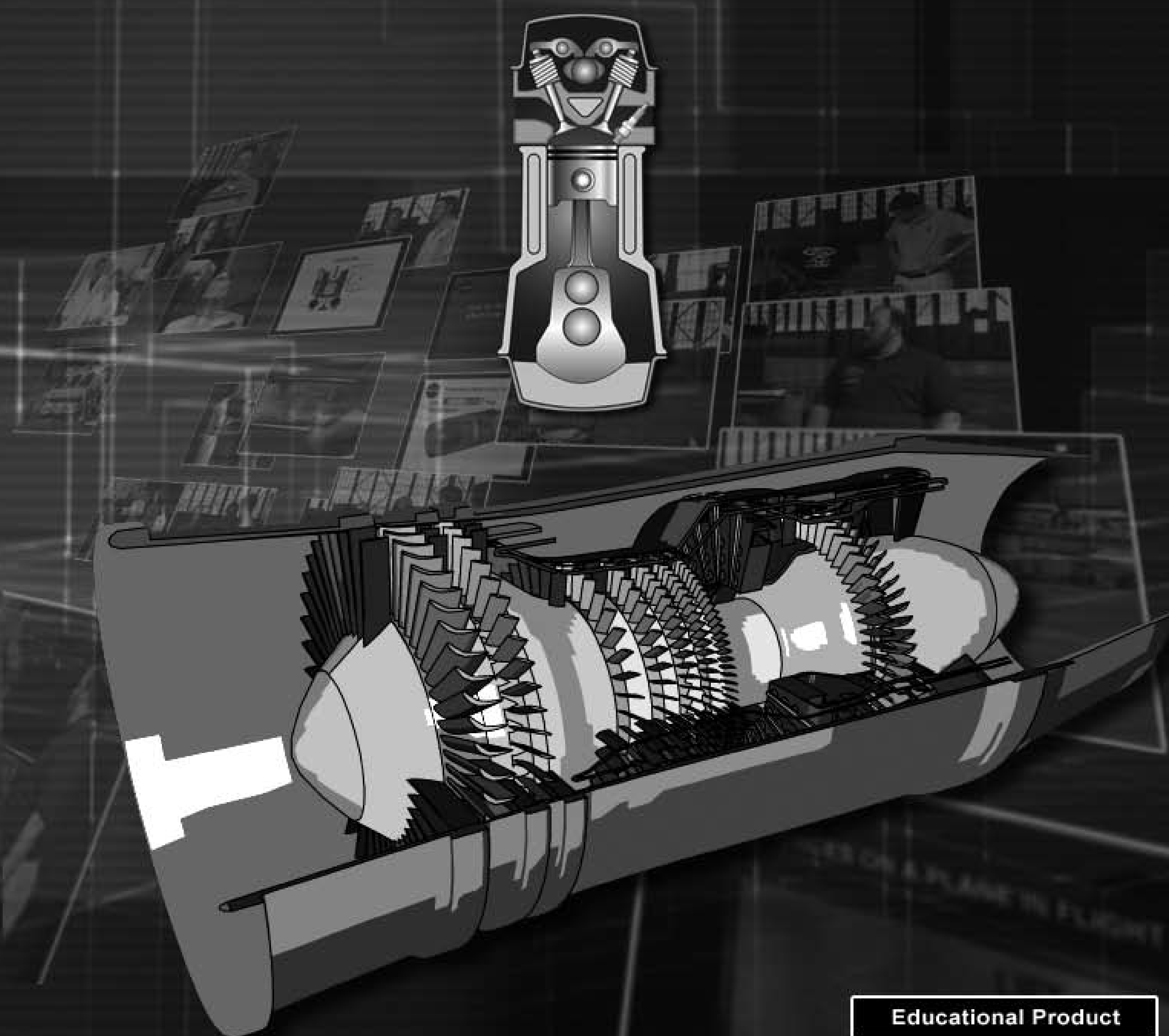
National Aeronautics and Space Administration

Pushing the Envelope:
A NASA Guide to Engines



Educational Product

Educators and Students	Grades 8–12

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Pushing the Envelope: A NASA Guide to Engines

A Guide for Educators and Students With Chemistry, Physics, and Math Activities

National Aeronautics and Space Administration

Acknowledgments

Writers and Contributors
Roger Storm, Oklahoma State University
Mark Skor, North Royalton High School
Lisa D. Koch, NASA Glenn Research Center
Tom Benson, NASA Glenn Research Center
Carol Galica, NASA Glenn Research Center/SGT, Inc.

Editor
Laura Becker

Proofreader
Lorraine Feher

Design and Layout
James Lucic

Problems and Solutions
Roger Storm
Mark Skor

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PREFACE

The Pushing the Envelope Educators Guide has been developed by the NASA John H. Glenn Research Center's Educational Programs Office in support of the NASA's Aeronautics Research Mission Directorate (ARMD). ARMD is working to transform our Nation's air transportation system by developing the knowledge, tools, and technologies to support future air and space vehicles. The focus is on cutting-edge, fundamental research in traditional aeronautical disciplines, as well as in emerging fields with promising application to aeronautics. We are investing in research for the long term in areas that are appropriate to NASA's unique capabilities and meeting our charter of addressing national needs and benefiting the public good. We are advancing the science of aeronautics as a resource to our Nation as well as advancing technologies, tools, and system concepts that can be drawn upon by civilian and military communities and other government agencies.

The Pushing the Envelope Educators Guide has been created for grades 9 to 12 to aid in teaching math, physics, and chemistry concepts from the viewpoint of propulsion and aeronautics. The guide is aligned to the national mathematics and science standards. The design of the guide allows for sections to be completed independently and in any order. Problems using real-world applications are included in each section to provide practice on the concepts. A teacher section is included in the back of the guide that provides worked-out solutions to problems as well as a listdefining the units of measure used throughout the guide and a glossary.

National Standards

Science (Grades 9–12):

Physical Science

Chemical reactions
Motions and forces

Mathematics (Grades 9–12)

Algebra

Generalize patterns using explicitly defined and recursively defined variables

Interpret representations of functions of two variables

Approximate and interpret rates of change from graphical and numerical data

Understand pattern, relations, and functions

Represent and analyze mathematical situations and structure using algebraic symbols

Problem Solving

Solve problems that arise in mathematics and in other contexts

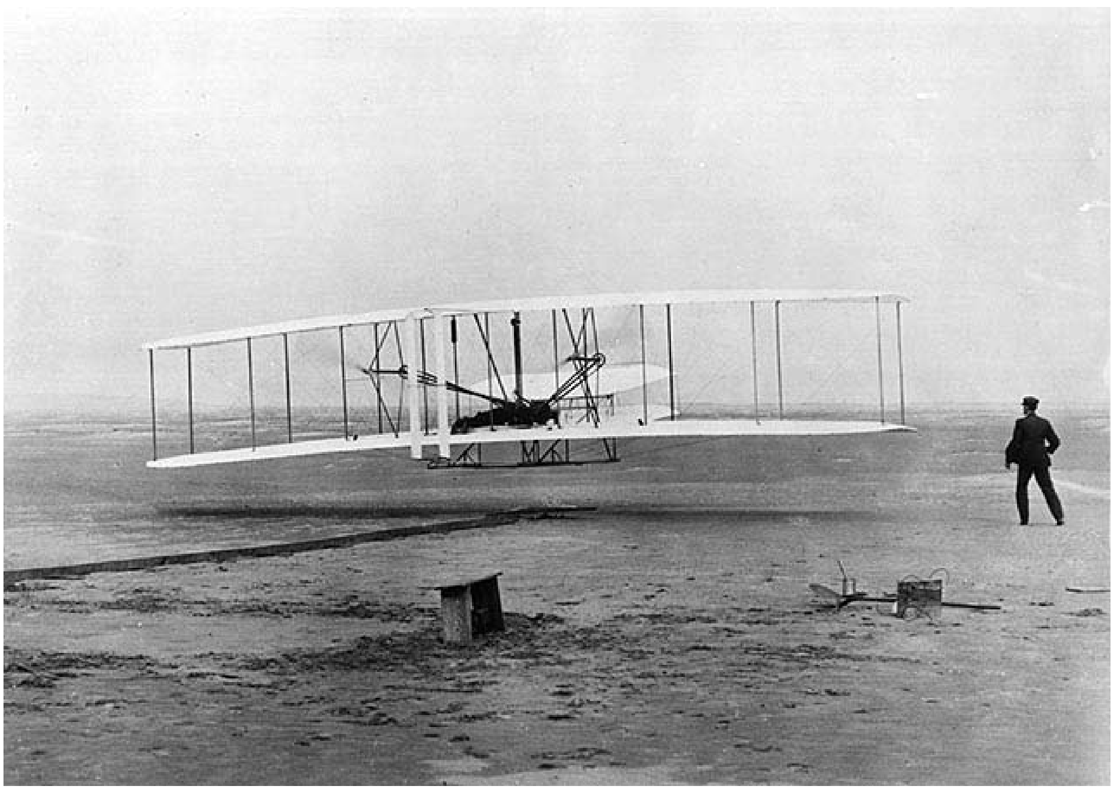
Apply and adapt a variety of appropriate strategies to solve problems

Understand Numbers

Understand and use ratios and proportions to represent quantitative relationships

Contents

INTRODUCTION



Introduction

"What is propulsion? The word is derived from two Latin words: *pro* meaning before or forwards and *pellere* meaning to drive. Propulsion means to push forward or drive an object forward. A propulsion system is a machine that produces thrust to push an object forward. On airplanes and spacecraft, thrust is generated through some application of Newton's third law of action and reaction. A gas, or working fluid, is accelerated by the engine, and the reaction to this acceleration produces a force on the engine.

The amount of thrust generated depends on the mass flow through the engine and the exit velocity of the gas. Different propulsion systems generate thrust in slightly different ways. We will discuss several propulsion systems including the propeller, the turbine (or jet) engine, the ramjet and scramjet, and ion engines.

Why are there different types of engines? If we think about Newton's first law of motion, we realize that an airplane propulsion system must serve two purposes. First, the thrust from the propulsion system must balance the drag of the airplane when the airplane is cruising. And second, the thrust from the propulsion system must exceed the drag of the airplane for the airplane to accelerate. In fact, the greater the difference between the thrust and the drag, called the excess thrust, the faster the airplane will accelerate.

Some aircraft, like airliners and cargo planes, spend most of their life in a cruise condition. For these airplanes, excess thrust is not as important as high engine efficiency and low fuel usage. Since thrust depends on both the amount of gas moved and the velocity, we can generate high thrust by accelerating a large mass of gas by a small amount, or by accelerating a small mass of gas by a large amount. Because of the aerodynamic efficiency of propellers and fans, it is more fuel efficient to accelerate a large mass by a small amount. That is why we find high-bypass fans and turboprops on cargo planes and airliners.

Some aircraft, like fighter planes or experimental high-speed aircraft require very high excess thrust to accelerate quickly and to overcome the high drag associated with high speeds. For these airplanes, engine efficiency is not as important as very high thrust. Military aircraft typically employ afterburning turbojets to gain extra thrust for short periods of time."*

In this educator's guide related topics such as pollution, air density, noise, gas laws, and Newton's laws as related to aircraft engines will be examined.

** From Benson, Tom: Beginner's Guide to Propulsion http://www.grc.nasa.gov/WWW/K-12/airplane/bgp.html. Accessed March 12, 2007.*

History of Aviation Propulsion

HISTORY OF PROPULSION FOR AVIATION

Throughout man's history there has been a constant need for power to move. Whether to hunt for food, to escape predators or enemies, to plow a field, to take goods to trade, to go to war; there has always been a need to get from one place to another.

ANIMAL POWER

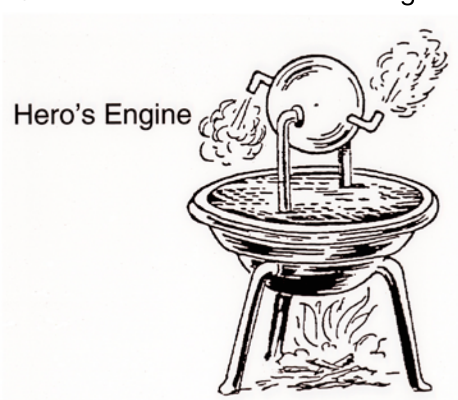
Initially the only power available was your own muscles or the muscles of some beast of burden. One could go faster by riding a horse. More power could be had by using teams of horses or oxen or hundreds or even thousands of people, but there were certainly limitations as to what could be done and how fast it could be done.

WATER AND WIND

Water travel allowed for more speed and greater loads, but one had to either row, sail, or go with the current. Men did learn how to sail against the wind, but the wind does not always blow. They built canals to go where they wanted, but speed was a limitation.

STEAM ENGINES

The first steam engine was called an aeolipile ("wind ball") and was invented by a Greek, Hero of Alexandria, in the 1st century AD. Steam entered a ball and exited from one of two bent pipes. This caused the ball to spin, but it was only used as a toy. The first steam device to do actual work wasn't invented until 1698: An engine developed by Thomas Savery in England was used to pump water out of flooded mines. Refinements to the engine were made by Thomas Newcomen in 1712 and James Watt in 1769. These engines worked by introducing steam into a cylinder and then cooling it, causing the steam to condense. This created a rapid decrease in the volume of gas present and thus caused a piston to move. Watt's improvement, condensing the steam outside the working cylinder, was so efficient that he is often wrongly credited with the invention of the steam engine. His work brought on the Industrial Revolution. Factories and mills no longer had to be located on a source of water power, and the way was opened to create self-propelled vehicles.

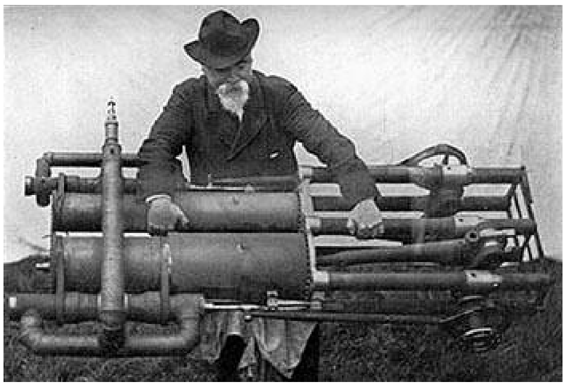


Aeolipile.

This new technology was first applied to a vehicle by Nicolas-Joseph Cugnot, a French military engineer, in 1769. His three-wheeled steam "wagon" was designed to carry cannons, and it ran at almost 3 miles per hour (mph). It was heavy and hard to control, and after smashing into a wall it quickly lost support. By 1840, however, steam power was in regular use in steam coaches, railroads, and steamboats. Man's greatest dream, to fly through the air like the birds, was just starting to appear on scene. Hot air balloons got man into the air, but at the whim of the wind. To use steam power in a practical way to power an aircraft was an impossible dream. Steam engines were heavy and required both fuel and water. However, inventors were not deterred, and experimental aircraft using steam engines to turn large fans for propulsion appeared as early as 1882. French engineer Clement Ader built a series of light, steam-powered aircraft. One of these, the E'tole, weighted only 653 pounds (lb), including the operator. Witnesses said that the craft made a few hops, the longest being 165 feet (ft). Ader, however, had no means to control the craft.

Cugnot steam engine.

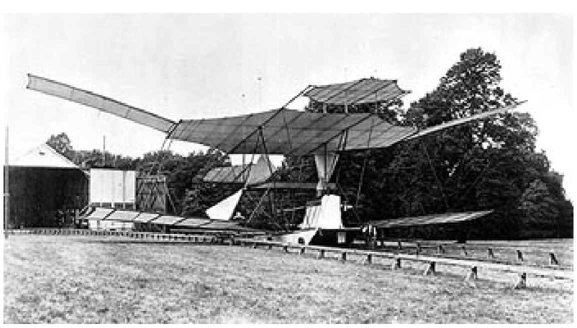
In the late 1880s American expatriate and inventor of the machine gun, Hiram Maxim, became interested in aviation and actually became the first person to pilot a self-propelled heavier-than-air craft. Spending £20,000 of his own funds, Maxim had a huge biplane craft constructed. It was about 200 ft from front to rear with a wingspan of 104 ft. Two 18-ft propellers were each turned by a separate steam engine that produced 180 horsepower (hp) and were run from a common boiler. The craft carried four people and weighed an astounding 8000 lb. On July 31, 1894, the craft moved down its 1800-ft launch rail and actually lifted off.



Hiram Maxim holds one of his steam engines.

A second restraining rail—set at a height of 9 inches (in.) and designed to keep the craft from gaining altitude—broke, and the craft rose almost 5 ft in the air for a distance of almost 1000 ft before a part of the structure broke and it crumpled to the ground. Although it lacked any form of adequate control in the air, Maxim's plane showed that an engine with sufficient horsepower—even steam engines—could make very heavy aircraft fly.

About this time another aviation pioneer, Samuel P. Langley, entered the race for powered flight. In 1897 he developed a steam-powered model aircraft that weighed 26 lb and had a 5-ft wing span that flew for over a half mile (mi). Langley's efforts to scale up this aircraft to be large enough to carry a pilot, however, proved to be very difficult.



Maxim's aircraft.

INTERNAL COMBUSTION PISTON ENGINES

During the period of time from 1860 to 1900 a number of creative people developed a variety of reciprocation piston engines that burned fuel within cylinders. The first patent for such an engine was by Samuel Morey of the United States in 1826. In 1858, Belgium-born Jean Lenoir patented a double-acting piston engine that ran on coal gas. He applied it to a three-wheeled vehicle that he drove 50 miles in 1862. The French inventor Alphonse deRochas created a piston engine that compressed the gas within the cylinder before ignition and placed it on a wheeled vehicle in 1862. Siegfried Marcus in Austria did the same in 1864. When removed from a museum cellar in 1950 Marcus's vehicle was still drivable!

In Germany in 1876, Nikolaus Otto patented the Otto cycle four-stroke engine consisting of intake, compression, ignition, and exhaust. Most cars still use the Otto cycle today. Gottlieb Daimler invented the first "modern" gasoline engine with vertical cylinders and a carburetor, which he patented in 1887. Karl Benz sold his first gasoline-powered cars in 1887.

During this same time, Samuel Langley had constructed a one-quarter-scale model of his previously steam-powered airplane but with a gasoline engine. It flew successfully in 1901 and was the first gasoline-powered aircraft.

In 1899, Wilbur and Orville Wright began constructing kites and gliders and unlocking the secrets of aerial control. In 1902 they developed a 32-ft glider that could be controlled along all three axes—pitch, roll, and yaw. In just 6 weeks during the winter of 1902–03, along with their mechanic Charlie Taylor, they built a lightweight four-cylinder aluminum block engine. They used their own wind tunnel data to design the first true aircraft propellers, which had an airfoil cross section and an efficiency of 66 percent, a great improvement over Maxim's flat blades. On December 17, 1903, they made the first controlled flight of a powered airplane at Kitty Hawk, North Carolina.

During this same time, Samuel Langley made a full-scale version of his successful quarter-scale model with a 5-cylinder, air-cooled radial engine that produced a remarkable 52 hp. Unfortunately, in two launch attempts in October and December of 1903, his aircraft's structure failed at launch.

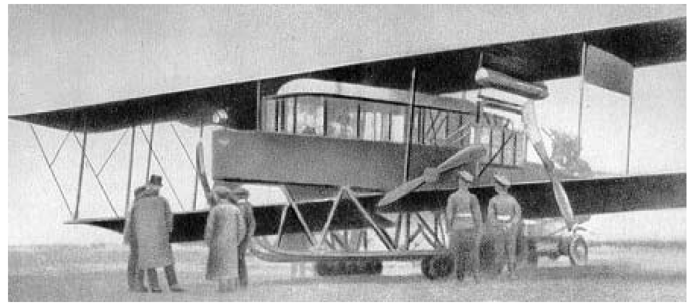
During 1904 and 1905, the Wrights built larger engines with increased horsepower. They also further improved their propeller design and by October of 1905 they could remain in the air until they ran out of gas—a period of over 30 min. For the next 3 years the Wright brothers stopped flying and concentrated on developing engines and securing patents.

Wright flyer.

By 1911 the Europeans, some of whom did not honor the Wrights' patents, had made a number of advances in aircraft design and developed many new aircraft. They found tractor propellers (front mounted) to be more efficient than pusher propellers. They tried 4-, 8-, and 12-cylinder engines as well as 3- and 5-cylinder rotary engines. Propellers with two, three, and four blades were also tried as well as propellers with variable pitch, but most engines of the day were only powerful enough to drive two-blade propellers. Planes were able to fly over 1100 mi in distance and above 13,000 ft in altitude, and they could stay aloft for over 28 hours (hr).

In 1913 Igor Sikorsky developed the first four engine aircraft that could carry 13 passengers. It would eventually create 600 hp and be used as a bomber in World War I. In January of 1914 he flew it from St. Petersburg to Kiev and back, a distance of 1600 mi. The war accelerated aircraft development among the European powers until by 1918 aircraft had reached speeds of up to 140 mph and effective altitudes (operating ceilings) of over 20,000 ft. The British Sopwith Dolphin carried a 300-hp Hispano-Suiza engine, while deHaviland was using a 400-hp American-made Liberty engine in its DH–4 aircraft.

The years after the war saw a number of young former military pilots looking to replace the thrill of combat flying. Some became barnstormers and members of aerial "circuses" while others got involved in air races. The races, especially the Schneider Cup seaplane trophy races, led various countries to accelerate the development of improved aircraft, particularly in the area of propulsion. Superchargers, which increased the pressure of the air entering the engine cylinders, first showed up in 1919 and greatly increased performance at higher altitudes. These were both mechanical and turbo powered. Another significant development was an engine block with built-in water cooling rather than exterior tube cooling. This improved the power-to-weight ratio from 1:2 down to 1:1.5, resulting in lighter, more powerful engines.



Sikorsky's four-engine aircraft.

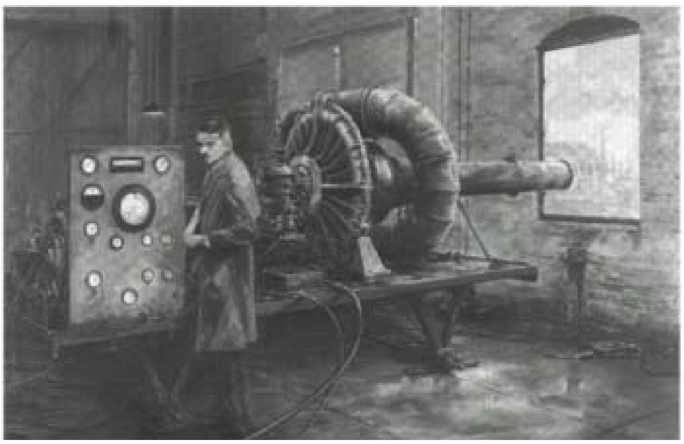
Advances were made in air-cooled radial engines, which had a much better weight-to-horsepower ratio than in-line engines. The development of the National Advisory Committee for Aeronautics (NACA) cowl helped to eliminate the drag caused by the large frontal area of a radial engine. Propellers were designed with controlled pitch and constant speed gearing to get maximum power under different load conditions: high-revolutions-per-minute (rpm) fine pitch at takeoff and low-rpm coarse pitch at cruise conditions.

By the end of the World War II, speeds of 440 mph and operation ceilings of 42,000 ft had been reached with piston-driven engines, producing up to 2200 hp.

P–51 Mustang.

TURBINE ENGINES

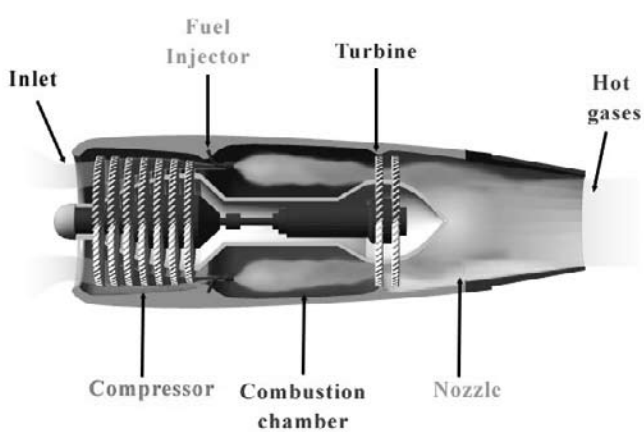
By the middle of World War II, nearly every variation of piston engines had been investigated. To get more power required more cylinders; this meant more cooling would be needed, and there was also a limit to the speed at which propellers could turn. As the tips approached the speed of sound, shock waves develop, which cause a loss of performance. Thus propellers had to actually be geared down as engine revolutions per minute (rpm) increased.



Frank Whittle demonstrating the first jet engine.

In 1928 a young Royal Air Force (RAF) cadet named Frank Whittle designed a gas turbine engine and took out a patent in 1930. No interest was shown in his ideas because strong enough metals had not yet been developed. By 1937 the alloys were available so Whittle renewed his patent and ground tested his engine. In 1941 it propelled a Gloster E28/39 fighter plane at over 400 mph.

During this same time a young German engineer, Hans von Ohain, independently patented a gas turbine engine, and on August 27, 1939, it flew in a Heinkel He178 aircraft. Improvements were made, including attempts at turboprops. Turbine-powered planes (jet planes or turbojets) entered combat near the end of World War II, but they did not have much of an impact on the outcome of the war.



Turbojet engine.

After the war, development of turbine engines greatly accelerated since they had a much better power-to-weight ratio than piston engines and could run many more hours before maintenance. The first turboprop airline service began in 1948, and the first turbojet airline began in 1952 with the De Havilland Comet. In the 1950s Rolls-Royce introduced the first turbofan engine, the Conway, a low-bypass turbine with a ratio of 0.3:1.0, where 0.3 liters (L) of air went around (bypassed) the engine for every 1.0 L that went through the core for combustion. Today's high-bypass engines will run up to a ratio of 17:1 for bypass air.

ROCKET ENGINES

During World War II, the Germans developed a rocket-propelled plane called a Komet. It was very fast but ineffective mainly due to high fuel consumption. After the war, the Bell Aircraft Company built the rocket-powered Bell X–1. Launched from a B–29 bomber at 23,000 ft, the "Glamorous Glynnis" piloted by Chuck Yeager reached a speed of Mach 1.06, or 1.06 times faster than the speed of sound. This broke the sound barrier for the first time.

Bell X–1.

In the 1960s the North American X–15, a rocket plane, became the first aircraft to go Mach 6 and fly above 100,000 ft.

X–15 rocket plane.

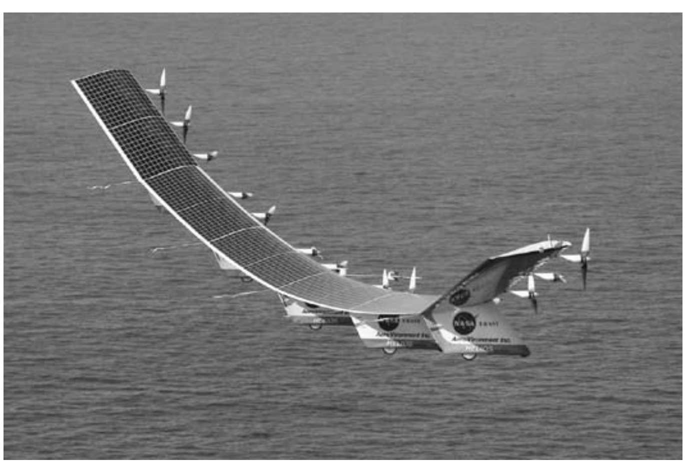
ANIMAL POWER AGAIN

After all this speed and power, materials were developed that were so strong and yet so lightweight that on August 23, 1977 the “Gossamer Condor” an extremely light pedal-powered plane flew a figure eight in the air. Less than two years later the “Gossamer Albatross” crossed the English Channel powered only by the pilot turning pedals. We have seemingly come full circle in means of propulsion.

Gossamer Albatross.

SOLAR POWERED ELECTRIC MOTORS

A NASA program researched high-altitude long-duration flights based on solar power. In 1977 the first solar-powered airplane, the “Solar Challenger,” flew six miles. In 2001 the 247-ft wingspan solar plane “Helios” built by NASA achieved a height of 98,000 ft. Only rocket planes have gone higher.



Solar Challenger.

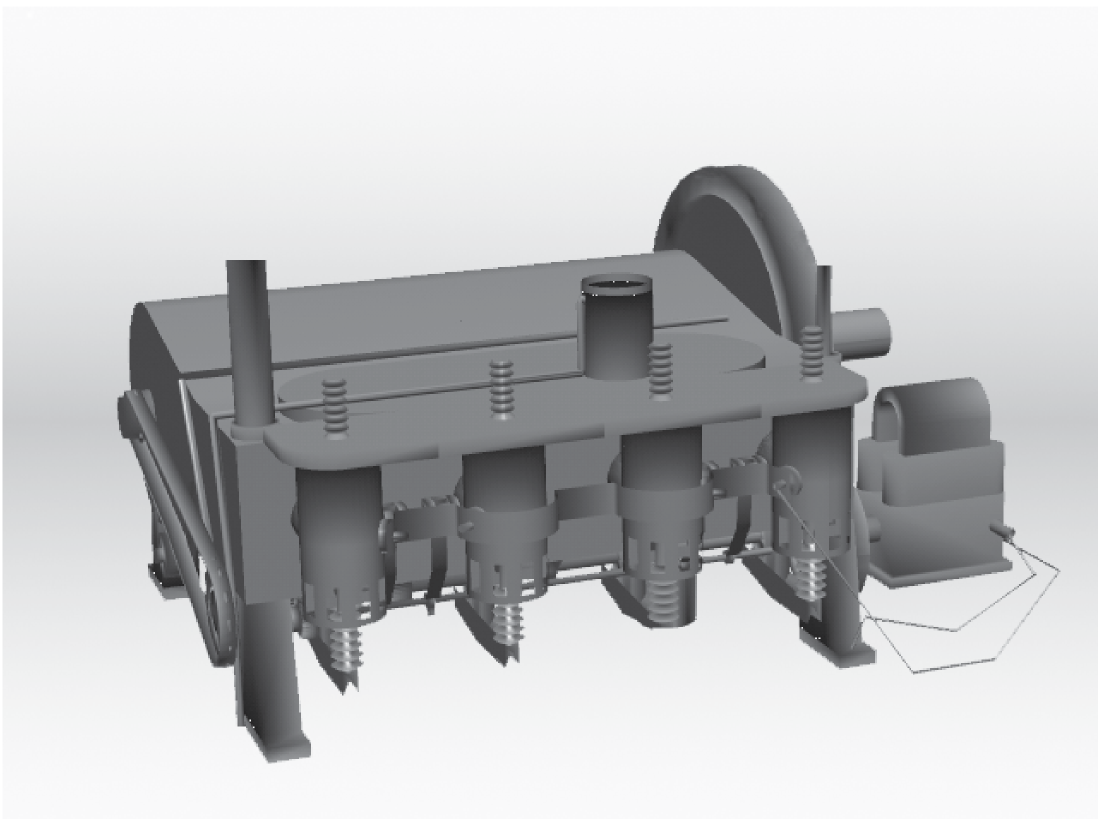
EXOTIC ENGINES

As man seeks to fly faster, higher, and further into space, new engines have been developed. Ramjets and scramjets fly in the atmosphere in the hypersonic range, scooping oxygen from the atmosphere to avoid carrying it like rockets. On November 16, 2004, NASA’s X–43A unmanned scramjet achieved an astounding speed of nearly Mach 10! Ion propulsion engines produce a small amount of thrust by accelerating charged particles. Over a long period of continuous operation they efficiently accelerate spacecraft to extremely high speeds for deep-space travel.

NASA X–43A scramjet.

Ion propulsion engine.

TYPES OF ENGINES



Internal Combustion (Piston) Engines

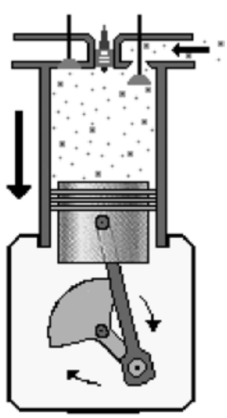
For the 40 years following the first flight of the Wright brothers, airplanes used internal combustion engines to turn propellers, which generate thrust. Today, most general aviation or private airplanes are still powered by propellers and internal combustion engines, much like your automobile engine.

As the name implies, the combustion process of an internal combustion engine takes place in an enclosed cylinder where chemical energy is converted to mechanical energy. Inside the cylinder is a moving piston which compresses a mixture of fuel and air before combustion and is then forced back down the cylinder following combustion. On the power stroke the piston turns a crankshaft, which converts the linear (up and down) motion of the piston into circular motion. The turning crankshaft is then used to turn the aircraft propeller. The motion of the piston is repeated in a thermodynamic cycle called the Otto Cycle, which was developed Dr. N. A. Otto of Germany in 1876 and is still used today. For a complete discussion of piston engine operation look at the following Web site:

http://www.grc.nasa.gov/WWW/K-12/airplane/otto.html

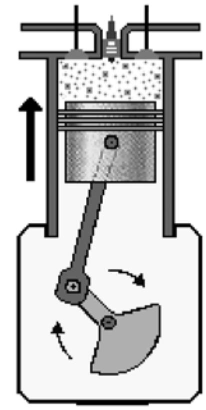
INTAKE

The first stroke of this four-stroke process is called INTAKE. As the piston moves down from the top of the cylinder, called “top dead center,” the intake valve opens and a mixture of air and a very fine mist of fuel, usually gasoline, is drawn into the cylinder at constant pressure. The ideal mixture is about 14.7 parts air to one part fuel. This means that 1 lb of gasoline uses 115 lb of air! In your car engine this fine mist of fuel is sprayed directly into the intake by a fuel injector. The fine mist of liquid fuel provides a great deal of surface area that can react quickly with the oxygen in the air.


Intake

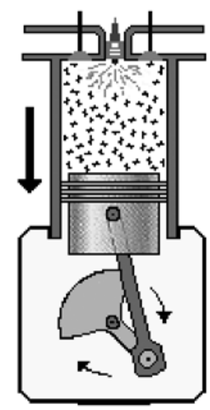
COMPRESSION

The second stroke is COMPRESSION. When the piston reaches “bottom dead center” the intake valve closes, sealing the cylinder, and the piston moves back up the cylinder. As the volume is decreased, the piston does work on the gas mixture. The fuel-air mixture is compressed to about one-ninth of its volume, raising its temperature and increasing its pressure. Now the gas particles are very close together so they will be able to react quickly when ignited.


Compression

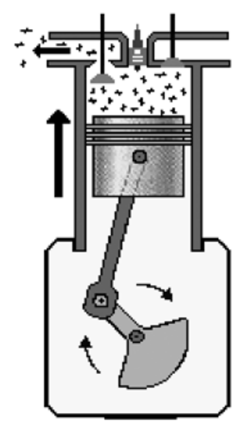
POWER

As the piston nears top dead center, a surge of high-voltage current is sent to the spark plug. This produces a high-energy spark, which ignites the compressed air-fuel mixture. The fuel rapidly combines with the oxygen (burns) and produces carbon dioxide gas and water vapor. These hot gases expand and exert tremendous force on the piston, driving down the cylinder and turning the crankshaft. This is called the POWER stroke, and work is done by the gases.

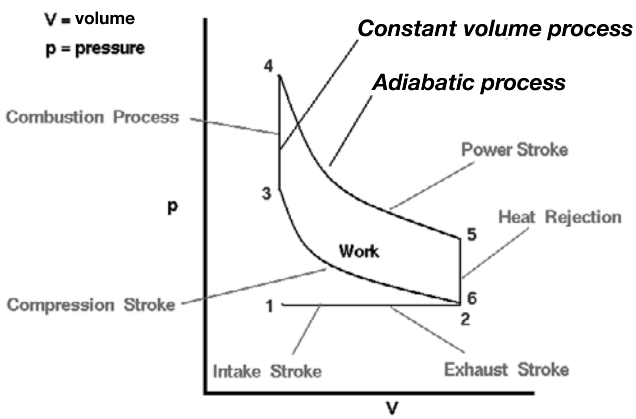

Power

EXHAUST

Once bottom dead center is reached and the piston starts back up the cylinder, the EXHAUST stroke begins. The exhaust valve opens, residual heat is exchanged (released), and pressure returns to atmospheric conditions. The piston pushes the waste gases out of the cylinder, and the process is ready to begin again.


Exhaust

The amount of power derived from this type of engine depends on a number of factors. There is no work done by either the intake or exhaust cycle, so half of the strokes of the engine do nothing to add to or subtract from the engine's performance. The remaining strokes determine the work available from the engine.



Ideal Otto cycle.

In an ideal Otto cycle, as shown on this diagram, the area enclosed between the compression stroke (2–3) and the power stroke (4–5) is the work done by the engine. To increase the amount of work done this area needs to be made larger. Increasing the volume of the cylinder, having more cylinders, raising the pressure, decreasing the volume during compression, or forcing more air into the cylinder (supercharging) are all ways this can be accomplished. With aircraft engines these changes cause some problems. Increasing the number or size of the cylinders adds weight to the engine and creates more heat that must be dissipated. Some aircraft engines are air-cooled to save weight, and radial arrangements of cylinders as shown below allow for more cooling but increase drag. Others are water cooled, requiring the additional weight of a radiator and water. Raising the pressure in the cylinders creates more heat, stresses metal, and requires special fuel to prevent knocking. Engineers are always trying to maximize the balance between the positive and negative forces in any processes.

Radial engine.

Also note that the Otto cycle to the left is labeled "ideal." In actual operation, gasoline engines are in the range of 30 percent efficient because gases don't burn instantly at constant volume, there are losses due to friction, and much of the heat generated goes to waste in the radiator and exhaust rather than to power.

Types of Turbine Engines

In turbine engines, air is drawn in and compressed, fuel is added and burned, and the hot gases expand out the rear of the engine, pushing the aircraft forward. Some of these exhaust gases turn a turbine, which drives the compressor. A number of different types of gas turbine engines have been developed for use depending upon the specific needs of a particular type of aircraft.

BASIC TURBINE ENGINES, OR TURBOJETS

Turbojets were the first type of turbine engines developed. All the thrust of these engines comes through the turbine and nozzle, which is called the core of the engine. These are what people commonly refer to as jet engines.

Lear jet.

TURBOFANS

These engines have a central engine core that uses about 10 percent of the intake air while a large turbine-powered fan pushes about 90 percent of the intake air around the outside of the core to produce the majority of the thrust. These are used on most commercial passenger aircraft because they make more thrust for every pound of fuel burned in the core.

DC–9.

TURBOPROPS

In a turboprop engine the turbine section takes most of the energy from the exhaust gas stream and uses it to turn a propeller as well as the compressor. These are often found on slower cargo aircraft and on helicopters.

Cargo.

AFTERBURNING TURBOJETS

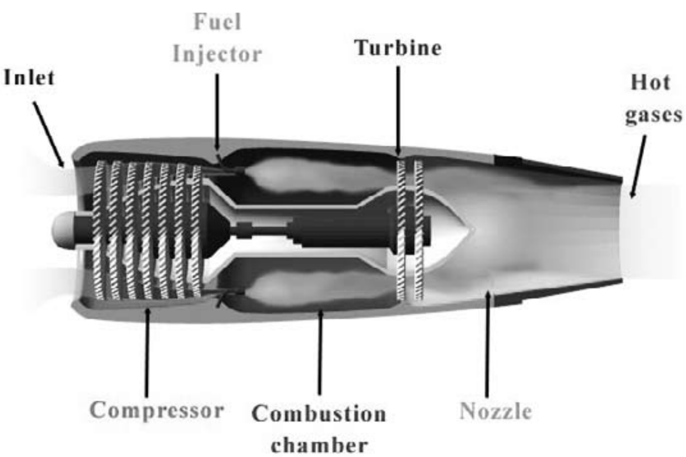
Afterburners are used only on supersonic fighter aircraft and only for short periods of time. Fuel is injected into the hot exhaust stream to produce additional thrust, allowing for high speed at a cost of high fuel consumption.

Fighter.

Turbojet Engines

TURBOJET

The turbojet engine, developed for aircraft in the years prior to World War II, was a departure in thinking from the standard piston engine. Instead of burning fuel in a confined space that is dependent upon precise timing of ignition, the turbojet engine is essentially an open tube that burns fuel continuously. According to Newton's Third Law (see "Newton's Laws" in chapter 4, "Physics and Math"), as hot gases expand out from the rear of the engine, the engine is accelerated



Cutaway view of turbojet engine.

in the opposite direction. The engine consists of three main parts, the compressor, the burner, and the turbine, along with the inlet, shaft, and nozzle, as shown above.

A large mass of air enters the engine through the INLET and is drawn into a rotating COMPRESSOR. There are two types of compressors, centrifugal and axial. The axial type is shown above. The compressor raises the pressure of the air entering the engine by passing it through a series of rotating and stationary blades. As the gas is forced into smaller and smaller volumes, the pressure of the gas is increased. The gas also heats up as its volume is decreased by the compressor. Today's compressors can have a compression ratio of over 40:1, much higher than a piston engine. Also, in order to maximize the engine's performance, turbojets will have two different compressors operating on different shafts: a low-pressure compressor followed by a high-pressure compressor.

At the BURNER stage fuel is injected and ignited, raising the energy of the gas by raising it's temperature. A typical engine will add about 2 lb fuel/second (s) for every 100 lb air/s. The energy of the gas increases dramatically and is accelerated toward the turbine(s) due to the high pressure created by the compressor. Since these engines can produce temperatures well over the melting points of the materials used to make the turbine, only 12 to 25 percent of the air from the compressor is combusted while the rest cools the combusted gases down to temperatures just below that which would damage the turbine. The larger the difference between the temperature of gas at the turbine face and that of the outside air, the more thrust is created and the more efficient the engine.

The next stage is the TURBINE. Here the heated gas passes over the turbine blades causing them to rotate and, in turn, to rotate a shaft that is connected to the compressor. The turbine removes some energy from the flow to drive the compressor, but there remains sufficient energy in the gas to do work as it exits the nozzle.

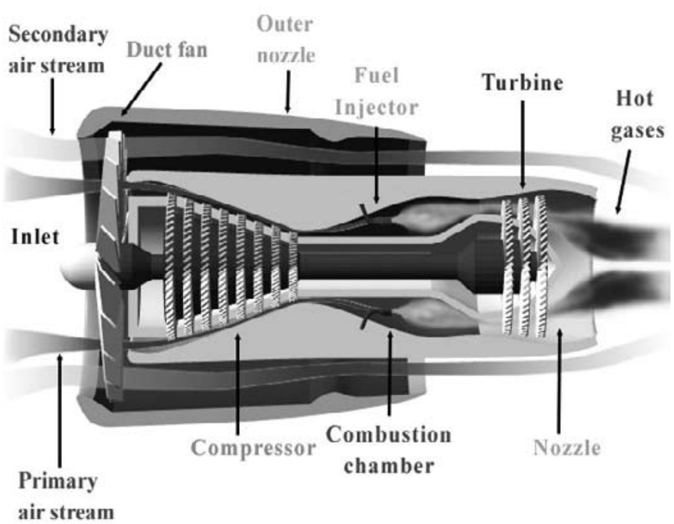
The purpose of the NOZZLE is to convert energy into velocity thus producing thrust. The nozzle allows the flow of hot gases to exit the rear of the engine until they reach free-stream pressure, which creates the thrust of the engine. Most nozzles restrict the flow somewhat before allowing it to expand. This creates additional pressure and thus, additional thrust. It also controls the mass flow through the engine, which along with the velocity, determines the amount of energy the engine produces.

Overall, turbine engines have a much higher power-to-weight ratio than piston engines. They can operate at much higher temperatures and can produce much more thrust than propeller engines. However, they are less efficient at low speeds and low altitudes.

Turbofan and Turboprop Engines

TURBOFAN

A turbofan is a modified version of a turbojet engine. Both share the same basic core of an inlet, compressor, burner, turbine, and nozzle, but the turbofan has an additional turbine to turn a large, many-bladed fan located at the front of the engine. This is called a “two-spool” engine. One spool is used to power the compressor and another spool to turn the large fan. Some of the air from this large fan enters the engine core where fuel is burned to provide some thrust, but up to 90 percent of it goes around or “bypasses” the core of the engine. As much as 75 percent of the total thrust of the engine comes from the bypass air. Although there is less energy added to this bypass air compared with that going through the core, by moving a very large amount of air the turbofan gets a large boost in thrust for very little additional fuel. It is thus a very fuel-efficient engine and good for cruising.

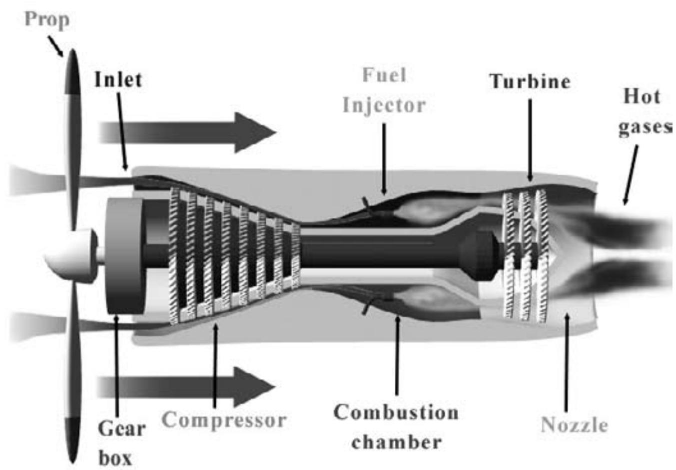


Cutaway view of turbofan engine.

Also, since the fan has many blades and the air is ducted, turbofans can operate faster and more efficiently than simple propeller aircraft. The pressure ratio of a 50-blade ducted fan may be 1.4 to 1.6 (i.e., the pressure is increased by a factor of 1.4 to 1.6), whereas a propeller may have a pressure ratio of only 1.02. This is why large passenger planes using turbofans are able to cruise at high subsonic speeds and still use fuel efficiently. Even jet fighters will often use low-bypass turbofan engines, where a smaller amount of air bypasses the core, so they can conserve fuel while in cruising mode.

TURBOPROP

This engine is a hybrid of a turbojet and a propeller engine. It has at its heart a turbojet core to produce power, but with two turbines. The first turbine powers the compressor while the second powers the propeller through a separate shaft and gear reduction. The gears are necessary to keep the propeller from going supersonic and losing efficiency.



Cutaway view of turboprop engine.

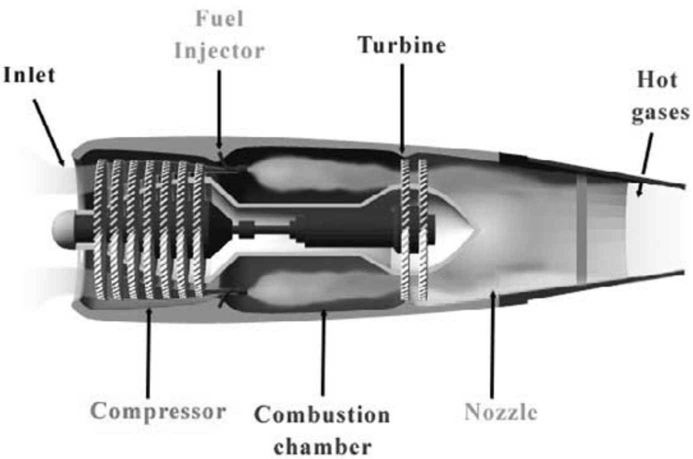
Unlike a basic turbojet, the second turbine removes most of the remaining energy from the flow to power the propeller and less than 10 percent of actual thrust is produced by the core. Turboprops operate well in the low subsonic range, with much more power than a piston-driven propeller aircraft. This is why turbojets are used by long-range military cargo planes.

Another version of the turboprop is the turboshaft engine. Instead of driving a propeller, the shaft is used to power such things as helicopters, tanks, train engines, and even race cars.

Afterburning Engines

AFTERBURNING TURBOJET

This engine is a turbojet with the added capability of injecting fuel into the hot gases after they have passed through the turbine. The fuel ignites to produce additional thrust of over 50 percent.



Cutaway view of afterburning engine.

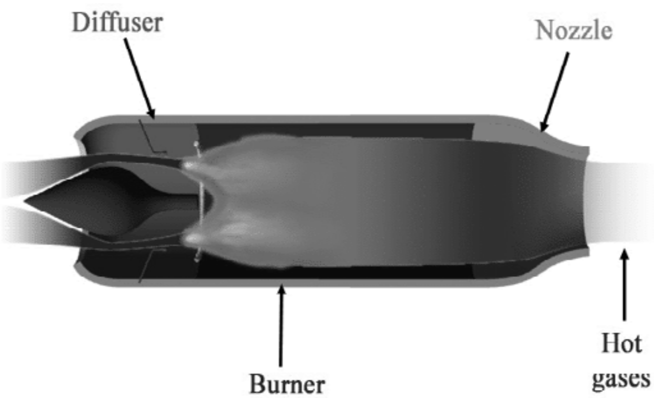
Since most of the compressor air has not been used for burning in the combustor, there is sufficient hot oxygen available to burn this added fuel. Stabilizer rings hold the flame and keep it from getting blown out the back of the engine. A variable nozzle is used to change how the gas leaves the engine, producing maximum thrust when the afterburners are used.

The afterburner does not burn fuel as efficiently as the combustors, so its operation dramatically increases fuel consumption. Thus, it is generally only employed on fighter aircraft to gain short bursts of speed such as in short takeoffs and in dog fighting. Otherwise, the aircraft would quickly run out of fuel.

Ramjet and Scramjet Engines

RAMJETS

Rockets are a proven way to accelerate crafts to very high speeds, but rockets must carry their own supply of oxidizer as well as fuel. About 82 percent of the mass of the external tank of the space shuttle is liquid oxygen (oxidizer). Ramjets are designed to scoop up their oxygen from the atmosphere and eliminate this extra weight.



Cutaway view of ramjet engine.

Thrust is produced by passing hot, combusted gases through a nozzle where the nozzle accelerates the flow. To maintain flow, combustion must occur at a pressure higher than the nozzle pressure. In a standard turbojet engine this pressure is created by the action of the compressor.

In a ramjet, however, there is no compressor. Instead, the forward speed of the vehicle is employed to “ram” air into the combustor. At supersonic speeds air enters the intake where a diffuser nozzle causes the air to slow down to around Mach 0.2 through a series of shock waves. This sudden slowing creates the pressure needed to operate the engine. Fuel is injected and burned with the aid of a flame holder. Since there is no compressor to power, there is no need for a turbine and the hot gases expand directly out the nozzle. It is important to note that, other than an external turbopump to inject fuel, the ramjet has no moving parts and is lighter in weight than a turbojet. It also can operate at higher temperatures than a turbojet because there is no turbine that might melt: thus it is more efficient.

The downside is that the ramjet engine can only work when the vehicle is already moving at a considerable speed. A ramjet produces little thrust below about half the speed of sound and works best when operating at low supersonic speeds (ranging from Mach 1 to 3)—

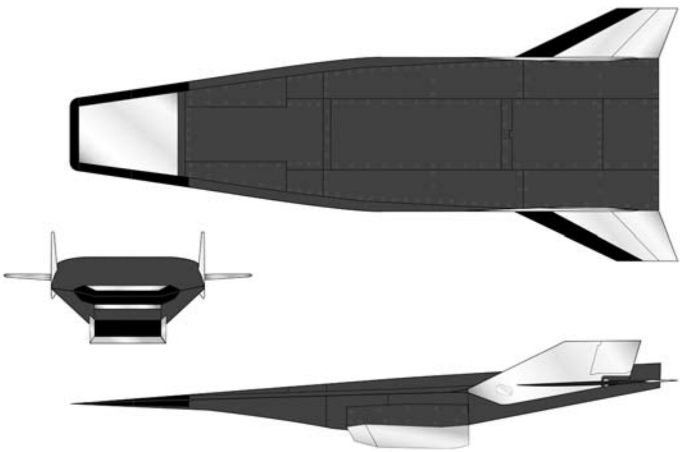
SR–71 Blackbird.

where they are more efficient than turbojet aircraft. Depending on their design, ramjets will operate best at different ranges (operational envelope) of Mach number and altitude. Design factors must also compensate for increased drag, which increases with the square of the Mach number.

Ramjet engines were experimented with in the early 1950’s in such programs as the Lockheed X–7 and the French Leduc and were used in some missile systems such as the Bomarc. The SR–71 Blackbird reconnaissance plane used some ramjet principles in what would become known as “bypass engines.” At low aircraft speeds, all of the air went through the inlet, compressor, burner, turbine, afterburner, and nozzle. At high speed, the inlet did most of the compressing where much of the air was ducted around the later stages of the compressor, burner, and turbine, and injected directly into the afterburner with some air still passing through the core of the engine. This arrangement achieved a speed slightly over Mach 3.2.

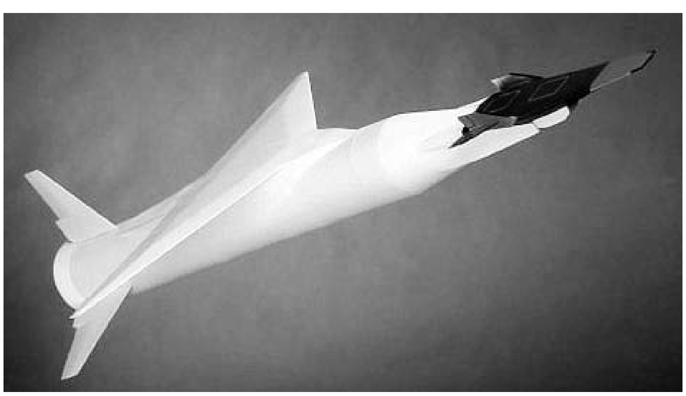
SCRAMJETS

When the speed of a ramjet increases above Mach 5, the temperature in the combustion chambers would exceed 2000 °C. At this temperature the air is so hot that not much additional energy can be gained by burning fuel. There would also be some serious material damage to the inside of the engine.



Three views (top, front and side) of X–43A Hypersonic Experimental Vehicle.

Scramjets are a way to overcome this speed limitation. In a scramjet (supersonic combustion ramjets), the incoming air is not slowed down to subsonic speeds, but is burned at supersonic speed. This creates other problems. The biggest of these is getting the fuel to mix efficiently with the air and burn in milliseconds or less before it exits the nozzle. It has been shown that hydrogen gas can be made to mix efficiently and burn under these conditions.



Model of X–43A mounted on nose of Pegasus rocket.

Airframes need to be extremely aerodynamic to minimize temperature increases resulting from the friction they experience when slamming into air at such high speeds. The frictional energy from any colliding air is transferred to the airframe, and temperatures can get high enough to destroy the aircraft. The diagram at the left shows how the nose of NASA's X–43A is designed to slice through the air and eliminate as much drag as possible.

Pegasus with X–43A (in circle) mounted under wing of B–52 launch plane.

Also, like in regular ramjets, the scramjet must be accelerated to an operational velocity around Mach 5. One way to do this is to use a rocket as shown on the model at the lower left. On November 16, 2004, NASA successfully flew the X–43A at Mach 9.6 by first having a B–52 carry the first stage of a Pegasus rocket with an X–43A attached (see inside the circle, on the photograph above) to an altitude of 40,000 ft. At that point the Pegasus was dropped and ignited. It carried the X–43A to an altitude of around 110,000 ft where the rocket released the X–43A to fire its own scramjet engine.

At present much more research needs to be done on hypersonic flight, where it is predicted that scramjets may some day reach speeds between Mach 10 and 25.

Ion Engines

In 1959, Dr. Harold Kaufman of the NASA Lewis (now Glenn) Research Center built the first ion propulsion engine. This type of engine works by creating ions (charged particles) and then ejecting the ions at high speeds to push the spacecraft forward.

Dr. Harold Kaufman

A cathode produces high-energy electrons, which, along with a propellant like xenon, are injected into a diffusion chamber. When these two collide, additional electrons are knocked off the xenon atoms, creating positively charged xenon ions. At the downstream end of the engine are two charged grids containing thousands of coaxial apertures, the first grid is positively charged and the second is negatively charged.

The positive xenon ions in the discharge plasma have a higher voltage than the positive grid and therefore are attracted to it. As they pass through this first grid they are highly accelerated by the attraction of the negative grid since opposite charges attract. The grid design sets up a potential gradient that focuses the xenon ions through the holes in the negative grid so they accelerate out the back of the engine at speeds of up to 60,000 mph. Electrons are then injected into the positive beam so the engine does not build up a charge over time.

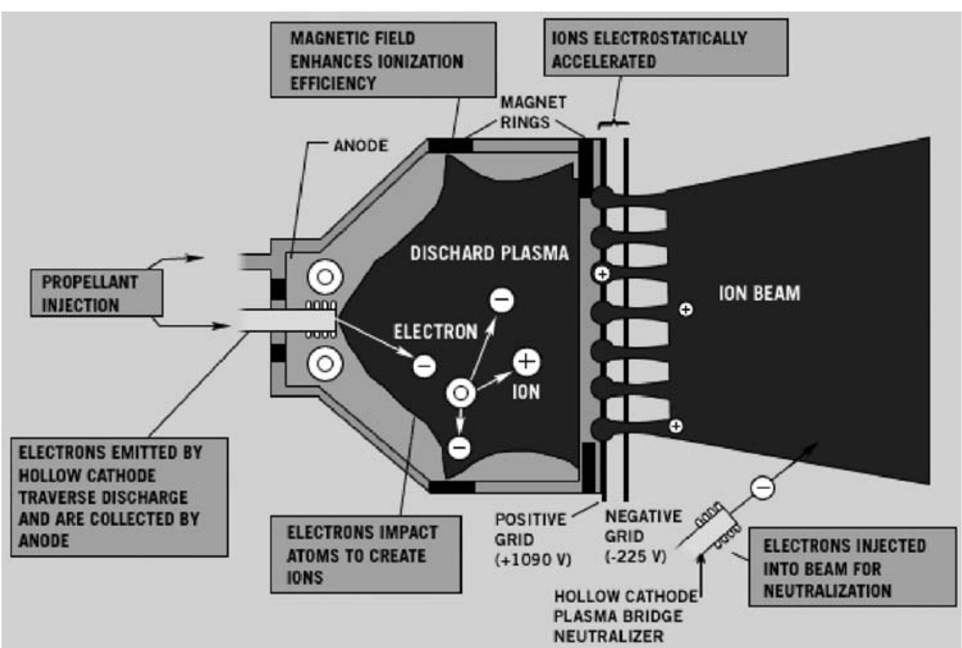


Diagram of ion engine.

Thrust *T* is equal to the product of the mass flow rate $\dot{m}$ of the fluid and its velocity *V*:

$$T = \dot{m}V^2$$

For ion engines, *V* is very large but $\dot{m}$ is very, very small. Consequently, the thrust produced is very small, especially when compared to chemical rockets. On the space shuttle, the main engines, which are chemical rockets, produce 5 million watts (W) of power; the NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) ion thruster engine on the Deep Space 1 probe produces only 10,000 W of power. The accelerating force of an ion engine is about equal to the weight of 22 pennies. The advantage, however, is twofold.

First, unlike chemical rockets, ion engines do not have to carry any oxidizer, only fuel. Eighty-two percent of the weight of the external tank on the space shuttle is liquid oxygen. Thus, ion engine systems are relatively lightweight and can carry more payload.

Second, rather than applying thrust and accelerating for minutes like a chemical rocket, the ion engine thrusts and accelerates for many months. This gentle push over an extended period of time can result in speeds of 200,000 mph. In comparison, chemical rockets can reach speeds of up to 25,000 mph. Ion engines are about 10 times more efficient, but the must operate over a long period of time to reach their operating potential. This means that they cannot be used to launch payloads from Earth, but once in space they can accelerate payloads.

The electricity to operate the cathode and charge the

Testing an ion engine.

grids typically comes from solar panels. Among the inner planets there is sufficient power to run the engine at full power, but beyond this there is less and less solar energy available to collect. In these deeper space missions, the heat from onboard nuclear fuel is used to generate the electricity needed to create the ions and charge the grids of the ion engine. Unlike chemical rockets, which generally are either on or off, ion engines can operate at a variety of thrust levels. The NSTAR ion thruster engine can throttle down from 2.5 kW to a minimum of 500 W to conserve fuel on long missions.

Finally, because they can operate for such long periods, ion engines can be used in station keeping for Earth-orbiting satellites. A geosynchronous orbit keeps a satellite located above the same spot on the equator all the time. Gravitational forces of the Sun and Moon cause this orbit to change by about 1° a year, so some propulsion is needed to counteract this and keep these satellites in the correct orbit. An ion engine is perfect for the job.

Alternative Means of Propulsion

Perhaps the biggest dream in powered flight is to be able to obtain energy directly from the surroundings and not have to carry the additional weight of fuel. An extreme example of this would be human-powered aircraft. The Gossamer Condor was the first successful aircraft of this type, flying 1.35 mi in 1977. Its successor, the Gossamer Albatross, crossed the English Channel in 1979 with the pilot generating one-third of a horsepower as he pedaled the aircraft. The current distance record for human-powered flight was set in Greece by the Daedalus Project aircraft, which flew 109 kilometers (km).

Gossamer Albatross.

Another “no fuel” approach is to use solar cells, which convert the energy of sunlight directly into electricity. Since 1980, AeroVironment, Inc., in conjunction with NASA Dryden, has been developing this type of aircraft. Solar cells were placed on the top of the wings, and the electricity they generated powered electric motors that drove propellers on the lightweight craft. As part of NASA’s Environmental Research Aircraft and Sensor Technology (ERAST) program, the Solar Challenger reached an altitude of 14,300 ft in 1980. In 1981 with 16,128 solar cells on its wings, it flew 163 mi, crossing the English Channel in the process. By 1995 its successor, the Solar Pathfinder, had flown to an altitude of 50,500 ft, and in 1998 the modified Pathfinder-Plus set an altitude record of 80,201 ft for a propeller-driven aircraft. It had a wingspan of 121 ft and used newer solar cells that were 19 percent efficient as compared with a 14 percent efficiency on previous models. These newer solar cells developed 12,500 W of power.

The latest model was Helios with 62,000 solar cells mounted on a 247-ft-long wing producing 35,000 W of power. This aircraft was designed for long-duration as well as high-altitude flights, meaning that some method of obtaining power at night was required. Since batteries would add too much weight to the aircraft, a system of fuel cells was used to generate electricity. One system used solar energy during the day to separate hydrogen gas and oxygen gas from water and then stored the gases under pressure. The gases would be recombined to make water in the fuel cell, which generated the electricity to keep the electric motors running at night. The water was stored to be reused when the Sun came up, and the whole process repeated itself. Helios set an unofficial altitude record for nonrocket-powered aircraft of 98,863 ft in 2001. Unfortunately, in June of 2003, turbulent wind conditions caused the craft to begin to undulate out of control, and it crashed into the Pacific Ocean.

Helios in flight.

Solar aircraft suffer from the limitation of weight and weather. They cannot fly in high winds or bad weather and the power limitations of solar cells limit the overall weight of the airframe so that payloads are limited. As the efficiency of solar cells improve, this type of aircraft will become more viable.

CHEMISTRY

Gas Laws

Nearly all of the sources of propulsion for aviation, from steam engines to turbines, depend upon engines that do work on gases. Knowledge of gas behavior, therefore, is essential to understanding how these engines function.

Of all the three common states of matter, gases have a unique set of properties. In solids, intermolecular forces (the forces between molecules) are strong enough to keep molecules vibrating about fixed positions so that solids have a definite shape and volume. As the temperature is raised, the molecules can gain enough kinetic energy to overcome some of these attractive forces and the substance melts. At this point the liquid molecules have enough attraction to have a definite volume, but not enough to stay in a fixed position. Liquids take the shape of their container. Raise the temperature high enough and the molecules move fast enough to overcome nearly all the remaining intermolecular forces so that the substance becomes a gas. Gases both fill their container and take its shape. In the case of many small molecules like oxygen, methane, or carbon dioxide, the forces between molecules are so small that these substances are already gases at room temperature.

Because the motion of these widely spaced gaseous molecules is random, they collide with each other and with the walls of their containers, creating the force we call pressure. Because gas molecules are so far apart, gases are compressible and readily mix. Unlike solids and liquids, a gas can undergo significant changes in pressure and volume. The mathematical expressions that describe these changes are called the gas laws. Be aware that the laws discussed here apply to what is termed an "ideal gas," where all interactions between molecules and the volumes of the molecules themselves are ignored.

BOYLE'S LAW

In 1662, the Irish scientist Sir Robert Boyle published the results of his experiments with a trapped volume of air in a "J" tube. Boyle added different amounts of mercury to vary the pressure on the trapped air and discovered that the volume of gas varies inversely with the pressure (the temperature remaining constant). If the pressure on a gas is increased by adding more mercury, the volume of the air decreased. This relationship has come to be known as "Boyle's Law" and states that

$$(\text{Volume})(\text{Pressure}) = a$$

where "*a*" is a proportionality constant specific to each gas. On a molecular level, as the pressure increases the molecules are forced closer together and the space between the gas particles decreases. Thus the volume of the gas decreases.

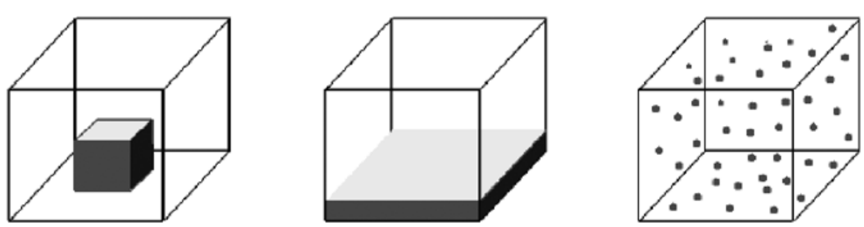
CHARLES'S LAW

Jacques Charles was a French experimenter who developed the first hydrogen-filled balloon. In observing gases around 1787, he developed the theory now known as "Charles's Law." What Charles had noticed was that the volume of a gas is directly proportional to the temperature. If the temperature goes up, the volume goes up. This would be expressed as

$$\frac{\text{Volume}}{\text{Temperature}} = b$$

where *b* is a proportionality constant specific to each gas.

It is important to note that the temperature used must be absolute temperature. An absolute temperature scale such as the Kelvin scale starts with zero at the coldest temperature possible, which is



Solid

Holds shape

Fixed volume

Liquid

Shape of container

Free surface

Fixed volume

Gas

Shape of container

Volume of container

Three states of matter.

absolute zero. The Celsius (C) scale has zero at a point well above absolute zero (–273 °C), so a change from 10 to 20 °C would not be a true doubling of temperature. The Kelvin temperature scale uses the same size degrees as the Celsius scale, and since it starts with absolute zero as zero, it has no negative temperatures. The units are called kelvins (not degrees kelvin), and the abbreviation is K (not °K). Add 273 to the Celsius temperature to convert to kelvins; 0 °C is equal to 273 K.

GAY-LUSSAC'S LAW

Joseph Louis Gay-Lussac, a French scientist who studied gases and reactions, proposed a relationship between the pressure of a gas and its absolute temperature. Gay-Lussac found they are directly proportional, and his law (also known as Amonton's law or the Constant Volume law) can be stated as

$$\frac{\text{Pressure}}{\text{Temperature}} = c$$

where *c* is a proportionality constant specific to each gas. Again, absolute temperature must be used.

The relationships discussed in this section can be further investigated in the "Animated Gas Lab" in NASA Glenn's Beginner's Guide to Propulsion found at the following Web site:

http://www.grc.nasa.gov/WWW/K12/airplane/Animation/frglab.html

Gas Laws Problems—Boyle's Law

INSTRUCTIONAL OBJECTIVES

Students will

- Recognize that gas volume and gas pressure are directly proportional
- Evaluate energy available in different compounds
- Recognize the need for oxygen in combustion

NATIONAL SCIENCE CONTENT STANDARD B

Chemical reactions

- Chemical reactions may release or consume energy. Some reactions, such as burning fossil fuels, release large amounts of energy by giving off heat and emitting light.
- In gases, molecules or atoms move almost independently of each other and are mostly far apart.

INTRODUCTION

Boyle's law relates the changes in pressure and volume for an ideal gas when the temperature is held constant. In real piston and turbine engines the temperature does not remain constant, and Boyle's law does not really apply. A much more complex relationship exists between pressure and volume in real engines. As a first approximation, however, assume that the temperature is constant in the problems below and apply Boyle's law. For another example of how these are related, see the Web site below:

http://www.grc.nasa.gov/WWW/K-12/airplane/compexp.html

Example Problem:

The Allison V-1710 was a water-cooled piston engine used during World War II. It was a 12-cylinder, 28.0-L engine with a compression ratio of 6.65:1 (i.e., the volume decreases by a factor of 6.65). If the atmospheric pressure is 760 millimeters of mercury (mm Hg), what is the maximum pressure in one cylinder due to piston compression?

Solution:

a. First find the maximum volume of just one cylinder. This would be the volume when the piston is at bottom dead center.

$$\frac{28.0\text{ L}}{12\text{ cylinders}} = 2.33\frac{\text{L}}{\text{cylinder}}$$

b. Now use Boyle's law. Since (Volume)(Pressure) = a where a is a constant,

(Old Volume)(Old Pressure) = (New Volume)(New Pressure)

Since the compression ratio is 6.65:1, the new volume will be 1/6.65 of the original volume:

$(V_1)(P_1) = (V_2)(P_2)$ $\qquad$ $(2.33\text{ L})(760\text{ mm}) = \left(\frac{2.33}{6.65}\text{L}\right)x$ $\qquad$ $x = 5054$ mm

CHEMISTRY

PROBLEMS

1. Diesel engines run at high compression. A 12-cylinder marine diesel has a total displacement of 139.7 L and a compression ratio of 25:1. What is the highest pressure reached in one of the cylinders if the atmospheric pressure is 745 mm Hg?

2. In a model airplane one-cylinder engine the bottom dead center volume of the cylinder is 0.90 in^3. If the atmospheric pressure is 775 mm at bottom dead center, and if the pressure at top dead center is 7926 mm, what is the volume of the gas at top dead center?

3. A turbojet engine has 900 ft^3 of air enter the compressor and leave at a volume of 35 ft^3 and a pressure of 28.8 atmospheres (atm). What would the atmospheric, or "free stream," pressure be?

4. While an airliner is waiting at a terminal at the airport, a small auxiliary turbine engine is used to provide power for airconditioning and so forth. If the outside air pressure is 740. mm and the turbine engine has a compressor ratio of 8.5:1, what volume of air would need to be drawn into the engine to have 1.00 ft^3 of air in the combustor?

Gas Laws Problems—Charles's Law

INSTRUCTIONAL OBJECTIVES

Students will

- Recognize that gas temperature and gas volume are directly proportional
- Evaluate energy available in different compounds
- Recognize the need for oxygen in combustion

NATIONAL SCIENCE CONTENT STANDARD B

Chemical reactions

- Chemical reactions may release or consume energy. Some reactions, such as burning fossil fuels, release large amounts of energy by giving off heat and emitting light.
- In gases, molecules or atoms move almost independently of each other and are mostly far apart.

INTRODUCTION

Charles's Law relates to changes in temperature and volume of an ideal gas when the pressure is held constant. In real piston and turbine engines, the pressure does not remain constant and Charles's law does not really apply. A much more complex relationship between temperature and volume exists in real engines. As a first approximation, however, it is assumed that the pressure is constant in the problems below and apply Charles's law. For another example of how these are related, see the Web site below:

http://www.grc.nasa.gov/WWW/K-12/airplane/compexp.html

Example Problem:

If 10.0 L of gas (air) enters a piston engine at a temperature of 25 °C and comes out the exhaust pipe at a temperature of 300 °C, how many liters of gases would exit, just considering the effects due to the temperature change?

Solution:

a. First, all gas problems need to be solved using absolute temperature, so adding 273 to 25 °C gives 298 K and adding 273 to 300 °C gives 573 K.

b. Now use Charles's law. Since $\frac{\text{volume}}{\text{temperature}} = b$ where b is a constant,

$$\frac{\text{old volume}}{\text{old temperature}} = \frac{\text{new volume}}{\text{new temperature}}$$

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \qquad \frac{10.0\text{ L}}{298\text{ K}} = \frac{x\text{ L}}{573\text{ K}} \qquad x = 19.2\text{ L}$$

CHEMISTRY

PROBLEMS

1. On a very hot day, 95 °F (35 °C), a 5.0 L Mustang is running at 2500 rpm. That means that in 1 minute 12,500 L of air are taken in. If 25,300 L of gas come out the exhaust, what is the exhaust temperature in °C?

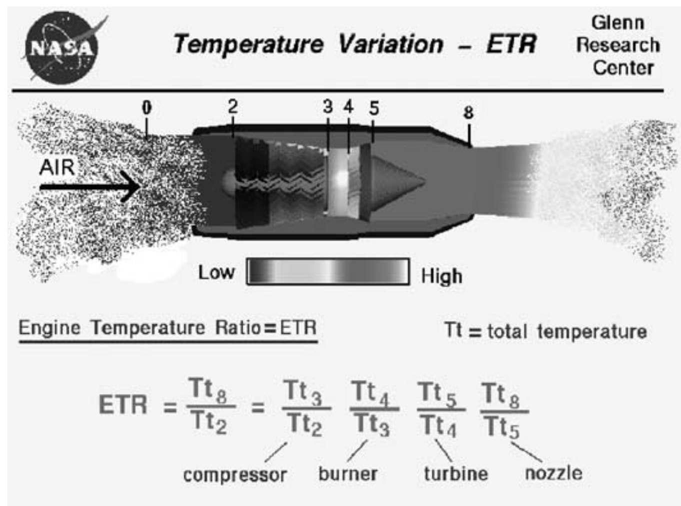
2. Consider the effect of burning gasoline, C_8H_{18}. In the engine, gasoline combines with oxygen to produce carbon dioxide and water vapor according to the equation

   $2\ C_8H_{18} + 25\ O_2 \rightarrow 16\ CO_2 + 18\ H_2O$

   Since both O_2 and CO_2 are gases, the coefficients can be used as volume ratios. This means that reacting 25 L of oxygen would produce 16 L of carbon dioxide and 18 L of water vapor. If 250. L of oxygen enter the engine at 25 °C, how many liters of carbon dioxide would exit the exhaust at 400 °C?

3. The diagram to the right represents a J85 jet engine working at a speed of 615 mph and an altitude of 22,260 ft. In the table below are the temperature readings at each of the marked stations of the engine. Considering only the changes in absolute temperature, what would the volume of 900. ft^3 of air at station 0 become at each of the stations on the chart?

Station	0	2	3	4	5	8
Temp	282 K	282 K	567 K	634 K	368 K	368 K
Volume	900 ft^3					



Temperature variations in turbine engine.

4. Use the temperatures from the previous problem and the engine temperature ratios (ETRs) for the compressor (Tt_3/Tt_2), burner (Tt_4/Tt_3), turbine (Tt_5/Tt_4), and nozzle (Tt_8/Tt_5), calculate how much a given volume of gas would change as it moved through each part of the engine if the temperature change were the only factor.

   compressor = ______ burner = ______ turbine = ______ nozzle = ______

   (a) In which part of the engine is the overall change the greatest?
   (b) Why is this the case?
   (c) Now calculate the total ratio for the whole engine (Tt_8/Tt_2).
   (d) Comment on the significance of this ratio being larger than one.

Gas Laws Problems—Gay-Lussac's Law

INSTRUCTIONAL OBJECTIVES

Students will
- Recognize that gas temperature and gas pressure are directly proportional
- Evaluate energy available in different compounds
- Recognize the need for oxygen in combustion

NATIONAL SCIENCE CONTENT STANDARD B

Chemical reactions
- Chemical reactions may release or consume energy. Some reactions, such as burning fossil fuels, release large amounts of energy by giving off heat and emitting light.
- In gases molecules or atoms move almost independently of each other and are mostly far apart.

INTRODUCTION

Gay-Lussac's law describes the relationship between pressure and temperature for an ideal gas when the volume is held constant. In real piston and turbine engines the volume does not remain constant and this law does not apply. A much more complex relationship between pressure and volume exists in real engines. As a first approximation, however, we are going to assume that the volume is constant in the problems below and apply Gay-Lussac's law. For another example of how these are related, see the Web site below:

http://www.grc.nasa.gov/WWW/K-12/airplane/compexp.html

Example Problem:

There are four main tires and two smaller nose tires on the space shuttle. The main tires are 34-ply tires and are filled with nitrogen at a pressure of 340 pounds per square inch (psi). If the temperature at takeoff is 24 °C and the temperature at altitude (in space) is –43 °C, what is the pressure of the nitrogen gas in the tire when the shuttle is in orbit?

Solution:

a. First, all gas problems need to be solved using absolute temperature, so adding 273 to 24 °C gives 297 K and adding 273 to –43 °C gives 230 K.

b. Now use Gay-Lussac's law $\frac{\text{pressure}}{\text{temperature}} = c$ where c is a constant,

$$\frac{\text{old pressure}}{\text{old temperature}} = \frac{\text{new pressure}}{\text{new temperature}}$$

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \qquad \frac{340 \text{ psi}}{297 \text{ K}} = \frac{x \text{ psi}}{230 \text{ K}} \qquad x = 263 \text{ psi}$$

PROBLEMS

1. Upon landing, the temperature of the nitrogen gas in the shuttle's main tire is raised from –45 to 130 ºC, mostly due to friction from braking and from the runway.
   (a) Find the new pressure of the nitrogen gas.
   (b) If the shuttle tire has a failure pressure of 5000 psi, how hot would the nitrogen have to be to blow the tire from internal pressure?

2. When an airliner flies at high altitude, conditions inside the plane change dramatically. Go to this Web site and find out the outside pressure and temperature of a 737 cruising at 500 mph at an altitude of 40,000 ft.
   http://www.grc.nasa.gov/WWW/K-12/airplane/atmosi.html

   Would anyone be able to survive under these conditions? NO: People would die of oxygen depravation and would freeze to death. To correct this, the cabin of the plane is pressurized and heated. Air is bled from the compressor in the jet engines and fed into the cabin. Since pressure and temperature are directly proportional, raising the gas pressure in the engine's compressor also raises the temperature. The bleed of air is at a pressure of 29.3 atm and a temperature of 649 °C (1200 ºF). If introduced directly into the cabin, this would seriously "distress" the passengers, so it must be changed. If the air is cooled to 22.2 ºC (72 ºF), would any further adjustments in pressure be needed?

3. When an airliner is climbing the engine is running at high power, so air for the cabin is bled from the "low" stage of the compressor. At this point in the compressor the pressure is 2.2 atm and the temperature is 165.6 ºC (330 ºF). If this air is cooled to 22.2 ºC (72 ºF), what will its pressure become?

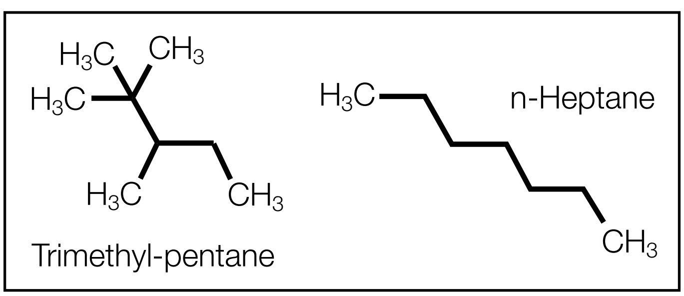
4. In a piston engine, the ideal point for the spark to fire to ignite the air-gas mixture is as the piston is approaching TDC, or "top dead center." Now "freeze" the piston at this point so that volume is going to remain constant. At the instant just before the spark plug fires, the piston has compressed the air in the cylinder to a pressure of 742 psi and a temperature of 693 ºC (1280 ºF). If the ignition of the fuel raises the temperature to 1280 ºC (2336 ºF), and the piston did not move, what would the resulting pressure be? If the air entered the cylinder at 1 atm, how many atmospheres would the pressure be right after combustion (14.7 psi = 1 atm)?

Fuel

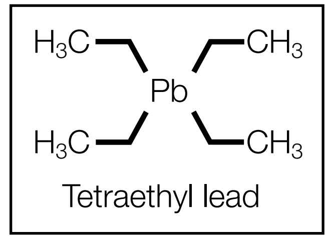
FUEL

Energy in an engine ultimately comes from the energy stored within the chemical bonds of the molecules used as fuel. Historically, these have been hydrocarbons (usually liquids) because they have a high energy content and are easily transported and combusted. One gallon of gasoline produces 1.32×10^8 J, the same amount of energy as from eating 110 hamburgers! One aspect of creating efficient engines is to match engine design with fuel design. Fuel design? Yes. The size and shape of the fuel molecules play a role in how an engine operates. Combustion engines work by combining a fuel with oxygen, generally from the atmosphere. In a piston engine, this occurs near the end of the compression stroke when the spark plug fires. It is important for the fuel to burn at the correct rate. If it burns too slowly, not all the fuel will burn, producing hydrocarbon pollution in the exhaust and carbon deposits that leave hot spots in the cylinder. If it burns too quickly the gas-air mixture can detonate and cause severe and sudden pressure and temperature spikes that will damage the engine. The noise from this is called "knocking."

Straight alkane molecules like hexane and heptane knock severely while a branched molecule like trimethylpentane is very resistant to knock. The reason for this is a bit complex, but simply stated, oxygen can get to the carbons in the straight chain all at once, and so the molecule reacts very quickly, causing knocking. The branched hydrocarbon has carbon atoms that are surrounded by other carbons and can't react with oxygen until after the outside carbons react, thus making it burn slower and be more resistant to knocking.



Previously, tetraethyl lead was used in fuel mixtures that contained a high percentage of straight hydrocarbons to slow down the rate of burning. The emissions of harmful lead into the environment led to this being banned in the 1980s.



The *octane rating* is a way to measure how smoothly a fuel burns. Simply stated, heptane, which knocks severely, is burned in a one-cylinder engine and the noise is recorded. This noise level is assigned an octane rating of "0." Trimethylpentane, which knocks much less, is burned and the sound is assigned a rating of "100." If your car uses "87" octane gasoline, this mixture makes the same amount of knocking as a mixture of 87 percent trimethyl pentane and 13 percent heptane. It is possible to have a mixture of hydrocarbons with octane ratings above 100. Aviation gas at the end of World War II was rated at 115 octane.

Jet fuel, unlike piston engine fuel, does not need to be timing dependent since combustion in a turbine engine is continuous. Most commercial jet aircraft today burn one of two kinds of jet fuel, either JET A–1 (JET A), which is a kerosene-based fuel, or JET B–1 (JET B), which is a naphtha-based fuel. The major difference is that Jet B has a lighter composition, higher volatility, and thus is easier to ignite, which makes it better for cold weather operation but more dangerous to handle. It is Jet A that is used for most commercial jet operation.

Military fuel in this country is designated by a jet propellant (JP) number. JP–8 is most similar to Jet A and again is most commonly used since its flashpoint is around 38 °C, making it safer to handle. JP–4 is more like Jet B and has cold weather applications. The U.S. Air Force stopped using JP–4 in 1996 because it is more hazardous. An estimated 60 billion gallons of JP–8 are used each year worldwide.

Other specialty fuels are made by blending hydrocarbon distillates to meet specific needs. These include JP–5, which is used on carrier-based aircraft because it has a high flashpoint (60 °C) that reduces the risk of fire onboard ship. Another is JP–7, which was used in the SR–71 Blackbird. Since the SR–71 operated at a wide range of temperatures, from the extreme cold of very high altitude to the high heat generated by flying above Mach 3, JP–7 had to be stable under all these conditions. It had a low volatility that made it very difficult to ignite. This was done by design to keep the fuel from auto-igniting at the high temperatures reached by the airframe at Mach 3+ flight. JP–7 was so stable that a lit match dropped into a bucket of it would just go out. A special chemical called triethylborane, which ignites upon exposure to air, had to be injected into the engine and the afterburner to cause the JP–7 to ignite. Fluorocarbons were added for slipperiness, and a cesium compound was added to help hide the exhaust from radar detection.

Hess's Law

INSTRUCTIONAL OBJECTIVES

Students will
- Recognize that heat of reaction are additive
- Evaluate energy available in different compounds
- Recognize the need for oxygen in combustion

NATIONAL SCIENCE CONTENT STANDARD B

Chemical reactions
- Chemical reactions may release or consume energy. Some reactions, such as burning fossil fuels, release large amounts of energy by giving off heat and emitting light.

INTRODUCTION

Hess's Law states that enthalpy changes (ΔH) are additive. This means that the sum of the heats of formation of the products minus the sum of the heats of formation of the reactants (each multiplied by their respective coefficients in a chemical reaction) will equal the ΔH for the overall reaction. $\Delta H = \sum\left(\Delta H_{f\ products}^{o}\right) - \sum\left(\Delta H_{f\ reactants}^{o}\right)$. One must first balance the chemical equation and then find the value of ΔH_f^o for each component.

Example Problem:

When hydrocarbon fuels are burned in an engine, oxygen (O_2) is a reactant and carbon dioxide (CO_2) and water (H_2O) are products. When grilling in the backyard with propane, the equation is

$C_3H_8 + O_2 \rightarrow CO_2 + H_2O$

Standard heats of formation in kilocalories per mole (kcal/mol) are

$C_3H_8 = –25.0$ $O_2 = 0$ $CO_2 = –94.0$ $H_2O = –68.3$

Balance the equation $C_3H_8 + 5\ O_2 \rightarrow 3\ CO_2 + 4\ H_2O$

Solution:

For each product, multiply the heat of reaction by its reaction coefficient and add them together. Do the same for the reactants. Then take the sum of the heats of formation of the products and subtract the sum of the heats of formation of the reactants to find the overall heat of reaction:

$\Delta H = [3\ (–94.0) + 4\ (–68.3)] – [(25.0) + 5\ (0.0)] = –530.2$ kcal

PROBLEMS

1. Calculate the heat produced for burning the following hydrocarbons. Assume one mole unless otherwise indicated.

   (a) Heptane C_7H_{16} ΔH°_f = –44.9 kcal/mol

   (b) Octane C_8H_{18} ΔH°_f = –49.8 kcal/mol

   (c) 2,2,3-trimethylpentane C_8H_{18} ΔH°_f = –52.6 kcal/mol

2. How much heat could be gained from the burning of 250. grams (g) of 2,2,3-trimethylpentane?

3. Of the three substances mentioned above, which would be the better fuel and why?

4. EPA regulations require that gasoline in some regions of the country be oxygenated by adding 10 percent by weight ethanol, C_2H_5OH . If the ΔH°_f of ethanol is –56.2 kcal/mol and the gasoline is assumed to be 2,2,3-trimethylpentane, how much heat is given off by burning 250. g of this mixture? How does that compare to the answer in problem 2 for pure 2,2,3-trimethylpentane?

Pollution

Nearly every form of propulsion today involves the application of energy derived from oxidizing fuels (combustion). The energy is applied to machinery in some manner to move objects. The downside is that combustion is never 100 percent efficient and so always produces some unwanted byproducts. According to the EPA, aircraft account for 2 percent of all nitrogen oxides (NO_x) and carbon monoxide produced by vehicles and can be as high as 4 percent in areas around airports. A recent study showed aircraft at London's Heathrow airport contributed between 16 and 32 percent of ground-level NO_x.

Jet taking off.

The fuels of choice—whether avgas (aviation gasoline) for small piston planes or kerosene for large passenger jets—are hydrocarbons, compounds composed of hydrogen and carbon. When they burn they combine with oxygen to produce water and carbon dioxide as shown here:

$$2\ C_8H_{18} + 25\ O_2 \rightarrow 16\ CO_2 + 18\ H_2O$$

The production of water is not generally considered polluting, although there is some evidence that the increase of water vapor in the stratosphere where passenger jets fly (5 to 6 mi high) has caused an increase in cloud cover. The production of carbon dioxide, however, is much more of a current concern as many studies have associated its increase with a rise in global warming. Aircraft currently produce up to 4 percent of the annual global carbon dioxide emissions from fossil fuels, and it is projected that the amount of air traffic is going to increase over the next decade. Reducing CO_2 production will require the development and use of alternative fuels such as hydrogen rather than fossil fuels.

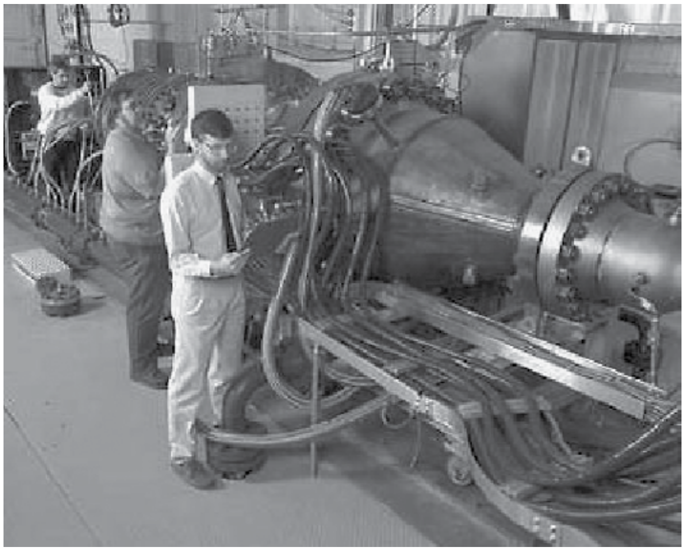
The previous equation indicates complete combustion of C_8H_{18}, where 100 percent of the reactants go to make products. In the real world, engines are not 100 percent efficient in burning fuels. When engines are not running near full power, such as when aircraft descend or taxi, the engine temperatures are lower, resulting in less efficiency and thus incomplete combustion. In incomplete combustion, not all of the carbon atoms of the hydrocarbon molecules are oxidized to CO_2. The result is the production of carbon monoxide, CO, which is partially oxidized carbon, and soot and smoke, which are particles of completely unburned carbon. This is seen in a candle flame, where the unburned carbon particles glow yellow and then are deposited as soot (carbon) on anything held above the flame. Both carbon monoxide and particulate matter are related to breathing difficulties.

A third problem with engine inefficiency is unburned hydrocarbons. Some of the fuel gets through the engine unburned. This results in what engineers call "volatile organic compounds" or VOCs being released into the atmosphere. These molecules react with sunlight and oxides of nitrogen to produce ground-level ozone, a pollutant gas. The solution is to run engines at higher temperature to react all the carbon. NASA Glenn is studying new materials that withstand higher temperature, which would allow engines to run hotter and cleaner under these conditions and yet not increase weight.

The trade-off to higher temperature engines is the production of pollutant nitrogen oxides NO_x. In normal combustion the two major components of the air, nitrogen and oxygen, do not react with each other. However, in the high pressures and temperatures of both piston and turbine engines, they do react to form a group of nitrogen oxides such as NO, N_2O, NO_2, and N_2O_4 . These are usually referred to as a group designated NO_x (pronounced "nox"). They are a precursor to ozone formation, a factor in acid rain, and an irritant in breathing. Cars reduce these emissions by means of a catalytic converter that causes the NO_x to split back into N_2 and O_2. On turbine-powered aircraft

CHEMISTRY

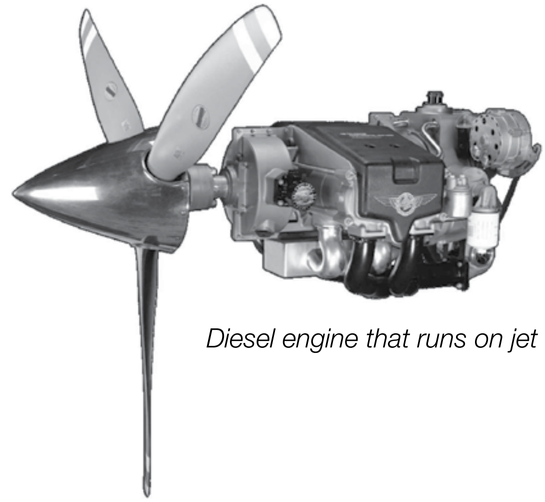
it is the engine design, particularly how fuel is injected and burned, that plays a major role in reducing NO_x production. The NASA Glenn Advanced Subsonic Combustion Rig shown below can simulate combustion conditions and give researchers valuable data on pollution production. Lasers that visualize fuel-air flow patterns and computer modeling help determine best designs for combustors.



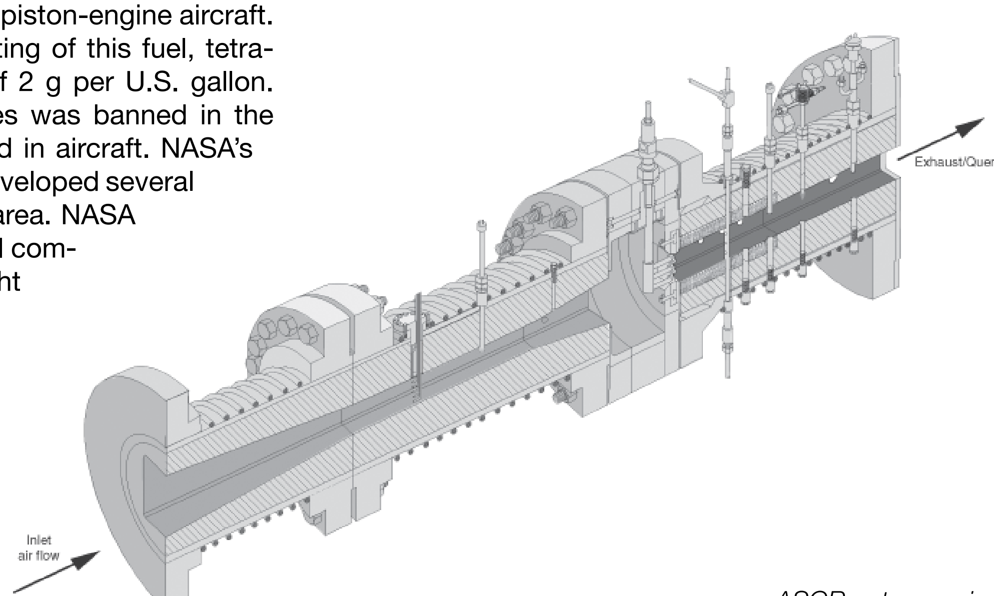
Advanced Subsonic Combustion Rig (ASCR).

Higher temperatures in turbine engines reduce pollutants, but require new materials be developed to withstand the temperature increase. New ceramics matrix composites have been developed at Glenn that survived over 9000 hr at 2200 °F.

Finally, one source of pollution in general aviation is the fuel, called 100LL, used in piston-engine aircraft. In order to boost the octane rating of this fuel, tetraethyl lead is added at a level of 2 g per U.S. gallon. Leaded gasoline for automobiles was banned in the 1980s, but continues to be used in aircraft. NASA's General Aviation Program has developed several engines that would help in this area. NASA Glenn has partnered with several companies to produce a lightweight diesel (2-stroke) engine with a low-speed propeller that runs on jet fuel; it would get 25 percent lower fuel consumption than current engines, run quieter and vibration free, and could also be manufactured for half the cost of piston engines. Williams International also developed the FJX–2 turbofan engine that is environmentally friendly and low cost, weighs 85 to 100 lb, and yet produces 700 lb of thrust. Although neither of these companies produces these engines, Thielert GmbH of Germany is flying diesels and Pratt & Whitney is flying a new turbine engine for the Very Light Jet market. Since both types of engines use (unleaded) jet fuel instead of 100LL, they would reduce lead pollution.



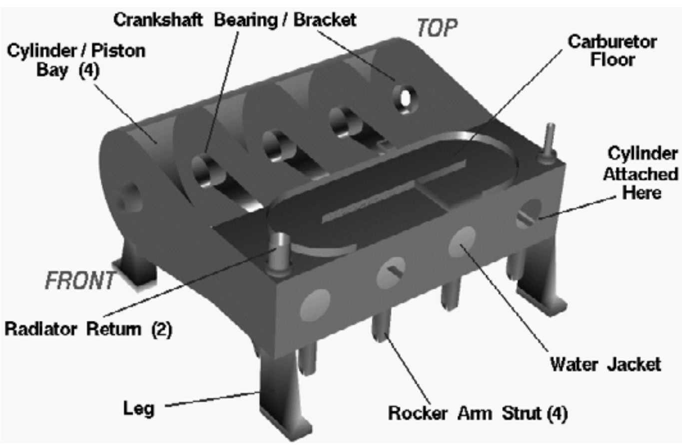
Diesel engine that runs on jet fuel.



ASCR cutaway view.

High-Temperature Materials

When you make an engine that runs at very high temperature, such as a jet engine, it is critical to select the right materials from which to make the engine parts. In 1903, the Wright brothers built an aluminum block engine because of its light weight compared to cast iron. Its melting point of 660 °C was well above the engine's operating temperature, so for them it was a good choice. However, aluminum could not be used in the hotter parts of a turbine engine where temperatures reach of 1800 °C or more because it would melt.



Wright brother's aluminum block engine.

For turbines, engineers must not only choose high-temperature materials, but materials able to withstand high-temperature oxidation and strong enough to maintain their shape while spinning at many revolutions per second. The specific requirements for the materials used in the engine are dictated by the conditions experienced in each part of the engine (see the Turbine Engines section for details).

At the front of turbofan engines is a large fan. This typically does not get very hot (<150 °C) so aluminum, titanium, or stainless steel are all suitable for the fan blades. Most engines use titanium because it has a high strength-to-weight ratio, is corrosion and fatigue resistant, and would be able to withstand the impact of a bird strike.

Next in line is the compressor section. Here the spinning blades of the compressor push the incoming air against the nonmoving stator vanes, which raises both the pressure and temperature of the air. The pressure of the air can be raised up to 30 times and the temperature, depending on the number of stages in the compressor, can rise to 1000 °C. Here the materials must have high strength at high temperatures; must resist fatigue, cracking, and oxidation; and also must resist "creep." Creep is the tendency of a material to slowly change shape when stressed at high temperature. Since no single metal would have all the desired properties, an alloy (a mixture of metals) is used. Very-high-temperature alloys are called superalloys and are generally nickel-, cobalt-, or iron-based alloys. Aluminum and/or titanium are added for strength, and chromium, as well as rare earth elements like yttrium, are added to improve corrosion resistance.

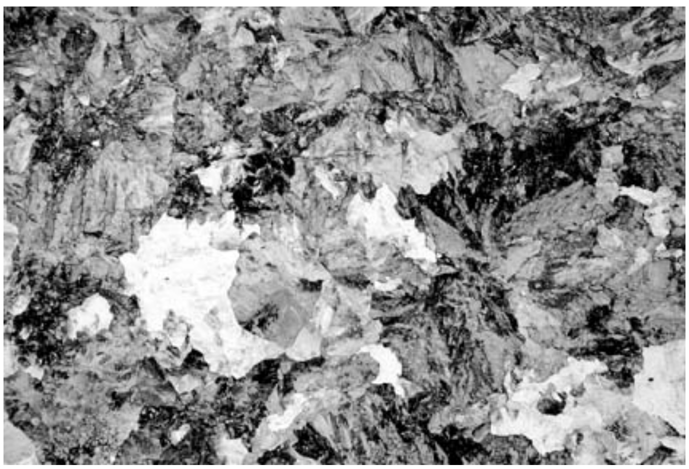
After the air is compressed, it enters the combustion chamber where fuel is added and burned. Here the temperatures can exceed 1800 °C and again superalloys are used, but without the titanium or aluminum for strength because there are no moving parts. Instead, refractory metals are often added to a superalloy. These are metals of unusually high resistance to heat, corrosion, and wear such as tungsten, molybdenum, niobium, tantalum, and rhenium. They are used in alloys and not as pure metals because they are among the densest of all the elements, a negative property when it comes to aircraft that need to keep weight to a minimum. Ceramics and ceramic-metal mixes are also used here because of their high heat resistance. We are familiar with pottery, tile, crucibles, and fire bricks as types of ceramics. They have very high melting points and don't require the cooling systems like those needed to keep metals from melting so they make for lighter, less complicated engine parts. The down side is that they tend to fracture under stress, so engineers seek to create new ceramics composites that incorporate other materials to improve properties.

As the hot gases move toward the rear of the engine they cause the turbine to spin. This drives the fan and compressor by means of connected shafts to keep the engine operating. The first set of turbine blades are in the highest pressure, hottest part of the gas flow and are generally made of nickel-based-superalloy or ceramic blades. Unheated outside air is circulated through channels inside of the turbine blades to keep them from melting in this extreme environment. Further down the engine lower pressure turbine blades

CHEMISTRY

often sit. Since the gases have somewhat cooled by this point, the blades can be made of iron-based superalloy or even stainless steel.

It is interesting to note that for strength, the metals used for turbine blades are often grown as a single crystal. A close look at most metals and alloys show that they are composed of crystals (also called "grains"), and the places where the crystals meet are called grain boundaries. A material is weaker at the grain boundaries than within the grains—especially at high temperatures—so turbine blades fashioned from metal formed as a single grain (no boundaries) are stronger.

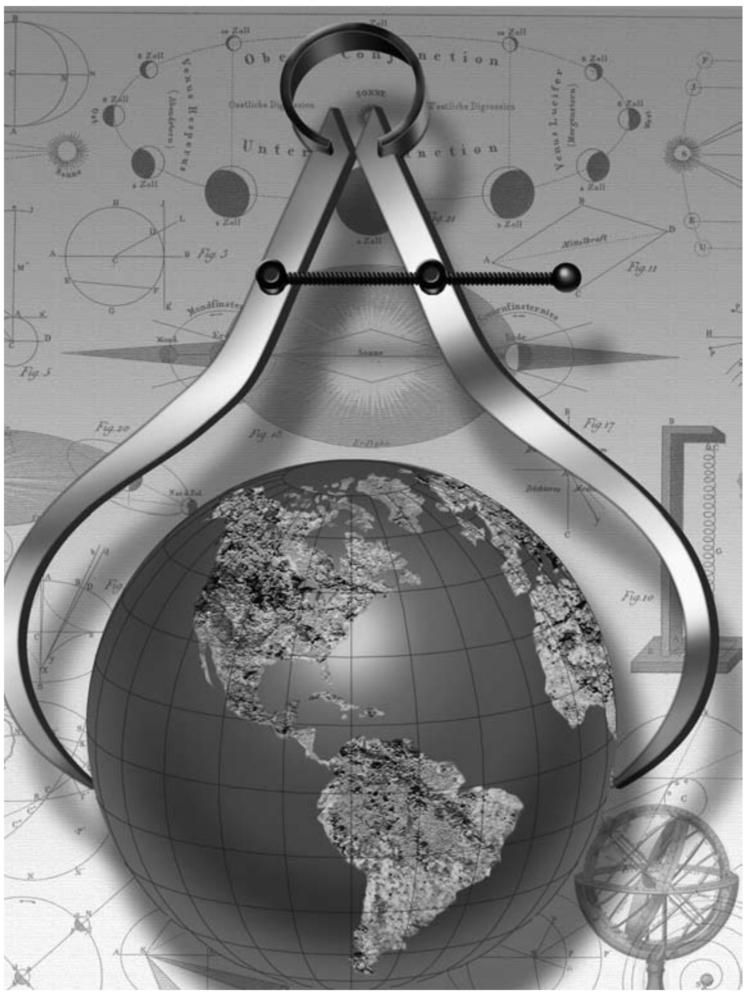


Metal crystals.

Finally, there is a casing surrounding the engine. Although it need not withstand high temperatures like the core of the turbine, the materials here need to be strong enough that if a blade were to break off it would be contained within the casing and not enter the wing or cabin of the aircraft and cause further damage. Aluminum or some polymer matrix materials are used as engine casings.

Since the development of more powerful engines depend on the availability of ever stronger and higher-melting materials, engineers continue to seek new alloys, ceramics, and polymers that will meet these more rigorous demands.

PHYSICS AND MATH



Sir Isaac Newton

Sir Isaac Newton.

On Christmas day in 1642 in Woolsthorpe, England, a premature baby by the name of Isaac Newton was born. His father died before his birth and his mother, seeking a second marriage, left 3-year-old Isaac with his grandmother. As Isaac progressed through his childhood, he isolated himself from social interaction and spent time "playing" independently by building water clocks, sundials, and model windmills powered by mice. At age 10, Isaac's mother returned to him after the death of his stepfather. She sent him to Kings School where the schoolmaster, Henry Stokes, taught not only Latin, theology, Greek, and Hebrew, but also some arithmetic—claiming it was for the future farmers. In the fall of 1659, this curious 16-year-old was pulled out of school by his mother to become a farmer.

While Isaac farmed the lands, he observed different phenomenon in nature, such as the whorls in a water stream. His old school master Stokes and his uncle William Ayscough sent young Isaac to Trinity College in Cambridge. After the completion of his Bachelor of Arts degree in 1665, he returned to the farm at Woolsthorpe to continue to research the sciences. It was during this isolation that Newton developed the foundations of the calculus, optics, motion, celestial mechanics, and gravity. In 1686, Isaac Newton's three laws of motion were first published in his "Principia Mathematica Philosophiae Naturalis." Newton spent much of the rest of his life quarreling with other mathematicians and scientists. One example is the dispute with Gottfried Leibniz over the development of calculus. These disputes, along with his work in alchemy (involving mercury), is said to have caused depression in Newton. During the latter part of his life, Isaac was appointed Master of the Royal Mint, and he was the first scientist ever knighted. Sir Isaac Newton also served as the president of the Royal Society from 1703 until his death in 1727.

Newton's First Law of Motion

"*Every object persists in its state of rest or uniform motion in a straight line unless it is compelled to change that state by forces impressed on it*."

Newton's Second Law of Motion

"Force is equal to the change in momentum (mv) per change in time. For a constant mass, force equals mass times acceleration $\left(\sum F = ma\right)$*."*

Newton's Third Law of Motion

"*For every action, there is an equal and opposite reaction*."

PHYSICS AND MATH

Newton's First Law of Motion

INSTRUCTIONAL OBJECTIVES

Students will
- Use rate equation to compute distance and time
- Evaluate acceleration as a change in velocity over time

NATIONAL MATHEMATICS STANDARDS

Algebra
- Generalize patterns using explicitly defined and recursively defined variables
- Interpret representations of functions of two variables
- Approximate and interpret rates of change from graphical and numerical data

Problem Solving
- Solve problems that arise in mathematics and in other contexts
- Apply and adapt a variety of appropriate strategies to solve problems

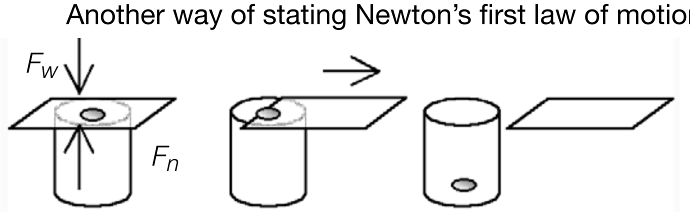
NATIONAL SCIENCE CONTENT STANDARD B

Motions and forces
- Objects change their motion only when a net force is applied. Laws of motion are used to calculate precisely the effects of forces on the motion of objects. The magnitude of the change in motion can be calculated using the relationship F = ma, which is independent of the nature of the force. Whenever one object exerts force on another, a force equal in magnitude and opposite in direction is exerted on the first object.

INTRODUCTION

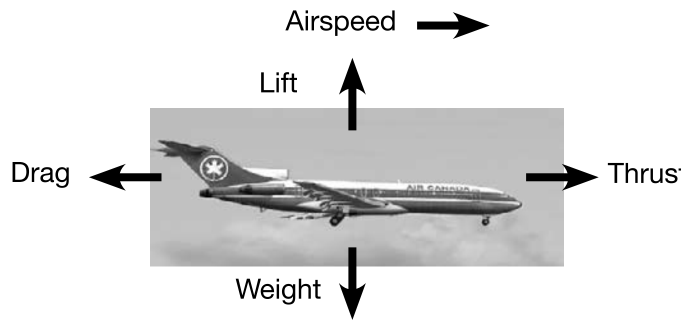
"*Every object persists in its state of rest or uniform motion in a straight line unless it is compelled to change that state by forces impressed on it*."

Another way of stating Newton's first law of motion is that when the sum of the forces $\sum F$ (net force) acting on a body is zero, its acceleration a is zero. Any sum is denoted by the Greek letter sigma, $\sum$. Symbolically, this is written as "if, $\sum F = 0$ then $a = 0$." This therefore implies, $\frac{\Delta v}{\Delta t} = 0$ where $\frac{\Delta v}{\Delta t}$ is the ratio of the change of velocity v to the change in time t, which is acceleration. This law has two parts: (1) An object at rest stays at rest unless acted upon by an unbalanced force. (2) An object in motion stays in motion unless acted upon by an unbalanced force. This law is normally taken as the definition of inertia. Inertia is the property of matter that makes an object stay in motion if it is moving or remain motionless if it is not moving. For example, a coin placed on a note card on a jar can be used to demonstrate the first law. In part (a) of the figure above, $F_n + (-F_w) = 0$, where F_w is the force due to the coin's weight and F_n is the normal force. This means that the net force acting on the coin is zero. If one flicks the card from left to right in part (b), the coin will fall into the jar. If the card is flicked fast enough, there is little friction between the coin and the card. Thus, since no force was applied directly to the coin, the coin does not accelerate horizontally. With the card no longer in place, there is an unbalanced force F_w acting on the coin in part (c).



(a) (b) (c)

Another example of Newton's first law is a car trying to stop on ice. Once the car is moving in a certain direction and the brakes are applied, the car will not stop easily because of the minimal friction force between the tires and the ice. The car continues to move in its original horizontal direction because the unbalanced force of friction is small compared with the forward motion of the car. As a result, the car stays in motion.



Four forces.

The first law of motion can also be observed in an aircraft in flight. The four major forces acting on an aircraft in flight are lift, drag, thrust, and weight. Considering an aircraft traveling at a constant altitude, the lift and weight can be neglected (they cancel one another out). For this example, the weight change due to the decrease in fuel is neglected. If an aircraft travels at a constant speed, thrust equals the drag. As a result, there is no net force on the plane and the plane continues to travel in a horizontal line. If, however, the engine produces any additional thrust, the plane's motion will change.

Example Problem:

A Boeing 747 has a mass of 174,000 kg. What is the minimum lift force required to get it off the ground?

Solution:

The lift force must overcome the force due to the weight of the plane. The weight force is calculated as follows:

$W = mg$

$W = (174{,}000 \text{ kg})(9.8 \text{ m/s}^2)$

$W = 1{,}705{,}200$ Newtons (N)

Because the force due to the weight of the plane is 1,705,200 N in the downward direction, the lift force must be greater than 1,705,200 N in the upward direction to stay in the air.

PROBLEMS

1. When an airplane is moving at a constant speed at a constant altitude, the sum of the forces acting on the airplane equal _______________.

For questions 2 to 4, use the following information: A jet is flying at a constant height of 10,894 km with a constant speed of 1210 km/hr. This jet weights 109,000 kg. Assume gravity is 9.80 m/s^2.

2. What is the force acting on the plane due to its weight ($W = mg$)?

3. How much lift force is being applied to the jet?

4. If the jet is providing a thrust of 104,525 N, what is the drag force applied to the jet?

5. If the drag of a plane is greater than the thrust generated by the engine, the plane will _________.

6. Use Newton's first law of motion to explain why people should wear seatbelts.

Newton's Second Law of Motion

INSTRUCTIONAL OBJECTIVES

Students will
- Use $F = ma$ equation to compute force, mass, and acceleration

NATIONAL MATHEMATICS STANDARDS

Algebra
- Generalize patterns using explicitly defined and recursively defined variables
- Interpret representations of functions of two variables
- Approximate and interpret rates of change from graphical and numerical data

Problem Solving
- Solve problems that arise in mathematics and in other contexts
- Apply and adapt a variety of appropriate strategies to solve problems

NATIONAL SCIENCE CONTENT STANDARD B

Motions and forces
- Objects change their motion only when a net force is applied. Laws of motion are used to calculate precisely the effects of forces on the motion of objects. The magnitude of the change in motion can be calculated using the relationship F = ma, which is independent of the nature of the force. Whenever one object exerts force on another, a force equal in magnitude and opposite in direction is exerted on the first object.

INTRODUCTION

"Force is equal to the change in momentum (*mv*) per change in time. For a constant mass, force equals mass times acceleration $\left(\sum F = ma\right)$."

For a nonconstant mass, force equals the change in momentum with change in time $F = \frac{\Delta(mv)}{\Delta t}$. For a constant mass, force equals mass times the change in velocity with respect to time $\left(F = \frac{m(v_1 - v_0)}{(t_1 - t_0)} = m\frac{\Delta v}{\Delta t}\right)$.

Acceleration is the change in velocity with respect to time. Therefore, another expression of Newton's second law for a constant mass is force equals mass times the acceleration ($F = ma$). Note that force, acceleration, momentum, and velocity are all vector quantities; that is, they have both magnitude and direction.

The net force acting on an object is the sum of all of the forces acting on that object. Any sum is denoted by the Greek letter sigma, $\sum$. For example, if F_1, F_2, and F_3 are all acting on an object, then the net force acting on the object is $\sum F = F_1 + F_2 + F_3$. Newton's second law of motion $\left(\sum F = ma\right)$ can also be broken down into the following three component equations:

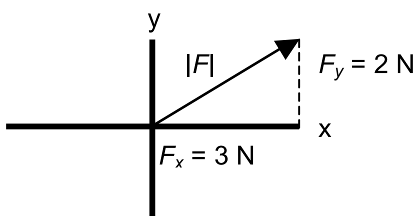
$$\sum F_x = ma_x \qquad \sum F_y = ma_y \qquad \sum F_z = ma_z$$

where F_X is the force in the x-direction and so on. Force and acceleration are vector quantities and mass is a scalar quantity. Vector quantities have both magnitude and direction whereas scalars have only magnitude. A force can be written as follows: **F** = (3**i** + 2**j**) **N**, which means the force is applied three units in the positive

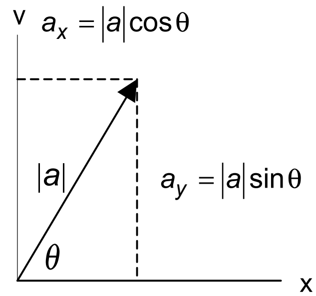
PHYSICS AND MATH

x-direction and two units in the positive y-direction (illustrated below at the left). There is another way to obtain the component parts of a given vector. If, for example, the magnitude of the acceleration and the angle of motion are known, then the component parts of the acceleration can be determined by using trigonometry (illustrated below at the right).

F = (3**i** + 2**j**) **N**



$$|F| = \sqrt{3^2 + 2^2} = \sqrt{13} \text{ N}$$



Newton's second law answers the question of what happens to an object that has a nonzero net force acting on it. The following explanations are for a constant mass. One observation from Newton's second law is that the acceleration of an object is directly proportional to the net force acting on it. For example, if you are pushing a block of metal across a frictionless horizontal surface with some horizontal force **F**, the block moves with some acceleration **a**. If you apply a force of 3**F** on the same metal block, the acceleration of the block also triples. Another observation is that the acceleration of an object is inversely proportional to its mass. Using the block example from above, if one doubles the mass of the metal block and applies the same force **F**, the acceleration of the block will be $\frac{a}{2}$.

Newton's second law of motion can also be observed in the motion of an aircraft. If an airplane is not traveling at a constant velocity $\left(\frac{\Delta v}{\Delta t} \neq 0\right)$, then the airplane is accelerating or decelerating. For example, before takeoff, the airplane is stationary (Newton's first law). The throttle is then increased to overcome the inertia of the plane. Because of the positive net force (thrust), the airplane accelerates (Newton's second law).

Example Problem:

A jet with a mass of 250,000. kg is cruising at 241.30 m/s at a constant altitude. If the afterburners apply an additional thrust of 50,000. N, what speed does the jet reach in 100. s?

Solution:

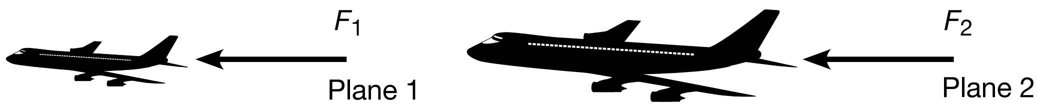
This problem can be solved using Newton's second law of motion, $F = m\frac{\Delta v}{\Delta t}$. $F = m\frac{v_f - v_i}{t_f - t_i}$, where F is the additional thrust (note that until the afterburners are turned on, the net force equals zero), v_f is the velocity when t_f = 100. s, and v_i = 241.30 m/h when t_i = 0 s. The final velocity can be determined:

$$50{,}000.\text{ N} = (250{,}000.\text{ kg})\,\frac{(v_f - 241.30)\text{ m/s}}{(100. - 0)\text{ s}}$$

v_f = 261 m/s

PROBLEMS

1. Fill in the blank below the illustration.



If $F_1 = F_2$ and $m_1 < m_2$, then a_1 ___________

2. A 10,000. kg airplane touched the runway at 85.0 m/s. It took 30.0 s for the airplane to stop.
   (a) What is the average acceleration of the plane?
   (b) What force is applied to this airplane?
   (c) What distance is needed to stop this plane in 30.0 s?

3. A Boeing 747 (m = 174,000 kg) undergoes an acceleration of a = (0.500i + 0.800j) m/s^2. What is the resultant force, F, and its magnitude?

4. A 5000. kg helicopter accelerates upward at 4.00 m/s^2. What is the lift force exerted on this helicopter?

5. If the jet is cruising at 241.30 mph and accelerates at an average of 0.2700 m/s^2 for 1000. s, what is the jet's final speed?

6. If a rocket that weighs 2.00×10^5 kg is launched vertically from the Earth's surface, what is the upward acceleration if the engine produces a thrust of 3.00×10^6 N?

7. If a rocket in space accelerates at 5.0 m/s^2, what is the mass of the rocket if the engine produces a thrust of 210,000 N?

8. A specific model rocket is designed to carry cargo in its tip. Calculate the mass of the cargo such that the rocket can be launched vertically upward with the following characteristics:
   mass of the rocket = 0.017 kg
   a_y = 136.36 m/s^2
   engine thrust = 3.2 N

9. At takeoff, a plane produces a force of 85,000 N at an angle of elevation of 60°.
   The plane rises at a constant velocity in the vertical direction while continuing to accelerate in the horizontal direction.
   (a) What is the mass of the plane?
   (b) What is the horizontal acceleration?
   (c) How would this problem change if the angle of elevation was 45°?

Newton's Third Law of Motion

INSTRUCTIONAL OBJECTIVES

Students will
- Evaluate forces in action/reaction

NATIONAL MATHEMATICS STANDARDS

Algebra
- Generalize patterns using explicitly defined and recursively defined variables
- Interpret representations of functions of two variables
- Approximate and interpret rates of change from graphical and numerical data

Problem Solving
- Solve problems that arise in mathematics and in other contexts
- Apply and adapt a variety of appropriate strategies to solve problems

NATIONAL SCIENCE CONTENT STANDARD B

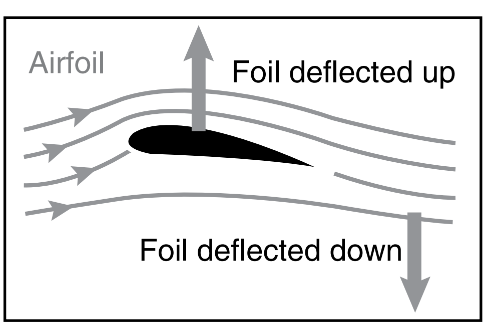
Motions and forces
- Objects change their motion only when a net force is applied. Laws of motion are used to calculate precisely the effects of forces on the motion of objects. The magnitude of the change in motion can be calculated us ing the relationship F = ma, which is independent of the nature of the force. Whenever one object exerts force on another, a force equal in magnitude and opposite in direction is exerted on the first object.

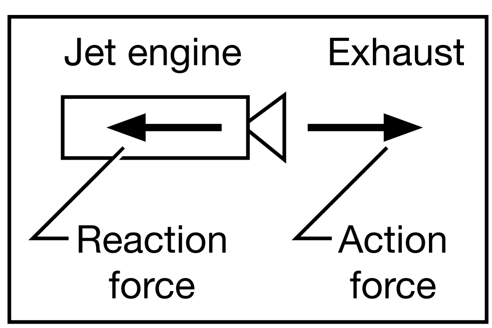
INTRODUCTION

"*For every action, there is an equal and opposite reaction*."

Another way to state Newton's third law is that if two bodies interact, the force exerted on body 1 by body 2 is equal to and opposite the force exerted on body 2 by body 1: $F_{12} = F_{21}$. For example, if you try to accelerate a brick by kicking it, it hurts. The brick provides the same force, but opposite in direction, back to your foot as you applied to kicking the brick. These forces are called action-reaction forces.

Newton's third law is very important to aircraft. In order to create lift, the flow of air must be turned by a solid object. During the lifting of a plane (see figure below at the left), the air is turned downward by both the upper and lower surfaces of the wing. As the airflow is turned in one direction (action force), the lift force on the plane is generated in the opposite direction (reaction force). Therefore, the more air that is pushed in the downward direction by the wings, the greater the lift. Another demonstration of Newton's third law is the acceleration of an airplane (see figure below at the right). As the compressed fuel-air mixture burns, the engine dispenses hot exhaust gasses out the nozzle. The resulting reaction force is a thrusting force in the opposite direction of the exhaust flow. This action-reaction is the principle behind aircraft acceleration and lift.





PHYSICS AND MATH

PROBLEMS

1. If a sparrow (m = 0.0200 kg) and a Boeing 747 (m = 174,000 kg) collide head on, which experiences the greater impact force? Which experiences the greater acceleration in opposite direction?

2. The thrust of a rocket is given by the equation

   Thrust = $\frac{\Delta m}{\Delta t} v_e + (p_e + p_o) A_e$

   where $\frac{\Delta m}{\Delta t}$ = mass flow rate, v_e = exhaust velocity, p_e = exhaust pressure,

   p_o = free-stream pressure, and A_e = exhaust area.

   Fuel aboard a rocket is being ejected out the nozzle with a speed of 2750. m/s. The mass rate of the ejected fuel is 909.09 kg/s.
   (a) What is the thrust of the rocket (assume that the exhaust pressure is about equal to the free-stream pressure)?
   (b) What is the relationship between the direction of the exhaust and the direction of rocket travel?

3. (a) Derive a formula for the force acting on a rocket due to its weight. Use the variables given below:

   fuel mass flow rate = $\frac{\Delta m_e}{\Delta t}$
   mass of the rocket = M_r
   acceleration due to gravity = g
   duration of observation = t

   (b) Use 3(a) to calculate the force due to its weight acting on a 280,000 kg rocket with the given characteristics:

   exhaust mass flow rate = 1100 kg/s
   duration of observation = 1 min
   assume g is constant = 9.80 m/s^2

Displacement

INSTRUCTIONAL OBJECTIVES

Students will
- Use rate equation to compute distance and time
- Evaluate acceleration as a change in velocity over time

NATIONAL MATHEMATICS STANDARDS

Algebra
- Generalize patterns using explicitly defined and recursively defined variables
- Interpret representations of functions of two variables
- Approximate and interpret rates of change from graphical and numerical data

Problem Solving
- Solve problems that arise in mathematics and in other contexts
- Apply and adapt a variety of appropriate strategies to solve problems

INTRODUCTION

Ratios are used in evaluating the average velocity and average acceleration of an airplane. The average velocity of a plane is the change in distance with respect to the change in time: $v_{ave} = \frac{\Delta d}{\Delta t} = \frac{d_2 - d_1}{t_2 - t_1}$. From that equation comes the simple rate equation $r = \frac{d}{t}$ or equivalently, $d = r \cdot t$ (r is the rate). The average acceleration of a plane is the change in velocity to the change in time: $a_{ave} = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{t_2 - t_1}$.

Example problem:

A plane is traveling at a constant speed of 525 mph for 30. s. How far did the plane travel in those 30. s?

Solution:

The plane is traveling at a constant speed t so $d = r \cdot t$ is the appropriate relationship for this problem.

$$d = r \cdot t$$

$$d = (525 \text{ mph})\left(30.\text{ s} \cdot \frac{1 \text{ hr}}{3600 \text{ s}}\right)$$

$$d = 4.4 \text{ mi}$$

This airplane traveled 4.4 mi in those 30. s.

PHYSICS AND MATH

PROBLEMS

1. The pilot observed that the airplane had a velocity of 505 mph. One minute later, the pilot observed a velocity of 450 mph.
   (a) What is the average acceleration over the 1.0 min?
   (b) What does the negative sign indicate?

2. Determine how many miles it is from New York City, NY, to San Francisco, CA, if it took an airplane 5.0 h to travel from one city to the other with an average velocity of 500. mph.

3. Before the afterburners are turned on, an airplane is traveling 475 mph. Twenty seconds after the afterburners were turned on the plane is traveling 560 mph.
   (a) What is the average acceleration of this airplane over those 20. s?
   (b) How far does the plane travel in those 20. s?

4. In order for a Boeing 757 to take off, the airplane must have an average velocity of 190. mph. How long will it take this plane to liftoff by the end of a 3000.-ft runway (1 mi = 5280 ft)?

5. A Boeing 767 has an approach speed of 250. mph. How long must the runway be in order to land this plane if its maximum deceleration is 0.0120 mi/s^2?

6. An airplane (m = 174,000 kg) is cruising at 241.40 m/s. The afterburners are ignited for 2.00 min providing an average thrust of 20,000. N.
   (a) What is the velocity of the airplane after those 2.00 min?
   (b) How far did the airplane travel over those 2.00 min? (Assume the mass of the airplane stays constant.)

Vectors

INSTRUCTIONAL OBJECTIVES

Students will
- Evaluate vector forces on aircraft

NATIONAL MATHEMATICS STANDARDS

Geometry
- Analyze characteristics and properties of two- and three-dimensional geometric shapes and develop mathematical arguments about geometric relationships
- Use trigonometric relationships to determine lengths and angle measures

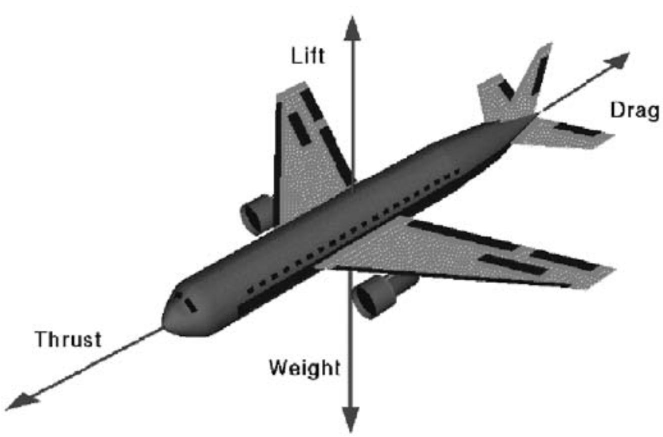
Problem Solving
- Solve problems that arise in mathematics and in other contexts
- Apply and adapt a variety of appropriate strategies to solve problems

NATIONAL SCIENCE CONTENT STANDARD B

Motions and forces
- Objects change their motion only when a net force is applied. Laws of motion are used to calculate precisely the effects of forces on the motion of objects. The magnitude of the change in motion can be calculated using the relationship F = ma, which is independent of the nature of the force. Whenever one object exerts force on another, a force equal in magnitude and opposite in direction is exerted on the first object.

INTRODUCTION

A vector quantity has both magnitude and direction. Forces acting on an airplane are vectors. Below is an illustration of the four major forces acting on an airplane.

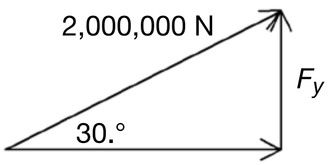


Four forces.

Example problem:

The net force of an airplane is 2,000,000. N 30° above the horizontal. What is the net force on this airplane in the vertical direction? What is the excess thrust (thrust – drag) of this airplane?

Solution:



Vertical net force (F_y): $\sin 30.° = \dfrac{F_y}{2{,}000{,}000.}$

$F_y = 2{,}000{,}000. \cdot \sin 30.°$

$F_y = 1{,}000{,}000.$ N

Excess thrust (F_x): $\cos 30.° = \dfrac{F_x}{2{,}000{,}000.}$

$F_x = 2{,}000{,}000. \cdot \cos 30.°$

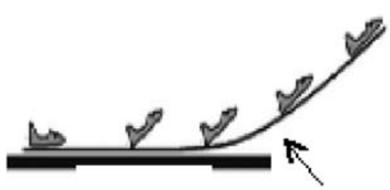
$F_x = 1{,}700{,}000.$ N

PROBLEMS

1. A small airplane can travel with a speed of 150. mph with respect to the air. Determine the resultant velocity of the plane (magnitude only) if it encounters a
   (a) 20.0 mph headwind
   (b) 20.0 mph tailwind
   (c) 20.0 mph crosswind
   (d) 60.0 mph crosswind

2. A small airplane has a cruising speed of 135 mph relative to the ground when there is no wind. The pilot points the airplane at 35.0° north of east and flies for 2.00 hr. How far north and how far east is the plane from its original location after the 2.00 hr?

3. The takeoff angle of an airplane is about 12°. If the takeoff speed of an airplane is 300. ft/s, approximately how long will it take that plane to reach 14,000 ft if the angle of elevation and speed stays constant?



4. An airplane initially moving eastward at 325 mph travels into an area where the wind is blowing 85 mph 25° north of west.
   (a) Determine the new speed of the airplane.
   (b) Determine the new direction of the airplane.

5. An airplane flying with an airspeed of 225 m/s headed –120.° encounters a 100. m/s wind blowing toward the plane at 15.0°.
   (a) Draw an accurate diagram illustrating this situation.
   (b) Determine the resulting velocity of the airplane.

Ratios

INSTRUCTIONAL OBJECTIVES

Students will

- Use ratios to compare quantities

NATIONAL MATHEMATICS STANDARDS

Understand numbers, ways of representing numbers, relationships among numbers, and number systems

- Understand and use ratios and proportions to represent quantitative relationships

Algebra

- Generalize patterns using explicitly defined and recursively defined variables
- Interpret representations of functions of two variables

Problem Solving

- Solve problems that arise in mathematics and in other contexts
- Apply and adapt a variety of appropriate strategies to solve problems

INTRODUCTION

Many different types of mathematics are used in the evaluation of propulsion. One way that engineers describe different characteristics of a plane is by using ratios. The ratio of a scalar quantity ***a*** to a scalar quantity ***b*** is equal to ***a*** divided by ***b***: ratio = $\frac{a}{b}$.

Recall that a scalar quantity has only a magnitude, not a direction.

Below are just some of the ratios that engineers use when studying aircraft.

Visit http://www.grc.nasa.gov/WWW/K-12/airplane/ratio.html for many more types of ratios, additional examples, and interactive simulations on these topics.

- The Mach number M is the ratio of the speed of an object to the speed of sound in a gas. The Mach number defines the various flight regimes of an aircraft and the importance of the compressibility of the flow. Note that because the temperature and density of the air decreases with increasing altitude, the speed of sound also decreases with altitude.

  Classifications of high-speed flight:
  – Subsonic, $M < 1$
  – Transonic, $M = 1$
  – Supersonic, $1 < M < 3$
  – High supersonic, $3 < M < 5$
  – Hypersonic, $M > 5$
  – High hypersonic, $M >> 25$

- The thrust-to-weight ratio of an aircraft determines the climb rate and performance of an aircraft. The thrust to-weight ratio of an aircraft determines the g-loading on the payload and structure; g-loading refers to how many times the force of gravity a structure can withstand.
- The aspect ratio of a wing is equal to the square of the wingspan divided by the wing area. This factor influences the induced drag and downwash effects on the lift of a wing. High-aspect-ratio wings are more efficient than low-aspect-ratio wings, as first discovered by the Wright brothers in 1901 to 1902.
- Other ratios include glide ratio, lift-to-drag ratio, engine's fuel-to-air ratio, and compression ratio.

Example Problem:

What is the Mach number of a plane if the speed of sound is 761 mph and the plane is traveling at 500. mph? Classify this high-speed flight as subsonic, transonic, supersonic, or hypersonic.

Solution:

The Mach number is defined as the following ratio: $\dfrac{\text{speed of object}}{\text{speed of sound}}$.

$$\text{Mach number} = \frac{500.\ \text{mph}}{761\ \text{mph}}$$

$$= 0.657$$

This airplane is traveling at a subsonic speed.

PROBLEMS

1. For each statement below, say something about the relationship between ***a*** and ***b*** if their ratio = $\dfrac{a}{b}$.

    If the ratio is equal to 1.0, then ___________________________.
    If the ratio is less than 1.0, then ___________________________.
    If the ratio is greater than 1.0, then ___________________________.
    If the ratio is nearly zero, then ___________________________.
    If the ratio is very large, then ___________________________.

2. A typical cruise speed of a Boeing 757 is Mach 0.800. What is the typical cruise speed (in miles per hour) of a Boeing 757 if the speed of sound at cruise altitude is 760. mph?

3. What is the thrust-to-weight ratio of a Boeing 747 (m = 174,000 kg) when a thrust of 215,000 N is generated?

4. What is the wingspan and wing area of a Boeing 757? What is the aspect ratio of a Boeing 757? (Use the Internet to obtain the necessary data.)

5. (Optional) Visit the Web page in the Introduction, and write a description on one of the ratios not previously mentioned in this section. Then create a word problem dealing with this ratio. Also include the solution.

Air Density

When early aviators were learning to fly they stayed fairly close to the ground, rarely going over 1000 ft. At low altitudes there is plenty of oxygen in the air for engines to be able to perform well. The atmosphere, however, is not uniform. As altitude increases, the density of the air decreases. This means that the total number of gas molecules in every cubic foot of air becomes less and less. Mountain climbers refer to this as “thin air” because as they ascend there are fewer gas molecules in each breath. Most climbers carry bottles of oxygen when climbing very high.

It is the same with engines which need oxygen to operate. As altitude increases, performance and power decrease because less oxygen becomes available. By the end of World War I, it became evident that the performance ceiling of a piston-engine aircraft was not going to be much above 20,000 ft. There is a definite combat advantage in being able to fly higher than your enemy, so programs were started to allow engines to operate better in thinner air. These involved supercharging and turbocharging, both of which are a means of forcing a greater mass of air into the engine. In a supercharged engine, air is drawn into a compressor and then forced into the cylinders of the engine. The power to drive the supercharger is geared off of the engine, which does reduce some of the engine’s power. In turbocharging, exhaust gases from the engine are allowed to flow over a turbine that drives the compressor, which is a more efficient arrangement, but there is some power loss due to backpressure in the exhaust. The exhaust stroke of the engine must force exhaust gas to flow through the turbine.

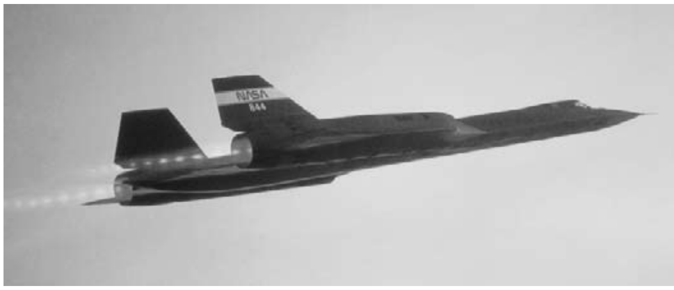
Avro Lancaster bomber.

The result is dramatic. In World War II, an unsupercharged Avro Lancaster bomber had an operational ceiling of 21,500 ft while a supercharged B–17G could operate up to 35,000 ft. The crew of the B–17G had to wear oxygen masks to fly at such high altitudes. By the end of the war, the B–29 bomber, which could fly up to 40,000 ft, had a pressurized cabin for crew comfort in the cold, thin air.

B–17G bomber.

Gas laws still apply at high altitudes, and the heat generated by compressing the air in a supercharger caused the air to expand. This creates more gas pressure, but the goal is not greater pressure but a greater mass of air going into the engine, and heating makes it less dense. Engineers solved this by adding intercoolers, which act like radiators and cool the compressed gas, decreasing the volume and thus increasing the density.

Finally, aircraft flying at high altitudes must fly at high speeds to compensate for the loss of lift caused by less dense air. Modern airliners use large turbofan engines to be able to cruise at 500 mph at 30,000 ft. Since the turbofan moves large volumes of air, they can generate sufficient thrust in less dense air to maintain high speed.

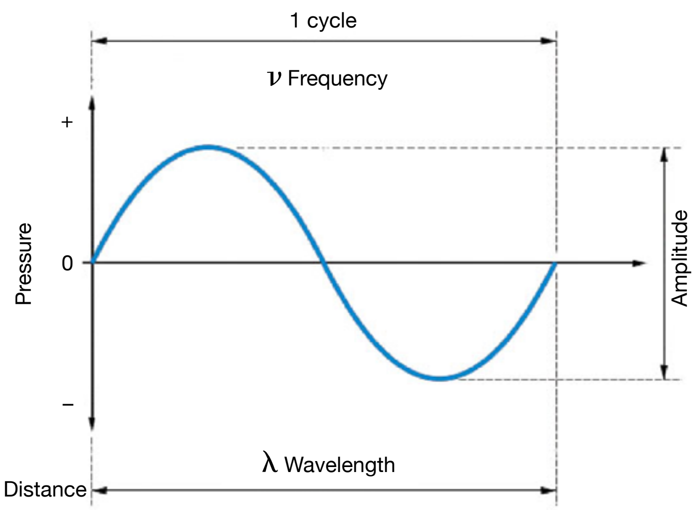


SR–71 Blackbird.

One can foresee limits in altitude for air-breathing engines as air becomes less dense. The world record is 85,500 ft at Mach 3.3 by an SR–71 Blackbird reconnaissance aircraft powered by two afterburning turbo-ramjet engines. Much beyond this, one enters the realm of rockets which must carry their own oxygen in order to burn fuel.

Noise

Sound waves are characterized by a wavelength, frequency, and amplitude. The wavelength, λ (the Greek letter lambda), is the physical distance between adjacent identical points on the wave, such as crest-to-crest. The frequency, ν (the Greek letter nu), is the number of cycles per second. Multiplying the wavelength times the frequency gives the speed of sound, $c = \lambda\nu$. The height of the wave is called the amplitude and is the loudness of the sound.



Sound wave.

Sound is a major concern with aircraft propulsion. Aircraft engines, whether internal combustion piston engines or jet turbine engines, generate power from expanding gases. Propellers and turbine fans move large volumes of air backwards in order to push aircraft forward. All these activities push on the surrounding air causing compression and rarefaction of the air molecules. This produces pressure waves, which we perceive as sound if they are strong enough and of the right frequencies.

Generally, an aircraft achieves its best performance at cruise and spends most of its operating life at high altitude, away from populations, so the noise it produces at this time is not a great concern. It is when an aircraft is landing, taxiing, and especially taking off at full power that noise becomes an issue. As air traffic grows, communities surrounding airports experience an increase in noise pollution. There are many ways to combat airport noise pollution including residential noise insulation programs, land use planning, modified takeoff and landing procedures, and by restricting the number of flights and the time of day flights may take off or land. Finding ways to make airplanes fly more quietly, however, is one of the most effective ways to reduce airport noise pollution.

The various sound intensities listed in the chart below show that a jet airplane can generate an extreme amount of noise. There are many parts of an aircraft that can make noise, but since the aircraft engine is one of the noisiest parts of the aircraft, designing quieter engines continues to be a priority.

Intensity, W/m^2	Decibel level (sound intensity level, SIL)	Examples
0.000000000001	0	Threshold of hearing
0.00000000001	10	Rustling of leaves
0.0000000001	20	Quiet whisper
0.000000001	30	Whisper
0.00000001	40	Mosquito buzzing
0.0000001	50	Normal conversation
0.000001	60	Air conditioner at 6 m
0.00001	70	Vacuum cleaner
0.0001	80	Alarm clock
0.001	90	Lawn mower
0.01	100	Subway
0.1	110	Auto horn at 1 m
1	120	Threshold of pain
10	130	Machine gun
100	140	
1000	150	Nearby jet airplane

Researchers in the Acoustics Branch at NASA Glenn, working with engineers at universities and in the aircraft industry, are looking for ways to reduce the noise of aircraft engines. Finding ways to reduce engine noise without sacrificing aerodynamic performance of the engine is a real challenge. You are aware that cars control exhaust noise by means of a muffler, but you may not be aware that this causes backpressure in the exhaust system and reduces the engine's effective horsepower. This is why dragsters and racecars do not have much in the way of mufflers; they need maximum horsepower. The same is true in aircraft. Altering the geometry of an exhaust nozzle may reduce noise, but it can also reduce engine thrust. Likewise, altering the number or orientation of fan blades or stator vanes in an engine may help reduce noise, but it may also affect the structural integrity of the engine.

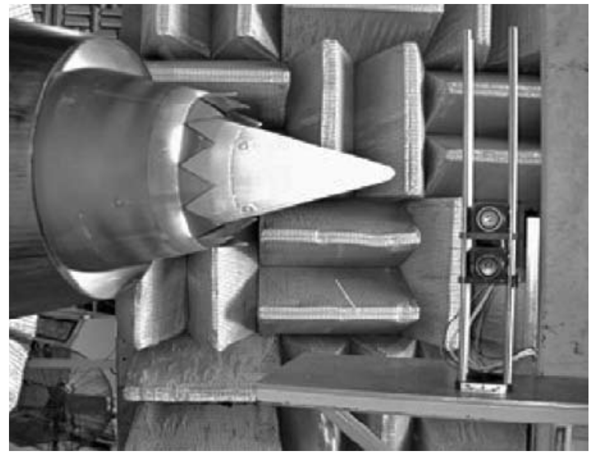
Since an aircraft engine is so complex, it helps to study parts of the engine individually. An engine's exhaust jets are one dominant source of noise, and the noise generated by the rotating parts of the engine—like the fan and the compressor—are another.

Data from experiments on nozzles and fans are used to develop new computer programs that engineers can use to design quieter engines. When sound, pressure, temperature, and velocity measurements are compared against the calculations made to predict them, engineers learn many things, such as whether a new nozzle or fan design is quieter or whether calculations are correct. Then they know if adjustments need to be made in the designs or if the computer models should be improved.

The teeth cut into the edge of the nozzle in the picture below are often called chevrons and are used to reduce jet exhaust noise. Tests at NASA Glenn confirmed that chevrons are a practical way to reduce noise. Data show that the chevrons change the way that engine exhaust mixes with the surrounding air and can help reduce noise. Developing new computer codes that model the complex mixing of the exhaust streams will help design engineers optimize their nozzles by deciding how many chevron teeth should be cut, what shape they should be, and so forth.

Chevrons on Lear jet.

Scale models of aircraft exhaust nozzles are tested in NASA Glenn's Aero-Acoustic Propulsion Laboratory (AAPL). It is a geodesic dome that houses several experiments. The dome helps researchers collect high-quality data in two ways: first by shielding the experiments from outside noise sources (such as cars driving by and airplanes flying overhead) and second by preventing sound reflections within the dome from contaminating the data. To prevent sound reflections from contaminating the data, fiberglass wedges are permanently installed on the inside of the dome and movable wedges are used to cover the floor during a test. All of these wedges absorb sound creating what is called an anechoic chamber. The walls of the dome also keep the noise of tests from bothering neighbors living near the lab.



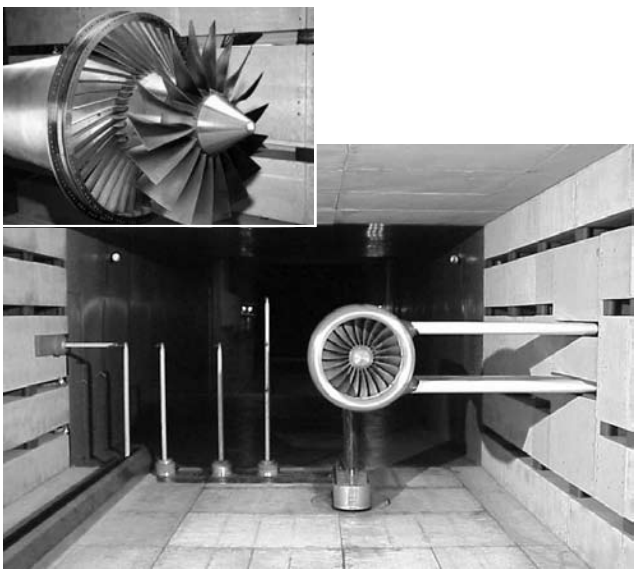
Test nozzle in AAPL.

Have you ever been near an airport when an airplane is landing and heard a "whine" above the roar of the engine? The large bypass fan of an engine can produce two types of noise, tone noise (the whine) and broadband noise (the roar). As the fan accelerates air down the fan duct, the flow is swirling because of the spinning fan. This swirl causes loss of momentum before the air exits the nozzle so it is straightened out with a set of nonmoving vanes called stators. Broadband noise, which is sound at many different frequencies, is created by the turbulence in the airflow. Tone noise, which is sound at specific frequencies, is created when the fan wakes (disturbances in the airflow downstream of the fan blade) hit the stator vanes like waves hitting the beach. Tone noise from a bypass fan of an engine occurs at the blade passing frequency (BPF) and its harmonics (whole-number multiples of the BPF). The BPF is related to the number of fan blades B and the rotational speed N (in revolutions per second, or rps) by the equation BPF = BN, which equals the frequency of the tone produced in cycles per second (Hertz, Hz). Acoustic engineers are also interested in the wavelengths of tones generated, as there is a complex relationship between the length of the wave,

AAPL.

the diameter of the duct in the engine, and the noise produced.

Tests in the NASA Glenn 9- by 15-Foot Low-Speed Wind Tunnel were conducted to investigate theories that fan tone noise could be reduced by changing the number and orientation of the fan blades and stator vanes. One-fifth-scale fan models were created: The baseline fan stage with radial stators is shown in the figure below, and the low-noise fan stage with the ducting removed is shown in the inset. Tests confirmed that tone noise could be reduced by carefully selecting the number of rotor blades and stator vanes, sweeping the stator vanes downstream (increasing the distance between the fan blades and the stator vanes), and leaning the stator vanes (preventing the wake from hitting just one stator vane at a time). These types of changes

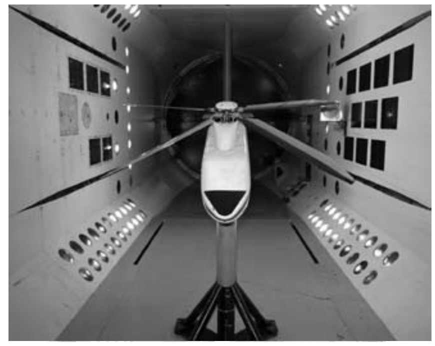


One-fifth-scale model in 9- by 15-Foot Low-Speed Wind Tunnel.

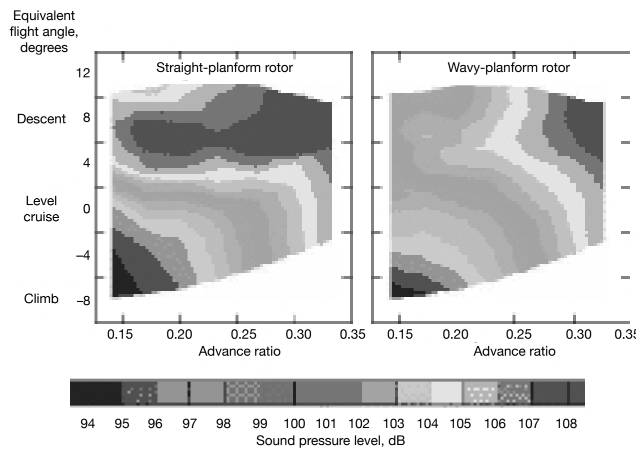
reduce noise by altering the way the fan wakes interact with the stator without adding a lot of weight to the engine or increasing engine complexity.

Noise reduction is an ongoing quest for propulsion engineers. Tests conducted at NASA Langley led to the design of a seamless "sound-absorbing" inlet liner by BFGoodrich, which reduced fan tones in front of the aircraft by up to 15 decibels (dB). Other research at Langley demonstrated the noise reduction capability of "wavy" rotor blades for helicopters as shown at top right along with a computer visualization of the data compared to the usual straight rotors.

One interesting way to reduce noise is called "active noise reduction." In this method, an inverted form of the unwanted sound wave is generated. Since these two waves are exactly out of phase with each other, when they meet they effectively cancel each other out and eliminate the sound. NASA Glenn has begun testing this concept with the Advanced Noise Control Fan, a 4-ft-diameter fan specifically designed to test this concept.

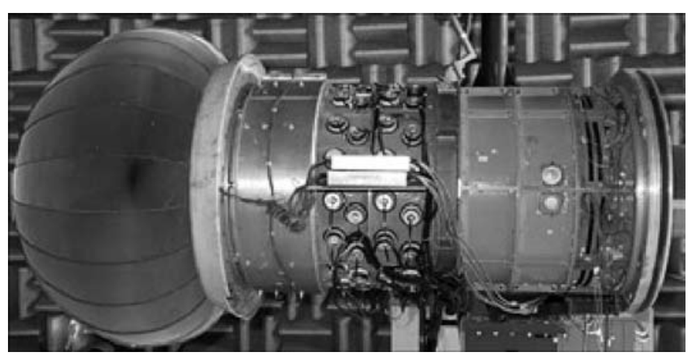


Wavy-planform rotor on model helicopter in the wind tunnel.



Computer visualization of rotor blade noise.

Reducing noise generated by complicated engine parts is challenging and interesting work. It takes the efforts of many people to design, build, and run the experiments and analyze the data. These include people skilled in the trades, engineers, mathematicians, scientists, and computer programmers, to name a few. Working as a team they continue to develop new theo-



Advanced Noise Control Fan.

ries, new computer programs for calculating aerodynamic and acoustic performance, and new techniques to make quieter engines—improving the quality of life for those living and working near aircraft.

Noise Problems

INSTRUCTIONAL OBJECTIVES

Students will

- Understand the relationship between sound intensity and distance
- Investigate factors which cause noise in turbine engines

NATIONAL MATHEMATICS STANDARDS

Algebra

- Understand patterns, relations, and functions
  - Understand and perform transformations such as arithmetically combining, composing, and inverting commonly used functions, using technology to perform such operations on more-complicated symbolic expressions
  - Understand and compare the properties of classes of functions, including exponential, polynomial, rational, logarithmic, and periodic functions
- Represent and analyze mathematical situations and structures using algebraic symbols
  - Understand the meaning of equivalent forms of expressions, equations, inequalities, and relations
  - Write equivalent forms of equations, inequalities, and systems of equations and solve them with fluency—mentally or with paper and pencil in simple cases and using technology in all cases
  - Use symbolic algebra to represent and explain mathematical relationships

Problem Solving

- Solve problems that arise in mathematics and in other contexts
- Apply and adapt a variety of appropriate strategies to solve problems

INTRODUCTION

One of the major concerns with aircraft noise is the level of sound experienced in relationship to distance from the airport. As sound moves out from a source, the compression waves are transferred from air molecule to air molecule. One way to quantify this is to look at a measure called "sound intensity." The intensity is the rate of the energy transfer through a unit area of the plane wave. The rate of energy transfer is power, so it follows that intensity I is a measure of the power of the sound P per unit area, A:

$$I = \frac{\Delta E / \Delta t}{A} = \frac{P}{A}$$

Since the SI unit for power is the watt, then the units of intensity I are watts/area, or W/m^2. If it is assumed that the sound wave propagates evenly over a spherical area, then the surface area of a sphere is used to write:

$$I = \frac{P}{4\pi r^2}$$

This shows that as the distance r increases, the intensity of the sound decreases.

Sound intensity level (SIL) is a related measure with the units decibels. It is the logarithmic measure of the sound intensity as compared to the intensity of the softest sound a person can hear, designated I_{ref} (the reference intensity). The value of I_{ref} is 1.00×10^{-12} W, or 0 dB.

$$\text{SIL} = 10.0\left(\log_{10} \frac{I}{I_{\text{ref}}}\right)$$

PHYSICS AND MATH

Example problem:

You are standing 50.0 m away from a jet engine where the SIL is measured at 130. dB. What is the power of the sound at that distance?

Solution:

$$\text{SIL} = 10.0\left(\log_{10}\frac{I}{I_{ref}}\right)$$

Substituting values gives

$$130.\text{ dB} = 10.0\left(\log_{10}\frac{I}{1\times10^{-12}}\right)$$

$$13.0\text{ dB} = \log_{10} I - \log_{10} 10^{-12}$$

$$13.0\text{ dB} = \log_{10} I - (-12.0)$$

$$1.00\text{ dB} = \log_{10} I$$

$I = 10.0\text{ W/m}^2$

Since $P = IA$ or $P = I\,(4\pi r^2)$

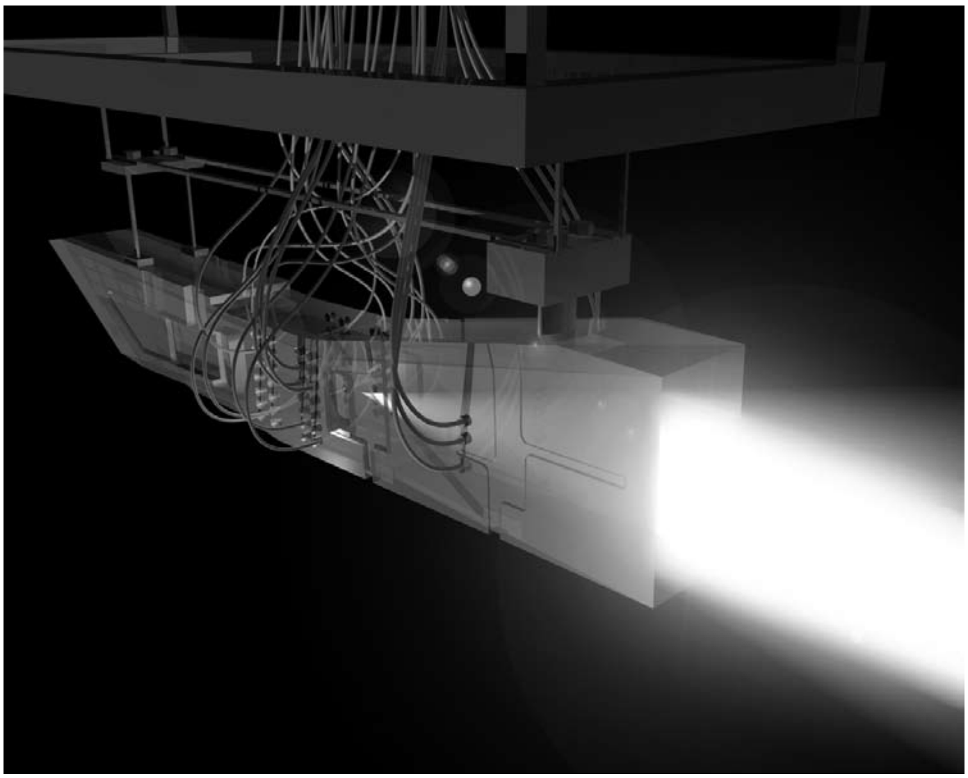
then $P = (10.0)(4)(3.14)(50.0)^2$

$P = 314{,}000$ W

PROBLEMS

1. Given a sound intensity of 3.14×10^5 W/m^2, what would the SIL be at a distance of 8050 m (5.00 mi)?
2. How far away would you need to be from a sound source with 2.50×10^5 W of power in order to have the SIL be 75.0 dB?
3. An airplane baggage loader shouts to a coworker to try to be heard over engine noise. If the sound he produces has 3.10×10^{-3} W power and the coworker is 5.00 m away, what is the sound intensity when it reaches the coworker?
4. How close to your coworker would you need to be to be able to shout above the whine of a jet if its SIL was 110. dB?
5. If the fan in a scale model engine rotates at 12,657 rpm and if it has 22 blades, what is the BPF?
6. Wavelength is related to frequency by the equation $\lambda = c/\nu$. What is the wavelength of a tone from a BPF of 4640 cycles per second (4640 hertz, or Hz)?

THE FUTURE



THE FUTURE

Engineers and engine designers are never content to stop “pushing the envelope” in aviation propulsion. Since the early days of the Wright brothers’ 12-hp 4-cylinder engine they have gone on to develop jet engines that produce over 90,000 lb of thrust. The power of engines of the future will only be limited by being able to develop materials that can withstand extremely high temperatures and stresses required by more powerful engines.

Future engineers will find many opportunities to develop engines with increased efficiency, reduced mass, and exotic materials. New fuels, reduced noise, and reductions in pollution await further study, testing, and design. As NASA seeks to return humans to space, as air travel continues to expand, and as humans seek to fly higher, faster, and farther, propulsion will play a major role in the design for the vehicles of the future.

Rocket Activity

POP BOTTLE ROCKETS DEMONSTRATION

INSTRUCTIONAL OBJECTIVES

Students will
- Apply Newton's Third Law
- Evaluate energy available in different compounds
- Recognize the need for oxygen in combustion

NATIONAL SCIENCE CONTENT STANDARD B

Chemical reactions
- Chemical reactions may release or consume energy. Some reactions, such as burning fossil fuels, release large amounts of energy by giving off heat and emitting light.

Motions and forces
- Objects change their motion only when a net force is applied. Laws of motion are used to calculate precisely the effects of forces on the motion of objects. The magnitude of the change in motion can be calculated using the relationship F = ma, which is independent of the nature of the force. Whenever one object exerts force on another, a force equal in magnitude and opposite in direction is exerted on the first object.

INTRODUCTION

This activity demonstrates the thrust that can be generated by burning a fuel and demonstrates Newton's laws. Unlike 2-liter water bottle rockets in which the propulsion pressure is created by ejecting water under pressure, the combustion of alcohol in this activity creates heated gases that expand out of a nozzle and propel the bottle just like actual rockets.

MATERIALS

- 20-oz **pop or soda bottles**,* clean and dry, with lids
- Electric drill
- Long-necked butane lighter
- Rubbing alcohol
- Fishing line or a tripod rocket launcher
- Plastic straws
- Piece of wire coat hanger, ≈10 in. long
- Piece of aluminum foil, 6 by 6 in.
- Pliers
- Tape
- Fire extinguisher
- Waste bottle with lid
- Safety goggles

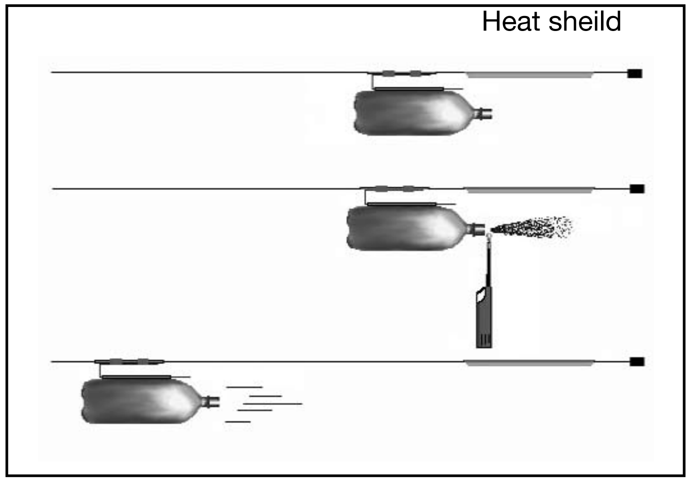
20-oz pop bottle.

ROCKET ACTIVITY

* ONLY USE POP OR SODA BOTTLES, AS THEY ARE DESIGNED TO WITHSTAND PRESSURE. **DO NOT** USE WATER BOTTLES OR ANY OTHER NONCARBONATED DRINK BOTTLES.

PROCEDURE

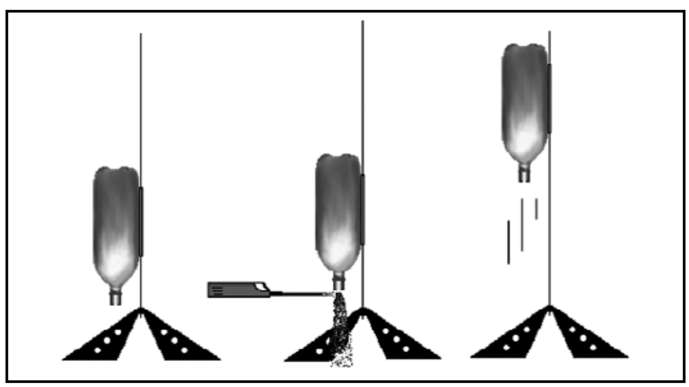
1. Put on safety goggles.
2. Using a pair of pliers, hold the lid on a scrap piece of wood and drill a 3/8-in. hole in the center of the bottle's lid. **DO NOT** DRILL A SMALLER HOLE OR THE BOTTLE MAY CRACK—OR WORSE, EXPLODE.
3. Tape the straw along the length of the bottle to serve as a launch guide.
4. Using the pliers, bend the coat hanger into a U shape, with the base of the U about 2 in. long. Tape one side of the U to a straw and slide this onto the string so the base of the U points down range. This will serve as the rocket carrier.
5. Roll the piece of aluminum foil around a pencil, then remove it and slide the foil onto the string to act as a heat shield.
6. Tie one end of the string to a chair or other solid object, and then tie off the other end at least 20 ft away so it is level.
7. Put on the lid with the hole, and use an eyedropper to add 2 or 3 dropperfuls of alcohol to the bottle.
8. Cover the hole with your finger, and shake the bottle 20 to 30 times to vaporize the alcohol.
9. Drain **ALL** of the unevaporated liquid out the hole in the lid and into the waste bottle. Tightly cap the waste bottle.
   WARNING: ALCOHOL VAPOR IS VERY FLAMMABLE SO IT IS VERY IMPORTANT TO HAVE ALL ALCOHOL CONTAINERS CAPPED AND AWAY FROM THE LAUNCH AREA BEFORE ANY FLAMES ARE LIT. STUDENTS SHOULD NOT BE CLOSE, AND A FIRE EXTINGUISHER SHOULD BE AT HAND IF THERE IS A PROBLEM.
10. Slide the bottle's straw onto the carrier until the straw is up against the base of the U. Slide the aluminum foil heat shield so that it is above the lid (see above figure).
11. With safety goggles on, bring the lighter to the hole and light. With a "whoosh" the rocket should shoot down the string.



Launching horizontal rocket.

VARIATIONS

1. It is possible to shoot the rockets vertically (see figure to the right). You will need a model rocket launch rail. You will also need to do this outdoors in an open area with no flammable material under the launch rail. Again, be sure to allow any liquid alcohol to drain before lighting and be sure there is nothing flammable below the rocket.
2. You may also want to try 2-L pop bottles for more altitude.
3. Have students tape or glue lightweight fins on their rockets for stability.
4. Try a launch with no lid screwed on the bottle, or try hole sizes larger than 3/8 in. (**DO NOT** USE HOLES SMALLER THAN 3/8 IN. BECAUSE OF PRESSURE CONCERNS.)
5. Chemistry students can be given the *heat of formation* for different alcohols and then calculate the *heat of the reaction*.
6. Investigate the fuel/air ratio by trying different numbers of drops of alcohol and measuring the distance traveled. (Use a fresh bottle each time.)



Launching vertical rocket.

7. Students can weigh bottles, time flights, measure distances traveled down the line, or determine altitudes on a vertical launch. (http://www.grc.nasa.gov/WWW/K-12/TRC/Rockets/altitude_tracking.html)
8. Whether vertically or horizontally, have students do a second launch with the same bottle simply by adding more alcohol. Ask them to explain the results.

DISCUSSION

The reaction that takes place within the bottle is between the isopropyl alcohol and oxygen and is very exothermic:

$$2\ C_3H_7OH + 9\ O_2 \rightarrow 6\ CO_2 + 8\ H_2O + \text{heat}$$

The amount of heat involved can be found by application of Hess' Law:

$$\Delta H = \Sigma\ \Delta H_f^o\ \text{products} - \Sigma\ \Delta H_f^o\ \text{reactants}$$

For the reaction above, the standard heats of formation are

ΔH_f^o of isopropyl alcohol	=	–272.8 kJ/mol
ΔH_f^o of oxygen	=	0.0 kJ/mol
ΔH_f^o of carbon dioxide	=	–393.5 kJ/mol
ΔH_f^o of water	=	–285.8 kJ/mol

To calculate the heat of reaction,

$$\left[6(-393.5)+8(-285.8)\right]-\left[2(-272.8)+9(0.0)\right]=-4101.8\ \text{kJ/2 mol}\ C_3H_7OH$$

The inside of the 2-liter bottle is saturated with isopropyl alcohol vapor. This is mixed with air (20 percent oxygen), so the reaction is between gases and thus is very fast. The pressure and volume of the gases produced increase greatly with the heat of reaction, and the gases are forced out the nozzle, creating thrust and launching the bottle according to Newton's Third Law. Once the bottle has been launched, a second try fails to do much since most of the oxygen was used up in the first launch. You might want to have students suggest what they would have to do to make a successful second launch using the same bottle.

If the bottle is tried without the lid, the thrust produced is expended very quickly out the larger opening. Since power is the rate at which the energy change is taking place, this rocket has less power than one with a small hole in the lid where the gas is expelled over a longer period of time. This is a good demonstration of Newton's first law, attempting to overcome inertia. Students might suggest using a hole smaller than 3/8 inches diameter, but too much restriction would allow pressure to build up inside the bottle that could be dangerous and split the bottle.

TEACHERS SECTION

Solutions to Problems

GAS LAW PROBLEMS WORKED OUT

Boyle's Law

1. Since the compression ratio is 25:1, the highest pressure will be 25 × 745 mm, or 8900 mm.

2. $V_1P_1 = V_2P_2$ (0.90 in^3) (775 mm) = (x in^3) (7926 mm) x = 0.088 in^3

3. $V_1P_1 = V_2P_2$ (900 ft^3)(x atm) = (35.0 ft^3) (28.8 atm) x = 1.11 atm

4. Since the compression ratio is 8.5:1, the pressure at the combustor is 8.5 × 740. mm = 6290 mm.

   $V_1P_1 = V_2P_2$
   (x ft^3) (740. mm) = (1.0 ft^3) (6290 mm)

   x = 0.088 ft^3

Charles's Law
For all problems, °C must first be converted to K by adding 273, since all calculations involving gases must be done in absolute temperature.

1. $\frac{V_1}{T_1} = \frac{V_2}{T_2}$ $\frac{12{,}500\ \text{L}}{308\ \text{K}} = \frac{26{,}600\ \text{L}}{T_2}$

   T_2 = 655 K

2. $250.\ \text{L O}_2\left(\frac{16\ \text{L CO}_2}{25\ \text{L O}_2}\right) = 160.\ \text{L CO}_2$ at 25 °C

   $$\frac{160.\ \text{L CO}_2}{298\ \text{K}} = \frac{x\ \text{L CO}_2}{673\ \text{K}}$$

   x = 361 L

3. Station 2: $\frac{900.\ \text{ft}^3}{282\ \text{K}} = \frac{x\ \text{ft}^3}{282\ \text{K}}$ x = 900. ft^3

   Station 3: $\frac{900.\ \text{ft}^3}{282\ \text{K}} = \frac{x\ \text{ft}^3}{567\ \text{K}}$ x = 1810 ft^3

   Station 4: $\frac{900.\ \text{ft}^3}{282\ \text{K}} = \frac{x\ \text{ft}^3}{634\ \text{K}}$ x = 2020 ft^3

   Station 5: $\frac{900.\ \text{ft}^3}{282\ \text{K}} = \frac{x\ \text{ft}^3}{368\ \text{K}}$ x = 1170 ft^3

   Station 8: $\frac{900.\ \text{ft}^3}{282\ \text{K}} = \frac{x\ \text{ft}^3}{282\ \text{K}}$ x = 1170 ft^3

TEACHERS SECTION

Charles' Law Continued

4. Compressor: $\frac{Tt_3}{Tt_2} = \frac{567\text{ K}}{282\text{ K}} = 2.01$ times

   Burner: $\frac{Tt_4}{Tt_3} = \frac{634\text{ K}}{567\text{ K}} = 1.12$ times

   Turbine: $\frac{Tt_5}{Tt_4} = \frac{368\text{ K}}{634\text{ K}} = 0.580$ times

   Nozzle: $\frac{Tt_8}{Tt_5} = \frac{368\text{ K}}{368\text{ K}} = 1.00$ times

   (a) Compressor

   (b) Compressing the gas raises the temperature

   (c) $\frac{Tt_8}{Tt_5} = \frac{368\text{ K}}{282\text{ K}} = 1.30$ times

(d) Since the value is greater than one, the overall work by the gas is greater than the work done to the gas, so the engine produces thrust.

Gay-Lussac's Law

For all problems, degrees Celsius must first be converted to kelvins by adding 273, since all calculations involving gases must be done in absolute temperature.

1. (a) $\frac{P_1}{T_1} = \frac{P_2}{T_2}$ $\qquad \frac{340\text{ psi}}{297\text{ K}} = \frac{x\text{ psi}}{403\text{ K}}$

   $x = 461$ psi

   (b) $\frac{P_1}{T_1} = \frac{P_2}{T_2}$ $\qquad \frac{340\text{ psi}}{297\text{ K}} = \frac{5000\text{ psi}}{x\text{ K}}$

   $x = 4370$ K (4097 °C)

2. $\frac{P_1}{T_1} = \frac{P_2}{T_2}$ $\qquad \frac{29.3\text{ atm}}{962\text{ K}} = \frac{x\text{ atm}}{295\text{ K}}$

   $x = 8.98$ atm; pressure needs to be decreased

3. $\frac{P_1}{T_1} = \frac{P_2}{T_2}$ $\qquad \frac{2.20\text{ atm}}{439\text{ K}} = \frac{x\text{ atm}}{295\text{ K}}$

   $x = 1.48$ atm

4. $\frac{P_1}{T_1} = \frac{P_2}{T_2}$ $\qquad \frac{742\text{ psi}}{966\text{ K}} = \frac{x\text{ psi}}{1553\text{ K}}$ $x = 1190$ psi

   $1190\text{ psi}\left(\frac{1\text{ atm}}{14.7\text{ psi}}\right) = 81.0\text{ atm}$

Hess's Law

1. (a) Heptane, C_7H_{16}, ΔH_f^o = –44.9 kcal/mol

   $C_7H_{16} + 11\ O_2 \rightarrow 7\ CO_2 + 8\ H_2O$

   $\Delta H = [7(-94.0) + 8(-68.3)] - [-44.9 + 11(0.0)] = -1160.$ kcal/mol

   (b) Octane, C_8H_{18}, ΔH_f^o = –49.8 kcal/mol

   $2\ C_8H_{18} + 25\ O_2 \rightarrow 16\ CO_2 + 18\ H_2O$

   $\Delta H = [16(-94.0) + 18(-68.3)] - [2(-44.9) + 25(0.0)] = -2634$ kcal/2 mol = –1317 kcal/mol

   (c) 2,2,3-Trimethylpentane, C_8H_{18}, ΔH_f^o = –52.6 kcal/mol

   $2\ C_8H_{18} + 25\ O_2 \rightarrow 16\ CO_2 + 18\ H_2O$

   $\Delta H = [16(-94.0) + 18(-68.3)] - [2(-52.6) + 25(0.0)] = -2634$ kcal/2 mol = –1317 kcal/mol

2. $$250\text{ g}\left(\frac{1\text{ mol}}{114.188\text{ g}}\right)\left(\frac{1320\text{ kcal}}{1\text{ mol}}\right) = 2880\text{ kcal/mol}$$

3. In order to compare the fuels, one must find calories per gram for each fuel:

   Heptane = $\dfrac{1160\text{ cal/mol}}{100.20\text{ g/mol}} = 11.6$ cal/g Octane = $\dfrac{1320\text{ cal/mol}}{114.19\text{ g/mol}} = 11.6$ cal/g

   2,2,3-Trimethylpentane = $\dfrac{1320\text{ cal/mol}}{114.19\text{ g/mol}} = 11.6$ cal/g

   To three significant digits, all are equivalent in the number of calories per gram of fuel burned.

4. First, find cal/g for the burning of the ethanol:

   $2\ C_2H_5OH + 7\ O_2 \rightarrow 4\ CO_2 + 6\ H_2O$

   $\Delta H = [4(-94.0) + 6(-68.3)] - [2(-56.2) + 7(0.0)] = -673$ cal/2 mol = –337 cal/mol

   Ethanol: $\dfrac{336.7\text{ cal/mol}}{46.07\text{ g/mol}} = 7.308$ cal/g

   For 10%, 0.1(7.308 cal/g) = 0.7308 cal/g

   2,2,3-Trimethylpentane: $\dfrac{1317\text{ cal/mol}}{114.19\text{ g/mol}} = 11.53$ cal/g

   For 90%, 0.9(11.53 cal/g) = 10.38 cal/g

   Adding the two together gives 11.11 cal/g, which is less than pure 2,2,3-trimethylpentane.

NEWTON'S LAWS PROBLEMS WORKED OUT

First Law of Motion

1. Zero

2. $W = mg$
   $= (109{,}000 \text{ kg})(9.80 \text{ m/s}^2)$
   $= 1{,}070{,}000 \text{ N}$

   The force acting on the plane due to its weight is 1,070,000 N.

3. Because the plane is not moving in the vertical direction, the lift force is equal to the force due to its weight, 1,070,000 N.

4. Because the plane is traveling at a constant speed, the thrust equals the drag. Thus, the drag force is 104,525 N.

5. Slow down

6. If a person does not have their seatbelt on during the accident, then there is no force holding the person back in their seat. The inertia of the person keeps the person moving in the direction of the car's original movement. As a result, the person will be thrown with the same speed of the car before impact. Since the car is no longer moving, the person will collide with some part of the car and be injured.

Second Law of Motion

1. If $F_1 = F_2$ and $m_1 < m_2$, then $a_1 > a_2$.

2. (a)

$$a_{\text{ave}} = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t_f - t_i} = \frac{0 \text{ m/s} - 85.0 \text{ m/s}}{30.0 \text{ s}} = -2.83 \text{ m/s}^2$$

   The negative acceleration indicates that the plane is slowing down.

   (b) $F = ma$
   $= (10{,}000. \text{ kg})(2.83 \text{ m/s}^2)$
   $= -28{,}300 \text{ N}$

   The negative force indicates that the force is acting in the opposite direction of the plane's movement.

(c) $\dfrac{85.0\text{ m/s}+0\text{ m/s}}{2}=\dfrac{d_f-d_i}{30.0\text{ s}}$

$1280\text{ m} = d_f - 0\text{ m}$

The runway needs to be 1280 m.

3. $F = ma$

$$= (174{,}000\text{ kg})\left[(0.500\mathbf{i}+0.800\mathbf{j})\text{ m/s}^2\right]$$

$$= \left(87{,}\bar{0}00\mathbf{i}+139{,}000\mathbf{j}\right)\text{ N}$$

$$F=\sqrt{87{,}\bar{0}00^2+139{,}000^2}$$

$$=164{,}000\text{ N}$$

4. If the helicopter is accelerating upward at 4 m/s^2, then the helicopter is overcoming the 9.80 m/s^2 due to gravity. Thus the total acceleration of the helicopter is 13.8 m/s^2. The lift force is then calculated as follows:

$$F = ma$$

$$= (5000.\text{ kg})\left(13.80\text{ m/s}^2\right)$$

$$= 69{,}0\bar{0}0\text{ N}$$

5. $a_{\text{ave}}=\dfrac{\Delta v}{\Delta t}$

$$=\frac{v_f-v_i}{t_f-t_i}$$

$$0.2700\text{ m/s}^2=\frac{v_f-241.30\text{ m/s}}{1000.\text{ s}-0\text{ s}}$$

$$v_f=511.3\text{ m/s}$$

6. $F = ma$

3.00×10^6 N = (2.00×10^5 kg) a

Note that the rocket needs to overcome the acceleration due to gravity, so the upward acceleration is just

15.0 m/s^2 – 9.80 m/s^2 = 5.2 m/s^2

7. $F = ma$

210,000 N = m(5.0 m/s^2)

m = 42,000 kg

Note that when a rocket is in space, the force due to its weight is zero.

TEACHERS SECTION

8. $m_{total} = m_{cargo} + m_{rocket}$

$F = m_{total}a$

thrust − weight = F

thrust $- m_{total}g = m_{total}a$

thrust $= m_{total}a + m_{total}g$

$= m_{total}(a + g)$

$3.2 \text{ N} = m_{total}(9.80 + 136.36) \text{ m/s}$

$m_{total} = 0.022 \text{ kg}$

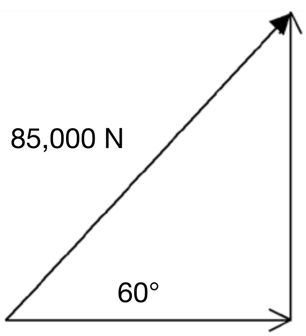
$m_{total} = m_{cargo} + m_{rocket}$

$m_{cargo} = m_{total} - m_{rocket}$

$m_{cargo} = (0.022 - 0.017) \text{ kg}$

$m_{cargo} = 0.005 \text{ kg}$

9.



$F_y = 85{,}000 \sin 60° \text{ N}$
$= 73{,}612.16 \text{ N}$

$F_x = 85{,}000 \cos 60° \text{ N}$
$= 42{,}500 \text{ N}$

(a) There is no net acceleration in the y-direction. As a result, the only force acting on this plane in the y-direction is due to its weight.

$F_y = ma_y \qquad m = \dfrac{(85{,}000)(\sin 60°)}{9.8 \text{ m/s}^2} = 7511.44 \text{ kg}$

(b) $F_x = ma_x$

$85{,}000 \cos 60° = (7511.44 \text{ kg})\, a_x$

$a_x = 5.66 \text{ m/s}^2$

(c) If the angle of elevation were 45°, $F_y = F_x$. The mass would be less (m = 6133.07 kg), and the acceleration in the x-direction would be greater (a_x = 9.80 m/s^2).

Third Law of Motion

1. Since the sparrow and the plane constitute an action-reaction pair, the force the sparrow exerts on the plane is equal to the force the plane exerts on the sparrow. Since $F = ma$, $m_{sparrow}\, a = m_{plane}\, a$. This means a will be huge for the sparrow and it will undergo a massive, lethal decelleration while a will be tiny for the plane and no one onboard will notice.

2. (a) $\text{Thrust} = \frac{\Delta m}{\Delta t} v_e + (p_e + p_o) A_e$

   where $\frac{\Delta m}{\Delta t}$ = mass flow rate

   v_e = exhaust velocity

   p_e = exhaust pressure

   p_o = free-stream pressure

   A_e = exhaust area

   Because $p_e \approx p_o$, $(p_e + p_o)\, A_e \approx 0$. Thus, thrust $\approx \frac{\Delta m}{\Delta t} v_e$.

   Thrust $\approx$ (909.09 kg/s)(2750 m/s)

   $\approx 2.500 \times 10^6$ N

   (b) The direction of the exhaust is opposite to the direction of the rocket travel. The thrust is opposite in direction but equal in magnitude.

3. (a) $F_W = \left(M_r - \frac{\Delta m_e}{\Delta t} t \right) g$

   (b) From part 3(a),

   $$F_W = \left(M_r - \frac{\Delta m_e}{\Delta t} t \right) g$$

   So F_w = [280,000 kg – (1100 kg/s)60 s](9.80 m/s^2)

   = 2,100,000 N

TEACHERS SECTION

PHYSICS AND MATHEMATICS PROBLEMS WORKED OUT

Displacement, Rate, and Acceleration

1. $a_{ave} = \frac{\Delta v}{\Delta t}$

$= \frac{v_f - v_i}{t_f - t_i}$

$= \frac{450 \text{ mph} - 505 \text{ mph}}{(1.0 - 0)\text{min}\left(\frac{1 \text{ hr}}{60 \text{ min}}\right)}$

$= -3300 \text{ mi/hr}^2$

The negative sign indicates the airplane is slowing down, or decelerating.

2. $v_{ave} = \frac{\Delta d}{\Delta t}$

$500. \text{ mph} = \frac{d_f - d_i}{t_f - t_i}$

$500. \text{ mph} = \frac{d_f - 0}{5.0 \text{ hr}}$

$d_f = 2500 \text{ mi}$

The distance from New York City, NY, to San Fransisco, CA, is about 2500 mi.

3. (a) $a_{ave} = \frac{\Delta v}{\Delta t}$

$= \frac{v_f - v_i}{t_f - t_i}$

$= \frac{560 \text{ mph} - 475 \text{ mph}}{20. \text{ s}\left(\frac{1 \text{ hr}}{3600 \text{ s}}\right)}$

$= 15{,}300 \text{ mi/hr}^2$

$= 0.0012 \text{ mi/s}^2$

The average acceleration is 0.0012 mi/s^2.

(b) $v_{ave} = \frac{(560 + 475) \text{ mph}}{2} = \frac{d_f - 0}{20.\text{s}\left(\frac{1 \text{ hr}}{3600 \text{ s}}\right)}$

$d_f = 2.9 \text{mi}$

The plane travels 2.9 mi in those 20. s.

4. $v_{\text{ave}} = \dfrac{\Delta d}{\Delta t}$

$$190.\text{ mph} = \frac{(3000.\text{ ft} - 0\text{ ft})\left(\dfrac{1\text{ mi}}{5280\text{ ft}}\right)}{t_f - 0}$$

$$t_f = 0.00299\text{ hr}$$
$$= 10.8\text{ s}$$

5. $a_{\text{ave}} = \dfrac{(-0.0120 + 0)\text{ mi/s}^2}{2} = -0.00600\text{ mi/s}^2 = -77{,}800\text{ mi/hr}^2$

$$a_{\text{ave}} = \frac{\Delta v}{\Delta t}$$

$$-77{,}800\text{ mi/hr}^2 = \frac{0 - 250\text{ mph}}{t_f - 0}$$

$$t_f = 0.00321\text{ hr}$$
$$= 11.6\text{ s}$$

$$v_{\text{ave}} = \frac{\Delta d}{\Delta t}$$

$$\frac{250.\text{ mph} + 0}{2} = \frac{d_f - d_i}{t_f - t_i}$$

$$125\text{ mph} = \frac{d_f - 0}{11.6\text{ s}\left(\dfrac{1\text{ hr}}{3600\text{ s}}\right)}$$

$$d_f = 0.403\text{ mi}$$

The runway needs to be 0.403 mi.

TEACHERS SECTION

6. (a) From Newton's Second Law of Motion, $F = ma$. Assuming that the mass stays constant, $F_{\text{ave}} = ma_{\text{ave}}$.

$$20{,}000.\ \text{N} = (174{,}000\ \text{kg})a_{\text{ave}}$$

$$a_{\text{ave}} = 0.115\ \text{mi/s}^2$$

$$a_{\text{ave}} = \frac{\Delta v}{\Delta t}$$

$$0.115\ \text{m/s}^2 = \frac{v_f - 241.40\ \text{m/s}}{(2.00\ \text{min} - 0)\left(\frac{60s}{1\,\text{min}}\right)}$$

$$255\ \text{m/s} = v_f$$

The velocity of the airplane after those 2 minutes was 255 m/s.

(b) $v_{\text{ave}} = \frac{\Delta d}{\Delta t}$

$$\frac{255\ \text{m/s} + 241.40\ \text{m/s}}{2} = \frac{d_f - 0}{(2.00\ \text{min} - 0)\left(\frac{60\ \text{s}}{1\ \text{min}}\right)}$$

$$d_f = 29{,}800\ \text{m}$$

The plane traveled 29,800 m in those 2 minutes.

PHYSICS AND MATHEMATICS PROBLEMS WORKED OUT

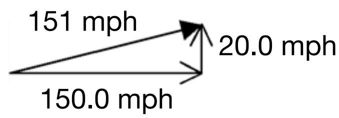
Vectors

1. (a) 150. – 20.0 = 130. mph

   (b) 150. + 20.0 = 170. mph

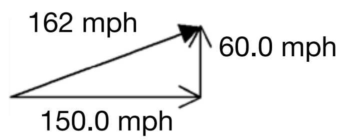
   (c) Using the Pythagorean Theorem,
   $150.^2 + 20.0^2 = (\text{hypotenuse})^2$
   Hypotenuse = 151

   The resultant velocity is 151 mph.

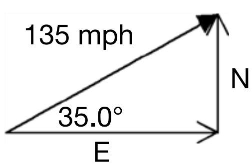


   (d) Using the Pythagorean Theorem,
   $150.^2 + 60.0^2 = (\text{hypotenuse})^2$
   Hypotenuse = 161.6

   The resultant velocity is 162 mph.



2.



North

$$\sin 35.0° = \frac{N}{135}$$
$$N = 77.4 \text{ mph}$$

To calculate the north distance, multiply the magnitude of the north velocity vector by 2.00 hr:

(77.4 mph)(2.00 hr) = 154.9 mi

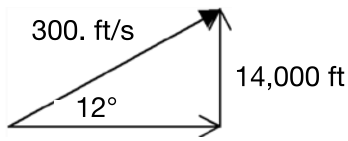
East

$$\cos 35.0° = \frac{E}{135}$$
$$E = 111 \text{ mph}$$

To calculate the east distance, multiply the magnitude of the east velocity vector by 2.00 hr:

(111 mph)(2 hr) = 222 mi

3.



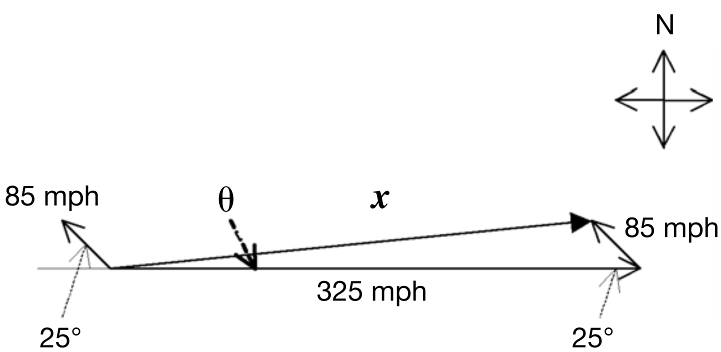
$$\sin 12^\circ = \frac{v_y}{300.\text{ ft/s}}$$
$$v_y = 62 \text{ ft/s}$$

$$v_{\text{ave}_y} = \frac{\Delta d}{\Delta t} = \frac{d_f - d_i}{t_f - t_i}$$
$$62.4 \text{ ft/s} = \frac{14{,}000 \text{ ft} - 0}{t_f - 0}$$

$$t_f = 226 \text{ s}$$

It will take this airplane about 226 s to reach 14,000 ft.

4.



(a) Use the Law of Cosines to determine the new speed (x):

$x^2 = 325^2 + 85^2 - 2(325)(85) \cos 25°$

$x^2 = 63{,}000$

$x = 250$ mph

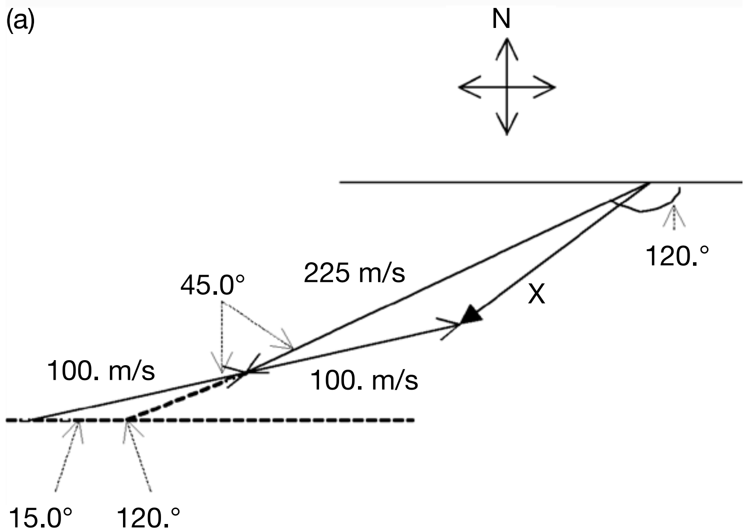
(b) Use the Law of Sines to determine θ:

$$\frac{250}{\sin 25^\circ} = \frac{85}{\sin\theta}$$
$$\frac{85(\sin 25^\circ)}{250} = \sin\theta = 0.144$$
$$\theta = \sin^{-1}(0.144)$$

$$\theta \approx 8.0^\circ$$

The plane is traveling about 8.0° north of its original eastward direction.

5. (a)



(b) To solve for x, first determine the various angles as illustrated in the diagram. Then use the Law of Cosines:

$x^2 = 225^2 + 100.^2 - 2(225)(100.) \cos 45°$
$x^2 = 28{,}800$
$x = 170.$ m/s

The resultant velocity of this plane is about 170. m/s.

PHYSICS AND MATHEMATICS PROBLEMS WORKED OUT

Ratios

1. $a = b$
   $a < b$
   $a > b$
   $a << b$
   $a >> b$

2. $$\text{Mach number} = \frac{\text{speed of object}}{\text{speed of sound}}$$

   $$0.800 = \frac{\text{speed of object}}{760.\text{ mph}}$$

   Speed of object = 608 mph

   The typical cruise speed of a Boeing 757 is 608 mph.

3. $$\text{Thrust-to-weight ratio} = \frac{215{,}000\text{ N}}{(174{,}000\text{ kg})\cdot\left(9.80\text{ m/s}^2\right)} = 0.126$$

4. Wingspan of a Boeing 757 = 124 ft, 10 in. =124.83 ft
   Wing area = 1994 ft^2

   $$\text{Aspect ratio} = \frac{\text{wingspan}^2}{\text{wing area}}$$

   $$= \frac{(124.83\text{ ft})^2}{1994\text{ ft}^2}$$

   $$= 7.815$$

5. Answers will vary.

PHYSICS AND MATHEMATICS PROBLEMS WORKED OUT

Noise

1. First find intensity, I:

$$I = \frac{P}{A} = \frac{P}{4\pi r^2}$$
$$I = \frac{(314{,}000\ \text{W})}{4(3.14)(8050\ \text{m})^2}$$
$$= 0.000386\ \text{W/m}^2$$

Now find SIL:

$$SIL = 10.0(\log_{10} I - \log_{10} I_{\text{ref}})$$
$$= 10.0\left(\log_{10} I - \log_{10} 10^{-12}\right)$$
$$= 10.0\left[\log_{10} 0.00386 - (-12)\right]$$
$$= 10.0(-3.41 + 12)$$

$$SIL = 85.9\ \text{dB}$$

2. First find intensity, I:

$$75.0\ \text{dB} = 10.0(\log_{10} I - \log_{10} I_{\text{ref}})$$
$$= 10.0\left(\log_{10} I - \log_{10} 10^{-12}\right)$$

$$7.50\ \text{dB} = \log_{10} I + 12$$
$$\log_{10} I = -4.50$$

$$I = 0.0000316\ \text{W/m}^2\ (\text{or } 3.16\times10^{-5}\ \text{W/m}^2)$$

Now calculate the distance, r:

$$I = \frac{P}{A} = \frac{P}{4\pi r^2}$$
$$3.16\times10^{-5} = \frac{250{,}000}{4(3.14)r^2}$$
$$r = \sqrt{6.30\times10^8}$$

$$r = 25{,}100\ \text{m}\ (\text{or } 15.6\ \text{mi})$$

Note: This would hold true if there were a direct line of sight and atmospheric absorbtion were neglected. Generally, there are any number of obstructions such as trees and buildings that would disrupt sound transmission.

3. First find intensity, I:

$$\begin{aligned} I &= \frac{P}{A} \\ &= \frac{P}{4\pi r^2} \\ &= \frac{3.10\times10^{-3}}{4(3.14)(5.00)^2} \\ &= 9.87\times10^{-6}\ \text{W/m}^2 \end{aligned}$$

Now calculate the sound intensity level, SIL:

$$\begin{aligned} \text{SIL} &= 10.0(\log_{10} I - \log_{10} I_{\text{ref}}) \\ &= 10.0\left(\log_{10} 9.87\times10^{-6} - \log_{10} 10^{-12}\right) \\ &= 10(-5.01+12.0) \end{aligned}$$

$$\text{SIL} = 69.9\ \text{dB}$$

Note: He would not be heard.

4. First find intensity, I:

$$\begin{aligned} 110.\ \text{dB} &= 10(\log_{10} I - \log_{10} I_{\text{ref}}) \\ &= 10\left(\log_{10} I - \log_{10} 10^{-12}\right) \\ 11.0\ \text{dB} &= \log_{10} I + 12 \\ \log_{10} I &= -1.00 \end{aligned}$$

$$I = 0.100$$

Now calculate the distance, r:

$$\begin{aligned} I &= \frac{P}{A} \\ &= \frac{P}{4\pi r^2} \\ 0.100 &= \frac{3.10\times10^{-3}}{4(3.14)r^2} \\ r^2 &= 0.00247 \\ r &= \sqrt{0.00247} \end{aligned}$$

$$r = 0.0497\ \text{m}$$

At this distance $\text{SIL}_{\text{person}} = \text{SIL}_{\text{jet}}$, so he would need to be closer than 0.0497 m.
Note: 0.0497 m = 4.97 cm = 1.96 in. He would have to yell right in his ear!

5. $\text{BPF} = BN$

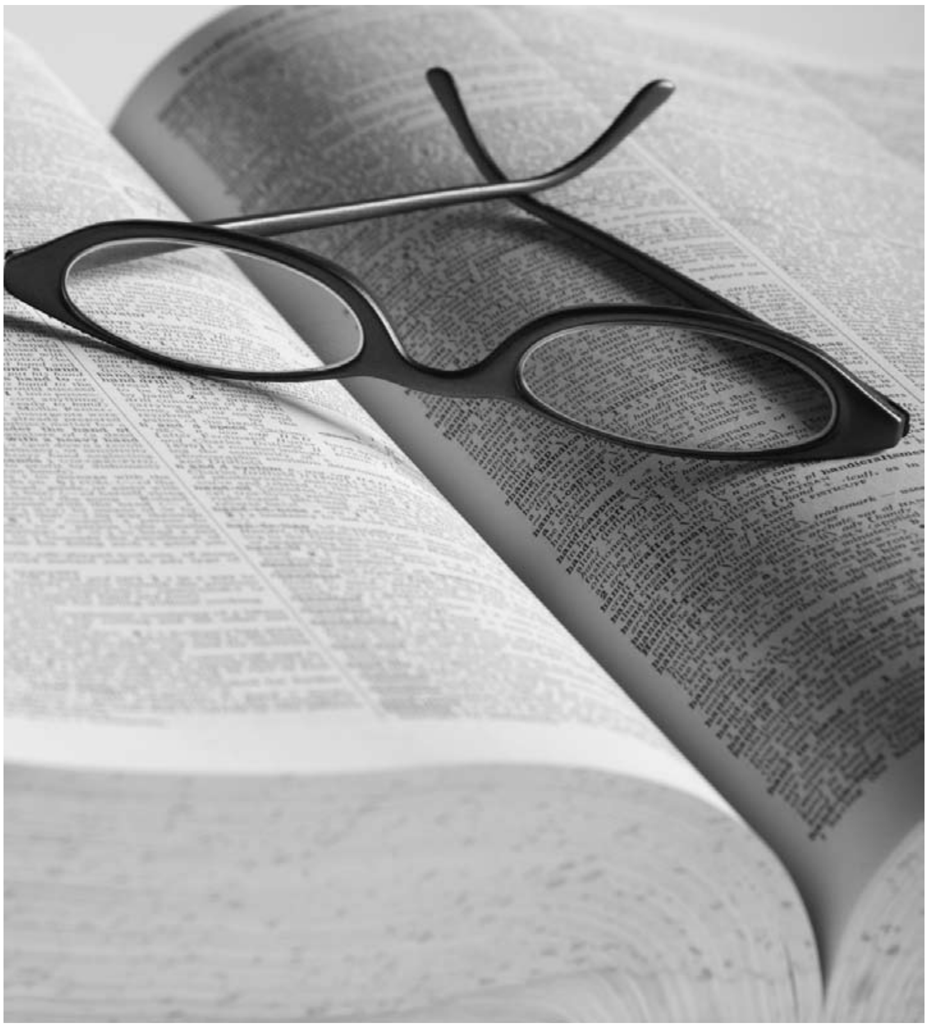
$$= 22(12{,}657 \text{ rpm})\left(\frac{1 \text{ min}}{60 \text{ s}}\right)$$

$$= 4640 \text{ cycles/s}$$

$$= 4640 \text{ Hz}$$

6. $$\lambda = \frac{343 \text{ m/s}}{4640 \text{ cycles/s}}$$

$$= 0.0739 \text{ m}$$



REFERENCE

Units of Measure

The following is a list of the units of measure used with the quantities presented in this guide.

Note: Metric units may be preceded by a prefix indicating multiples of the unit:
For example,

k = kilo = 1000 times; thus kW = kilowatts = 1000 watts
c = centi = 0.01 times; cm = centimeters = 0.01 meters
m = milli = 0.001 times; mg = milligrams = 0.001 grams

atm	atmosphere	pressure
°C	degree Celsius	temperature
cal	calorie	energy
dB	decibel	sound
°F	degree Fahrenheit	temperature
ft	foot	length
g	gram	mass
hp	horsepower	power
hr	hour	time
Hz	Hertz	frequency
in.	inch	length
K	kelvin	temperature
L	liter	volume
lb	pound	mass
m	meter	length
mi	mile	length
min	minute	time
mol	mole	quantity
mm Hg	millimeters of mercury	pressure
mph	miles per hour	velocity
N	Newton	force
psi	pounds per square inch	pressure
rpm	revolutions per minute	velocity
rps	revolutions per second	velocity
s	second	time
W	watt	power

Glossary

ABSOLUTE TEMPERATURE	Temperature as measured on a scale in which the hypothetical lowest limit of physical temperatures is assigned the value zero (absolute zero), such as the Kelvin scale.
ACCELERATION	The time rate of change of velocity with respect to magnitude or direction; the derivative of velocity with respect to time.
ACOUSTIC	Pertaining to the sense or organs of hearing, to sound, or to the science of sound.
AFTERBURNER	A device placed within, or attached to the exit of, a jet-engine exhaust pipe to produce afterburning.
ALKANE	Any of a series of saturated aliphatic hydrocarbons with the general formula C_nH_{2n+2}.
ALLOY	A substance composed of two or more metals.
ANECHOIC	Neither having nor producing echoes.
ASPECT RATIO	Equal to the square of the wingspan divided by the wing area.
BOTTOM DEAD CENTER	The point in the travel of a piston that creates the greatest volume in the cylinder.
BYPASS AIR	In a turbofan engine, this is the air that is pushed backwards by the fan that does not go through the core of the engine.
CARBURETOR	A device for mixing vaporized fuel with air to produce a combustible or explosive mixture, as for an internal combustion engine.
CATHODE	The electron-emitting electrode of an electron tube. It is the positive electrode.
CERAMIC	Any of various hard, brittle, heat-resistant, and corrosion-resistant materials made by shaping and then firing a nonmetallic mineral, such as clay, at a high temperature.
CHEVRON	A device shaped like an inverted “V” that, when placed on a nozzle, allows jet exhaust to better mix with the outside air.
COMBUSTOR	The apparatus in a jet engine for initiating and sustaining combustion, consisting of the igniter, fuel-injection system, combustion chamber, and flame holder.
COMPRESSOR	A machine for reducing volume and increasing pressure of gases in order to condense the gases; in jet engines they keep combusted gases moving toward the rear of the engine.

CRANKSHAFT	A shaft having one or more cranks, usually formed as integral parts that translates up-and-down motion into rotary motion.
CREEP	To become deformed, as under continuous loads or at high temperatures.
DENSITY	Mass per unit volume.
DRAG	The aerodynamic force exerted on an airfoil, airplane, or other aerodynamic body that tends to reduce its forward motion; the resistance to moving through the air.
ENTHALPY	A thermodynamic quantity equal to the internal energy of a system plus the product of its volume and pressure; the amount of energy in a system capable of doing mechanical work. In chemistry, the heat content of a substance.
FATIGUE	The weakening or breakdown of material subjected to stress, especially a repeated series of stresses.
FLASH POINT	The temperature at which the vapor above a liquid will ignite.
FLUOROCARBONS	Hydrocarbons with fluorines attached.
FORCE	An influence on a body or system that produces or tends to produce a change in movement or in shape. A push or a pull.
FOSSIL FUEL	Any combustible organic material, such as oil, coal, or natural gas, derived from the remains of former life.
FREQUENCY	The number of cycles or completed alternations per unit time of a wave or oscillation.
GAS	A substance possessing perfect molecular mobility and the property of indefinite expansion, as opposed to a solid or liquid, and characterized by no definite shape or volume.
GASOLINE	A volatile, flammable liquid mixture of hydrocarbons, obtained from petroleum, and used as fuel for internal combustion engines.
GEOSYNCHRONOUS	Of or pertaining to a satellite traveling in an orbit 22,300 mi (35,900 km) above the Earth's equator: at this altitude the satellite's period of rotation, 24 hr, matches the Earth's, and the satellite always remains in the same spot over the Earth.
HEAT OF FORMATION	The heat evolved or absorbed during the formation of one mole of a substance from its component elements.
HYDROCARBON	Any of numerous organic compounds, such as benzene and methane, that contain only carbon and hydrogen atoms.
IDEAL GAS	A gas composed of molecules on which no forces act except upon collision with one another and with the walls of the container in which the gas is enclosed; a gas that obeys the ideal gas law.

ION	An electrically charged atom or group of atoms formed by the loss or gain of one or more electrons, such as a cation (positive ion), which is created by electron loss and is attracted to the cathode in electrolysis, or an anion (negative ion), which is created by an electron gain and is attracted to the anode.
KNOCKING	A pounding or clanking noise made by an engine, often as a result of faulty fuel combustion; also called ping.
LIFT	A lifting or raising force.
LIQUID	Composed of molecules that move freely among themselves but do not tend to separate like those of gases; neither gaseous nor solid, having definite volume but not definite shape.
MACH	A number indicating the ratio of the speed of an object to the speed of sound in the medium through which the object is moving.
MASS	The quantity of matter as determined from Newton's second law of motion.
MOMENTUM	A quantity expressing the motion of a body or system, equal to the product of the mass of a body and its velocity, and for a system equal to the vector sum of the products of mass and velocity of each particle in the system.
NO_x	An abbreviation for oxides of nitrogen where the "x" represents one of a number of possible subscripts.
NOZZLE	In a jet engine, a specially shaped tube sitting downstream of the power turbine to produce thrust, to conduct the exhaust gases back to the free stream, and to set the mass flow rate through the engine.
OCTANE RATING	A designation of antiknock quality, numerically equal to the percentage of isooctane by volume in a mixture of isooctane and normal heptane that matches the given gasoline in antiknock characteristics.
OTTO CYCLE	An idealization of the thermodynamic cycle of the internal combustion engine with air as the working substance: intake of air at atmospheric pressure, then adiabatic compression, then ignition with an increase of pressure and temperature at constant volume, then adiabatic expansion and performance of work, then a drop to atmospheric pressure at constant volume and a rejection of heat to the environment, then the exhaust of air at constant pressure.
OXIDATION	The process of oxidizing; the addition of oxygen to a compound.
OXIDIZER	A substance that oxidizes another substance, especially one that supports the combustion of fuel; an oxidizing agent.
OZONE	A form of oxygen, O_3, with a peculiar odor, produced when an electric spark or ultraviolet light is passed through air or oxygen.
PLASMA	A highly ionized gas containing an approximately equal number of positive ions and electrons.

POLYMERS	Any of numerous natural and synthetic compounds of usually high molecular weight consisting of up to millions of repeated linked units, each a relatively light and simple molecule.
PRESSURE	Force applied uniformly over a surface, measured as force per unit of area.
SCALAR	A quantity possessing only magnitude and not direction.
SOLAR CELL	A photovoltaic cell that converts sunlight directly into electricity.
SOLID	A substance having a definite shape and volume; one that is neither liquid nor gaseous.
SPEED	Distance traveled divided by the time of travel.
SUBSONIC	A speed less than that of sound in a designated medium.
SUPERCHARGER	A mechanism for forcing air into an internal-combustion engine in order to increase engine power.
SUPERSONIC	A speed greater than the speed of sound in a given medium, especially air.
TEMPERATURE	A measure of the average kinetic energy of the particles in a sample of matter, expressed in terms of units or degrees designated on a standard scale.
THRUST	A linear reactive force exerted by a propeller, propulsive gases, or other means to propel an object (e.g., ship or aircraft).
TOP DEAD CENTER	The point in the travel of a piston that creates the least volume in the cylinder.
TRANSONIC	Relating to aerodynamic flow or flight conditions at speeds near the speed of sound.
TURBINE	Any of various machines having a rotor, usually with vanes or blades, driven by the pressure, momentum, or reactive thrust of a moving fluid, such as steam, water, hot gases, or air, either occurring in the form of free jets or as a fluid passing through and entirely filling a housing around the rotor.
TURBOCHARGER	A supercharger that is driven by a turbine turned by exhaust gases from the engine.
TURBOFAN	A jet engine having a large impeller that takes in air, a small part of which is sent through the core of the engine to combust with fuel, the remainder being pushed back around the core to add to the thrust.
TURBOJET	A jet engine having a turbine-driven compressor and developing thrust from the exhaust of hot gases.
TURBOPROP	A turbojet engine used to drive an external propeller.
VECTOR	A quantity, such as velocity, completely specified by a magnitude and a direction.

VELOCITY	A vector quantity whose magnitude is a body's speed and whose direction is the body's direction of motion.
VOLATILITY	A measure of the ease of evaporation.
VOLUME	The amount of space, measured in cubic units, that an object or substance occupies.
WAVELENGTH	The distance, measured in the direction of propagation of a wave, between two successive points in the wave that are characterized by the same phase of oscillation.
WEIGHT	The force that gravitation exerts upon a body, equal to the mass of the body times the local acceleration of gravity.

National Aeronautics and Space Administration

Glenn Research Center
21000 Brookpark Road
Cleveland, Ohio 44135
www.grc.nasa.gov
www.aeronautics.nasa.gov

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