CHAPTER

1

# Introduction to Space Propulsion

## 1.1 INTRODUCTION

In the early 20th century space flight was a dream with very few countries engaging in space systems development. During the middle of the 20th Century when Yuri Gagarin of the Soviet Union went to outer space and orbited the Earth in 1961, the Space Race heated up within the world. This resulted in the United States developing the Apollo launch vehicle and sending the first astronauts to land on the Moon in July 1969 and successfully bringing them back to earth. Several other nations in the world also got into space technologies and systems development during the early 1960's. The 21st Century saw a rapid increase in the number of launches by government agencies and commercial companies to utilize space for global communications, study the environments of Earth and other planets, explore space to benefit humanity, national defence, and understand the origins of the Universe. Space has become a new frontier which presents humanity with complex challenges and opportunities to research, develop and implement new technologies and methodologies to achieve safe and cost-effective space systems. Advancements in areas such as vehicle configurations, propulsion systems, new materials and structures, sensing and control, communications, radiation protection, space medicine, computing, utilization of in-situ resources in space and on planetary surfaces, and in-space manufacturing are continuing to realize fault-tolerant systems to launch a variety of payloads into low-earth and deep space orbits in the exploration of space for commercial use and manned missions to space, Moon and other Planets. Propulsion systems are required to launch satellites, spacecraft landers, in-space and interplanetary vehicles, and auxiliary controls. Significant opportunities also exist to improve existing propulsion technologies and provide advanced electrical and nuclear propulsion for deep space missions.

Propulsion systems are required to launch satellites, spacecrafts, landers, interplanetary vehicles and to operate auxiliary controls. To achieve a space mission, basic components required are launchers and payloads like satellites or spacecraft.

1. *Launchers*: They are used to move payload from Earth's surface to space in different orbits. Depending on their payload launching capability and performance, they can be classified in different types. The medium expendable launch-vehicle (MLV), like Delta2 of USA, PSLV of India and Ariane 40 to 44L of European Space Agency, are capable transferring payload up to 4000 kg to Low Earth Orbits (LEO) at different latitudes and inclinations. The heavy expendable launch-vehicle (HLV), like Delta 4, Ariane 5 and GSLV are capable of handling

higher payloads of order 10 tons to LEO and 4000 to 6000 kg payload to high Earth orbits (HEO) like Geostationary orbit (GEO). SpaceX's FALCON vehicle is a type of reusable launch vehicle (RLV). NASA’s Space Launch System (SLS), the super-heavy lift expendable launch vehicle launched during 2022 has capability to launch 13,000 kg payload to translunar injection with ability to take people to the Moon and Mars.

2. *Satellites*: They are placed in low Earth orbit (LEO)/medium Earth orbit (MEO)/highly inclined orbit and geostationary orbit (GEO). The International Space Station (ISS), is at about 400 km of altitude.
3. *Spacecrafts*: They are space vehicles from Earth orbit to anywhere in the space: interplanetary, planetary orbiter (like Galileo, Magellan and Cassini), planetary landers (like HUYGENS, Rosetta and Mars pathfinder) and outer solar system.

## 1.2 BRIEF HISTORY

*Konstantin Tsiolkovsky (1857-1935)*

*Robert Goddard (1882-1945)*

Konstantin Tsiolkovsky (1857-1935), a mathematics teacher from a small city southwest of Moscow, Russia, published in 1903 the article "The Investigation of Space by Means of Reactive Devices". The article explains in detail the relation between fuel (propellant), velocity and total mass of rocket. This is the fundamental equation for rocket propulsion and is known as the Tsiolkovsky equation.

Robert Goddard (1882-1945), a professor of physics at Clark University in Worcester, Massachusetts, USA, was granted patents in 1914 on the design of liquid rockets and its components like combustion chambers and nozzles. In his article, "A Method of Reaching Extreme Altitudes”, published in 1919, developed the theory of spaceflight and its design. He also mentioned, though highly ridiculed by the press and people of that time, about the possibility of sending an unmanned rocket to the moon. He launched the very first liquid rocket weighing 5 kg, on the 16th March 1926, propelled by liquid oxygen and petrol.

Hermann Oberth (1894-1980)

Wernher von Braun (1912-1977)

Another, the most influential spaceflight pioneer was Hermann Oberth (1894-1989), Hungarian settled in Germany. His doctoral thesis "The Rocket to the Planets" ("Die Rakete zu den Planetenräumen") was rejected at the University of Heidelberg but he published it as a book. It was a best seller book that stimulated interest in many youngsters in rocket science leading to many rocket societies in Germany. The most famous society is *Verein für Raumschifffahrt,* in which Wernher von Braun was a member.

The Treaty of Versailles that followed the end of World War I prohibited Germany from using long-range artillery. As alternative many leaders were interested in the development of rockets to use as a long-range missile to circumvent the prohibition. In 1932, The German army gave a contract to the young Wernher von Braun, Oberth's assistant, to develop a rocket that can be used as a missile. The efforts of von Braun team led to development of the medium range missile, the A-4 rocket, better well known as the V-2 rocket. Advanced versions of the A-4 rocket were ready before the end of World War II. The version A-9/10 would have been the first intercontinental ballistic missile (ICBM) capable of delivering a nuclear warhead from Western France to New York, but could not reach from drawing stage to manufacturing due to Germany's surrender. During the War thousands of V-2 missiles were manufactured and fired by the German Army. After the end of War, teams from the Allied forces the USA, the UK, and the Soviet Union (USSR) raced to the Peenemünde Army Research Center, where the world's first functional large-scale liquid-propellant rocket, the V-2, was developed, to seize key German manufacturing facilities, procure Germany's missile technology, and capture key personnel involved in the missile development. Hundreds of rail-car loads of V-2s and parts were captured and shipped to the United States and USSR. Around 126 of the principal designers, including Wernher von Braun and Walter Dornberger, were in American hands and moved to the USA. After the Nazi defeat, German engineers were moved to the United States, the United Kingdom and the USSR, where they further developed the V-2 rocket for military and civilian purposes. The V-2 rocket also laid the foundation for the liquid fuel missiles and space launchers used later in the USA and USSR. Under the guidance of Von Braun USA continued the research in rocket sciences that led to development of the powerful Saturn-V rocket that brought the first men to the moon in 1969. The Russians under the guidance of Sergei Korolev, the Russian counterpart to Wernher von Braun, developed reliable rocket engines based on V-2 technology.

Now, many countries are involved in space research and developed their own launch vehicles such those of the highly successful Ariane program of the European Space Agency (ESA), the Japanese H-Family, the Chinese Long March and the Indian PSLV and GSLV. The world has witnessed the gradual construction of orbital platforms such as the Russian Mir Space Station and the International Space Station (ISS). Mankind now is living in the satellite communication age enabled by space technology.

Manned missions need high reliability and the best quality. To achieve it requires multiple subsystems with always a backup if one fails. The Saturn V had all of this, but it was used only once, and then discarded. After the success of Apollo 11, the space budget could not be sustained at high levels and to continue the manned exploration of space needed a more cost-effective program. This led to development of the Space Shuttle, the concept to reuse the main vehicle. As of now, the space shuttle main engine (SSME) is the most advanced engine that the world has ever developed. The Space Shuttle was a partially reusable low Earth orbital spacecraft system operated from 1981 to 2011 by the U.S. The disaster of space shuttle Challenger on January 28, 1986, disintegrated 73 seconds after launch due to the low-temperature impairment of an O-ring between segments of the rocket booster casing and another shuttle Columbia on February 1, 2003, disintegrated during re-entry due to damage of the leading edge of the wing caused during launch, killing all the 7 astronauts in each flight, led the U S to review the manned space program and NASA itself.

In January 2004, President George W. Bush called for the retirement of the Space Shuttle on completion of the International Space Station (ISS). It was planned to replace Shuttle with a Crewed Exploration Vehicle, using Apollo style re-entry rather than the complicated system of heat resistant tiles. The last Space Shuttle was launched on July 8, 2011, and landed at the Kennedy Space Center (KSC) on July 21, 2011. From then until the launch of SpaceX's Crew Dragon using Falcon Heavy rocket in 2020, the US launched its astronauts aboard to the ISS with Russian Soyuz spacecraft.

Up to recently, these space accomplishments have been driven and owned by national governments. Now, private industrialists like SpaceX and Boeing, encouraged by national agencies with start-up funds and new technologies, have entered the space business. The space tourism market is now opening with active participation of private industries. With the collaboration of nation and private agencies in the development frontier of space technologies, in the coming a few decades, it is possible to colonization of the Moon, Mars and asteroids by humankind.

## 1.3 SPACE

Space, as we are interested in outer space, begins at about 100 km above sea level where Earth's atmosphere is said to stop. Space is a zone of near vacuum between celestial bodies, a boundless three-dimensional extent in which objects and events have relative position and direction. It contains planets, stars, galaxies, dust, black holes and many other objects. Figure 1.1 shows the variation of atmospheric pressure along altitude. The jet planes fly at about 10 km above the ground level.

Space is very vast. It contains billions of galaxies. Galaxies are concentrations of stars, dust, gas and black matter. All held together by gravity. There are billions of galaxies in endless space. Our Earth belongs to one of the galaxies called the Milky Way galaxy. Our solar system, with the Sun as its center, is a relatively minute section of the vast galactic star system called the Milky Way. This is in turn only one galactic star system among the numerous such systems composing the universe.

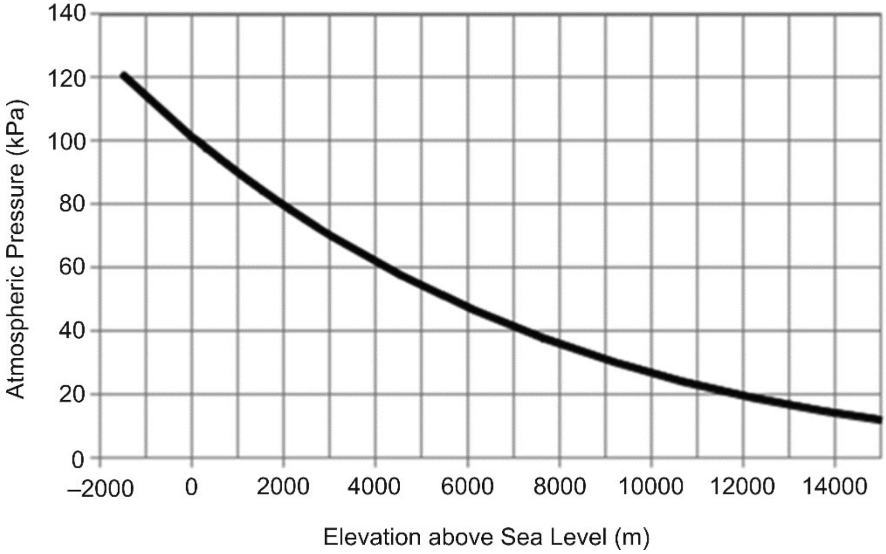


**Figure 1.1** Atmospheric Pressure Vs Elevation from sea level.

A galaxy is a system of stars and can best be visualized as a disc standing on edge. The Milky Way is like a barrel *spiral galaxy*, about two hundred thousand light-years across and thousand light years height. A light year is the distance travelled by light in a year. The speed of light is $3\text{x}10^5$ km/s. So, the light year is $3 \times 10^5 \times 365 \times 24 \times 60 \times 60$ is approximately $9.46 \times 10^{12}$ km.

Earth's solar system is located quite far down on the disc. The size of the Milky Way galaxy can easily be visualized: the Sun's light takes 26,080 years to reach the center of the galaxy whereas it takes only eight minutes to reach the Earth.

There are several stars in the Milky Way galaxy and we are particular about one star called the Sun, which we say is the solar system with which we are concerned. Our solar system consists of our star, the Sun, and everything bound to it by gravity the planets – Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune, dwarf planets such as Pluto, dozens of moons and millions of asteroids, comets and meteoroids. Moons are objects moving around the planets. Earth has got one moon.

All planets move around the sun in elliptical orbits and in the same direction. All nine planets orbit around the sun on nearly the same plane, except dwarf Pluto, but at different distances from the Sun. The dwarf Pluto planet's orbit is highly inclined. The four inner planets Mercury, Venus, Earth, and Mars are relatively small dense bodies known as terrestrial planets. The planets Jupiter, Saturn, Uranus, and Neptune are called the giant planets and are principally composed of gases with solid ice and rock cores at unknown depths. Humankind's dream to discover a multitude of planets which are comparable to Earth and which could sustain human life depends on exploration of the solar system, development of foolproof means of travel and communication methods of interplanetary and intergalactic space.

## 1.4 PROPULSION

The word Propulsion has come from the Greek word Propellerie, meaning '*pushing forward'*. Space propulsion means pushing forward in space. To move from one place to another, the space vehicle must be accelerated i.e., it gathers incremental velocity (change in velocity $\Delta U$) during the travel. To impart acceleration to the vehicle, a propulsive device is required. One way to give the propulsive force is an internally driven engine, i.e., the propellants are combusted by some means internally within the vehicle and then accelerated to produce a reaction force. This is how conventional rockets work. In gunnery, the energy of the cannonball is given externally to it in the barrel of the gun by the explosion of the gunpowder and expansion of the hot gasses. But, once the ball leaves the barrel, due to air friction or drag, continuously its velocity decreases. On the other hand, the rocket accelerates due to continuous propulsive force. The cannonball is classified as a projectile and the rocket as a vehicle.

Both rockets and jet engines operate on the principle of action and reaction, Newton's third law of mechanics, and achieve the thrust by expanding exhaust gases generated due to burning of fuel and oxygen mixture. The main difference between them is that a jet engine gets the oxygen it needs for combustion from the outside atmosphere whereas a rocket carries its own oxygen source. A jet engine, therefore, can operate only within the earth's atmosphere but a rocket engine can operate anywhere, even in vacuum.

There is a difference between a rocket and a missile. A missile is a powered vehicle designed to carry explosives to a target The guided missile can change its direction by internal or external command at any time during its flight. A ballistic missile is powered and guided during the first part of its flight only, afterwards it proceeds like a projectile or thrown object, without power or guidance. Missiles are rocket engine powered and there is a tendency to call them all rockets. The rockets, we refer, are principally the engines that propel the vehicle into space.

A rocket is basically a thermodynamic system. It converts heat generated through chemical reaction of oxidizer and fuel (propellants) into kinetic energy using a device called nozzle. These propellants can be solid or liquid or gaseous. There are also monopropellant engines which use a catalyzer to decompose and start the reaction. Different propulsion systems generate thrust in different ways, but always through application of Newton's third law of motion. Chemical rocket engines generate a wide range of thrust ranging from a few newtons to millions of newtons. As of present technology levels, these are only powerful enough to use in launch vehicles i.e., to lift the spacecraft from Earth's surface to space i.e., to overcome Earth's gravitational force.

There are two general measures of performance of a rocket engine: (1) the amount of thrust, which determines the amount of propellant ejected or in other words the speed of the rocket that must be used to accomplish a given task, and (2) the fixed weight of the engine including the necessary tankage, power supply, and structure. The propulsion systems that reduce the need of the propellant making the spacecraft lighter or increase the speed of the propellant ejection are considered as advanced propulsion. Long-term, deep-space missions with significant payloads have a critical need for these advanced propulsion systems.

For a space mission, the trajectory analysis provides the required thrust and velocity change $\Delta U$. Other important factors are gravity assists, initial transfer orbit, spacecraft mass and duration of the flight to complete the mission. A manned flight, say to Mars, requires faster transfer time to avoid space travel fatigue and stress. For such missions some key constraints like psychological, safety, and radiation dose are strictly linked to the problem of time. For such flights the selected trajectory is the shortest and the propulsion unit is capable of providing high change in velocity and high thrust. On the other hand, unmanned missions may use a longer duration involving gravity assists and a much less powerful propulsion system.

Electric propulsion (EP) encompasses any propulsion technology in which electrical power is used to generate propellant exhaust velocity. Electric propulsion provides high exhaust velocities that in turn results in reduction of propellant requirement for a given space mission compared to conventional propulsion systems. The reduction in propellant mass can significantly decrease the launch mass of a spacecraft, leading to lower costs from the use of smaller launch vehicles. Electric thrusters use the same basic principle as chemical rockets, i.e., accelerating propellant mass and ejecting it from the vehicle. The ejected mass from electric thrusters, however, is primarily in the form of energetic charged particles. Electric thrusters operate in the power range of hundreds of watts up to tens of kilowatts with very high specific impulse (specific impulse is simply the thrust of the rocket, divided by the mass flow of propellant) of 1000s to 10,000s. The thrust levels are typically of some fraction of a newton. Ion and Hall thrusters generally use heavy inert gases such as xenon as the propellant.

The first extensive application of electric propulsion was by Russia using Hall thrusters for station keeping on communications satellites. Electric propulsion use in spacecraft has grown steadily and advanced electric thrusters have found applications, as an attractive alternative to chemical thrusters, for station-keeping, orbit insertion and communications satellites. The exhaust velocity of chemical rockets is limited by the energy contained in the chemical bonds of the propellant used and of typical values are up to 4 km/s. In electric thrusters, the energy source is power supply, separated from propellant and thus are not subject to the same limitations.

The function of the propulsion system is to produce thrust, which is the force that moves a rocket through air and space. In the space age, spacecrafts are the key to explore space, to conduct experiments in space to understand nature, to place scientific and commercial satellites and to make space travel as a commercial venture. The propulsion system used in rocketry can be categorized into two different types:

**Primary Propulsion:** Used to launch rockets from Earth surface.

**Secondary or Auxiliary Propulsion:** propulsion systems used in spacecraft to propel in space, e.g., satellites and control systems like attitude and guidance units.

Thousands of satellites orbiting the Earth form the backbone of the present communication system. Many countries’, like United States, Russia, Europe, China, Japan, India and South

Korea, projections in space programs include to achieve before 2030: manned missions to secure a foothold on the Moon, landing humans on Mars, reaching and intercepting asteroids that might threaten our planet and accomplishing missions to Jupiter and other interplanetary travels. Space launch vehicles, using primary propulsion, must be capable of reaching transfer orbits and detaching the spacecraft, which, driven by secondary propulsion systems with high energy levels, will continue until the destination. An orbit is a path in which a body moves in relation to its source of gravity. A satellite or an interplanetary spacecraft can achieve the designed orbit by launching directly from the Earth's surface or launching from an initial orbit. The major difference is the thrust requirements. An interplanetary trip starting from the initial orbit at low Earth level needs much less power. The thrust required for launching a vehicle from Earth's surface to overcome gravity force will be of the order of Kilonewtons to meganewtons. The thrust requirement for spacecraft to propel in space requires a few hundreds of newtons only.

*The thrust requirements in reducing order for operation of spacecraft as follows*:

- final orbit acquisition from the initial orbit established by the launch vehicle,
- station-keeping and orbit control,
- attitude control (also called as Reaction controlled system, RCS)

*Orbit changes* include transferring a spacecraft to a desired orbit, plane changes, orbit injection and de-orbit.

*Orbit Maintenance or Station Keeping* requires keeping a spacecraft in the desired mission orbit compensating the disturbing forces like drag, solar wind and gravitational forces**.**

*Attitude control (RCS)* is required to change the attitude, that is changing the orientation of a spacecraft to the desired direction and keeping it in desired direction by compensating for disturbing torques.

## 1.5 PROPULSION REGIONS AND PROPULSION TECHNOLOGIES

Depending on the sphere of usage and scope of use, the space propulsion can be divided into three different categories as shown in Figure 1.2:

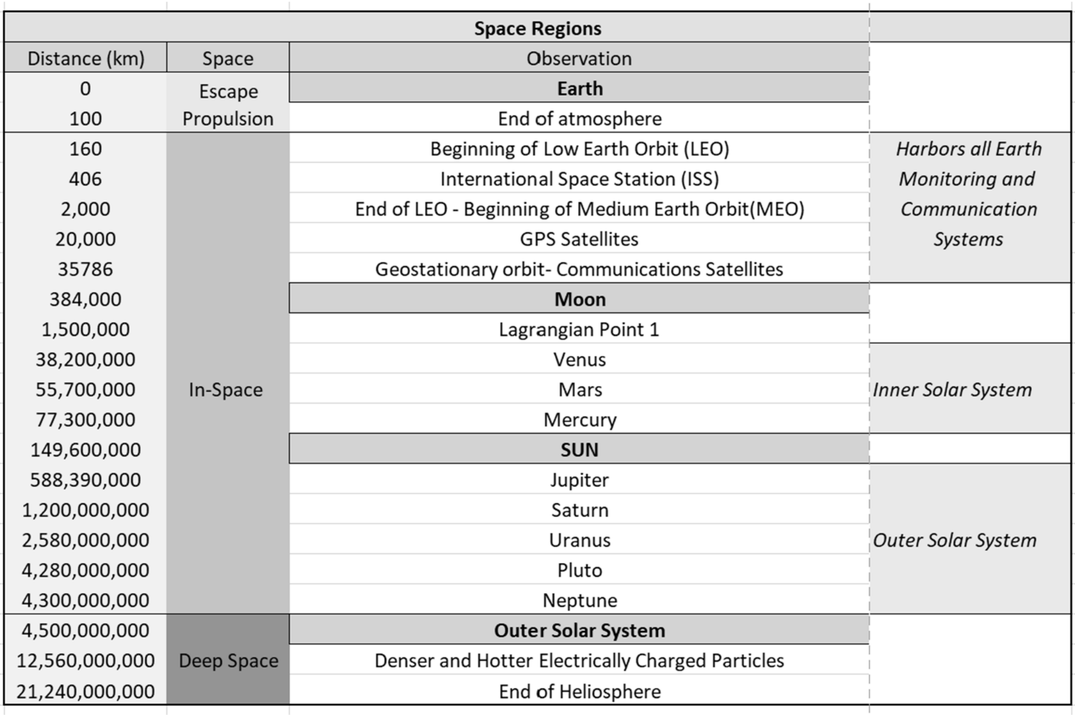
(a) *Escape propulsion – Earth to orbit*: Thrust is required to overcome the gravitational and drag forces to place the spacecraft in orbit

(b) *In-space propulsion*: Thrust requirements to achieve orbital movements, maintaining the orbit and travel from an orbit to outer space

(c) *Deep space Propulsion*: Thrust requirement to travel intergalactic space

The spacecraft launch vehicle should overcome the drag force and Earth gravitational force to escape into space. The Earth monitoring and communication satellites are placed in the in-space starting at 160 km, the start of low earth orbit (LEO), to around 35,000 km, geostationary earth orbit. The medium Earth orbit (MEO) starts around 2000 km and ends below 35000 km. The International Space Station (ISS) is at an orbit of 330 to 410 km. The Lagrangian Point, i.e., where gravitational effects of Earth and Sun balance out is at 1,500,000 km. The Moon is at 384,000 km. Between the Earth and Sun we have planets Venus, Mars and Mercury known as inner planets. In the outer solar system, i.e., after Earth we have Jupiter, Saturn, Uranus etc.

Human exploration beyond Earth to destinations such as the Moon, Mars or Near-Earth Objects, are daunting unless more efficient space propulsion technologies are developed and fielded. There is no single propulsion technology for space use that fits all space missions and mission types, and varies widely according to their intended applications. Selection of technology for in-space propulsion depends on thrust level requirement, specific impulse ($I_{sp}$), power, specific mass (or specific power), volume, system mass, system complexity, previous experience in other spacecraft systems, durability and cost.



| Space Regions | | | |
|---|---|---|---|
| Distance (km) | Space | Observation | |
| 0 | Escape Propulsion | **Earth** | |
| 100 | | End of atmosphere | |
| 160 | In-Space | Beginning of Low Earth Orbit (LEO) | *Harbors all Earth Monitoring and Communication Systems* |
| 406 | | International Space Station (ISS) | |
| 2,000 | | End of LEO - Beginning of Medium Earth Orbit(MEO) | |
| 20,000 | | GPS Satellites | |
| 35786 | | Geostationary orbit- Communications Satellites | |
| 384,000 | | **Moon** | |
| 1,500,000 | | Lagrangian Point 1 | |
| 38,200,000 | | Venus | *Inner Solar System* |
| 55,700,000 | | Mars | |
| 77,300,000 | | Mercury | |
| 149,600,000 | | **SUN** | |
| 588,390,000 | | Jupiter | *Outer Solar System* |
| 1,200,000,000 | | Saturn | |
| 2,580,000,000 | | Uranus | |
| 4,280,000,000 | | Pluto | |
| 4,300,000,000 | | Neptune | |
| 4,500,000,000 | Deep Space | **Outer Solar System** | |
| 12,560,000,000 | | Denser and Hotter Electrically Charged Particles | |
| 21,240,000,000 | | End of Heliosphere | |

**Figure 1.2** Space regions.

The launch vehicle propulsion system performs the function of primary propulsion to lift the payload from Earth surface following the designed trajectory, reaction control, placing the payload in the initial designed orbit, station keeping and orbital maneuvering. From there the space propulsion begins, the main engines used in space provide the primary propulsive force for orbit transfer, planetary trajectories and extra planetary landing and ascent. The auxiliary propulsion systems provide propulsive force to the reaction control and orbital maneuvering systems for orbit maintenance, position control, station keeping, and spacecraft attitude control.

Space exploration requires safe travel in space, arriving quickly to mission targeted places, and transporting maximum mass with low cost. Based on the physics of the propulsion system and how it derives thrust, space propulsion technologies can be classified into three basic types:

(1) Chemical Propulsion, (2) Non-Chemical or Electric Space Propulsion (3) Advanced Propulsion. Figure 1.3 shows the basic propulsion types and their sub classification.

The launch vehicle (rocket) propulsion is generally based on chemical propulsion and the technology is highly matured. Thrust-to-weight ratios greater than unity are required to launch from the surface of the Earth, and chemical propulsion is currently the only flight-qualified propulsion technology capable of producing the magnitude of thrust necessary to overcome Earth's gravity. There are significant technology advancements of in-space propulsion. Once in space, higher specific impulse propulsion systems can be used to reduce total mission propellant mass requirements. Electric propulsion is commonly used for station keeping on commercial communications satellites and for prime propulsion on some scientific missions, robotic deep-space exploration to space stations and human missions to Mars.

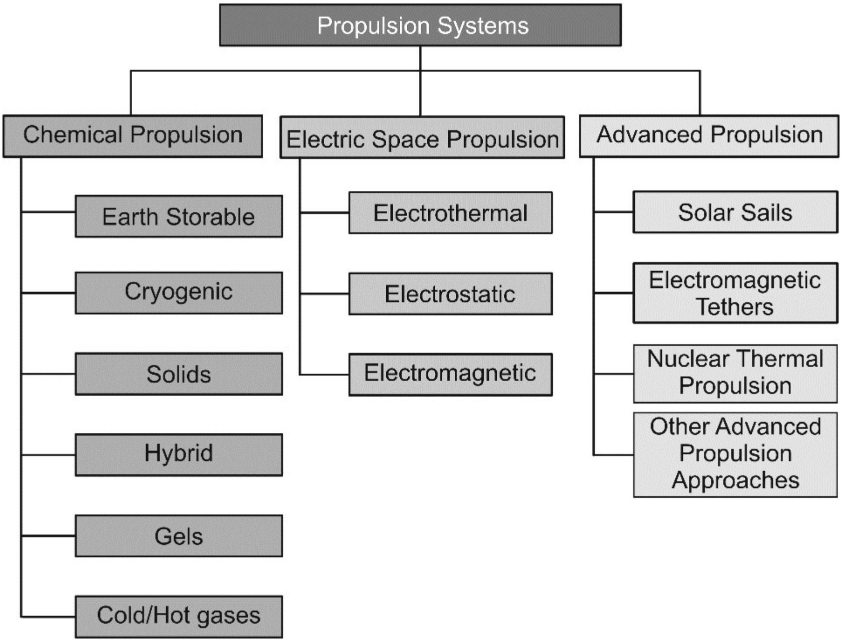


**Figure 1.3** Space Propulsion Technologies.

### 1.5.1 Chemical Propulsion

It includes systems that operate through chemical reactions that produce hot gasses and expand or use a fluid dynamic expansion as in a cold gas to provide thrust.

1. *Earth Storable*: Earth storable propellants remain stable over a range of Earth terrestrial pressures and temperatures and can be stored in a closed vessel for long periods of time.

   *Examples*: Kerosene, Hydrazine, Monomethyl hydrazine, Nitrogen tetroxide, Mixed oxides of nitrogen, Hydroxylammonium nitrate (HAN)-based propellants.

2. *Cryogenic*: Propellants that are liquefied gases at low temperatures. These systems provide high performance, but can present storage and handling challenges to prevent vaporization losses.

   *Examples*: Liquid oxygen (LOX), Liquid hydrogen ($LH_2$)

3. *Solid*: Solid propellants are pre-mixed oxidizers and fuels that are then cast into a particular shape. When ignited the surface area burns at a predetermined and tailored burn rate to generate the thrust and duration required for the mission.

   *Examples*: Polybutadiene Acrylic Acid Acrylonitrile (PBAN), Hydroxyl Terminated Polybutadiene (HTPB).

4. *Hybrid*: Hybrid rockets utilize a solid fuel and liquid oxidizer. They are also less complex and cheaper than liquid rockets.

   *Examples*: Acrylonitrile butadiene styrene thermoplastic, Paraffin-based fuels

5. *Gels*: Gelled and metallized fuels are a class of thixotropic (shear-thinning) fuels that improve the performance of rocket and air-breathing systems.

   *Examples*: Gelled oxygen ($O_2$)/hydrogen ($H_2$), Gelled MMH/IRFNA propellants, Nano Gelled propellants

6. *Cold Gas/Warm Gas*: Gas propulsion systems are typically used for small rocket engines or when small total impulse is required.

## 1.5.2 Electric Space Propulsion

Electric energy is converted to interact with and accelerate a reaction mass (e.g., Propellant) to generate thrust.

1. *Electrothermal*: The propellant is heated and expanded through a nozzle.

   *Example*: Resisto jet, Arc jet

2. Electrostatic: This area covers electric propulsion systems that use electrostatic fields to ionize and accelerate a propellant.

   *Examples*: Ion engines, Hall thrusters, Electrospray propulsion

3. *Electromagnetic*: The electromagnetic fields interact with a reaction propellant to generate thrust.

   *Example*: Pulsed inductive thruster, Magneto plasma dynamic (MPD) thruster

### 1.5.3 Advanced Propulsion

This area includes propellant-less and emerging technologies and physics concepts.

1. *Solar Sails*: Sail propulsion uses lightweight structures with a large surface area to produce thrust by reflecting solar photons or atmospheric molecules (drag), thereby transferring much of their momentum to the sail.
2. *Electromagnetic Tethers*: They are long, lightweight cables that produce thrust through the Lorentz force by carrying electrical current and interacting with a planetary magnetosphere.

3. *Nuclear Thermal Propulsion*: The engine uses a fission reactor (solid, liquid or gas) to heat a large mass flow of propellant to extremely high temperatures for high specific impulse at high thrust.
4. *Other Advanced Propulsion Approaches*: These advanced propulsion technologies include Beamed energy, Fusion Propulsion and Advanced Fission technologies and are in a research stage that could result in breakthroughs for future space missions. Other technologies like High Energy-density Materials and Antimatter propulsion are physics concepts that are actively under consideration for advancement of propulsion technologies.

Beamed energy propulsion uses laser or microwave energy from a ground- or space-based energy source and beams it to an orbital vehicle, which uses it to heat a propellant or reflected photon momentum exchange. Advanced fission and Fusion propulsion systems produce energy required by using the thermal/ kinetic energy resulting from the reactions to accelerate a propellant.

The aim of the book is to provide the reader with knowledge to better understand the fundamental concepts of propulsion technologies for design, analysis and programming of rocket and spacecraft propulsion systems. The book covers the syllabus of undergraduate and postgraduate engineering students of most of the universities. practicing professionals would find the book helpful for solving specific problems related to rocket propulsion systems. The approach and explanation with worked examples provide a comprehensive capability to the reader to conduct an initial design and sizing of propulsion devices. Chapter 2 deals with the basic laws and relations for the objects to propel into different orbits or escape from the planet. Chapter 3 provides the understanding of rocket propulsion and derivation of the fundamental rocket equation. It explains the basic importance of staging in the design of launch vehicles. The compressible flow expansion of high temperature and pressure gases through rocket nozzle is explained from fundamentals and derived various relations useful for the estimation of performance in chapter 4. In chapter 5 chemical propellants used in rocket engines, their properties, performance and thermodynamic procedures for estimation of energy release are discussed. Chapters 6, 7 and 8 provide in-depth discussion of solid, liquid, and hybrid rocket propulsion systems. The merits and limitations of the different systems are included in these chapters. The solid rocket motor (SRM), covering all aspects of design and development are included in chapter 6. Chapter 10 provides an overview of the complex topic of combustion instability that occurs due to intensive energy release rates in the thrust chamber and the dynamics of interactions of the different subsystems of a rocket. The mitigation techniques and use of devices to control the instabilities are presented. Chapter 11 and 12 deals with various orbit maneuvering techniques and interplanetary trajectories. These chapters provide the methods to estimate propellant requirements of spacecraft propulsion. Chapter 13 discusses chemical propulsion systems used in spacecraft and their merits and demerits. The final chapter 14 of the book discusses the different electric propulsion systems used in spacecraft.