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Excerpt
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CHAPTER 1 CLASSIFICATION OF ROCKET PROPULSION SYSTEMS AND HISTORICAL PERSPECTIVE

1.1 INTRODUCTION

This text is intended to provide undergraduate and first-year graduate students with an introduction to the principles governing the design and performance of rocket propulsion systems. Readers of the text are expected to have a good working knowledge of thermodynamics and the principles of fluid flow in addition to a background in chemistry at least to the college freshman level. Fundamentally, the text has been developed as a compilation of resources from two courses offered at Purdue University: AAE439, *Rocket Propulsion* and AAE539, *Advanced Rocket Propulsion*. The former course is taught at the Senior level, while the latter is targeted to Seniors and first-year graduate students. The primary emphasis of the text is placed in the area of chemical rocket propulsion systems, the realm that includes solid rocket motors, liquid rocket propulsion devices, and hybrid systems that utilize one liquid propellant and one solid propellant. Electric and nuclear propulsion devices are not discussed in detail, but are highlighted briefly within this chapter to place them within the broad context of existing or future rocket propulsion devices. Specifically, this book places emphasis on the propellant systems, combustion processes, and thermodynamic and fluid flow processes occurring within the rocket combustion chamber and nozzle. In addition, overall system sizing is presented as well as the interaction of propulsion system performance with vehicle trajectory calculations. Control and structural aspects of a rocket are not considered in detail in this course, but structural issues and sizing considerations are discussed at a mainly conceptual level.

In this introductory chapter, we will briefly discuss the history of rocketry and will introduce the various types of rocket propulsion systems in use today.

1.2 A BRIEF HISTORY OF ROCKETRY

It would be difficult to envision a student who has absolutely no exposure to the world of rockets since we are clearly living in the "space age" with literally hundreds of space flights and missile firings occurring during the year. While we all have some sense of the current state of affairs, it is useful to take a brief look into the past to understand how we managed to end up in the state we see today. The field of rocketry has a rich and storied history, and there are a number of good resources

Figure 1.1 Photo/sketch of Chinese "fire arrow" battery dating to the thirteenth century. We can only imagine the hazards faced by those who were asked to ignite such a system (Source: Wikipedia).

for those interested in gaining additional background in this subject area. Many of these resources are listed in the further reading section of this chapter, so in the interest of brevity only a brief compendium will be provided here.

The earliest rockets date back as far as the tenth century Chinese "fire arrows," which were similar to the fireworks we observe today in the USA on July 4 (or other suitable celebration) with the exception that they were mounted on an arrow. By the thirteenth century, the Chinese had developed sizable rocket batteries for use against enemies. These rockets utilized a solid propellant, which was essentially gunpowder, and were launched as unguided projectiles against the enemy (see Figure 1.1).

Rockets similar to these were used in various civilizations through the ages; in fact every major nation in Europe had rocket brigades by the nineteenth century. The British contribution here was designed by Sir William Congreve and hence dubbed the Congreve rocket. Congreve rockets were developed in a variety of sizes ranging from 6 to 300 lb and were employed in the Napoleonic Wars and the War of 1812. Unguided rockets used extensively in the early 1800s. During the Civil War, both the Union and Confederate Armies worked to develop rockets to use against the opposing forces. There are accounts that the Confederate army built a 12-foot tall rocket and launched the device towards Washington DC. The missile quickly ascended out of sight and the impact point was never recorded.

In the context of today's systems, all these devices would be characterized as military weapons and unguided missiles. Beginning in the late 1800s, another group of individuals began to gain some attention from their developments. These pioneers, whose inspiration was drawn from science fiction works such as those of H. G. Wells and Jules Verne (Wells wrote *The War of the Worlds* in 1898 and Verne wrote *From the Earth to the Moon* in 1863), dreamt of sending humans into space. Today, we regard three of these individuals: Konstantin Tsiolkovsky, Herman Obert, and Dr. Robert Goddard as "Fathers of Modern Rocketry."

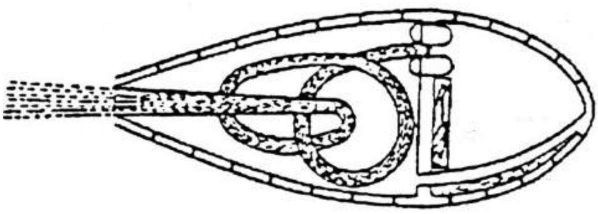

Figure 1.2 Early rocket/spaceship design (1903) of Tsiolkovsky using a circuitous delivery system to the combustion chamber. The overall shape of the rocket is quite similar to those shown in Jules Verne's books (Source: nasaimages.org).

Tsiolkovsky (also spelled Tsiolkovskii) was a Russian schoolteacher and mathematician who developed much of the theory for the requirements for orbiting the Earth and pursuing spaceflight. He is credited with derivation of what we call "The Rocket Equation" or "The Tsiolkovsky Equation," which relates a rocket's speed to its mass properties and fuel efficiency (see Chapter 3) and was one of the first to suggest the development of liquid propellant systems and propellants such as liquid oxygen and liquid hydrogen for spaceflight. He also is credited with discovering the advantages of using multiple stages for increasing rocket performance. Figure 1.2 shows the design of one of his liquid rocket propulsion devices – a far cry from today's engines with the circuitous path to the combustion chamber and the absence of a throated nozzle. In 1935, he published *Na Lune* (*On the Moon*); a copy of the cover from this book is shown in Figure 1.3. (For more about the history of rocket propulsion, see Smith, 2014.)

Ask a German or Romanian about the father of modern rocketry, and you will likely hear the name "Herman Oberth" in response. Herman Oberth was a Romanian-born scientist who studied medicine and physics, spent much of his life in Munich and was inspired by Verne's works even as a teenager. His doctoral dissertation, *Wege zur Raumschiffahrt* ("Ways to Spaceflight") was initially rejected as being too far-flung but this setback did not deter Oberth from publishing his works.[1] Oberth's 1923 book, *The Rocket into Planetary Space*, contained detailed accounts of many aspects required for such a mission (see also Oberth, 1972). Figure 1.4 provides a photo of the author. This work served as a particular inspiration for an energetic and passionate teenager by the name of Werner von Braun. Von Braun eventually came to work with Oberth for a period of time at the Technical University of Berlin. While mainly a theoretician, Oberth worked on numerous development programs during his long career and eventually came to work with his former student, Dr. Werner von Braun, in Huntsville, Alabama after World War II.

In America, Dr. Robert Goddard is acknowledged as the father of modern rocketry due to his extensive testing of solid and liquid propellant rockets between 1915 and 1941. While Tsiolkovsky and Oberth are generally known for their theoretical contributions, Dr. Goddard

[1] He eventually was granted his Doctoral degree for this work by the Romanian Babes-Bolyai University.

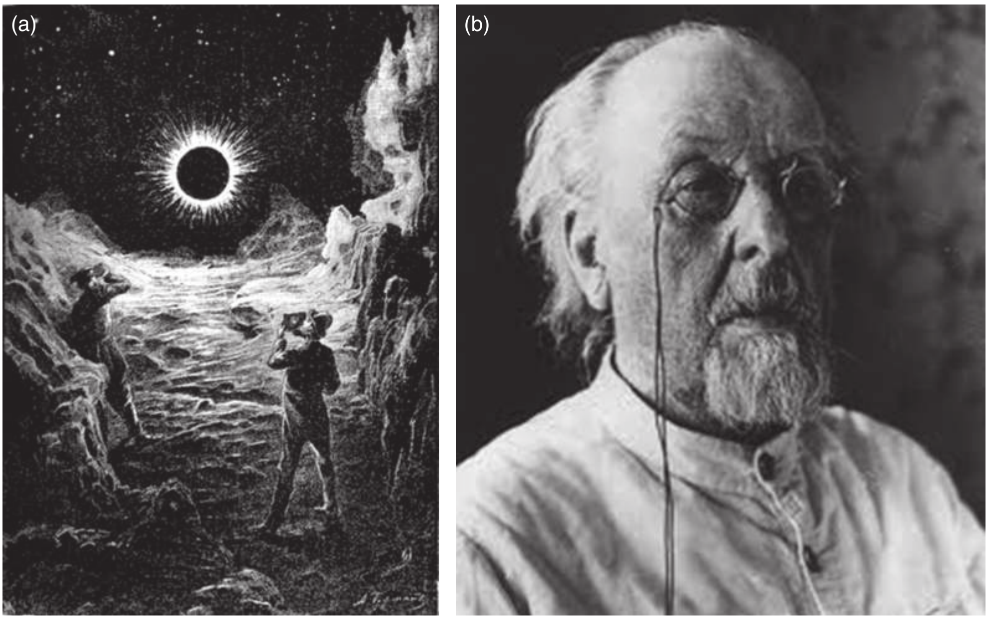

Figure 1.3 (a) The cover of Tsiolkovsky's book *Na Lune* (1935). Note that he hadn't considered the lack of a lunar atmosphere in his research. (b) Konstantin Tsiolkovsky (Source: en.wikipedia.org).

Figure 1.4 Dr. Herman Oberth (Source: NASA).

had a strong experimental component to his studies. A graduate of Clark University, he performed much of his research as a physics professor within this institution and conducted extensive testing of solid and liquid propellant rockets between. Like Tsiolkovsky, he recognized the potential for liquid propellants and worked to develop and fly the first liquid propellant rocket in 1926. He is also credited with the first patent on multi-stage rockets, for the use of jet vanes and gimballing systems for guidance and control, and for proving that rockets can provide thrust in a vacuum. This latter proof resulted from a famous exchange that Dr. Goddard had with the *New York Times*. In a reaction to Goddard's now famous paper, "A Method of Reaching Extreme Altitudes," the *Times* published an editorial berating the work and the notion that rockets could successfully provide thrust in a vacuum (see Goddard, 1919). Goddard devised an experiment using a .22 caliber revolver that was mounted on a turntable and placed in a vacuum bell jar. A blank cartridge was loaded into the gun and once a vacuum was established, he fired the gun. The impulse generated caused the table/gun pair to rotate, thereby proving his point. The *New York Times* eventually published a retraction on July 17, 1969, three days before Neil Armstrong set foot on the surface of the moon for the first time.

Figure 1.5 provides a scale drawing of the 1926 Model A rocket that utilized liquid oxygen (LOX) and gasoline propellants. The interesting arrangement, with tankage placed below the thrust chamber, was undoubtedly employed by Goddard to enhance vehicle stability. The arrangement has generated substantial debate on modern websites. If the rocket was rigid with a thrust that did not gimbal, the fact that the thrust center lies above the center of mass is insufficient to guarantee stability. However, the flexibility of the long structure that supports the engine and feed plumbing plays a role in providing a pseudo-gimbal for the thruster, thereby aiding overall stability of the system.

While Oberth, Goddard, and Tsiolkovsky proposed peaceful uses for rocket-propelled vehicles, as World War II approached it became clear that the military establishment also had a great deal of interest in these devices. While we mentioned that virtually all the world's powers possessed rocket-propelled weapons well before this time, it was the advent of inertial guidance systems that really opened a new realm of rocketry.

The Germans were the first to incorporate this innovation into a long-range rocket, the V-2. The V-2 was clearly the most advanced rocket in the world at the time it was built and was an amazing achievement considering the technologies available at the time. It was over 46 feet (14 m) tall, weighed 27,000 pounds (12,250 kg), and had a range of 200 miles (320 km) with a payload of 2000 pounds (900 kg) (see Figure 1.6). The famous German scientist, Dr. Werner Von Braun, was instrumental in the development of the V-2. The missile incorporated two gyroscopes and an integrating gyro-accelerometer in its revolutionary guidance system, and utilized LOX and alcohol as propellants.

The V-2 rocket served as a basis for both American and Russian missile designs after the war. The German scientists involved in the rocket program at the famed Peenemunde, Germany site on the Baltic Sea aided in Russian, American, and British developments. Most notably, Dr. Von

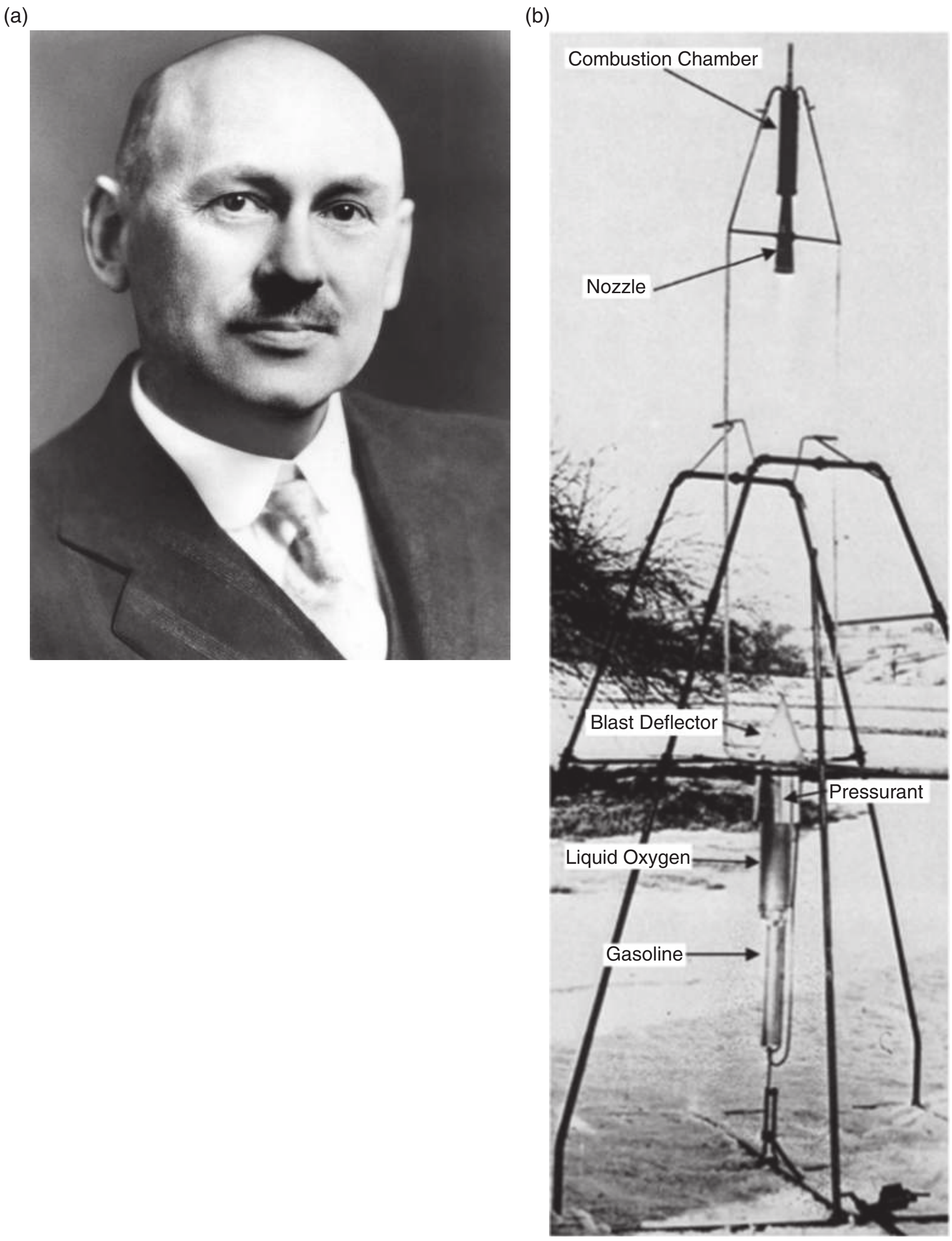

Figure 1.5 (a) Dr. Robert Goddard and (b) his Model A Rocket. Note that he placed the combustion chamber above the propellant tanks in order to maintain stability with the rocket's center of gravity below its center of thrust.

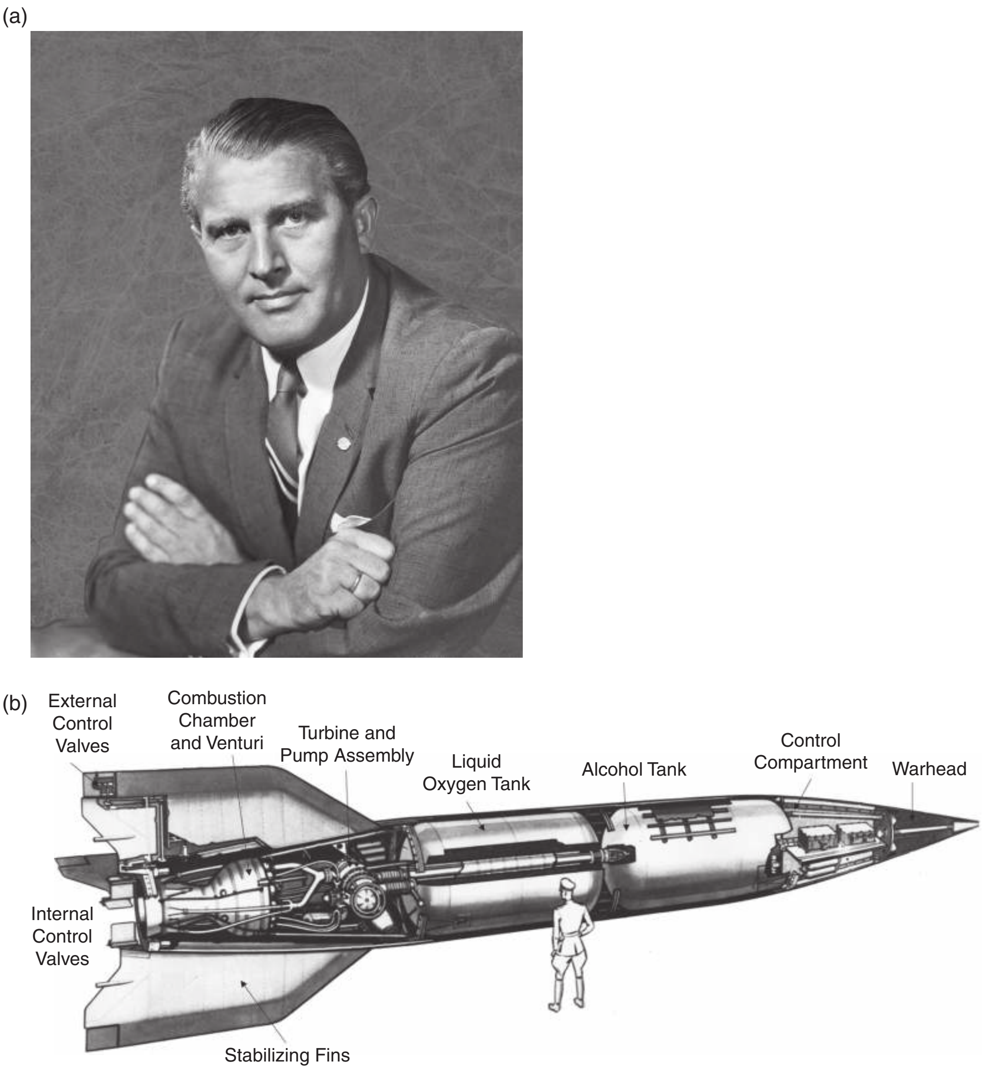

Figure 1.6 (a) Dr. Werner Von Braun. (b) The German V-2 rocket (Source: www.nationalmuseum.af.mil/).

Braun came to the United States and eventually became the director of NASA's Marshall Space Flight Center. Dr. Von Braun was an instrumental part of the Apollo program, which eventually put men on the moon.

In spite of the end of World War II, military applications still ushered in most of the rocket developments of the 1940s and 1950s. In the mid 1950s the cold war was in full swing and both Russia and America raced to develop intercontinental ballistic missiles (ICBMs) with nuclear capabilities. Out of these efforts came the US ballistic missile fleet summarized in Table 1.1.

Table 1.1 Early US ballistic missiles

Missile, program start date	Propulsion system	Range (miles)
Atlas-A, 1954	LOX-kerosene	2,500
Titan I, 1954	LOX-kerosene	6,000
Titan II, 1955	N_2O_4-aerozine 50*	7,000
Polaris, 1957	Solid propellant	1,400
Thor/Delta, 1957	LOX-kerosene	1,600
Minuteman I, 1957	Solid [ropellant	6,500

* Aerozine 50 is a blend of monomethyl hydrazine and unsymmetrical dimethyl hydrazine.

To say that rocket developments were occurring at a frenzied state in the late 1950s is an understatement. As Table 1.1 demonstrates, six separate ICBM/SLBM programs were initiated over a three-year period with missiles going through design and development in a matter of months. The Atlas, Titan, and Thor/Delta (now known as Delta) rockets have evolved to the backbone of the US unmanned launch vehicle force we have today. This fact highlights the importance of the military in developing viable rocket-propelled vehicles.

It is also worth noting that parallel development of a number of rocket-assisted takeoff, or more commonly called jet-assisted takeoff (JATO), devices were in development to provide augmented thrust for aircraft sporting the new gas turbine/jet engines in development at the time. While the jet engines provided the aircraft the ability to attain higher speeds, early models lacked sufficient takeoff thrust to lift a fully laden aircraft, and numerous rocket systems were built to provide thrust augmentation during this time. While some of these systems used cryogenic liquid oxygen, non-cryogenic oxidizers such as nitric acid and variants red-fuming and white-fuming nitric acid were developed for these applications.

The Soviets were certainly not standing still while the US was feverishly working on several types of rockets. In fact, much of the vigor within the US industry was aimed at “catching up” with the Russians in large rocket technology. The true evidence of the success of the Soviet space program occurred on October 4, 1957 when a modified SS-6 ICBM launched a small satellite called “Sputnik” into orbit around the Earth. On this day, the space age was born. The US response wasn’t far behind; on January 31, 1958 Explorer 1 was placed into orbit using a Juno launcher.

In April 1958, President Eisenhower signed a declaration creating the National Aeronautics and Space Administration (NASA), and the civilian space program was born. Since derivatives of ICBMs did not promise enough capability for manned missions beyond low Earth orbit, NASA embarked on the development of the Saturn family of vehicles which culminated in the creation of the gigantic Saturn V used for the Apollo lunar missions. As most of you probably know, the Saturn V enabled Neil Armstrong to take the first steps on the surface of the moon on the evening of July 20, 1969.

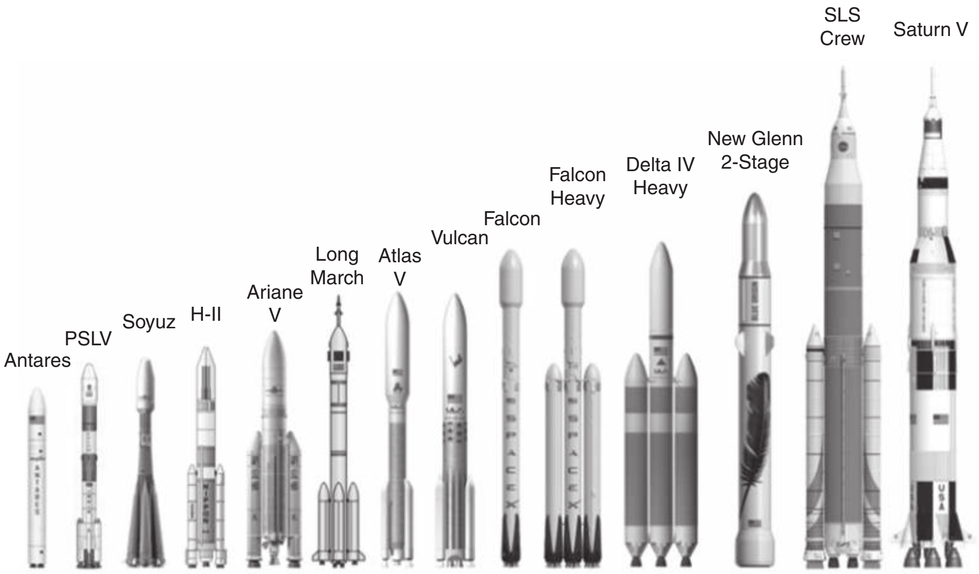

Figure 1.7 Comparison of launch vehicles from around the world (Source: Blue Origin).

Figure 1.7 describes much of the current landscape in terms of vehicles that are actively flying or in major development. The famed Saturn V lunar launch vehicle, which stood 363 feet (111 m) tall is also shown as a basis of comparison. The payload of the vehicle is defined as the useful mass that is delivered to low Earth orbit (LEO) and this ranges from roughly 1 metric ton for the smallest vehicles shown to over 140 metric tons for the Saturn V. The gross liftoff weight (GLOW) of this compilation ranges from 300 to 3000 metric tons. Dividing these two numbers (payload mass/GLOW) gives the payload fraction for the vehicle and we can see that it is a small number typically less than 2%. It is an unfortunate consequence that the energy level of propellants we have available (I_{sp} as defined in Eq. 1.1 below) and the tremendous gravity well represented by the Earth creates a situation where we must use very large devices to place relatively small devices in orbit. In Chapters 2 and 3 we explain the physics leading to this conclusion.

Many of the vehicles employ *strap-on boosters* that utilize either solid rocket motor or liquid rocket engines to augment first stage thrust. The strap-on systems typically burn for about 1–2 minutes during the ascent, then are jettisoned from the main vehicle as it climbs to higher altitudes. All of the rockets utilize multiple *stages* in order to deliver payloads into low earth orbit and beyond. By jettisoning some of the structural mass part way through the mission, we can reduce the overall size of the vehicle since the dropped mass need not be accelerated to the highest velocities required for orbit. In Chapters 2 and 3 we investigate the issue of staging and its benefits in reducing overall vehicle size. The compilation in Figure 1.7 is by no means exhaustive and interested readers are referred to a wealth of online information as well as to *International Reference Guide to Launch Systems* by Isakowitz *et al*. (2004).

1.3 Classification of Rocket Propulsion Systems

As with any product, it is desirable to develop measures of "goodness" that can be used to compare various alternatives. In order to classify the various rocket propulsion systems in terms of a general performance parameter, we first need to define this parameter in terms of known quantities. Probably the best-known parameter used to describe the performance of rocket propulsion systems is its *specific impulse* or I_{sp}. A rocket's specific impulse is simply the current thrust of the rocket, divided by the mass flow (or weight-flow) of propellant gases currently exiting the nozzle:

$$I_{sp} = F/\dot{m} = \text{specific impulse (s or N-s/kg)} \tag{1.1}$$

In general, rockets types are quite cavalier with units, especially when using the English measurement system. Formally, I_{sp} should be reported in units of lbf/(slug/s) or lbf/(lbm/s), but generally propulsion folks report the flow rate in terms of weight-flow such that the resultant units are lbf/(lbf/s) = seconds. In SI units, the proper measure is N-s/kg, but if weight-flow is used instead of mass flow the units of seconds are once again obtained. From a practical standpoint, we determine masses by weighing things on the surface of the Earth, and it is this notion that has driven the community to adopt this convention for reporting I_{sp}.

The specific impulse of a rocket is a measure of its propellant usage efficiency since it measures the flow rate required to attain a given thrust level. The system I_{sp} is a measure of the energy of the propellant chosen as well as the specific nozzle selected. We can see where the term specific impulse comes from if we define the total impulse as the thrust integrated over the rocket's burn time (t_b):

$$I = \text{total impulse} = \int_0^{t_b} F \, dt = F t_b \quad \text{for } F = \text{constant} \tag{1.2}$$

Substituting Eq. 1.2 into 1.1 assuming that I_{sp} is constant gives:

$$I = I_{sp} \int_0^{t_b} \dot{m} \, dt = I_{sp} \, m_p \tag{1.3}$$

where m_p is the total propellant mass (weight) consumed during the firing. If we solve Eq. 1.3 for I_{sp} we see that this quantity is the amount of impulse obtained from a unit mass of propellant, hence the term "specific impulse."

For aerospace systems, or anything that we have to lift, the weight is always a critical parameter. Having a high I_{sp} is great, but if the system that provides such performance is very heavy, it will not be a good performer when compared against other alternatives. Typically, the weight or structural efficiency of a rocket propulsion system is prescribed in terms of a parameter called the *propellant mass fraction,* λ. This quantity measures the structural efficiency of the system by determining the proportion of the propulsion system made up of propellant. The remainder (non-