

Trajectories and Propulsion



History of Rockets

- 400 BCE One of the earliest mentions of anything rocket-like in history appears to be from the writings of Aulus Gellius, a Roman. Gellius writes about a Greek individual named Archytas who is from the city of Tarentum, a part of what is now known as Southern Italy. In this story by Gellius, the character Archytas uses a wooden pigeon suspended by wires and propelled by steam to amaze and mystify the Tarentum locals.
- 1st Century BCE Sometime in the 1st century BCE, the Greek inventor Hero of Alexandria (70 to 10 BCE) is noted to have invented the device known as the aeolipile. The aeolipile was a steam-driven device that, like Archytas's pigeon, also implemented Newton's Third Law of action and reaction. Figure 1.1 shows an artist's rendition of the aeolipile. It should also be noted here that the device is sometimes described as Hero's engine.
- 904 AD The Chinese began using gunpowder in warfare as incendiary projectiles by this time. These projectiles were known as "flying fires." They were fired as arrows, grenades, and catapults.
- Taylor, Travis S.. Introduction to Rocket Science and Engineering (p. 3). CRC Press. Kindle Edition.

History of Rockets

- 1449 AD Frenchman Jean Froissart discovered a means of improving the accuracy of rockets. He realized that rockets were more accurate when launched from a tube. This was the birth of the bazooka and actually the launch tube.
- 1696 AD In 1696, the Englishman Robert Anderson published a document on how to build solid rockets. He described how to mix the propellants and then to pour them into molds. He also described how to prepare the molds. This is sometimes suggested as the first step in the mass production of rockets.
- In 1806, Frenchman Claude Ruggieri launched small animals in rockets equipped with parachutes. Perhaps this is the first mention of actual rocket passengers or occupants that were returned with some, at least potentially, safe method.
- Taylor, Travis S.. Introduction to Rocket Science and Engineering (p. 3). CRC Press. Kindle Edition.

History of Rockets

-
- 1841 AD Russo–Turkish War. In 1841, a patent was granted in England for the first-ever “rocket airplane.” The patent was granted to one Charles Golightly. The idea apparently employed a steam-driven rocket. No prototype was ever constructed.
 - 1903 AD Tsiolkovsky reportedly worked as a high school mathematics teacher until he retired in 1920. In 1903, he published what has become known to the rocket science community as the first true book or treatise on the subject. *The Exploration of Cosmic Space by Means of Reaction Devices* describes most of the aspects and intricacies of modern rocket science.
 - Robert Goddard was born in 1882 in Worcester, Massachusetts. Goddard suffered from stomach problems as a child and, as a result, fell two years behind in his schoolwork. As he matured, he became deeply interested in reading and reportedly made regular visits to his local library. He received a bachelor’s degree in physics from Worcester Polytechnic Institute in 1908, a master’s degree from Clark University in 1910, and a PhD from Clark University in 1911. In 1912, he moved to Princeton University on a research fellowship. Goddard’s earliest experiments were with solid rockets, and, after various experiments 1915, he became more and more convinced that liquid rocket fuel would enable the rocket to carry more payload to higher altitudes. Undoubtedly, World War I helped fund and fuel the need for Goddard’s and others’ research. In 1919, he published a book titled *A Method of Reaching Extreme Altitudes*, which is one of the reasons he is known as one of the founders of modern rocketry. He set about experimenting with liquid engines and launched his first successful flight on March 26, 1926. Figure 1.4 shows Goddard and his rocket. The flight lasted 2.5 sec and traveled a ground distance of about 56 m. The rocket peaked at only 12.5 m.
 - Taylor, Travis S.. *Introduction to Rocket Science and Engineering* (p. 3). CRC Press. Kindle Edition.

Four Classes of Flight Vehicles

- **Winged re-entry vehicles (RV)**
 - Space Shuttle Orbiter, Buran, Hermes
 - pressure-effect dominated, strong real-gas effects, radiation, low density effects
- **Hypersonic cruise vehicles (CV)**
 - NASP, first stage of the Sänger system
 - viscous-effect dominated, transition important, surface radiation
- **Ascent and re-entry vehicles (ARV)**
 - upper stage of the Sänger system
 - partly viscous dominated, transition important, real-gas effects, low density effects, radiation
- **Aeroassisted orbit transfer vehicles (AOTV), also known as aeroassisted space transfer vehicles (ASTV)**
 - ionization, radiation, strong real-gas effects, low density effects
- **Ballistic re-entry vehicles not included (they're not "flying"):**
ICBMs

Sänger Reusable Launch Vehicle (RLV)

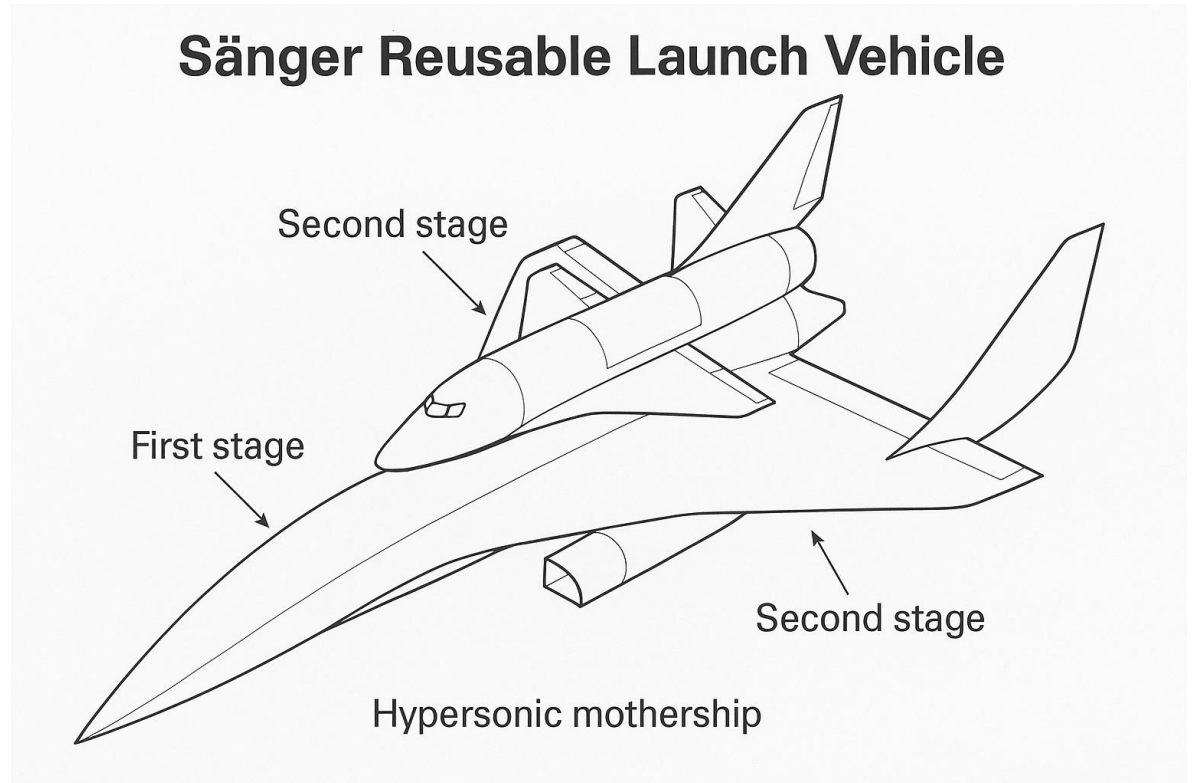
The Sänger Reusable Launch Vehicle (RLV) refers to a post–World War II evolution of the Silbervogel concept originally proposed by Eugen Sänger and Irene Sänger-Bredt. This later version was conceived as a two-stage, air-breathing and rocket-powered spaceplane system that could launch payloads into orbit and return for reuse, making it one of the earliest forerunners of modern reusable launch systems.

Feature	Description
Type	Two-stage-to-orbit (TSTO) spaceplane
Launch Mode	Horizontal takeoff using a hypersonic first stage
Mission	Deliver satellites, cargo, or crew to low Earth orbit
Propulsion	Combined-cycle: air-breathing in lower atmosphere, rockets in upper atmosphere
Reusability	Both stages designed for reuse

Sänger Reusable Launch Vehicle (RLV)

- **Stage 1: Hypersonic Carrier Aircraft**
 - Large, winged vehicle using air-breathing ramjet/scramjet engines.
 - Accelerates to Mach 6–7 at high altitude (~30–40 km).
 - Carries the second stage piggyback and separates after reaching speed/altitude.
 - **Stage 2: Orbital Spaceplane**
 - Compact, rocket-powered vehicle.
 - Boosts from separation point into low Earth orbit (LEO).
 - Designed for crew or cargo missions.
 - Reenters and lands like a conventional aircraft (glide landing).
-

Sänger Reusable Launch Vehicle (RLV)



Hermes

The Hermes project by the European Space Agency (ESA) was an ambitious but ultimately canceled initiative to develop a reusable spaceplane capable of transporting humans and cargo to low Earth orbit:

- Initiated by: European Space Agency (ESA)
- Timeline: Concept work began in the 1980s; officially abandoned in 1992.
- Goal: Develop a reusable, human-rated spacecraft for independent European access to space, particularly to service space stations like Columbus and Freedom (the precursors to the ISS).

Hermes

Vehicle Configuration

- Type: Manned spaceplane (mini-shuttle)
- Launch Configuration: Mounted atop the Ariane 5 launch vehicle
- Reusability: Designed for up to 10 missions

Size and Mass

- Length: Approx. 19 meters
- Wingspan: Approx. 7 meters
- Total launch mass: Around 21 metric tons
- Crew capacity: 3 astronauts, with provision for future expansion to 6

Aerodynamics and Shape

- Blended lifting-body design with short, stubby wings and a small vertical stabilizer
- Optimized for both orbital flight and controlled re-entry
- Thermal protection system (TPS) similar in concept to NASA's Space Shuttle, using ceramic tiles and reinforced carbon-carbon

Propulsion and Power

- No onboard launch propulsion: Entirely dependent on Ariane 5 for ascent
- Onboard systems for orbital maneuvering and re-entry control
- Power supply: Batteries and fuel cells (solar panels were considered but not implemented)

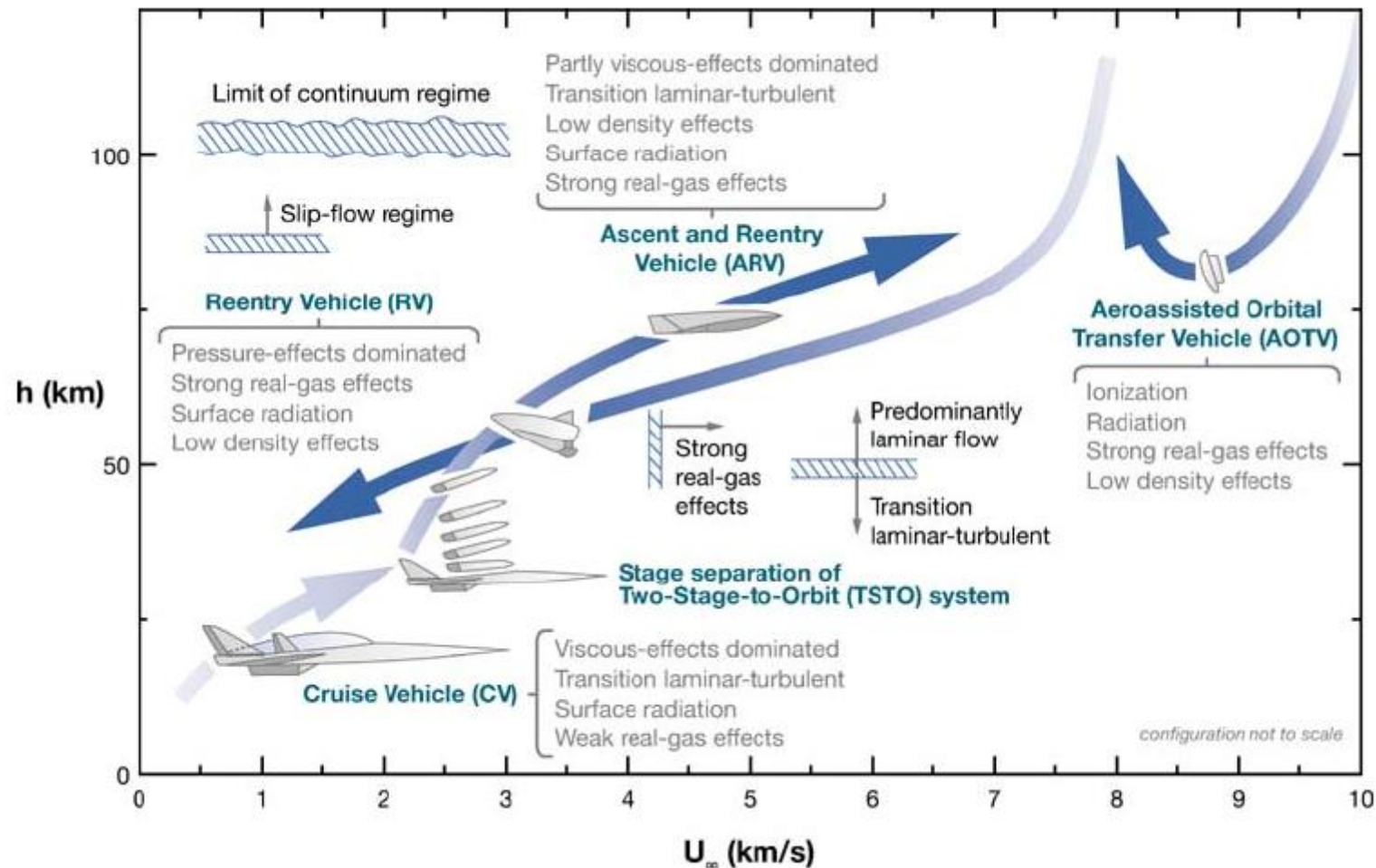
Avionics and Safety

- Fly-by-wire controls and redundant safety systems
- Designed for autonomous or manual piloted flight
- Crew escape system: ejection seats in early versions; later replaced by an emergency escape module



Hermes

Typical Hypersonic Trajectories



Bertin & Cummings, "Critical Hypersonic Aerothermodynamic Phenomena," Annual Review of Fluid Mechanics, 2006

Classification of Hypersonic Vehicles

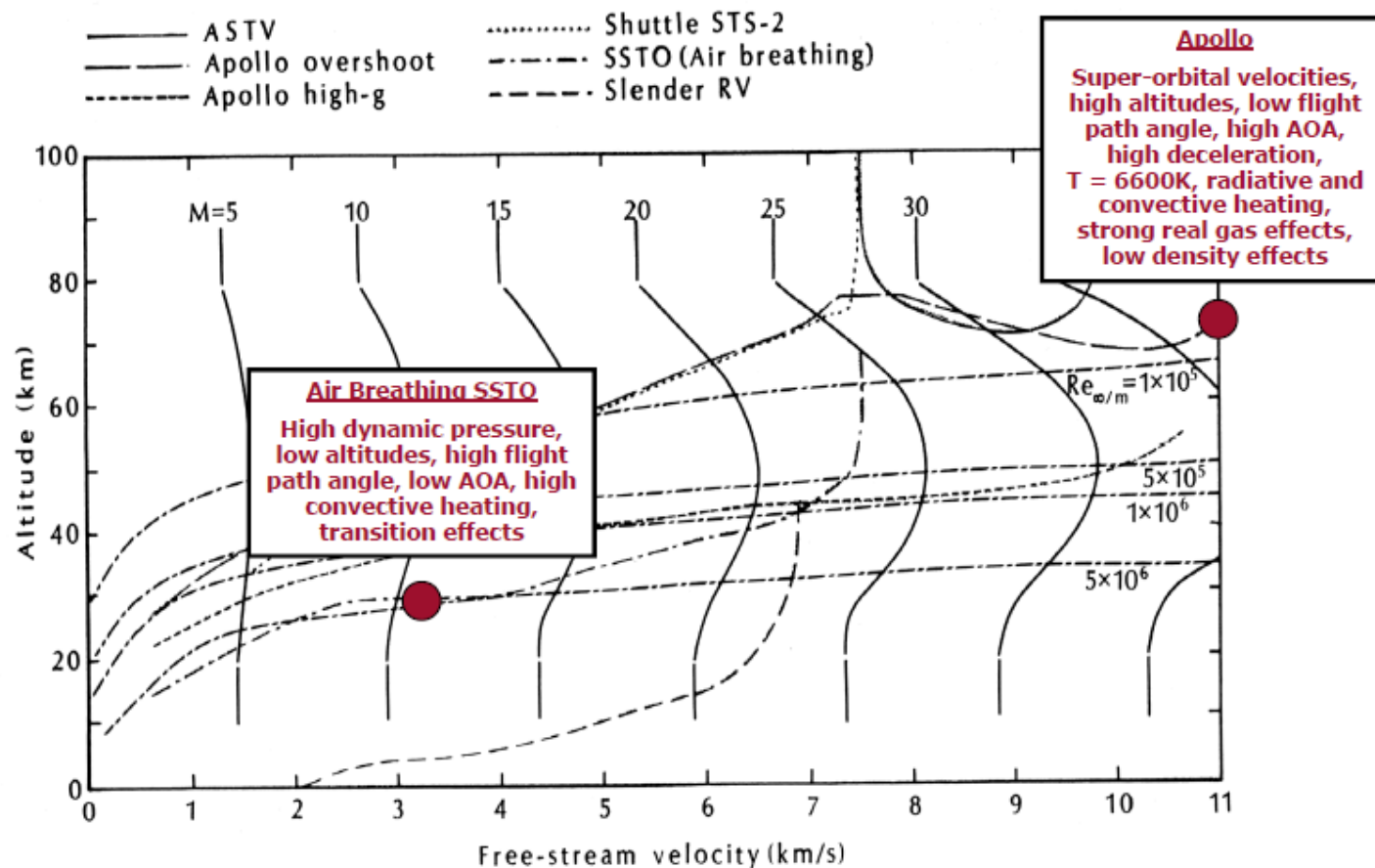
<i>Item</i>	<i>RV</i>	<i>CV</i>	<i>ARV</i>	<i>AOTV</i>
Mach number	28 – 0	0 – 7 (12)	0 (7) – 28	20 - 35
Configuration	blunt	slender	opposing situation	very blunt
Flight time	short	long	long/short	short
Angle of attack	large	small	small/large	head on
Drag	large	small	small/large	large
Lift/Drag	small	large	large/small	small
Flow field	compressibility-effects dominated	viscosity-effects dominated	viscosity/compressibility dominated	compressibility-effects dominated
Thermal surface effects (viscous)	not important	<u>very important</u>	opposing situation	not important
Thermal surface effects (thermochemical)	<u>very important</u>	important	opposing situation	<u>very important</u>
Thermal loads	<u>large</u>	medium	medium/large	<u>large</u>
Thermo-chemical effects	<u>strong</u>	weak/medium	medium/strong	<u>strong</u>
Rarefaction effects	initially strong	weak	medium/strong	<u>strong</u>
Critical components	control surfaces	inlet, nozzle/afterbody, control surfaces	inlet, nozzle/afterbody, control surfaces	control devices
Special problems	large Mach number span	propulsion integration, thermal management	<u>propulsion integration, opposing design requirements</u>	plasma effects

RV = Reentry Vehicle
 CV = Cruise Vehicle
 ARV= Ascent and Reentry Vehicle
 AOTV = Aero assisted Orbital Transfer Vehicle

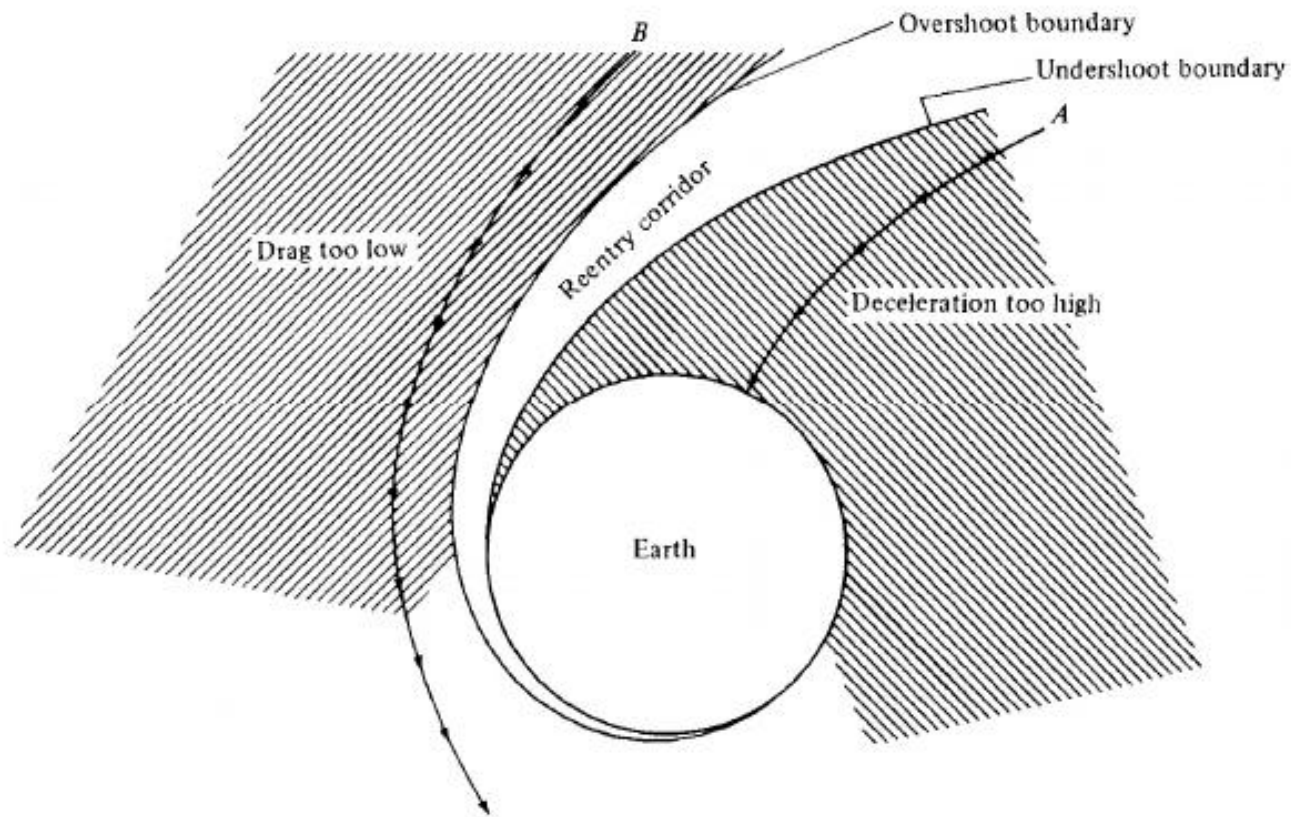
Aerothermodynamics

- “*aerothermodynamics* couples the disciplines of *aerodynamics* and *thermodynamics*.” (Gnoffo et al. 1999)
- Sounds easy . . . but . . .
- Look at the ballistic coefficient of the vehicle based on work of Allen and Eggers (1957):
$$\beta = \frac{m}{C_D A}$$
 - Low β : minimize convective heating with high pressure drag (blunt body; single tiles from Columbia re-entered with $\beta = 2.4 \text{ kg/m}^2$)
 - High β : minimize convective heating with low shear drag (slender cone; ballistic missile typically with $\beta = 500 \text{ kg/m}^2$)
 - Medium β : combination of the extreme ranges (capsules, Shuttle *Orbiter*, Hermes)
- All of these cases lead to difficult aerothermodynamic issues

Typical Hypersonic Trajectories



Re-Entry Limits

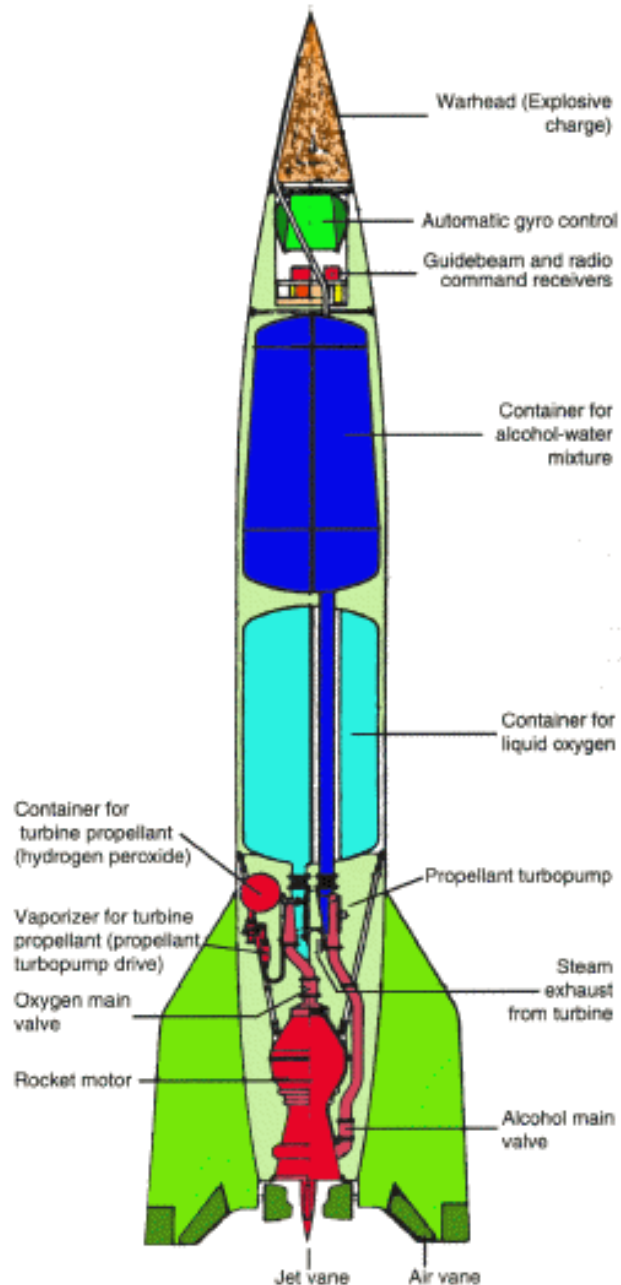


Propulsion Types

	Energy Source ^a			
Propulsion Device	Chemical	Nuclear	Solar	Propellant or Working Fluid
Turbojet	D/P			Fuel + air
Turbo-ramjet	TFD			Fuel + air
Ramjet (hydrocarbon fuel)	D/P	TFD		Fuel + air
Ramjet (H ₂ cooled)	TFD			Hydrogen + air
Rocket (chemical)	D/P	TFD		Stored propellant
Ducted rocket	TFD			Stored solid fuel + surrounding air
Electric rocket	D/P		D/P	Stored propellant
Nuclear fission rocket		TFD		Stored H ₂
Solar-heated rocket			TFD	Stored H ₂
Photon rocket (big light bulb)		TFND		Photon ejection (no stored propellant)
Solar sail			TFD	Photon reflection (no stored propellant)

Sutton, George P.; Biblarz, Oscar. Rocket Propulsion Elements. Wiley.

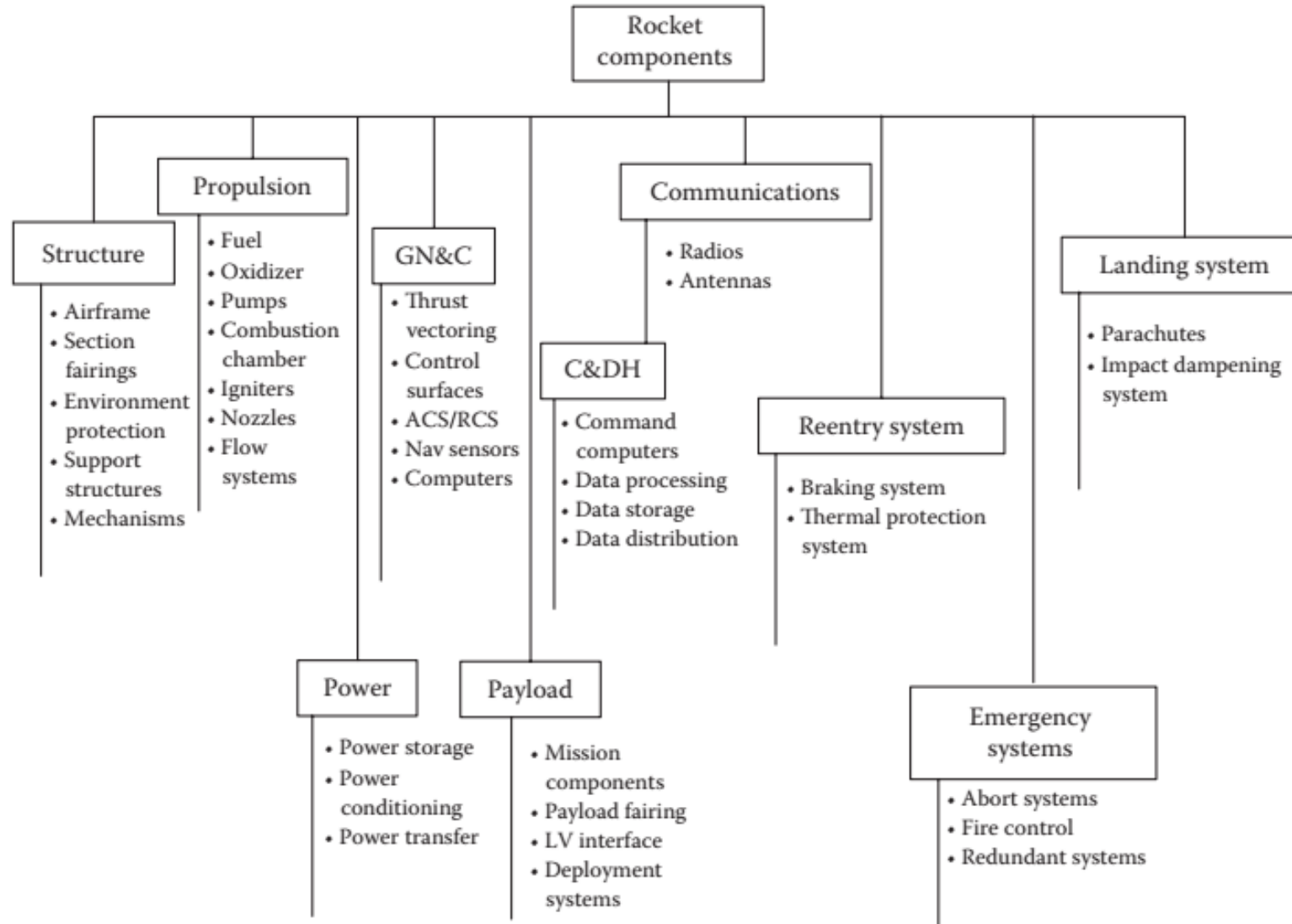
Thermodynamic rockets



German V-2 (A-4) Missile

- Thermodynamic rockets convert thermodynamic energy (heat and pressure) transferred to a propellant into high-speed exhaust using nozzles. There are a wide variety of other thermodynamic rockets currently available or being considered. We can classify these based on their source of energy:
 - Cold-gas—use mechanical energy of a gas stored under pressure
 - Chemical—rely on chemical energy (from catalytic decomposition or combustion) to produce heat
 - Solar thermal—use concentrated solar energy to produce heat
 - Thermoelectric—use the heat produced from electrical resistance
 - Nuclear thermal—use the heat from a nuclear reaction
- Agrawal, Brij N.; Platzer, Max F.. Standard Handbook for Aerospace Engineers, Second Edition. McGraw Hill LLC.

Rocket Components



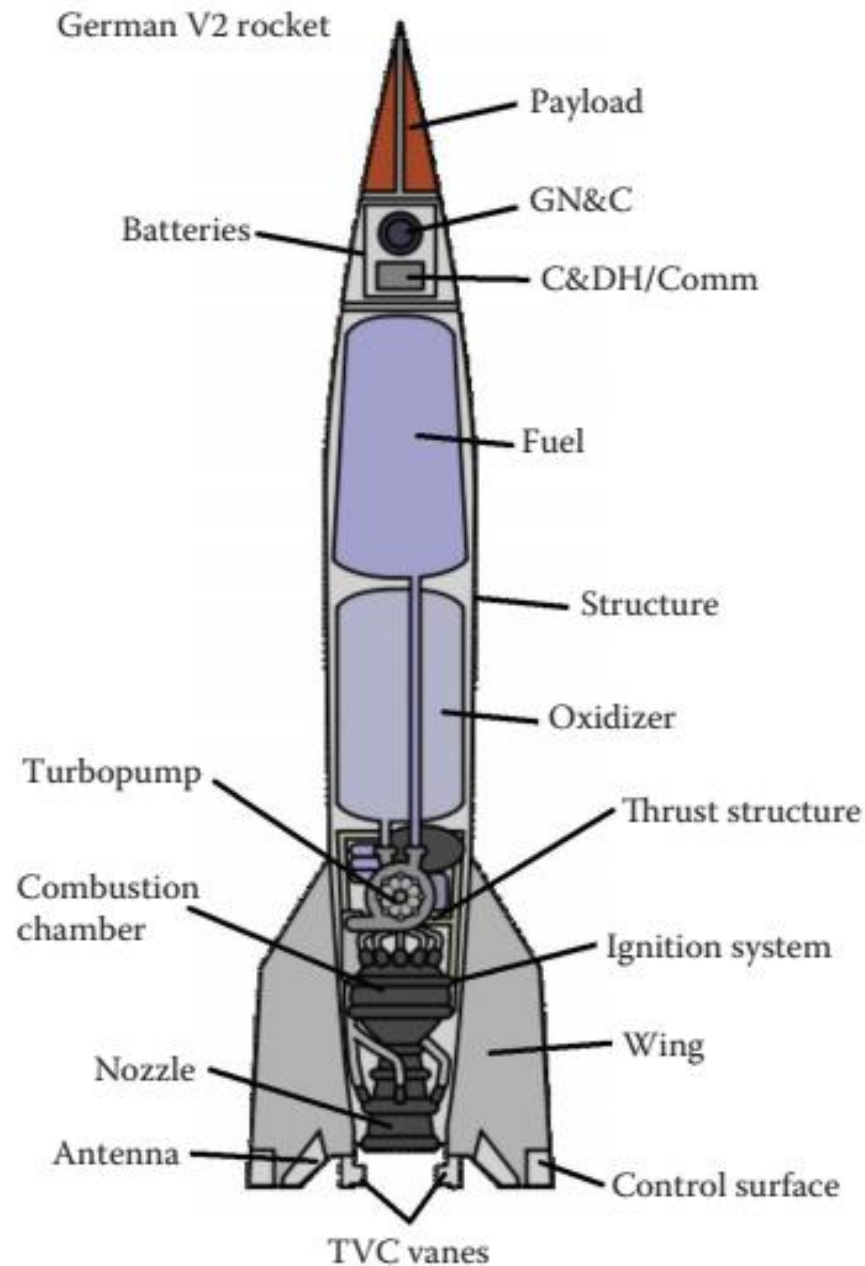
Rocket Components

- Payload: This is the reason for the rocket and contains the science instruments, cargo, or crew.
- Command and data handling (C&DH): Has command computers, data processors, data storage systems, and the data distribution protocols and infrastructure.
- Communications (Comm): Contains radios, low- and high-gain antennas, and telemetry systems.
- Reentry systems: These are for rockets that must safely return a payload to Earth and contain braking systems, such as the orbital maneuvering system thrusters on the Space Shuttle, and reentry thermal protection, such as the shuttle tiles or the ceramic shields on the Apollo capsules.
- Emergency systems: These systems are for use in fault condition situations and include sensors for leak, fire, and damage detection, backup systems, and abort systems.
- Landing systems: For return vehicles, there must be some means of landing the payload safely on Earth, which could include parachutes, wings, airbags, or even rockets.

-Taylor, Travis S.. Introduction to Rocket Science and Engineering (p. 35). CRC Press.

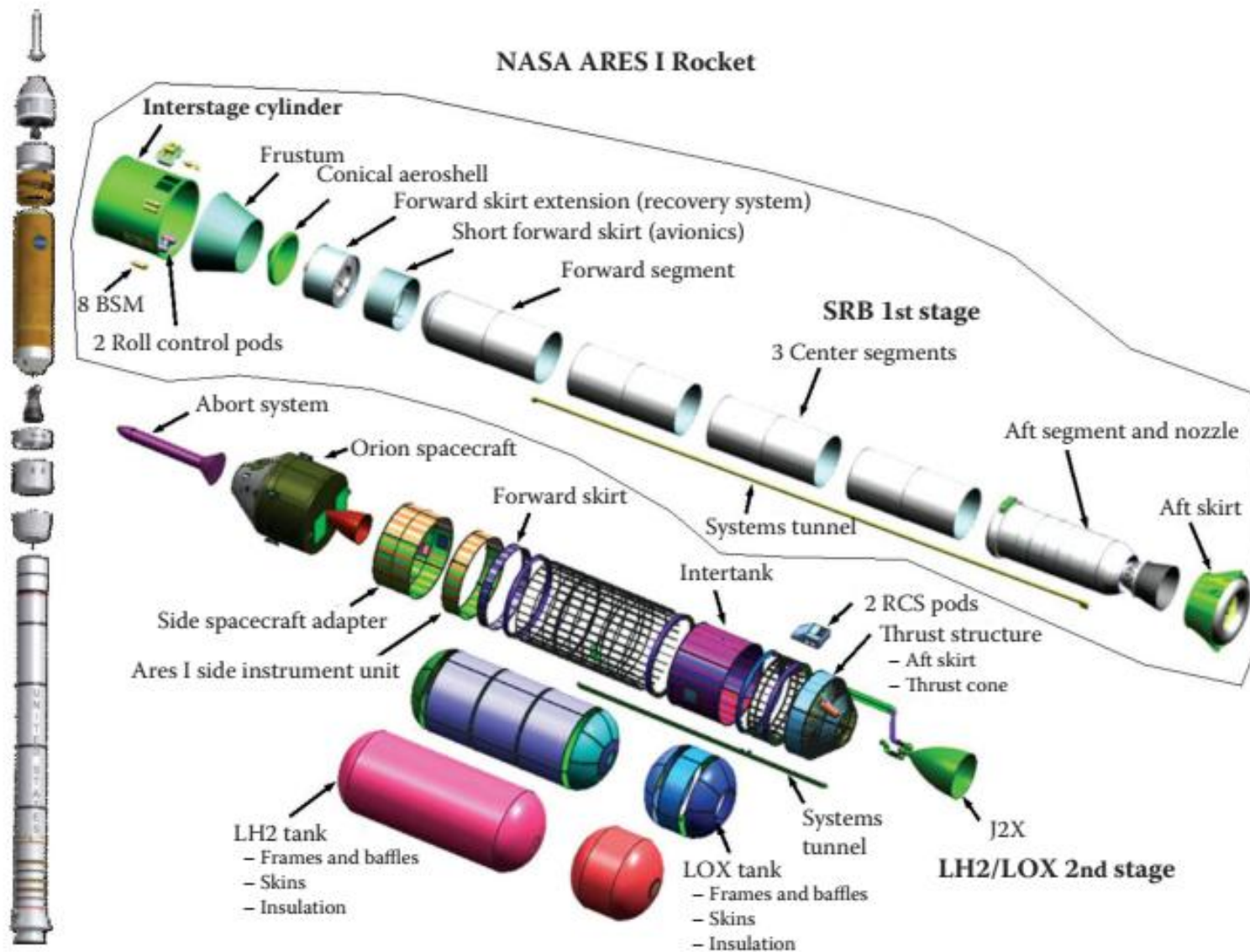
German V-1

The V-1 (“Vergeltungswaffe 1” = “Retaliation Weapon 1”) was the world’s first operational cruise missile, developed by Nazi Germany in World War II. It wasn’t a “rocket” in the strict sense (like the V-2, which used a true liquid rocket engine). Instead, it was powered by a pulsejet engine



The German V2 Rocket

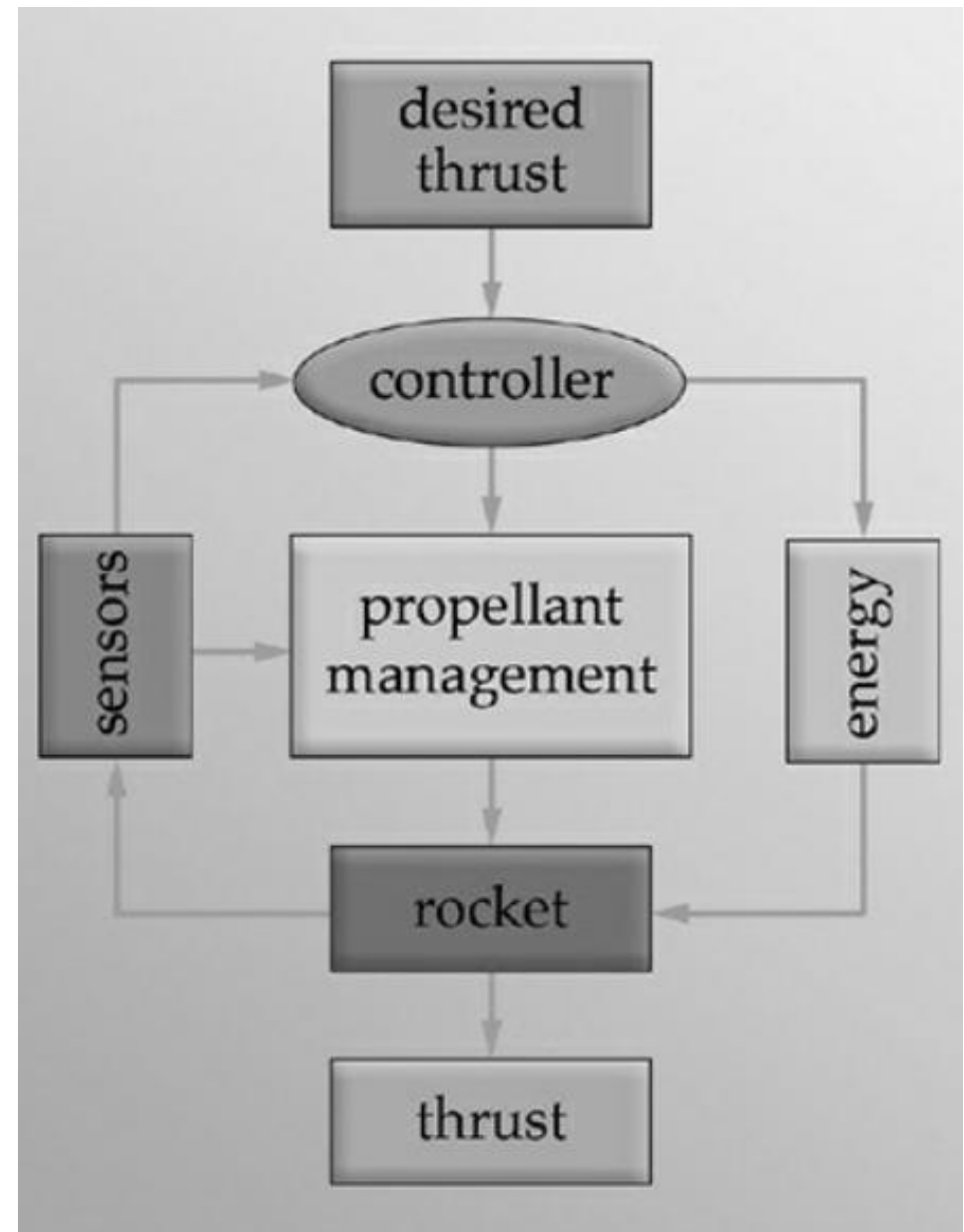
NASA Ares 1



Propulsion

Figure 9.11 shows a block diagram for an entire propulsion system. To design a specific system, we start with the desired thrust, usually at some very specific time. The propulsion system controller manages these inputs and formulates commands to send to the propellant management actuators to turn the flow of propellant on or off. For some systems, the controller also manages the energy input to the rocket. For example, in an electrodynamic rocket or a thermoelectric rocket, the system has to interface with the spacecraft's electrical power subsystem (EPS) to ensure it provides the correct power level. The controller uses sensors extensively to monitor the temperature and pressure of the propellant throughout.

- Agrawal, Brij N.; Platzer, Max F.. Standard Handbook for Aerospace Engineers, Second Edition. McGraw Hill LLC.



Combustion

The combustion process converts a solid (or liquid) into a gas (this is known as a “change in state”).

A gas takes up more space than a solid (or liquid), so if the volume of the container (combustion chamber) is constrained, then the pressure inside the container will go up as the solid is converted into a gas.

If a hole at one end of the container is provided, the high pressure gas will move through that hole to get to the lower pressure outside the container.

This change in state and associated gas dynamics are what makes a rocket motor work.

Rocket Propellant

Solid Propellant Rocket Motors

Propellant is in solid form

Propellant includes fuel, oxidizer, and a binder

Simple solid motors have no moving parts

Liquid Fuel Rocket Motors

Liquid Oxidizer (typically liquid oxygen)

Liquid Fuel (gasoline, liquid hydrogen)

Fuel is fed into the combustion chamber via high pressure pumps or by using pressurized gas such as helium

Hybrid Rocket Motors

Solid fuel (various plastics and rubber, asphalt, almost any carbon material)

Liquid oxidizer (liquid oxygen, nitrous oxide)

Fuel is contained in the combustion chamber like a solid motor, but oxidizer is fed via pumps or pressure.

Rocket Propellant

Solid Propellant Rocket Motors

- Tend to be very robust (military uses them extensively)
- Generally, no moving parts (though guided versions using gimbaled nozzles are used)
- Can be loaded and launched quickly

Liquid Fuel Rocket Motors

- Generally, more energetic (have a higher Specific Impulse)
- Can be throttled and stopped/started to better control flight trajectories
- Are more complex due to plumbing and pumps

Hybrid Rocket Motors

- Complexity is generally between that of the liquid and solid
- Can be throttled and stopped/started to better control flight trajectories
- Some say hybrids combine the best of both types of motors – while others say they combine the worst of both types of motors

Liquid Fuel

One of the most common liquid propellant combinations is liquid oxygen (LOX) as the oxidizer and liquid hydrogen (LH₂) as the fuel. This combination is extremely efficient and is used in major space programs, including the Space Shuttle Main Engines (SSMEs) and many launch vehicles. Other combinations include liquid oxygen and RP-1 (a highly refined kerosene), used in the Saturn V rocket

- Peterson, Alex. Aerospace Engineering Step by Step: Fundamentals of Aircraft Design, Structures & Systems: From Theory to Practice (Step By Step Subject Guides)

Liquid Fuel

Advantages of Liquid Fuel Engines:

- **Throttling and Restart Capability:** Liquid fuel engines can be throttled (controlled for varying thrust) and restarted multiple times, making them flexible for missions that require precision, such as placing satellites into different orbits or crewed space missions where specific maneuvers are necessary.
- **High Specific Impulse:** Specific impulse (I_{sp}) measures the efficiency of a rocket engine. Liquid fuel engines generally have a higher specific impulse compared to solid rockets, meaning they can produce more thrust per unit of propellant.

Challenges:

- **Complexity:** Liquid fuel engines are more complex because they require sophisticated pumps, cooling systems, and valves. Managing cryogenic liquids like liquid oxygen and liquid hydrogen presents significant engineering challenges, including the need for insulation to keep the propellants at extremely low temperatures. 2
- **Handling and Storage:** Storing and handling liquid propellants, especially cryogenic ones, can be difficult and dangerous due to the risk of leaks, freezing, or explosion.

Peterson, Alex. Aerospace Engineering Step by Step: Fundamentals of Aircraft Design, Structures & Systems: From Theory to Practice (Step By Step Subject Guides)

Solid Fuel

Solid Fuel Engines Solid fuel engines use propellants that are stored in a solid state within the rocket itself. The fuel and oxidizer are mixed together in a solid form called the propellant grain, which is shaped to burn in a controlled manner. Once ignited, the entire propellant burns until all fuel is consumed, generating thrust continuously. One of the most widely used solid propellants is a mixture of ammonium perchlorate (oxidizer) and powdered aluminum (fuel) bound together in a rubbery substance called hydroxyl-terminated polybutadiene (HTPB). Solid rockets are often used in booster stages to provide initial thrust during liftoff, such as the Solid Rocket Boosters (SRBs) used on the Space Shuttle. Advantages of Solid Fuel Engines:

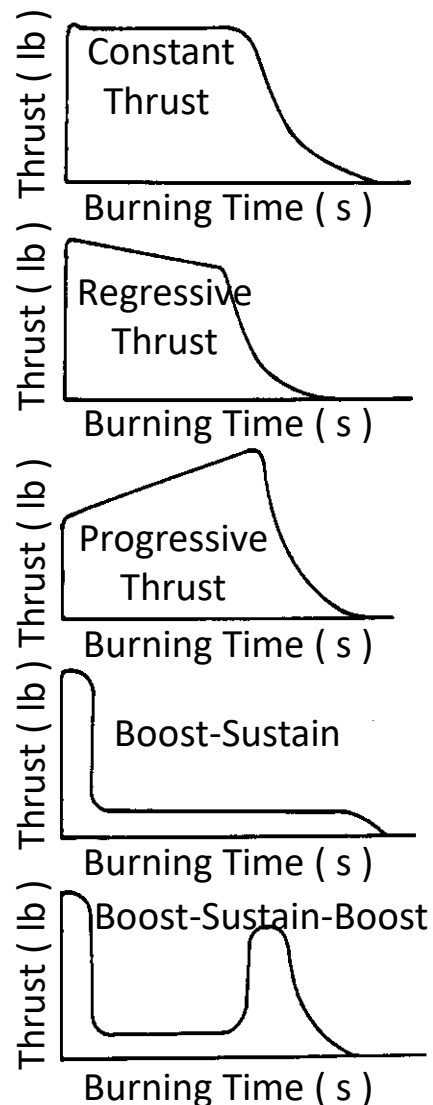
- **Simplicity and Reliability:** Solid fuel rockets have no moving parts, making them simpler and more reliable than liquid fuel engines. This simplicity makes them easier to manufacture and maintain.
- **Storage and Readiness:** Solid rockets can be stored for long periods and are ready to ignite at a moment's notice. This makes them ideal for military applications, missiles, and emergency launch systems where quick response times are crucial.
- **Challenges:**
 - **Lack of Throttling or Restarting:** Once ignited, solid rockets cannot be throttled or shut down. They will burn until all the fuel is consumed, limiting their flexibility for missions that require precise control or midflight adjustments.
 - **Lower Specific Impulse:** Solid rockets generally have a lower specific impulse than liquid rockets, meaning they are less efficient in terms of fuel usage for the amount of thrust produced.

Missile Thrust - Time Requirements Drive Solid Propellant Rocket Grain Cross Section Geometry

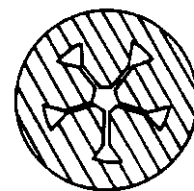
Example Mission

- $\approx$ Cruise
- Dive at $\approx$ constant dynamic pressure
- Climb at $\approx$ constant dynamic pressure
- Fast launch – $\approx$ cruise
- Fast launch – $\approx$ cruise – high speed terminal

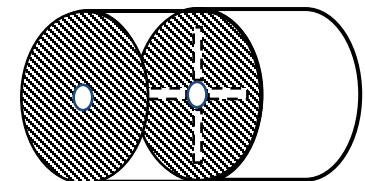
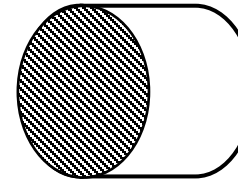
Thrust Profile



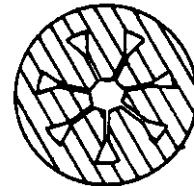
Example Web Cross Section Geometry / Volumetric Loading



$\sim 82\%$



End Burner $\sim 95\%$ Radial Slotted Tube $\sim 90\%$



79%



87%



85%



85%



Extrusion Production of Star Web Propellant. Photo Courtesy of BAE.



Case Bonded Production of Propellant. Photo Courtesy of BAE.



Propellant Grain



High Burn Rate Propellant

Note: High thrust and chamber pressure require large surface burn area.

Solid Propellant

Typical Ingredients:

- **Oxidizer:** Ammonium perchlorate (AP), Ammonium nitrate (AN), sometimes HMX (High Melting Explosive Cyclotetramethylene-tetranitramine $C_4H_8N_8O_8$) or RDX (Research Department Explosive Cyclotrimethylenetrinitramine $C_3H_6N_6O_6$)
- **Fuel/binder:** Hydroxyl-terminated polybutadiene (HTPB), polyurethane, PBAN (polybutadiene acrylonitrile).
- **Additives:** Aluminum powder (improves energy release and combustion temperature).

Hybrid Fuel

- A hybrid propulsion system uses a solid fuel and a liquid oxidizer, blending characteristics from both liquid and solid fuel engines. In a hybrid system, the solid fuel is stored inside the rocket, while the liquid oxidizer is stored separately and is pumped into the combustion chamber where it mixes with the solid fuel and burns. This creates thrust while offering some advantages over both traditional liquid and solid fuel systems.
- One of the most common hybrid propellant combinations is hydroxyl-terminated polybutadiene (HTPB) as the solid fuel and nitrous oxide (N_2O) as the oxidizer. This type of system has been used in rockets like SpaceShipOne and SpaceShipTwo, developed by Virgin Galactic.

-Peterson, Alex. Aerospace Engineering Step by Step: Fundamentals of Aircraft Design, Structures & Systems: From Theory to Practice (Step By Step Subject Guides)

Rocket Propulsion

At its core, rocket propulsion works by forcing mass (usually in the form of hot gases) out of a nozzle at high speed. The reaction force pushes the rocket in the opposite direction.

- Action: High-speed gas is expelled backward.
- Reaction: Rocket moves forward.

This method allows rockets to operate in space, where there is no atmosphere—unlike jet engines, which require atmospheric oxygen.

Turbojet

Atmospheric air taken in through the turbojet inlet is compressed up to 3–12 times its original pressure in the axial compressor. Fuel is added to the air and burned in a combustion chamber to raise the temperature of the fluid mixture to about 593–704 °C (1100–1300 °F). The resulting hot gas is passed through a turbine, which drives the compressor. If the turbine and compressor are efficient enough, the gas pressure at the turbine discharge will be nearly twice the atmospheric pressure, and this excess pressure is sent to the nozzle to produce a high-velocity stream of hot gas which produces the thrust force. Substantial increases in thrust can be obtained by employing an afterburner.

-Musielak, Dora. Scramjet Propulsion: A Practical Introduction (Aerospace Series) (p. 7). Wiley. Kindle Edition.

Afterburner

An afterburner (also called *reheat*) is a device added to the exhaust section of a turbojet or low-bypass turbofan engine. It works by injecting additional fuel into the hot exhaust gases after they pass the turbine and igniting it. An afterburner will temporarily boost thrust, often by 50–70% or more.





Turbojet

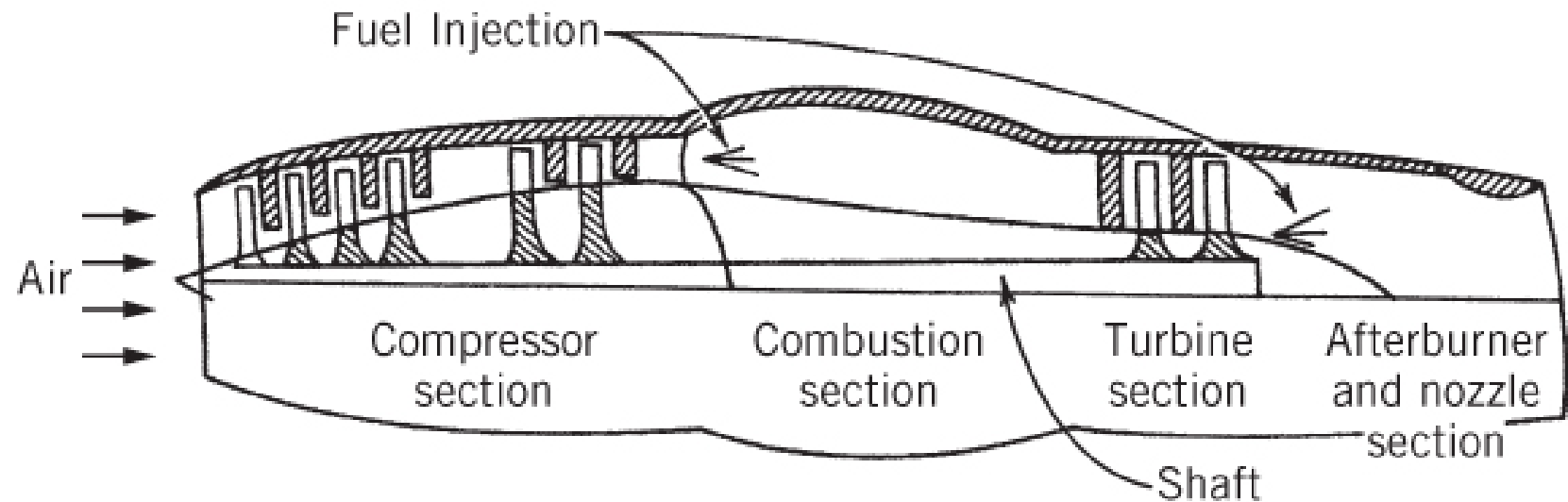
Turbojets are the simplest form of jet engines, designed primarily for high-speed flight. They were the first type of jet engine to be widely used in aviation, particularly in military aircraft during and after World War II. Turbojets work by compressing incoming air, mixing it with fuel, igniting the mixture, and expelling the exhaust gases at high speed to generate thrust.

The main components of a turbojet are:

- **Compressor:** The air is compressed as it enters the engine, increasing the pressure and temperature.
- **Combustion chamber:** Fuel is injected and burned in the compressed air, creating high-energy exhaust gases.
- **Turbine:** The expanding gases pass through a turbine, which powers the compressor at the front of the engine
- **Exhaust nozzle:** Finally, the high-velocity exhaust gases are expelled through the nozzle, producing thrust.

- Peterson, Alex. Aerospace Engineering Step by Step: Fundamentals of Aircraft Design, Structures & Systems: From Theory to Practice (Step By Step Subject Guides) .

Turbojet



Turbofan

- A turbofan engine is a type of air-breathing jet engine widely used in modern aircraft, especially commercial airliners and military jets. It combines the high-speed efficiency of a jet engine with the high-thrust, low-noise advantages of a propeller, using a large fan at the front to produce the bulk of its thrust.
- Main components of a typical turbofan engine:
 - Fan
 - Large front-facing blades that accelerate air.
 - Most of the air bypasses the core and flows around it—this is called bypass air.
 - Compressor
 - Increases the pressure of the air entering the combustion chamber.
 - Typically consists of low-pressure and high-pressure stages.
 - Combustion Chamber
 - Injected fuel is mixed with compressed air and ignited.
 - The expanding gases flow downstream to drive the turbines.
 - Turbine
 - Extracts energy from the hot gases to drive the compressor and the fan.
 - Some energy is converted to mechanical rotation of the front fan.
 - Nozzles
 - Accelerate the exhaust gases to generate thrust.
 - Separate nozzles may exist for the core and the bypass air, depending on design.

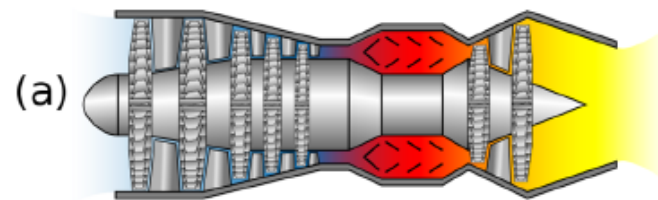
Turbofan

Turbofans are the most common type of jet engine used in commercial aviation today. They are essentially an evolution of the turbojet, designed to be more efficient at subsonic speeds while still offering significant thrust. The key difference between a turbofan and a turbojet is the large fan located at the front of the engine. In a turbofan engine, the large fan pulls in much more air than a turbojet. Some of this air is directed into the core of the engine (where it follows the same path as in a turbojet), but most of the air bypasses the engine core and is accelerated by the fan. This creates what's called a bypass ratio, which is the ratio of air bypassing the engine core to the air going through the combustion process. High bypass ratios make turbofan engines more fuel-efficient and quieter than turbojets because they rely more on the fan-driven bypass air to generate thrust. Turbofan engines are divided into two categories:

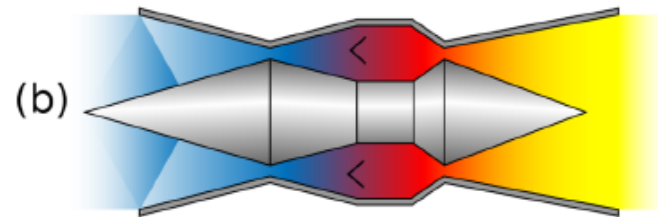
- Low-bypass turbofans: These engines have a relatively small fan and a higher proportion of air passing through the engine core. They are used in military jets and some business jets where both speed and agility are important.
- High-bypass turbofans: These engines, used in most commercial airliners, have a much larger fan and a higher bypass ratio. This makes them much more efficient at lower speeds, such as during takeoff, landing, and cruising at subsonic speeds.

Airbreathing Engine Types

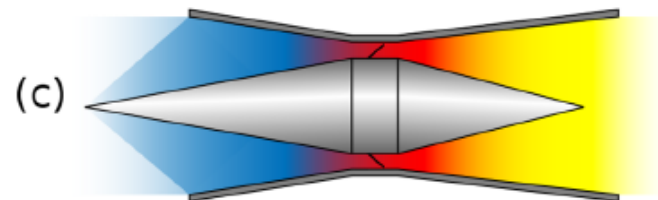
The compression, combustion, and expansion regions of:
(a) turbojet, (b) ramjet, and (c) scramjet engines



Subsonic inlet, subsonic combustion, subsonic or supersonic exit (with a nozzle)



Supersonic inlet, subsonic combustion, supersonic exit—NO MOVING PARTS!



Supersonic inlet, supersonic combustion, hypersonic exit (with a nozzle)—NO MOVING PARTS!

Compression Combustion Expansion

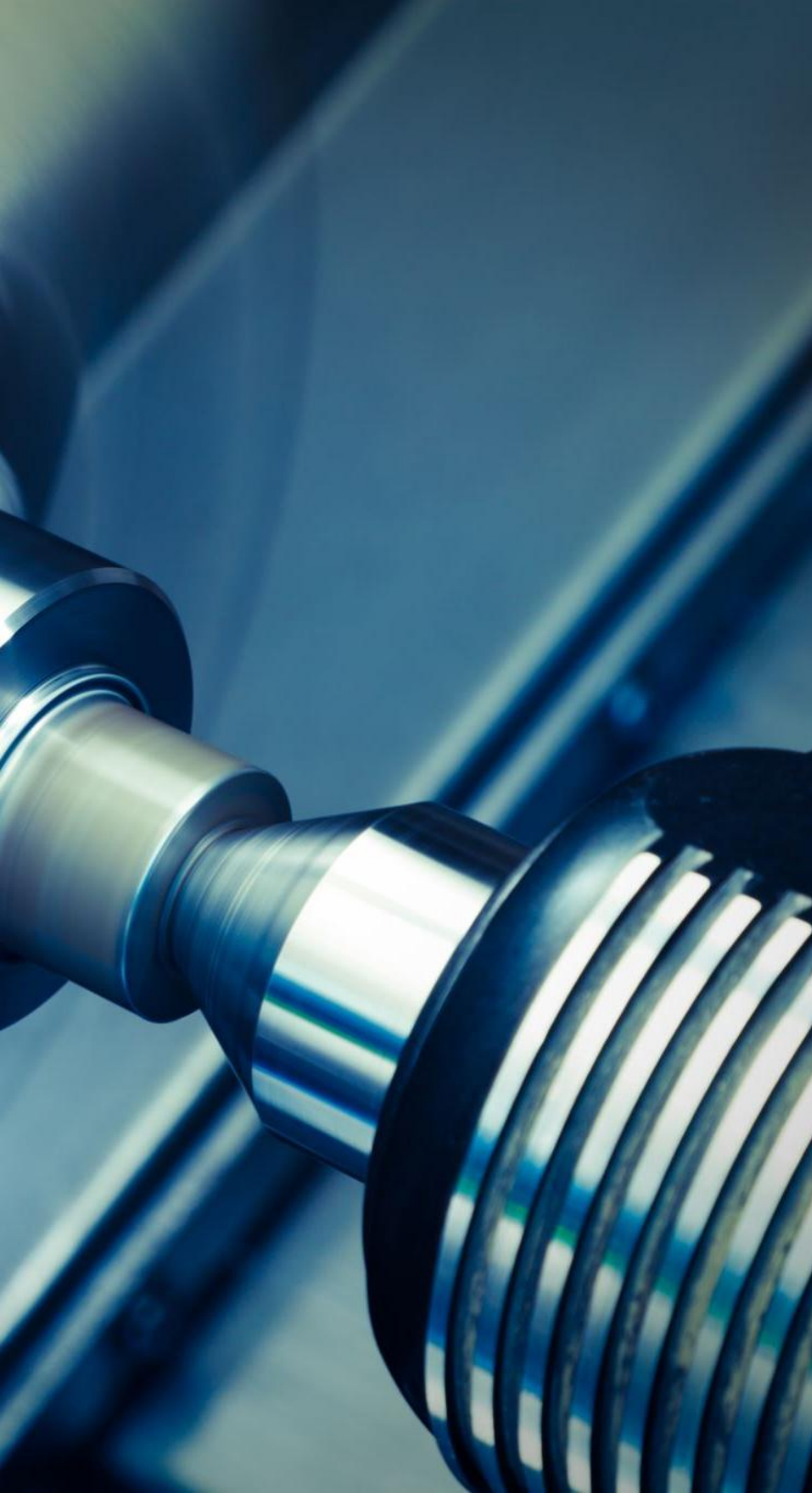
Airbreathing Engines

“For air-breathing propulsion, hypersonic flight is interpreted to mean flight speeds V_0 higher than five times the speed of sound, that is,

$$M_0 \equiv \frac{V_0}{a_0} > 5$$

where M_0 denotes a vehicle's flight Mach number and a_0 is the local speed of sound. For the analysis of hypersonic air-breathing propulsion, we can define hypersonic flow as the regime where the calorically perfect gas model for air becomes invalid. For calorically perfect gas or temperatures less than 400 K, the specific heats c_p and c_v are constant. As the air temperature increases, in the range of temperature $400 \text{ K} < T < 1700 \text{ K}$ air behaves as a thermally perfect gas, the value of the specific heats is function of temperature; and thus the specific heat ratio ($\gamma = c_p / c_v$) is also a function of temperature.”

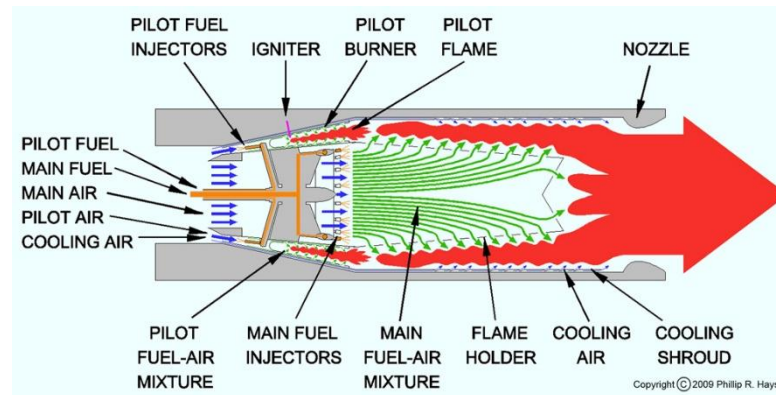
-Musielak, Dora. Scramjet Propulsion: A Practical Introduction (Aerospace Series) (p. 3). Wiley. Kindle Edition.



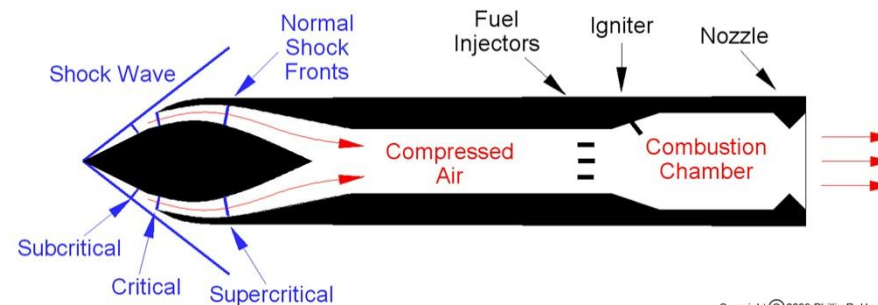
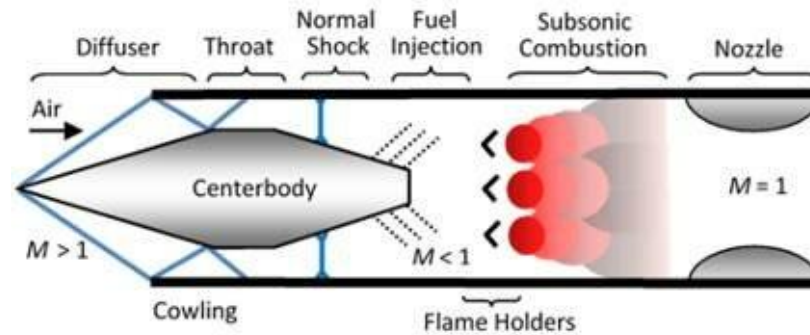
Characteristics of Hypersonic Airbreathing Propulsion Systems

- Ramjets, Dual-Mode Ramjets, Scramjets:
 - Utilize ram (i.e., shockwave) compression of the vehicle forebody and inlet to
 - compress the flow in lieu of rotating machinery
 - Produce no static thrust, must be boosted to takeover speed
- Ramjets:
 - Terminal normal shock and subsonic diffuser
 - Subsonic combustion with mechanical throat
 - As Mach number increases, large total pressure losses and high static pressures/temperatures occur with a terminal normal shock. This makes pure RJs
 - challenging for “true hypersonic” ($M > 5$) flight
- Dual-Mode Ramjets:
 - Oblique shocktrain and isolator
 - Subsonic combustion with thermal throat
 - Ideal for “low- to mid- hypersonic” Mach numbers (approximately, $4 < M < 7$)
- Scramjets:
 - Flow remains supersonic throughout
 - Minimal precombustion pressure rise, (i.e., much shorter shocktrain)
 - Ideal for Mach numbers greater than 7-8
 - DMRJs and SJs are highly airframe-integrated!

Ramjet Schematics



Ramjet Engine



Ramjet

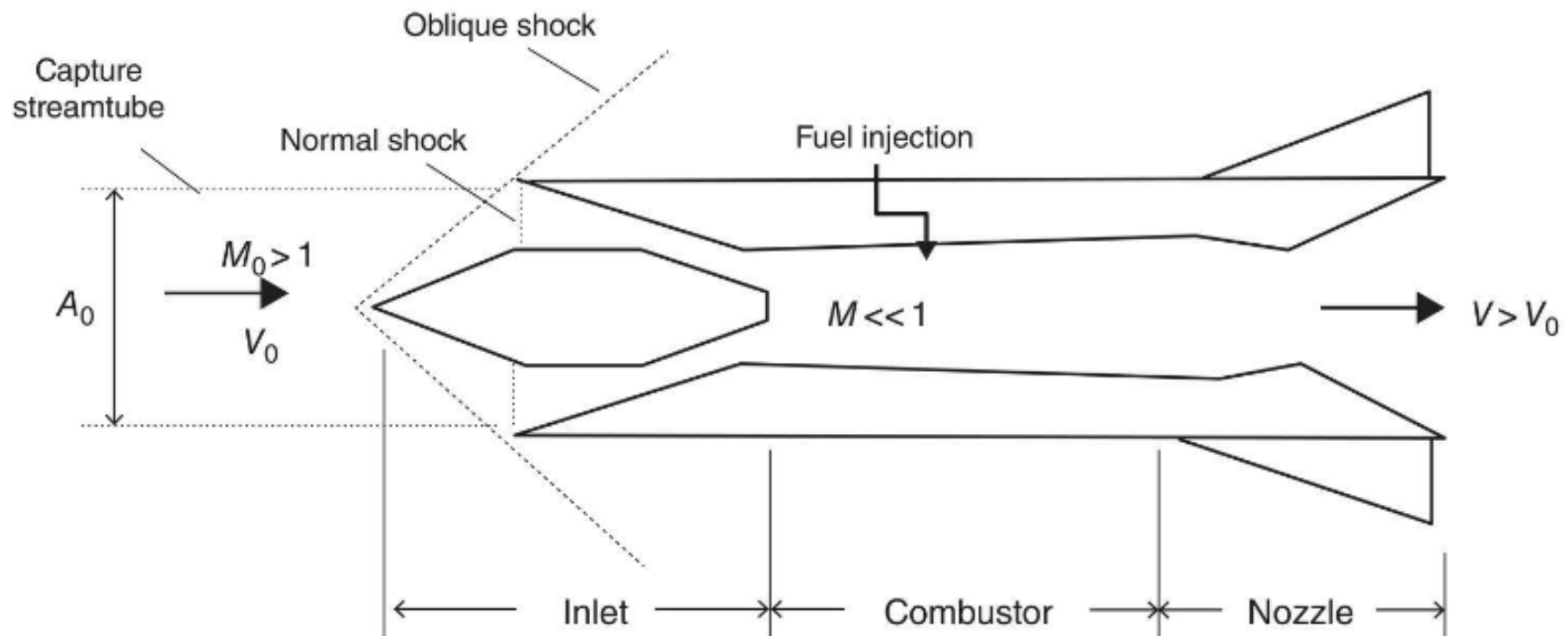


Figure 1.4 Schematic of a conventional ramjet engine.

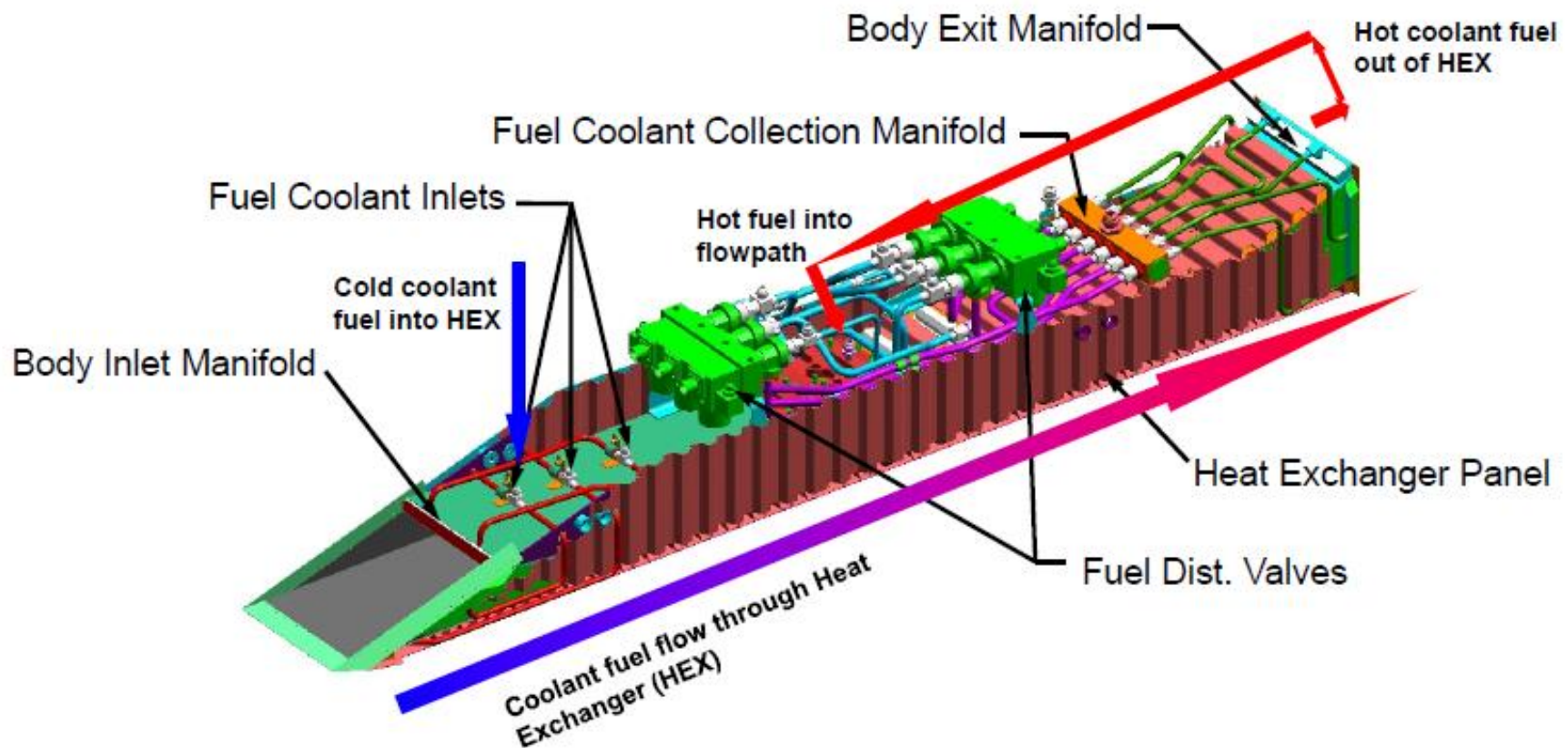
- Musielak, Dora. Scramjet Propulsion: A Practical Introduction (Aerospace Series)

Ramjet

“The ramjet engine has three main components: an inlet, a combustion chamber, and a nozzle. The dynamic action of the freestream air is used to produce the compression in the inlet as the vehicle flies at high speed. This action is referred to as the ram effect. The higher the velocity of the incoming air, the greater the pressure rise. The fundamental principle underlying ram compression in the ramjet inlet lies in converting the kinetic energy of the air into pressure. The compressed air then enters the combustion zone where it is mixed with the fuel and burned. The hot, high-pressure gas flow then accelerates back to a supersonic exit speed through the nozzle to develop thrust.”

-Musielak, Dora. Scramjet Propulsion: A Practical Introduction (Aerospace Series) (p. 1). Wiley. Kindle Edition.

Fuel-Cooled Scramjet Overview



SJX61-1 Ground Test Engine Configuration

Dual-Mode Ramjets

A dual-mode ramjet is an advanced air-breathing propulsion system that can operate in two different combustion modes: subsonic combustion (ramjet mode) and supersonic combustion (scramjet mode). It is designed to work efficiently across a wide range of flight speeds, typically from Mach 3 to Mach 7+.

Ramjet Mode (Subsonic Combustion)

- Speed Range: Mach 3–5
- Incoming air is slowed to subsonic speed through a series of shock waves in the inlet.
- Fuel (often hydrogen or hydrocarbon) is injected and burned in subsonic flow.
- Expanding gases exit the nozzle and generate thrust.
- Higher combustion stability
- More efficient at lower hypersonic speeds

2. Scramjet Mode (Supersonic Combustion)

- Speed Range: Mach 5–7+
- Airflow is not fully decelerated—it remains supersonic throughout the engine.
- Fuel burns in this supersonic stream, requiring extremely fast mixing and ignition.
- Avoids severe heating and losses from decelerating airflow
- Enables flight at very high Mach numbers

Scramjet – Dual Mode Scramjet

Scramjet : Supersonic combustion ramjet engine that can operate effectively in the Mach flight range $5.0 < M_0 < 15$. The pure scramjet is the true hypersonic air-breathing engine.

Dual-mode Scramjet : Air-breathing engine that can operate as a ramjet and as a scramjet, depending on whether it combusts its fuel at subsonic or supersonic conditions, transitioning to each engine mode as needed. It can propel a vehicle in the flight regime $3.0 < M_0 < 15$.

Chemical Propulsion

All chemical propulsion systems (rockets and airbreathers) can be compared using a unifying figure of merit, namely their specific impulse, I_{sp} . This parameter determines the ability of a propulsion system to produce thrust with the least amount of fuel or propellant consumption. For an air-breathing engine, its specific impulse is given by this formula:

$$I_{sp,a} = \frac{F}{g_0 m_f}$$

where F is the thrust and g_0 is the gravitational acceleration on the surface of the Earth, that is 9.807 m/s² or 32.2 ft/s². The dimension of $g_0 m_f$ in the denominator of Eq. (1.3) is the weight flow rate of the fuel based on Earth's gravity, or force per unit time. Consequently, the dimension of specific impulse is “Force/Force/second” that simplifies to just the “second.”

- Musielak, Dora. Scramjet Propulsion: A Practical Introduction (Aerospace Series). Wiley

Chemical Propulsion

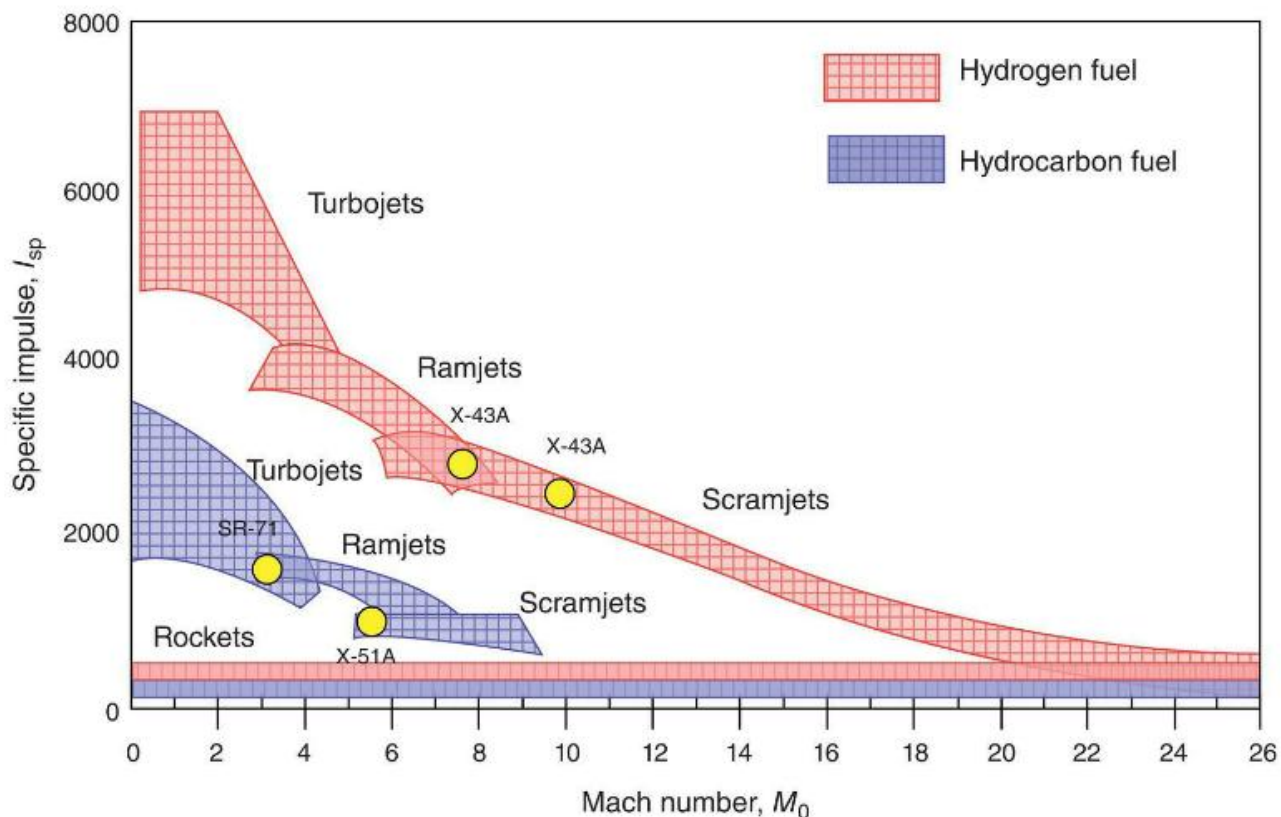
For a rocket, $I_{sp,a} = \frac{F}{g_0 \dot{m}_f}$, where $g_0 \dot{m}_p$ is the propellant weight flow rate, i.e. the sum of oxidizer and fuel weight flow rates. This means that both substances (oxidizer plus fuel) contribute to the “expenditure” in the rocket to produce thrust, and as such the oxidizer flow rate $\dot{m}_o$ needs to be accounted for as well in the calculation of specific impulse, that is:

$$I_{sp,r} = \frac{F}{g_0 \dot{m}_p} = \frac{F}{g_0 (\dot{m}_f + \dot{m}_o)}$$

Musielak, Dora. Scramjet Propulsion: A Practical Introduction (Aerospace Series) . Wiley.

Chemical Propulsion

Although the scramjet performance shown in this plot is theoretical, the trends depicted in Figure 1.8 are significant. Later in the book, we will address the following facts about air-breathing propulsion systems: At low velocities, turbojet engines produce the highest thrust with the least amount of fuel consumption. For the regime of flight Mach numbers $0 < M_0 < 3$, the I_{sp} range between ~ 2000 and 3500 seconds. The I_{sp} of turbojets drops with flight Mach number. Near $M_0 = 3$, a conventional ramjet begins to outperform the turbojet. The scramjet is a better propulsion choice when the ramjet engine performance deteriorates (near $M_0 = 5$).



Ion Propulsion

Ion propulsion is a type of electric propulsion system used primarily in spacecraft. Unlike traditional chemical rockets that burn fuel to produce thrust, ion propulsion systems use electric fields to accelerate charged particles (ions) to extremely high velocities, generating a small but continuous thrust.

Despite its low thrust, ion propulsion is extremely efficient, allowing spacecraft to reach very high speeds over long durations, making it ideal for deep-space missions. It functions in the following step:

- 1. Ionization
 - A neutral gas (typically xenon) is introduced into a chamber.
 - Electrons from a cathode or electron gun are injected to ionize the gas, turning it into positively charged ions.
- 2. Acceleration
 - The positively charged ions are accelerated by an electric field between a positively charged grid (anode) and a negatively charged grid (cathode).
 - The ions exit the engine at 30,000–50,000 m/s, creating thrust in the opposite direction.
- 3. Neutralization
 - A neutralizer releases electrons into the exhaust to prevent the spacecraft from becoming electrically charged and to neutralize the ion beam.

Ion propulsion

Feature	Description
Thrust	Very low (millinewtons), but continuous
Efficiency	Very high; specific impulse (Isp) of 2,000–10,000 seconds
Fuel	Usually xenon, due to its high atomic mass and inert nature
Power source	Solar panels or nuclear reactors (to generate electricity)
Operational duration	Can run for months or even years

Ion propulsion

Technology Commonly Used:

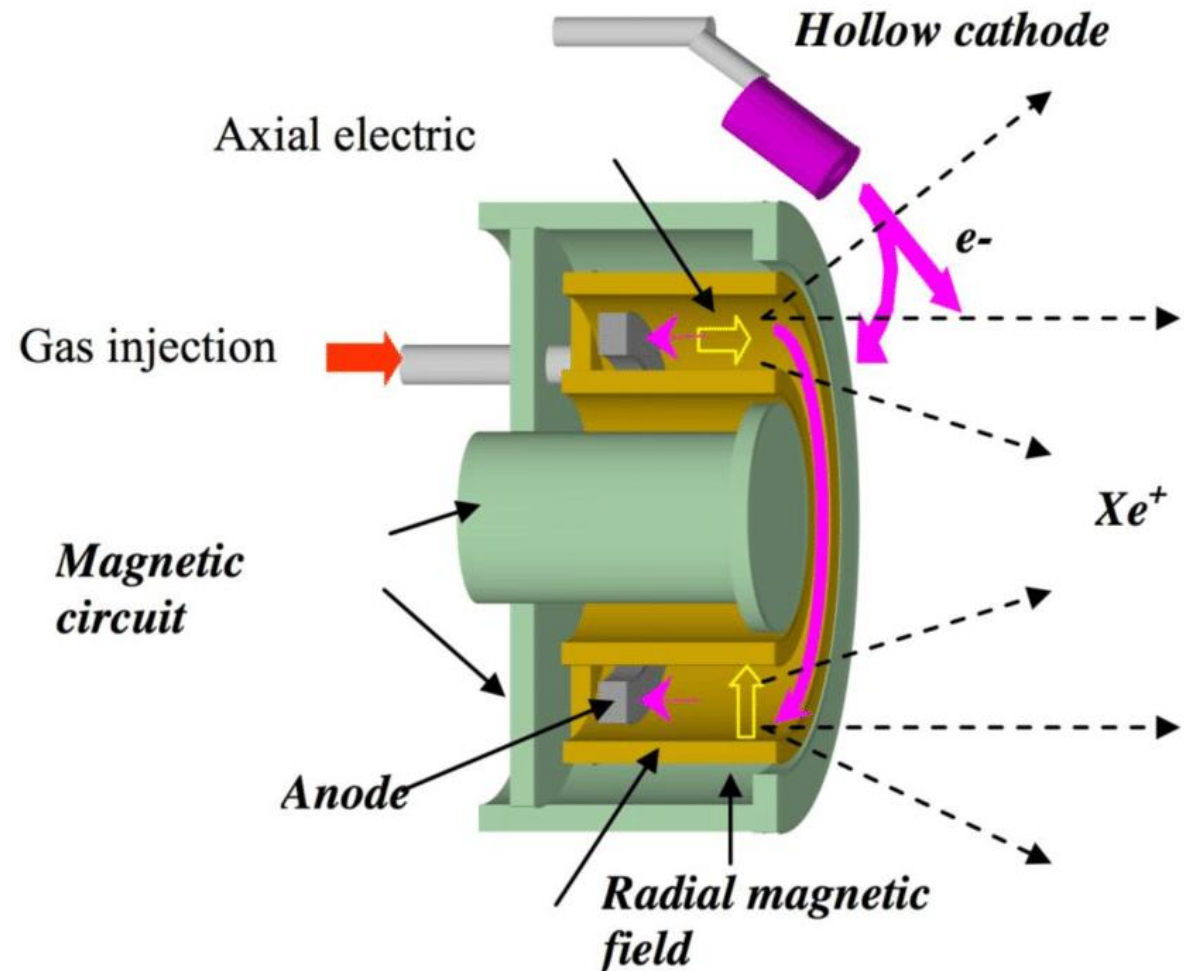
- Hall Effect Thrusters
- Gridded Ion Thrusters
- NEXT (NASA's Evolutionary Xenon Thruster)

Craft using this propulsion:

- NASA's Deep Space 1: First mission to use ion propulsion beyond Earth orbit
- Dawn spacecraft: Explored Vesta and Ceres using ion propulsion
- ESA's BepiColombo: Mission to Mercury with ion engines for cruise phase

Hall-effect thruster (HET)

Hall-effect thruster (HET) is a type of ion thruster in which the propellant is accelerated by an electric field. The HET gets its name because it traps electrons with an intense radial magnetic field in an azimuthal Hall current moving around the circumference of an annular ceramic channel. The electrons in the circulating Hall current ionize the onboard propellant - the inert gas xenon - and create an ionized plasma. The xenon plasma is then accelerated axially, via an applied electric field along the coaxial channel, to an exit velocity of up to 65,000 miles per hour to produce thrust. The interaction of the accelerated plasma and the downstream edge of the channel, where the plasma is the most energetic, results in erosion of the surrounding magnetic system used to generate the plasma.



Hall-effect thruster (HET)

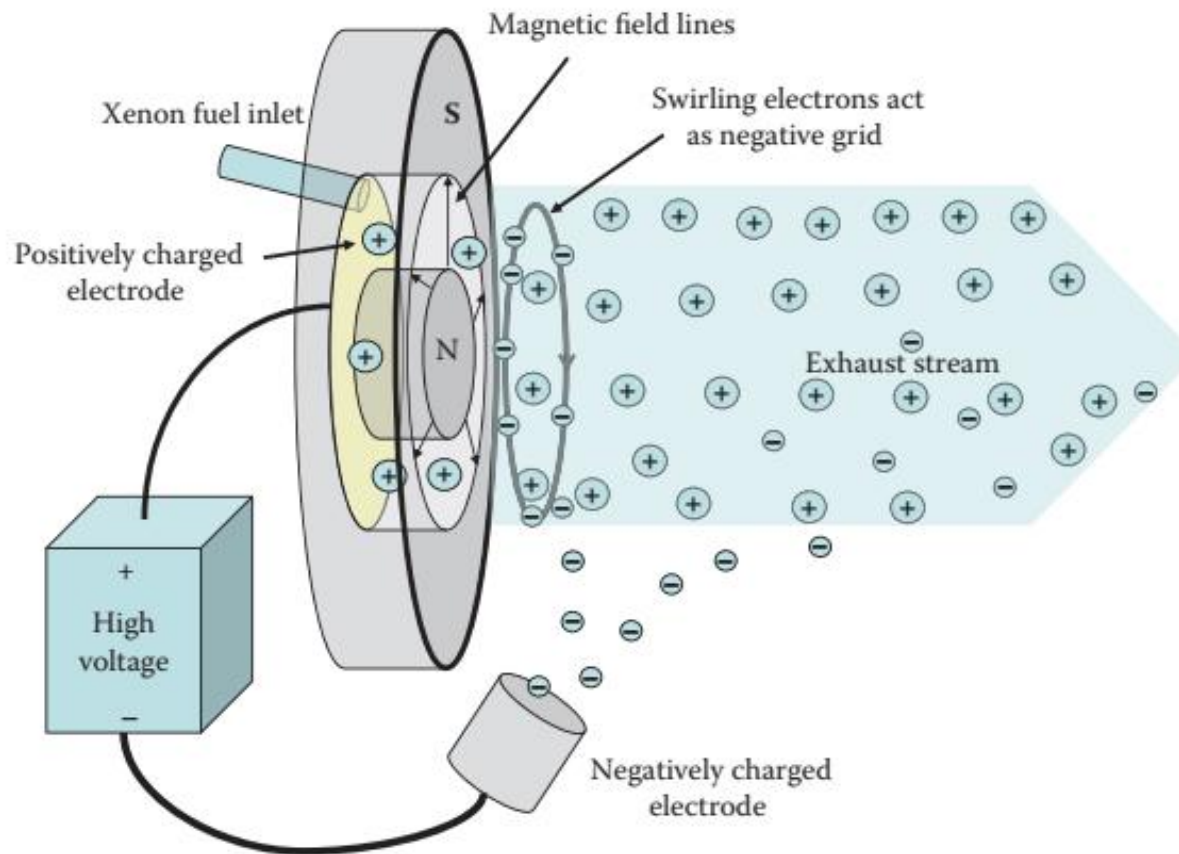


FIGURE 5.19
Schematic of a Hall effect thruster.

Taylor, Travis S.. Introduction to Rocket Science and Engineering CRC Press.

Gridded ion thrusters

Gridded ion thrusters are a type of electrostatic space propulsion system that generate thrust by accelerating ions through electrostatic grids. They are one of the most efficient forms of propulsion available for spacecraft, especially suitable for long-duration, deep-space missions.

These engines are often simply called “ion thrusters,” but the term “gridded” distinguishes them from Hall effect thrusters, which use magnetic fields.

1. Ionization Stage

- A neutral propellant (usually xenon) is injected into the discharge chamber.
- High-energy electrons from a cathode (often called a hollow cathode) collide with xenon atoms, ionizing them to form positively charged xenon ions (Xe^+).

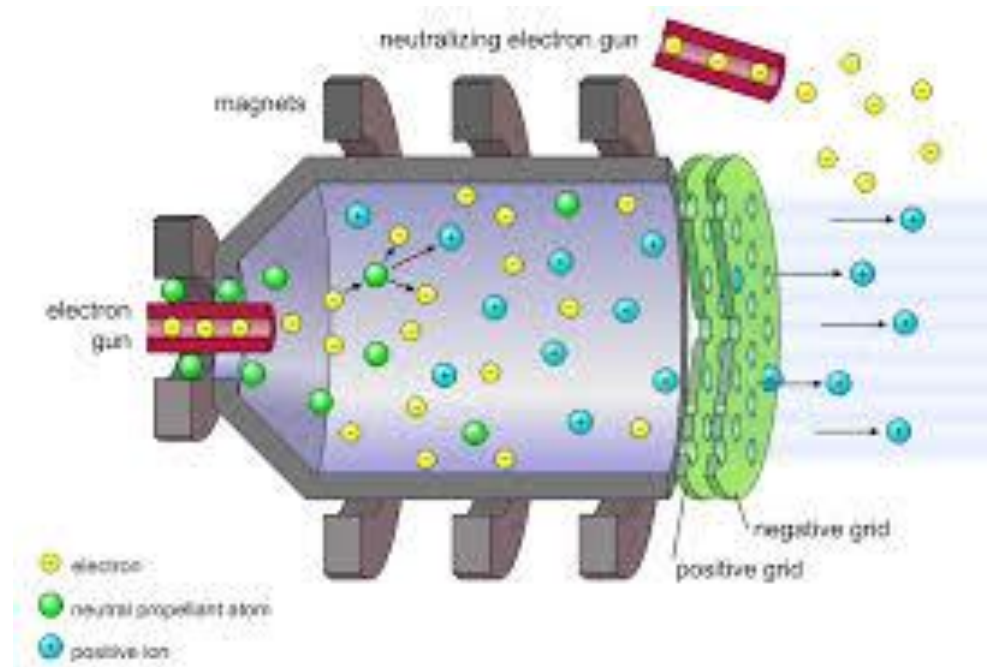
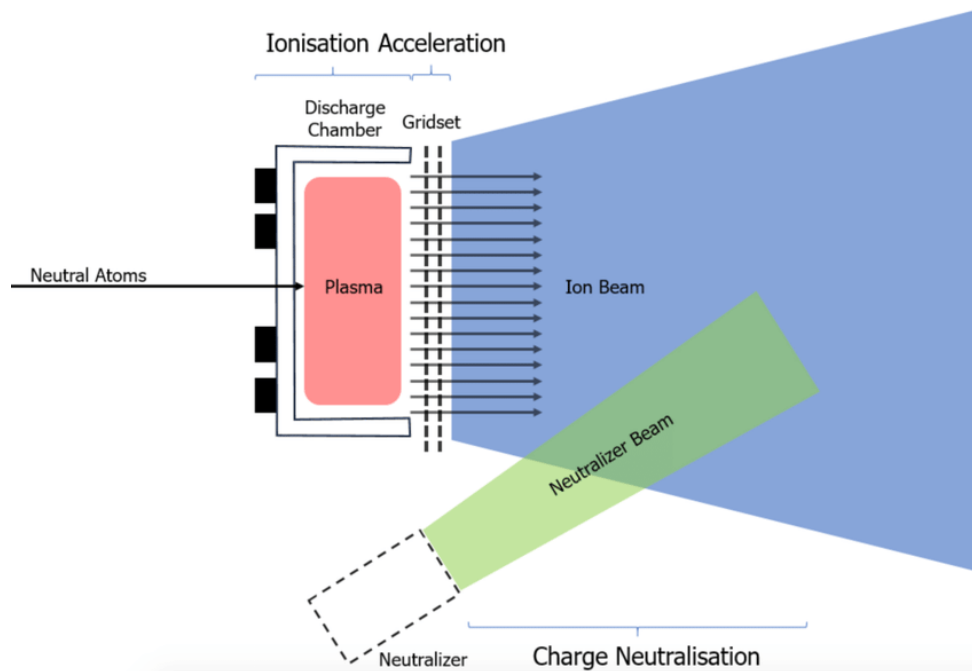
2. Acceleration Stage (Grids)

- The ionized gas passes through a set of fine electrostatic grids:
- Screen Grid (positively charged)
- Accelerator Grid (negatively charged)
- A large electric potential difference (typically 1,000–3,000 volts) between these grids accelerates the ions to high velocities (20–50 km/s).

3. Neutralization

- After acceleration, a neutralizer cathode releases electrons into the exhaust beam to prevent spacecraft charge buildup and ensure electrical neutrality of the exhaust.

Gridded Ion Thruster



Gridded ion vs Hall

Feature	Gridded Ion Thruster	Hall Effect Thruster
Acceleration method	Electrostatic grids	Magnetic + electric fields
Isp (efficiency)	Higher (up to 10,000 s)	Moderate (~1,500–2,500 s)
Thrust	Lower	Higher
Grid erosion	Present	Less pronounced
Control	Precise	Less fine control

NASA's Evolutionary Xenon Thruster (NEXT)

NASA's Evolutionary Xenon Thruster (NEXT) is a gridded ion propulsion system developed by NASA Glenn Research Center and partners as a next-generation electric propulsion technology for deep-space missions. It builds on earlier ion engines like NSTAR (used on the Deep Space 1 and Dawn missions), offering higher power, greater efficiency, and longer operational life.

NEXT is one of the most advanced ion thrusters ever developed, optimized for planetary missions, asteroid rendezvous, and cargo transport in space.

Like all gridded ion thrusters, NEXT uses electric fields to accelerate positively charged xenon ions to extremely high speeds to generate thrust.

NEXT vs NSTAR

Feature	NSTAR (Dawn)	NEXT
Power	~2.3 kW	Up to 7 kW
Thrust	~90 mN	~236 mN
Isp	~3,100 s	~4,190 s
Operational Life	~10,000 hrs	>50,000 hrs

Why Xenon

- “The most common propellant used in ion propulsion is xenon, which is easily ionized and has a high atomic mass, thus generating a desirable level of thrust when ions are accelerated. It also is inert and has a high storage density”
- -https://www.nasa.gov/wp-content/uploads/2015/08/ionpropfact_sheet_ps-01628.pdf
- Xenon is the heaviest non-radioactive elemental inert gas. The added mass allows for denser packing at less pressure. The mass is one of the limiting factors, so having a more dense gas helps tremendously.

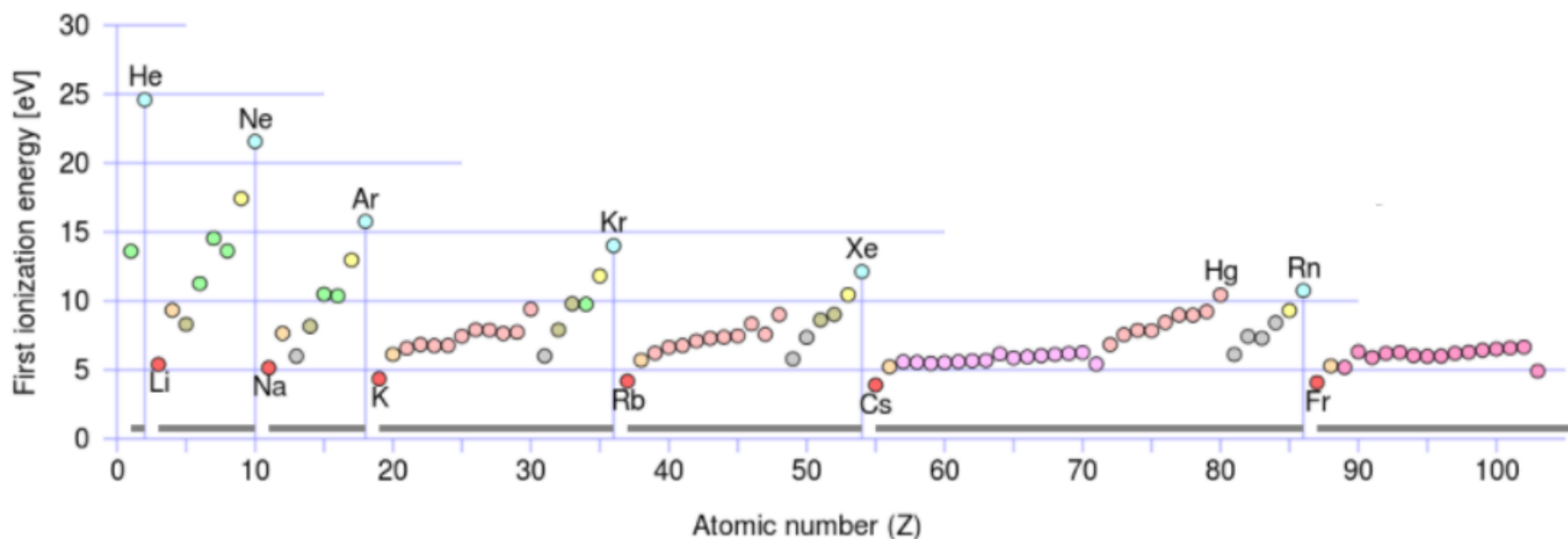
Why Xenon

- Radon is radioactive with a short half life (3.8235 days) and is expensive.

Property	Helium	Neon	Argon	Krypton	Xenon	Radon
atomic symbol	He	Ne	Ar	Kr	Xe	Rn
atomic number	2	10	18	36	54	86
atomic mass (amu)	4.00	20.18	39.95	83.80	131.29	222
valence electron configuration*	1s ²	2s ² 2p ⁶	3s ² 3p ⁶	4s ² 4p ⁶	5s ² 5p ⁶	6s ² 6p ⁶
triple point/boiling point (°C)	—/−269 [†]	−249 (at 43 kPa)/−246	−189 (at 69 kPa)/−189	−157/−153	−112 (at 81.6 kPa)/−108	−71/−62
density (g/L) at 25°C	0.16	0.83	1.63	3.43	5.37	9.07
atomic radius (pm)	31	38	71	88	108	120
first ionization energy (kJ/mol)	2372	2081	1521	1351	1170	1037

Why Xenon

- Ionization energy



[https://chem.libretexts.org/Bookshelves/General_Chemistry/ChemPRIME_\(Moore_et_al.\)/06%3A_Chemical_Bonding_-_Electron_Pairs_and_Octets/6.06%3A_Ionization_Energies](https://chem.libretexts.org/Bookshelves/General_Chemistry/ChemPRIME_(Moore_et_al.)/06%3A_Chemical_Bonding_-_Electron_Pairs_and_Octets/6.06%3A_Ionization_Energies)

Comparing Thrusts

- 1 pound of force (lbf) = 4.44822 newtons
- **NASA NSTAR Thrust** ~ 90 millinewtons (mN)
- **NASA NEXT Thrust** ~ 0.24 N (240 mN)
- **Ramjet:** ~20–50 kN (depending on speed/size).
- **Scramjet** ~ 20–100 kN of thrust
- **Saturn V Rocket first stage** ~ 33.4 million newtons
- **Saturn V Rocket second stage** ~ 4.9 million newtons
- **Saturn V Rocket third stage** ~ 1.0 million newtons

Electromagnetic Engines

ElectroMagnetic engines operate mostly through the Lorentz force interaction between charged particles and electric and magnetic fields. The easiest-to-understand engine of this type is the pulsed plasma thruster (PPT). The basics of the PPT are not at all unlike a rail gun. In fact, the function is practically identical. Figure 5.23 shows the basic schematic for an electromagnetic engine. A high voltage power supply is connected across the electrodes of a capacitor to charge it. The capacitor is connected through a switch to electrode rails, as shown in the figure. When the switch is closed, the capacitor discharges rapidly, allowing a current flow between the rails, either through a physical piece of conductor, such as a metal bar, or a plasma arc that can be initiated in a propellant gas. The current loop created by the completed circuit generates a strong vector magnetic field, B , out of the plane of the circuit in the negative z direction, as shown in Figure 5.23.

Taylor, Travis S.. Introduction to Rocket Science and Engineering CRC Press. Kindle Edition.

Electromagnetic Engines

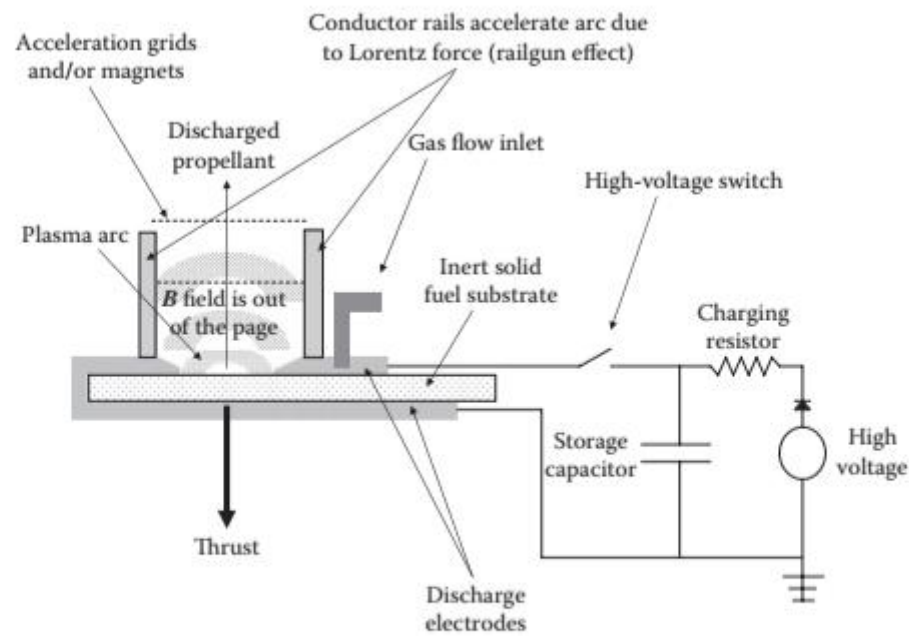


FIGURE 5.23
Schematic diagram of a pulsed plasma thruster.

Taylor, Travis S.. Introduction to Rocket Science and Engineering CRC Press. Kindle Edition.

The Lorentz force

The Lorentz force describes the interaction between a charged particle and electromagnetic fields. It is the fundamental force that governs how electric and magnetic fields influence the motion of charged particles (such as electrons and ions). This concept is essential in electromagnetism, plasma physics, electromechanical systems, and space propulsion technologies like magnetoplasmadynamic thrusters and Hall effect thrusters. The Lorentz force $\vec{F}$ on a particle of charge q moving with velocity $\vec{v}$ in an electric field $\vec{E}$ and a magnetic field $\vec{B}$ is

$$\vec{F} = q(\vec{E} + \vec{v} * \vec{B})$$

Where:

F = Total electromagnetic force (Newtons)

q = Charge of the particle (Coulombs)

$\vec{E}$ = Electric field (V/m)

$\vec{v}$ = Velocity of the particle (m/s)

$\vec{B}$ = Magnetic field (Tesla)

$\vec{v} \times \vec{B}$ = Cross product (determines direction of magnetic force)

The Lorentz Force

Application	Lorentz Force Role
Electric motors & generators	Converts electrical energy to mechanical energy and vice versa
Plasma propulsion (e.g., Hall thrusters)	Accelerates ions to produce thrust using crossed E and B fields
Mass spectrometry	Separates particles based on charge-to-mass ratio
Charged particle beams	Controls steering and focusing
Auroras and magnetospheres	Governs how charged solar particles interact with Earth's magnetic field

Electromagnetic engines

The force on the bar or plasma is due to the Lorentz force, $Id \times B$, and is calculated as

$$F = m \frac{dv}{dt} = Id \times B = IdB_o(x),$$

where I is the current in amperes, B_o is the magnitude of the magnetic field, m is the mass of the bar of propellant in the current flow, d is the length of the bar, v is the velocity of the bar, and x is the vector direction out of the thruster along the axis of the rails. Integrating Equation 5.16 and realizing that the motion is all in the x direction, we can solve for the scalar velocity, which is

Taylor, Travis S.. Introduction to Rocket Science and Engineering. CRC Press. Kindle Edition.

Electromagnetic Engines

$$v(t) = \frac{IdB_o t}{m}. \quad (5.17)$$

Integrating Equation 5.17 gives us the position as a function of time:

$$x(t) = \frac{IdB_o t^2}{2m}. \quad (5.18)$$

Assume x to be the finite length of the electrode rails, and solving for t yields

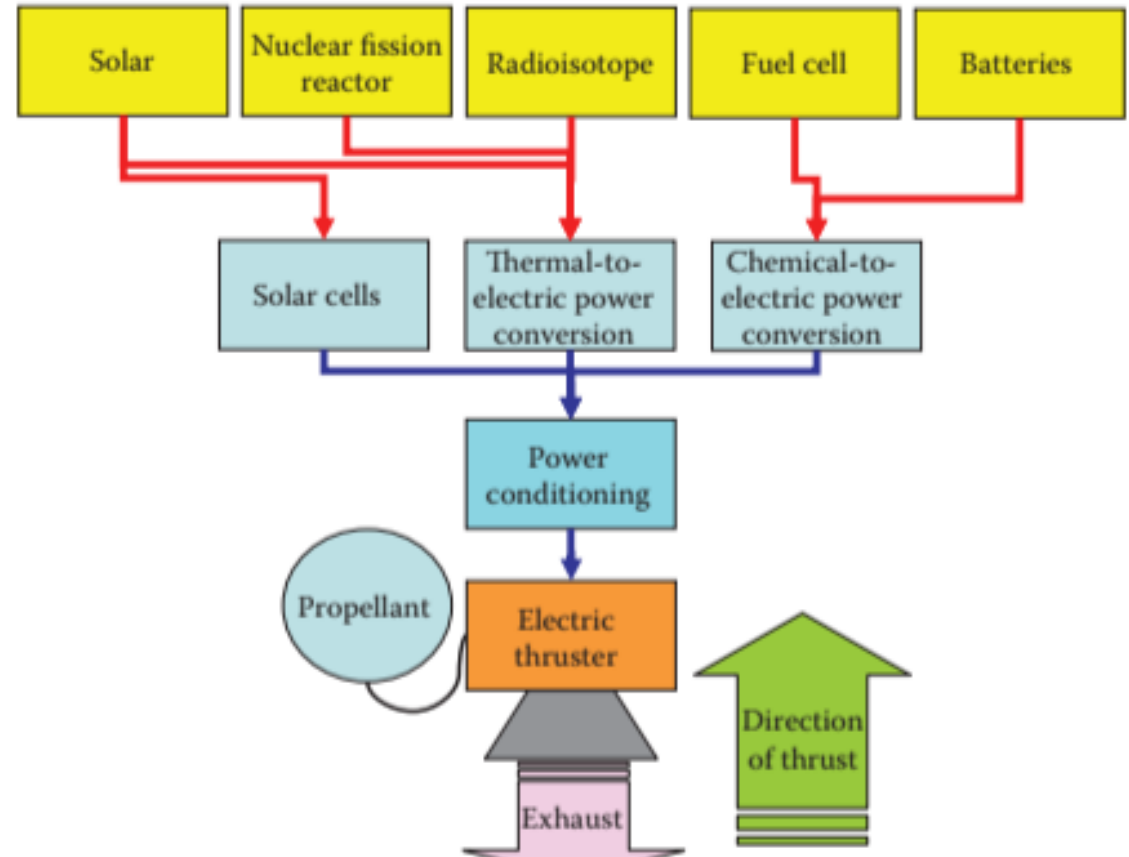
$$t = \sqrt{\frac{2xm}{IdB_o}}. \quad (5.19)$$

Substituting Equation 5.19 into Equation 5.17 results in an equation for the exit velocity of the bar as a function of design space parameters only. The resulting equation is

$$v(t) = \frac{IdB_o t}{m} = \frac{IdB_o}{m} \sqrt{\frac{2xm}{IdB_o}}. \quad (5.20)$$

Overview of Electro Propulsion Systems

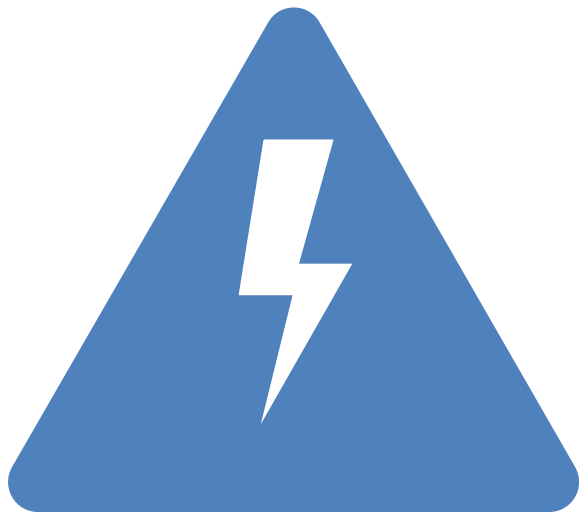
Taylor, Travis S..
Introduction to Rocket
Science and
Engineering. CRC
Press. Kindle Edition.



Pulse Plasma Thrusters

- A Pulsed Plasma Thruster (PPT) is a type of electric propulsion system used in spacecraft for attitude control and station-keeping, especially on small satellites. It is one of the simplest and most compact forms of electric propulsion and operates by creating and accelerating plasma in short bursts or "pulses." PPTs work by ablation and electromagnetic acceleration:
 - A solid propellant, usually Teflon (PTFE), is placed between two electrodes.
 - A high-voltage pulse is discharged across the electrodes, causing a small amount of the Teflon surface to vaporize and ionize into plasma.
 - The resulting plasma is accelerated out of the thruster via Lorentz forces (interaction between electric current and magnetic fields), producing a small amount of thrust.

Pulse Plasma Thruster



Components

- Solid Propellant Block: Typically, Teflon, serves as both the propellant and the dielectric.
- Electrodes: Anode and cathode positioned to channel and accelerate the plasma.
- Energy Storage Unit: Usually, a capacitor that stores the high-voltage pulse used for each discharge.
- Switching Mechanism: Often uses a spark plug or transistor to trigger each discharge.

Pulse Plasma Thruster

The first step is to determine how much of the Teflon fuel is ejected with each pulse of the high-voltage capacitor discharging across it. The way to do this is to equate the energy stored in the capacitor with the energy of the exhaust velocity. So, we have :

$$\frac{1}{2}CV^2 = mv^2$$

In Equation 5.21, the C is capacitance in farads, V is electric potential in volts, m is the mass of the exhaust due to one capacitor discharge across the Teflon, and v is the exhaust velocity of the ionized Teflon plasma.

Taylor, Travis S.. Introduction to Rocket Science and Engineering. CRC Press. Kindle Edition.

Rocket Performance

Table 2-1 Ranges of Typical Performance Parameters for Various Rocket Propulsion Systems

Engine Type	Specific Impulse ^a (sec)	Maximum Temperature (°C)	Thrust-to-Weight Ratio ^b	Propulsion Duration	Specific Power ^c (kW/kg)	Typical Working Fluid	Status of Technology
Chemical—solid or liquid bipropellant, or hybrid	200–468	2500–4100	10^{-2} –100	Seconds to a few minutes	10^{-1} – 10^3	Liquid or solid propellants	Flight proven
Liquid monopropellant	194–223	600–800	10^{-1} – 10^{-2}	Seconds to minutes	0.02–200	N ₂ H ₄	Flight proven
Resistojet	150–300	2900	10^{-2} – 10^{-4}	Days	10^{-3} – 10^{-1}	H ₂ , N ₂ H ₄	Flight proven
Arc heating—electrothermal	280–800	20,000	10^{-4} – 10^{-2}	Days	10^{-3} –1	N ₂ H ₄ , H ₂ , NH ₃	Flight proven
Electromagnetic including pulsed plasma (PP)	700–2500	—	10^{-6} – 10^{-4}	Weeks	10^{-3} –1	H ₂ Solid for PP	Flight proven
Hall effect	1220–2150	—	10^{-4}	Weeks	10^{-1} – 5×10^{-1}	Xenon	Flight proven
Ion—electrostatic	1310–7650	—	10^{-6} – 10^{-4}	Months, years	10^{-3} –1	Xenon	Flight proven
Solar heating	400–700	1300	10^{-3} – 10^{-2}	Days	10^{-2} –1	H ₂	In development

Nuclear Rocket Engines

Nuclear rocket engines operate by using the energy from nuclear fission (splitting atoms) to heat a propellant, which then expands and is expelled through a nozzle to generate thrust. Unlike chemical rockets, where combustion provides the energy, nuclear rockets use a reactor as the heat source. These are often referred to as NTR (Nuclear Thermal Rocket)

Reactor Core: Contains fissile material (like uranium-235 or plutonium-239) where controlled nuclear fission occurs.

Heat Transfer: The reactor heats a working fluid (usually liquid hydrogen).

Exhaust: The heated hydrogen expands rapidly and is expelled through a nozzle, generating thrust.

Nuclear Rocket Engines

Types of Nuclear Rocket Engines

a. Nuclear Thermal Propulsion (NTP)

- Most developed concept.
- Uses fission to heat hydrogen, achieving much higher specific impulse than chemical rockets (~900 seconds vs ~450 seconds).
- Examples: NASA's NERVA program (1960s–70s), current DARPA/DRACO initiatives.

b. Nuclear Electric Propulsion (NEP)

- Fission reactor generates electricity, which powers electric thrusters like ion or Hall-effect thrusters.
- Provides high efficiency but very low thrust—useful for long-duration missions where time is less critical.
- Requires large radiators and power management systems.

c. Nuclear Pulse Propulsion

- Conceptualized in Project Orion.
- Involves detonating nuclear bombs behind the spacecraft to produce thrust.
- Extremely high performance, but not feasible under current space treaties due to nuclear explosions in space.

DRACO

- The Demonstration Rocket for Agile Cislunar Operations (DRACO) program is an effort to advance nuclear propulsion technology for critical space missions.
- Nuclear thermal rockets (NTRs) use a nuclear reactor to heat propellant to extreme temperatures before exhausting the hot propellant through a nozzle to produce thrust. Compared to conventional space propulsion technologies, NTRs offers a high thrust-to-weight ratio around 10,000 times greater than electric propulsion and two-to-five times greater specific impulse (i.e. propellant efficiency) than in-space chemical propulsion.
- <https://www.darpa.mil/research/programs/demonstration-rocket-for-agile-cislunar-operations>

DRACO

- **Propulsion System:** DRACO employed a nuclear thermal propulsion system where a nuclear reactor heats liquid hydrogen to high temperatures (approximately 3,600 to 5,400°F), converting it into high-velocity gas expelled through a nozzle to produce thrust.
- **Fuel:** The reactor utilized HALEU fuel, enriched to levels between 5% and 20% uranium-235, balancing performance with regulatory considerations.
- **Performance:** NTP systems like DRACO offer two to three times greater efficiency compared to conventional chemical propulsion, enabling faster transit times for missions beyond Earth's orbit.
- **Launch Vehicle:** The DRACO spacecraft was planned to be launched aboard a Vulcan Centaur rocket provided by the U.S. Space Force.
- **Mission Objectives:** The primary goals included demonstrating the safe operation of a nuclear thermal rocket engine in space, collecting performance data, and validating the use of HALEU fuel in such systems.



DRACO

As of January 2025, the DRACO program's planned 2027 launch was placed on indefinite hold due to technical and regulatory challenges, including complex safety and testing requirements for ground-based nuclear reactor validation and unresolved final design aspects of the propulsion system. Subsequently, the FY2026 federal budget released in May 2025 proposed significant cuts to NASA's Space Technology Mission Directorate, effectively leading to the cancellation of the DRACO program.

Solid Core Nuclear Engine

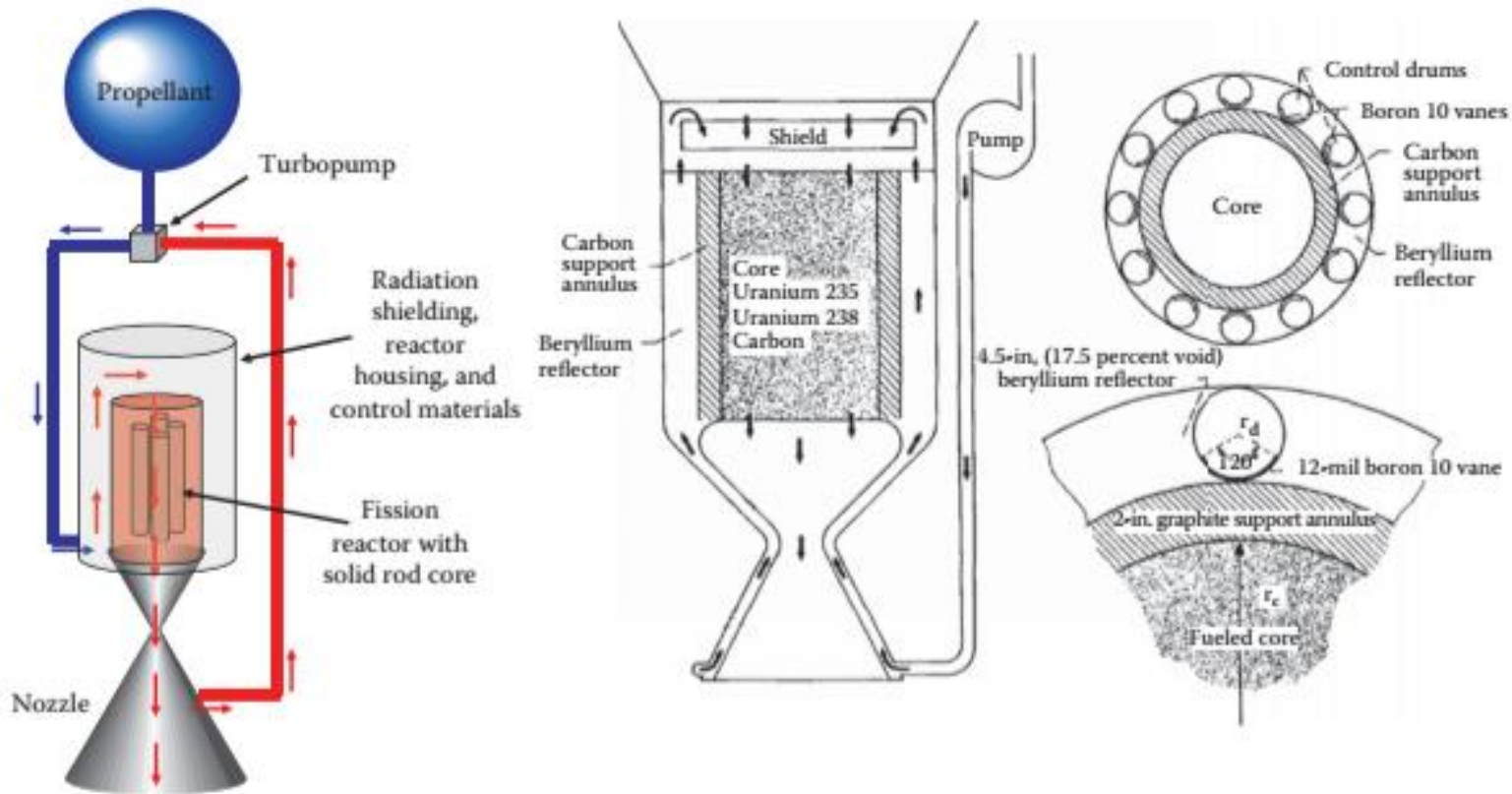


FIGURE 5.37
Schematic of an NTR engine.

The diagram in Figure 5.37 illustrates an NTR system that uses solid fuel rods for the nuclear reactor core. The solid core is the most traditional.

Taylor, Travis S.. Introduction to Rocket Science and Engineering. CRC Press, 2015. Kindle Edition.

Liquid Core

A liquid core engine uses a liquid material as the fissile source. Because the core in these types of reactors is already in liquid form, they can be heated to temperatures above the melting point of the core materials, and, therefore, the heat source can grow much hotter. The limiting factors in how hot such a reactor can get is the stress the container wall can handle and the melting point of the reflectors and moderators. Liquid core engines could potentially deliver specific impulses as high as 1,500 sec. However, how to go about building such an engine safely is still in question. The radioactive fluids must be maintained inside the engine. The process of transferring the heat between the radioactive fluid and a propellant gas is a difficult one and has yet to be completely worked out. There are some concepts for liquid core engines; however, more research needs to be done.

- Taylor, Travis S.. Introduction to Rocket Science and Engineering. CRC Press. Kindle Edition.

Gas Core

- A gas core engine would use a pocket of gaseous uranium as the fuel of the reactor. In order to prevent the gas escaping from the rocket engine, it must be housed in a very high-temperature quartz container. This “nuclear lightbulb” would sit in the middle of the expansion chamber where hydrogen is flowed around it and superheated. The expanded hydrogen gas would then flow through a convergent–divergent nozzle. Studies suggest that such an engine could attain specific impulses of over 2,000 sec.

-Taylor, Travis S.. Introduction to Rocket Science and Engineering. CRC Press. Kindle Edition.