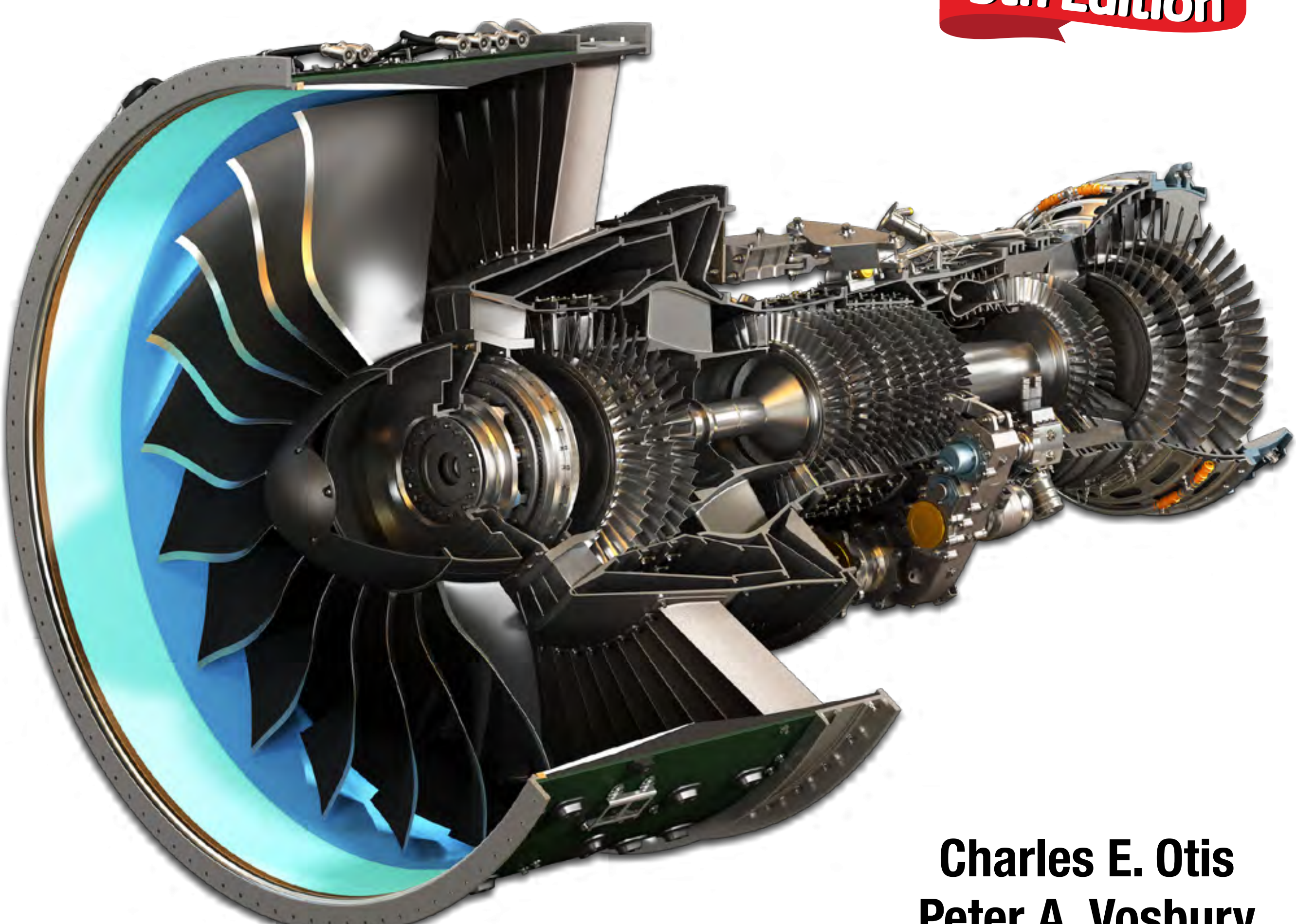
AIRCRAFT GAS TURBINE POWERPLANTS TEXTBOOK

5th Edition



Charles E. Otis
Peter A. Vosbury

AIRCRAFT TECHNICAL BOOK COMPANY

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Introduction

The first historical application of the jet propulsion principle occurred when a steam-driven toy was demonstrated in Egypt before the Common Era. For nearly twenty centuries, the idea of jet propulsion evolved slowly. It wasn't until the early 20th century that Sir Frank Whittle, an English inventor, first described the possibility of using a gas turbine device as a means of jet propulsion for aircraft. From this modest idea, jet aircraft use has grown into the large multinational industry we know today. Whittle, the "father of the modern gas turbine engine," remained active in gas turbine engine design well into his 70s. He died at the age of 89 in 1996.

To meet the growing demands of modern aircraft, gas turbine engine designs have become increasingly complex and powerful, and the technical tasks required to maintain them have become more and more demanding. It is no longer possible for technicians to gain expertise based on hands on experience alone. Today's complex turbine engines and systems require expert technical training. This textbook serves as a starting point for this training process. It is intended both for those just beginning to explore the world of gas turbine engines and for experienced technicians and flight personnel who are exploring new directions and opportunities within the aviation industry.

Whether you proceed through this book in a formal classroom setting or as an independent student, the material in this textbook provides a sound foundation of the principles of gas turbine engine theory, design, maintenance, and troubleshooting.

Every successful technical educational endeavor begins by providing learners with solid entry-level knowledge. The proven way to acquire this knowledge is to read the material carefully, answer the questions at the end of each chapter, review and research the text, and finally reinforce this knowledge by applying it in actual work experience.

These engines have fans that are not much larger in diameter than the engine core, and they would typically have a bypass ratio of 0.5:1. In other words, 0.5 pounds of air exit the fan duct for every 1 pound of air that goes through the core of the engine. This type of fan engine is typically used on military fighter airplanes, like the Navy F-18 or Air Force F-22, where a larger diameter fan would produce a prohibitive amount of drag.

The low-bypass classification indicates that the fan and the compressor sections use approximately the same mass airflow. They have a bypass ratio of 1:1. The fan discharge may be slightly higher or slightly lower. Keep in mind that the bypass ratio concerns airflow mass. The fan discharge air is ducted along the entire length of the engine from what is called a full fan duct. The end of the duct is configured with a converging discharge nozzle to produce a velocity increase and reactive thrust.

In the fully ducted fan engine shown in Figure 2-16, the hot and cold streams mix before being discharged to the atmosphere, which results in a reduction in the aerodynamic drag associated with short-ducted turbofans. Air passing over the core engine outer surfaces has much less skin friction if the air remains in the fan duct until it leaves the engine. With the full duct, there is gain of mass-airflow and thrust implied when drag is reduced. This design also has a noise attenuating quality as hot gas becomes diluted by fan air in the common exhaust duct.

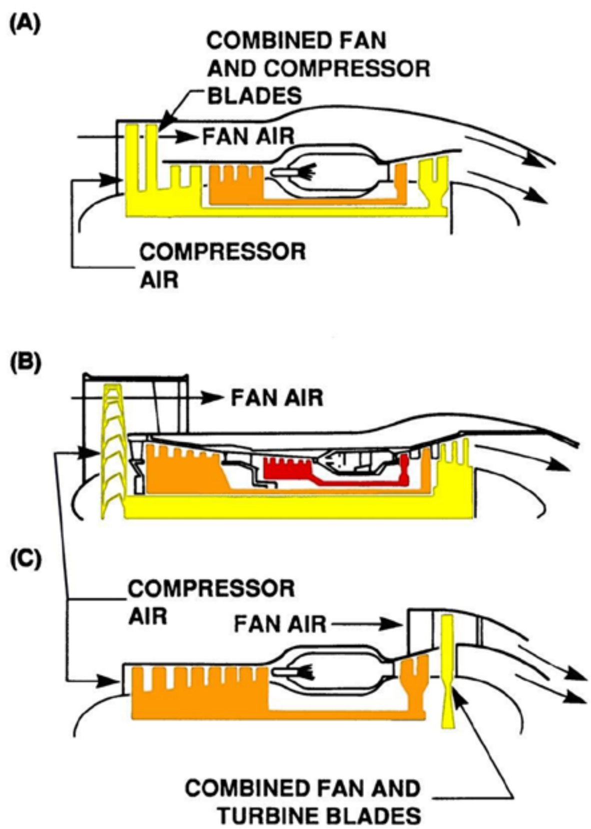

Figure 2-15A. Dual axial flow compressor, forward fan engine with mixed exhaust
Figure 2-15B. Triple-spool front fan engine with unmixed exhaust
Figure 2-15C. Turbofan engine with an aft-fan and unmixed exhaust

Early turbofan powered airplanes like the Boeing 707 and 727 and the Douglas DC-9 used low-bypass engines. Newer airplanes manufactured by large airliner manufacturers such as Boeing and Airbus, as well as many other regional jet aircraft manufacturers, have engines with a much higher bypass ratio that makes them much more fuel efficient and quieter. Consequently, new airplanes will unlikely use engines with the low-bypass design.

The turbofan core engine compresses, ignites, and discharges air in the same manner as a turbojet engine. The thrust of each gas stream of the fully ducted engine shown in Figure 2-16 has approximately equal airflow, and each delivers approximately the same thrust.

Medium- or intermediate-bypass engines have a mass airflow ratio of 2:1 or 3:1, with a thrust ratio in approximate proportion to the bypass ratio. The fan will be slightly larger in diameter than a low-bypass fan of comparable engine power, and its diameter will determine both the bypass ratio and thrust output of the fan versus the core of the engine.

The high-bypass turbofan engine, with fan ratios of 4:1 to 9:1, have even wider diameter fans in order to move more air. Figure 2-17 shows the design features of current high-bypass turbofans produced by Pratt & Whitney, General Electric, and Rolls-Royce with fans over 100 inches in diameter and representing the current state-of-the-art large engine designs for jumbo-jet aircraft.

Ultra high-bypass turbofan engines with fan ratios of 10:1 and higher are becoming more common. The Rolls Royce Trent 1000 turbofan for the Boeing 787 has a bypass ratio

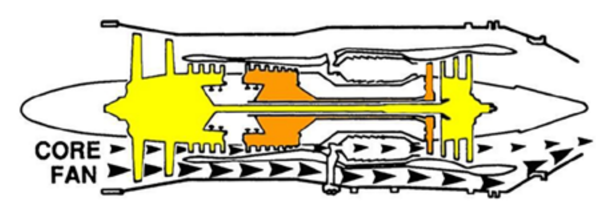

Figure 2-16. Fully ducted low- and medium-bypass turbofan design

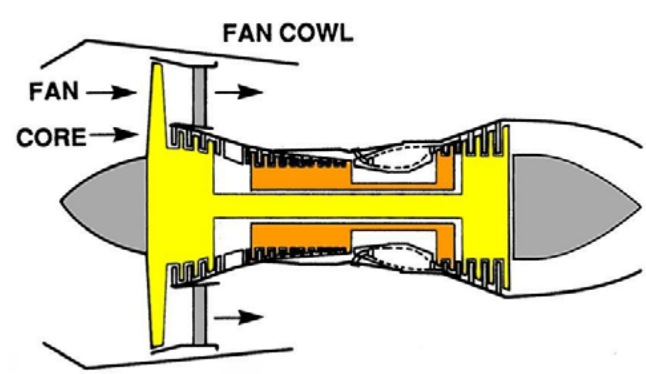

Figure 2-17. High-bypass ratio turbofan

of 10:1, and the Pratt and Whitney geared turbofan for the Airbus A320neo has a bypass ratio of 12.5 to 1. Over time even higher bypass ratios will be developed, because when a greater percentage of the mass airflow is directed out the fan duct the engine can have greater thermal and propulsive efficiency. There is a limit, of course, on how high the bypass ratio can go. It is not possible to send all the air out the fan duct because there would be no air in the core to support combustion and to drive the turbines.

High-bypass and ultra high-bypass engines boast the lowest fuel consumption of the various turbofan engines because of the smaller percentage of air that supports combustion in the core portion of the engine. For example, the Pratt & Whitney PW4000 series turbofans currently have a 5:1 to 9:1 bypass ratio engine with approximately 80 percent of the thrust produced by the fan and 20 percent by the core engine. The thrust percentages vary from engine to engine and are determined by such considerations as fuel economy at altitude, cruise speed, and propulsive efficiency for a particular aircraft design. For these higher bypass engines, the amount of air going out the fan duct falls between 80 and 92 percent of the total mass airflow.

In the past, the fan duct on high-bypass engines typically extended aft only 1/3 to 1/2 of the engine's length, unlike low-bypass engines that typically had full-length fan ducts. Even though the full-length duct provides thrust and drag advantages, the additional weight was a problem for the high-bypass engines. By using lower weight, high strength composites for the fan duct, it is now more common to extend the duct farther aft, and on some airplanes, to use a full-length duct.

Today's high-bypass fan engine has become the most widely used engine type for medium to large aircraft because it offers the best fuel economy by increasing the total mass airflow and decreasing the hot exhaust wake. This conservation of energy keeps more power within the engine to drive the fan and leads to a considerable increase in propulsive and thermal efficiency.

ULTRA HIGH-BYPASS TURBOFAN ENGINES (DUCTED, VARIABLE PITCH)

Another development in turbofans is the variable pitch (variable-bypass ratio) model, which, as of this writing, is being tested for certification. This model is predicted to have the lowest fuel consumption rate per thrust ratio of any turbofan currently in service. It is also expected to have much of the same flexibility of operation that the turboprops enjoy, and it will still be capable of the high subsonic cruising speeds that elude the conventional turboprop. Its bypass ratio will fall somewhere between the high-bypass turbofan and the propfan, and it will likely be fitted with a variable exhaust nozzle. [Figure 2-18]

HYBRID TURBINE-ELECTRIC AIRCRAFT PROPULSION

Airplanes of the future will have the ability to fly utilizing electric motors to power the propeller or ducted fan, and some or all of the electricity to power the electric motors will come from high energy density batteries. Just like many of today's cars are being powered by electric motors and battery packs made up of lithium-ion cells, some airplanes will also have that capability. One inherent problem for the airplane, however, is the battery packs are extremely heavy and the distance the airplane can fly on battery power alone is very limited.

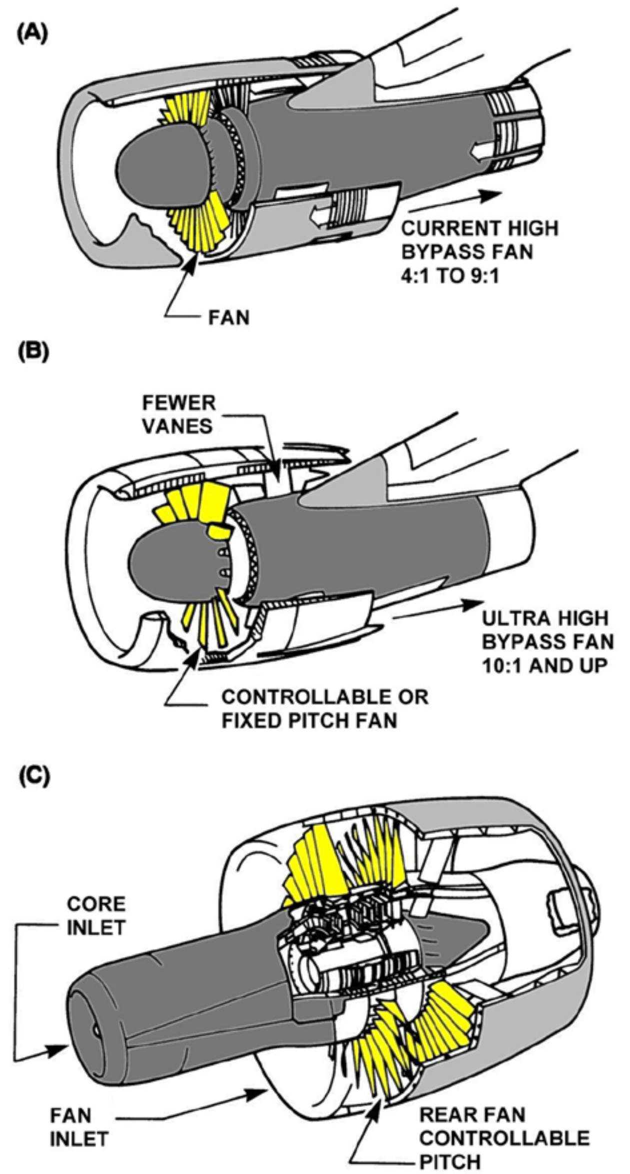

Figure 2-18A. Current technology turbofan engine
Figure 2-18B. Variable pitch front turbofan engine
Figure 2-18C. Variable pitch rear turbofan engine

TURBOGENERATOR

The solution to being able to power the aircraft with electric motors, but not having the inherent limitation of how much energy is stored in the battery pack, is to have a second source of electrical energy that can be used to supplement the batteries. The second source of electrical energy can be a turboshaft engine driving an electrical generator, in other words an auxiliary power unit (APU). Turbine engines operate at various levels of efficiency based on the RPM they are running at, and their RPM varies from ground idle to takeoff thrust. A turboshaft engine being used to solely run a generator at a constant speed can be designed to always operate at its most efficient RPM, and that would allow the combination of the turbine engine and the electric motor to be more efficient. Pictured in Figure 2-19 is a new design from Rolls Royce called a turbogenerator. It is a turboshaft engine of 700 to 1,400 horsepower driving a generator rated at 500,000 to 1,000,000 watts. It is being designed to run on sustainable aviation fuel (SAF) and in the future on hydrogen.

Figure 2-19. Rolls Royce turbogenerator

SERIES ARCHITECTURE

The airplane's power system shown in Figure 2-20 would be known as a Series Architecture, where there is a single mechanical device that drives the propeller or fan. For this airplane the mechanical device is an electric motor. Figure 2-21 also shows the Series Architecture, with the arrows in red showing the possible direction of electrical current flow. Notice the battery can have current flowing in or out, but the engine generator and the electric motors have current flowing in only one direction.

PARALLEL ARCHITECTURE

Figure 2-22 shows what is known as a Parallel Architecture, where there are two separate mechanical devices that can drive the propeller or fan. The turbine engine has a shaft that drives the gearbox for the propeller/fan, and an electric motor/generator that attaches to the gearbox can also drive the propeller/fan. The aircraft can be operated on the ground with just the electric motor driving the gearbox, and then for takeoff the turbine engine can be started and used to drive the gearbox. If additional power is needed for takeoff, the turbine engine and the electric motor/generator can both be used to drive the gearbox.

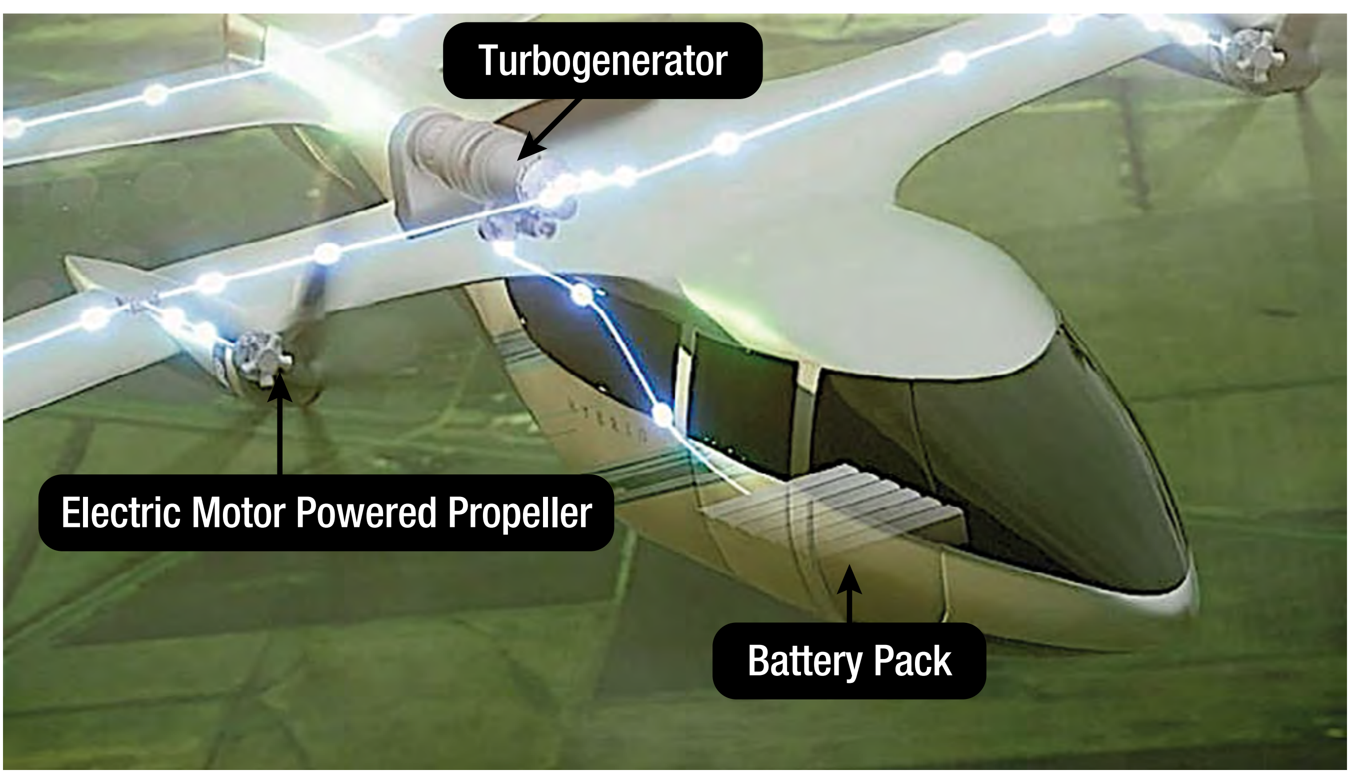

Figure 2-20. Electric airplane with a turbogenerator

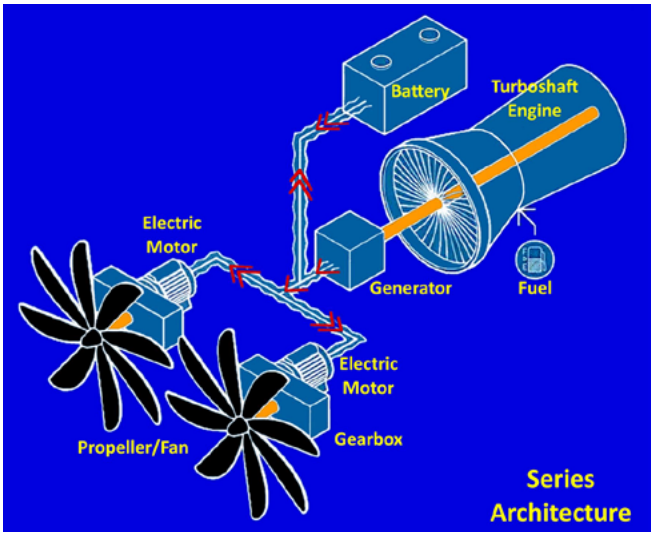

Figure 2-21. Airplane hybrid propulsion with a series architecture

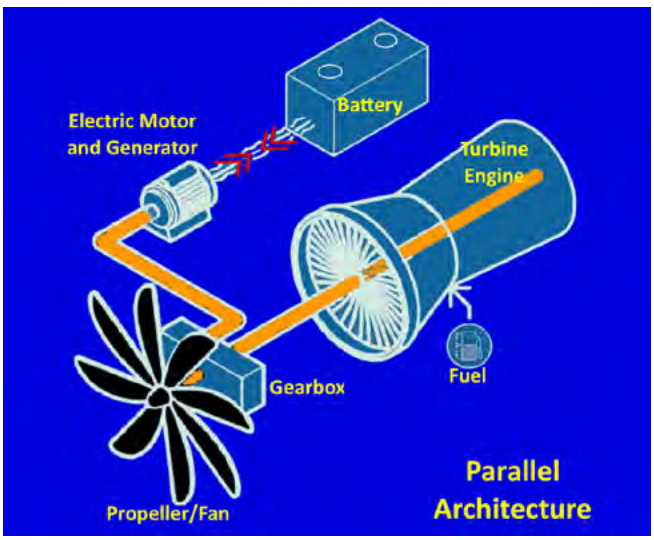

Figure 2-22. Airplane hybrid propulsion with a parallel architecture

PHYSICS OF THE GAS TURBINE ENGINE

A clear understanding of jet propulsion requires understanding the principles of physics that govern the action of mass or matter. The physics described in this section present the basic ideas necessary for understanding the physical relationships of gases and the turbo-machinery within a gas turbine engine.

In a discussion of turbine engines, we are concerned with the mass-flow of atmospheric air, which is compressed and accelerated to create useful work at the turbine wheel and, ultimately, thrust. The thrust is created from either pure reaction to the flowing gases or from a propeller or fan driven by a turbine.

Some of the most important physical properties that apply to the gas turbine engine are weight, density, temperature, pressure, and mass. These properties are useful when applied to formulas such as force, work, acceleration, thrust, and others that measure certain valuable performance factors. These properties will be described by formula in English Units throughout this text, for example, pounds instead of kilograms

Weight has direction and quantity and is measured in pounds of force. Figure 2-23A shows that weight is one-directional, toward the center of the earth, regardless of the type of material.

Density is the amount of material per unit volume. Figure 2-23B illustrates how two containers with identical contents will have different weights if the contents are packed closer together. The compressor of a gas turbine engine uses this principle by packing more molecules of air into a given space to increase the density and weight of the airflow to create thrust.

For example, at standard day condition the weight of air is 0.076475 pounds/cubic foot. In an engine with an overall compressor pressure ratio of 30:1, the weight of air per cubic foot will be 30 times 0.076475, or 2.295 pounds/cubic foot.

Figure 2-23C illustrates that temperature is the molecular energy of motion due to heat. Molecular motion is low at low temperature, but it increases at higher temperatures. This creates a problem in the compressor of a gas turbine engine because it requires more and more work in terms of compressor speed and fuel consumption to increase density if the air temperature increases.

Pressure is an omni-directional force of motion per unit area. [Figure 2-23D] Air molecules inside a container will rebound off the inner walls with such great rapidity that an essentially even pressure is exerted over all of the inner surfaces. If a pressure gauge were inserted into the closed container, it would produce a steady reading in pounds per square inch.

Figure 2-23E illustrates that mass is the amount of material a body contains. In this respect, it is similar to the description of density. Within a gas turbine engine, the denser the air per unit volume, the more weight it has and the more mass.

FORCE

Force is the capacity to do work or the tendency to produce work. It is also a vector quantity that tends to produce acceleration of a body in the direction of its application. It can be measured in pounds. The formula for force is:

Force = Pressure × Area, or $F = P \times A$

Where:

F = Force in pounds

P = Pressure in pounds per square inch (psi)

A = Area in square inches

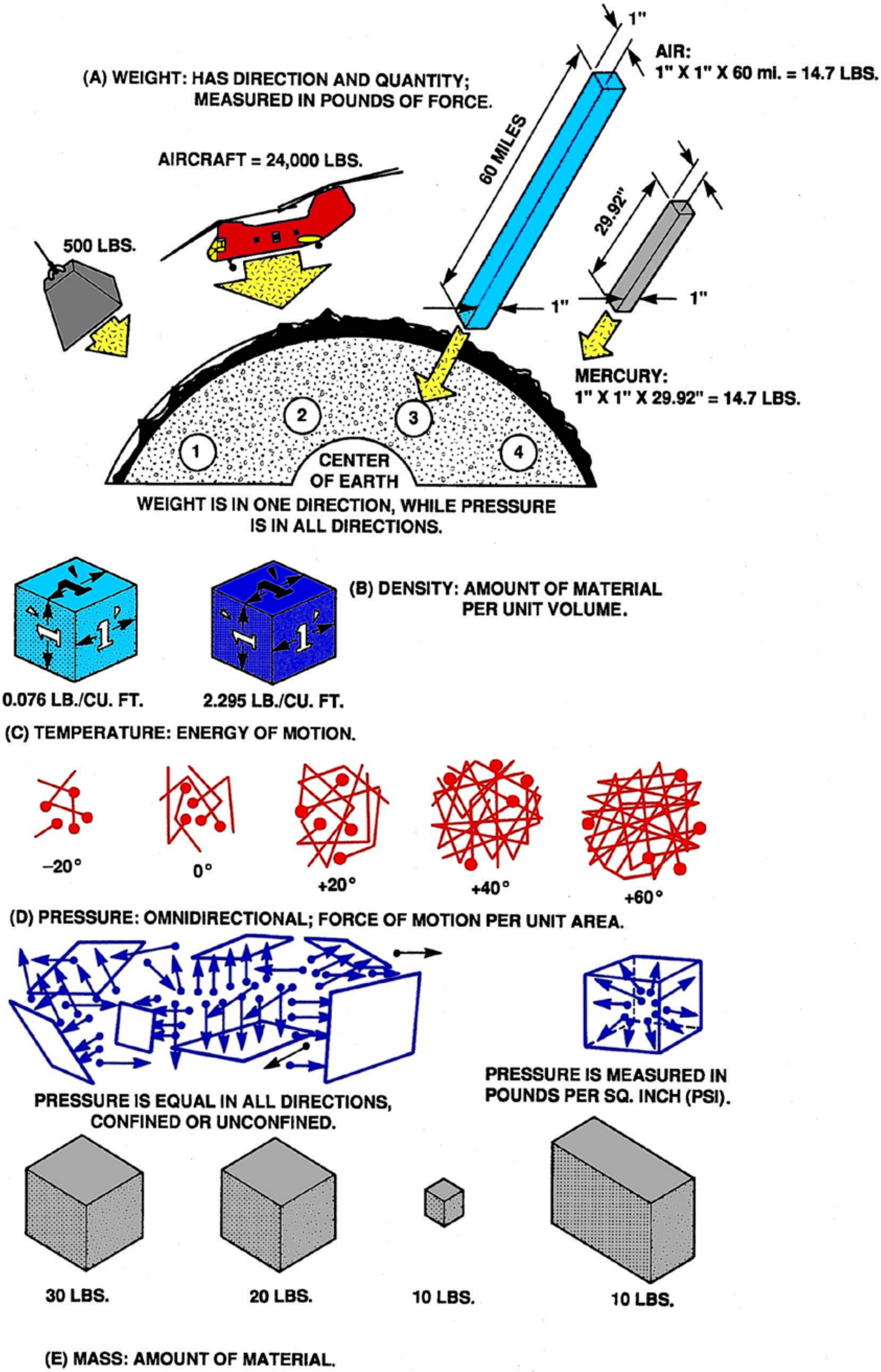

Figure 2-23 A, B, C, D, E. Some important physical properties of matter

AIRCRAFT GAS TURBINE POWERPLANTS

WORKBOOK

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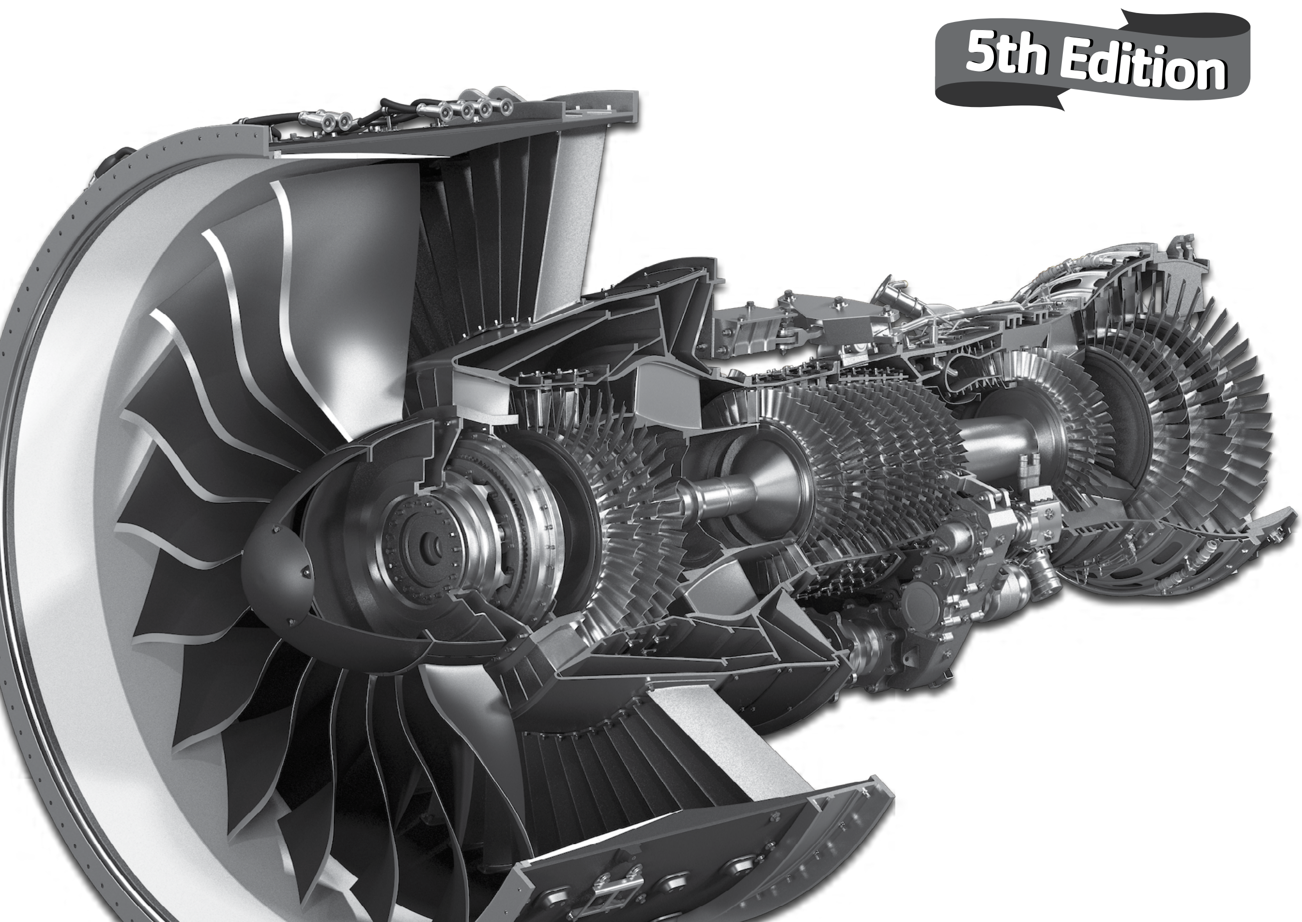

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POTENTIAL AND KINETIC ENERGY

Page 2-16

KEY POINTS

1. Refer to Figure 2-26B in the textbook. When the water is flowing from the sprinkler heads, it is referred to as ________ energy.
   A. Potential
   B. Kinetic

RESEARCH QUESTIONS

1. What terms best represent potential and kinetic energies in a turbine engine?
   A. Velocity and acceleration of airflow
   B. Velocity and motion of airflow
   C. Heat and motion of airflow

BERNOULLI'S PRINCIPLE

Page 2-16 to 2-18

KEY POINTS

1. Bernoulli's principle refers to airflow at a constant value (lb/sec) through a frictionless duct and at a ________ flowrate.
   A. Supersonic
   B. Subsonic

2. In a convergent duct, when a constant, subsonic air flowrate exists, velocity is ________.
   A. Increasing
   B. Decreasing

3. In a divergent duct, when a constant, subsonic air flowrate exists, velocity is ________.
   A. Increasing
   B. Decreasing

4. In either a convergent or divergent duct, when a constant subsonic air flowrate exists, total pressure will ________.
   A. Increase
   B. Decrease
   C. Remain the same

RESEARCH QUESTIONS

1. What are the components of total pressure?
   A. Static plus ram
   B. Ram plus venturi
   C. Static minus ram

2. When applying Bernoulli's principle, what gas flow (lbs./hr) performs best?
   A. Accelerating in the direction of flow
   B. Decelerating in the direction of flow
   C. Constant in the direction of flow

THE BRAYTON CYCLE

Page 2-18 to 2-20

KEY POINTS

1. The four events of the constant pressure cycle, also known as the Brayton cycle, are inlet, compression, expansion, and ________.
   A. Thrust
   B. Exhaust

2. The constant pressure cycle occurs because internal engine pressure is fairly constant across the ________ section.
   A. Compressor
   B. Combustor

3. The pressure drop in compressor discharge air as it passes through the remainder of the engine is controlled by the size of the ________ nozzle.
   A. Exhaust
   B. Turbine

RESEARCH QUESTIONS

1. Refer to Figure 2-30A in the textbook. What is the point of highest pressure within a turbine engine?
   A. Compressor
   B. Diffuser
   C. Combustor

2. Look at Figure 2-1 and select the lettered engine location that would properly match the following statements. Write your letter choice on the line next to the statement.
   _____ The point of highest static pressure
   _____ The point of highest axial velocity
   _____ The point of highest temperature

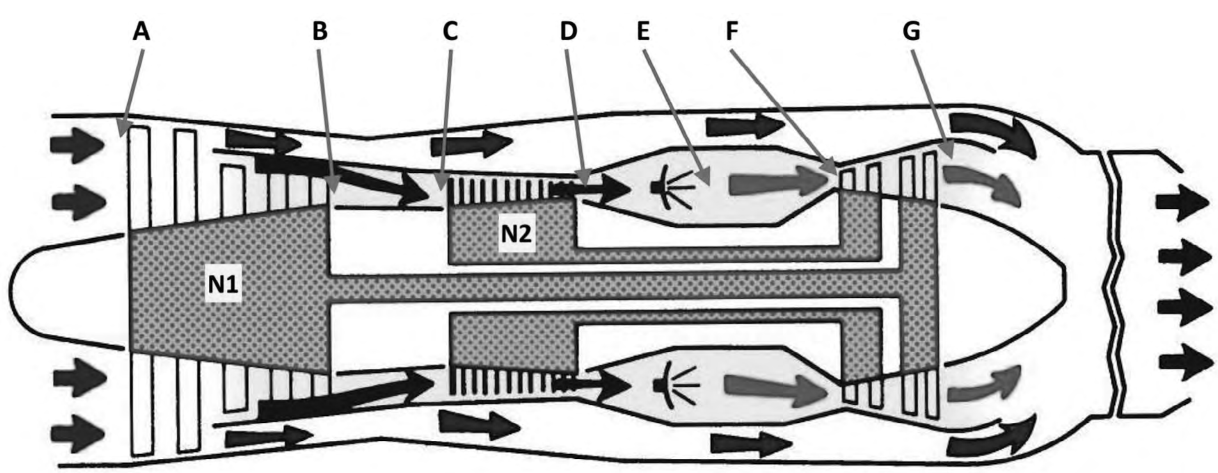

Figure 2-1.

NOTES

NEWTON'S LAWS AND THE GAS TURBINE

Page 2-20 to 2-22

KEY POINTS

1. Newton's _______ law states: A body at rest tends to remain at rest and a body in motion tends to remain in motion.
   A. First
   B. Second
   C. Third

2. Newton's _______ law states: For every acting force there exists an equal and opposite reacting force.
   A. First
   B. Second
   C. Third

3. Newton's _______ law provides the formula ($F = m \times A$) for computing the value of his third law of "action and reaction."
   A. First
   B. Second
   C. Third

RESEARCH QUESTIONS

1. What is the thrust created when 644 pounds of air is accelerated through an engine from 0 to 1,400 ft/sec in one second?

   $$F = \frac{(\qquad)}{(\qquad)} \times \frac{(\qquad)}{(\qquad)}$$

   F = _____ × _____

   F = _____________ lbs.

   Where:
   W = _______ lbs.
   V_1 = _______ ft/sec
   V_2 = _______ ft/sec
   g = _______ ft/sec^2
   t = _______ sec.

2. It is possible to convert "m" to W/g in the thrust formula; the logic of this conversion is as follows:
   A. If a one-pound object exerts a 1-pound force (weight) on an ordinary scale by the pull of gravity.
   B. Then: F = mA, when A = 32.2 ft./sec.^{2} and F = 1 lb.
   C. Therefore when:

   $F = m \times A$

   1 lb. = _____ m × 32.2

   _____ = lb./32.2

3. If one mass unit of air enters a turbine engine, another unit leaves. How does the unit of air leave?
   A. At higher velocity
   B. At higher mass