INTRODUCTION TO ROCKET PROPULSION

L6: Introduction to Chemical Rockets

How do chemical rockets produce thrust?
In this lecture, we will investigate how chemical rocket engines work! We’ll start by learning about energy conversion and chemical reactions. Then, we’ll survey several types of chemical rocket engines: liquid bi-propellant, liquid monopropellant, and solid propellant. We will calculate the heat released per unit mass of products in a chemical combustion reaction. We’ll use this quantity to estimate the specific impulse of a chemical rocket. Finally, we’ll learn about the many systems that make liquid bi-propellant rocket engines work.

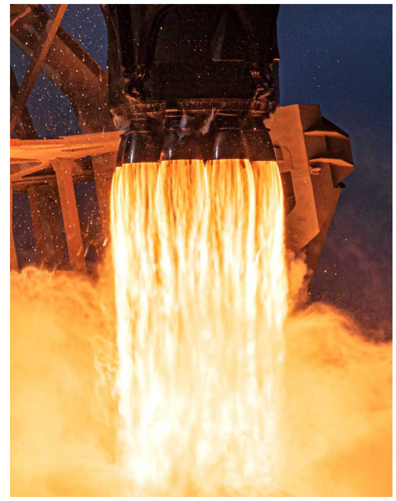

Figure 1: A close-up of the Falcon 9 launch vehicle as it lifts off the launch pad. The first stage of the Falcon 9 has 9 liquid bi-propellant rocket engines, which use liquid oxygen and RP-1 to create a powerful combustion reaction. We’ll learn about liquid bi-propellant rocket engines in this lecture!

Learning Goals:

1. Explain the path of energy conversion in chemical rockets and draw a flow chart.
2. Compare and contrast the various types of chemical rockets.
3. Compute the heat released per unit mass of products for chemical combustion reactions.
4. Name the systems of a liquid bi-propellant rocket engine and describe their functions.

ENERGY CONVERSION IN CHEMICAL ROCKETS

In some of our earlier examples, we considered serving tennis balls as a form of rocket propulsion. In this situation, the propellant was the tennis balls and the "engine" was the astronaut. Where does the energy come from to accelerate the tennis ball to high velocity? It comes from the astronaut, who swings their arm and hits the ball. The energy to swing their arm comes from the body, which gets its energy from eating food. The path of energy conversion for a "tennis ball propulsion system" is shown in Figure 2.

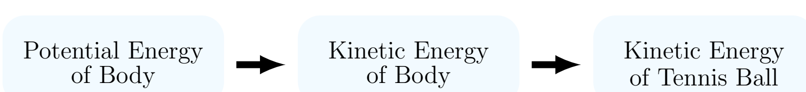

Figure 2: Path of energy conversion in a tennis ball propulsion system.

Chemical rockets work differently. The energy used to accelerate the propellant is stored in the propellant itself as *chemical energy*.

> DEFINITION 6.1 **Chemical energy** is the potential energy stored in the bonds of molecules. When chemicals react, their bonds may break and release the potential energy as heat.

Figure 3: The F-1 rocket engine was used on the Saturn V launch vehicle that sent astronauts to the Moon. The large bell-shaped portion of the engine is called the *nozzle*. Notice the human (me!) in the photo for size scale. The first stage of the Saturn V used five of these engines!

The propellant in a chemical rocket, which is typically a liquid or solid substance, undergoes a chemical reaction that produces gaseous products. The reaction releases the chemical energy stored in the propellant and heats up the products of the reaction. Essentially, a chemical rocket uses propellants to produce very hot gases.

The gaseous reaction products are at a high temperature and therefore have considerable thermal energy. The gas can be accelerated to high velocities by a rocket nozzle, which is the large "bell-shaped" structure at the bottom of launch vehicles. The nozzle converts the thermal energy of the gas to kinetic energy. As a result, gas leaves the rocket nozzle at high velocity and at a cooler temperature. The high velocity gas produces significant thrust force!

There are many types of chemical rockets, and yet, the path of energy conversion is the same for all of them. The chemical energy stored in the propellant is converted to the thermal energy of gaseous products of a chemical reaction. The thermal energy of the gas is converted to kinetic energy of the gas through the use of a nozzle. Figure 4 shows the path of energy conversion in a chemical rocket engine.

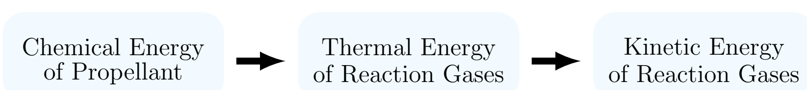

Figure 4: Path of energy conversion in a chemical rocket engine.

TYPES OF CHEMICAL ROCKETS

There are three main types of chemical rockets: liquid bi-propellant, liquid monopropellant, and solid propellant. The variations come from the different types of propellants and chemical reactions used.

Liquid Bi-Propellant Rocket Engines

As the name suggests, liquid bi-propellant rockets utilize two liquid propellants. They are called *fuel* and *oxidizer*. When mixed together, the fuel and oxidizer undergo a *combustion reaction*.

definition 6.2 **Chemical combustion** is an exothermic (heat releasing) reaction that occurs when fuel and oxidizer are mixed together. The reaction of fuel and oxidizer produces high temperature gaseous products. Combustion is a type of *redox* reaction.

definition 6.3 A **redox reaction**, or reduction-oxidation reaction, involves the transfer of electrons. In combustion reactions, the fuel gains electrons and the oxidizer loses electrons.

A combustion reaction releases a significant amount of energy, which is transferred to the reaction products. The resulting temperature of the reaction products in chemical rockets ranges from 2000-4000 K.

Liquid bi-propellant rocket engines are highly complex systems. They require two *propellant tanks* to store the fuel and oxidizer separately. They also require a *propellant feed system* to pump the propellant from the tanks to the *combustion chamber*, shown in Figure 5. The fuel and oxidizer are mixed together in the combustion chamber, where they react and produce hot gases. The gases are accelerated out of the nozzle to velocities that exceed the speed of sound.

The high heat release of liquid bi-propellant combustion reactions enables bi-propellant rockets to produce significant thrust force at high fuel efficiency relative to other types of chemical rockets. As a result, liquid bi-propellant rocket engines are often used on launch vehicles that carry payloads from Earth's surface to orbit.

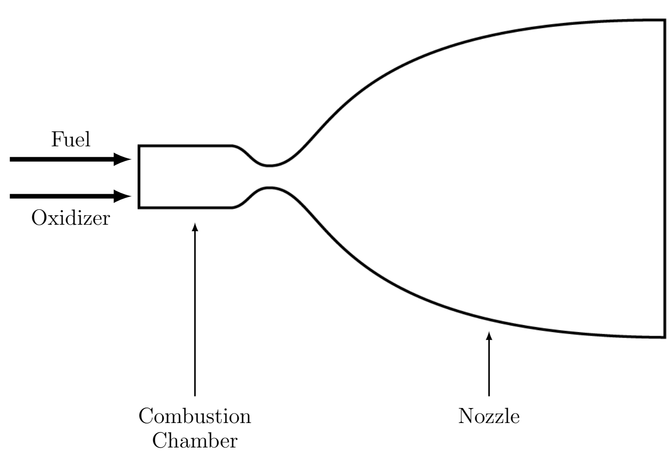

Figure 5: Diagram of a bi-propellant chemical rocket viewed from the side.

There are a variety of chemical propellants used in liquid bi-propellant chemical rocket engines. An important characteristic of a propellant is whether it is *storable* or *cryogenic*.

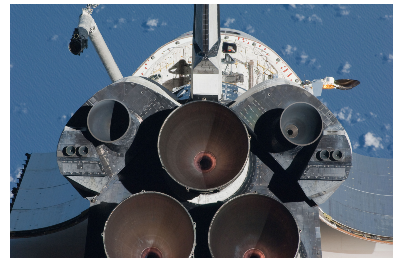

Figure 6: Rear view of the Space Shuttle Orbiter. The three large engines, called the Space Shuttle Main Engines (SSMEs), are used for launch. These engines utilize a powerful liquid oxygen, liquid hydrogen reaction.

The two smaller engines on the top left and right are the Orbital Maneuvering Engines (OMEs), which are used for high delta-v orbital maneuvers. The OMEs use a reaction of nitrogen tetroxide and monomethylhydrazine, which are storable propellants.

DEFINITION 6.4 **Storable** propellants are liquid at room temperature and do not need to be temperature controlled.

DEFINITION 6.5 **Cryogenic** propellants are gaseous at room temperature and liquid at extremely low temperatures. They require complex cooling systems to maintain their liquid state. For example, liquid oxygen must be stored at 123 K (-150°C) and liquid hydrogen must be stored at 21 K (-252°C). It takes considerable energy to keep cryogenic propellants in the liquid state, which is why they are not used on most spacecraft.

Storable propellants are best suited for use on satellites and spacecraft with longer duration missions. These propellants can be easily stored on a spacecraft without the need for a cooling system. However, one of the drawbacks of storable propellants is that they are less fuel efficient. Storable propellants release less chemical energy in combustion reactions than cryogenic propellants.

Cryogenic propellants are used primarily on launch vehicles because they provide high fuel efficiency. The propellants are stored in external tanks, kept at the proper temperature, near the launch pad. Shortly before launch, the cooled propellants are pumped into the launch vehicle. The launch vehicle has insulated tanks that can keep the propellants cool just long enough to complete the launch.

Since 1980, there has been very little development of new liquid rocket propellants. Much of the propellants used today are tried and proven combinations that have been in use for many decades. Two commonly used *oxidizers* are:

1. Liquid Oxygen (LOX, LO_2)
2. Nitrogen Tetroxide (N_2O_4)

Two commonly used *fuels* are:

1. Liquid Hydrogen (LH_2)
2. Rocket Propellant 1 (RP1)
3. Monomethylhydrazine (MMH)

Liquid oxygen and liquid hydrogen are cryogenic propellants. Nitrogen tetroxide, RP-1, and MMH are storable propellants.

The top three liquid bi-propellant *combustion reactions* are:

1. LOX-LH_2
2. LOX-RP1
3. Storable fuel and oxidizer

Let's consider a common propellant combination for liquid bi-propellant rocket engines: LOX-LH_2. The *stoichiometric reaction* for this propellant combination is:

$$H_2(\ell) + \frac{1}{2}O_2(\ell) \rightarrow H_2O(g) \tag{1}$$

DEFINITION 6.6 A **stoichiometric reaction** is a chemical reaction in which all of the reactants are converted into products. In the example above, notice that there is no excess hydrogren or oxygen remaining.

An important quantity used to describe reactions in chemical rockets is called the *oxidizer-to-fuel ratio* or the *O/F ratio*.

DEFINITION 6.7 The **oxidizer-to-fuel ratio** or **O/F ratio** is the ratio of the oxidizer mass to the fuel mass used for the combustion reaction in a chemical rocket engine. For example, consider the reaction in equation 1. The oxidizer mass is half that of a diatomic oxygen molecule, which is 16 amu. The fuel mass is that of one diatomic hydrogen molecule, which is 2 amu. Therefore, O/F ratio for this reaction is 8.

Example 1:

Let's estimate the specific impulse of a rocket that uses a stoichiometric liquid hydrogen liquid oxygen reaction! We'll need to calculate the energy released by the chemical reaction. Then we'll use this quantity to estimate the exhaust velocity of the rocket.

We can calculate the energy released by a chemical reaction by using the energies of the chemical bonds that break and form. The fuel and oxidizer are molecules in which atoms are bonded together. These bonds store energy, which can be thought of as a chemical potential energy. When a reaction occurs, the bonds break, which releases that stored energy. New

Bond	Bond Energy (kJ/mol)
H−H	436
O=O	498
O−H	428
H−OH	499

Table 1: Energies for various bonds involved in the combustion reaction of liquid hydrogen and liquid oxygen. The bond energy is the energy required to break the bond.

molecules may form in the reaction, which means new bonds are formed. The new bonds require energy to form, which can come from the energy released in the reaction.

The net energy released from a chemical reaction can be computed by subtracting the total bond energy of the products from the total bond energy of the reactants:

$$\Delta\mathcal{E} = \mathcal{E}_{products} - \mathcal{E}_{reactants} \tag{1.1}$$

Let's identify our reactants and products for the following liquid hydrogen, liquid oxygen chemical reaction:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{1.2}$$

The reactants are diatomic hydrogen, H_2, and diatomic oxygen, O_2. Each of these has one bond. The diatomic hydrogen has one $H - H$ bond and the diatomic oxygen has one $O = O$ bond. The total energy of the reactant bonds is the sum of the energy of the $H - H$ and the energy of the $O = O$ bond.

The product of the reaction is water vapor, H_2O. Water has two bonds: $H - O$ and $H - OH$. The total energy of the product bonds is the sum of the energy of the $H - O$ bond and half of the energy of the $H - OH$ bond.

Table 1.1 shows the bond energies for the various types of bonds in this combustion reaction. The total energy of the reactant bonds is:

$$\begin{aligned} \mathcal{E}_{reactants} &= 436\,\text{kJ/mol} + \frac{1}{2}(498\,\text{kJ/mol}) \\ &= 685\,\text{kJ/mol} \end{aligned} \tag{1.3}$$

The total energy of the product bonds is:

$$\begin{aligned} \mathcal{E}_{products} &= 428\,\text{kJ/mol} + 499\,\text{kJ/mol} \\ &= 927\,\text{kJ/mol} \end{aligned} \tag{1.4}$$

The energy released in the reaction is:

$$\begin{aligned} \Delta\mathcal{E} &= \mathcal{E}_{products} - \mathcal{E}_{reactants} \\ &= 927\,\text{kJ/mol} - 685\,\text{kJ/mol} \\ &= 242\,\text{kJ/mol} \end{aligned} \tag{1.5}$$

We found that 242 kJ are released per mol of products formed. We can convert the energy released per mol of products to the energy released per kilogram of products by dividing by the molar mass of the products, which is water vapor. The molar mass of water is is 18 g/mol, so 1.34×10^7 J/kg are released in this reaction. That's a lot of energy!

The LOX-LH_2 reaction is the most energetic reaction used in rocket engines. This means that it releases the most energy per unit mass of products formed. The more energy released, the higher the kinetic energy of the exhaust! Therefore we can expect that the liquid hydrogen, liquid oxygen reaction will provide the highest specific impulse for a chemical rocket.

How do we estimate the specific impulse? Let's assume that we can convert 100% of the energy released to the kinetic energy of the exhaust gas. The conservation of energy of a water molecule passing through the rocket engine is:

$$\Delta E = \frac{1}{2}mc^2 \tag{1.6}$$

where ΔE is the energy released, m is the mass of the water molecule, and c is the final velocity of the water molecule. If we divide ΔE by m, we get $\Delta\mathcal{E}$, which is the energy released per unit mass of product. Now we can solve for the final velocity of the water molecule:

$$\begin{aligned} c &= \sqrt{2\Delta\mathcal{E}} \\ &= \sqrt{2(1.34 \times 10^7\,\mathrm{J/kg})} \\ &= 5177\,\mathrm{m/s} \end{aligned} \tag{1.7}$$

Finally, we can estimate the specific impulse:

$$\begin{aligned} I_{sp} &= \frac{c}{g} \\ &= \frac{5177\,\mathrm{m/s}}{9.81\,\mathrm{m/s^2}} \\ &= 528\,\mathrm{s} \end{aligned} \tag{1.8}$$

The maximum possible specific impulse for the most energetic reaction used in chemical rockets is 528 s. In reality, there will be some energy losses, so the maximum possible specific impulse is closer to 500 s. This is the best fuel efficiency that chemical rockets can provide, unless a new, more energetic reaction is discovered one day.

Liquid Monopropellant Rocket Engines

Liquid monopropellant rocket engines use one type of propellant, typically a liquid fuel. The propellant undergoes a *decomposition reaction* when it is heated or comes into contact with a catalyst. This type of reaction releases energy, although not as much as combustion. As a result, monopropellant rockets have lower specific impulse than bi-propellant rocket engines.

DEFINITION 6.8 A reaction in which a chemical breaks down into one or more components is a **decomposition reaction**.

DEFINITION 6.9 A **catalyst** is a substance that initiates or enhances a chemical reaction.

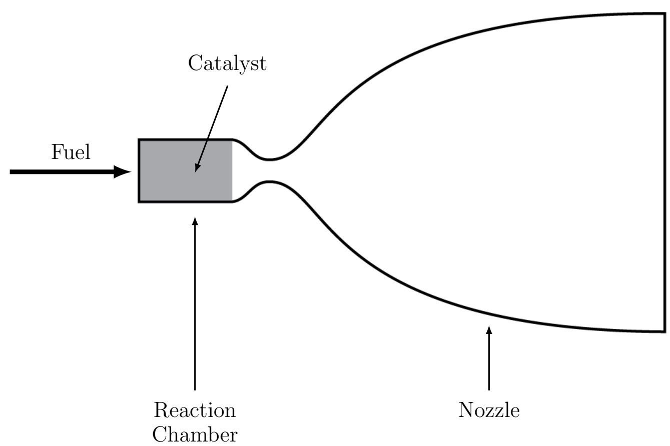

Figure 7: Diagram of a monopropellant chemical rocket engine viewed from the side.

Monopropellant rockets have their advantages, however. Only one propellant storage tank is needed, and a simpler propellant feed system can be used. Monopropellant rockets are typically used to perform orbital maneuvers on spacecraft, which have limited volume and mass available for a rocket propulsion system. Bi-propellant rockets are too complex and massive to be used on most spacecraft.

One of the most common propellants used in monopropellant rockets is a liquid fuel called *hydrazine* (N_2H_4). Hydrazine decomposes when it comes into contact with metals such as iridium, iron, nickel, and cobalt. The hydrazine decomposition reaction can be expressed as:

$$\mathrm{N_2H_4} \rightarrow \frac{4}{3}\mathrm{NH_3} + \frac{1}{3}\mathrm{N_2} \tag{2}$$

While hydrazine can be stored at room temperature, it cannot be handled easily. Hydrazine corrodes certain metals, is extremely flammable, and is very hazardous to humans.

Solid Rocket Engines

Solid rocket engines, also called solid rocket motors, use solid propellant, similar to fireworks. The solid propellant is made from many ingredients and is essentially a solid mixture of fuel and oxidizer. The propellant doesn't react until it is sufficiently heated by an electric spark created by an igniter. Once the reaction starts, the solid propellant burns and produces hot gases. The hot combustion gases are sent through a converging-diverging nozzle, which accelerates them to high velocities. A diagram of a solid rocket motor is shown in Figure 8.

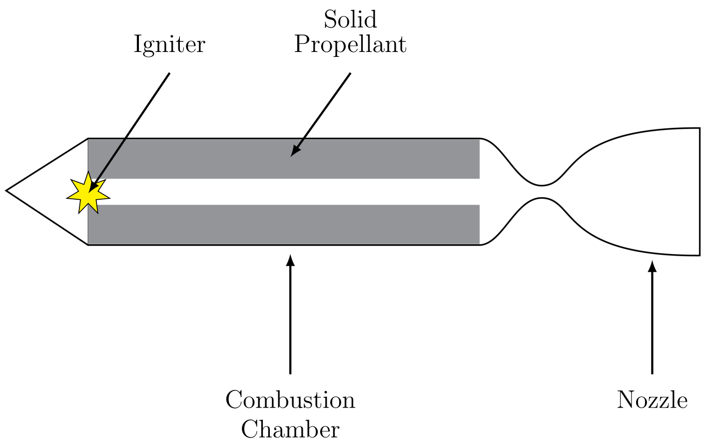

Figure 8: Diagram of a solid rocket booster viewed from the side.

The geometry of the solid propellant is typically cylindrical with a hole down the center. Sometimes the hole has a star-shaped geometry. This design ensures that the propellant burns evenly and that there is only a small amount of left over, unburned propellant. The solid propellant is made from a liquidy mixture of fuel and oxidizer, called a *slurry*. The slurry is poured into molds and is cast into the shape required for the application. Figure 9 shows the assembly of solid rocket booster segments used on the Space Shuttle.

Figure 9: Two segments of the solid rocket booster for the Space Shuttle are being fitted together in this photo. The boosters are constructed out of four segments in total. It's easier to produce smaller segments of the solid propellant and assemble them together rather than make one big segment of solid propellant. Notice that the solid propellant has a hole in the middle.

For a variety of reasons, solid rocket motors are used on launch vehicles, but not on spacecraft. First, once solid rocket motors are lit, they can't be turned off! This mode of operation is useful for launching to orbit because the rockets only need to fire once to get to space. Spacecraft in orbit typically need to perform many orbital corrections and changes, which requires a propulsion system that can be turned on and off many times. Second, solid rocket propellant poses significant hazards. The fuel and oxidizer are already mixed together, instead of being safely stored in separate tanks. Any excess heat or a spark could cause the solid propellant to ignite unexpectedly. Finally, the solid propellant is fragile and is prone to cracking. Launching to orbit involves strong vibrations and other forces that could damage the solid propellant before reaching orbit.

Figure 10: Solid rocket booster for the Space Launch System (SLS). The entire length of the booster, except for the nozzle, is filled with solid propellant. This is the largest solid rocket booster ever tested!

Solid rocket motors have advantages over liquid chemical rockets when used on launch vehicles. Solid rockets are simple in design and don't require any moving parts. The solid propellant is denser than liquid propellant, providing more chemical energy per unit volume. This allows a rocket-propelled vehicle to be more compact, which reduces drag and thus the propellant mass required to reach orbit.

Solid rocket motors are typically used in combination with liquid chemical rockets on launch vehicles. In this application, they are typically referred to as solid rocket boosters because they provide an added boost during launch. Some of the largest solid rocket boosters ever made were used on the Space Shuttle. They burned for about two minutes, before detaching from the vehicle and landing in the Atlantic Ocean where they were later recovered so that they could be refilled and reused in future launches.

Solid rocket motors are also used in missiles because they are simple and most importantly, storable. Missiles are not used to bring payload to space, so they require less total impulse and less propellant. Solid rocket motors, while not the most fuel-efficient chemical rocket technology, can provide the necessary impulse in a compact form to achieve mission objectives for missile applications.

BI-PROPELLANT ROCKET ENGINE SYSTEMS

During our study of chemical rockets in this course, we will focus mostly on bi-propellant rocket engines. This section outlines the major systems of a bi-propellant chemical rocket engine, which is a highly complex piece of machinery. The combustion chamber and nozzle are just a small part of the systems required to operate the rocket engine.

Propellant Storage

First and foremost, the propellants need to be stored somewhere on the launch vehicle or spacecraft. Since we are talking about bi-propellant rocket engines, we will focus on launch vehicle applications. Bi-propellant rocket engines require two types of propellant, which need to be stored in two separate tanks. Figure 11 shows the inside of a single-stage launch vehicle. Notice how much volume is occupied by propellant!

Typically the propellant tanks are made of metal, usually aluminum. The propellants on launch vehicles are stored at atmospheric pressure, which allows the tank walls to be thin. In contrast, monopropellant rockets on board spacecraft typically store their propellant at high pressure. This means that the tank walls must be thick enough to withstand the pressure of the propellant inside.

If the launch vehicle uses cryogenic propellant, then the tanks will need to be surrounded by foam insulation to keep the propellants cold. Launch vehicles don't have refrigeration systems to actively cool the propellant, which is why the propellant is pumped into the insulated tanks just hours before launch. The cryogenic propellant is stored in large holding tanks near the launch site, which have refrigeration systems to keep the propellant at the right temperature.

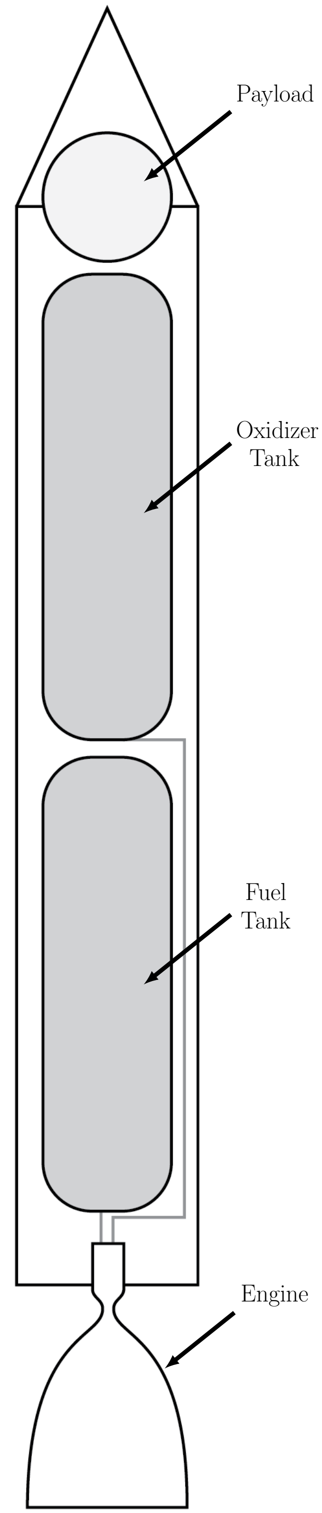

Figure 11: A schematic of the inside of a single-stage launch vehicle that utilizes liquid bi-propellant rocket engines.

Propellant Feed System

Before the propellant is injected into the combustion chamber of the rocket engine, it needs to be pressurized. High pressure propellant ensures that the chemical reaction proceeds quickly and efficiently within the combustion chamber. The high pressure also increases the thrust because the gas has more potential to do mechanical work.

One option is to store the propellant at high pressure in the tanks. In this case, the tanks need to be thick to withstand the pressure of the propellant inside. On a launch vehicle, the tanks are so large that the extra thickness would make the tanks too heavy. Another strategy is to store the propellant at low pressure and use pumps to increase the pressure of the propellant as it is transported to the combustion chamber. This method is used on launch vehicles because the weight of a pumping system is less than the weight of thick-walled tanks.

The propellant feed system consists of the machinery and piping required to transport propellant from the tanks to the combustion chamber. In launch vehicles, the machinery consists of *turbopumps* and *turbines*. The turbopumps are used to increase the pressure of the liquid propellant flowing through them. They work by forcing the propellant through a region with rapidly spinning blades that abruptly changes the direction of the fluid flow, thus increasing its pressure. Two turbopumps are required, one for the fuel and one for the oxidizer.

How do the turbopumps start spinning in the first place? This is where the turbine comes in. There are many types of turbines, such as those that extract energy from wind or turbines in a hydroelectric powerplant. Even jet engines use turbines to spin the large fan blades at the front of the engine.

A turbine looks like a fan and has blades positioned in a radial pattern around a central shaft. When warm pressurized gas flows through a turbine, the gas exerts a force on the blades, causing them to spin around the central shaft. The flow of gas through a turbine can force the shaft to spin rapidly. Once the shaft starts spinning, it can be used to rotate something else, like the large fan blades on a jet engine or a turbopump in a chemical rocket engine. Anything that is mounted to the central shaft will spin because of the action of the turbine.

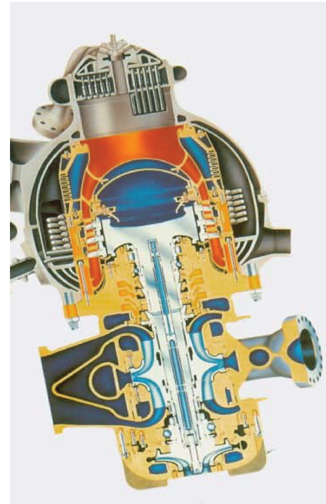

Figure 12: A schematic of the turbomachinery for the liquid oxygen propellant on the Space Shuttle Main Engine. The SSME turbine spins at approximately 22,000 rpm? These machines operate under very high stress conditions. Their operation lifetimes are only about ten minutes, which is just enough time to ensure that the launch vehicle reaches outer space. If operated longer, the metal could crack and the machines would break in a catastrophic manner.

Turbines are used on bi-propellant chemical rocket engines to spin the turbopumps that pressurize the propellants. Where does the gas come from that spins the turbine? There are lots of ways to provide warm gas to the turbine. A common design for liquid bi-propellant rocket engines is called a "gas generator". In this design, a small amount of fuel and oxidizer are used to start a small combustion reaction, which produces warm gas that can be sent through the turbine. Figure 13 shows a schematic of a gas generator cycle. There are many types of engine cycles used in bi-propellant chemical rocket engines, such as the expander cycle and staged combustion. We wont cover these here, but you can check out the course resources to learn more about them.

Injection and Ignition

Once the propellants have passed through the turbopumps, they are at the appropriate pressure to be sent into the combustion chamber. A special piece of equipment, called the *injector*, is used to inject the fuel and oxidizer into the combustion chamber. Injectors are designed to maximize both the rate and efficiency of the combustion reaction. The rate of reaction can be increased by atomizing the propellant. The injector sprays a jet of tiny liquid droplets, just like a bottle of perfume or cologne does. The tiny liquid droplets quickly vaporize into gas, after which the combustion reaction proceeds quickly.

The efficiency of the reaction can be increased by ensuring that the fuel and oxidizer mix togther well. This can be a challenge when the oxidizer-to-fuel ratio is not close to one. If the oxidizer-to-fuel ratio is 8, for example, then eight times as much oxidizer needs to be injected into the combustion chamber for a given amount of fuel. For every nozzle that sprays droplets of fuel, potentially eight nozzles to spray oxidizer are needed to surround the fuel nozzle. The patterns of the fuel and oxidizer nozzles are a critical part of the engine design.

Nozzle Cooling System

The combustion reaction releases significant thermal energy, which heats the gaseous combustion products to high temperatures. The high temperature gas comes in contact with the internal walls of the combustion chamber and nozzle, which heats them up. The gases are hot enough to soften the metal walls, which could weaken them and cause a failure of the engine.

To avoid such a catastrophic situation, cooling systems are designed to keep critical components of the rocket nozzle at safe temperatures. There are a variety of techniques that are employed depending on the application. In launch vehicle rocket engines, regenerative cooling systems are used. Tiny channels, or tubes, line the exterior of the combustion chamber and nozzle. Cold liquid propellant, typically the fuel, is pumped through the channels before being injected into the combustion chamber. The fuel absorbs some of the heat given off by the hot combustion gases. This allows the metal structure of the engine to remain at a safe operating temperature.

Solid rocket engines typically use a heat sink near the throat of the engine, which is the narrow part between the combustion chamber and the nozzle. The heat sink is made of thermally conductive metal, like copper, and absorbs thermal energy from the hot combustion gases, keeping the nozzle cool. Over time the temperature of the heat sink increases and, at some point, it can no longer absorb heat from the gases. Therefore, heat sinks can only be used for short durations, perhaps a few minutes. This is a reason why solid rocket boosters only fire for a few minutes.

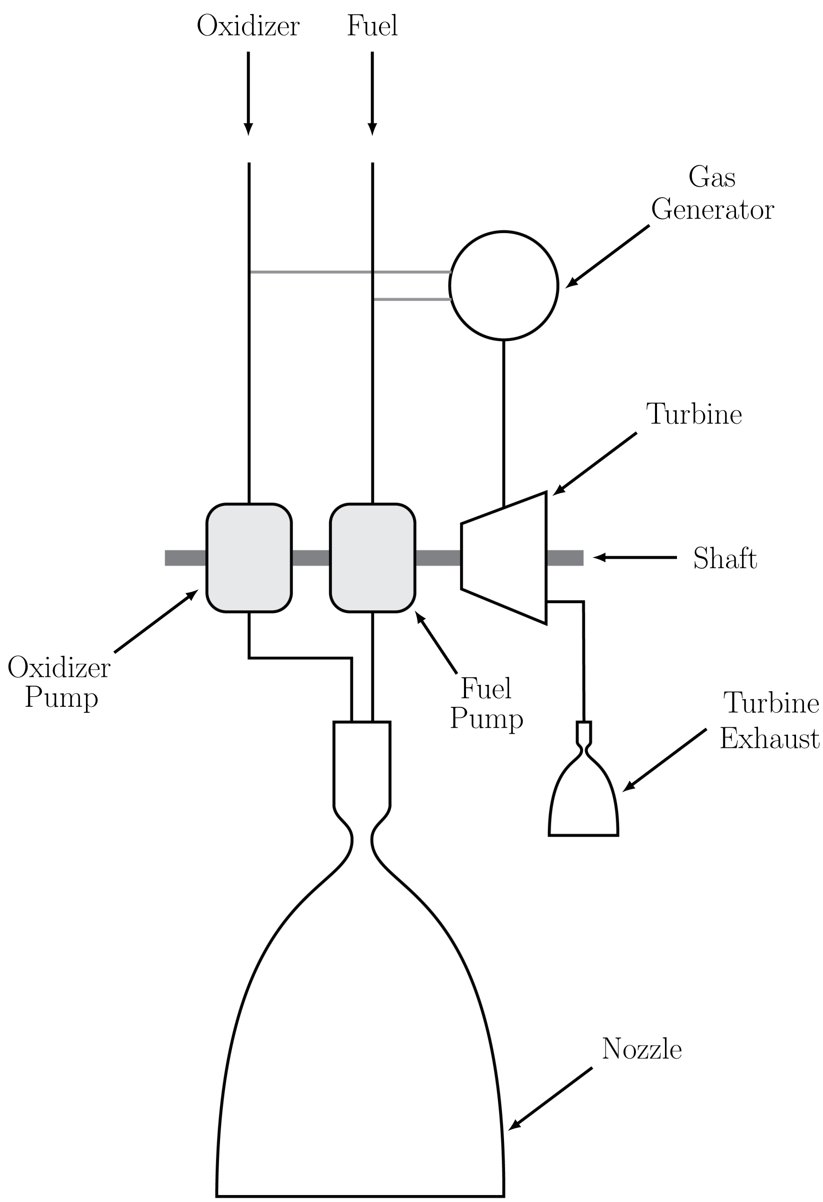

Figure 13: Diagram of a gas generator engine cycle for a liquid bi-propellant rocket engine.