, and the rotation of the earth is a steering mechanism. Were the sun alone at work and the earth did not rotate, all large-scale winds would blow to a point directly under the sun and spread radially in all directions at some higher level. But since the earth does rotate, the flow of air from colder to warmer regions is deflected to the right of its expected path in the northern hemisphere, and to the left in the southern hemisphere.

Warm air from the tropics continually mingles with cool air from the poles, moderating climate and preventing violent temperature extremes around most of the world. In each hemisphere, warm and cool air masses meet at about 40° latitude, where they form a vast, shifting, and unstable boundary, mobile and irregular. Aloft, this boundary is marked by deep folds which alternately advance and retreat northward and southward and swing in great orbits around the poles from west to east. Great waves of cold air are hurled toward the equator and warm air is sucked toward the pole. Simultaneously, great

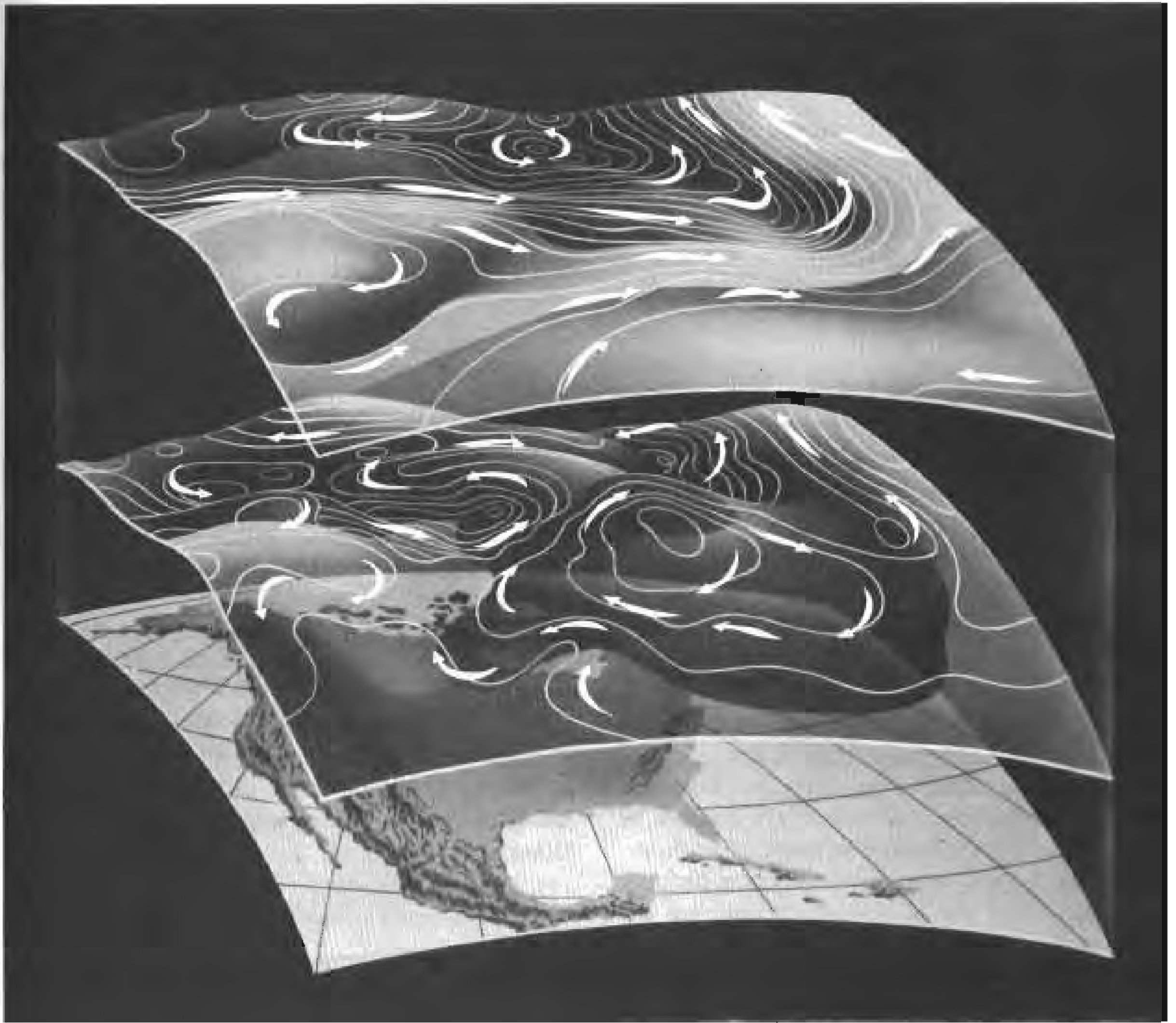

Figure 4-4. The Undulating Atmosphere

Courtesy Time Incorporated

cells of high and low pressure areas appear, which in turn are related to the wind systems at sea level.

In addition to these major pools of air, minor ones are caused by the effects of local earth formations such as oceans, continents, mountain ranges, lakes, deserts, valleys, and even large tracts of forest. These local disturbances create updrafts, downdrafts, cold fronts, and warm fronts; creating or destroying cloud patterns which, when carefully analyzed by the pilot and flight engineer, may help them to arrive at decisions relating to flight missions.

The Jet Stream

The *jet stream* is a strong, generally westerly air current, found aloft over the temperate zones of each hemisphere. It can usually be found with an intense, rapidly moving cold front separating a continental polar air mass from a tropical air mass. The jet stream appears to form near latitudes 60° and 70° and frequently is identified as far toward the equator as latitude 20°. It appears farther toward the poles in summer than in winter, and definitely moves equatorward in conjunction with a polar outbreak.

The jet stream can be pictured as a high-speed, meandering river of winds in an otherwise "normal" flow of air. The horizontal rate of change of wind speed outward from the core of the jet stream may be as much as 100 knots in 300 miles. Vertically, this rate of change of speed, generally called *shear,* is often as much as 100 knots in

12,000 feet. The jet stream is about 100 to 125 miles wide and 3000 to 7000 feet deep. Its core, on the average, is about 200 nautical miles behind the surface cold front and between 30,000 to 40,000 feet high.

Wind speeds in the jet stream are generally 100-200 knots, and in the winter-half of the year they are always stronger than in the summer-half. The direction of flow of the winds in the jet stream is roughly parallel to the orientation of the accompanying surface cold front. Although the wind directions in the jet stream vary with both distance and time, they always have a westerly component.

The daily change in position of the jet stream is slow and sometimes erratic. In the northern hemisphere, usual movement is a slow southward or southeastward drift, generally following the movement of the surface cold front.

PHYSICAL LAWS CONCERNING THE AIR

Gases differ from liquids in two important respects—first, they are compressible; and second, they completely fill any closed vessel in which they are placed. In most other respects, however, gases act like liquids. Since both are capable of flowing, they are commonly referred to as *fluids*. Gases, like liquids, exert pressure upon surfaces with which they are in contact. Gases are affected by heat, expanding and contracting as do liquids and solids.

Because of their simple structure, gases are well adapted to mathematical study. The simpler gas fundamentals and laws are explained as follows.

Specific Gravity of Gases

The specific gravity of liquids and solids was defined with water as a basis. In the case of gases, air is usually taken as the standard so that *the specific gravity of a gas can be defined as the ratio of the weight of gas to the weight of an equal volume of air, with both at the same pressure and temperature*. The standard pressure and temperature normally are 76 cm of mercury and 0° C, respectively. Previously density was defined as the ratio of mass to volume. The relative density of a gas is defined as the ratio of the density of the gas to the density of air. The relative density of a gas is numerically the same as the specific gravity, using air as the standard.

The density of a gas is often represented by the Greek letter ρ (rho). The unit in which ρ is measured is often written slugs/ft^3.

As for liquids, the pressure of gases is also measured in pounds per square inch (lb/in^2 or psi).

Gas Laws

If you had air or any other gas enclosed in a chamber equipped with a movable piston, you could study the behavior of the gas under varying conditions. You could heat the gas and let it expand and move the piston, thus keeping the pressure constant; you could increase the pressure and keep the temperature constant to see how the density would be affected; or you could vary the temperature and the density simultaneously to see how the pressure would be affected. The relationship of density, pressure, and temperature is expressed under the laws of Boyle, Charles, and Dalton, and in one other law known as the General Gas Law.

BOYLE'S LAW. Boyle's law states that if *the temperature remains constant, the density of any gas is directly proportional to the pressure*. This relationship may be expressed mathematically as follows:

$$\frac{\rho_1}{\rho_2} = \frac{P_1}{P_2} \tag{32}$$

where ρ_1 and P_1 represent one condition of density and pressure and ρ_2 and P_2 represent the other condition of density and pressure of the same sample of gas. In other words, *if the pressure is doubled, the density is doubled.*

Example: The density of the air is .002378 slugs/ft^3 when the pressure is 14.69 psi and the temperature is 15° C. If the temperature remains constant, find the density if the pressure drops to 14.27 psi.
Substituting in the equation, you obtain

$$\frac{.002378}{\rho_2} = \frac{14.69}{14.27}$$

Therefore,

$$\rho_2 = \frac{.002378 \times 14.27}{14.69} = \frac{.03393406}{14.69} = .002310 \text{ slugs/ft}^3$$

Notice that as the pressure dropped from 14.69 psi to 14.27 psi, the density decreased from .002378 slugs/ft^3, to .002310 slugs/ft^3, while the temperature remained constant at 15° C. This

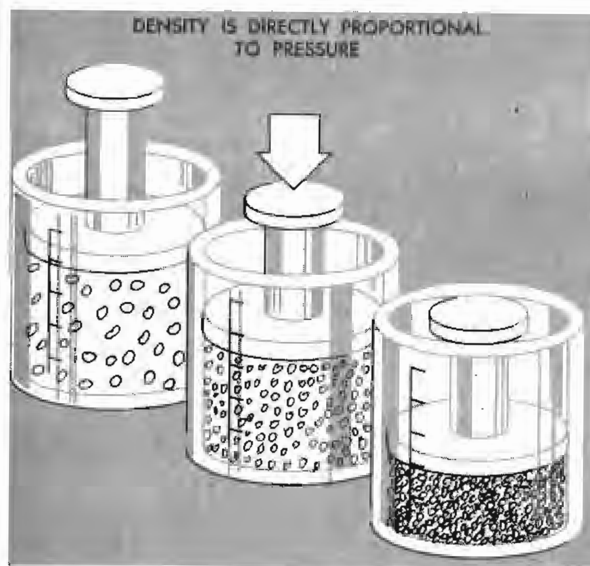

Figure 4-5. Density Pressure Relationship

example has illustrated that the density and pressure of any gas are directly proportional when the temperature remains constant. (See figure 4-5.)

CHARLES' LAW. Charles' law states that *if the pressure remains constant, the density of a gas is inversely proportional to the absolute temperature.* This relationship is expressed by the mathematical proportion:

$$\frac{\rho_1}{\rho_2} = \frac{T_2}{T_1} \qquad (33)$$

Example: The density of the air is .001756 slugs/ft³ when the pressure is 9.90 psi and the temperature is −5° C. If the pressure remains constant, find the density if the temperature drops to −20° C.

First convert the temperature to Kelvin

$T_1 = -5°$ C, or $T_1 = -5°$ C + 273
$= 268°$ Kelvin
$T_2 = -20°$ C, or $T_2 = -20°$ C + 273
$= 253°$ Kelvin

Substituting in the equation, we obtain

$$\frac{.001756}{\rho_2} = \frac{253}{268}$$

Therefore,

$$\rho_2 = \frac{.001756 \times 268}{253}$$

$$= \frac{.470608}{253}$$

$$= .001860 \text{ slugs/ft}^3$$

This example shows that the density of a gas is inversely proportional to the absolute temperature when the pressure remains constant.

GENERAL GAS LAW. Charles' and Boyle's Laws may be combined into a single relationship, which considers the variation of both the temperature and the pressure. This combination is called the General Gas Law, and it is expressed mathematically by the following equation:

$$\frac{\rho_1 T_1}{P_1} = \frac{\rho_2 T_2}{P_2} \qquad (34)$$

where the letters have their usual meanings. With this equation, given initial conditions of temperature, pressure and density we can determine all the possible combinations of temperature, pressure and density which the sample can assume. Knowing two of the final values we can calculate the third.

Example: If a charge is taken into a cylinder of a reciprocating engine and at the end of the compression event the pressure is 120 psi, the temperature is 127° C and the density is 0.018 slug/ft³, what is the force in the piston after combustion if the temperature reaches 2127° C, the burning occurs at constant volume (same density), and the piston area is 100 in²

$\rho_1 = 0.018$
$T_1 = 127°$ C $= 400°$ K
$P_1 = 120$ psi
$\rho_2 = 0.018$
$T_2 = 2127°$ C $= 2400°$ K
$P_2 = ?$

Therefore,

$$\frac{0.018 \times 400}{120} = \frac{0.018 \times 2400}{P_2}$$

$$\text{or } P_2 = \frac{0.018 \times 2400 \times 120}{0.018 \times 400}$$

$$= 720 \text{ psi}$$

$$\text{but } F = P \times A$$

$$\text{or } F = 720 \times 100$$

Therefore the force on the piston is 72,000 pounds. This force on the top of the piston actually does the work.

The gas equation can be simplified by calculating the value of $\frac{\rho_1 T_1}{P_1}$ for standard conditions. This value is a constant for each gas and can be used at all times since the above equation is valid. The equation then becomes:

$$\rho = \frac{KP}{T}$$

where K is a constant for a particular gas, P is pressure, and T is temperature.

Example: Find the density of the air in slugs per cubic foot when the atmospheric pressure is 12.65 psi and the temperature 0° C. The constant (K) for air is .0467.

Convert the temperature to Kelvin. Since the temperature is 0° C, the corrected temperature is 273° K. Substituting the values in the General Gas Law,

$$\rho = \frac{KP}{T}$$
$$= \frac{.0467 \times 12.65}{273}$$
$$= \frac{.5907558}{273}$$
$$= .002165 \text{ slugs/ft}^3$$

The General Gas Law will be applied later in the development of the Density Altitude chart. This chart is used extensively in flight engineering practices.

DALTON'S LAW OF PARTIAL PRESSURES. Dalton's law of partial pressures can be stated as follows: *If several gases, not reacting chemically upon each other, are introduced into the same container, the pressure of the resulting mixture is equal to the sum of the pressures which would be observed if each of the gases were separately enclosed in that container.*

To illustrate this law, let us consider a sample of air, in a container, which is a mixture of nitrogen, oxygen, and small quantities of carbon dioxide, argon, krypton, and other gases. Each gas exerts a pressure proportional to the amount present. The sum of these pressures is the total pressure of the sample. This may be expressed by the equation

$$P = P_N + P_O + P_{CO_2} + P_A + P_{Kr} + \ldots\ldots$$

Where

P_N represents the pressure of nitrogen.

P_O represents the pressure of oxygen.

P_{CO_2} represents the pressure of carbon dioxide.

P_A represents the pressure of argon.

P_{Kr} represents the pressure of krypton.

Suppose additional CO_2 were added to the sample. The pressure exerted by the CO_2 would, of course, increase. This would increase the total pressure of the sample.

Temperature Scales

In any temperature scale, it is necessary to define at least two fixed points on the scale, then divide the space between the fixed points into equal increments. The two fixed points commonly used are the temperature at which pure ice melts, and the temperature at which pure water boils under standard barometric pressure (76 cm Hg). On the two common thermometers used today, the *Fahrenheit* and the *Centigrade (celsius)*, these fixed points are 32° and 212° F, and 0° and 100° C, respectively. On the two absolute scales, the *Rankine* and the *Kelvin*, the scales differ from the regular Fahrenheit and Centigrade scales only in position of the zero point, the divisions being the same as on each respective scale.

The zero point is the temperature at which theoretically there is no trace of heat. This point was established as a result of the gas law, not stated earlier, which relates the variation of volume of a sample to the variation of temperature. The Kelvin and Rankine scales are normally used only in scientific work when dealing with very high or very low temperatures and especially in computations involving the laws of gases. Figure 4-6 shows a comparison of the four scales.

The zero point on the Rankine and Kelvin scales is equal to —459.4° on the Fahrenheit, and —273° on the Centigrade scale. Therefore, to change Fahrenheit to Rankine temperature, add 459.4° to the Fahrenheit reading, and to change Centigrade to Kelvin, add 273° to the Centigrade reading. To convert from Centigrade to Fahrenheit, or vice versa, use the following equations:

$$F = 1.8C + 32, \text{ or } F = 9/5C + 32 \qquad (35)$$

$$C = \frac{F - 32}{1.8} \text{ or } C = 5/9\,(F - 32) \qquad (36)$$

Figure 4-6 provides a convenient temperature conversion chart.

Moisture Content of Air

In the troposphere, the air is never completely dry. It contains moisture in three forms—*solid, liquid,* and *water vapor (gas).* As a result of evaporation, the troposphere always contains some moisture in the form of water vapor. The water vapor in the air does *not* consist of tiny particles of liquid or solid held in suspension as in the case of clouds, but it is an invisible vapor, which is as truly gaseous as the air with which it is mixed. Moreover, it obeys the gas laws. Since the water vapor replaces molecules of dry air and the water vapor weighs less than dry air, any given volume of moist air will weigh less (be less dense) than an equal volume of dry air.

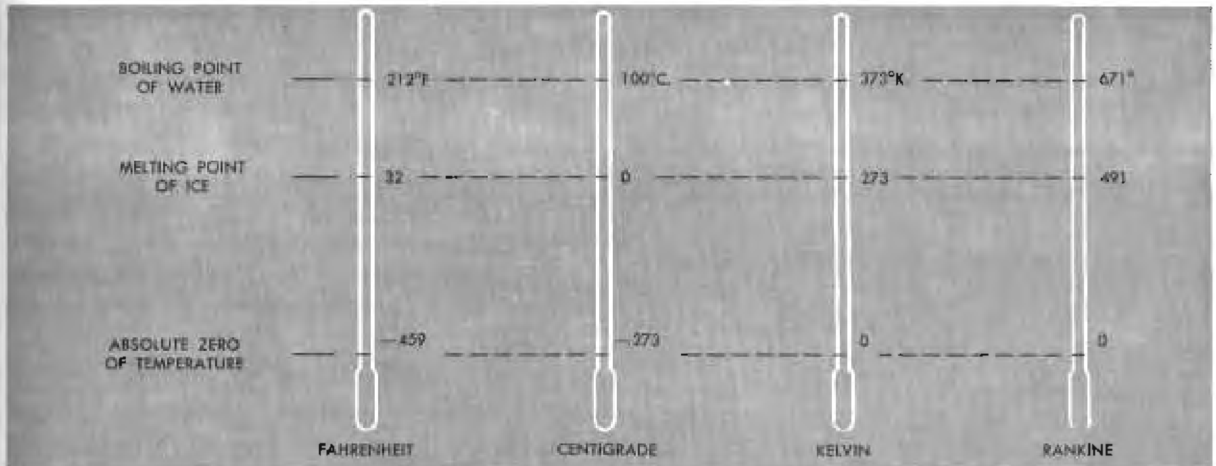

Figure 4-6. Comparison of Standard Temperature Scales

The water vapor content of the air is called *humidity.* The amount of water vapor in the air can be expressed in several ways, one of which is called *absolute humidity* and another of which is called *relative humidity.*

ABSOLUTE HUMIDITY. *Absolute humidity is the density of the water vapor in the air.* It is usually expressed in grams per cubic meter or in pounds per cubic foot. The amount of water vapor that can be present in the air is almost entirely dependent upon the temperature. The higher the temperature, the more water vapor the air is capable of holding. When the air has all the water vapor it can hold, it is said to be *saturated.*

RELATIVE HUMIDITY. *Relative humidity is the ratio of the actual amount of water vapor present in the air to the amount required to saturate the air.* This ratio is multiplied by 100 and expressed as a percentage. Suppose for example, that a weather report were to include the information that the temperature is 75° F and the relative humidity is 56%. This indicates that the air holds 56% of the water vapor required to saturate it at 75° F. If the temperature should drop, the relative humidity would increase because less water vapor would be required to saturate the air at the lower temperature.

DEWPOINT. The *dewpoint is the temperature at which air, being cooled at constant pressure, becomes saturated.* From this definition you can see that the dewpoint can never be higher than the temperature. If the air temperature drops to its dewpoint, visible condensation, such as fog, rain, drizzle, low clouds, and the like, occur.

If you wear glasses, you have probably had the experience of leaving the cold and going into a warm room and having your glasses "fog up." This happened because the temperature of the glasses was below the dewpoint temperature of the air in the room. The air immediately in contact with the glasses was chilled below the original dewpoint, and consequently the water formed. This demonstrates how the dewpoint is determined. The temperature at which condensation just begins to form on an object that is being cooled is the dewpoint.

VAPOR PRESSURE. The term *vapor pressure* is defined as *the pressure exerted by the water vapor in the atmosphere.* There is a direct relationship between vapor pressure and dewpoint, because for a given condition the dewpoint is determined by the amount of water vapor in the air.

WET- AND DRY-BULB TEMPERATURES. Vapor pressure and humidity may be determined from charts based on wet- and dry-bulb temperatures. The *dry-bulb temperature* is obtained from an ordinary thermometer. The *wet-bulb temperature* is obtained from a thermometer which has the bulb covered with a thin piece of wet cloth.

Because of evaporation of the moisture from the wet cloth, the wet-bulb reads lower than the dry-bulb thermometer. There is a greater difference in readings between the two as the rate of evaporation becomes more rapid. The rate of evaporation is dependent upon the degree of sat-

STANDARD ALTITUDE TABLE

Standard Sea Level Air:

$T = 15^{\circ}C.$ $W = 0.07651$ lb/cu ft $\rho_o = 0.002378$ slugs/cu ft

$P = 29.921$ in. of Hg 1 in. of Hg = 70.732 lb/sq ft = 0.4912 lb/sq in.

This table is based on NACA Technical Report No. 218 $a_o = 1116$ ft/sec

Altitude Feet	Density Ratio ρ/ρ_o	$\frac{1}{\sqrt{\sigma}}$	Temperature Deg C	Temperature Deg F	Speed of Sound Ratio a/a_o	Pressure In. of Hg	Pressure Ratio P/Po
0	1.0000	1.0000	15.000	59.000	1.0000	29.92	1.0000
1000	0.9710	1.0148	13.019	55.434	0.997	28.86	0.9644
2000	0.9428	1.0299	11.038	51.868	0.993	27.82	0.9298
3000	0.9151	1.0454	9.056	48.301	0.990	26.81	0.8962
4000	0.8881	1.0611	7.075	44.735	0.986	25.84	0.8636
5000	0.8616	1.0773	5.094	41.169	0.983	24.89	0.8320
6000	0.8358	1.0938	3.113	37.603	0.979	23.98	0.8013
7000	0.8106	1.1107	1.132	34.037	0.976	23.09	0.7716
8000	0.7859	1.1280	-0.850	30.471	0.972	22.22	0.7427
9000	0.7619	1.1456	-2.831	26.904	0.968	21.38	0.7147
10,000	0.7384	1.1637	-4.812	23.338	0.965	20.58	0.6876
11,000	0.7154	1.1822	-6.793	19.772	0.962	19.79	0.6614
12,000	0.6931	1.2012	-8.774	16.206	0.958	19.03	0.6359
13,000	0.6712	1.2206	-10.756	12.640	0.954	18.29	0.6112
14,000	0.6499	1.2404	-12.737	9.074	0.950	17.57	0.5873
15,000	0.6291	1.2608	-14.718	5.507	0.947	16.88	0.5642
16,000	0.6088	1.2816	-16.699	1.941	0.943	16.21	0.5418
17,000	0.5891	1.3029	-18.680	-1.625	0.940	15.56	0.5202
18,000	0.5698	1.3247	-20.662	-5.191	0.936	14.94	0.4992
19,000	0.5509	1.3473	-22.643	-8.757	0.932	14.33	0.4790
20,000	0.5327	1.3701	-24.624	-12.323	0.929	13.75	0.4594
21,000	0.5148	1.3937	-26.605	-15.890	0.925	13.18	0.4405
22,000	0.4974	1.4179	-28.586	-19.456	0.922	12.63	0.4222
23,000	0.4805	1.4426	-30.568	-23.022	0.917	12.10	0.4045
24,000	0.4640	1.4681	-32.549	-26.588	0.914	11.59	0.3874
25,000	0.4480	1.4940	-34.530	-30.154	0.910	11.10	0.3709
26,000	0.4323	1.5209	-36.511	-33.720	0.906	10.62	0.3550
27,000	0.4171	1.5484	-38.493	-37.287	0.903	10.16	0.3397
28,000	0.4023	1.5768	-40.474	-40.853	0.899	9.720	0.3248
29,000	0.3879	1.6056	-42.455	-44.419	0.895	9.293	0.3106
30,000	0.3740	1.6352	-44.436	-47.985	0.891	8.880	0.2968
31,000	0.3603	1.6659	-46.417	-51.551	0.887	8.483	0.2834
32,000	0.3472	1.6971	-48.399	-55.117	0.883	8.101	0.2707
33,000	0.3343	1.7295	-50.379	-58.684	0.879	7.732	0.2583
34,000	0.3218	1.7628	-52.361	-62.250	0.875	7.377	0.2465
35,000	0.3098	1.7966	-54.342	-65.816	0.871	7.036	0.2352
36,000	0.2962	1.8374	-55.000	-67.000	0.870	6.708	0.2242
37,000	0.2824	1.8818	-55.000	-67.000	0.870	6.395	0.2137
38,000	0.2692	1.9273	-55.000	-67.000	0.870	6.096	0.2037
39,000	0.2566	1.9738	-55.000	-67.000	0.870	5.812	0.1943
40,000	0.2447	2.0215	-55.000	-67.000	0.870	5.541	0.1852
41,000	0.2332	2.0707	-55.000	-67.000	0.870	5.283	0.1765
42,000	0.2224	2.1207	-55.000	-67.000	0.870	5.036	0.1683
43,000	0.2120	2.1719	-55.000	-67.000	0.870	4.802	0.1605
44,000	0.2021	2.2244	-55.000	-67.000	0.870	4.578	0.1530
45,000	0.1926	2.2785	-55.000	-67.000	0.870	4.364	0.1458
46,000	0.1837	2.3332	-55.000	-67.000	0.870	4.160	0.1391
47,000	0.1751	2.3893	-55.000	-67.000	0.870	3.966	0.1325
48,000	0.1669	2.4478	-55.000	-67.000	0.870	3.781	0.1264
49,000	0.1591	2.5071	-55.000	-67.000	0.870	3.604	0.1205
50,000	0.1517	2.5675	-55.000	-67.000	0.870	3.436	0.1149

Figure 4-7. Standard Altitude Table

uration of the air. The wet-bulb thermometer must be ventilated so that the air is properly sampled to obtain an accurate reading. This is accomplished by mounting both the wet- and dry-bulb thermometers on a frame, which can be hand-rotated or slung around a pivot to attain the desired change of air around the wet-bulb.

If the air is saturated, no evaporation takes place and the wet- and dry-bulb temperatures are the same.

Effect of Humidity on Reciprocating Engine Performance

Humidity affects the performance of an aircraft. In flight at cruising power, the effects are small, so they are not taken into consideration. During takeoff, however, humidity decreases the power output of the engines, and the greater the humidity, the less the power output. Two things are done to compensate for the effects of humidity on takeoff performance. Since humid air is less dense than dry air, the allowable takeoff gross weight is generally reduced for operation in areas which are consistently humid. Secondly, because power output is decreased by humidity, the manifold pressure must be increased above that recommended for takeoff in dry air in order to obtain the required power output.

Flight crews are responsible for compensating for power loss due to humidity. They may make compensations by using data obtained from the control tower. These data are used in conjunction with a chart plotted for that purpose. There are several types of charts in use. Some merely show the expected reduction in power due to humidity; others show the increase in manifold pressure that would be necessary to restore full takeoff power. These charts may be plotted in terms of humidity, vapor pressure, dewpoint, or wet- and dry-bulb temperatures. Humidity does not greatly affect *turbine engines*.

STANDARD ATMOSPHERE CHART

For purposes of all computations, which include meteorological parameters, a standard atmosphere has been defined. Three basic assumptions based on observed data are made. They are a sea-level pressure (29.92″ Hg), sea-level temperature (15° C), and a temperature decrease with altitude of 6.5° C per kilometer up to the tropopause. From these assumptions the pressure and temperature at each height are mathematically defined and the general gas law allows us to calculate the density at each height.

The conditions for each height are shown on a Standard Altitude Table, figure 4-7. The table is also called the Standard Day Chart and lists average values for temperature, pressure, and density of the air at various altitudes up to 50,000 feet. The purpose of the chart is to provide constant values for computation purposes, and it is the basis for aircraft performance charts and data. Above approximately 36,000 feet, the assumed height of the tropopause, the assumption about the temperature change with height changes to one of constant temperature. At higher elevations this assumption changes again, but all changes are defined mathematically.

CHAPTER 5

Temperature, Altitude, Airspeed

In the previous chapter, the structure and behavior of the atmosphere was discussed. Now it becomes necessary, as a requirement for precision flight engineering, to "measure" the atmosphere when the aircraft is in flight. This measurement involves airspeed, temperature, and altitude. Consequently, we shall first describe the instruments used to make these measurements: the *temperature gage,* the *altimeter,* and the *airspeed indicator.*

TEMPERATURE GAGE

Several types of temperature gages are used in the Air Force. One of these, the bimetallic thermometer, is identified as a free air temperature gage in figure 5-1. This unit consists of a stainless steel stem which projects into the airstream, and a head which contains the pointer and scale. The bimetallic element consists of two dissimilar metals fused together. Variations in heat cause the metals to expand and contract, but the different metals expand and contract at different rates and this difference causes the element to actuate the pointer. The scale is calibrated in degrees (C) (Celsius) and reads from −60° C to +50° C in increments of 2°.

Like other instruments, temperature gages are subject to error. One error, known as *scale error,* is caused by slight errors in calibration. Another error is *heat of compression error.* The element is installed immediately outside the fuselage in the airstream, and therefore is rushing through the air at the speed of the aircraft. This rapid movement of air around the sensitive element produces compression and friction (absorption of kinetic energy by temperature sensing, element), causing the thermometer to indicate a temperature higher than the actual temperature of the air. Heat of compression correction is always a negative value and is always subtracted from the thermometer reading. The amount of heat compression error depends on the true airspeed of the aircraft. As airspeed increases, the error increases.

The corrections that must be made for errors at different airspeeds have been determined and can be extracted from charts in the flight performance section of the TO pertaining to the applicable aircraft. The use of this type of correction factor is discussed fully later in this chapter.

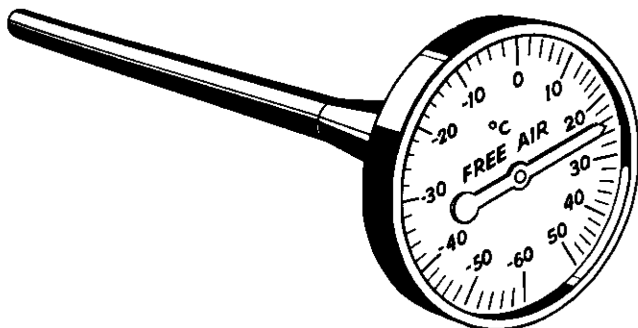

Figure 5-1. Free Air Temperature Gage

ALTITUDE AND THE ALTIMETER

Altitude may be defined as the *vertical distance above a point or plane used as a reference.* It follows, then, that there may be as many kinds of altitudes as there are reference planes from which to measure. These are: true altitude, absolute altitude, and pressure altitude as illustrated in figure 5-2.

True altitude is the height measured from mean sea level, *absolute altitude* is the height measured from the terrain directly below the aircraft, and

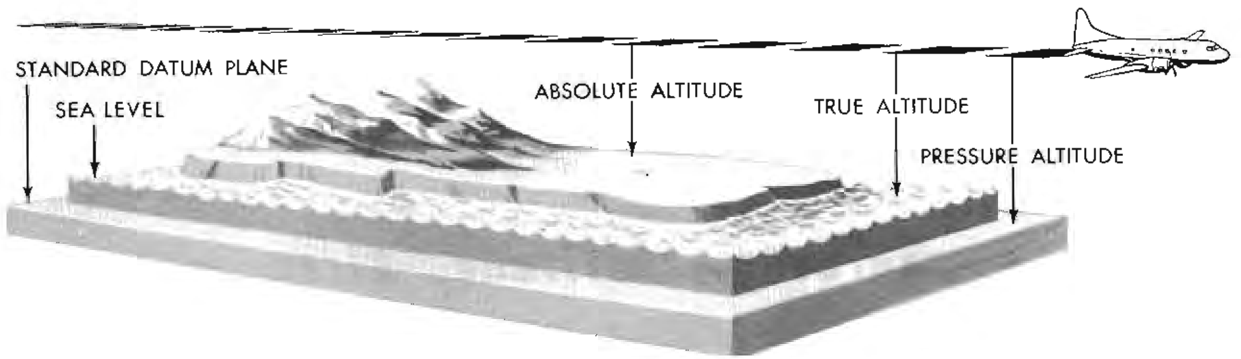

Figure 5-2. Types of Altitude

pressure altitude is the height in a standard atmosphere where the actual existing outside air pressure should occur. Pressure altitude, as the name implies, is altitude measured by determining existing air pressure. The altitude-measuring instrument is the *altimeter,* the internal mechanism of which is an aneroid *barometer* that responds to hanges in air pressure.

There are two types of barometers used to measure air pressure, the *mercury* and *aneroid.* The mercury barometer is used in weather stations while the aneroid is used in other places as well.

Mercury Barometer. The principle is shown in figure 5-3, *Atmospheric pressure.* Under standard conditions at sea level, the pressure of the air column raises the column of mercury 29.92 inches. In other words, the pressure at the bottom of an

Figure 5-3. Atmospheric Pressure

air column one-inch square extending to the top of the atmosphere is the same as that at the bottom of a column of mercury one-inch square and 29.92 inches high. Since one cubic inch of mercury weighs 0.491 pounds, 29.92 cubic inches weighs 14.69 pounds. Under standard conditions—that is, at 40° latitude, at sea level, with perfectly dry air—the atmosphere has a pressure of 14.69 pounds per square inch. This is called a pressure of *one atmosphere.*

Figure 5-3 also shows the comparative heights of mercury, water, and air that produce a pressure of one atmosphere (14.7 psi). Atmospheric pressure is sometimes given in inches of mercury and sometimes in pounds per square inch. To convert from inches of mercury to lb/sq in. multiply by 0.491. Thus, a pressure of 29 inches of mercury (written 29″ Hg) is a pressure of 14.2 lb/in^2.

Aneroid Barometer. The all-mechanical aneroid barometer mechanism is more practical for use in aircraft than the mercury type because the aneroid barometer contains no liquid and is much smaller. The primary unit of the mechanism is the aneroid, which is a sealed corrugated-metal unit that has been partially evacuated (some of the air pumped out). A typical aneroid mechanism is shown in figure 5-4. Atmospheric air enters the case through the pressure entrance and surrounds the aneroid. As the altitude increases (lower air pressure), the aneroid expands, moving the pointer to a higher reading. As the altitude decreases (higher air pressure) the aneroid contracts moving the pointer to a lower reading. Aneroid action is transmitted to the pointer through the rocker arm, sector gear, and pinion gear.

Density Altitude

Density altitude is a calculated altitude obtained by correcting pressure altitude for temperature. In the *Density Altitude Chart,* figure 5-5, the outside air temperature, in degrees Celsius, is represented by the vertical lines, and the values are located at the bottom of the chart. At the left margin of the chart is the density altitude in thousands of feet. The pressure altitude lines slant upward from the left to the right of the chart. The *Standard Day, Hot Day,* and the *Alaska Cold Day lines* extend from the lower right section of the chart upward to the left.

To find the density altitude, enter the chart with the outside air temperature; follow the temperature line to the point where it intersects the pressure altitude line, and from this point go horizontally to the left margin to get the value for density altitude. For example, if the temperature at a pressure altitude of 15,000 feet is −10° C, the density altitude is 15,600 feet.

Seldom are conditions such that the pressure altitude and the density altitude are the same. Using the same pressure altitude as in the example above, 15,000 feet, the outside air temperature would have to be −15° with a density altitude of 15,000 feet.

The chart indicates that for a given altitude, as the outside air temperature decreases, the den-

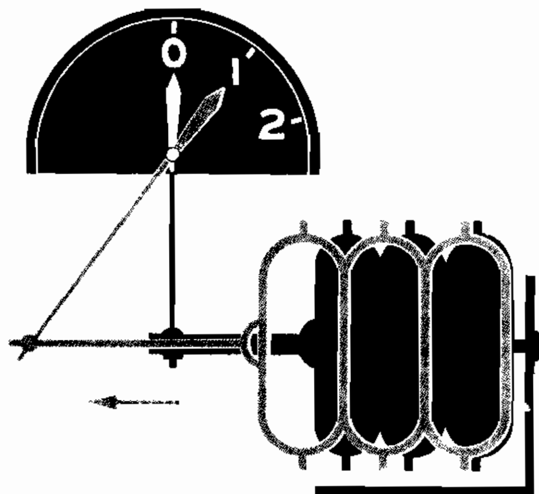

Figure 5-4. Aneroid Mechanism

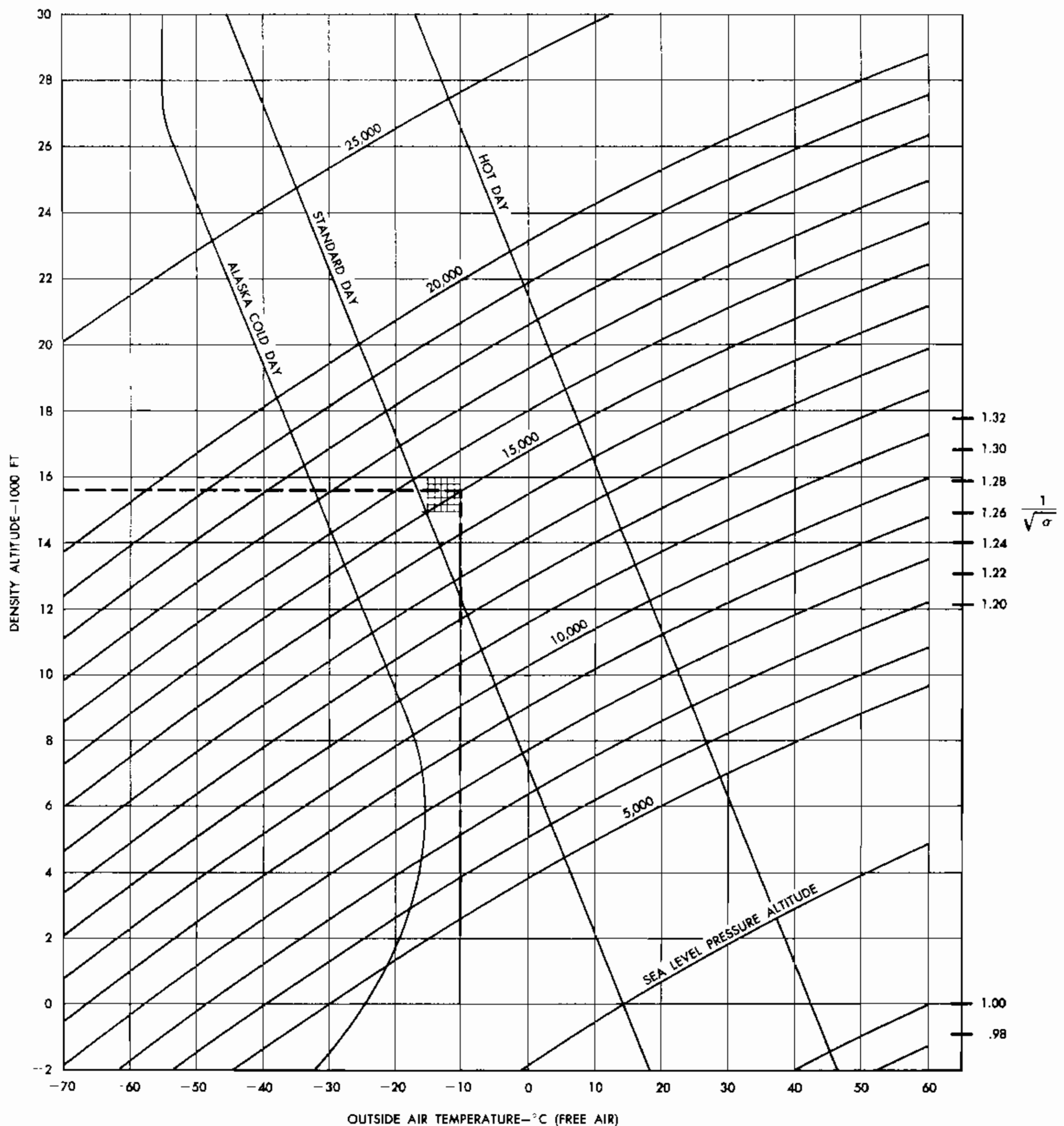

Figure 5-5. Density Altitude Chart

sity altitude decreases; and as the temperature increases, the density altitude increases.

The values listed along the right margin of the *Density Altitude Chart* are called "smoe" values and are discussed later in this chapter. These values are useful to the flight engineer in calculating the power required at altitude and correcting equivalent airspeed. By use of the smoe values, charts may be plotted for standard sea-level conditions, and then mathematically these conditions can be transformed to any altitude condition.

Altimeter Settings

The altimeter measures atmospheric pressure, and converts the pressure to feet on the scale. As shown in figure 5-6, *The Pressure Altimeter,* the instrument has three pointers, a pressure setting knob, and a "window."

The shortest pointer is the 10,000-foot pointer,

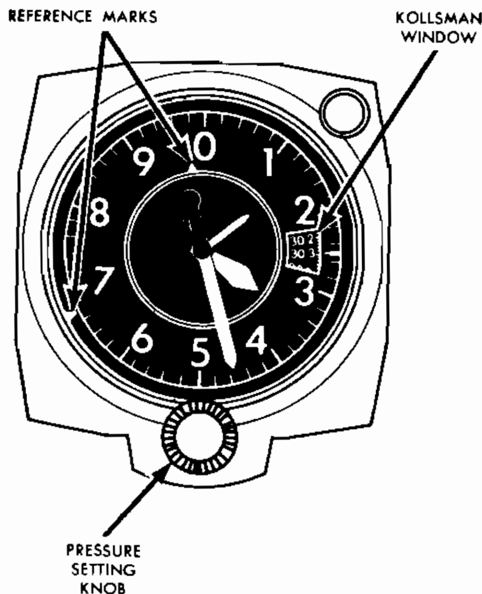

Figure 5-6. The Pressure Altimeter

the intermediate is the 1,000-foot pointer, and the longest is the 100-foot pointer. To illustrate, the reading on the altimeter shown is 13,460 feet. The altimeter is designed so that it indicates pressure altitude above sea level when a fictitious sea level pressure (not the pressure shown on a surface weather chart) is in the range of 28.00" to 31.00" Hg. The fictitious sea level pressure, called altimeter setting, is calculated to relate the standard atmosphere to existing atmospheric conditions.

Remember that the indication of the altimeter and the pressure acting on the aneroid are related according to the standard atmosphere. Pressure values other than altimeter setting can be set on the scale. *Whatever pressure is set in the window on the dial face represents a reference point. The altimeter then measures the pressure altitude difference between this point and the altitude where the aircraft is flying.* When the appropriate pressure is set in the window, the altimeter indicates pressure altitude above sea level or above the ground.

The pilot is interested mainly in his altitude above sea level so that the altimeter pointers will read field elevation when the aircraft touches down.

The engineer is also interested in pressure altitude. However, he is interested in knowing the position of the aircraft with respect to the standard atmosphere, therefore the scale in the altimeter window is set at 29.92" Hg, so the altimeter indicates altitude above the standard datum plane, not necessarily sea level, because the pressure at sea level usually differs from 29.92" Hg.

The engineer must use this system because all his charts are based on standard day conditions; therefore actual atmospheric condition (pressure, temperature, and density) must be corrected to standard atmospheric values (pressure altitude and density altitude) before information from the charts may be used.

Altitude Correction Card

The altimeter, like any other instrument, may have some inherent error. Therefore, altimeters are calibrated in a pressure chamber before they are installed in aircraft. The error at various indicated altitudes is determined, and the corrections are recorded on an *altitude correction card,* which is placed near the instrument on the panel. Before any corrections are made to obtain either true or absolute altitude, the correction card error must be taken into account.

AIRSPEED PHYSICS

Speed is defined as *rate of motion* or, in other words, *distance* traveled per unit of time. Speed is measured in statute miles per hour (mph) and knots (k) which are nautical miles per hour. The speed of an aircraft is measured by the airspeed indicator, which indicates the speed of the aircraft through the air mass, and not the speed in relation to the ground. Many corrections must be made to the indicated airspeed before the true airspeed through the air mass can be obtained. This section discusses the "types" of airspeed, the causes of errors, and the corrections that must be made.

Types of Airspeed

There are several "types" of airspeed associated with flight engineering. They are defined and explained briefly as follows. More detailed explanations are given later in this chapter.

- Indicated Airspeed (IAS)—reading on airspeed indicator.
- Basic Airspeed (BAS)—IAS corrected for instrument error.
- Calibrated Airspeed (CAS)—BAS corrected for errors in static pressure.

• Equivalent Airspeed (EAS)—CAS corrected for compressibility errors.

• True Airspeed (TAS)—EAS corrected for variations in air density.

• True Airspeed in Knots (TASK)—TAS ÷ 1.1152.

• Ground Speed (GS)—TAS or TASK corrected for wind velocity.

Airspeed and Kinetic Energy

Because air has density (mass), when it is in motion it has kinetic energy. The amount of the aerodynamic lift force that an airfoil can derive from an airstream is dependent upon the kinetic energy in the airstream, which is determined by the density (mass) and velocity of the airstream as follows:

$$\text{Kinetic energy} = \frac{\text{mass} \times \text{velocity}^2}{2}$$

The mass of the airstream is the amount of fundamental particles (the number of molecules) of which the airstream is composed. Mass is expressed in slugs, and the slugs per cubic foot in the atmosphere can be found on an ICAO table for any density altitude. The velocity of the airstream is the rate of motion per unit of time in reference to the airfoil over which it is flowing.

If an airfoil is to maintain a constant lift force, the kinetic energy in the airstream about the airfoil must be held constant. If the density of the airstream (the number of molecules per unit of volume, that is, mass) is decreased, such as is experienced with an increase in altitude, then the velocity of the airstream must be increased to maintain the same kinetic energy in the airstream. If the density of the airstream is increased (such as at low altitude), then the velocity must be decreased to maintain the same kinetic energy value.

The amount of the lift force that can be derived from an airstream is dependent upon the kinetic energy in the airstream; therefore, as the required value of the lift force changes, the kinetic energy value of the airstream must change.

The kinetic energy value in an airstream that is required to establish a certain lift force is expressed in miles per hour and is called the equivalent airspeed (EAS). The EAS is the most important factor in aircraft operation because all performance characteristics of the aircraft depend on it. For a particular gross weight, a specific EAS and only this EAS determines the lift, drag,

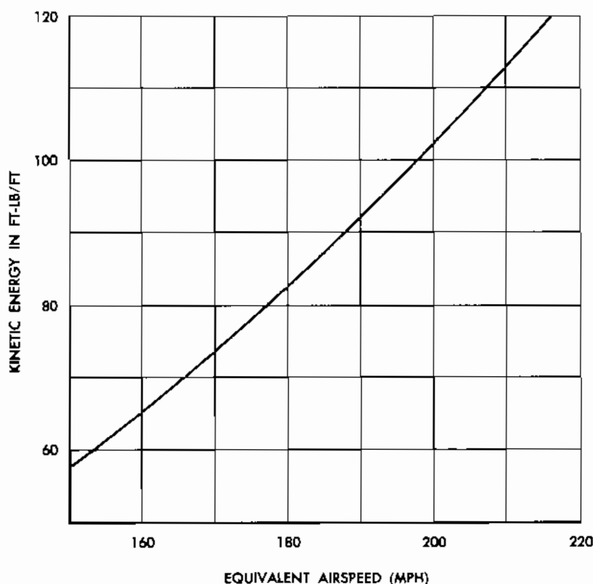

Figure 5-7. EAS vs. Kinetic Energy

specific range, altitude limit, and cooling requirements of the engines regardless of power settings and altitude.

In figure 5-7, the kinetic energy values for the normal operating ranges of multi-reciprocating engine aircraft are plotted against their representative expressions of EAS. Instead of kinetic energy units, however, the units are in terms of work that can be done. From this chart it can be found, for example, that an EAS of 180 mph is equivalent to that amount of kinetic energy which can do 82.5 ft-lbs of work for each cubic foot of air in the air stream. This is the maximum amount of energy that can be extracted from each cubic foot of air passing over the aircraft. This kinetic energy in the airstream determines the performance characteristics of the aircraft. Regardless of the density altitude at which the aircraft is flying, to obtain the same aircraft performance the airstream must possess the same kinetic energy value; that is, the EAS must remain the same at all altitudes so the aircraft will maintain the same performance characteristics.

As altitude increases, the mass density of the airstream decreases. Therefore, to maintain the same EAS the velocity of the airstream must be increased.

Example A: What is the kinetic energy in an airstream that has a velocity of 200 mph at sea level at standard day conditions?

1. Kinetic energy formula:

$$KE = \frac{Mass \times Velocity^2}{2}$$

2. From the density altitude table, the mass for air at sea level is found to be .002378 slugs per cubic foot.
3. Since the mass is stated in slugs per cubic foot, it is necessary to correct the velocity of 200 mph to an expression of velocity in feet per second; which is done by multiplying the velocity in mph by 1.467.

$$200 \text{ mph} \times 1.467 = 293.4 \text{ feet per second}$$

4. Substituting in the KE formula:

$$KE = \frac{.002378 \times 293.4^2}{2}$$

$$= \text{102.2 foot pounds per cubic foot of airflow}$$

Example B: What would be the velocity required at a density altitude of 15,000 feet to maintain the same kinetic energy in the airstream?
1. By rearranging the kinetic energy formula to solve for velocity:

$$Velocity^2 = \frac{KE \times 2}{Mass}$$

or

$$Velocity = \sqrt{\frac{KE \times 2}{Mass}} \quad (38)$$

2. From the density altitude table the density of the air at 15,000 feet is found to be .0014959 slugs per cubic foot.
3. Substituting in the formula for velocity:

$$Velocity = \sqrt{\frac{102 \times 2}{.0014959}} = 370 \text{ feet per second}$$

4. Correcting the velocity in feet per second to miles per hour by dividing by 1.467:

$$\frac{370 \text{ feet per second}}{1.467} = 251.7 \text{ miles per hour}$$

Examples A and B show that at a density altitude of 15,000 feet the airstream's velocity must be 251.7 mph for the airstream to possess the same kinetic energy that it had at sea level with a velocity of 200 mph. This increased airspeed is necessary because of the decrease in mass density at the 15,000-foot density altitude.

The velocity of the airstream is called *true airspeed,* abbreviated TAS when expressed in statute miles per hour or TASK when expressed in nautical miles per hour. It should be noted that TAS represents the velocity with which the airstream flows about the airfoils and does not necessarily represent the velocity of the aircraft. By definition then, TAS is the velocity of *the airstream in reference to the airfoil.*

In previous Example A, the TAS was given as 200 mph, which resulted in a kinetic energy of 102.2 foot pounds per cubic foot of airflow. From the EAS vs kinetic energy chart, we find that the kinetic energy value of 102.2 is represented by an EAS of 200 mph; thus EAS and TAS are of equal values at sea level on a standard day.

In previous example B, a TAS of 251.7 mph was required to establish a kinetic energy value of 102.2 at a 15,000-foot altitude. In other words, at a density altitude of 15,000 feet flying with a TAS of 251.7 mph the resultant EAS is 200 mph.

Relative Density

The relationship between EAS and TAS is merely a function of the variation in mass density of the atmosphere through which the aircraft is flying in reference to mass density of the atmosphere at sea level. This variation between mass density at flight altitude and sea level mass density is called *relative density* and is signified by the Greek letter σ (sigma). Relative density is found by dividing sea level standard day mass density (.002378) into the mass density of the flight altitude. The values for sigma for any density altitude can be found in the *Standard Altitude Table.*

In Example B, previously worked, the TAS was found for a known kinetic energy value by the formula

$$Velocity = \sqrt{\frac{KE \times 2}{Mass}}$$

This formula can be used to yield TAS directly in miles per hour rather than feet per second by substituting TAS for velocity, EAS for kinetic energy, and introducing the smoe factor, which gives

$$TAS = EAS \times \frac{1}{\sqrt{\sigma}} \quad (39)$$

Although the Greek letter sigma (σ) represents relative density, note that in the formula this term has been changed to 1 divided by the square root of sigma, expressed as

$$\frac{1}{\sqrt{\sigma}}$$

The reason for the changing of the term is purely mathematical, to simplify airspeed calculations. Two benefits are achieved: It becomes unnecessary to square the airspeed, and also the value of the new term is always a number greater than 1, rather than a decimal fraction.

Note: Because the reciprocal of the square root of sigma is so widely used in cruise control work, flight engineers have given it the nickname smoe, which is now an acceptable Air Force term.

By using smoe in the airspeed formula, the formula can be simply expressed as follows:

$$TAS = EAS \times \frac{1}{\sqrt{\sigma}}, \text{ or}$$

$$TAS = EAS \times \text{smoe}$$

Rearranged for EAS, the formula becomes

$$EAS = \frac{TAS}{\frac{1}{\sqrt{\sigma}}}, \text{ or}$$

$$EAS = \frac{TAS}{\text{smoe}} \qquad (40)$$

The values for smoe are listed on the *Density Altitude Chart* and the *Standard Altitude Table* for altitudes up to 50,000 feet.

Airspeed Indicating System

The airspeed indicating systems used on aircraft are designed to measure the kinetic energy value of the airstream, thus the airspeed indicator basically measures EAS. If there were no errors in the airspeed indicating system, nor errors in the method used to measure the airstream's mass and velocity, the airspeed indicator would actually read EAS. However, because of the errors in the system, the reading on the indicator is referred to as *indicated airspeed* (IAS).

In order to measure the kinetic energy of the airstream, the indicating system must measure the mass density of the air through which the aircraft is flying and the velocity of the airstream relative to the airfoil. These measurements are obtained by the aircraft pitot-static system. The static system measures the mass density of the air and the pitot system measures the velocity of the airstream. These two measurements are directed to the airspeed indicating instrument where, through the use of a diaphragm, mechanical linkage, and a pointer, the differential between these measurements is resolved into an expression of EAS.

In any mechanical system that is used to obtain and record measurements there are inherent errors due to friction of the moving parts. These errors, called *instrument error* or *calibration error*, must be compensated for before a true indication of the condition being measured can be found. The errors are determined for each individual instrument by various tests conducted by the manufacturer or in the field by bench checks. In the airspeed measuring system, the errors are recorded on an instrument correction calibration card which is installed (as illustrated) in the aircraft alongside the instrument.

To use the airspeed calibration (correction) card, shown in figure 5-8, first obtain a reading from the airspeed indicator. The reading taken directly from the instrument is called the indicated airspeed, or IAS. On the airspeed calibration card, find the IAS in the center column marked *Airspeed Reading*. In the column to the left opposite the IAS, read the corrected value in miles per hour, or read to the right and see the corrected value in nautical miles per hour. This corrected value, which is IAS corrected for instrument error, is called basic airspeed (BAS).

THE PITOT-STATIC SYSTEM. The design of pitot heads is such that only slight error occurs in the pitot system. The error in the pitot head is so small that only minor correction factors are computed for this system. For example, the system functions accurately up to an angle of about 10° between the pitot head and the relative

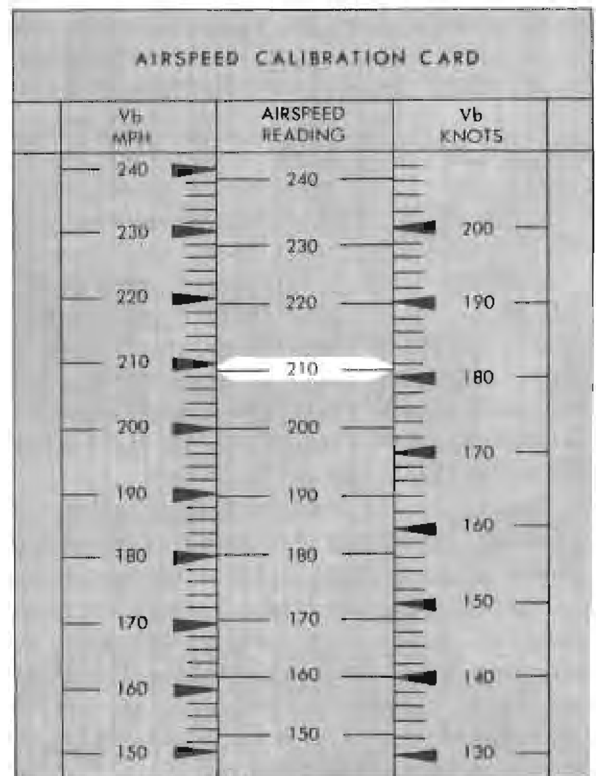

Figure 5-8. Airspeed Calibration Card

wind. If the angle is increased beyond 10°, as might occur during extreme crabbing, an appreciable error would result in the pitot system, because the airstream would be striking the pitot head at an angle too great to register the impact force of the airstream correctly.

The purpose of the static system is to sense the static pressure of the air through which the aircraft is flying. The static ports are located in the aircraft skin at points where the least amount of air turbulence occurs. These points are determined by wind tunnel tests.

AIRSPEED CORRECTION FACTORS

The need for the use of airspeed correction factors can better be comprehended if we first envision the ideal, though unattainable, conditions which would make such corrections unnecessary. Let us consider under what conditions the airspeed and finally the ground speed would be indicated accurately without the use of corrective procedures. First, the airspeed indicator would register pressure with perfect precision. Second, the angle of attack of the aircraft to the relative wind would be constant at all times to insure that the angle of the pitot tube to the relative wind would be constant. Third, there would be no variations in the compressibility of the air because of aircraft design or flight configuration. Fourth, the air would be at a given and constant density regardless of altitude. Let us now see why these conditions are unattainable.

Realistically, no instrument is perfect, and corrections must be made by use of data provided by the manufacturer to compensate for instrument inaccuracy. Then, of course, the angle of attack of the aircraft must be adjusted to compensate for the wide range of speed, weight, altitude, temperature, and air density factors. Several of these factors are interrelated, as you have learned. Air pressure, of course, varies greatly with altitude and temperature.

In the process of determining true airspeed and finally, the groundspeed, a series of corrections must be made. These corrections are as follows:

- Indicated Airspeed (IAS) is corrected for instrument error to determine Basic Airspeed (BAS).
- Basic Airspeed is corrected for errors in static pressure to determine Calibrated Airspeed (CAS).
- Calibrated Airspeed is corrected for compressibility to determine Equivalent Airspeed (EAS).
- Equivalent Airspeed is corrected for variations in air density to determine True Airspeed (TAS) in miles per hour.
- True Airspeed ÷ 1.1152 equals True Airspeed in Knots (TASK).
- True Airspeed in miles per hour or True Airspeed in Knots is corrected for wind velocity to determine groundspeed in miles per hour or knots, respectively.

The duties of the flight engineer in relation to the typical flight mission are detailed in Chapter 10.

CHAPTER 6

Flight Efficiencies

Fuel economy in engine operation is one of the principal aims of flight engineering. By proper choice of power settings, low specific fuel consumption may be attained. However, this is only the beginning of economical flight operation. The aircraft itself must be flown efficiently. This is not entirely the job of the pilot; it is up to the flight engineer to set up the power which enables the pilot to fly the aircraft most efficiently under the prevailing conditions. The engineer must, therefore, not only understand the relationship of engine operation to efficient flying, but he must also understand the relationship of aircraft aerodynamics to efficient flying. This chapter, in picturing this relationship, introduces certain principles of dynamics and aerodynamics and their applications.

The branch of physics which deals with motion due to forces and with forces due to motion is called *dynamics*. A special branch of physics which deals with air in motion and with motion of an object through the air is called *aerodynamics*. These two branches are broad technical fields, but in this manual only simple fundamentals, such as the existence and computation of lift and drag forces, determination of power requirements for level flight, propeller action, and an overall analysis of the factors making for economical flight are discussed.

THE FORCE OF AIR

An earlier chapter defined the term *force* as *any action which tends to produce, retard, or modify motion.* The "sea of air" through which aircraft fly has mass and inertia and is capable of exerting forces on any object moving through it. There are numerous forces acting on all parts of an aircraft, which are caused by *air resistance, gravity, friction,* and other factors. Consider a body moving through the air at a certain speed. There are four general forces present. One is the force the body exerts on the air when moving forward *(thrust).* In opposition to this is the force the air exerts on the body *(drag).* The other two forces are—the force of gravity *(pulling the body toward the earth),* and the force the body exerts in the opposite direction to keep itself aloft *(lift).*

Figure 6-1 shows that a body remains in the same condition (no acceleration) when all the opposing forces are equal; that is, the body is in a state of *equilibrium.* When any two opposing forces acting on the body are not equal, however, an acceleration results in the direction of the greater force. For example, in figure 6-2 you see another representation of forces acting on a body. The lengths of the arrows represent the respective magnitudes of the several forces, and the arrowheads point in the direction of the forces. The illustration shows that force A is equal to

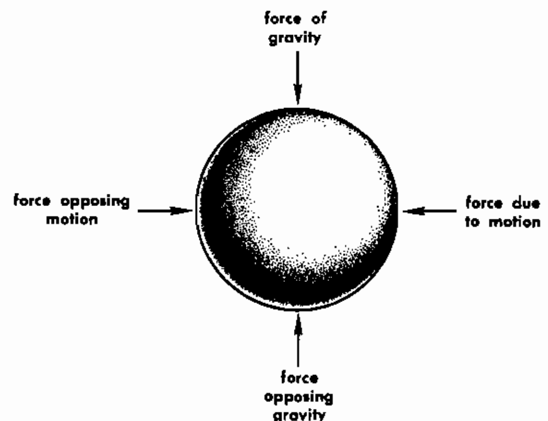

Figure 6-1. Equal Forces Acting on a Body

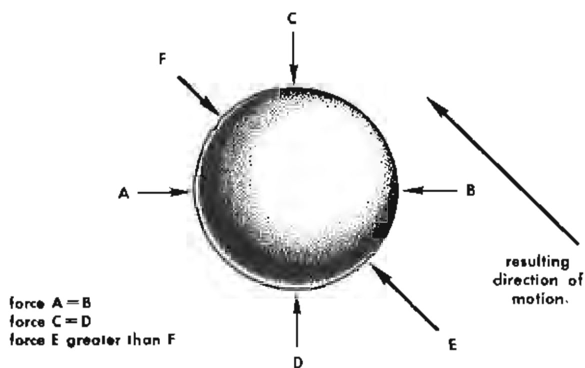

Figure 6-2. Unequal Forces Acting on a Body

and in the opposite direction to force B; that force C is equal to and opposite to force D; but that force E is greater than its opposing force F and, as indicated, the body moves in the direction of force E.

The preceding diagram exemplifies what is known as a *vector* representation of the forces acting on a body. Any number of forces may be shown by a vector representation and can be resolved or simplified into resultant forces to find what effect may result. Force diagrams of this type are used throughout this chapter.

AIRFLOW

Since air possesses mass and inertia, a stream of air moving at a certain velocity will, according to Newton's *first* law of motion, continue to move in the same direction at the same velocity until some outside force is exerted against it. For example, if a flat plate is held at a 90° angle against an airstream, the air that strikes the plate must change both its immediate direction and velocity to pass around the plate. The plate and the airstream exert the same force against each other, which is in accord with Newton's *third* law of equal and opposite reaction. This principle is used to change the direction of an aircraft in flight. The control surfaces of the aircraft apply forces to the air mass, and the air mass, in turn, applies equal and opposite forces to the aircraft. See figure 6-3.

When a flat plate is held up at an angle of 45° to the airstream, you will notice in the illustration that the airstream is turned downward. The position of the plate changes the direction of the air-

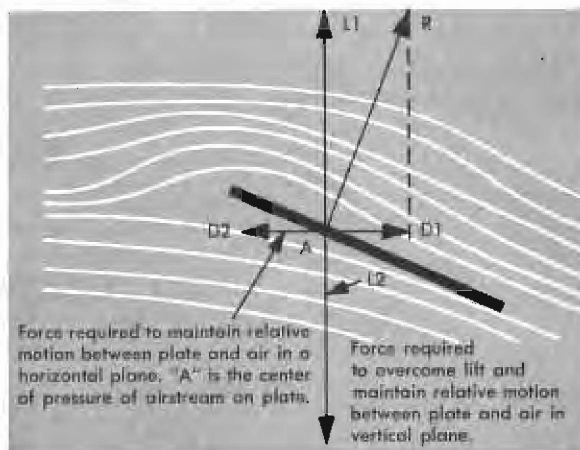

Figure 6-3. Airflow about an Inclined Plate

stream and reduces its velocity. Hence, the plate must apply a force on the air both downward and forward. The reaction to the air must be an equal pressure upward and backward as shown by vector AR. The vectors AL and AD, respectively, are the vertical and horizontal components of the airstream pressure against the plate. To maintain a balance of forces between the airstream and the plate, there must be downward force (AL_2) equal to that of the upward force (AL_1), and a forward force (AD_2) equal to the backward force (AD_1).

When the flat plate is held parallel to the airstream, as shown in the figure 6-4, the airstream lines separate at the leading edge, flow smoothly over the upper and lower surfaces, and reunite just back of the trailing edge. The little resistance of-

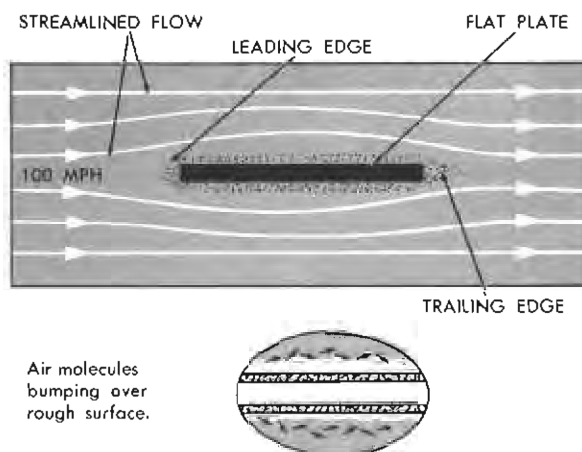

Figure 6-4. Airflow about a Thin Plate Held Parallel to the Airstream

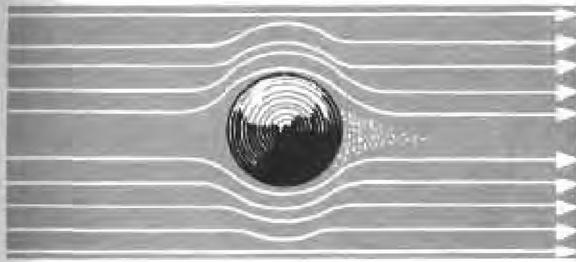

Figure 6-5. Airflow over a Sphere

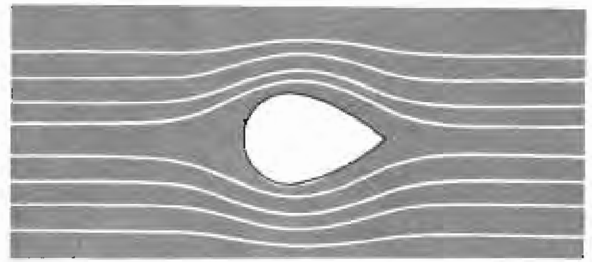

Figure 6-6. Airflow over a Streamlined Shape

fered by the flat place is largely skin friction caused by the air tending to cling to the surfaces. The small amount of drag that results from skin friction or boundary layer air will vary with the smoothness of the surfaces. When surface irregularities such as rivet heads, lapped joints, and so forth exist, the drag from skin friction is much greater, especially at high speed.

The airflow over a sphere is shown in figure 6-5. As the speed of the air increases, its increased momentum causes greater application of pressure on the leading edge of the sphere. This increase in pressure distorts the lines of air in such a way that they are unable to push together promptly at the rear of the sphere, thus creating a low-pressure area there. This low-pressure area causes burbling airflow and increased resistance of the sphere to the flow of air.

Figure 6-6 illustrates that the resistance imposed by the low-pressure area and burbling airstream has been reduced by building the area at the rear of the sphere to a point, thus filling in the burble space. As a result, the air flows smoothly over this additional surface, and resistance is thereby reduced for the same rate of airflow.

Thus far the discussion has dealt with the force and motion of air and its reaction to bodies that are placed in its path. It was shown that the shape of the body affects the flow of air. The next discussion concerns airfoils and how they are affected by the force of air.

AIRFOILS

An *airfoil* is a surface designed to obtain a desirable reaction from the air through which it moves. Thus, we can say that *any part of the aircraft which converts air resistance into a force useful for flight is an airfoil.* The blades of a propeller are so designed that when they rotate, their shape and position cause a higher pressure to be built up behind them than in front of them so that they will pull the aircraft forward. The profile of a conventional wing, shown in figure 6-7 is an excellent example of an airfoil. Notice that the top surface of the wing profile has greater curvature than the lower surface.

The difference in curvature of the upper and lower surfaces of the wing builds up the lift force. Air flowing over the top surface of the wing must reach the trailing edge of the wing in the same amount of time as the air flowing under the wing. To do this, the air passing over the top surface moves at a greater velocity than the air passing

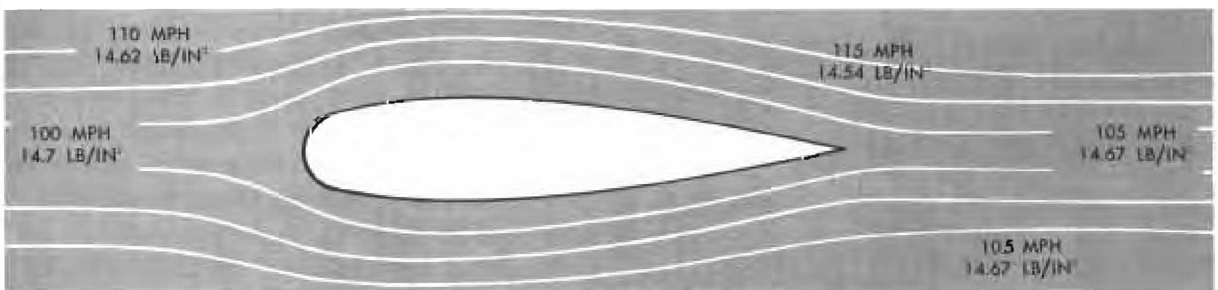

Figure 6-7. Airflow over a Wing Section

below the wing because of the greater distance it must travel along the top surface. This increased velocity, according to Bernoulli's principle, means a corresponding decrease in pressure on the surface. Thus, a pressure differential is created between the upper and lower surfaces of the wing, forcing the wing upward in the direction of the lower pressure.

The theoretical amount of lift of the airfoil at the velocity of 100 mph can be determined by sampling the pressure above and below the airfoil at the point of greatest air velocity. According to the illustration, this pressure is 14.54 pounds per square inch above the airfoil. Subtracting this pressure from the pressure below the airfoil, 14.67, gives a difference in pressure of 0.13 of a pound per square inch. Since there are 144 square inches in a square foot, multiply 0.13 by 144 and you find that each square foot of this wing lifts 18.72 pounds. From this, you can see that a small pressure differential across an airfoil section can produce a large lifting force. This lifting force is known as *induced lift,* and in subsequent illustrations is shown by a vector drawn perpendicular to the relative airstream. Within limits, lift can be increased by increasing the angle of attack, the wing area, the freestream velocity, or the density of the air, or by changing the shape of the airfoil.

Angle of Attack

Before beginning the discussion on *angle of attack* and its effect on airfoils, we shall first consider the terms, *chord* and *center of pressure.*

The chord of an airfoil or wing section is an imaginary straight line which passes through the section from the leading edge to the trailing edge, as shown in figure 6-8. The chord line provides one side of an angle which ultimately forms the angle of attack. The other side of the angle is formed by a line indicating the direction of the relative airstream. Thus, *angle of attack* is defined as *the angle between the chord line of the wing and the direction of the relative wind.* This is not to be confused with the *angle of incidence,* which is the angle between the chord line of the wing and the longitudinal axis of the aircraft.

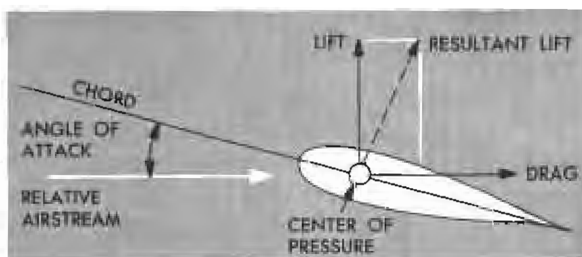

Figure 6-8. Positive Angle of Attack

From the previous discussion of airfoils, you should conclude that on each minute part of an airfoil or wing surface, a small force is present. This force is different in magnitude and direction from any forces acting on other areas forward or rearward from this point. It is possible to add all of these small forces mathematically, and the sum is called *resultant* force. This resultant force has magnitude, direction, and location, and can be represented as a vector, shown as "resultant lift" in figure 6-8. The point of intersection of the resultant force line with the chord line of the airfoil is called the *center of pressure.*

For small angles of attack, the resultant force is comparatively small. Its direction is upward and back from the vertical, and its center of pressure is well back from the leading edge. You should note from the illustrations that the center of pressure changes with the angle of attack, and that the resultant force line has an upward and backward direction. At positive angles of attack of 3° or 4°, the resultant force attains its most nearly vertical direction. Either increasing or decreasing the angle causes the direction of the resultant force to be farther from the vertical.

Effects of Varying Angles of Attack

Although the following discussion deals primarily with positive angles of attack, it begins with the airfoil position called *angle of zero lift* (angle of attack with zero lift). This angle is normally a negative angle of attack; that is, one which places the chord line of the airfoil below the line which represents the direction of relative airstream. This is shown in figure 6-9. The angle of zero lift is obtained when the resultant force line is exactly parallel to the relative wind line. At this angle, the force acting on the airfoil is entirely drag. This could be illustrated in a wind tunnel test by holding a wing section at the angle of zero lift and suddenly releasing it. Upon release of the wing section, it would neither lift nor fall, but would move straight rearward in the direction of the relative wind.

When the angle of attack is gradually increased

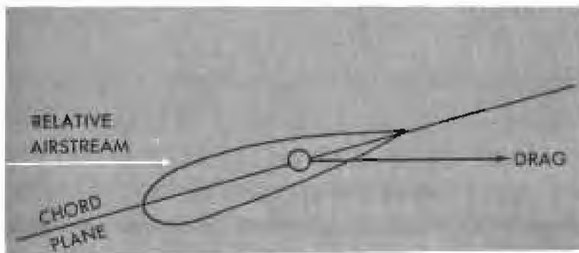

Figure 6-9. Negative Angle of Attack

toward a positive angle of attack, the lift component increases rapidly up to a certain point and suddenly begins to drop off. During this action, the drag component increases slowly at first and then rapidly as lift begins to drop off.

Finally, when the angle of attack increases to approximately 18° to 20° (on most airfoils) the air can no longer flow smoothly over the top wing surface because of the excessive change of direction required. This is the stalling angle of attack, sometimes called the burble point. At this point, turbulent airflow, which appears in small amounts near the trailing edge of the wing at lower angles of attack, suddenly spreads forward over the entire upper wing surface. See figure 6-10. The result is a sudden increase in pressure above the wing accompanied by a sharp loss of lift and a sudden increase in resistance or drag. These events show that Bernoulli's principle is true only in streamline or smooth airflow, and not in turbulent airflow. The center of pressure at the point of stall is at its maximum forward position, and as the wing stalls, the resultant force tilts sharply backward.

Wing Area

Wing area is measured in square feet and includes the part blanked out by the fuselage. Wing area is adequately described as the area of the shadow cast by the wing at high noon. The wing area of the C-124 is 2,510 square feet. Tests show that lift and drag forces acting on a wing are roughly proportional to the wing area. This means that if the wing area is doubled, all other variables remaining the same, the lift and drag created by the wing is doubled. If the area is tripled, lift and drag are tripled.

Shape of the Airfoil

The shape of the airfoil determines the amount of turbulence or skin friction that it will produce. The shape of a wing consequently affects the efficiency of the wing.

Turbulence and skin friction are controlled mainly by the *fineness ratio,* which is defined as the ratio of the chord of the airfoil to the maximum thickness. If the wing has a high fineness ratio, it is a very thin wing. A thick wing has a low fineness ratio. A wing with a high fineness ratio produces a large amount of skin friction. A wing with a low fineness ratio produces a large amount of turbulence. The best wing is a compromise between these two extremes to hold both turbulence and skin friction within desired tolerances.

Efficiency of a wing is measured in terms of the *lift over drag (L/D) ratio.* This ratio varies with

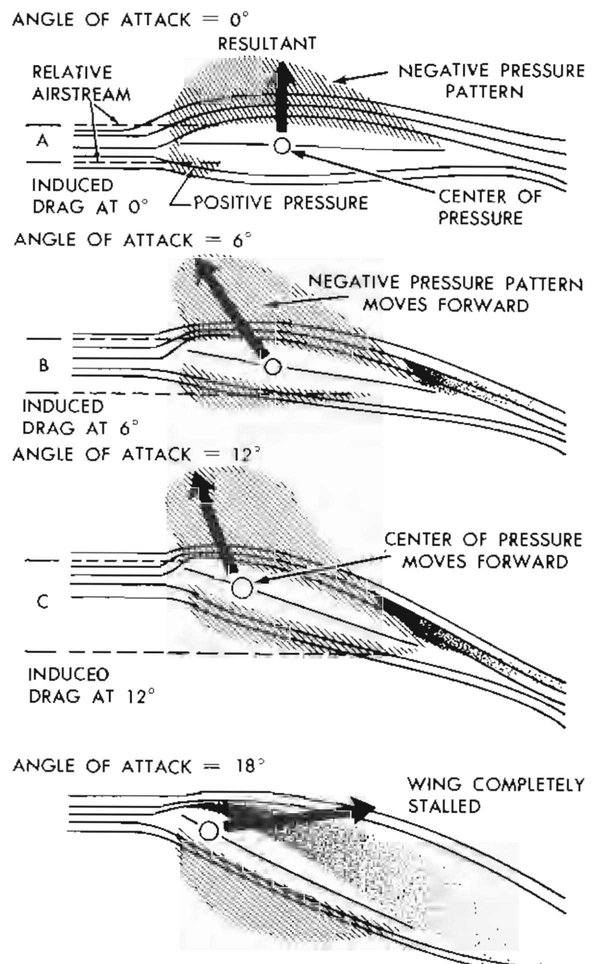

Figure 6-10. Effect of Increasing Angle of Attack

the angle of attack but reaches a definite maximum value for some particular angle of attack. At this peak the wing has reached its maximum efficiency. The shape of the airfoil is the factor which determines the angle of attack at which the wing is most efficient; it also determines the degree of efficiency. Research has shown that the most efficient airfoils for general use have the maximum thickness occurring about one-third of the way back from the leading edge of the wing.

High-lift wings and high-lift devices for wings have been developed by shaping the airfoils to produce the desired effect. The amount of lift produced by an airfoil will increase with an increase in wing *camber*. Camber refers to the curvature of an airfoil above and below the chord line surface. Upper camber refers to the upper surface, lower camber to the lower surface, and mean camber to the mean line of the section. Camber is positive when departure from the chord line is outward, and negative when it is inward. Thus, high-lift wings have a large positive camber on the upper surface and a slight negative camber on the lower surface. Wing flaps cause an ordinary wing to approximate this same condition by increasing the upper camber and by creating a negative lower camber.

Velocity and Angle of Attack

The shape of the airfoil or wing cannot be effective unless it is continually attacking new air. When figuring the lift and drag of an aircraft, you learn that lift is proportional to the square of the velocity. For example, an aircraft traveling 200 mph has four times as much lift as one traveling 100 mph when the angle of attack and the other factors remain the same. It is impossible to travel in level flight and maintain the same angle of attack when the speed is increased. Lift also increases and the aircraft climbs or will carry a greater load without climbing. For each angle of attack, an aircraft has a definite speed at which it will fly straight and level.

Density of the Air

When you study the lift and drag computations which are to follow, you will find that lift and drag vary directly with the density of the air. That is, when the density is doubled, lift and drag are also doubled, and vice versa. At an altitude of 18,000 feet, the density of the air is only one-half as much as it is at sea level. To maintain sea-level lift and drag conditions at this altitude, the aircraft must be flown at a greater true airspeed for any given angle of attack.

LIFT AND DRAG COMPUTATIONS

Basic Method

To devise a formula for computing lift and drag forces on an entire aircraft, it was necessary to take into consideration all of the factors that affect lift and drag. These factors are listed as follows:

1. Lift and drag are directly proportional to the density of the air.
2. Lift is directly proportional to the area of the wing.
3. Drag depends both upon wing area and the size and shape of the fuselage, nacelles, and empennage.
4. Lift and drag are proportional to the square of the velocity of the air.
5. Lift and drag increase with increases in the angle of attack. (Lift increases only up to the stalling angle of attack.)
6. Lift and drag are dependent upon the shape of the airfoil.

With these relationships, the equations for lift and drag are written as:

$$L = C_L \frac{\rho}{2} V^2 S$$

$$D = C_D \frac{\rho}{2} V^2 S$$

Where:

L is lift in pounds
D is drag in pounds
S is wing area in square feet
V is velocity (TAS) in feet per second
ρ is density of the air in slugs per cubic foot
C_L is the coefficient of lift
C_D is the coefficient of drag

The coefficients of lift and drag are dimensionless numbers determined from test data for a particular aircraft. These coefficients take into consideration wing shape as well as the size and shape of the fuselage, empennage, and nacelles. They also take into consideration other factors, the discussion of which is beyond the scope of this manual. The value of these coefficients varies with the angle of attack.

By the use of models in a wind tunnel, it is

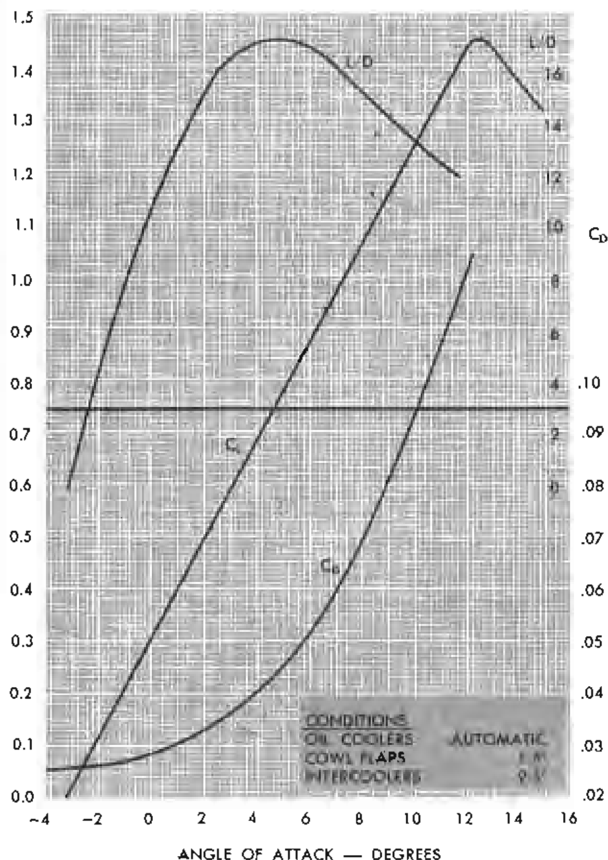

Figure 6-11. Lift and Drag Characteristics

possible to obtain test data from which values for C_L and C_D may be determined. These values are then plotted against an angle of attack on a graph. The results of such data are shown in figure 6-11.

The main use of the lift and drag curve is to find either the coefficient of lift or the coefficient of drag for a particular angle of attack. For example, to determine the values for C_L and C_D for a 4° angle of attack, using lift and drag curve, first locate the vertical line representing the 4° angle of attack. Follow this line up to the line labeled C_L. From this intersection proceed to the left and read the value 0.687. This is the coefficient of lift. From the point where the 4° angle of attack intersects the C_D curve, proceed to the right and read the value 0.0398. This is the value of C_D.

The following is a sample problem in computing lift and drag for a specific aircraft:

Example: Compute the lift and drag forces acting on an aircraft flying at 20,000 feet H_ρ (pressure altitude), OAT = −15° C. The TAS is 260 mph; the angle of attack is 5°, and S = 1739 square feet.

From the *Density Altitude Chart* and the *Standard Atmosphere Table:* ρ = .00122 slugs/ft³. From the *Lift and drag* characteristics curves, C_L = 0.781, and C_D = .0451. V = 260 × 1.467 (1 mph = 1.467 ft/sec) = 381 ft/sec.

Substituting these values into the lift and drag formulas:

$$L = C_L \frac{\rho}{2} V^2 S = \frac{.781 \times .00122 \times 381 \times 381 \times 1739}{2}$$

$$L = 120{,}200 \text{ lb}$$

$$D = C_D \frac{\rho}{2} V^2 S = \frac{.0451 \times .00122 \times 381 \times 381 \times 1739}{2}$$

$$D = 6{,}930 \text{ lb}$$

These equations mean more when you consider that the density and velocity factors $\frac{\rho V^2}{2}$ represent the kinetic energy of a cubic foot of air. The area and coefficient factors simply determine how many cubic feet of air are affected by the wing each second and how much this air is deflected.

Simplified Method

The basic method formula for lift and drag contains the same expressions that are used in finding dynamic pressure. Dynamic pressure is pressure created when a stream of air flows against an object (free air velocity). In flight, dynamic pressure (q) is equal to ½ ρV^2.

$$q = \frac{1}{2} \rho V^2$$

Where:

ρ is air density in slugs/ft³
V is aircraft velocity in ft/sec

The result of this equation is dynamic pressure in pounds per square foot. Later, a simpler formula for dynamic pressure was used and density had to be determined. Heretofore, true airspeed was used and density had to be determined. When equivalent airspeed is used rather than true airspeed, the density factor in the basic formula is eliminated, since equivalent airspeed has already been corrected for density of the air.

The dynamic pressure formula is changed as follows:

$$q = \frac{1}{2}\rho V^2$$

Converting V to ft/sec (1 mph = 1.467 ft/sec):

$$q = \frac{1}{2}\rho\,(1.467) \times (TAS)^2$$
$$= \frac{1}{2}\rho \times (1.467)^2 \times (TAS)^2$$
$$= \frac{(1.467)^2}{2}\,\rho\,(TAS)^2$$

Density is eliminated as follows:

$$TAS = EAS \times \frac{1}{\sqrt{\sigma}}$$

and

$$\sigma = \frac{\rho}{\rho_o} \text{ and } \rho_o = .002378 \text{ slugs/cu ft}$$

Therefore,

$$TAS = EAS \times \frac{1}{\sqrt{\frac{\rho}{.002378}}}$$

$$TAS = EAS \times \sqrt{\frac{.002378}{\rho}}$$

$$(TAS)^2 = \frac{(.002378)\,(EAS)^2}{\rho}$$

$$q = \frac{(1.467)^2}{2} \times \rho \times \frac{(.002378)\,(EAS)^2}{\rho}$$

The ρ's cancel out, and dividing .002378 by 2, we have

$$q = (1.467)^2\,(.001189)\,(EAS)^2$$
$$= .00256\,(EAS)^2$$

The reciprocal of .00256 is 391, which is used as the dynamic pressure constant.

Therefore,

$$q = \frac{EAS^2}{391}$$

NOTE: When using values in airspeed expressed in nautical miles per hour, the dynamic pressure formula must be corrected:

1 statute mile per hour = 1.467 (ft/sec)
1 nautical mile per hour = 1.688 (ft/sec)

Therefore, the above formula must be changed to:

$$q = \frac{(1.688)^2}{2} \times \rho \times \frac{(.002378)\,(EASK)^2}{\rho}$$

$$q = (1.688)^2\,(.001189)\,(EASK)^2$$
$$= .003388(EASK)^2$$

The reciprocal of .003388 is 295.

$$q = \frac{EASK^2}{295}$$

Substituting $\frac{EASK^2}{295}$ for $\frac{1}{2}\,\rho\,V^2$ in the basic formula we have:

$$L = C_L S\,\frac{EASK^2}{295}$$

$$D = C_D S\,\frac{EASK^2}{295}$$

Sample problem using the simplified formula: An aircraft is flying at an EASK of 175 and the angle of attack = 5°. Find the lift and drag when S = 1739 square feet.

$$C_L = .781$$
$$C_D = .0451$$
$$L = C_L S\,\frac{EASK^2}{295}$$
$$= .781 \times 1739 \times \frac{175 \times 175}{295}$$
$$= 148{,}200 \text{ lbs}$$
$$D = C_D S\,\frac{EASK^2}{295}$$
$$= .0451 \times 1739 \times \frac{175 \times 175}{295}$$
$$= 8{,}100 \text{ lbs}$$

HORSEPOWER REQUIRED BY AN AIRCRAFT

When rearrangements of the preceding formulas for lift and drag are used in conjunction with other formulas, it becomes possible to determine the horsepower required by the aircraft under a variety of circumstances.

Because drag increases with the square of the airspeed, the resistance created by a dent in the skin or by any projection into the airstream is four times as great at 200 knots as it is at 100 knots. To get some idea of the amount of thrust needed to balance out or overcome this drag, remember that the power required to move an aircraft through the air varies with the cube of the airspeed. Overcoming drag resulting from a dent in the wing would therefore require eight times more horsepower at 200 than at 100 knots.

With an increase in altitude, the required horsepower is still greater. The drag remains the same for a given angle of attack and indicated airspeed, regardless of altitude, but the true velocity (TAS) increases. Since the power required is determined (1) by true airspeed and (2) by drag, the requirement for horsepower will increase with the increase in airspeed.

The addition of drag items such as antennas, external tanks, and radomes is accounted for either by additional flat plate areas or in terms of added weight. Variations in temperature are compensated by the introduction of the smoe factor in the formula.

Formulas for Determining Required Horsepower

The horsepower required by an aircraft may be determined by using the formula for work:

$$W = F \times d \text{ ("d" refers to distance)}$$

and since power = $\frac{\text{work}}{\text{time}}$, if we substitute thrust for F and velocity in feet/sec for d, the formula becomes

Work/sec = power = thrust × velocity

But, since 550 ft-lb/sec is equal to one horsepower, divide by 550 and obtain

$$\text{Thrust Horsepower} = \frac{\text{thrust} \times \text{velocity}}{550}$$

This is the total thrust horsepower (thp) developed by an aircraft. Since thrust is equal to drag, the formula may be written:

$$\text{thp} = \frac{DV}{550}$$

where D is drag in pounds and V is velocity (TAS) in ft/sec.

Example: An aircraft in flight encounters an aerodynamic drag of 8,000 pounds and has a velocity of 330 ft/sec. Find the thp developed.

$$\text{thp} = \frac{DV}{550} = \frac{8{,}000 \times 330}{550} = 4800$$

This formula may be made more useful by substituting into it the formula for drag in place of D. Thus:

$$\text{thp} = \frac{DV}{550} = \frac{C_D\, S\, \rho\, V^2 \times V}{2 \times 550}$$

$$\text{thp} = \frac{C_D\, S\, \rho\, V^3}{1100}$$

Example: An aircraft is flying at 10,000 feet H_p on a standard day with a TAS of 400 ft/sec, and the angle of attack

$(\alpha) = 1\frac{1}{2}°$. Wing area is 1739. Find thp.

$$\text{thp} = \frac{C_D\, S\, \rho\, V^3}{1100} = \frac{.0310 \times .001756 \times 400^3 \times 1739}{1100}$$

thp = 5510

A still more usable formula may be developed from the work formula by using TAS in mph or TAS in knots

$$\text{thp} = \frac{D \times TAS}{375} \text{ or } \frac{D \times TASK}{295}$$

(375 mile-pounds/hr = one hp)

Now, by substituting the value for drag from the simplified formula for drag the following formula is derived:

$$\text{thp} = \frac{C_D\, S\, EASK^2 \times TASK}{295 \times 325}$$

But,

$$TASK = EASK \times \frac{1}{\sqrt{\sigma}}$$

$$\text{thp} = \frac{C_D\, S\, EASK^2 \times EASK \times \frac{1}{\sqrt{\sigma}}}{295 \times 325}$$

$$\text{thp} = \frac{C_D\, S\, EASK^3 \times \frac{1}{\sqrt{\sigma}}}{95{,}875}$$

Example: An aircraft is flying at 18,000′ H_p; OAT = −30° C; EASK = 180; $\alpha = 4\frac{1}{2}°$. Wing area is 1739. Find the thp being developed.

$$\text{thp} = \frac{C_D\, S\, EASK^3 \times \frac{1}{\sqrt{\sigma}}}{95{,}875} = \frac{.0423 \times 1739 \times 180^3 \times 1.30}{95{,}875}$$

thp = 5820

Determining bhp per Engine Under Given Conditions

More useful to the flight engineer than the preceding formulas is the formula used to determine the bhp per engine required to fly an aircraft under given conditions. Before developing this formula it is necessary to discuss propeller efficiency. The bhp required to fly an aircraft is partly dependent upon the efficiency of the propellers.

An aircraft engine developing 1000 bhp delivers 1000 bhp at the propeller shaft. The propeller dissipates all of this power, but does not convert all of it to thp. Part of the power dissipated by the propeller is used to overcome the aerodynamic drag on the propeller blades. The actual efficiency of the propeller is expressed by the relationship

$$\eta = \frac{\text{thp}}{\text{bhp}}$$

where η (eta, pronounced ate′-ah) is the Greek letter symbol for propeller efficiency. This relationship may also be expressed as:

$$\text{bhp} = \frac{\text{thp}}{\eta}$$

Substituting the formula for thp into the above relationship, we obtain

$$\text{bhp} = \frac{\text{thp}}{\eta} = \frac{C_D\, S\, EASK^3 \times \frac{1}{\sqrt{\sigma}}}{95{,}875 \times \eta}$$

To determine the bhp per engine (bhp/eng) required for level flight, it is necessary to divide the expression by the number of engines. Letting R represent the number of engines, the formula becomes

$$\text{bhp/eng} = \frac{C_D\, S\, EASK^3 \times \frac{1}{\sqrt{\sigma}}}{95{,}875 \times R \times \eta}$$

Example: Find the bhp/eng required by a four-engine aircraft to fly 169 EASK in level flight at 5,000′ H_p on a standard day. The angle of attack is 4.5° and S = 1739.

$\eta = .85$ approximately, for most aircraft during cruise
$C_D = .0423$ for $\alpha = 4.5°$

$$\frac{1}{\sqrt{\sigma}} = 1.0773 \text{ for } 5{,}000' \ H_p$$

$$\text{bhp/eng} = \frac{C_D \ S \ EASK^3 \times \frac{1}{\sqrt{\sigma}}}{95{,}875 \times R \times \eta}$$

$$\text{bhp/eng} = \frac{.0423 \times 1739 \times 169^3 \times 1.0073}{95{,}875 \times 4 \times .85}$$

$$\text{bhp/eng} = 1090$$

Miscellaneous Horsepower Problems

Example: An aircraft weighs 110,000 pounds and is flying at an EASK of 174 knots at sea level on a standard day. Find the bhp/eng required to maintain level flight when $S = 1739$ and $R = 4$.

The angle of attack is unknown, therefore the C_D cannot be found immediately. It is necessary to first determine the angle of attack. This may be determined from C_L which is found by rearranging the lift formula:

$$L = C_L \ S \frac{EASK^2}{295}$$

The formula is rearranged to read

$$C_L = \frac{295 \ L}{S \times EASK^2}$$

but, since $L = W$ in level, unaccelerated flight, the formula may be written:

$$C_L = \frac{295 \ W}{S \times EASK^2}$$

Now, by substituting into this formula the values for the problem:

$$C_L = \frac{295 \times 110{,}000}{1739 \times 174 \times 174}$$

it is found that

$$C_L = .619$$

With this value for C_L, the angle of attack may be determined by reversing the normal use of the lift/drag characteristics curves. The angle of attack is found to be 3.3°. C_D is then found to be .0367. Now it is possible to substitute into the bhp formula and determine the required bhp/eng.

$$\text{bhp/eng} = \frac{C_D \ S \ EASK^3 \times \frac{1}{\sqrt{\sigma}}}{95{,}875 \ R \ \eta}$$

$$\text{bhp/eng} = \frac{.0367 \times 1739 \times 174^3 \times 1.000}{95{,}875 \times 4 \times .85}$$

$$\text{bhp/eng} = 1028$$