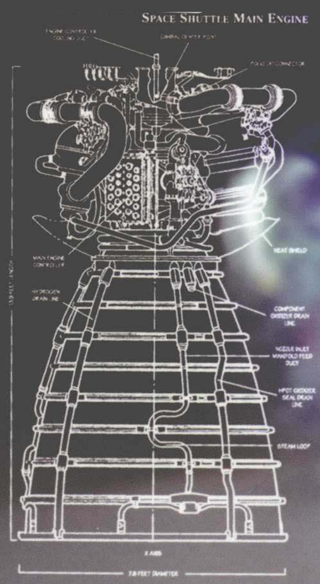

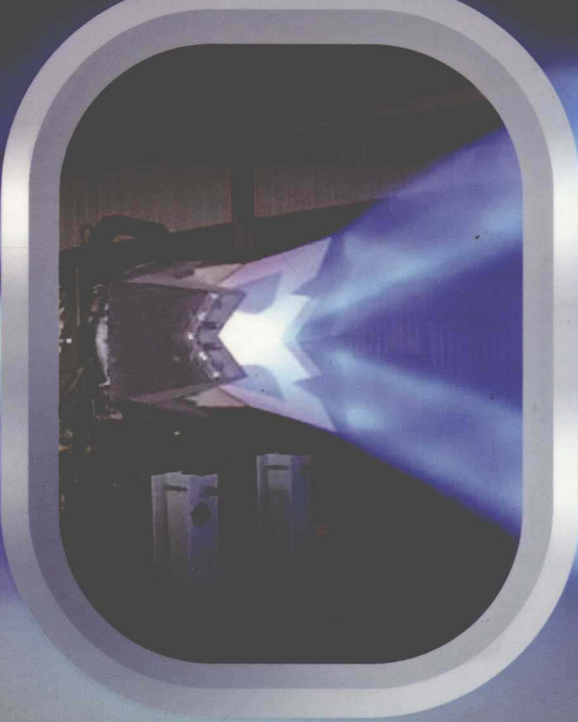

T.-W. Lee

Aerospace Propulsion

Aerospace Series

Editors Peter Belobaba, Jonathan Cooper
and Allan Seabridge

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AEROSPACE PROPULSION

T.-W. Lee
Arizona State University, USA

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Series Preface

There are books in the Aerospace Series that deal with propulsion systems for aircraft. They generally treat the engine and its control system as an integral part of the aircraft – as an installed system. The interactions between the propulsion system and the aircraft systems are described.

The power plant of an airborne vehicle is critical to its performance and its safe operation, so it is vital for engineers working in this field to understand the fundamentals of the propulsion system. This book provides a different viewpoint to that of the systems books: it is very much an analytical view of the power plant itself, and it should be read as a complement to the other propulsion books. The author introduces the reader to the principles of thrust and the gas turbine engine before providing a comprehensive mathematical treatment of the major components of the propulsion mechanism and the complex aerodynamic and thermodynamic processes within various engine types – both air-breathing and rocket. This is to provide a basis for developing an understanding of propulsion systems and the modeling tools that can be used to provide a comprehensive and practical knowledge for use in research and industry.

MATLAB® models are provided to reinforce the explanations, and exercises are also set for the diligent student to pursue.

The book covers gas turbine (aeronautical) systems and rocket propulsion (astronautic) systems and is hence of interest to engineers working in the fields of aircraft, missiles and space vehicles. Some novel propulsion systems are also described, that may be pertinent to emerging fields of aerospace transportation systems, setting out to meet environmental objectives.

This is a book for those engineers who wish to understand the fundamental principles of aerospace propulsion systems.

Peter Belobaba, Jonathan Cooper and Allan Seabridge

Preface

Aerospace propulsion devices embody some of the most advanced technologies, ranging from materials, fluid control and heat transfer and combustion. In order to maximize performance, sophisticated testing and computer simulation tools are developed and used. In undergraduate or introductory graduate courses in aerospace propulsion, we only cover the basic elements of fluid mechanics, thermodynamics, heat transfer and combustion science, so that either in industry or in research labs the students/engineers can address some of the modern design and development aspects.

Compressor aerodynamics, for example, is a dynamic process involving rotating blades that see different flows at different radial and axial locations. Cascade and transonic flow behavior can make the analyses more complex and interesting. In turbine flows, the gas temperature is high, and thus various material and heat transfer issues become quite important. Owing to the rotating nature of turbine and compressor fluids, intricate flow control between the axis and the blade section needs to be used, while allowing for cooling flow passage from the compressor to the turbine blades. Combustor flow is even more complex, since liquid-phase fuel needs to be sprayed, atomized, evaporated and burned in a compact volume. High heat release and requirements for downstream dilution and cooling again make the flow design quite difficult and challenging. All of these processes – spray atomization, phase change, combustion, heat transfer (convection and radiation) and mixing – occur in turbulent flows, and no computational tools can accurately reproduce real flows without lengthy modeling and calibration. Any one of the issues mentioned above, such as spray atomization, turbulent flow or combustion, is an unsolved problem in science and engineering, and this is the reason for industry and research labs developing expensive testing and computational analysis methods. This aspect makes aerospace propulsion an important part of engineering curricula, as it provides an interdisciplinary and "tough" training ground for aerospace engineers.

As noted above, owing to the multiple engineering topics involved, we only go into basic elements of aerospace propulsion. After some of the basics are covered, we try to expose the students to projects involving computational fluid dynamic (CFD) software, since this is frequently used in industry and in research labs. There are commercial CFD packages that can be readily made available to the students, using educational licenses. With online documentation and examples, students can learn to operate these codes, individually or in group projects. In addition, the gas-turbine lab at ASU allows the students to use actual testing data for performance analyses. These elements cannot be included in this book without stretching the physical and mental limits, but they are essential components in an aerospace propulsion course, to link the underlying science and engineering to practical applications.

I have included discussions of both gas-turbine and rocket propulsion, for combined or separate aerospace propulsion courses. There are some good interrelations between aeronautical (gas-turbine) and astronautical (rocket) propulsion, based on the same knowledge set. In addition, many students opt to take both aeronautical and astronautical propulsion, unless a combined course is offered, since their final career choices are made many years downstream.

Thank you for reading up to this point, and potentially beyond.

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1

Introduction to Propulsion Systems

Propulsion systems include some of the most advanced technologies. The high performance requirements, at low system weight, necessitate advanced thermal-fluid design, materials and system integration. The thrust, generated through a simple-looking principle of conservation of momentum (or Newton's second law), enables many human capabilities, such as high-speed civil transport (approximately 12 hours for trans-Pacific flights), affordable personal aircraft, advanced military aircrafts (e.g. F-22 Raptor, Sukhoi), Earth orbital operations (Space Shuttle) and numerous satellites, planetary probes and possible missions. The propulsion technology can also lead to potentially destructive uses, as in cruise missiles, intercontinental ballistic missiles and many other weapons propelled at high speeds.

A typical gas-engine shown in Figure 1.1 achieves the high exit momentum through a sequence of devices that include compressor, combustor, turbine and nozzle. The ambient air is ingested in gas-turbine engines. The compressor consists of a series of rotating blades, which aerodynamically is a set of airfoils using rotary motion to generate a pressure differential as the air traverses the blade elements. The air pressure is increased in the compressor, and sent into the combustor where the fuel is injected, mixed with the air, and burned. The air energy (enthalpy) increase is now used in the turbines to convert some of the thermal energy (enthalpy) into shaft power. This shaft power is used to power the compressor, by simply having a common axis between the turbine and the compressor in turbojet engines. However, in turbofan engines, the turbine power is used to run both the compressor and the fan. The fan adds enthalpy to the air stream in the fan section. The energy available at the end of the turbine section is converted to air kinetic energy in the nozzle. The high kinetic energy of the exhaust stream also has high momentum, which is useful in generating thrust. Ramjets are a much simpler form of turbojet engines, where "ram compression" of incoming stream at supersonic speeds is sufficient to elevate the pressure of the air. Fuel then needs to be injected into this high-pressure air stream and the resulting flame stabilized in the ramjet combustor, for sustained thrust.

Advances in practically all aspect of engineering, including propulsion technology, can be found in the Lockheed Martin F-22 Raptor (Figure 1.2) that entered service in 2005. New materials such as advanced alloys and composite materials are used in the Raptor

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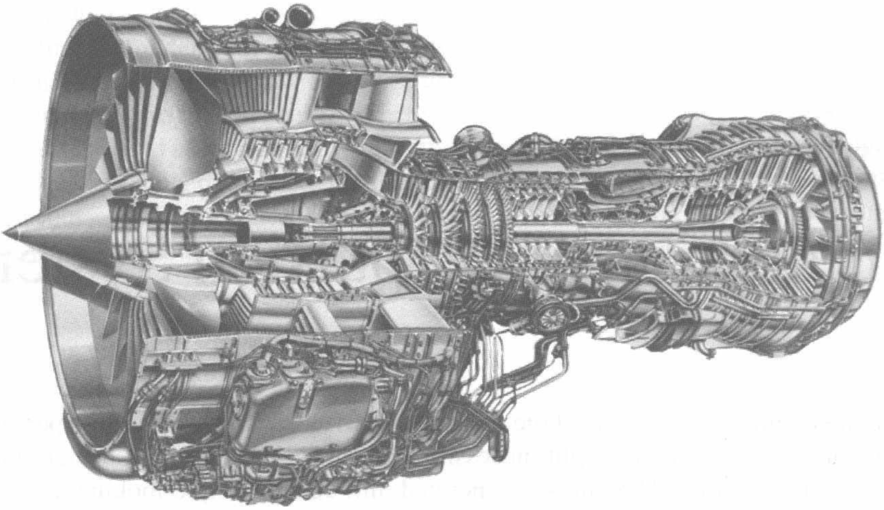

Figure 1.1 A typical gas-turbine engine. Copyright United Technologies Corporation.

airframe, aerodynamic surfaces and engine components. The power plant in the F-22 consists of Pratt-Whitney afterburning turbofans (F119-PW-100) with a high efficiency, which provide supersonic cruise speeds with long range and unmatched agility with pitch-vectoring thrust nozzles. But these technological advances came with a high price tag. Many of the new technologies were researched and developed specifically as part of the F-22 project. If all the development costs are added in, the F-22 carries a price tag of over $300 million per aircraft. Table 1.1 shows some of the main specifications of the F-22, including some of the propulsion characteristics.

The Pratt-Whitney F119-PW-100 engine is another component in the F-22 that is arguably the most advanced in aircraft technology. Each of these engines generates more

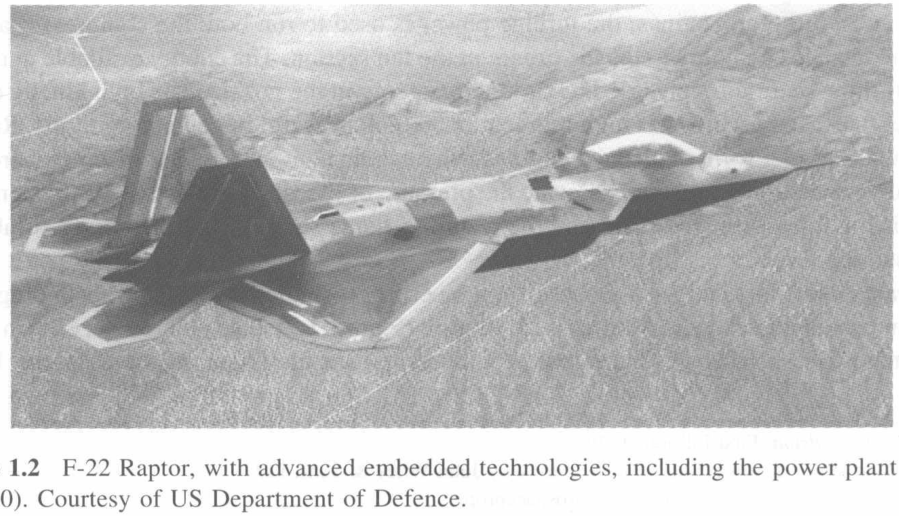

Figure 1.2 F-22 Raptor, with advanced embedded technologies, including the power plant (F119-PW-100). Courtesy of US Department of Defence.

Table 1.1 F-22 specifications.

Length	62.1 ft (18.9 m)
Wingspan	44.5 ft (13.56 m)
Height	16.8 ft (5.08 m)
Maximum take-off weight	80 000 lb (36 288 kg)
Power plant	Two Pratt-Whitney F119-PW-100 pitch-vectoring turbofans with afterburners
Total thrust	70 000 lb
Maximum speed	High altitude: Mach 2.42 or 1600 mph (2570 km/h) Low altitude: Mach 1.72 or 1140 mph (1826 km/h)
Ceiling	65 000 ft (20 000 m)
Range	2000 miles (5600 km)
Rate of climb	N/A (classified)
Thrust-to-weight ratio	1.26
Maximum g-load	−3/+9.5

thrust without the afterburner than most conventional engines with full afterburner power on, and its supersonic thrust is also about twice that of the other engines in the class. Using two of these engines to develop a total thrust of 70 000 pounds, the F-22 can travel at supersonic speeds without the afterburners for fuel-efficient high-speed cruise to the target area. This level of thrust is more than the aircraft weight, and enables the F-22 to fly vertically upward much like a rocket. The F119 is also unique in fully integrating the vector thrust nozzle into the engine/airframe combination, for a 20-degree up/down redirection of thrust for high-g turn capabilities. The thrust vectoring is designed to enhance the turn rates by up to 50% in comparison to using control surfaces alone. The F119 engine achieves all these functional characteristics with 40% fewer parts than conventional engines to furnish exceptional reliability, and maintenance and repair access. In a design method called integrated product development, inputs from assembly line workers and air force mechanics were incorporated to streamline the entire sequence of engine production, maintenance and repairs. These design innovations are expected to reduce the support equipment, labor and spare parts in demand by approximately half. Similar to the mid-fuselage airframe, the turbine stage, consisting of the disk and blades, is constructed in a single integrated metal piece for high integrity at lower weight, better performance and thermal insulation for the turbine disk cavity. The fan and compressor blade designs went through extensive permutations and modifications using computational fluid dynamic (CFD) simulations, resulting in unprecedented efficiency in both sections. Hardware cut-and-try of different designs would have cost way too much time and money. High-strength and degradation-resistant Alloy C was used in key components such as the compressors, turbines and nozzles to allow the engine to run at higher temperatures, one of the important contributing factors to the increased thrust and durability of F119 engines. The combustor – the hottest component in the engine – uses oxidation-resistant, thermally insulating cobalt coatings. A digital electronic engine control device called FADEC (FADEC is generally meant to signify 'Full Authority Digital Engine Control' the level of redundancy is at the discretion of the engine manufacturer) not only fine tunes the engine operating parameters to deliver the highest performance at the maximum efficiency, but also establishes responsive and precise engine operating parameters with inputs from the pilot control of the throttle and the engine/flight sensors.

As is well known, the F-22 has unique stealth capabilities, in spite of its size. In addition to the external geometry and surfaces, the jet-engine exhaust is a critical component in minimizing infrared signatures that can be detected by forward-looking infrared (FLIR) or IR sensors in heat-seeking missiles. The exhaust of the F-22 is designed to absorb the heat by using ceramic components, rather than conduct heat to the outside surface. Also, the horizontal stabilizers are placed to shield the thermal emission as much as possible.

The F-35 Lightning II Joint Strike Fighter (JSF) Program represents the effort to provide a capable, multi-mission aircraft while containing the budget. The F-35's price tag is about half that of the F-22 Raptor. The argument for wide adoption of this scaled-back aircraft is that the F-22's capabilities are best directed against opponents with similar technological capabilities, and with the changed geo-political environment the United States forces are less likely to be involved in such encounters. A unique variant of the F-35 (Figure 1.3) is the marine STOVL version, F-35B, also planned for adoption by the British Royal Navy to replace the Sea Harrier. The short take-off is facilitated by a number of auxiliary nozzles to divert the thrust. In a normal engine, the jet exhaust is pushed out of the nozzle at the rear of the engine to provide only forward thrust. In engines with thrust reversers, the fan stream is redirected to the forward direction to generate negative thrust. The same concept can be used to redirect the thrust to other directions by using auxiliary nozzles. For the F-35B, there is a lift nozzle that takes the fan exhaust and directs it vertically downward. Also, the pitch nozzle at the main nozzle can be turned to add a vertical component to the thrust. For control of the aircraft during this tricky maneuver, there are four additional nozzles. Two roll nozzles control the roll angle by sending a small fraction of the main exhaust at off-horizontal angles, while two yaw nozzles generate thrust in the forward and backward offset angles.

Rockets, on the other hand, carry all the working fluid (both fuel and oxidizers) on board. The main reason for carrying both the fuel and oxidizer is so that rockets can operate in an

Figure 1.3 F-35 Joint Strike Fighter. Courtesy of US Department of Defence.

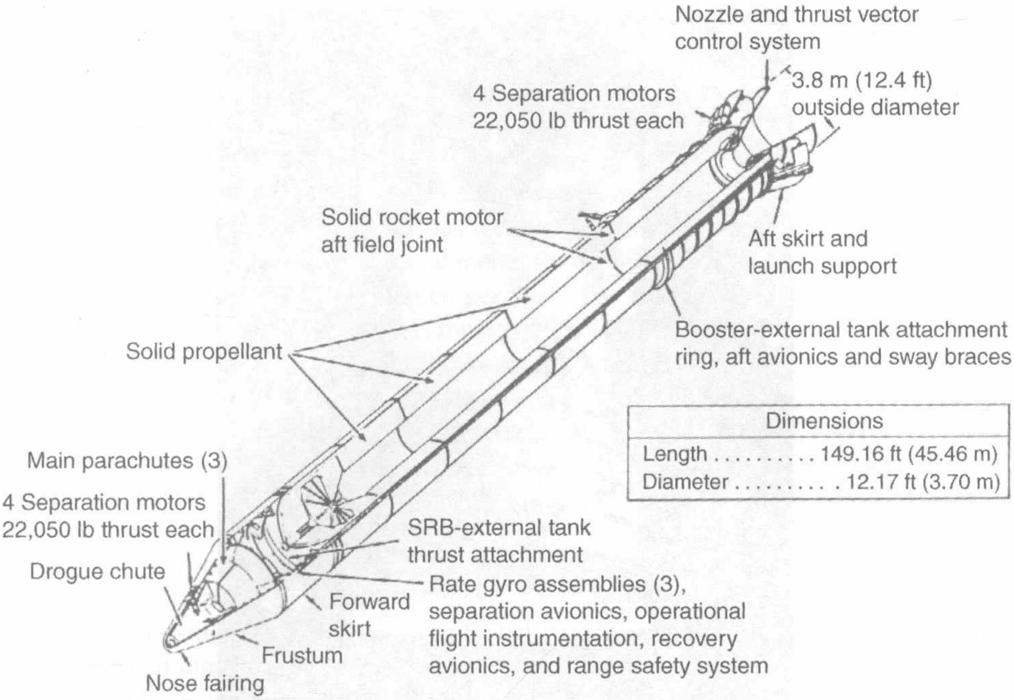

Figure 1.4 Solid-propellant rocket engine. Courtesy of US Department of Defence.

air-less environment (e.g. underwater or in outer space), but this also means zero incoming momentum. In addition, some rocket devices can be quite simple in design. Solid-propellant rockets, for example, only require the propellant and a nozzle (Figure 1.4). The documented use of rocketry dates back to 900 AD in China, where "black powder" was used as crude flame throwers ("fire lance"), grenades, siege weapons and other devices that delivered shock effects against the Mongols in the 10th century. Black powder consists of readily available ingredients – charcoal, sulfur and saltpeter (potassium nitrate), and was probably discovered by accident and perfected through trial-and-error. Combustion of black powder goes roughly as

$$\text{2 parts saltpeter} + \text{sulfur} + \text{3 parts charcoal} \rightarrow \text{combustion products} + \text{nitrogen} + \text{heat}$$

This technology was quickly adopted by the Mongols, and spread to Europe and other parts of the world. Rockets using liquid propellants are, in comparison, relatively new technologies, having been developed in the early 1900s. At the other extreme, modern liquid-propellant rockets contain some of the most advanced technologies (Figure 1.5), due to the high operating pressure and temperatures, in addition to the use of cryogenic propellants such as liquid oxygen and liquid hydrogen. The high operating pressure requires sophisticated pumping devices, while high temperature necessitates advanced combustion control and cooling technologies.

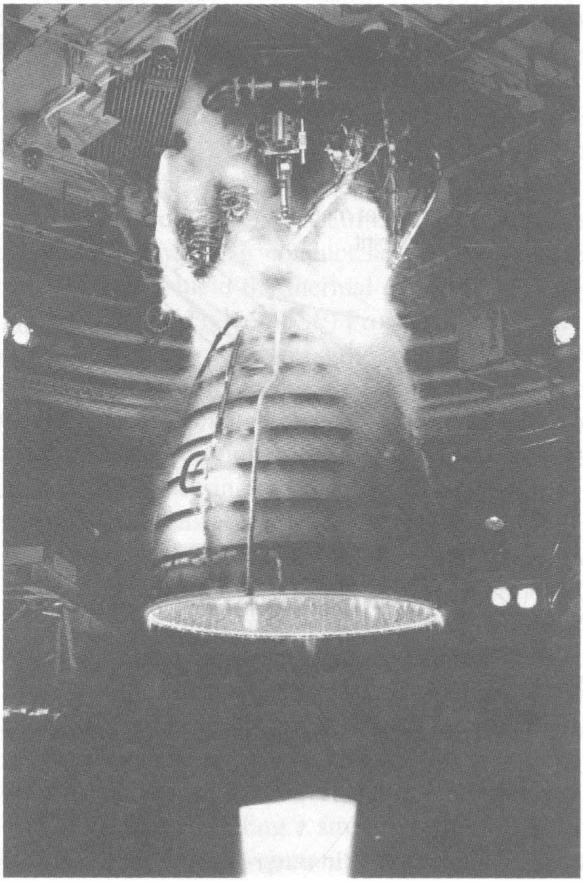

Figure 1.5 Liquid-propellant rocket engine (space shuttle main engine). Courtesy of NASA.

A large altitude change during a rocket flight requires modified designs for each of the stages. At launch, the ambient pressure is roughly equal to the sea level atmospheric pressure, while the pressure decreases with increasing altitude. This results in larger pressure thrust; however, at higher altitudes the nozzle exit pressure becomes greater than the ambient pressure and the nozzle operates in an under-expanded mode. This operation is less than optimum, and the gas expansion continues downstream, creating diamond-shaped shock waves. Upper stages are designed with this aspect in mind, where a larger expansion ratio in the nozzle is used. The first stage of a Delta II launch vehicle, for example, has a nozzle expansion ratio of 12. The propellant is liquid oxygen and RP-1 (a kerosene-based hydrocarbon), which is burned in the combustion chamber at a mixture ratio (O/F) of 2.25 and pressure of 4800 kPa. This combination results in a specific impulse of 255 s. The next stage, on the other hand, has a nozzle expansion ratio of 65. The propellant combination of nitrogen tetroxide and Aerozine 50 (hydrazine/unsymmetrical dimethyl hydrazine) is used at a mixture ratio of 1.90 and chamber pressure of 5700 kPa (830 psia), which provides a specific impulse of 320 s. The space shuttle main engine (SSME) has an even larger nozzle expansion ratio of 77.5.

Liquid oxygen and liquid hydrogen used in the SSME generates a high combustion chamber temperature, and also produces combustion product gases with a low molecular weight. These factors are optimum for producing large exit velocity and thus thrust. For this reason, a liquid hydrogen/oxygen combination is also used in the Atlas Centaur upper stage, the Ariane-4 third stage and the Ariane-5 core stage.

In addition to the boost, rockets are used for various orbit maneuvers, such as station-keeping and attitude adjustments. Various factors can contribute to deviations from the target orbit. Gravitational forces of the sun and moon, for example, can cause the orbital inclination to change by approximately one degree per year. The velocity increment that needs to be expended to compensate for this drift is roughly 50 m/s. Other smaller factors that lead to orbit deviations are the elliptical shape of the Earth's equator and the "solar wind" which is the radiation pressure due to the sun's radiation. Attitude adjustments are performed with a relatively large number of small thrusters, since all three degrees of freedom need to be accessed in addition to start/stop maneuvers. For example, the Ford Aerospace Intelsat V satellite had an array of four 0.44 N (0.1 lbf) thrusters for roll control, ten 2.0 N (0.45 lbf) thrusters for pitch and yaw control and station-keeping, and two 22.2 N (5.0 lbf) thrusters for repositioning and reorientation.

Since the thrust required for orbit maneuvers is small, simpler rocket boosters such as solid propellant or monopropellants can be used. For example, typical satellites in geosynchronous orbits launched during the 1980s were equipped with solid-propellant boosters for apogee maneuver and monopropellant hydrazine thrusters for station-keeping and attitude control. The solid propellant consisted of HTPB (fuel/binder) and ammonium perchlorate (oxidizer). Hydrazine is a monopropellant containing both fuel and oxidizer components in its chemical structure, and only requires a catalytic grid for decomposition. An interesting combination of electric and thermal thrust is the use of electrical heat for the hydrazine monopropellant, which increases the specific thrust.

For more recent satellites, electric or electromagnetic thrusters with high specific thrust are used for low propellant mass requirements and therefore longer mission durations. Arcjets, for example, use an electric arc to superheat propellants such as hydrazine, which nearly doubles the specific impulse to over 500 s with typical thrust levels of 0.20 N. Arcjet thrusters are used on Intelsat VIII and Lockheed Martin A2100 satellites, and Iridium satellites. Another type of electric propulsion system with even higher specific impulse (2000–4000 s) is the ion thruster (Figure 1.6), using xenon as propellant, which produces a typical thrust of less than 0.1 N. Xenon is an inert monatomic gas with a high atomic weight (131 kg/kmol). Xenon atoms are ionized by high-speed electrons, and then these positively charged ions are accelerated to a speed of some 34 000 m/s in an electric field of 750 V in thousands of ion beams. The momentum of these ion beams produces a thrust in the order of 10 mN.

A combination of electric and magnetic fields can also be used in so-called Hall thrusters. Other exotic space propulsion devices include solar sails and nuclear propulsion, still at the experimental stage (Figure 1.7).

1.1 Conservation of Momentum

We can see from the above examples that all propulsion devices generate some high-speed exhaust stream, through a variety of means. Thus, we can say that the objective of