DEPARTMENT OF AEROSPACE ENGINEERING

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UNIT I - FUNDAMENTALS OF ROCKET PROPULSION

Types of rockets - Rocket Staging

Rocket Propulsion System

A rocket propulsion system is an engine that provides **thrust** to a rocket. It works by ejecting fuel at high speed from the back of the rocket, which produces an equal and opposite force that propels the rocket forward.

Principle and Working of Rocket Propulsion

Newton's third law of motion, which states that every action has an equal and opposite reaction, is one of the principles underlying rocket propulsion. When a rocket ejects propellant at high speed from the back, it produces an equal and opposite force that propels the rocket forward.

- For instance, when standing on a skateboard and throwing something heavy away from you, the skateboard moves in the **opposite direction**. The rocket works the same way.
- The force created by the ejected gases is called **thrust**. The more thrust a rocket has, the faster it goes.
- In a rocket engine, **fuel and an oxidizer** are burned to produce hot exhaust gas.
- The hot exhaust gas from the rocket accelerates to the back of the rocket after passing through the nozzle. On the engine mount, a **thrusting force** is generated in response.
  - **Newton's second law** of motion describes how the thrust accelerates the rocket.
- The amount of thrust produced by a rocket is determined by the **mass flow rate of the propellant and the exhaust velocity**.

- The mass flow rate is the rate at which the fuel is ejected from the rocket, and the exhaust velocity is the speed at which the fuel exits the nozzle.

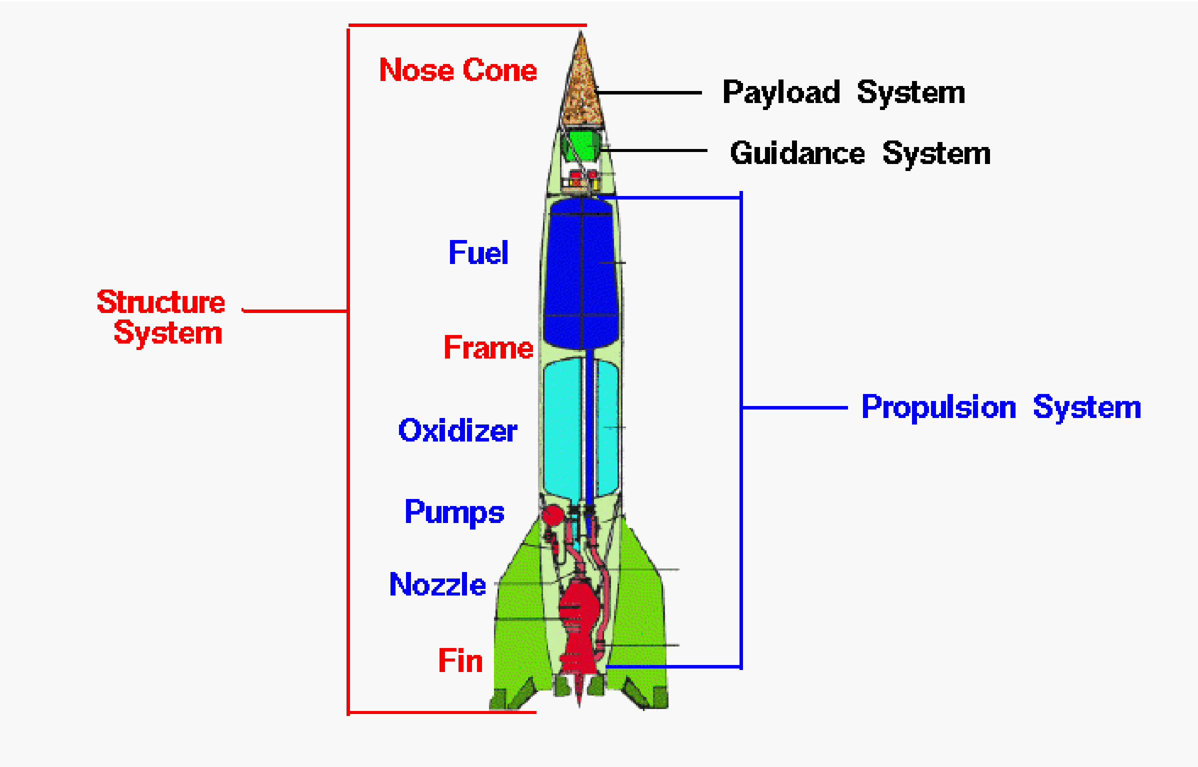
- The exhaust velocity of a rocket is determined by the type of propellant used and the design of the nozzle.

- The **nozzle** is a tapered tube that accelerates the exhaust gases to high speeds. The higher the exhaust velocity, the more thrust the rocket will produce.

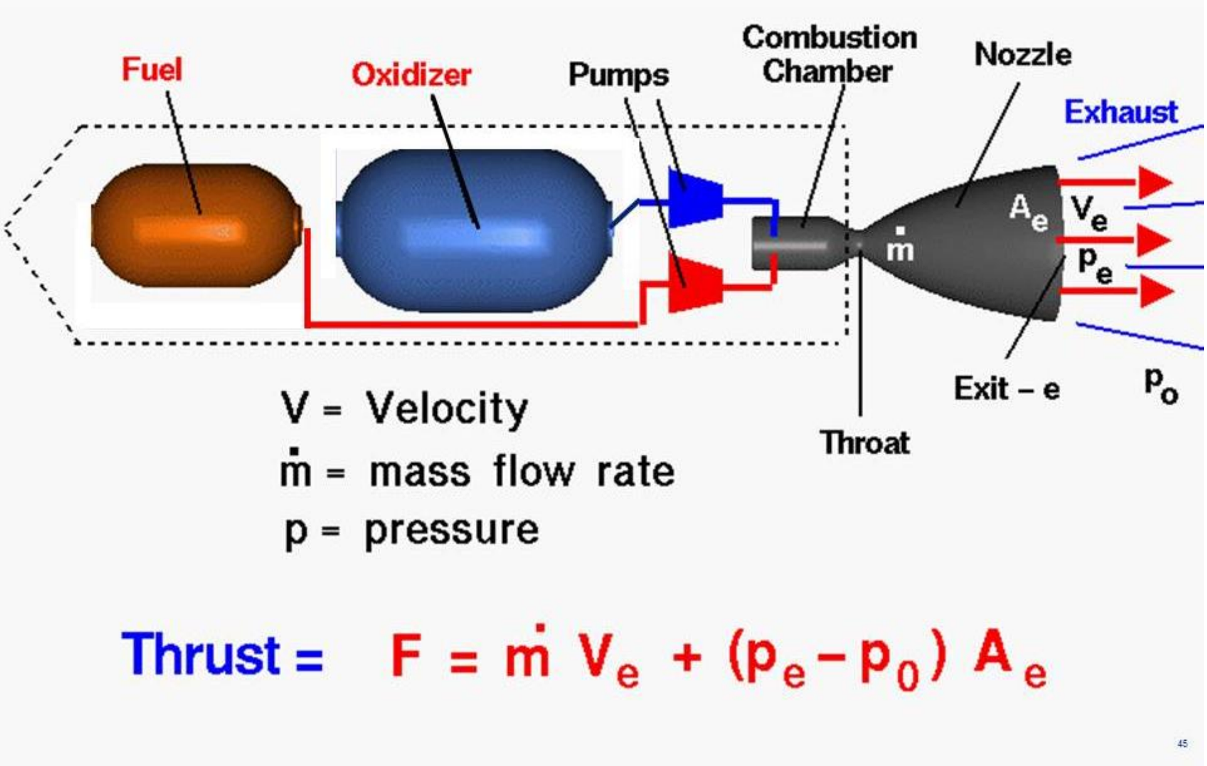
- **Ramjet and Scramjet** engines also work on the same principle as rocket propulsion systems.

Rocket Propulsion Diagram

A structure of a rocket propulsion system typically involves several key components, which include the payload system, fuel and oxidiser, combustion chamber and nozzle. Following is the given representation of the rocket propulsion system.



Rocket Parts



Liquid Rocket Engine

Types of Rocket Propulsion System

There are four main types of rocket propulsion systems. These are given as follows:

Solid Fuel Chemical Propulsion

- **Mechanism:** The solid motor is primarily used as a launch vehicle booster. Because they are uncontrollable, solid motors are almost never used in space. The boosters are ignited and then fired until all of the propellants have been consumed.
- **Significance:** Their primary advantages are **simplicity**, a **shelf life** that can last years, as in the case of missiles, and **high reliability.**
- **Example:** NASA's **Space Launch System Solid Rocket Booster** is one of the largest and most powerful solid propellant boosters.
- **Kalam-5:** In 2020, **Skyroot Aerospace** successfully tested a solid propulsion rocket stage called **Kalam-5**.
    - It is made of an advanced **carbon composite structure** that is five times lighter than a steel case.
    - It made Skyroot Aerospace the **first private player** in India to design and test a full solid propulsion rocket stage.

Liquid Fuel Chemical Propulsion

- **Significance:** Liquid motors are available in a variety of shapes and sizes. The majority of them are controllable (they can be throttled up and down) and restartable, and they are frequently used as control and maneuvering thrusters.
- **Types:** There are three types of liquid thrusters: monopropellant, bipropellant, and cryogenic thrusters. Thruster complexity and performance increase with each step, from monopropellant to bipropellant to cryogenic.
  - **Monopropellant:** A single propellant, such as hydrazine, is used in monopropellants. Bipropellants make use of a fuel and an oxidizer like RP-1 and H2O2.
  - **Bipropellant:** Liquid gases such as LiH and LOX (liquid hydrogen and liquid oxygen) are used in cryogenic systems.
  - **Cryogenic thrusters:** Cryogenic refers to extremely cold temperatures. To make hydrogen and oxygen liquids, they would have to be supercooled.
    - **Cryogenic technology** is the science of producing, storing, transporting, and using materials at extremely low temperatures.
- **Example: The SpaceX Merlin engine** is a liquid-fuel rocket engine used to power the Falcon 9 and Falcon Heavy rockets.
- **Vikas Engine:**
  - The Vikas engine (Vikram Ambalal Sarabhai) is a family of liquid-fueled rocket engines developed in the 1970s at ISRO's **Liquid Propulsion Systems Centre**.
  - It powers the **second stages of the PSLV and the GSLV,** as well as the GSLV's liquid strapons and the core liquid stage of the LVM3.
- **ISRO’s semi-cryogenic engine:**
  - Recently, ISRO successfully test-fired its semi-cryogenic engine at the ISRO Propulsion Complex (IPRC) in Mahendragiri.
  - Semi-cryogenic engines are propulsion technologies that use refined kerosene (known as **'ISROsene'**) and super-cooled liquid oxygen.

Cold-Gas Chemical Propulsion

- **Mechanism:**
  - Cold-gas motors have the same controllability as liquids but are simpler and lighter.
  - They are essentially high-pressure tanks with switches that alternate between open and closed states.
  - They work a little like spray paint, with the contents under pressure inside and streaming out when the valve is opened.

- **Example: The SpaceX Falcon 9 rocket** uses cold-gas thrusters for attitude control during flight's first and second stages.

Ion Engines

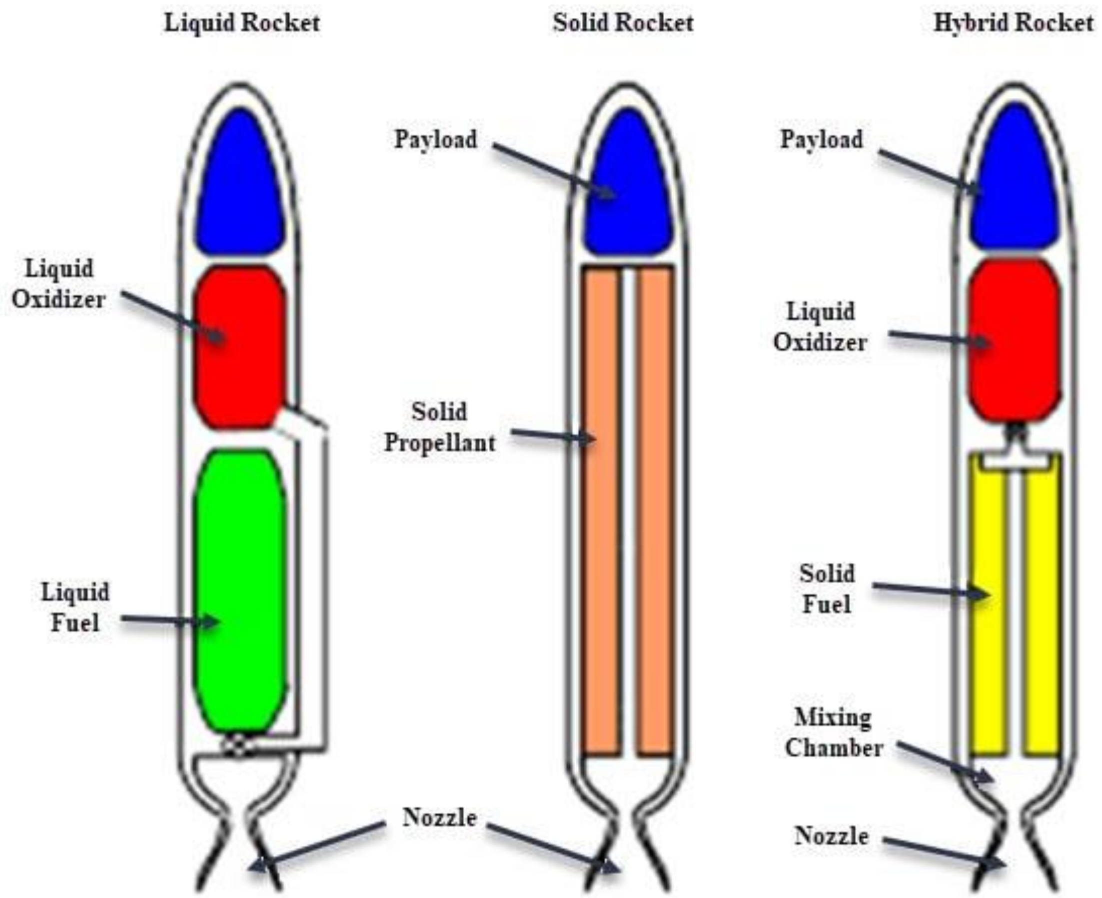
- **Mechanism**: Ion engines differ significantly from chemical (solid, liquid) engines in that they have low thrust and can run for extended periods of time.
- **Significance:** Chemical engines are typically **used for a few seconds** to a few days, whereas ion engines can be used for days to months.
- **Example: BepiColombo,** a joint mission between the ESA and the JAXA to study Mercury, is using **ion engines** to travel to Mercury.

Recent Developments in Rocket Propulsion System

Rocket propulsion systems have advanced significantly over the years, resulting in increased efficiency and power. These advancements include hybrid propulsion systems, space nuclear propulsion, etc.

Hybrid Propulsion System

- **Mechanism:** A hybrid propulsion system is any vehicle propulsion system that **combines two or more sources of propulsion** into a single design and can be used simultaneously or alternately.
- **Significance:**
  - The hybrid system is **more efficient, greener, and safer** to operate, and it paves the way for future missions to use new propulsion technologies.
  - Use of hybrid propulsion can **save fuel, increase average engine load, reduce maintenance costs, increase uptime,** etc.
  - Hybrid vehicles, for example, use the gasoline engine as a generator to power the electric motor. This allows them to use less petrol than conventional vehicles.
- **ISRO's Hybrid Propulsion System:**
  - In September 2022, the Indian Space Research Organization (ISRO) successfully demonstrated a hybrid propulsion system from the ISRO Propulsion Complex (IPRC), Mahendragiri.
  - The hybrid propulsion system by ISRO used Hydroxyl-terminated polybutadiene (**HTPB**)-based aluminised solid fuel and liquid oxygen (**LOX**) as the oxidiser.



Space Nuclear Propulsion

- **Mechanism:** It is a propulsion technology that can provide high thrust while also doubling propellant efficiency, making it a viable option for crewed missions to Mars.
    - The heat from the reactor is transferred directly to a gaseous hydrogen propellant in the system. To propel a spacecraft, heated hydrogen expands through a nozzle.
- **Significance:** It would enable more flexible abort scenarios, allowing the crew to return to Earth at various times, including immediately upon arrival at Mars.

Rotating Detonation Rocket Engine (RDRE)

- **Mechanism:** It is a new propulsion system by NASA. It generates thrust by rapidly rotating and detonating a fuel-and-oxidizer mixture in a continuous combustion cycle.
- **Significance:** It has the potential to power both human landers and interplanetary vehicles travelling to deep space destinations such as Mars and the Moon.

Introduction

Rocket engines are incredibly complex machines, pushing the boundaries of materials science and human ingenuity, with a multitude of different engine cycles that characterize the engine. In this article we discuss the many rocket engine cycles that engineers have used.

The types of power cycle range from very simple cycle types like cold gas thrusters, to more and more complicated ones like the famous full-flow staged combustion. This article will showcase all prominent types of engine cycles and describe and picture them in detail.

We can compare rocket engine cycle types to internal combustion engine types, in one sense. Car engine types include 2-stroke, 2 cylinder, or 4-stroke, 4 cylinder, supercharged, turbocharged, etc. They all operate under the same basic principles but employ different techniques to reach their power and/or efficiency goal.

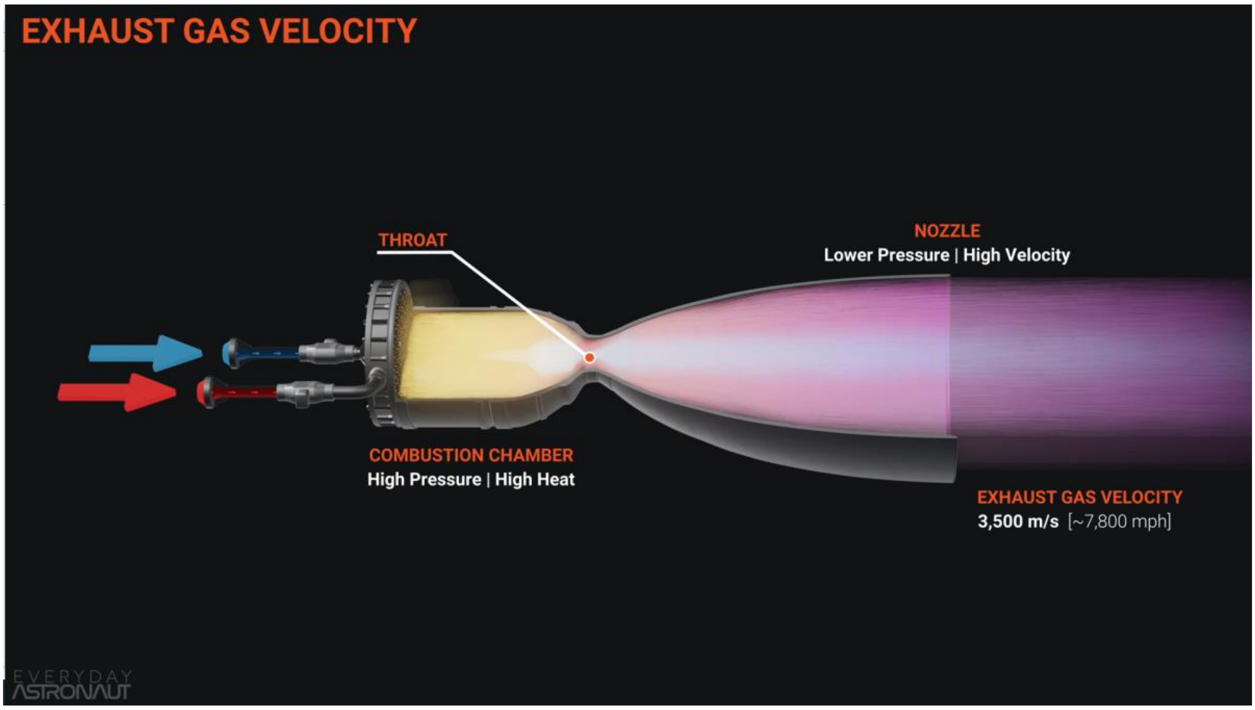
Some of the following will sound familiar if you've read or have seen our article and video about SpaceX' Raptor engine, but this time the whole article and the video will only focus on engine cycle types.

Requirements And Basic Principles

Please view our previous article or video about why rocket engines don't melt before reading this article. We mention some of those cooling principles discussed in that article/video. It provides a great base knowledge of how rocket engines work, which will help you to better understand the following. We will produce even more articles and videos about how rocket engines work in the future.

Newton's 3rd law of motion dictates how a rocket engine functions. For every action, there is an equal and opposite reaction. So, an engine expels some mass out of one end. The result is that the whole vehicle propels itself in the opposite direction. The faster and more matter that the engine expels, the greater the efficiency and the higher the thrust. The more thrust that the engine produces, the more payload the rocket can deliver.

Engineers refer to the speed of the nozzle exhaust as exhaust gas velocity. This velocity not only correlates to the thrust that the vehicle generates, but also correlates with the efficiency of the engine.



Combustion Chamber and Rocket Nozzle

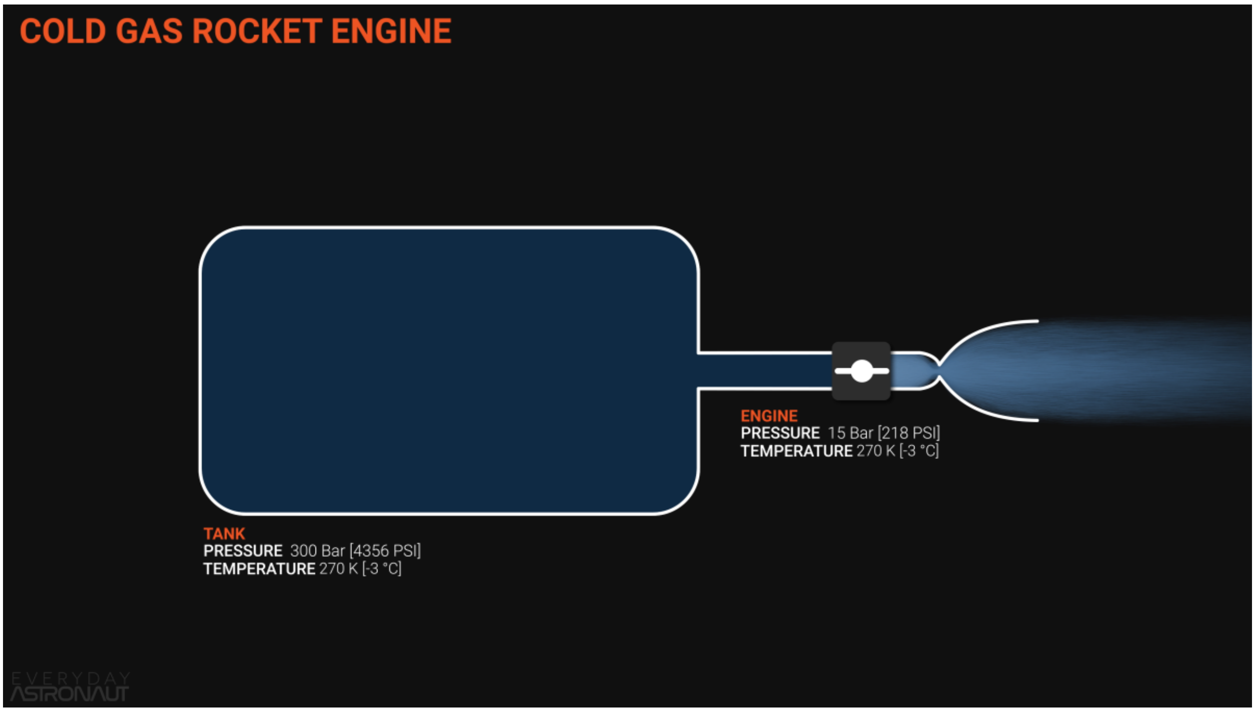
We convert pressure and heat inside the combustion chamber of a rocket engine into kinetic energy. This is done using a so-called de Laval nozzle, or a convergent-divergent nozzle. The nozzle which converts hot subsonic high-pressure gas into cooler supersonic lower-pressure gas.

The challenge here is to get the pressure and temperature inside of the engine as high as possible. All this while managing the heat. Heat and pressure give high performance, but can be difficult to contain and manage. Generally speaking, the higher the temperature inside the combustion chamber, the better, as heat is proportional to energy.

At this point, we have to introduce the term enthalpy. Enthalpy is the sum of all energy that a system contains. Specifically, enthalpy is the volume times the pressure plus its internal energy. The internal energy in this case consists of heat and microscopic kinetic energy. The higher the enthalpy in the system, the more potential it has to perform work.

Cold Gas Thrusters

The simplest form of a rocket engine just stores some sort of propellant in a tank at high pressure. Then, open a valve, and let that high pressure flow out through the engine. This is the basis of cold gas thrusters.



As the name suggests, these engines run cold, meaning that there is no chemical reaction or combustion taking place. The simple expansion of a stored gas through the nozzle is what provides thrust in these types of engines. The term "cold" in these engines comes from the fact that when gasses expand, the temperature drops as a result. Engineers call this effect the Joule-Thomson effect.

Cold Gas Thruster Pressure

Propellant tanks for most of those kinds of engines store the propellants in a gaseous form. Nitrous oxide or butane are examples of exceptions to this. Tanks can store them in liquid form under high pressure. With most propellants being sparse, the tanks must hold even higher pressures. This means that the tanks need to be heavier too, resulting in a bad runaway effect.

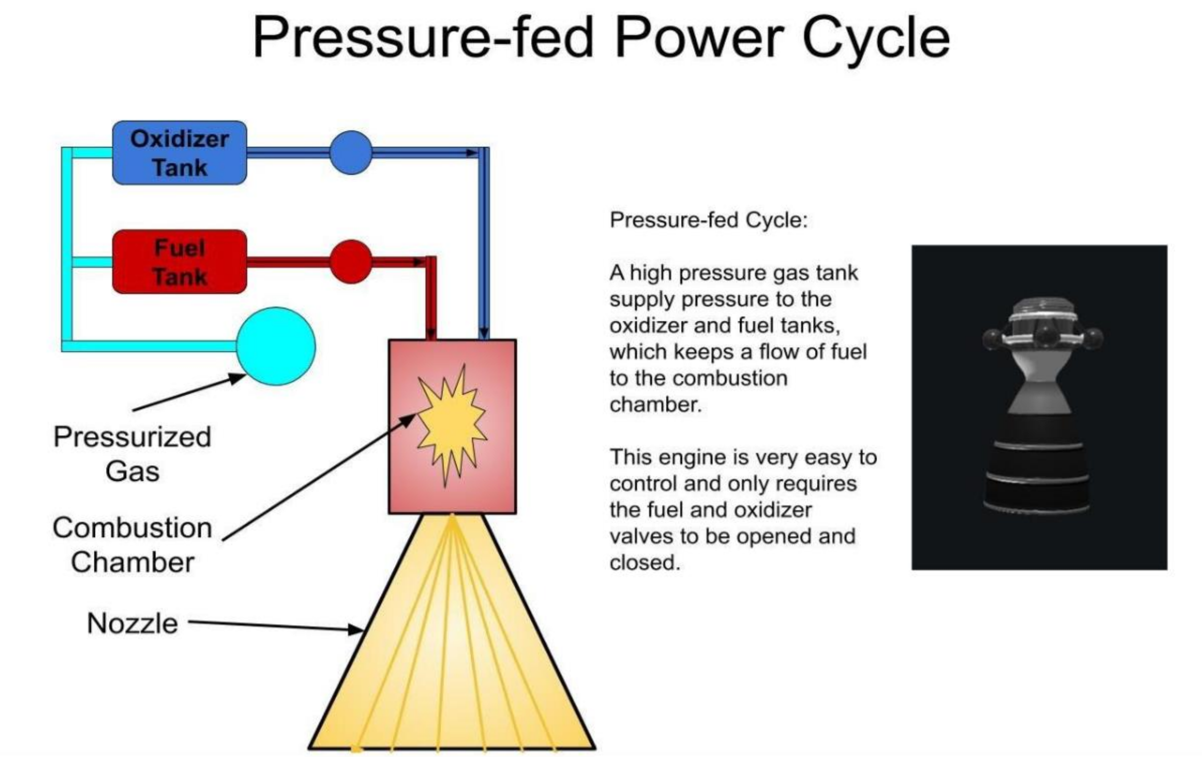
Cold gas thrusters usually use helium or nitrogen for their high compressibility and relatively low molecular weight. Such gases are easier to accelerate. It would be possible to use hydrogen or some other propellants. So far no-one has done this in a well-known prominent example.

Since both pressure and temperature are low in this system, the specific impulse is also low. The the simplest and most basic pressure-fed engine has only about 60 s of specific impulse, or ISP. However, it is already three to four times more efficient.

There is another limitation of cold gas thrusters. The nozzle can only expand so far before the gas turns into a liquid while still in the nozzle. This is in addition to the overall lack of enthalpy in the system. However, cold gas thrusters are extremely simple and reliable. They only have one moving part – a valve. This makes this design a great choice for many small spacecrafts like small satellites or CubeSats.

Pressure-Fed Engines

The pressure-fed engine cycle is the next most simple engine design. Similar to cold gas thrusters, pressure-fed engines have almost no moving parts. At the same time the offer much higher performance than cold gas thrusters.

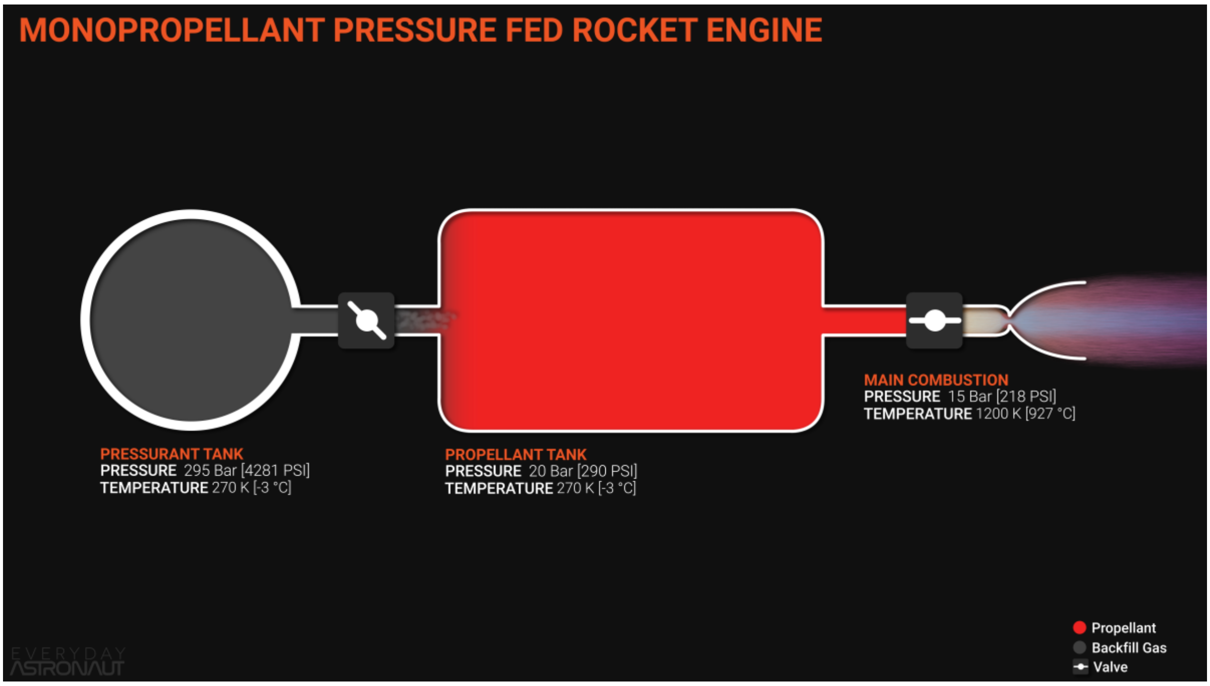


There are two types of pressure-fed engines – monopropellant pressure-fed engines and bipropellant pressure-fed engines. They differ in the number of propellants they use. As the names already suggest, monopropellant pressure-fed engines use only one propellant, while bipropellant pressure-fed engines use two different propellants.

Monopropellant Pressure-Fed Engines

A monopropellant pressure-fed engine, or (for short) monoprop pressure-fed engine, is very similar to a cold gas thruster. The engine still has one tank filled with high-pressure inert gas. However, in addition, there is also a low-pressure tank with propellant, often hydrazine.

Monoprop engines open the valve from the propellant tank to the engine, while maintaining the pressure inside the propellant tank. They also modulate another valve between the high-pressure tank and the propellant tank. This high pressure tank holds an inert gas like nitrogen or helium.



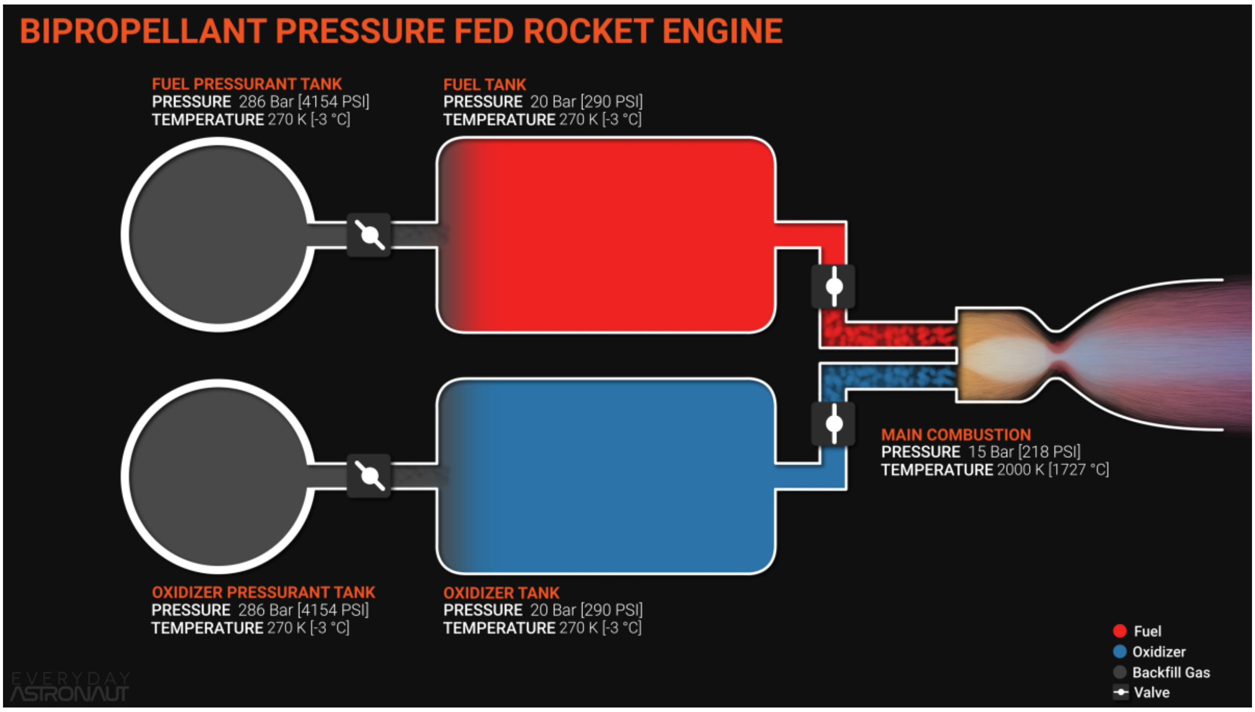
Monoprop pressure-fed cycle

Monoprop engines are more efficient than cold gas thrusters. This is because they harness some chemical energy from the used propellant by running it over a catalyst bed. Hydrazine is one of the most common monopropellants. It flows through an iridium-infused alumina bed, which is a strong reducing agent. The resulting reaction converts the chemical energy in hydrazine to heat and pressure. The engine nozzle then expels this pressure as hot gas.

Bipropellant Pressure-Fed Engines

Bipropellant pressure-fed engines, (or for short, biprop) pressure-fed engines, are basically the same as monoprop engines. The difference is, as the name already suggests, a pair of both fuel and pressurant tanks. One set stores the fuel, while the other one stores the oxidizer.

They still work with the same principle as monoprop engines and cold gas thrusters. This is that the only moving parts are simple valves. The difference to monoprop engines is that those engines can use more energetic and efficient propellants. Examples of such are RP-1 and LOx, or even CH4 and LOx. Most bipropellant systems will utilize hypergolic propellants for their simplicity. Hypergolic propellants are propellants that spontaneously combust upon contact with each other. Any system using hypergolics is extremely simple and reliable since it requires no ignition source. Such a system still offers decent performance.



Bi-propellant pressure-fed cycle

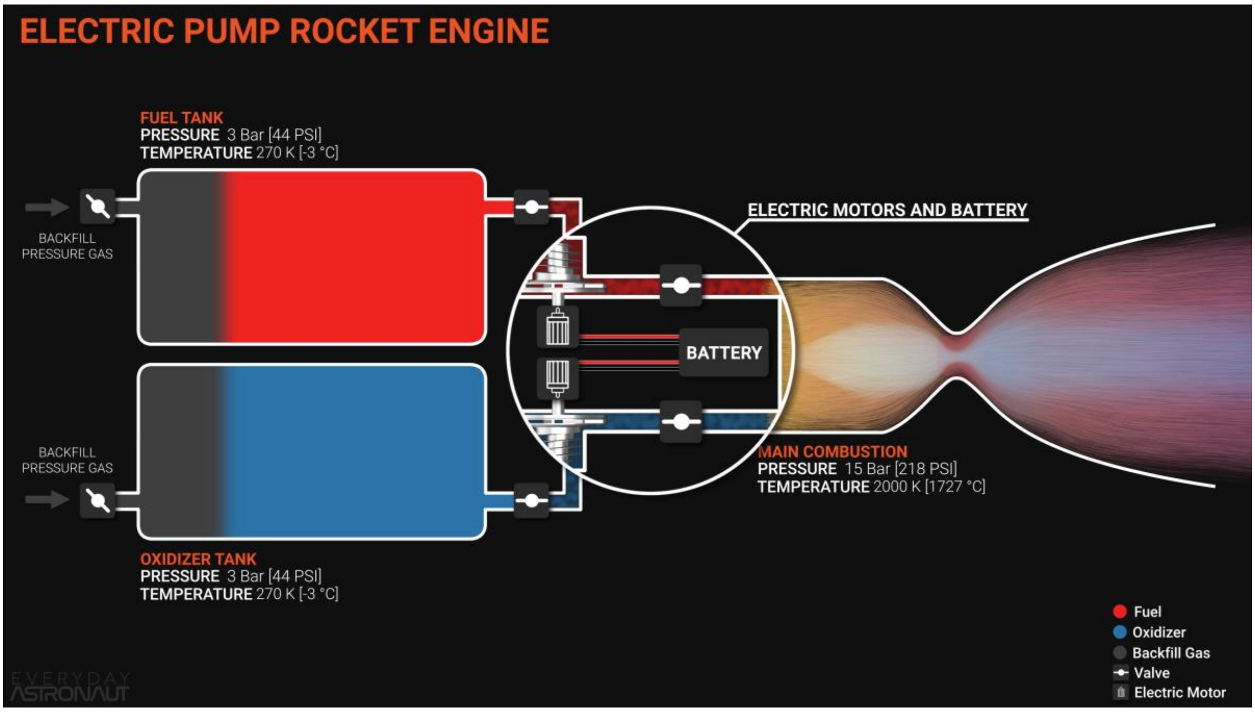
A problem here is the overall pressure in the system, meaning that the pressurant tanks are still the limiting factor. This is similar to what we saw with with cold gas thrusters and monopropellant pressure-fed engines. There is a trade-off where increasing pressure in the system increases weight. Too much additional weight ends up taking away more payload capacity than the increase in performance would add to it.

This helps to explain why we have never seen a purely pressure-fed orbital rocket. By that, we mean that all stages would be powered by pressure-fed engines. It is basically impossible to reach orbit with only pressure-fed engines due to their limited overall performance. This is true even with the newest and state of the art technology, such as carbon composite tanks.

Electric Pump-Fed Engine Cycle

So far in this article, natural pressure in the tanks pushes the propellants into the combustion chamber. This places a natural limit on the chamber pressure. Gases and fluids can only flow by themselves from a high pressure to a lower pressure.

Suppose we want to obtain a higher chamber pressure without increasing the propellant tank pressures. Then our rocket needs to use some form of active mechanism to force the propellants (against nature). This could allow a higher pressure in the combustion chamber than in the tanks.



Battery-powered pump-fed cycle

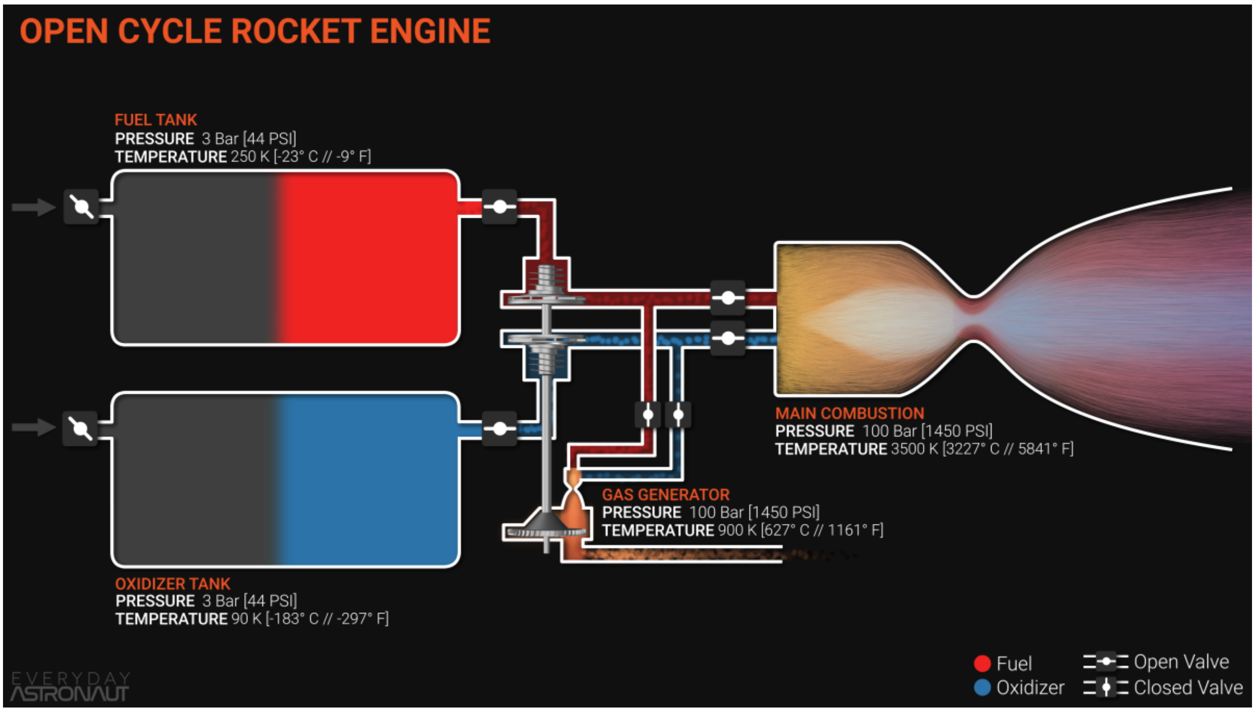
This is where pumps come in. We can use a pump to increase the pressure after the pump, without affecting the pressure before the pump. This is good news for rockets. So a pressure-fed engine might need a tank pressure of 30 bar. An equivalent pump-fed engine might only need a tank pressure of only 3 bar. This saves an enormous amount of mass for the tank. We almost certainly save more mass than we gain for the pump and related items. We can drive pumps using any source of energy, in principle. Let us first consider electric motors driven by battery storage.

Open Cycle (Gas Generator)

We mentioned earlier that pumps can generally require a lot of energy. Pumps must run fast enough to push the propellants into the combustion chamber at the required pressure.

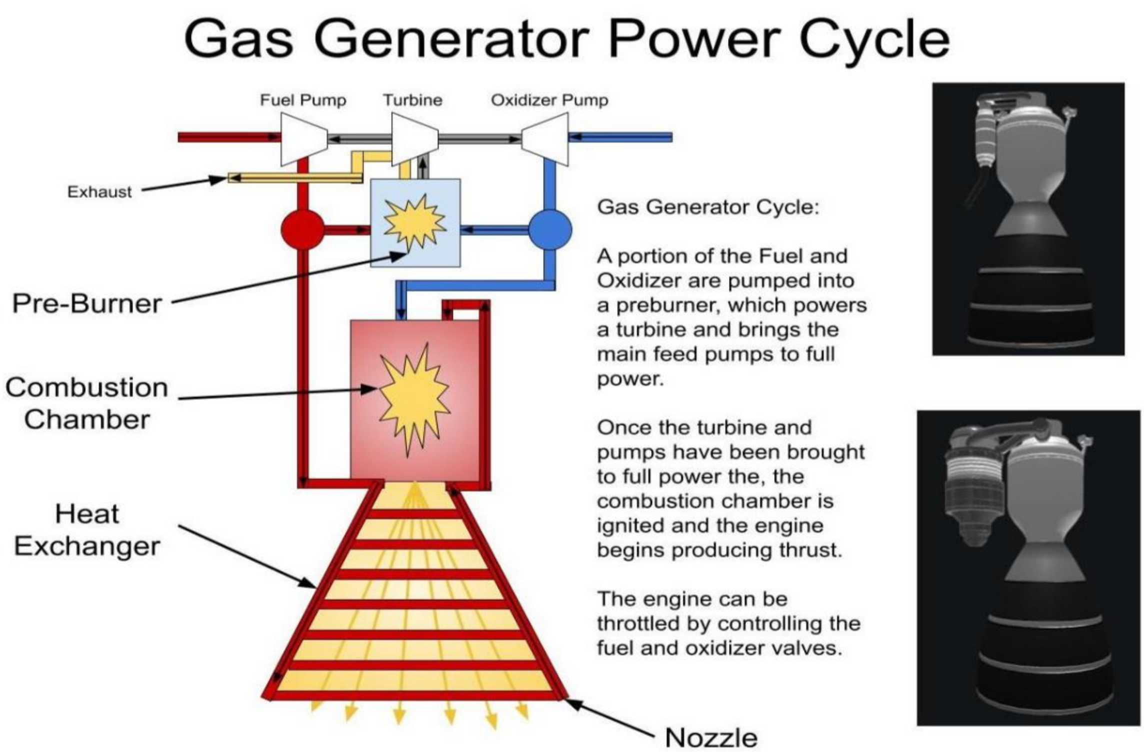
Battery energy density is lower than hydrocarbon energy density, for the right type of fuel. So it is possible to burn some of the propellant in a smaller combustion chamber, generating exhaust gases. We can pass these exhaust gasses over the turbine that spins the pump, to generate the required power.

This is the basis of the open cycle, also known as the gas generator cycle. The German-designed V-2 rocket, powering the A4 engine, was an early example of this. To drive the pumps on the engine, they did not use any of the propellants in the main tanks. Instead, they used a high concentration of hydrogen peroxide, H_2O_2 (which is rich in oxygen). They passed this over a catalyst of potassium permanganate pellets. This triggered a chemical reaction that produced heat and steam at high pressure. This steam had enough energy to spin the turbine that drove the pumps at the right speed.



Open cycle (or gas generator cycle)

The Mercury Redstone rocket also used this technique. It is still in use today on the Soyuz rocket, powering the RD-107A and RD-108A engines. However there is an inefficiency here. We have separate propellant systems for the gas generator than for the main engines.



Closed (Staged Combustion) Engine Cycle

The closed, or staged-combustion, cycle is a more highly developed approach to try to make use of the combustion products that are dumped overboard on the open cycle.

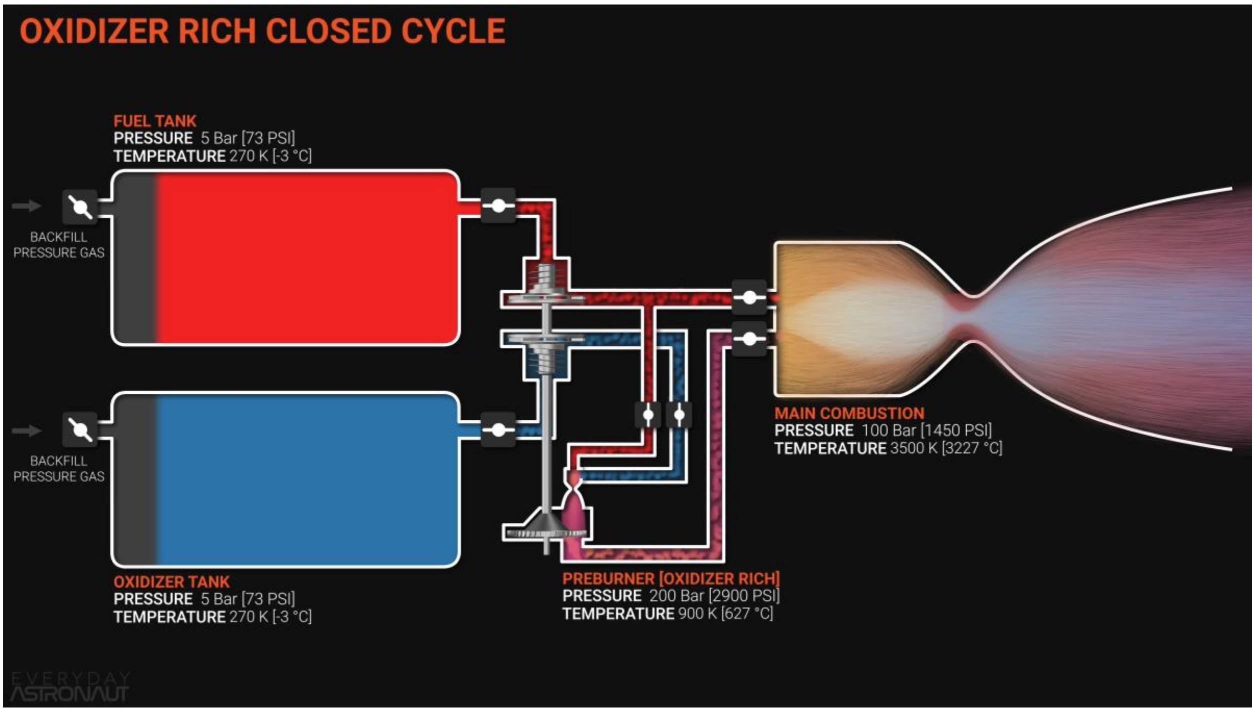
It is not as simple as merely attaching the exhaust from the gas generator to the main combustion chamber, and passing all the gas generator combustion products into the main chamber. This would have several disadvantages that would be very problematic very soon into flight.

The pressure that drives the turbine is usually kept as low as possible, and the pressure downstream from the turbine is lower than upstream of the turbine. As a result, the pressure in the exhaust pipe would be lower than that of the main combustion chamber. This would result in combustion chamber gasses flowing back up the exhaust pipe. This would be the opposite of what is intended.

Furthermore, if the fuel being used in the engine is RP-1 (or any similar fuel based on long-chain hydrocarbons), the exhaust from the gas generator contains enough soot that it would damage the engine by clogging up the injectors. The engine would not last long, at all.

Oxygen-Rich Staged Combustion Engine Cycle

Historically, the oxidizer-rich closed cycle was developed first. You may already be aware of this if you have watched the complete guide to Soviet Rocket Engine history, or read the article. Since this was the first to be developed, we will discuss it here first as well.



Soviet rocket designers and engineers had managed to overcome the challenges of oxidizer-rich staged combustion as early as the 1950s. The achieved this with S1.5400, the upper stage engine on the R7, and it was a major accomplishment. In fact, the United States has to this date never built and flown an engine with this cycle.

Oxygen-rich closed cycle

The Soviets chose to go down the oxygen-rich route because otherwise, if running on hydrocarbon-based fuels such as RG-1 or RP-1, the problems of coking and soot build-up would rapidly cause problems as mentioned earlier. So, in the oxygen-rich route, all of the oxygen runs through the turbine and on into the main combustion chamber.

Alongside the oxygen, only the minimal amount of propellant passes into the preburner – just enough to spin the pumps fast enough to create sufficient pressure and heat. The output from the preburner will lose pressure as it passes over the turbine. The turbine converts heat energy into mechanical work, spinning the pumps.

Now, let us make an observation here. The gas after the pressure drops across the turbine then flows into the main combustion chamber. If we remember what we said earlier about pressure and flow, fluids will always naturally flow from a region of high pressure to a region of low pressure.

Preburner Pressure

This means that the pressure in the preburner must be significantly higher than that of the main combustion chamber. This is necessary to ensure that the pressure after the turbine, and then again after the injector, is still higher than the pressure in the combustion chamber, with some margin of safety.

A decent "rule of thumb" to work with is to have a pressure in the preburner that is twice that of the main combustion chamber, and a pressure at the back of the injector that is 20% higher than that in the main combustion chamber. However, different engines, designed by different engineers, will vary the exact ratios depending on maturity and complexity of the design, and confidence in reliability of the specific design.

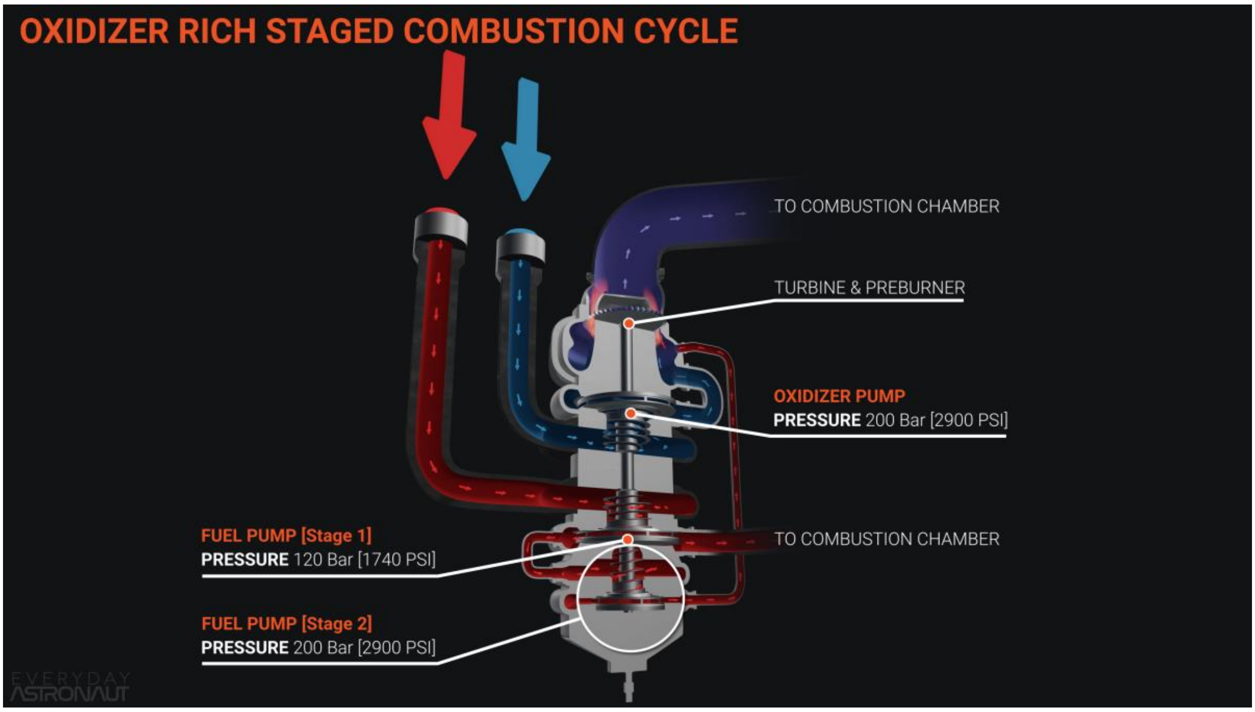
This leads to the next question of how is it possible to obtain a pressure in the preburner that is so much higher than that in the main combustion chamber.

In the oxygen-rich staged combustion cycle, all of the oxidizer must be compressed up to the highest pressure in the engine (for propellants at least), i.e. significantly higher than that of the main combustion chamber.

But the same cannot be said for the fuel. The majority of the fuel flows directly into the combustion chamber, so it only ever needs to be compressed up to 20% higher pressure than that in the combustion chamber. However, a small amount of fuel will need to be compressed further in order to enter the preburner.

Pump Stages

In other words, there are stages to the fuel pump. Most of the fuel passes through the first stage which will take it up to sufficiently high pressure to flow into the combustion chamber. Meanwhile only the minimum amount needed for the preburner goes through another compression stage that increases the pressure high enough to flow into the preburner.



Oxygen-rich pump stages

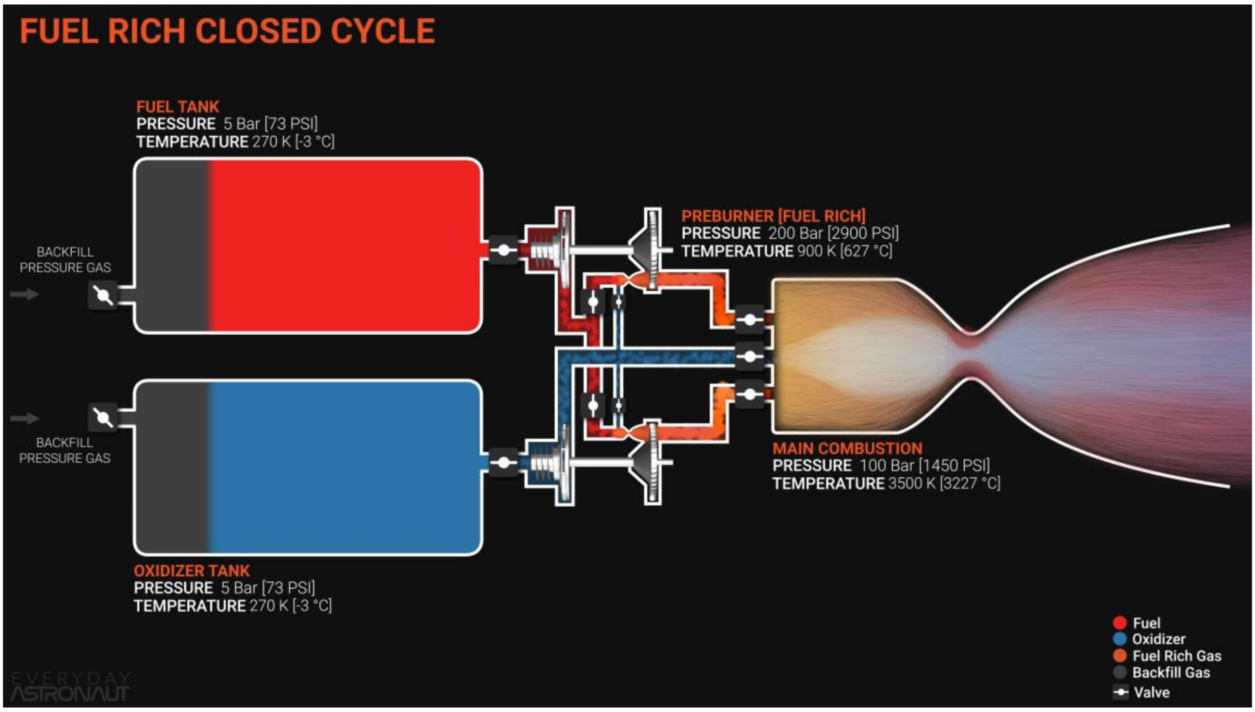
At this stage, you might wonder why, if the oxidizer has already been through the preburner, how can we burn it for a second time in the main combustion chamber? Remember that only a small amount of fuel goes into the preburner. Therefore only a small amount of oxidizer can have reacted with the fuel. Any remaining oxidizer leaves the preburner unburned. It has, however increased its temperature and changed from being in the liquid phase and is now in a gaseous phase.

The majority of the oxidizer has still not reacted with anything. So, it still retains all of its chemical energy when it enters the main combustion chamber, where it can then react with the fuel. This is where the main combustion takes place, unleashing the energy from the remaining un-reacted propellants.

Unfortunately, the oxidizer-rich staged combustion cycle is extremely difficult to implement. This is the result of creating very hot gaseous oxygen. Such hot oxygen tends to react with almost everything in its environment. It requires very specific metal alloys that are capable of surviving such a hostile environment.

Fuel-Rich Staged Combustion Engine Cycle

Now let us consider the alternative to the oxygen-rich cycle, the fuel-rich cycle. In this case, where in general the relationship between the oxidizer and the fuel is reversed from what we looked at previously. In this case, all of the fuel passes through the preburner, and only a minimal amount of oxygen passes through the preburner.



If this were to be attempted on an engine running on long-chain hydrocarbons such as RP-1, then such an engine would suffer quickly from soot build-up and coking as discussed previously. However, it is possible to use fuels that are not carbon-rich. This is the approach taken originally by the United States.

Fuel-rich closed cycle

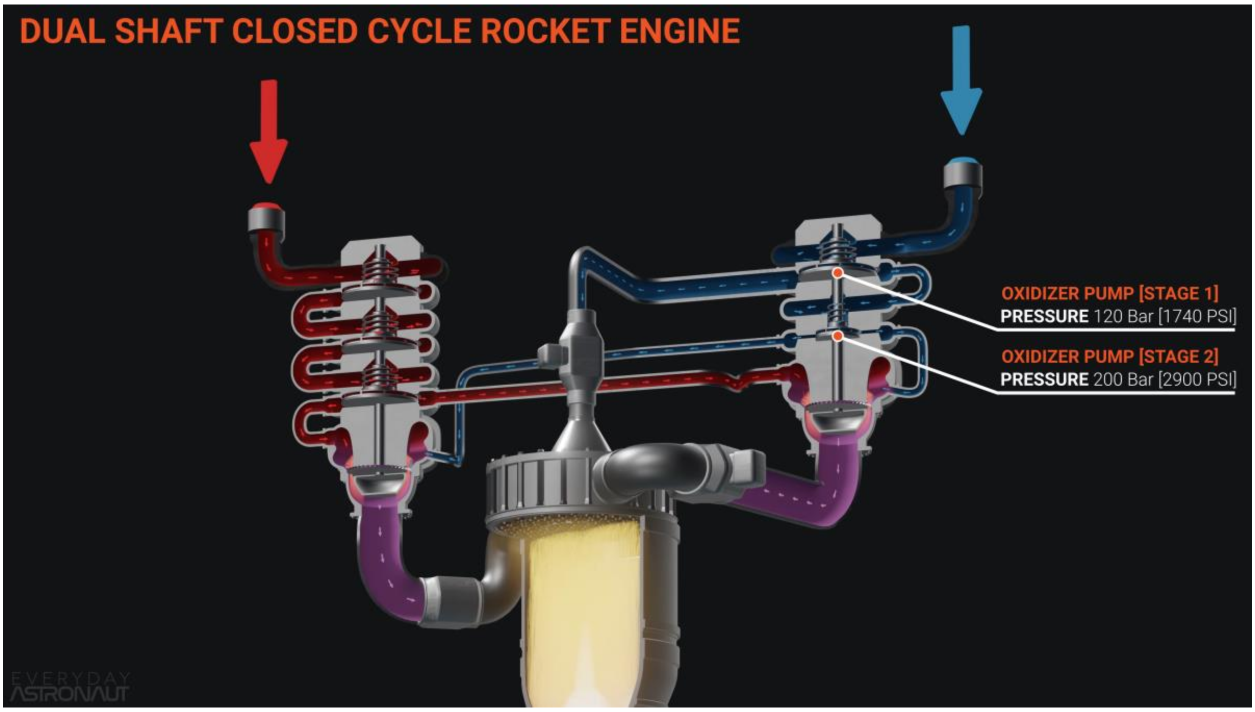
During the design of the main propulsion system for the Space Transportation System (or as mentioned earlier, better known as the Space Shuttle) the engineers opted for liquid hydrogen as the fuel, since they could run plain hydrogen fuel-rich through the preburner(s). Since hydrogen is such a light molecule and has zero carbon content, it does not lead to build-up of soot, and the engine is quite comfortable running on hot gaseous hydrogen.

This may appear to be an obvious solution, however fuel-rich staged combustion still has its own challenges – particularly when using hydrogen for fuel. This is because hydrogen is extremely light and volatile. It takes large pumps featuring multiple stages in order to achieve the high pressures that are needed.

One fairly common, and simple, mechanism for connecting pumps to the turbine is to have one shaft with the turbine on it and both pumps directly driven from it. This is fine if all three items can run at the same rotational speed.

Dual Preburners

Although single-shaft hydrolox fuel-rich closed cycle engines have been built, one example being the Soviet Union's RD-0120 at the heart of the Energia booster, the USA chose a different solution for the Shuttle engines. This raised its own set of problems to overcome.



The design for the RS-25 featured dual preburners, each with its own shaft, and each being fuel-rich. One preburner powers the fuel pump stages and the other powers the oxygen pump.

Dual-shaft preburners

Unfortunately, having high-pressure hot gaseous hydrogen in a preburner that is on the same shaft as high-pressure liquid oxygen is a recipe for disaster. Should any of that hot gaseous fuel seep through the seals on the shaft and encounter the oxygen, it would be "game over" for the engine very quickly.

Purge Seals

This meant that the US engineers had to develop an extremely elaborate so-called purge seal. This prevents propellant traveling up or down the shaft by having an even higher pressure inert gas in the middle. Helium was chosen for this role. The purpose of this helium is to guarantee that in the event of any leak in a seal, the helium flows towards the propellant, and the propellants remain well separated.

The diagram below shows the two separate turbines, each with its own preburner, on a dual-shaft, fuel-rich closed cycle engine.

As you might expect, one preburner powers the oxidizer pumps and the other power the fuel pumps. Since both of the preburners are fuel-rich, all of the fuel will flow through one of the preburners and over the turbines before entering the main combustion chamber. Thus approximately half of the fuel flows through each preburner and turbine.

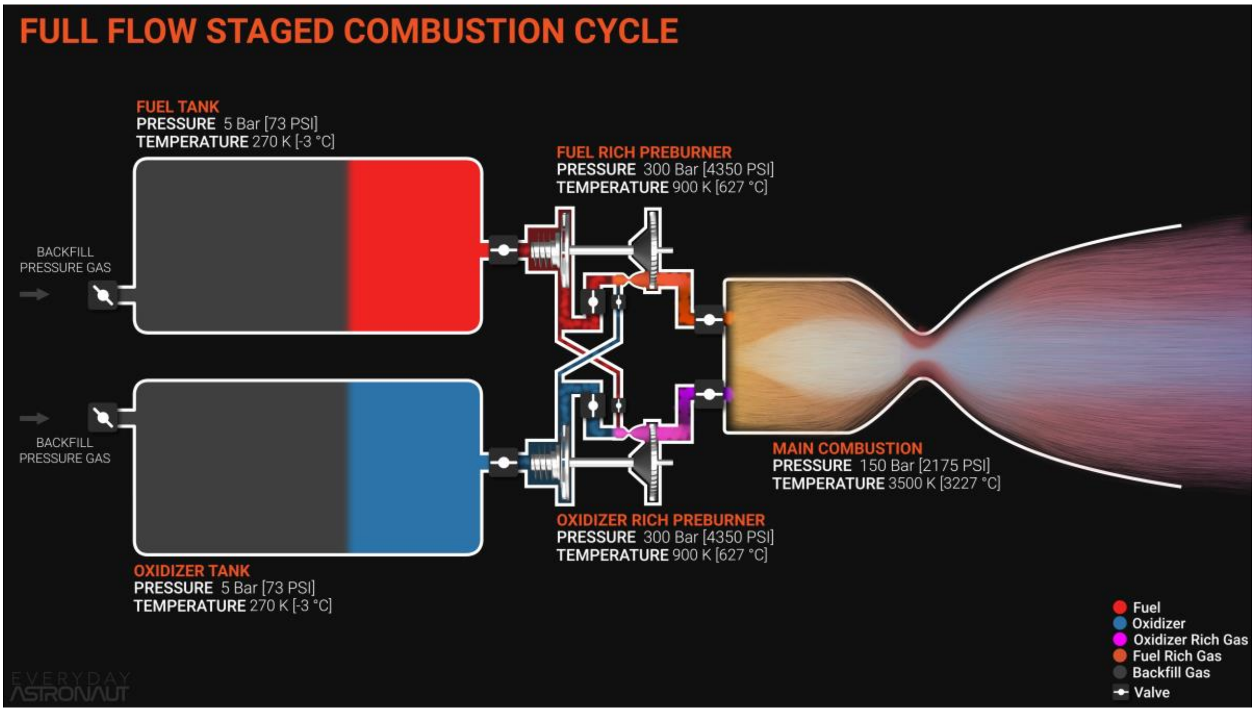
In the exact opposite to the oxidizer-rich closed cycle engine discussed earlier, only a minimal amount of oxidizer is fed through the preburners – just what is sufficient to extract enough combustion energy to spin the pumps. More specifically, to spin the pumps to the required speeds to drive the propellants through the preburners and into the combustion chamber.

Following the model discussed for the oxidizer-rich closed cycle, in this case most of the oxidizer flows through a single-stage pump that only needs to produce sufficient pressure to cause the oxidizer to flow into the main combustion chamber. Meanwhile, the small amount of oxidizer that is routed via the preburners then flows through a second stage of pumps in order to achieve the much higher pressures as discussed previously.

Full-Flow Staged Combustion Engine Cycle

The full-flow staged combustion cycle is named for the flow of the propellants through the preburners. Both the fuel and the oxidizer are totally routed through a preburner and a turbine. This means that the cycle design features both a fuel-rich preburner and an oxidizer-rich preburner.

The diagram illustrates the flow of the propellants as they are passed through the pumps and the turbines. Fuel and oxidizer both arrive at their respective pump inlets at tank pressure, then the pumps compress each of them up to full preburner pressures.



Full-flow, staged-combustion cycle

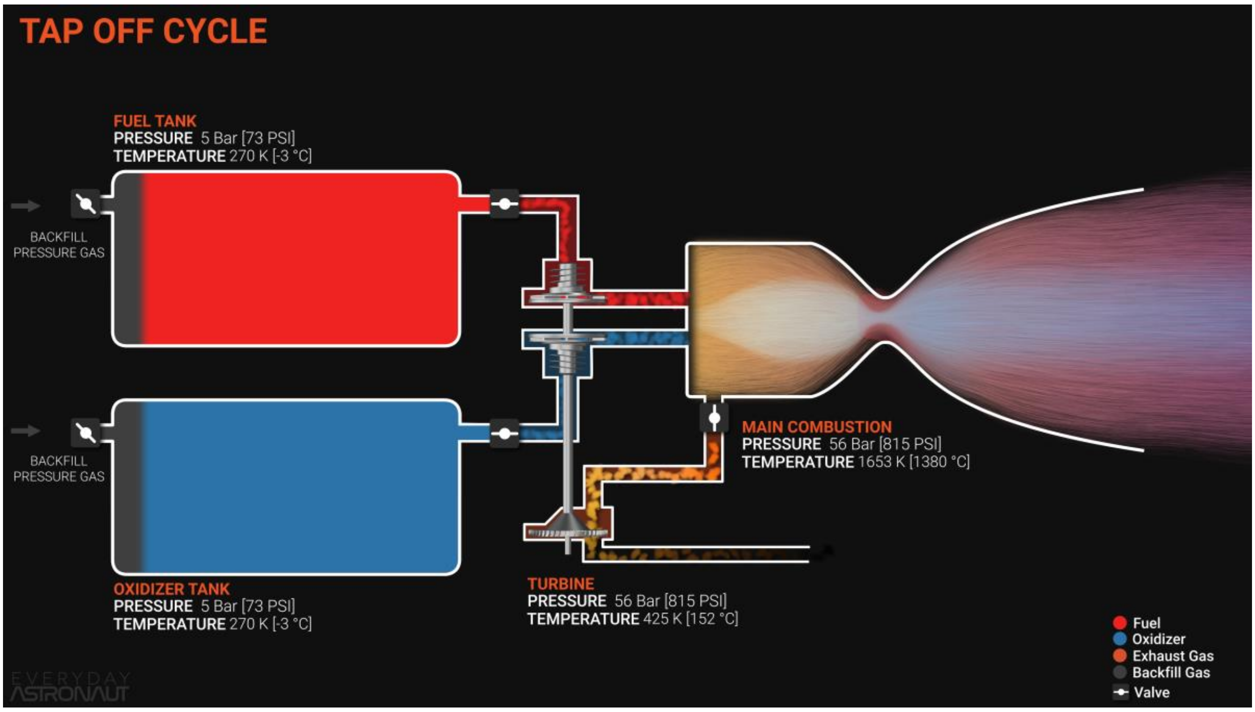
Almost all of the oxidizer is run through the oxidizer-rich preburner and turbine, with a minimal amount to oxidizer being sent through the fuel-rich preburner. In parallel, almost all of the fuel is run through the fuel-rich preburner and turbine, with a minimal amount of fuel being sent through the oxidizer-rich preburner.

This means that both propellants end up arriving at the combustion chamber already fully in gaseous form. This is a huge advantage over other cycles discussed earlier. A gas-gas interaction is extremely efficient, leads to improved mixing of gas products prior to combustion, leading to faster combustion with less unburnt residuals than liquid-liquid or liquid-gas interactions.

Tap-Off Engine Cycle

This next cycle may sound ridiculous, but let us consider punching a hole in the side of the main combustion chamber. This would lead to the escape of very hot, high-pressure gas. The engine designers remove the complications and weight of either a preburner or a gas generator, and just use the main combustion pressure instead.

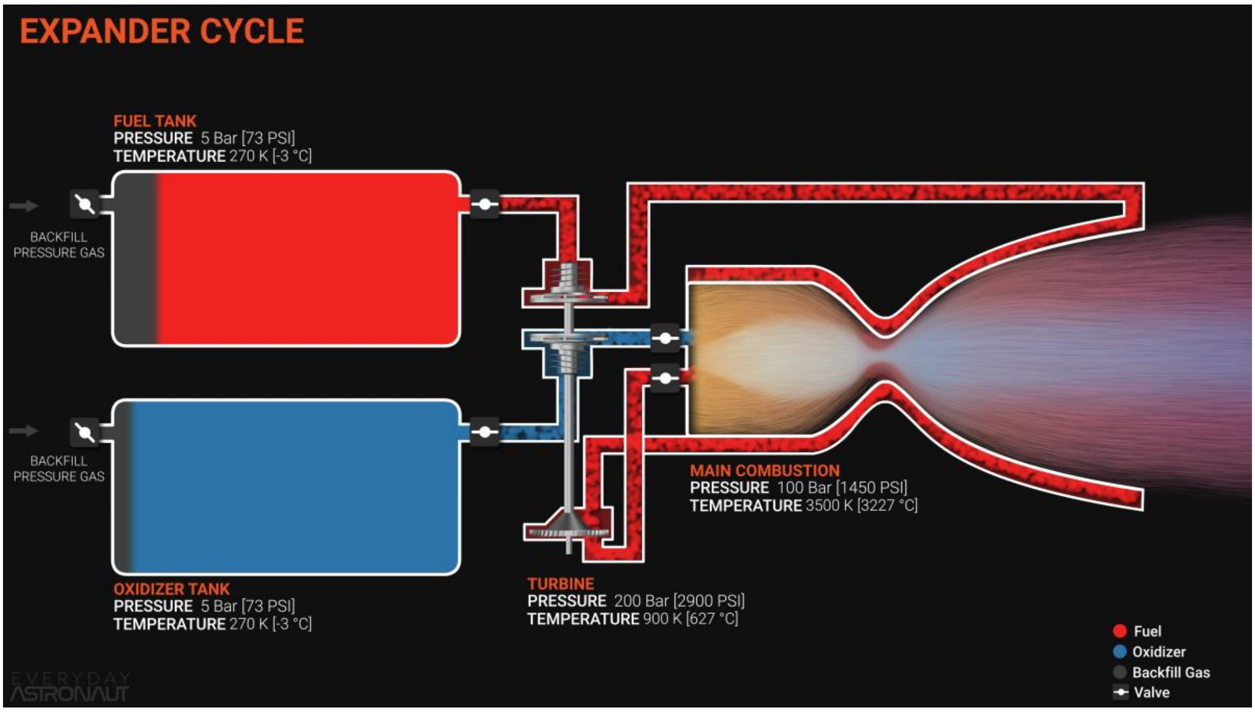
By having some gas products leave the combustion chamber from the side rather than from the nozzle, there is a small amount of performance loss. However its saves a lot of complexity which is an advantage.



An interesting aspect of the tap-off cycle is that it can be self-regulating to some extent, since it is possible to limit the amount of pressure that the turbine is exposed to with a choke, or by how much the throat leading to the turbine is reduced in diameter.

Expander Engine Cycle

We already explained that heat is both a friend and an enemy in rocket engines. High temperatures can unlock new amounts of useful energy in a system, but they can also be damaging if they occur in the wrong place.



Now, there is one useful thing that an engine can do with its own heat, and that is to actually run the engine. Is this a form of recursion?

This is the description of the expander cycle. During the thermal expansion of the fuel or the oxidizer, energy is released. (The fuel is used most commonly.) The expander cycles harnesses this energy to cool the engine.

Expander cycle

If you have seen the “why don’t rocket engines melt?” video or read the article, you may remember that a very common and extremely effective method of cooling a rocket engine is to pump the fuel through the walls of walls of the combustion chamber and nozzle to keep them cool.

In the process of cooling the walls, some of the heat from the combustion chamber passes to the fuel, so that the fuel absorbs some of that heat energy. Some fuels have better capacity for taking on such heat than others. Specifically, hydrogen is very good for this role due to its enormous heat capacity.

In all of the other engine cycles, they pump into the combustion chamber as a hot gas which then has to react with a liquid oxidizer. However, in the case of the expander cycle, we can take the heat energy removed by the fuel during regenerative cooling and use this to spin the turbine.

Expander Cycle Limitations

In a similar way to the closed cycle engines, the pressure of the gaseous fuel has to be fairly high before it reaches the turbine. It has to be sufficiently high that it can go through the turbine (leading to a drop in pressure) and still have a healthy pressure margin over that in the main combustion chamber.

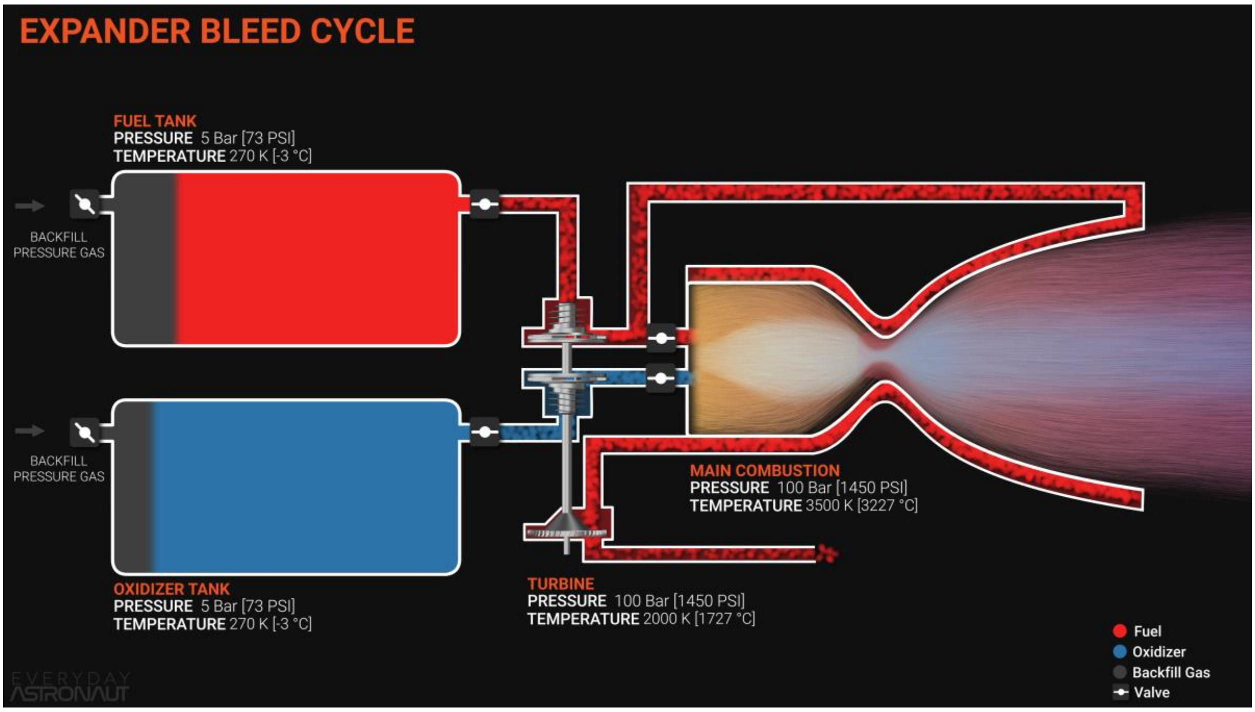
This means that the fuel pump has to do a lot of work to compress the fuel to these necessary pressures. In the case of liquid hydrogen, the pump will have to be huge, with several stages in order to obtain the required pressure.

In the case of a hydrogen-fueled engine with a single turbine, engineers may need to make use of a gearbox inside the turbopump so that they can arrange to direct the required speed and energy to the fuel pumps while sending less energy to the oxygen pump which does not need so much.

One again, we have a cycle that trades one form of simplicity and efficiency for a new complication and more moving parts. We can considered this as free energy available in the system in order to power the pumps. This is very efficient.

Expander Cycle Variants

There is a variant of the expander engine cycle type, the expander bleed cycle. In this variant, the system is a little bit more simple due to avoiding returning the fuel to the combustion chamber after it has spun the turbine.



This means that more of the pressure can spin the pumps. Therefore the pressure after the turbine no longer needs to be higher than that in the combustion chamber. The engine only uses a small amount of the expanded hot gas to drive the pumps and then throws it overboard. So it wastes a small amount of unburnt fuel, but overall it is still very efficient.

Expander bleed cycle

This variant helps to overcome the limitations of available thrust since it is possible to use more of the limited pressure that is available to power the pumps. In other words, it trades a little bit of efficiency loss in exchange for the potential for increased thrust and lower complexity.

There are few examples of this variant, such as the BE-3U that will power the upper stage of Blue Origin’s upcoming New Glenn orbital rocket and the LE-5A and LE-5B on Japan’s H-I, H-II, and upcoming H-III rockets.

There is yet another variant on the expander cycle, known as the dual expander cycle. This utilizes both the fuel and the oxidizer to each run a set of pumps. This could be useful on some smaller engines that tend to run hot, such as for example future aerospike engines.

Rocket Staging

Staging is the combination of several rocket sections, or stages, that fire in a specific order and then detach, so a ship can penetrate Earth's atmosphere and reach space.

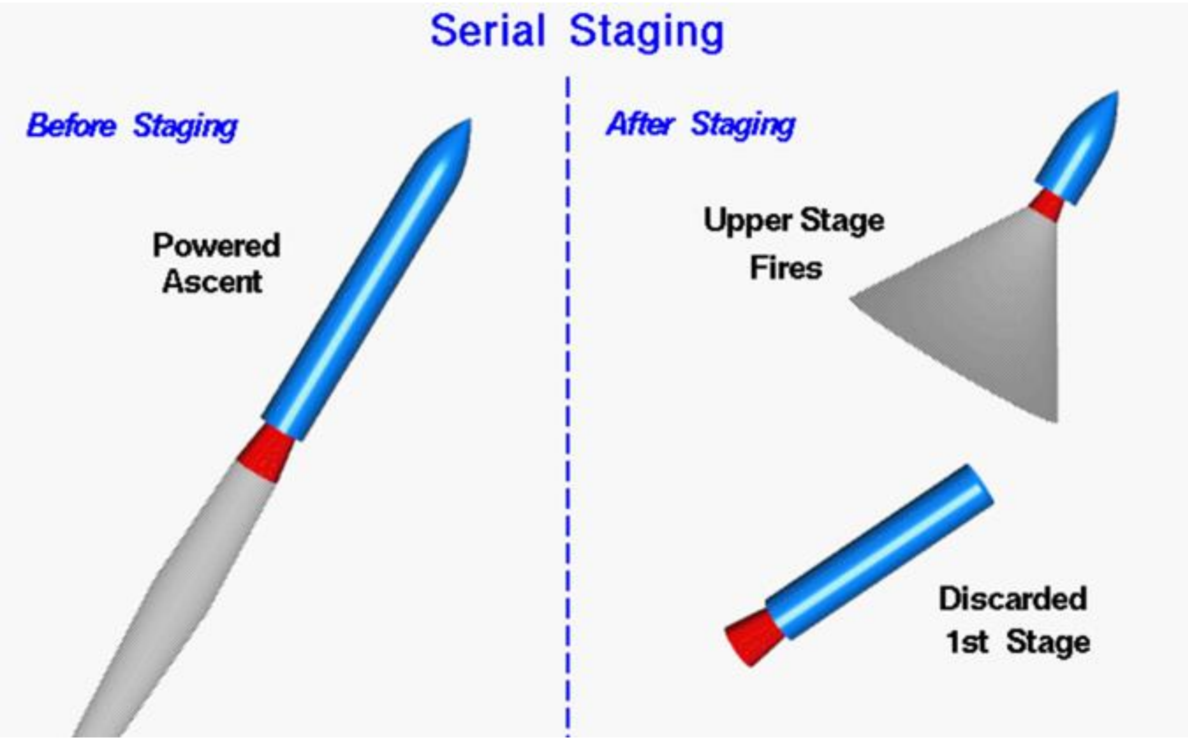
The operative principle behind rocket stages is that you need a certain amount of thrust to get above the atmosphere, and then further thrust to accelerate to a speed fast enough to stay in orbit around Earth (orbital speed, about five miles per second).

It's easier for a rocket to get to that orbital speed without having to carry the excess weight of empty propellant tanks and early-stage rockets. So when the fuel/oxygen for each stage of a rocket is used up, the ship jettisons that stage, and it falls back to Earth. This becomes part of the rocket's mass fraction—the portion of its fully fueled pre-launch mass that does reach orbit.

Different Kinds of Rocket Staging

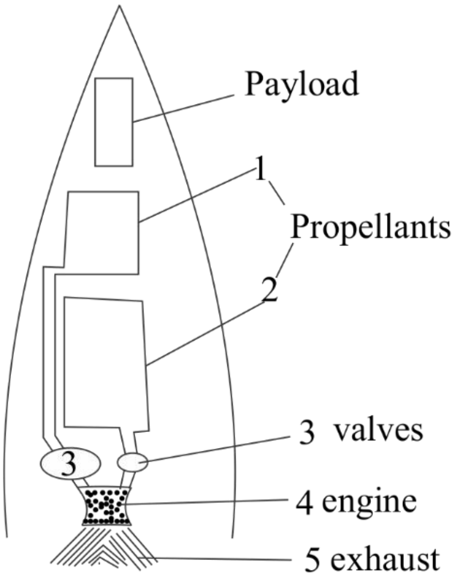
The kind of staging astronauts use depends upon their mission needs and what forces they need to overcome.

1. **Serial staging**. Stages are attached, one on top of the other, or stacked. The first stage ignites at launch and burns through its fuel until its propellants are spent. Now useless dead weight, in a staging maneuver the first stage breaks free from the previous stage, then begins burning through the next stage in straight succession. Depending on the rocket, the second stage may get the payload into orbit or require a third or fourth stage to ultimately deliver it to space. It depends on the individual rocket and mission.
2. **Parallel staging**. Whereas serial staging involves stacked stages, parallel staging features one or multiple booster stages strapped to a central sustainer, as on the space shuttle. At launch, all the engines ignite. When their propellant runs out, the strapped-on boosters fall away. The sustainer engine keeps burning to put the payload into orbit. With the shuttle, solid rocket boosters are the stages that fall away from the main sustainer, the external tank that fed the main engines. The Titan III is an example of a rocket that uses both serial and parallel staging; it used a two-stage Titan II as the sustainer and added two solid rocket stages as boosters that fell away once they were done, much like the SRBs on the shuttle.



3. **Stage-and-a-half**: This less common staging has a main core that acts like a sustainer stage and a booster stage that falls away during the flight. This dates back to the Atlas D that launched John Glenn in 1962 and the three Mercury astronaut who followed in his orbiting footprints. At the time, the upper stages of multistage rockets often didn't fire on time and rockets blew up. To make sure the engines all ignited properly, it made sense to Atlas designers to have all engines ignite while the rocket was still on the launch pad. Dropping the booster that was also sort of part of the main stage was how it dropped the dead weight in flight, making the rocket light enough to put a Mercury capsule into orbit.

4. **Single staging**. More a dream in development than a current reality, a single stage rocket is a simpler technology that doesn't require multiple complicated and dangerous stages to get through the atmosphere.



What Is the Purpose of the First Stage in a Serial Staging?

There are multiple staging schemes for rockets, and the number of stages varies depending upon the spacecraft and the mission objectives. Typically, a rocket with three stages will undergo the same process. In serial staging schemes, the first stage is at the bottom of the rocket and is usually the largest. Its primary purpose is to get the spacecraft to a height of 150,000 feet, above most of the Earth's air.

- **Launch location is important**. This comes down to physics. As a general rule, rockets launch from as near as possible to the equator, in order to take advantage of the velocity of Earth's rotation, which is highest at the equator—about 1,000 miles an hour. The more orbital velocity a rocket gets from Earth, the less fuel it requires to reach orbital speed, which increases its efficiency. Not all rockets can take advantage of Earth's spin—some are designed to send payloads such as satellites into north-to-south orbit, around the poles.
- **The ride is intensely physical**. G-forces are three times normal and there is rough, high-frequency vibration as the vehicle shoulders its way through the thick air. After two minutes the rocket is high enough that the air has thinned to almost nothing, and the first-stage boosters explode off in a burst of fireworks.
- **As velocity increases, so too does drag**. This is why flying a rocket through the atmosphere is so hard. To decrease drag, the cross-sectional area of the spaceship needs to be minimized, which is why rocket ships have to be streamlined.
- **Lower stages like this typically require more structure than the upper stages**. This is because they must bear their own weight as well as the mass of the stages above them that are not yet in use.
- **This initial rocket stage needs to rapidly push the rocket into higher altitudes**. As such, it typically has a lower specific impulse rating, trading efficiency for superior thrust.

What Is the Purpose of the Second Stage in a Serial Staging?

The second stage is second from the bottom of the rocket. Its purpose is to get the spacecraft to orbital velocity and achieve weightlessness.

- **The ride smooths out**. Above the majority of Earth's air, the ride gets suddenly smooth—but steadily heavier as the ship burns off fuel and the acceleration grows. The spaceship rolls through 180 degrees to let the communication antennae point at orbiting relay satellites.
- **Achieving weightlessness**. The ship becomes light enough that it reaches 3G, and the computers ease the throttles back to not overstress the vehicle. Each passing second takes the crew past emergency abort and failure options and improves astronauts' chances of

making it to orbit. And after eight and a half minutes, the stage engines shut down and they are safely there, weightless, in space.

- **Ideal acceleration occurs above the atmosphere**. Not only do the most efficient rockets have lower areas, but they also do as much of their accelerating (increase in velocity to orbital speed) as possible once they've gotten above the atmosphere into areas of lower air density. Once beyond the atmosphere, astronauts can increase the speed without increasing the force of drag because there's no atmospheric density.
- Since the vehicle is further outside the atmosphere and the exhaust gas does not need to expand against as much atmospheric pressure, this later stage usually has a higher specific impulse rating.

What Happens to Detached Stages?

The spent upper stages of launch vehicles are a significant source of space debris remaining in orbit in a non-operational state for many years after use, and occasionally, large debris fields created from the breakup of a single upper stage while in orbit.

Since the 1990s, when an upper stage is spent, astronauts have generally dumped any remaining fuel or discharged batteries, "passivating" them to reduce risks while those stages continue to orbit. Prior to that, many Soviet and U.S. space programs often did not passivate the upper stages after mission completion.