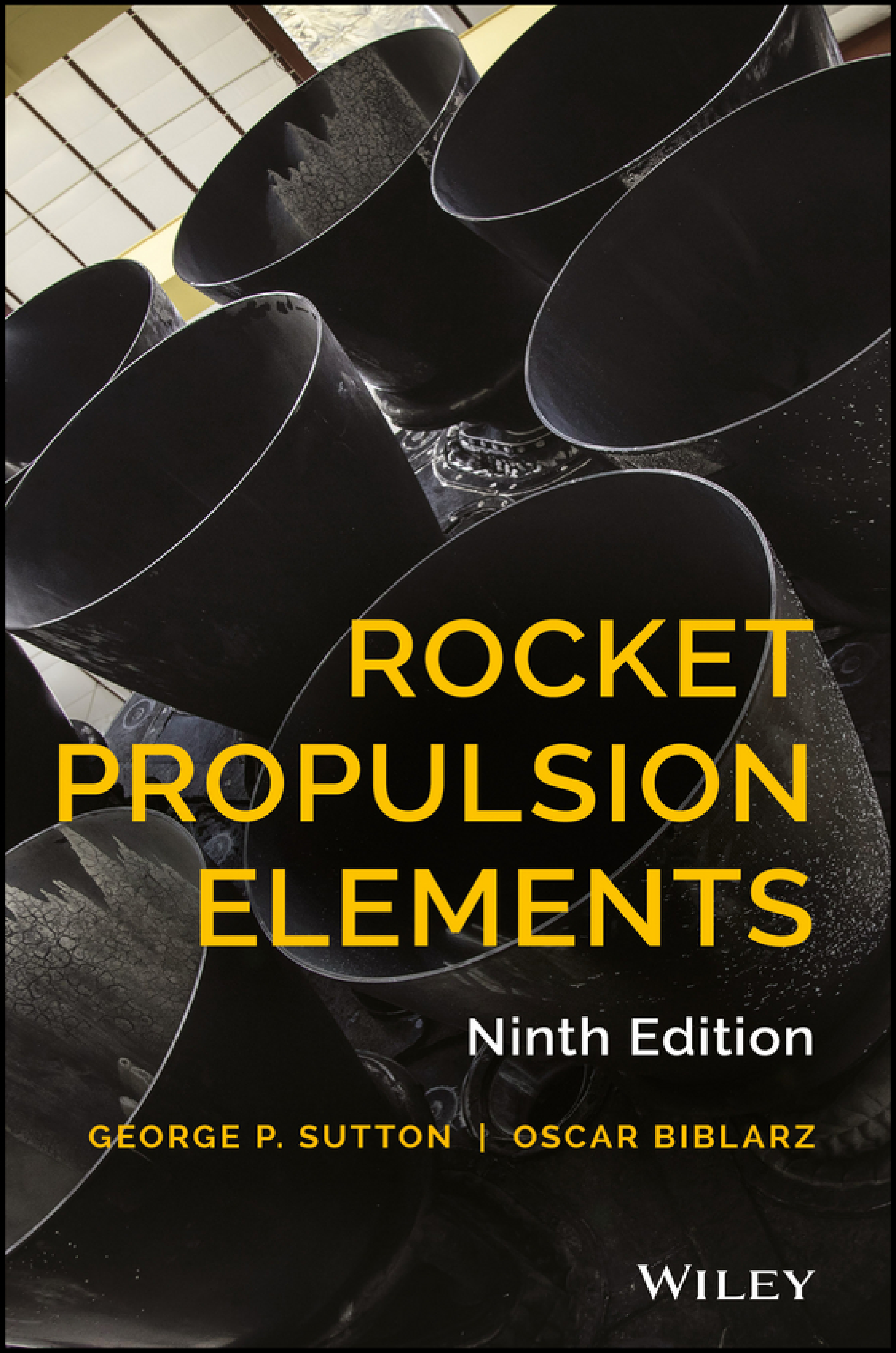

ROCKET PROPULSION ELEMENTS

Ninth Edition

GEORGE P. SUTTON | OSCAR BIBLARZ

WILEY

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Rocket Propulsion Elements

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This is a photograph of the rocket propulsion system at the aft end of the recoverable booster stage of the Falcon 9 Space Launch Vehicle. This propulsion system has nine Merlin liquid propellant rocket engines, but only eight of these can be seen in this view. The total take-off thrust at sea level is approximately 1.3 million pounds of thrust force and at orbit altitude (in a vacuum) it is about 1.5 million pounds of thrust. Propellants are liquid oxygen and RP-1 kerosene. More information about this multiple rocket engine propulsion system can be found in Chapter 11 Section 2 and more information about RP-1 kerosene can be found in Chapter 7. The Falcon space vehicle and the Merlin rocket engines are designed, developed, manufactured, and operated by Space Exploration Technologies Corporation, better known as SpaceX, of Hawthorne, California.

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PREFACE

The rocket propulsion business in the United States of America appears to be changing. In the past, and also currently, the business has been planned, financed, and coordinated mostly by the Department of Defense and NASA. Government funding, government test or launch facilities, and other government support was provided. As it happens in all fields old-time companies have changed ownership, some have been sold or merged, some went out of business, some reduced the number of employees, and other companies have entered the field. New privately financed companies have sprung up and have developed their own rocket propulsion systems and flight vehicles as well as their own test, manufacturing, and launch facilities. These new companies have received some government contracts. Several privately owned companies have developed on their own useful space vehicles and rocket propulsion systems that were not originally in the government's plan. Although business climate changes noticeably influence rocket activities, it is not the purpose of this book to describe such business effects, but to present rocket propulsion principles and to give recent information and data on technical and engineering aspects of rocket propulsion systems.

All aerospace developments are aimed either at better performance, or higher reliability, or lower cost. In the past, when developing or modifying a rocket propulsion system for space applications, the emphasis has been primarily on very high reliability and, to a lesser extent, on high performance and low cost. Each of the hundreds of components of a propulsion system has to do its job reliably and without failure during operation. Indeed, the reliability of space launches has greatly improved world wide. In recent years emphasis has been placed primarily on cost reduction, but with continuing lower priority efforts to further improve performance and reliability. Therefore, this Ninth Edition has a new section and table on cost reduction of rocket propulsion systems. Also, in this book environmental compatibility is considered to be part of reliability

This Ninth Edition is organized into the same 21 chapters and subjects, as in the Eighth Edition, except that some aspects are treated in more detail. The names of the 21 chapters can be found in the Table of Contents. There are some changes, additions, improvements, and deletions in every chapter. A few problems have printed answers so students or other readers can self-check their solutions.

About half of this new edition is devoted to chemical rocket propulsion (solid propellant motors, liquid propellant rocket engines, and hybrid rocket propulsion systems). The largest number of individual rocket propulsion systems (currently in use, on stand-by, or in production) are solid propellant rocket motors; they vary in size, complexity, and duration; most systems are for military or defense applications. The next largest number in production or currently in use for space flight or missile defense are liquid propellant rocket engines; they vary widely in size, thrust or duration. Many people in aerospace consider this rocket propulsion technology to be mature. Enough technical information is available from public sources and from skilled personnel so that any new or modified rocket propulsion system can be developed with some confidence.

There have been several new applications (different flight vehicles, different missions) using existing or modified rocket propulsion systems. Several of these new applications are mentioned in this book.

Compared to the prior edition this new edition has less information or data of recently retired rocket engines, such as the engines for the Space Shuttle (retired in 2011) or Energiya; these have been replaced with facts from rocket propulsion systems that are likely to be in production for a long time. This new edition gives data on several rocket propulsion systems that are currently in production; examples are the RS-68 and the Russian RD-191 engines. Relatively little discussion of current research and developments is contained in this Ninth Edition; this is because it is not known when any particular development will lead to a better propulsion system, a better material of construction, a better propellant, or a better method of analysis, even if it appears to be promising at the present time. It is unfortunate that a majority of Research and Development programs do not lead to production applications.

Subjects new to the book include the Life of Liquid Propellant Thrust Chambers, a powerful new solid propellant explosive ingredient and two sections on variable thrust rocket propulsion. The discussion of dinitrogen oxide propellant is new, and additions were made to the write-ups of hydrogen peroxide and methane. Several different liquid propellant rocket engines are shown as examples of different engine types. The rocket propulsion system of the MESSENGER space probe is described as an example of a multiple thruster pressure feed system; its flow diagram replaces the Eighth Edition's one for the Space Shuttle. The Russian RD-191 engine (for the Angara series of launch vehicles) serves as an example for a high performance staged combustion engine cycle. The RS-68A presently has the highest thrust of any liquid oxygen/liquid hydrogen engine and it is an example of an advanced gas generator engine cycle. The RD-0124 illustrates an upper stage rocket engine with four thrust chambers and a single turbopump. Currently, a new manufacturing process known as Additive Manufacturing is being investigated for replacing parts or components of existing liquid propellant rocket engines.

The Ninth Edition also has the following other subjects, which are new to this book: upper stages with all electric propulsion, a dual inlet liquid propellant centrifugal pump for better cavitation resistance, topping-off cryogenic propellant tanks just prior to launching, benefits of pulsing of small thrusters, avoiding carbon containing deposits in the passages of liquid propellant cooling jackets, and a two-kilowatt arcjet. Since it is unlikely that nuclear power rocket propulsion systems development will again be undertaken in the next decade or that gelled propellants or aerospike nozzles will enter into production anytime soon, these three topics have largely been deleted from the new edition.

All Problems and Examples have been reviewed. Some have been modified, and some are new. A few of the problems which were deemed hard to solve have been deleted. The index at the end of the book has been expanded, making it somewhat easier to find specific topics in the book.

Since its first edition in 1949 this book has been a most popular and authoritative work in rocket propulsion and has been acquired by at least 77,000 students and professionals in more than 35 countries. It has been used as a text in graduate and undergraduate courses at about 55 universities. It is the longest living aerospace book ever, having been in print continuously for 67 years. It is cited in two prestigious professional awards of the American Institute of Aeronautics and Astronautics. Earlier editions have been translated into Russian, Chinese, and Japanese. The authors have given lectures and three-day courses using this book as a text in colleges, companies and Government establishments. In one company all new engineers are given a copy of this book and asked to study it.

As mentioned in prior editions, the reader should be very aware of the hazards of propellants, such as spills, fires, explosions, or health impairments. The authors and the publisher recommend that readers of this book do not work with hazardous propellant materials or handle them without an exhaustive study of the hazards, the behavior, and properties of each propellant, and without rigorous safety training, including becoming familiar with protective equipment. People have been killed, when they failed to do this. Safety training and propellant information is given routinely to employees of organizations in this business. With proper precautions and careful design, all propellants can be handled safely. Neither the authors nor the publisher assume any responsibility for actions on rocket propulsion taken by the reader, either directly or indirectly. The information presented in this book is insufficient and inadequate for conducting propellant experiments or rocket propulsion operations.

This book and its prior editions use both the English Engineering (EE) system of units (foot, pound) and the SI (Systėme International) or metric system of units (m, kg), because most drawings and measurements of components and subassemblies of chemical rocket propulsion systems, much of the rocket propulsion design and most of the manufacturing is still done in EE units, Some colleges and research organizations in the United States, and most propulsion organizations in other countries use the SI system of units. This dual set of units is used, even though the United States has been committed to switch to SI units.

Indeed the authors gratefully acknowledge the good help and information obtained from experts in specific areas of propulsion. James H. Morehart, The Aerospace Corporation, (information on various rocket engines and propellants) 2005 to 2015; Jeffrey S. Kincaid, Vice President (retired), Aerojet Rocketdyne, Canoga Park, CA (RS-68 engine data and figures, various propulsion data) 2012 to 2915; Roger Berenson, Engine Program Chief Engineer, Aerojet Rocketdyne, Canoga Park, CA, (RS-68 and RS-25 engine and general propulsion data) 2015; Mathew Rottmund, United Launch Alliance, Centennial, CO. (launch vehicle propulsion issues), 2014 to 2015; Olwen M. Morgan (retired), Marketing Manager, Aerojet Rocketdyne, Redmond, WA, (MESSENGER space probe; monopropellants); 2013 to 2016; Dieter M. Zube, Aerojet Rocketdyne, Redmond (view and data on hydrazine arcjet); 2013-2015; Jeffrey D. Haynes, Manager, Aerojet Rocketdyne, (additive manufacturing information), 2015; Leonard H. Caveny, Consultant, Fort Washington, MD, (solid propellant rocket motors); Russell A. Ellis, Consultant, (solid propellant rocket motors); 2015; David K. McGrath, Director Systems Engineering, Orbital ATK, Missile Defense and Controls, Elkton, MD, (solid propellant rocket motors); 2014 to 2015; Eckart W. Schmidt, Consultant for Hazardous Materials, Bellevue, WA, (Hydrazine and liquid propellants), 2013 to 2015; Michael J. Patterson, Senior Technologist, In-Space Propulsion, NASA Glenn Research Center, Cleveland, OH (electric propulsion information), 2014; Rao Manepalli, Deptford, NJ, formerly with Indian Space Research Organization (rocket propulsion systems information); 2011 to 2013; Dan Adamski, Aerojet Rocketdyne, (RS-68 flowsheet), 2014; Frederick S. Simmons (retired), The Aerospace Corporation (review of Chapter 20); 2015 to 2016.

The authors have made an effort to verify and/or validate all information in this ninth edition. If the reader finds any errors or important omissions in the text of this edition we would appreciate bringing them to our attention so that we may evaluate them for possible inclusion in subsequent printings.

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ROCKET PROPULSION ELEMENTS

CHAPTER 1

CLASSIFICATION

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 either move bodies initially at rest or change their velocity or that 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 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. *Duct propulsion* is another class of jet propulsion and it includes turbojets and ramjets; these engines are more commonly called air-breathing engines. Duct propulsion devices mostly utilize their surrounding medium as the propellant, energized by its combustion with the vehicle's stored fuel. Combinations of rockets and duct propulsion devices have been attractive for some applications, and one is briefly described in this chapter.

The *energy source* most commonly used in rocket propulsion is *chemical combustion*. Energy can also be supplied by *solar radiation* and by a *nuclear reactor*. Accordingly, the various propulsion devices in use can be divided into *chemical propulsion, nuclear propulsion,* and *solar propulsion*. Table 1–1 lists many important propulsion concepts according to their energy source and type of propellant. Radiant energy may originate from sources other than the sun and theoretically includes 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. Energy sources are central to rocket performance and several kinds, both within and external to the vehicle, have been investigated. The useful energy

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

	Energy Source[a]			
Propulsion Device	Chemical	Nuclear	Solar	Propellant or Working Fluid
Turbojet	D/P			Fuel + air
Turbo–ramjet	TFD			Fuel + air
Ramjet (hydrocarbon fuel)	D/P	TFD		Fuel + air
Ramjet (H_2 cooled)	TFD			Hydrogen + air
Rocket (chemical)	D/P	TFD		Stored propellant
Ducted rocket	TFD			Stored solid fuel + surrounding air
Electric rocket	D/P		D/P	Stored propellant
Nuclear fission rocket		TFD		Stored H_2
Solar-heated rocket			TFD	Stored H_2
Photon rocket (big light bulb)		TFND		Photon ejection (no stored propellant)
Solar sail			TFD	Photon reflection (no stored propellant)

[a]D/P developed and/or considered practical; TFD, technical feasibility has been demonstrated, but development is incomplete; TFND, technical feasibility has not yet been demonstrated.

input modes in rocket propulsion systems are either heat or electricity. Useful output thrust comes from the kinetic energy of the ejected matter and from the propellant pressure on inner chamber walls and at the nozzle exit; thus, rocket propulsion systems primarily convert input energies into the kinetic energy of the exhausted gas. The ejected mass can be in a solid, liquid, 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.

1.1. DUCT JET PROPULSION

This class, commonly called *air-breathing engines*, comprises devices which entrain and energize air flow inside a duct. They use atmospheric oxygen to burn fuel stored in the flight vehicle. This class includes turbojets, turbofans, ramjets, and pulsejets. These are mentioned here primarily to provide a basis for comparison with rocket propulsion and as background for combined rocket–duct engines, which are mentioned later. Table 1–2 compares several performance characteristics of specific chemical rockets with those of typical turbojets and ramjets. A high specific impulse (which is a measure of performance to be defined later) relates directly to long-flight ranges and thus indicates the superior range capability of air-breathing engines over chemical rocket propulsion systems at relatively low earth altitudes. However, the uniqueness of rocket propulsion systems (for example, high thrust to weight, high thrust to frontal area, and thrust nearly independent of altitude) enables flight in rarefied air and exclusively in space environments.

TABLE 1–2. Comparison of Several Characteristics of a Typical Chemical Rocket Propulsion System and Two-Duct Propulsion Systems

Feature	Chemical Rocket Engine or Rocket Motor	Turbojet Engine	Ramjet Engine
Thrust-to-weight ratio, typical	75:1	5:1, turbojet and afterburner	7:1 at Mach 3 at 30,000 ft
Specific fuel consumption (pounds of propellant or fuel per hour per pound of thrust)[a]	8–14	0.5–1.5	2.3–3.5
Specific thrust (pounds of thrust per square foot frontal area)[b]	5000–25,000	2500 (low Mach[c] numbers at sea level)	2700 (Mach 2 at sea level)
Specific impulse, typical[d] (thrust force per unit propellant or fuel weight flow per second)	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 velocity	Flight speed always less than exhaust velocity
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 0.102 to convert to kg/(hr-N).
[b]Multiply by 47.9 to convert to N/m^2.
[c]Mach number is the ratio of gas speed to the local speed of sound (see Eq. 3–22).
[d]*Specific impulse* is a performance parameter defined in Chapter 2.

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

For supersonic flight speeds above Mach 2, the *ramjet engine* (a pure duct engine) becomes possible for flights within the atmosphere. Compression is purely gas dynamic and thrust is produced by increasing the momentum of the subsonic compressed air as it passes through the ramjet, basically as is accomplished in the turbojet and turbofan engines but without any compressor or turbine hardware. 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 to at least Mach 16. Ramjets with supersonic combustion, known as *scramjets*, have flown in experimental vehicles. All ramjets

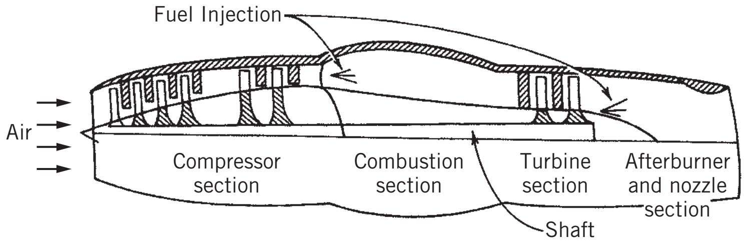

FIGURE 1–1. Simplified schematic diagram of a turbojet engine.

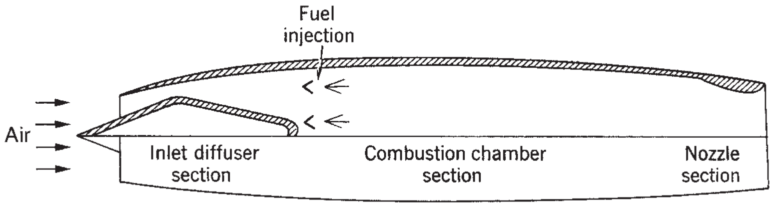

FIGURE 1–2. Simplified diagram of a ramjet with a supersonic inlet (a converging/diverging flow passage).

must depend on rocket or aircraft boosters for initial acceleration to supersonic conditions and operating altitudes, and on oblique shocks to compress and decelerate the entrance air. Applications of ramjets with subsonic combustion include shipboard- and ground-launched antiaircraft missiles. Studies of a hydrogen-fueled ramjet for hypersonic aircraft looked promising, but as of this writing they have not been properly demonstrated; one supersonic flight vehicle concept combines a ramjet-driven high-speed airplane and a one- or two-stage rocket booster for driving the vehicle to its operating altitude and speed; it can travel at speeds up to a Mach number of 25 at altitudes of up to 50,000 m.

No truly new or significant rocket technology concepts have been implemented in recent years, reflecting a certain maturity in this field. Only a few new applications for proven concepts have been found, and those that have reached production are included in this edition. 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.

1.2. ROCKET PROPULSION

Rocket propulsion systems may be classified in a number ways, for example, according to energy source type (chemical, nuclear, or solar) or by their basic function (booster stage, sustainer or upper stages, attitude control, orbit station keeping, etc.)

or by the type of vehicle they propel (aircraft, missile, assisted takeoff, space vehicle, etc.) or by their size, type of propellant, type of construction, and/or by the number of rocket propulsion units used in a given vehicle.

Another useful way to classify rockets is by the method of producing thrust. The thermodynamic expansion of a gas in a supersonic nozzle is utilized in most common rocket propulsion concepts. The internal energy of the propellant is converted into exhaust kinetic energy, and thrust is also produced by the pressure on surfaces exposed to the exhaust gases, as will be shown later. This same thermodynamic theory and the same generic equipment (i.e., a chamber plus a nozzle) is 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. 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.

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. Ziolkowsky, 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. For the history of rockets, see Refs. 1–1 to 1–7.

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/sec or 5900 to 14,100 ft/sec). Since such gas temperatures are about twice the melting point of steel, it is necessary to 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 is schematically shown in Fig. 1–3. The *bipropellant* consists of a liquid oxidizer (e.g., liquid oxygen) and a liquid fuel (e.g., kerosene). A *monopropellant* is a single liquid that decomposes into hot gases when properly catalyzed.

*The term *thrust chamber*, used for the assembly of the injector, nozzle, and chamber, is preferred by several official agencies 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.

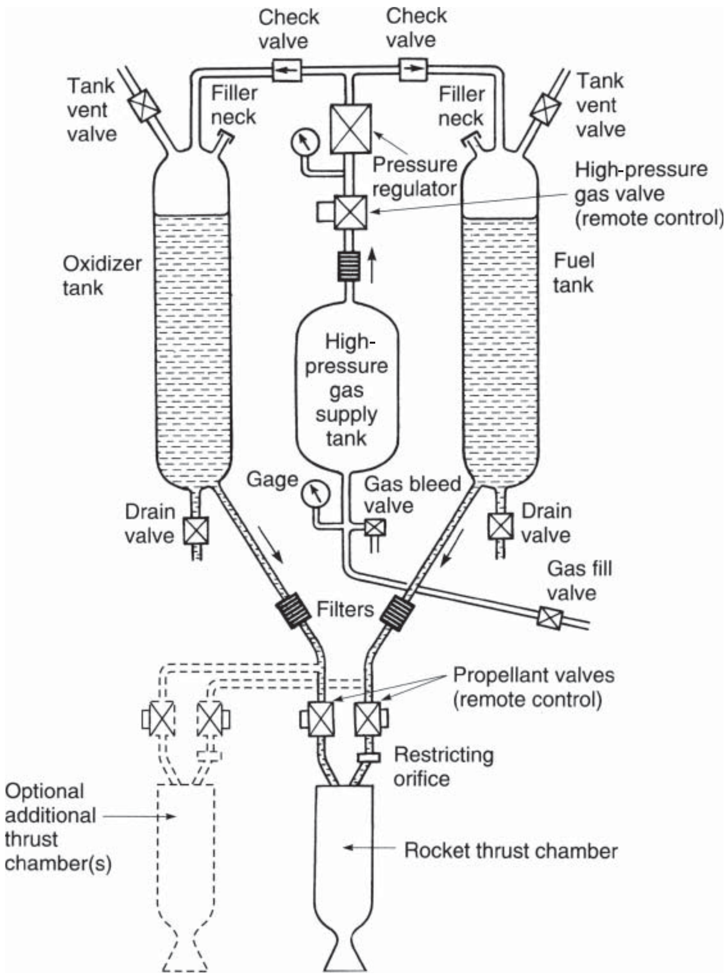

FIGURE 1–3. Schematic flow diagram of a liquid propellant rocket engine with a gas pressure feed system. The dashed lines show a second thrust chamber, but some engines have more than a dozen thrust chambers supplied by the same feed system. Also shown are components needed for start and stop, controlling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

Gas pressure feed systems are used mostly on low-thrust, low-total-energy propulsion systems, such as those used for attitude control of flying vehicles, often with more than one thrust chamber per engine. The larger bipropellant rocket engines use one or more turbopump-fed liquids as shown in Fig. 1–4. Pump-fed liquid rocket systems are most common in applications needing larger amounts of propellant and higher thrust, such as those in space launch vehicles. See Refs. 1–1 to 1–6.