CHAPTER 1

CLASSIFICATION

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In general terms, propulsion is the act of changing the motion of a body with respect to an inertial reference frame. Propulsion systems provide forces that move bodies initially at rest, change their velocity, or overcome retarding forces when bodies are propelled through a viscous medium. The word *propulsion* comes from the Latin *propulsus*, which is the past participle of the verb *propellere*, meaning "to drive forward or away." *Jet propulsion* is a type of motion whereby a reaction force is imparted to a vehicle by the momentum of ejected matter.

Rocket propulsion is a class of jet propulsion that produces thrust by ejecting matter, called the working fluid or *propellant*, stored entirely in the flying vehicle. *Air-breathing propulsion* is another class of jet propulsion which includes turbojets and ramjets. Air-breathing engines utilize their surrounding medium as both the working fluid and the oxidizing propellant, energized by combustion with the vehicle's stored fuel. Combinations of rockets and air-breathing propulsion devices have been attractive for some applications, and one is briefly described in this chapter. This book will focus on rocket propulsion and will reference air-breathing systems for comparison purposes.

Energy sources are central to rocket performance and several kinds, both within and external to the vehicle, have been investigated. The *energy source* most commonly used in rocket propulsion is *chemical combustion*. Heat energy can also be supplied by *solar radiation, electricity,* or a *nuclear reaction process*. Some systems use the adiabatic expansion and expulsion of *compressed gases* to impart momentum. Accordingly, the various propulsion sources can be classified into *chemical propulsion, nuclear propulsion*, *cold gas propulsion,* and *solar propulsion*. Table 1–1 lists many important propulsion concepts according to their energy source and type of working fluid or propellant. In addition to solar propulsion, other thermal energy options may originate from sources other than the sun and theoretically include the transmission of energy by ground-based microwaves and laser beams. Nuclear energy originates in transformations of mass within atomic nuclei and is generated by either fission or fusion. Thus, multiple energy sources are capable of producing thrust with rocket engines; thrust is the force that imparts a change in momentum of a body. Regardless of the energy source, the output thrust of the engine comes from the kinetic energy of the ejected matter and from the exhaust pressure

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TABLE 1–1. Energy Sources and Propellants for Various Propulsion Concepts

Propulsion Device	Energy Source				Propellant or Working Fluid
	Chemical	Nuclear	Solar	Other	
Turbojet	TRL 9	—	—	—	Fuel + air
Turbo-ramjet	TRL 9	—	—	—	Fuel + air
Ramjet (hydrocarbon fuel)	TRL 9	TRL 6	—	—	Fuel + air
Ramjet (H_2 cooled)	TRL 4	—	—	—	Hydrogen + air
Scramjet (hydrogen fueled)	TRL 6	—	—	—	Hydrogen + air
Scramjet (hydrocarbon fuel)	TRL 6	—	—	—	Fuel + air
Liquid augmented solid rocket (LASR)	TRL 4	—	—	—	Stored solid fuel + monopropellant
Ducted rocket	TRL 6	—	—	—	Stored solid fuel + surrounding air
Rocket (chemical)	TRL 9	TRL 6	—	—	Stored propellant(s)
Electric rocket	TRL 9	TRL 6	TRL 9	—	Stored propellant
Nuclear fission rocket	—	TRL 6	—	—	Stored propellant (H_2)
Solar-heated rocket	—	—	TRL 4	—	Stored propellant (H_2)
Solar sail	—	—	TRL 7	—	Photon reflection
Atmosphere-breathing electric propulsion	—	—	TRL 4	—	Residual atmosphere from 120 to 250 km altitude
Tethers (nonspinning)	—	—	—	TRL 6	Momentum exchange
Cold gas thruster	—	—	—	TRL 9	Pressurized gas

on key engine components; thus, rocket propulsion systems primarily convert thermal energy into the kinetic energy of the exhausted gas. The ejected mass can be in a solid (particulate), liquid (droplet), or gaseous state. Often, combinations of two or more phases are ejected. At very high temperatures, ejected matter can also be in a plasma state, which is an electrically conducting gas. The maturity of the technologies is assessed according to their technology readiness level (TRL) as defined in Table 1–2 (see Ref. 1–1).

In recent years, there have been several important new developments that have had an impact on space launch vehicles and their propulsion systems. This tenth edition includes information on many of these technologies, some of which are now mature and have been adopted by the aerospace industry. The culmination of research and development efforts in rocket propulsion often involves adaptations of new approaches, designs, materials, as well as novel fabrication processes, cost, and/or schedule reductions to new applications.

1.1. JET PROPULSION

This class, commonly called *air-breathing engines*, is comprised of devices that utilize ambient air as the primary working fluid. They use atmospheric oxygen to burn with fuel stored in the flight vehicle. This class includes turbojets, turbofans, ramjets, scramjets, and pulsejets. These are mentioned here primarily to provide a basis for comparison with rocket propulsion and as background for combined rocket/air-breathing engines, which are mentioned later. Table 1–3 compares several performance characteristics of specific chemical rockets with those of typical turbojets and ramjets. However, the uniqueness of rocket propulsion systems (i.e., high thrust-to-weight ratio, high thrust to weight, small frontal area, and broad thrust range nearly independent of altitude) enables flight in rarefied air and exclusively in space environments.

TABLE 1–2. Definitions of Technology Readiness Levels (TRLs) from Ref. 1–1

Technology Readiness Level	Description	Supporting Information
1–Basic principles observed and reported	Scientific research begins to be translated into applied research and development (R&D).	Published research that identifies the principles that underlie this technology.
2–Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
3–Analytical and experimental critical function and/or characteristic proof-of-concept	Analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems.
4–Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together.	System concepts that have been considered and results from testing laboratory-scale breadboard(s).
5–Component and/or breadboard validation in a relevant environment	The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment.	Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment.
6–System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume.
7–System prototype demonstration in an operational environment	Prototype near or at planned operational system.	Results from testing a prototype system in an operational environment.
8–Actual system completed and qualified through test and demonstration	Technology has been proven to work in its final form and under expected conditions.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate.
9–Actual system proven through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation.

The *turbojet engine* is the most common of air-breathing engines. Figure 1–1 shows its basic elements.

For supersonic flight speeds above Mach 2, the *ramjet engine* becomes a viable propulsion option for flights within the atmosphere. Compression is purely gas dynamic (no active mechanisms) and thrust is produced by thermally increasing the momentum of the subsonic compressed air as it passes through the combustion section. Figure 1–2 shows the basic components of a ramjet. Ramjets with subsonic combustion and hydrocarbon fuels have an upper speed limit of approximately Mach 5; hydrogen fuel, with hydrogen cooling, raises this upper limit somewhat relative to hydrocarbon fuels. Ramjets with supersonic combustion, known as *scramjets*, have flown in experimental vehicles and

TABLE 1–3. Comparison of Several Characteristics of a Typical Chemical Rocket Propulsion System and Two Air-Breathing Propulsion Systems

Characteristic	Chemical Rocket Engine or Rocket Motor	Turbojet Engine	Ramjet Engine
Thrust-to-weight ratio, typical	50–125:1	5:1, turbojet and afterburner	7:1 at Mach 3 at 9100 m[a]
Specific fuel consumption[b]	8–14	0.5–1.5	2.3–3.5
Specific thrust[c]	5000–25,000	2500 (low Mach[d] numbers at sea level)	2700 (Mach 2 at sea level)
Specific impulse, typical[e]	270 sec	1600 sec	1400 sec
Thrust change with altitude	Slight increase	Decreases	Decreases
Thrust vs. flight speed	Nearly constant	Increases with speed	Increases with speed
Thrust vs. air temperature	Constant	Decreases with temperature	Decreases with temperature
Flight speed vs. exhaust velocity	Unrelated, flight speed can be greater	Flight speed always less than exhaust	Flight speed always less than exhaust
Altitude limitation	None; suited to space travel	14,000–17,000 m	20,000 m at Mach 3 30,000 m at Mach 5 45,000 m at Mach 12

[a] Multiply by 3.28 to convert m to ft.
[b] Indicates pounds of propellant or fuel per hour per pound of thrust. Multiply by 0.102 to convert to kg/(hr-N).
[c] Indicates pounds of thrust per square foot of frontal area. Multiply by 47.9 to convert to N/m^2.
[d] Mach number is the ratio of gas speed to the local speed of sound (see Eq. 3–22).
[e] Thrust force per unit propellant or fuel weight flow per second. Multiply by 9.81 to convert to $N \cdot s/kg$.

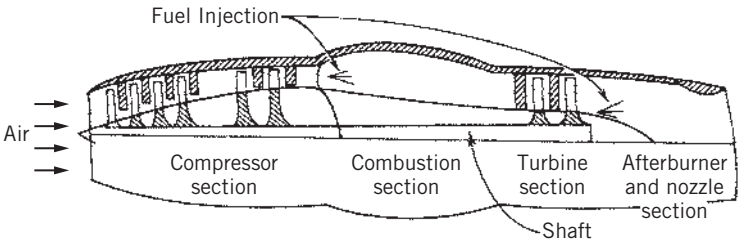


FIGURE 1–1. Simplified schematic diagram of a turbojet engine.

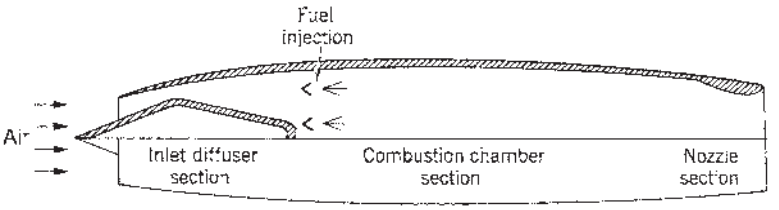


FIGURE 1–2. Simplified diagram of a ramjet with a supersonic inlet (a converging/diverging flow passage).

can achieve much higher speeds due to increased inlet compression achieved through careful design. Since ramjets cannot produce static thrust, they must depend on rocket boosters or other propulsion to bring the flight vehicle to supersonic conditions and operating altitudes where shocks form inside the ramjet inlet to compress and decelerate the incoming air. Past applications of ramjets with subsonic combustion included shipboard- and ground-launched antiaircraft missiles, but few applications remain active due to their reduced efficiency at low speeds and narrow operating limits. Hypersonic vehicles (capable of flight speeds at Mach 5 or greater) accelerated by hydrocarbon-fueled scramjet engines and developed under the sponsorship of the Defense Advanced Research Projects Agency (DARPA) have demonstrated successful flights since September 2021 (see Ref. 1–2). Prior to that, the NASA X-43A program successfully flew a hydrogen-fueled scramjet at speeds from Mach 6 to Mach 9.8.

1.2. ROCKET PROPULSION

Although there are many different types of rockets and applications, one of the most basic ways to classify rockets is by the method of producing thrust. The thermodynamic expansion of a gas in a supersonic nozzle is utilized in most rocket propulsion concepts. The internal energy of a working fluid is converted into kinetic energy through heat addition, typically by combustion, and thrust is produced by the pressure of the hot, energetic gases acting on exposed surfaces, as will be shown later. This same thermodynamic theory and the same generic equipment (i.e., a chamber plus a nozzle) are used for jet propulsion, rocket propulsion, nuclear propulsion, laser-thermal and solar-thermal propulsion, and in some types of electrical propulsion. Totally different methods of producing thrust are used in nonthermal types of electric propulsion (EP). As described below, these electric systems use magnetic and/or electric fields to accelerate electrically charged atoms or molecules at very low gas densities. It is also possible to obtain very small accelerations by taking advantage of the difference in gravitational attraction as a function of Earth altitude, but this method is not treated in this book. In contrast to chemical propulsion, electrical, nuclear, and solar propulsion operate using a source of thermal energy that is not ejected as ejected as an exhaust gas.

The Chinese developed and used solid propellant in rocket missiles over 800 years ago, and military "bombardment rockets" were used frequently in the eighteenth and nineteenth centuries. However, the most significant developments of rocket propulsion took place in the twentieth century. Early pioneers included the Russian Konstantin E. Tsiolkovsky, who is credited with the fundamental rocket flight equation and his 1903 proposals to build rocket vehicles. Robert H. Goddard, an American, is credited with the first flight using a liquid propellant rocket engine in 1926. German aerospace engineer Wernher von Braun (later American) was influential in the development of rocket technologies, initially in Nazi Germany and later in the U.S. space program. For the history of rockets, see Refs. 1–3 to 1–8.

Chemical Rocket Propulsion

Energy from the combustion reaction of chemical propellants, usually a fuel and an oxidizer, in a high-pressure chamber goes into heating reaction product gases to high temperatures (typically 2500 to 4100 °C or 4500 to 7400 °F). These gases are subsequently expanded in a supersonic nozzle and accelerated to high velocities (1800 to 4300 m/s or 5900 to 14,100 ft/sec). Since such gas temperatures are often well above the melting point of the material of the chamber in which they are contained, it is necessary to actively cool or insulate all the surfaces and structures that are exposed to the hot gases. According to the physical state of the stored propellant, there are several different classes of chemical rocket propulsion devices.

Liquid-propellant rocket engines use propellants stored as liquids that are fed under pressure from tanks into a *thrust chamber*.* A typical pressure-fed liquid-propellant rocket engine system

*The term *thrust chamber*, used for the assembly of the injector, chamber, and nozzle, is preferred by official agencies and industry, and therefore has been used in this book. For small spacecraft control rockets the term *thruster* (a small thrust chamber) is commonly used, and this term will be used in some sections of this book.

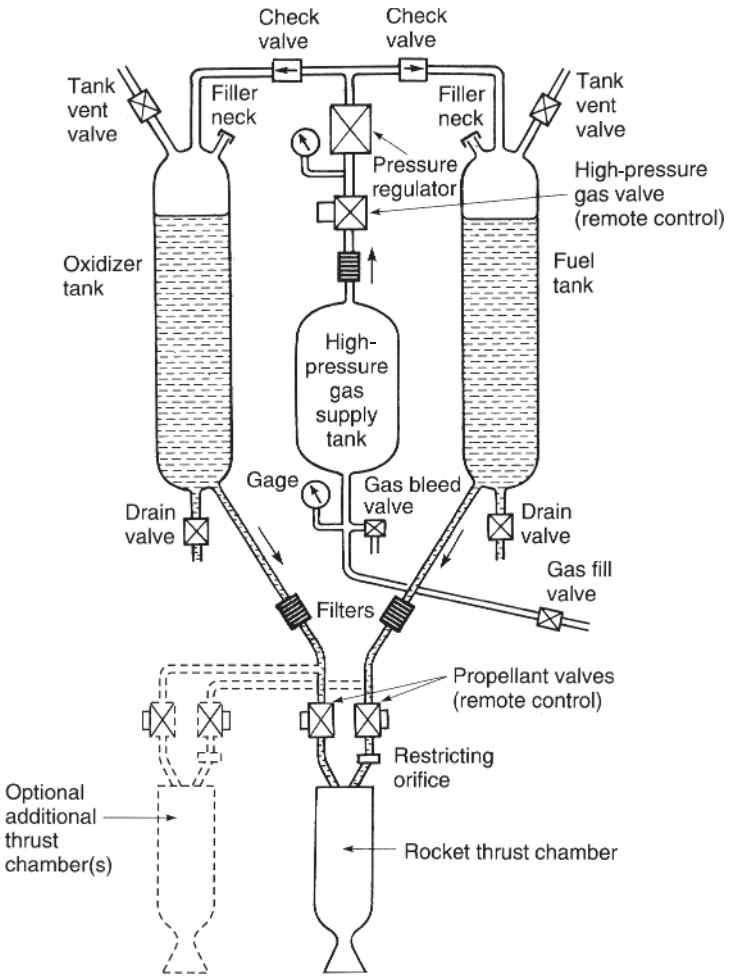


FIGURE 1–3. Schematic flow diagram of a liquid propellant rocket engine with a gas pressure feed system. The dashed lines show a second thrust chamber, but some engines have more than a dozen thrust chambers supplied by the same feed system. Also shown are components needed for startup and shutdown, controlling tank pressure, filling propellants and pressurizing gas, draining or flushing out remaining propellants, tank pressure relief or venting, and several sensors.

is schematically shown in Figure 1–3. A *bipropellant* system consists of a liquid oxidizer (e.g., liquid oxygen) and a liquid fuel (e.g., such as kerosene) that mix and combust inside the engine. A *monopropellant* system uses a single working fluid that either decomposes exothermically into hot gases when properly catalyzed or is heated by some thermal energy source inside the engine. Gas pressure feed systems are used mostly on low-thrust, low-total-energy propulsion systems, such as those used for attitude control of flight vehicles, often with more than one thrust chamber per engine. The larger bipropellant rocket engines use one or more pump-fed chambers as shown in Figure 1–4. Pump-fed rocket systems are most common in applications needing larger amounts of propellant flow and higher thrust, such as those in space launch vehicles (see Refs. 1–3 to 1–7).

Chemical propellants react to form hot gases inside the thrust chamber and are accelerated through a supersonic nozzle from which they are ejected at a high velocity, thereby imparting momentum to the vehicle. Supersonic nozzles consist of a converging section, a minimum area or throat, and a conical or bell-shaped diverging section, as further described in the next two chapters.

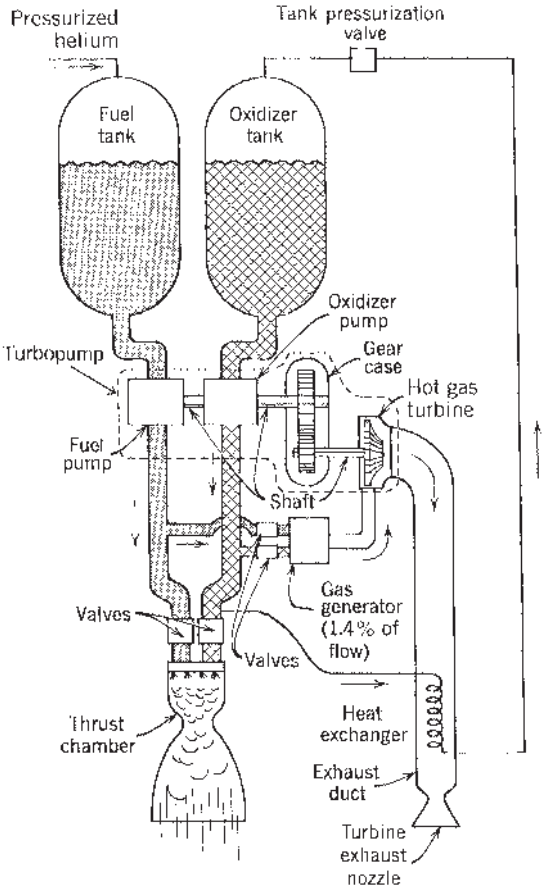


FIGURE 1–4. Simplified schematic diagram of a liquid-propellant rocket engine with one type of turbopump feed system and a separate gas generator, which generates "warm" gas for driving the turbine. Not shown are components necessary for controlling the operation, filling, venting, draining, or flushing out propellants, filters, pilot valves, or sensors. This turbopump assembly consists of two propellant pumps, a gear case, and a high-speed turbine. Many turbopumps use a single shaft and therefore have no gear case.

Some liquid rocket engines permit repeated firings and can be restarted multiple times. If the thrust chamber has adequate longevity, it is possible to run an engine for hours, limited only by the propellant supply. A rocket engine requires several precision valves, and some engines have complex propellant delivery mechanisms that include turbopumps (a high-powered liquid pump driven by a turbine), additional combustion devices, and ignition systems. All have propellant-pressurizing devices and thermally managed thrust chambers to contain and withstand the extreme pressures and temperatures of combustion.

In *solid-propellant rocket motors*,* the ingredients to be burned are loaded into a combustion chamber or *motor case* (see Figure 1–5) during manufacture. The solid propellant (or charge) is called the *grain*, and it contains all the chemical elements for complete burning. Once ignited, it is designed to burn continuously at a predetermined rate on all the exposed internal grain surfaces. In the figure, initial burning takes place at the internal surfaces of the cylinder perforation and at the four slots.

*Historically, the word *engine* is used for a liquid-propellant rocket propulsion system and the word *motor* is used for solid-propellant rocket propulsion. They were developed originally by different groups.

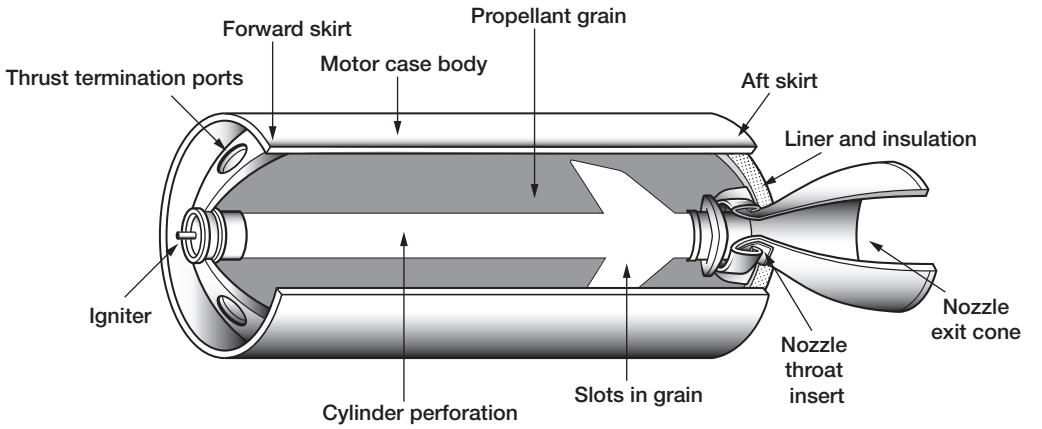


FIGURE 1–5. Simplified cross-section view of a notional solid-propellant rocket motor with the propellant grain bonded to the case and to the insulation layer, and with a conical exhaust nozzle. The cylindrical case with its forward and aft hemispherical domes forms a pressure vessel containing the combustion chamber pressure.

The internal cavity expands as propellant is burned and consumed. The resulting hot gases flow through the supersonic nozzle to impart thrust. Once ignited, propellant combustion proceeds until either thrust is terminated by releasing the motor case pressure through exhaust ports or until all of the usable grain has been consumed. There are no feed systems or complex valves (see Refs. 1–7 to 1–11), and the combustion temperatures are typically low enough to where the motor components do not require active cooling.

Gaseous propellant rocket engines, also called cold gas thrusters, use a stored high-pressure gas, such as air, nitrogen, or helium, as the working fluid without adding thermal energy prior to expulsion. They operate solely on the adiabatic expansion of the gas through a nozzle. These systems require comparatively heavy gas storage tanks due to the high pressures used to impart thrust. Cold gas thrusters were used in many early space vehicles for low-thrust maneuvers and for attitude-control systems, and some are still used today. Variations such as heating the gas with electrical energy or by the combustion of certain monopropellants in a chamber improves their performance, and this is referred to as *warm gas propellant rocket propulsion*. Chapter 7 reviews gaseous propellants.

Hybrid-propellant rocket propulsion systems use both liquid and solid propellant storage. For example, if a liquid oxidizing agent is injected into a combustion chamber filled with a solid-phase fuel grain, the chemical reaction produces hot combustion gases (see Figure 1–6). Hybrid systems often have the capability to be turned on and off as well as throttled to different thrust levels by controlling the liquid propellant flow. They are described further in Chapter 16. Several have flown successfully and additional concepts to improve their efficiency and performance are in development.

Liquid and solid propellants, together with the propulsion systems that use them, are discussed in Chapters 6 to 11 and 12 to 15, respectively. Rocket propulsion selection systems, for both liquid and solid propellants, are compared in Chapter 19.

Combinations of Air-Breathing Jet Engines and Rocket Motors

The Tomahawk surface-to-surface missile uses a sequenced two-stage *propulsion system*. A high-thrust, short-burn, solid-propellant rocket booster lifts the missile away from its launch platform and is dispensed with after completing its operation. A small turbojet engine then sustains its low-level flight at a nearly constant subsonic speed toward the target. Integrated systems are not limited to using all solid or all liquid propulsion.

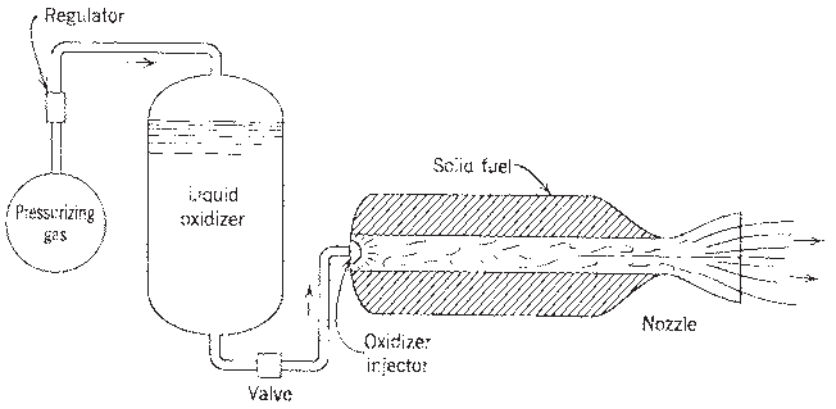


FIGURE 1–6. Schematic diagram of a typical hybrid rocket engine. The relative positions of the oxidizer tank, high-pressure gas tank, and the fuel chamber with its nozzle depend on the particular vehicle design.

Air-breathing rocket propulsion systems, also called *air-augmented rocket propulsion systems*, combine the application of solid-propellant rockets and ramjet engines; they give better performance and higher efficiency than chemical rocket engines alone but can only operate within the Earth's atmosphere. Usually, the term air-augmented rocket denotes mixing of air with the rocket exhaust (made fuel rich for afterburning) in proportions that enable the propulsion device to retain those characteristics that typify rocket engines, for example, high static thrust and high thrust-to-weight ratio. In contrast, air-breathing rockets are often like a ramjet in that they must be boosted to operating speed and use the rocket components more as a fuel-rich gas generator (liquid or solid).

The thermodynamic cycles of rocket propulsion systems and ramjets or scramjets can be combined. A notional example of this is when two propulsion systems operating in sequence and then in tandem utilizing a common combustion chamber volume, as shown in Figure 1–7. Such a low-volume configuration, known as an *integral rocket–ramjet*, has been attractive for air-launched missiles using ramjet propulsion. The transition from rocket engine to ramjet requires reliable yet complex mechanisms that must operate smoothly. These may include enlarging the exhaust nozzle throat (usually by ejecting rocket nozzle parts), opening the ramjet air inlet–combustion chamber interface by jettisoning blow-out port covers, and following these steps with the ramjet starting sequence.

A *solid-fuel ramjet* (SFRJ) uses grains of solid fuel that gasify or ablate and then react with air. A joint U.S.–Norway program called the Tactical High-speed Offensive Ramjet for Extended Range

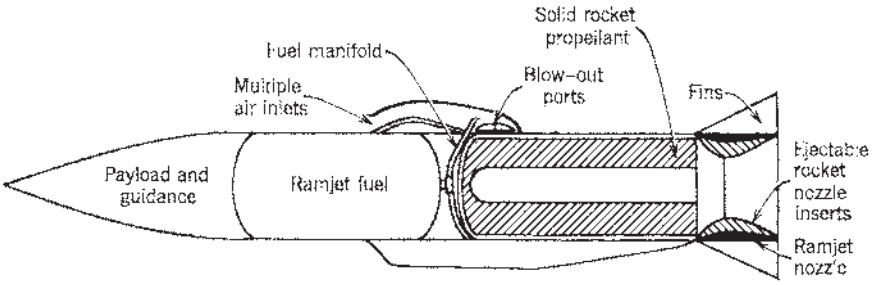


FIGURE 1–7. Simplified diagram of an air-launched missile with integral rocket–ramjet propulsion. After the solid propellant has been consumed in boosting the vehicle to flight speed, the rocket combustion chamber becomes the ramjet combustion chamber with air burning the ramjet liquid fuel. Igniter and steering mechanisms are not shown.

(THOR-ER) conducted successful flight tests in August 2022 at the Andøya Space Flight Range in Norway. According to Ref. 1–12, a solid-propellant booster accelerated the test vehicle to above Mach 2 before transitioning to ramjet mode. A challenge in SFRJ design is shaping the fuel grain to achieve the desired thrust profile and avoid unintended increases in acceleration as more grain area is exposed deeper into the burn.

Nuclear Rocket Engines

Nuclear propulsion generally refers to a broad category of systems where the thermal energy that drives the thermodynamic power cycle comes from some form of nuclear reaction rather than from chemical reactions. The two main categories that have been investigated include nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP).

A nuclear thermal propulsion system is a type of rocket engine that utilizes the thermal energy produced by a uranium-fueled nuclear fission reactor instead of chemical combustion. A propellant, typically liquid hydrogen, is pumped through the hot reactor core where the heat of the fission process raises its temperature before it is then accelerated and expelled through a conventional rocket nozzle. With hydrogen exhaust temperatures reaching above 2500 K (4000 °F), NTP systems could provide ideal specific impulse values approaching 900 sec (this parameter will be explained in Chapter 2), which is nearly twice as much as the state-of-the-art chemical rocket engines. NTP engines were successfully explored in the United States through a demonstration program called the Nuclear Engine for Rocket Vehicle Applications (NERVA), which took place from 1955 to 1972 (see Ref. 1–13). During the program, 20 individual NTP engines were ground tested and, in total, accumulated over 17 hours of runtime (per Ref. 1–14) at thrust levels ranging from 110 to 330 kN (25,000 to 75,000 lbf). NTP concepts as large as 1100 kN (250,000 lbf) thrust were envisioned to support NASA's Saturn space program, but the decline of that program in the early 1970s, coupled with an absent need for NTP engines, permanently halted the NERVA effort. As of this writing, no NTP system has been used in flight.

Nuclear electric propulsion describes an integrated system in which the thermal energy from a nuclear reactor is converted to electrical energy to power traditional EP devices such as Hall or ion thrusters. When propulsion is not needed, the power can be utilized for spacecraft functions and sensors, thus relaxing the demands on solar or battery systems. Nuclear electric systems can range in power from 1 kW to over 1 MW, making them competitive with radioisotope, solar, or battery options, but their complexity and integration offer unique challenges for both spacecraft and mission design. The reactor, power conversion system, power conditioning, and heat rejection radiators must all work seamlessly to reliably accommodate mission needs and duty cycles. While EP systems have thrust levels that are orders of magnitude less than chemical propulsion systems, they are substantially more efficient (with specific impulse values from 2000 to 8000 sec, per Ref. 1–13), making them ideal for on-orbit station-keeping, maneuvering, or long-duration continuous thrust events. NEP offers a way to perform these functions unhindered by solar alignment or energy storage limitations. Variants of key NEP subsystems have been developed and tested beyond the proof-of-concept phase over the years, but like NTP, no NEP system has ever flown.

Several U.S. government agencies have recognized that modern advancements in nuclear reactor design, materials, manufacturing, and modeling may enable the potential benefits of nuclear propulsion for scientific, commercial, and national security space applications. Some agencies are actively exploring the development of NTP engines and have recently awarded industry contracts for design concepts (see Refs. 1–15 and 1–16), while others are examining novel approaches for key subsystems that could support small modular reactors (SMRs) for fission power on planetary surfaces (see Ref. 1–17). These systems might also be extensible to flight systems to support NEP spacecraft. All these efforts are envisioned to proceed toward in-space tests within the next ten years.

Electric Rocket Propulsion (EP)

Electric propulsion is attractive because of its comparatively high performance, its capability to produce desired amounts of thrust with moderately low propellant utilization; however, systems are limited to relatively low thrust applications by existing electrical power supplies. Thrust from this type of propulsion is much too low for launches from the Earth's surface or atmospheric flight because it would require rather massive and relatively inefficient power sources (but in spacecraft, power sources can often be shared with other subsystems). Unlike chemical propulsion, EP utilizes energy sources (nuclear, solar radiation, or batteries) not contained in the propellant. The thrust is usually quite low, levels typical of orbit maintenance (0.005 to 1 N or 0.0011 to 0.225 lbf). To accomplish significant increases in vehicle velocity, it is necessary to apply such low thrusts (and their small accelerations) for durations considerably longer than with chemical propulsion, some for months and even years (see Ref. 1–18 and Chapter 17).

Of the three basic types of EP, *electrothermal* rocket propulsion most resembles the previously discussed liquid-propellant chemical rockets; a propellant is heated electrically either with solid resistors (these thrusters are called resistojets) or through direct exposure to the hot, energetic plasma created by electric arcs (these thrusters are called arcjets). The hot gas is then thermodynamically expanded through a supersonic nozzle (see Figure 1–8). Electrothermal thrusters typically have thrust ranges of 0.01 to 0.5 N (0.00225 to 0.112 lbf), with exhaust velocities of 1000 to 7800 m/s (3280 to 25,590 ft/sec); they can use ammonia, hydrogen, helium, nitrogen, or hydrazine decomposition products as the propellant.

The two other types—the *electrostatic* or *ion propulsion* thrusters and the *electromagnetic* or *magnetoplasma* thrusters—accomplish propulsion by different means, and no thermodynamic gas expansion in a nozzle is necessary. Both are designed to operate only within a vacuum environment. In an ion thruster (see Figure 1–9), the working fluid (typically xenon) is ionized by stripping off electrons and then accelerating the heavier ions to very high velocities (2000 to 60,000 m/s or 6560 to 196,850 ft/sec) by means of electrostatic fields. The ions are subsequently electrically neutralized by combining them with electrons emitted outside of the thruster to prevent the buildup of a "space charge" on the vehicle.

In electromagnetic thrusters, a plasma (an energized gaseous mixture of positive ions, free electrons, and neutral particles, typically at low pressures and/or very high temperatures) is accelerated by the interaction between electric currents and perpendicular magnetic fields. In these devices, plasma exhaust velocities can reach as high as 1000 to 75,000 m/s (3280 to 246,000 ft/sec). There are many different types and geometries, depending on how the fields and current flows are configured. An example is the Hall-effect thruster (see Chapter 17). A simply configured, pulsed electrical thruster with a solid (stored)

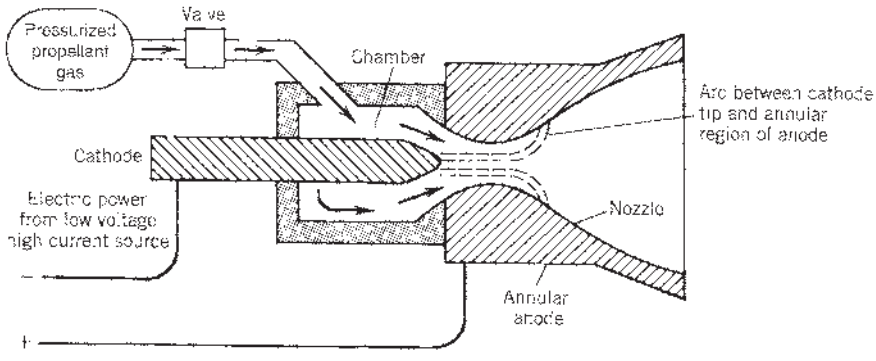


FIGURE 1–8. Simplified schematic diagram of an arcjet thruster. The arc plasma temperature is very high (perhaps 15,000 K or 26,540 °F) and the anode, cathode, and chamber will get hot (1000 K or 1340 °F) due to heat transfer.

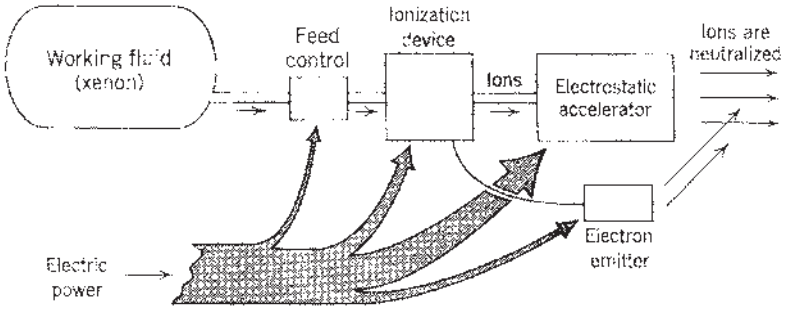


FIGURE 1–9. Simplified schematic diagram of a notional ion thruster, showing the approximate distribution of the electric power by the width of the arrow.

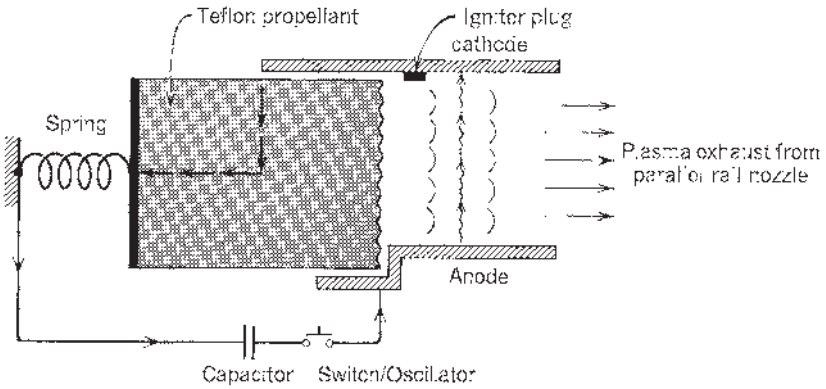


FIGURE 1–10. Simplified diagram of a pulsed plasma thruster with self-induced magnetic acceleration. When the capacitor is discharged, an arc is struck at the left side of the rails. The high arc current closes the loop, thus inducing a magnetic field. The action of the current and the magnetic field causes the plasma to be accelerated at right angles to both the magnetic field and the current in the direction of the rails. Each time the arc is created, a small amount of solid propellant (Teflon®) is vaporized and converted to a small plasma cloud, which (when ejected) gives a small pulse of thrust. Actual units can operate with many pulses per second.

propellant is shown in Figure 1–10; this type of thruster converts minute amounts of solid material to plasma that is then accelerated out of the engine. This configuration has been used for spacecraft attitude control (Ref. 1–18).

An atmosphere-breathing electric propulsion (ABEP) system uses a specialized intake to capture the rarefied atmosphere particles in very low Earth orbit (VLEO) for use as the propellant for an electric thruster (see Ref. 1–19). For long-duration missions at low altitude orbits, 120 to 250 km (75 to 155 miles), ABEP needs to compensate for drag forces on a spacecraft so as to avoid early orbit decay. In one concept, onboard power from a solar array drives an inductively heated plasma generator as the source for an inductive plasma thruster. Spacecraft operating in VLEO offer tactical and operational advantages compared to operating at higher altitudes, but these must be balanced with the mission needs of the spacecraft. Challenges are primarily in the design of the intake to increase collection efficiency (ratio of atmosphere particles delivered to the thruster to particles encountered) and electrode erosion from aggressive gases (e.g., atomic oxygen), reducing thruster service life.

Other Rocket Propulsion Concepts

One concept is the *solar thermal rocket;* it has large-diameter optics to coalesce the sun's radiation (e.g., with lightweight, precise parabolic mirrors or Fresnel lenses) onto a receiver or optical cavity

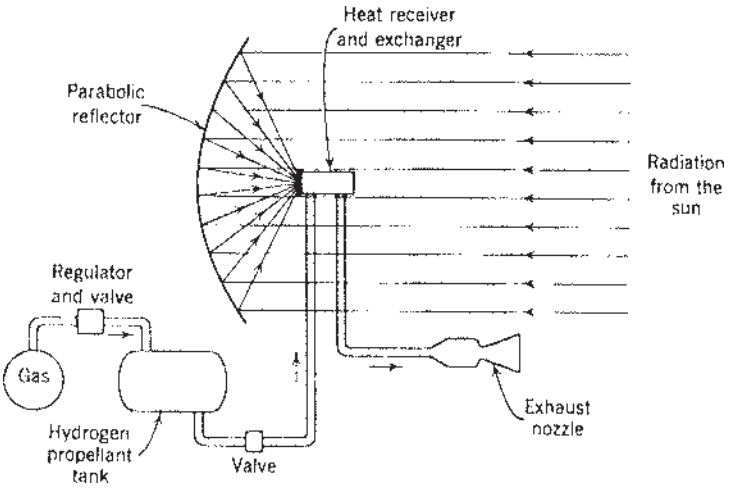


FIGURE 1–11. Schematic diagram of a solar thermal rocket concept.

(see Ref. 1–20). Figure 1–11 shows one embodiment, and some data is given in Table 2–1. The receiver is made of high-temperature metal (typically refractory metals such as tungsten or rhenium) and has a heat exchanger that heats the working fluid, usually hydrogen, up to perhaps 2800 K (4600 °F); the hot gas is then exhausted through one or more nozzles. The large reflective mirror must be pointed toward the sun, and this requires orientation adjustments if the spacecraft orbits around the Earth or other planets. Cycle efficiency can be two to three times higher than that of chemical rockets and thrust levels are low (1 to 10 N or 0.225 to 2.25 lbf). Since large lightweight optical elements cannot withstand drag forces without deformation, such units are only considered for exo-atmospheric applications. The storage or refueling of liquid hydrogen is also a formidable challenge. Possible improvements include rigid lightweight mirror materials or lens structures and deploying foldable mirror structures; increasing operational lifetimes; and minimizing hydrogen boil-off and heat losses to other spacecraft components.

The *solar sail* is another concept. It is basically a large solar photon reflecting surface (see Ref. 1–21). One approach uses a three-axis stabilized square sail that can span more than 100 m (328 ft) per side, made of ultrathin mirror-like material supported by lightweight trusses (Ref. 1–22). The continuous solar stream of photons provides enough thrust to perform maneuvers, e.g., hovering at a fixed location in space or rotating a spacecraft's orbital plane.

The power source for the solar sail is external to the vehicle. By using a larger sail surface area, more photons can be collected to improve thrust. Concepts for transmitting radiation energy (by lasers or microwaves) from ground stations on Earth to satellites have been proposed but not yet tested. Engineering challenges include minimization of mass and packaging, deployment of support booms, and reduction of bending and warping of the supports due to temperature changes. New materials are being used to address these shortcomings (Ref. 1–23).

International Rocket Propulsion Effort

Active development and/or production of rocket propulsion systems have been undertaken by more than 30 different countries. A few foreign rocket units are mentioned in this book, together with their characteristics and with references to the international rocket literature. Although most of the data in this book are taken from U.S. rocket experiences, this is not intended to minimize the significance of foreign achievements. There are a number of bilateral and multilateral launch vehicle programs that have reached service. Similarly, there have been rocket engine development programs involving component and subsystem design and/or testing performed in countries other than the country leading the development.

The International Space Station (ISS) continues to operate with participation from multiple space agencies, principally the United States, Russia, Europe, Japan, and Canada. Launched in 1998, the ISS is the largest space station ever constructed and has so far been visited by astronauts from 18 countries (see Ref. 1–24). Despite tensions between the governments of participating countries, it presents a unique opportunity to collaborate in performing space experiments benefiting the international scientific research community.

China's *Tiangong* space station is an assembly of the *Tianhe* core module, launched on April 29, 2021, and two laboratory cabin modules (LCMs, see Ref. 1–25). The first LCM, *Wentian*, was launched on July 24, 2022, and will conduct experiments with an emphasis on life sciences, per Ref. 1–26. The other LCM, *Mengtian*, was launched on October 31, 2022, and will focus on microgravity experiments. Propulsion on the Tianhe and Wentian modules includes conventional chemical propulsion and ion thrusters for orbit maintenance and adjustments (see Ref. 1–27). Four Hall-effect thrusters are mounted on the hull of Tianhe core module in what is purported to be the first use of Hall-effect thrusters for a human-rated space mission.

1.3. APPLICATIONS OF ROCKET PROPULSION

Because rocket propulsion can reach performance levels unequaled by other prime movers, it lends itself to a broad range of mission sets and applications where no other propulsion alternatives exist. Selection of the best rocket propulsion system and design for a given application can be a complex process involving consideration of many factors, including total system performance, reliability, cost, propulsion system size, and compatibility with other spacecraft systems, as described in Chapter 19. Given the potential for both civil and military applications, details regarding a rocket engine's unique or enabling technology, equipment, and materials are sometimes considered sensitive and are usually safeguarded by U.S. export control regulations. Examples of important applications are given below, and some are discussed further in Chapter 4.

Space Launch Vehicles

Since 1957, there have been numerous space launch attempts with a better than 95% success rate. *Space launch vehicles* or *space boosters* can be broadly classified as either expendable or recoverable/reusable, by the type of propellant (storable or cryogenic liquid or solid propellants), by the number of stages (single-stage or multi-stage), by the size/mass of payloads they can carry to select orbits, and as human-rated or uncrewed. Discussed below are the following categories: commercial missions (e.g., communications, Earth observation), military missions (e.g., tactical observation, surveillance, reconnaissance), civil missions (e.g., weather observation, crew transport, positioning-navigation-and-timing services), and space exploration missions (e.g., space telescopes, flights to beyond Earth orbits).

Each space launch has specific objectives, such as delivering a payload (or payloads) or a crewed vehicle to Earth orbit or sending a probe for landing on the Moon or Mars (see Ref. 1–28). All launch systems to date use between two and five stages, each with its own propulsion systems and each usually fired sequentially after the lower stage expends its propellant and is jettisoned. Selection for the number of stages is based on the specific flight trajectory, the number and types of maneuvers, the energy content of the propellants selected, the payload size, as well as other factors. The initial stage, also called the booster stage, is usually the largest and is used to lift the rest of the launch vehicle and the payload off the ground to commence flight. Once the booster stage has ascended to a point in flight where the high thrust to overcome retarding forces is no longer needed, it separates from the ascending vehicle. Briefly after the booster separates, the second-stage propulsion system ignites and operates. As explained in Chapter 4, adding extra stages does permit significant increases in the payload (such as more scientific instruments or more communications gear).

Each stage of a multistage launch vehicle at a minimum includes propellant and a rocket propulsion system or systems. Once the propellant of a given stage is expended, its remaining mass (empty tanks, cases, structure, instruments, etc.) is no longer useful to succeeding stages. By jettisoning the spent stages, it is possible to accelerate the subsequent stages and payload to a higher velocity than would be attained if multiple staging were not used. Both solid propellant and liquid propellant rocket propulsion systems have been utilized to reach low Earth orbits.

Figure 1–12 shows the Atlas V space launch vehicle. The first stage Common Core Booster is powered by the twin-chambered RD-180 liquid propellant rocket engine by NPO Energomash (Khimki, Russia) operating on liquid oxygen (LOX) and kerosene fuel (see Ref. 1–4). At launch, it produces 3826 kN (860,200 lbf) of thrust. The first stage core can be augmented by up to five strap-on solid rocket boosters (SRBs). The upper stage, known as Centaur III, is powered by variants of the Aerojet Rocketdyne RL10 engine operating on LOX/liquid hydrogen propellants in either the Single-Engine Centaur (SEC) or the Dual-Engine Centaur (DEC) configuration.

Figure 1–13 shows the Antares 230 rocket shortly after liftoff from the Mid-Atlantic Regional Spaceport (MARS). The first stage is propelled by two Russian-built RD-181 liquid-propellant rocket engines (also by NPO Energomash), each producing 1922 kN (432,000 lbf) of thrust. The engines operate on liquid oxygen and refined kerosene (RP-1). The second stage is powered by a solid-propellant rocket motor from the Castor 30 series.

As of this writing, Northrop Grumman Space Systems is developing an improved version called the Antares 330. The first stage will use seven Miranda engines that are in development by Firefly Aerospace, each producing 1023 kN (230,000 lbf) of vacuum thrust. The second stage will continue to use the Castor 30XL solid-propellant rocket motor. The Antares 330 is expected to enter service in the second half of 2025 to conduct resupply missions to the ISS.

In both launch vehicles, the payload is carried above the second stage and typically has its own propulsion composed of a set of small thrusters. Table 1–4 gives data for the primary propulsion systems in these two launch vehicles.

After the retirement of the Space Transportation System (STS), i.e., the Space Shuttle in 2011, NASA started the development of a new super heavy-lift replacement launcher. Known as the Space Launch System (SLS), it consists of a two-stage core with two side-mounted SRBs (see Ref. 1–35). The core's Main Propulsion System (MPS) is designed around four RS-25 rocket engines operating on LOX and liquid hydrogen. The RS-25D is a modified version of the Space Shuttle Main Engine (SSME) and the first four SLS launches will expend the remaining 16 engines from the Space Shuttle program. These previously flown engines have been newly outfitted with modern engine controllers, an increased throttling range, and new exhaust nozzle insulation (see Ref. 1–36). The thrust of the RS-25D Block I engines is increased to 2279 kN (512,300 lbf) while operating at 109% of rated thrust. A future expendable version, RS-25E, will increase the thrust further to 2318 kN (521,000 lbf) per engine operating at 111% of rated thrust. The evolution path for the SLS launchers is illustrated in Figure 1–14.

Space Launch System Blocks I and IB will use two SRBs each weighing 726,000 kg (1.6 M lbm) when loaded with propellant. At launch, each booster is driven by a five-segment Reusable Solid Rocket Motor (RSRMV) which provides a thrust of 14,679 kN (3.3 M lbf). The motor case segments were used for the Space Shuttle's four-segment SRBs, now with an added center segment that increases the total impulse of the booster by about 25%. After the supply of remaining Shuttle casings is expended, enough for eight SLS missions, new composite case SRBs will be used for the Block II evolution. In development since 2019, the Booster Obsolescence and Life Extension (BOLE) SRB replacement program will include several improvements for increasing payload capacity.

The first three SLS flights will include the Interim Cryogenic Propulsion Stage (ICPS) equipped with a single RL10B-2 engine (Artemis I mission) or a single RL10C-2 engine (Artemis II, III) for the upper stage. The liquid oxygen-liquid hydrogen stage was developed from the cryogenic second stage of the Delta launch vehicle. The RL10 versions on ICPS provide 110 kN (24,750 lbf) of thrust in vacuum. Following separation from the core stage, ICPS performs an orbital insertion burn and a



FIGURE 1–12. Atlas V space launch vehicle with three (or five) strap-on stages using Aerojet Rocketdyne solid rocket motors and a central NPO Energomash (Russia) RD-180 liquid propellant booster rocket engine running on LOX/kerosene. See Table 1–4 for key characteristics. Courtesy of United Launch Alliance.

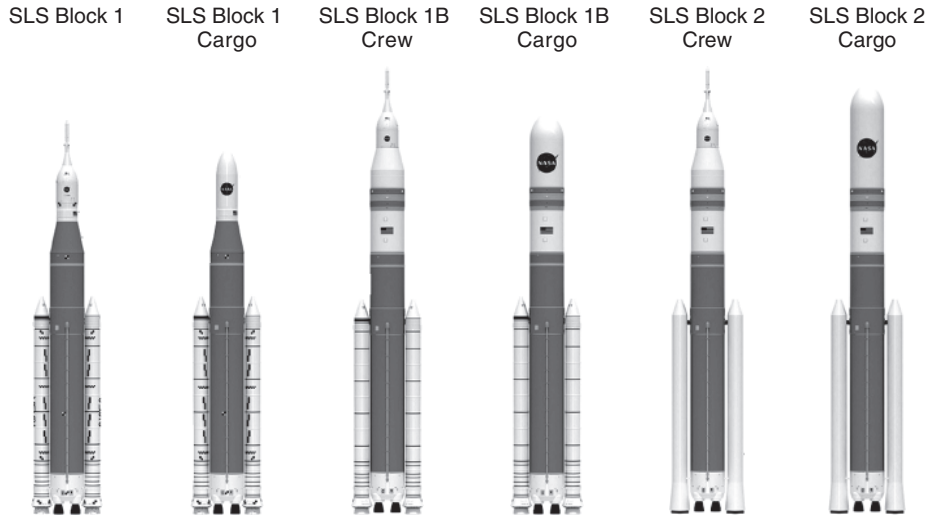


FIGURE 1–13. Antares 230 space launch vehicle after lift-off from the Mid-Atlantic Regional Spaceport (part of the Wallops Flight Facility, VA). The first stage is powered by two RD-181 rocket engines made by NPO Energomash (Russia), providing 3844 kN (864,200 lbf) of thrust at launch. The upper stage uses the Castor 30XL solid-propellant rocket motor. For higher energy orbits, a third stage can be added using either a Star 48BV or an Orion 38 solid rocket motor. The uncrewed Commercial Resupply Services (CRS) missions deliver the Northrop Grumman Cygnus (enhanced) cargo vehicle to the International Space Station. Credit: NASA/Bill Ingalls.

TABLE 1–4. Primary Propulsion System Characteristics for Two Space Launch Vehicles

Vehicle	Propulsion System Designator, Propellants	Stage	No. of Propulsion Systems per Stage	Thrust per Engine/Motor kN (lbf)	Specific Impulse, sec	Mixture Ratio, Oxidizer to Fuel Flow	Chamber Pressure MPa (psia)	Nozzle Exit Area Ratio	Engine/Motor Mass kg (lbm)
Atlas V	GEM 63, QDL-4, solid[e]	0	up to 5	1244 (277,589)[h, f] 1663 (373,800)[h, g]	279.06[b]	N/A	<6.89 (1000)	14:1	49,342 (108,781)[d] 4811 (10,607)[i]
	RD-180, LOX/RP-1	1	1	3825 (853,300)[a] 4148 (933,400)[b]	311[a] 339[b]	2.72	25.66 (3722)	36.9:1	5480 (12,081)[c] 5950 (13,117)[d]
	RL10C-1-1, LOX/LH_2	2	1	105.98 (23,825)[b]	453.8[b]	5.5	4.34 (630)	155:1	188.2 (414.9)[c]
Antares 232	RD-181, LOX/RP-1	1	2	1922 (432,000)[a] 2079 (467,000)[b]	311[a] 339[b]	2.63	25.75 (3735)	36.9:1	2200 (4850)[c] 2330 (5137)[d]
	Castor 30XL, QDL-1, solid[e]	2	1	464 (104,350)[h, f] 533 (119,900)[h, g]	294.4[b]	N/A	4.83 (700)[h]	55.9:1	26,407 (58,217)[d] 1392 (3069)[i]
	STAR 48BV, TP-H-3340, solid[e]	3	1	69,161 (15,430)[h, f] 78,394 (17,490)[h, g]	292.1[b]	N/A	3.99 (579)[f] 4.26 (618)[g]	54.8:1	2165 (4772)[d] 138.6 (305.5)[i]

[a]Sea level value.
[b]Vacuum value.
[c]Dry engine mass.
[d]Loaded engine or motor mass.
[e]HTPB binder, 19% aluminum fuel.
[f]Burn time average thrust/chamber pressure.
[g]Maximum thrust/chamber pressure.
[h]Estimate from thermochemical analysis, burn time average value.
[i]Burnout mass (est.).
Sources: Refs. 1–29 through 1–34.



Core Engines	4 × RS-25D	4 × RS-25D	4 × RS-25D/E	4 × RS-25D/E	4 × RS-25E	4 × RS-25E
Boosters	2 × RSRMV	2 × RSRMV	2 × RSRMV	2 × RSRMV	2 × BOLE	2 × BOLE
Maximum Thrust	39,144 kN (8.8M lbf)	39,144 kN (8.8M lbf)	39,144 kN (8.8M lbf)	39,144 kN (8.8M lbf)	42,260 kN (9.5M lbf)	42,260 kN (9.5M lbf)
Upper Stage	1 × RL10B-2	1 × RL10C-2	4 × RL10C-3	4 × RL10C-3	4 × RL10C-3/X	4 × RL10C-3/X

FIGURE 1–14. The Space Launch System's (SLS) evolutionary path for the Artemis lunar landing program. The launcher will reuse components from the Space Shuttle program that have been modernized and improved. As an expendable system, it has the highest payload capacity of any rocket in service and the greatest liftoff thrust. The first launch carried the Orion spacecraft without a crew into a lunar orbit. The launch occurred on November 16, 2022 from Cape Canaveral. Credit: NASA / Public Domain.

subsequent translunar injection burn to send the Orion spacecraft toward the moon. Starting with the fourth flight (Artemis IV), a new stage called the Exploration Upper Stage (EUS) will be equipped with four RL10C-3 engines. Future editions of the EUS will switch to an improved version, the RL10E-1, which extensively uses additive manufacturing for major components such as the injector and combustion chamber and carries a monolithic lightweight composite (carbon-carbon) nozzle (see Ref. 1–37).

Several human-rated space flight systems have recently been developed or are in development by private companies. Some of these vehicles were designed for suborbital flights to promote space tourism, while others provide services such as crew transportation to and from the ISS. Many of the operational and emerging spacecraft are launched by rockets with reusable booster stages that employ vertical takeoff and vertical landing (VT/VL) methods of operation. A primary motive for engineering reusable space vehicles and recoverable/reusable booster stages is to reduce the costs of space flight by refurbishing previously flown hardware instead of building new every time. Booster stage reuse imposes three crucial requirements related to the rocket engines: the engine must be capable of in-flight restarts in order to maneuver the booster stage into a trajectory for landing, it must possess a deep throttling capability to safely control the rate of descent during reentry and landing, and it must be affordable to both produce and service for consecutive uses.

Spacecraft

Based on their mission, *spacecraft* can be categorized as Earth orbiting satellites, lunar, interplanetary, and trans-solar types, and/or as human-rated or uncrewed spacecraft. Reference 1–38 covers satellite technologies, markets, and applications related to communications, broadcasting, and networking for

civilian and military systems. To assure that the spacecraft is on the proper trajectory and oriented correctly for these missions, spacecraft need a variety of different rocket propulsion systems. Rocket propulsion is used for both *primary propulsion* to perform high-energy maneuvers such as accelerating along the flight path, orbital insertion, or orbit change maneuvers, and for *secondary propulsion* such as attitude/pointing control, spin control, momentum wheel and gyro unloading, rendezvous and proximity operations, stage separation, and for the settling of liquids in tanks. For spacecraft attitude control about 3 perpendicular axes, each in 2 rotational directions, the system must allow the application of pure torque for 6 modes of angular freedom, thus requiring a minimum of 12 thrusters. Some missions require as few as 4 to 6 thrusters, whereas a more complex crewed spacecraft may have 20 to 50 thrusters in all of its separate components. Often, small *attitude control thrusters* must give pulsed, short duration bursts of thrust, to accurately orient the vehicle and sustain that position. This means that such thrusters may require thousands of restarts over the lifetime of the spacecraft (see Section 6.7 and Ref. 1–39).

A majority of spacecraft use liquid propellant engines for primary and secondary propulsion because of their multiple-start capability as opposed to a single start for solid propellant systems. Some spacecraft use single-burn solid propellant rocket motors to achieve coarse orbital insertion after separation from the launch vehicle upper stage. This can be referred to as a kick stage. Depending on the mission, some spacecraft operate successfully with EP for attitude control and station-keeping. Recently, EP systems have been used as primary and secondary propulsion in long-duration space missions. Due to their low thrust, space operations and maneuvers with EP can require significantly longer times to reach desired velocity changes. For example, transfer from a low Earth orbit (LEO) to a geosynchronous Earth orbit (GEO) may take as long as two or three months compared to a few hours with chemical propulsion systems. Topics in EP are covered in Chapter 17.

Micropropulsion systems can produce a change in momentum on a micro-spacecraft (typically those having a mass of less than 100 kg or 220 lbm). It encompasses several different propulsion concepts, such as varieties of very low thrust liquid mono- and bipropellant rocket engines, small gaseous propellant rocket engines (including compressed cold gas thrusters), several types of EP systems, and emerging advanced versions of these. Many are based on newly flight-qualified fabrication techniques for very small components (valves, thrusters, switches, insulators, or sensors) by micromachining and electromechanical processing, or more recently by additive manufacturing.

Military and Other Applications

Military applications can be grouped as shown in Table 1–5. Primary propulsion for U.S. missiles is based almost exclusively on solid propellant rocket motors due to their immediate readiness (no field handling of propellants), reliability, and logistic simplicity. These can be *strategic-class missiles*, such as long-range ballistic missiles that can target an adversary's military facilities, or *tactical-range missiles* intended to support or defend military ground forces, aircraft, or naval vessels.

The term *surface launch* can refer to launching from ground level (launch stand or ground-mobile launcher) or from an ocean surface vessel. A launch from a submerged submarine would be a *sub-surface launch*. Some tactical missiles, such as the air-to-surface AGM-69 Short Range Attack Missile (SRAM), have a two-pulse solid propellant motor, where two separate insulated grains of different propellant composition are loaded in a single motor case; the time interval before starting the second pulse can be timed to control the flight path or speed profile. Many countries now have tactical missiles in their military inventories, and many of these countries have the capability to produce their own vehicles and the associated rocket propulsion systems.

A new rocket propulsion concept has been tested which combines a solid-propellant motor with a chemically reacting monopropellant inside the motor chamber (Ref. 1–40). Developed by Exquadrum, Inc. of Adelanto, CA, the system injects a storable liquid monopropellant into the combustion chamber where the heat of combustion of the solid fuel causes a chemical reaction that releases the oxygen and

TABLE 1–5. Selected Military Applications Using Rocket Propulsion Systems

Category	Vehicle/System	Comments/Examples
Military Satellites	Reconnaissance/Earth observation Secure communications Early warning of missile launches Weather monitoring	Launches on vehicles certified for NSSL[a] missions, e.g., Falcon 9 and Falcon Heavy, eventually Vulcan-Centaur Small launch vehicles for national security payloads under contracts with DARPA, NRO, and U.S. Space Force, e.g., Electron[b], Pegasus XL
Strategic Weapons	Intercontinental ballistic missiles (ICBMs) Submarine-launched ballistic missiles Hypersonic glide vehicles (nonnuclear) Hypersonic cruise missile (nonnuclear)	Minuteman III, Sentinel (ground-based strategic deterrent) Trident II D5 CPS, ARRW, LRHW[c] HAWC, MoHAWC, HACM[d]
Surface-to-Surface Tactical Weapons	Intermediate range ballistic missile Battlefield rockets, land attack cruise missiles (LACMs), ship-launched anti-ship ballistic missiles, and other small ordinance	Prototype ballistic, cruise missiles tested in 2019 (nonnuclear) Almost exclusively using solid-propellant rocket motors (smokeless propellants), typically single-stage systems Guided or unguided
Surface-to-Air and Kinetic Intercept Missiles	Local area defense, e.g., military airfield Large area defense, e.g., military bases	Standard Missile 3 (Aegis ballistic missile defense system) Standard Missile 6 (anti-air/anti-surface interceptor missile)
Air-to-Surface Missiles	Short range Long range (includes hypersonic boost-glide or boost-cruise with scramjet engines)	Single-stage solid-propellant rocket motors SATNAV[e] guided, single or two boost stages, ramjet engines
Air-to-Air Missiles	Carried inboard, under fuselage or wings	Phoenix, Sidewinder, Sparrow, AMRAAM[f]

[a] National Security Space Launch, formerly the Evolved Expendable Launch Vehicle program.
[b] Rocket Lab has conducted launches under multiple contracts for rapid launch and responsive space missions.
[c] Conventional Prompt Strike, Air-launched Rapid Response Weapon (AGM-183A), Long Range Hypersonic Weapon (prototype boost-glide systems).
[d] Hypersonic Air-breathing Weapon Concept, More Opportunities with HAWC, Hypersonic Attack Cruise Missile (prototype boost-cruise systems).
[e] Satellite-based navigation system, e.g., the Global Positioning System (GPS).
[f] Advanced Medium-Range Air-to-Air Missile.

fuel components of the monopropellant, resulting in its combustion. The concept is known as Liquid Augmented Solid Rocket (LASR). The thrust of the system is augmented by an amount determined by the flow of monopropellant into the chamber, thus making the combined output more energetic and throttleable which cannot be done with solid propellants alone. The monopropellant can continue to burn after the solid propellant has been fully consumed due to the heat in the empty chamber.

More generally, Table 1–6 shows selected examples of propulsion characteristics for several current common rocket applications.

TABLE 1–6. Selected Examples of Propulsion Characteristics of Rocket Applications

Applications	Type of Propellant	Thrust Profile	Typical Firing Duration	Maximum Acceleration[a]
Large space launch vehicle core stages, reusable main engines	Fully or semi-cryogenic liquid (LOX/H_2, LOX/CH_4, LOX/RP-1), solid or hybrid propulsion	Variable thrust with throttling to control acceleration rate, multiple flights with same engine; capable of restarting	120–480 sec duty cycle, 20+ missions	1.2–6 g_0
Strap-on booster	Solid or liquid	445–14,680 kN	30–180 sec	1.2–3 g_0
Separation of strap-on booster from core stages	2 to 8 solid rocket motors	44.5–89 kN	Less than 1 sec	N/A
Anti-aircraft or missile interceptor	Solid, some with liquid terminal divert stage	High thrust boost, decreasing thrust in sustain phase, high thrust for divert	2–75 sec each phase	5–20 g_0, but can reach 100 g_0
Spacecraft orbit maneuvers and/or station-keeping	Storable liquid—bipropellant or monopropellant; electric propulsion; xenon	Multiple restarts in space (up to several thousand); can be pulsed	Up to 600 sec cumulative; pulses <5 sec	From less than 0.1 up to 6 g_0
Spacecraft attitude control—small vehicles	Electric propulsion; cold or warm gas; storable liquid	Many restarts (up to several thousands); pulsing	Up to several hours total	Less than 0.1 g_0
Air-launched guided missile	Solid	High thrust boost phase with low thrust or decreasing thrust for sustain phase; sometimes two pulses	Boost: 2–5 sec Sustain 10–30 sec	Up to 25 g_0
Battlefield support—surface launched	Solid	Decreasing thrust	Up to 120 sec each stage	Up to 10 g_0
Rocket–assisted projectile, gun launched	Solid	Constant or decreasing thrust	Less than 5 sec	Up to 20,000 g_0 in gun barrel
Lunar landing spacecraft	Storable bipropellant	Deep throttling (100–10% thrust)	Up to 480 sec	Up to several g_0
Sounding rocket	Solid	Single burn phase—often decreasing thrust	5–30 sec	Up to 15 g_0
Anti-tank missile	Solid	Single burn phase	0.2–3 sec	Up to 20 g_0

[a] g_0 is the acceleration of gravity at the Earth's surface = 9.80665 m/sec^2 or 32.174 ft/sec^2.

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