ME EN 5830/6830
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Spring 2025

Aerospace Propulsion

Lecture 22

Rocket Propulsion V

Rocket Propulsion: Part V

- Solid Propellant Rocket Motors
- Propellant Grain
- Hybrid Propellant Rockets
- Electric Propulsion

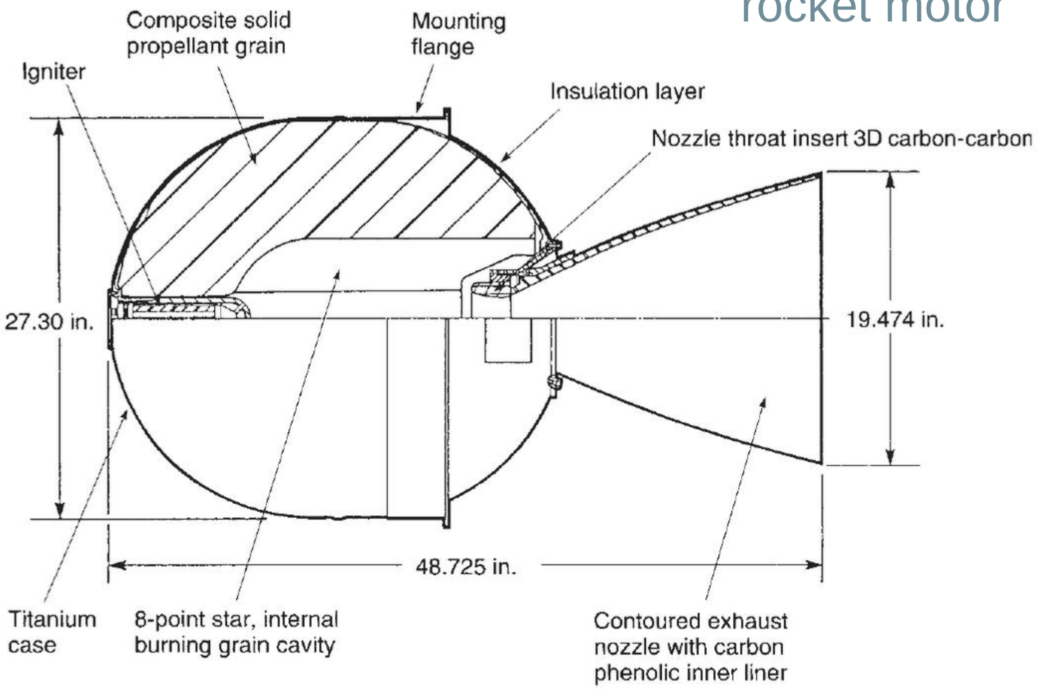
Solid Propellant Rocket Motors

- SPRMs have several benefits over liquid engines
  - Simpler
  - Often no moving parts
  - Long term storage
  - Ready to ignite
  - Do not leak propellants
- SPRMs unfortunately also have downsides
  - Thrust cannot be varied in flight as needed
  - Cannot “test” solid motor beforehand
  - Generally, less efficient

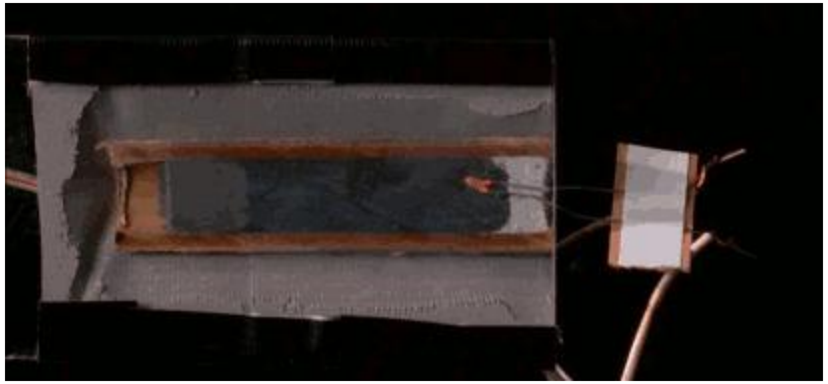
Solid Propellant Rocket Motors

- Major components of a solid motor
  - Grain
    - Solid body of hardened propellant
      - Fuel AND Oxidizer (mixed)
    - 80-95% of motor mass
  - Igniter
    - Initiates burning of the grain
  - Cavity
    - Internal channel through which gases flow
  - Nozzle
    - Converging-diverging
    - Efficiently accelerates flow

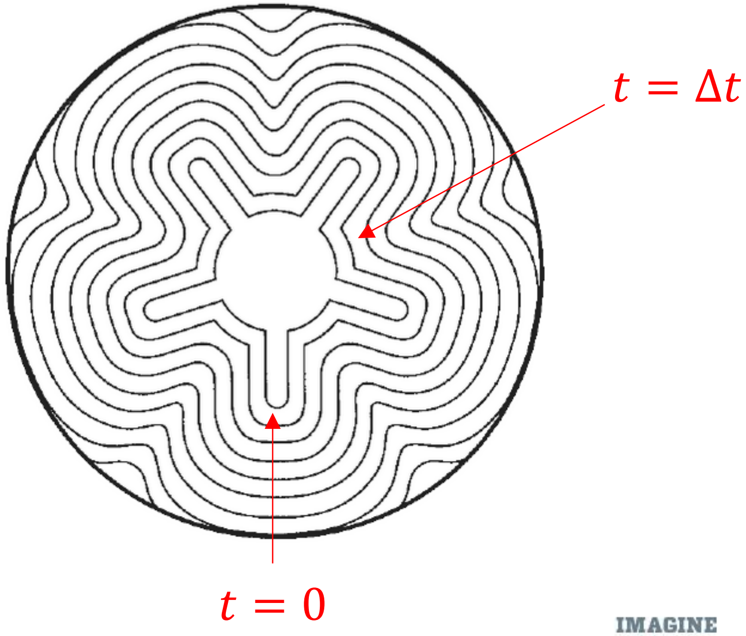
STAR 27
rocket motor



Propellant Burning



- Once propellant is ignited, it won't stop
- Propellant burns along the entire exposed surface at once
  - This surface recedes perpendicular to itself
  - Burning rate r is rate of regression (velocity)



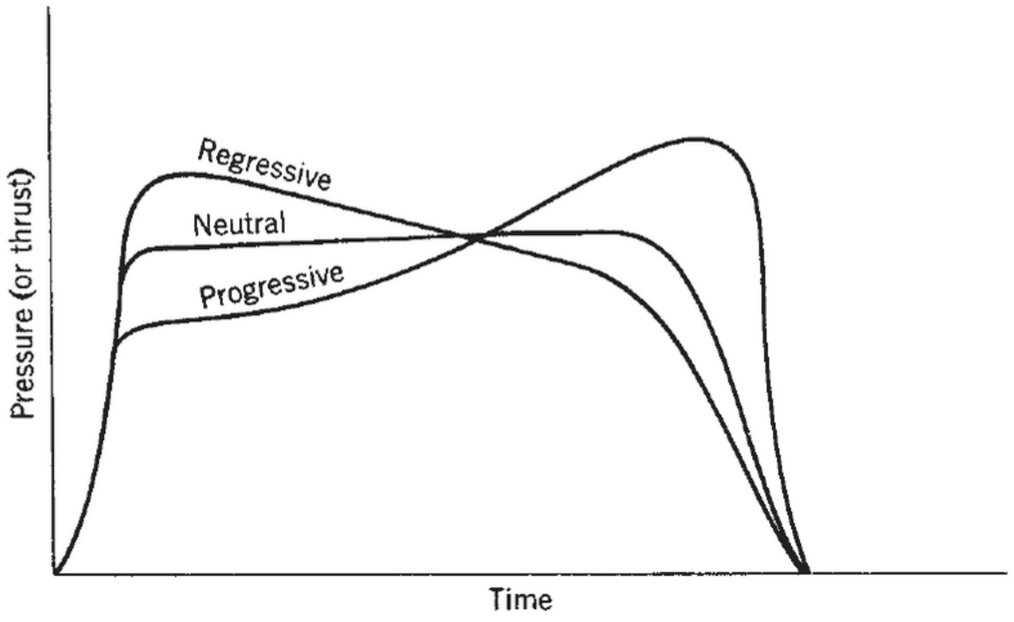
- As propellant burns, the internal cavity geometry and area changes significantly
  - Pressures and velocities also change

Propellant Burning

- Successful rocket motor design hinges on understanding and controlling burn rate
- Adjustments to burn rate can be made by:
  - Propellant adjustments
    - Adding a burning catalyst
    - Adjust particle sizes and propellant ratios
    - Increase heat of combustion
  - Chamber adjustments
    - Higher initial propellant temperature
    - Higher combustion chamber pressure
    - Higher gas flow velocities across surface

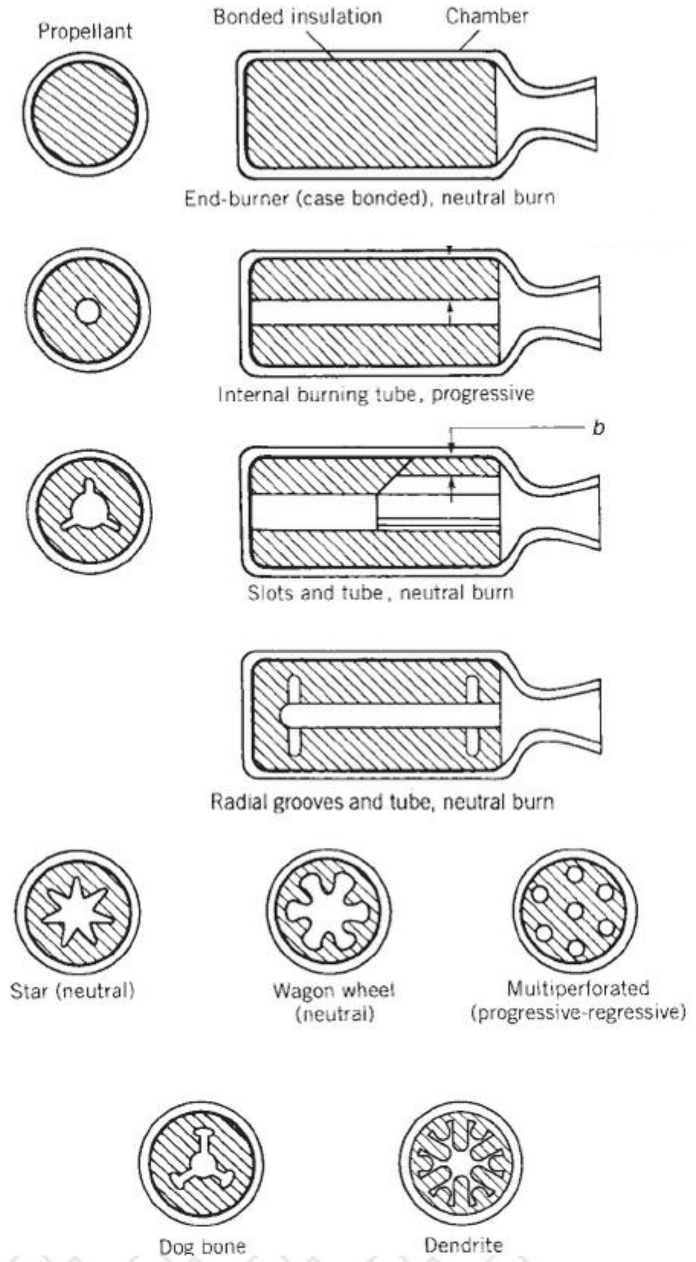
Propellant Grain

- Grain material and geometry is selected to achieve certain mission goals
  - Total impulse
    - Mass of grain
    - Grain energy density
  - Specific impulse
    - Burn rate of grain
  - Thrust as a function of time
    - Regressive – thrust decreases with time
    - Neutral – thrust constant with time
    - Progressive – thrust increases with time
    - How is this controlled without valves?

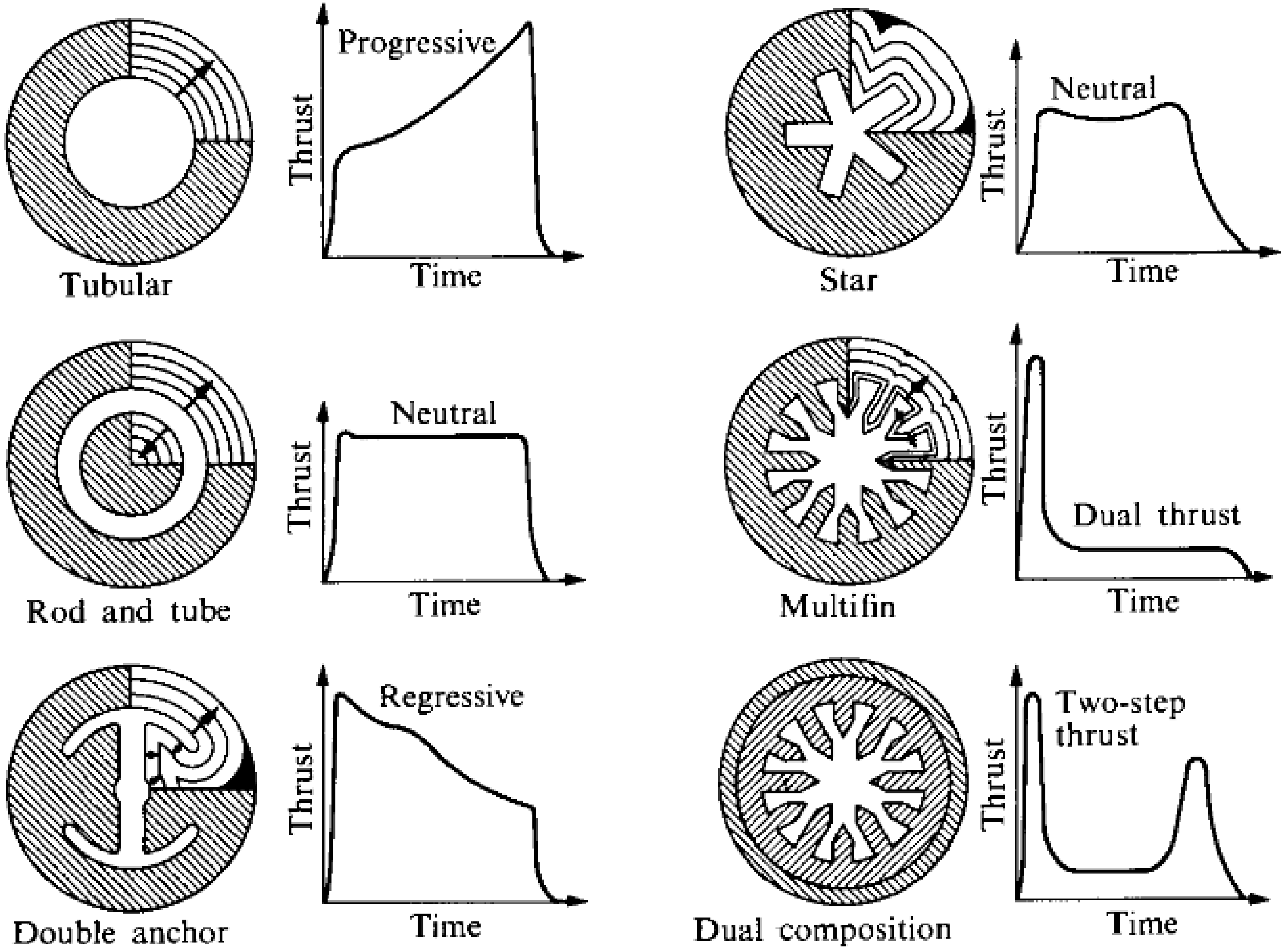


Propellant Grain

- Geometry of grain has two major effects on thrust
  - As grain is burned, cavity area (may) expand
    - Gas velocity decreases
  - As grain is burned, grain surface area (may) expand
    - More grain burns simultaneously
    - Gas velocity increases
  - Depending on how these two effects are balanced, thrust can be regressive, neutral, or progressive

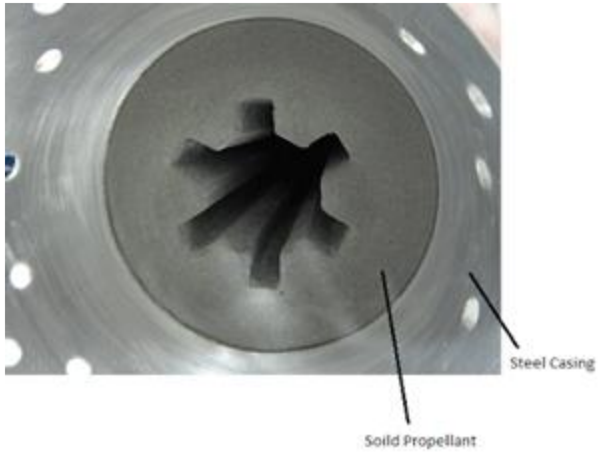


Propellant Grain

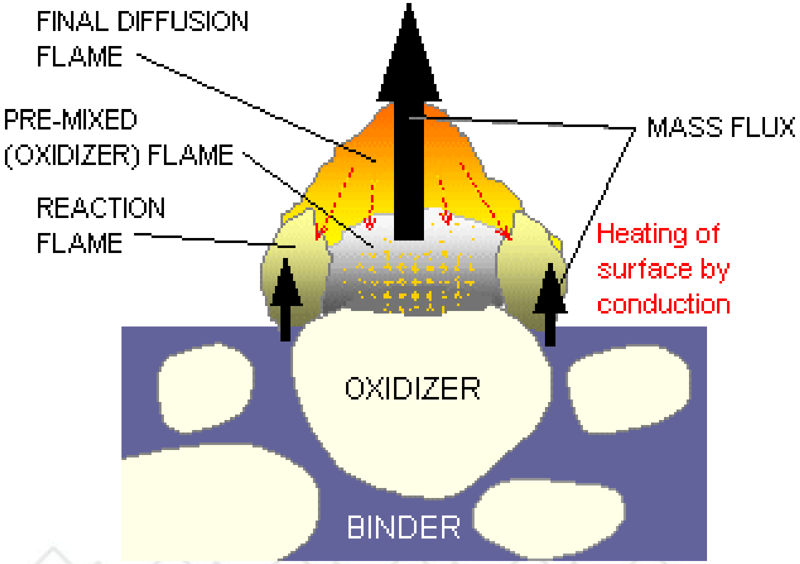


Propellant Grain

- Solid Propellant Casting
  - Mix Fuel + Oxidizer
    - Typically take a liquid form
  - Pour into mold
  - Cured in oven to solidify



- Solid Propellant Combustion
  - Vaporize individual components
  - Combustion occurs mainly in gas phase
  - Burns roughly non-premixed

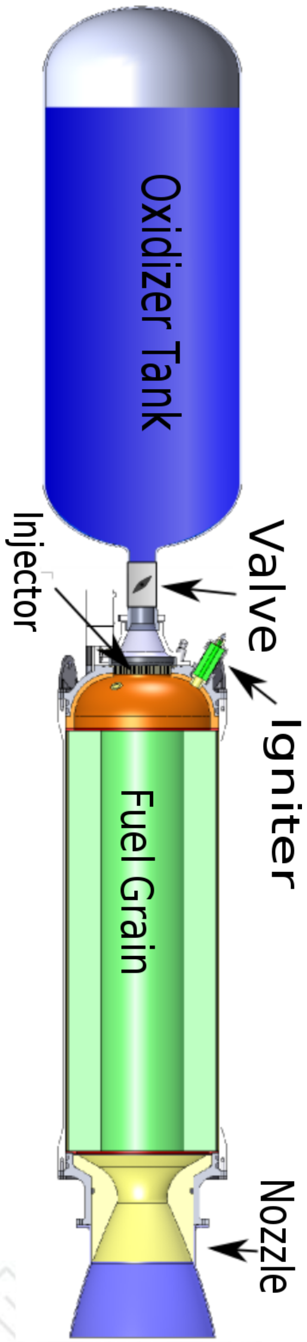


Hybrid Propellant Rockets

- Hybrid propellant rockets utilize one solid-phase and one liquid/gas-phase propellant
  - Generally solid fuel, liquid/gas oxidizer
    - Solid oxidizers generally hazardous and less energetic
- Advantages
  - Start-stop-throttling capability
  - Higher specific impulse than solid motors
- Disadvantages
  - Difficulty of controlling mixing between two phases of propellants
  - Can’t spin a turbopump when fuel is solid

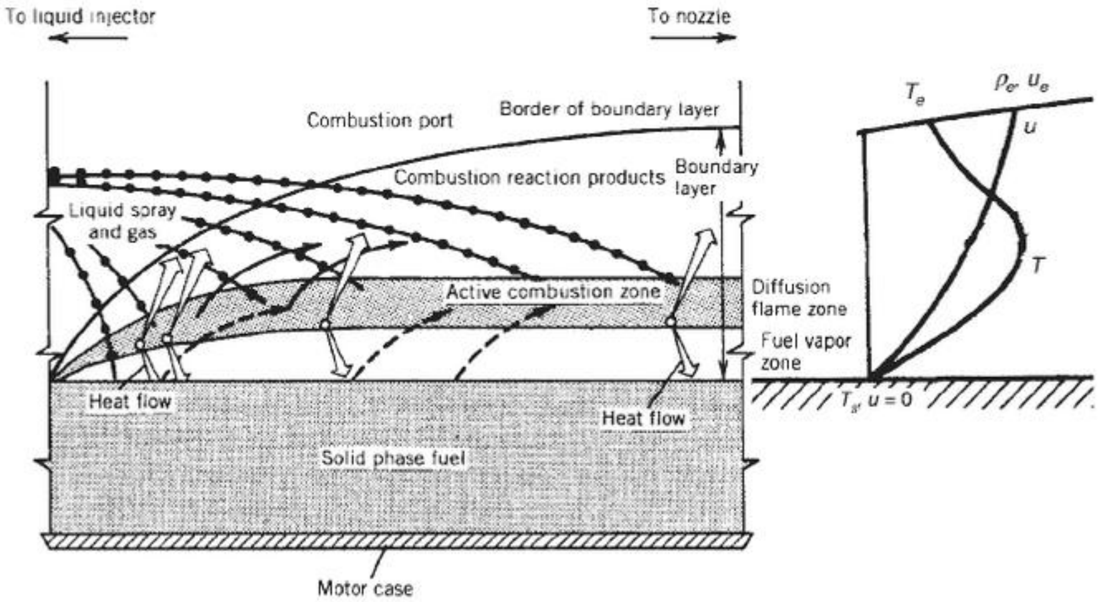
Hybrid Propellant Rockets

- Major components
  - Liquid Oxidizer
    - Stored in a pressurized tank
    - Controlled by a valve
    - Typically, no turbopump because no fuel to burn before combustion section
  - Solid Fuel
    - Grain much like in solid rocket, but no oxidizer component
  - Igniter
    - Like solid rocket but ignites surface when oxidizer flowing
  - Nozzle
    - Efficiently accelerate flow



Hybrid Propellant Rockets

- Combustion in HPRs
  - Complex combination of solid fuel and liquid oxidizer leads to different burning rate of solid fuel
  - A <u>non-premixed</u> flame forms in the boundary layer, slightly away from fuel
  - Heat of flame (convection + radiation) heats up solid fuel and liquid oxidizer which both vaporize
    - Gaseous fuel and oxidizer mix and burn



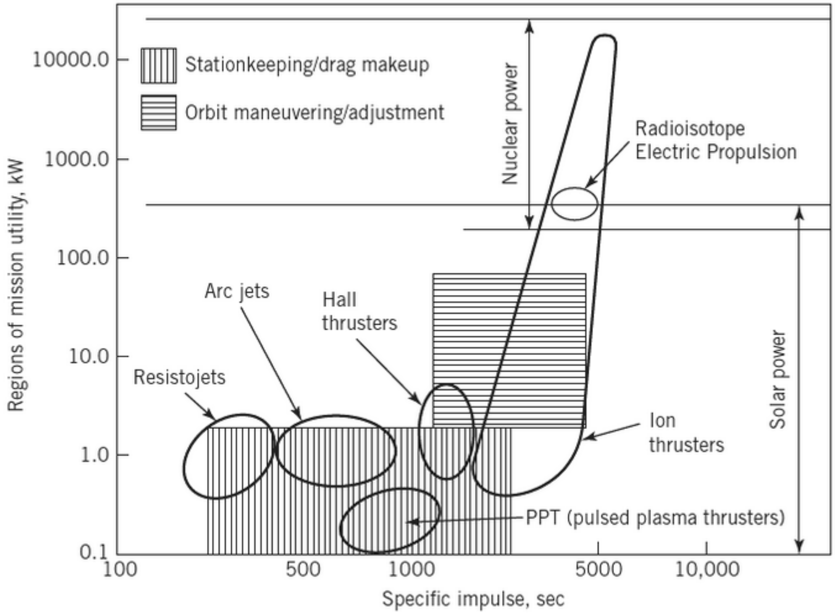
Hybrid Propellant Rockets

- HPRs are less common, but exist
- Virgin Galactic's SpaceShipTwo operates on a hybrid rocket motor
- BYU, Utah State, and UofU teamed up in 1995 and 2003 to launch the Unity IV hybrid propellant rocket
  - 20 feet tall, 4500 feet elevation rise

Hybrid Propellant Rockets

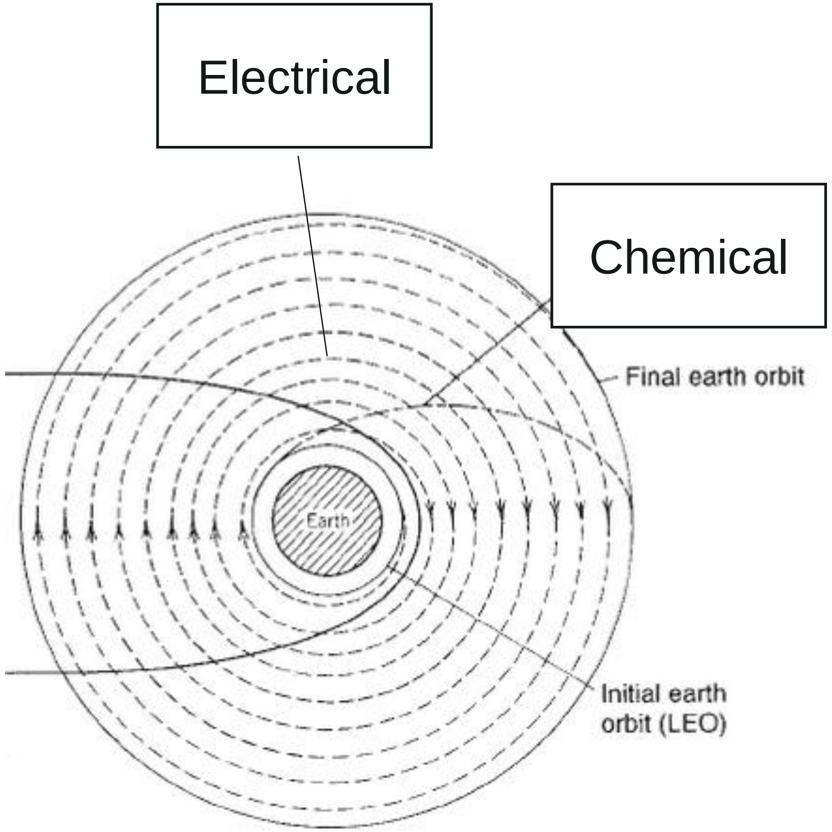
Electric Propulsion

- Electric Propulsion has two broad meanings
    - Electrical energy used for heating propellant
    - Electrical energy for directly ejecting propellant
- Liquid Rocket Engine, Solid Rocket Motor, Electric Rocket Thruster
- Typically have massive exhaust velocities
    - Use less propellant, very efficient
- Low power output (bad density/generation)
    - Low thrust
    - Only used in space



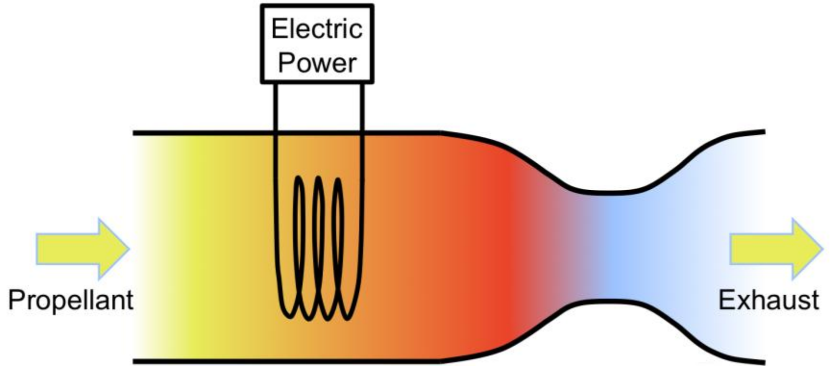
Electric Propulsion

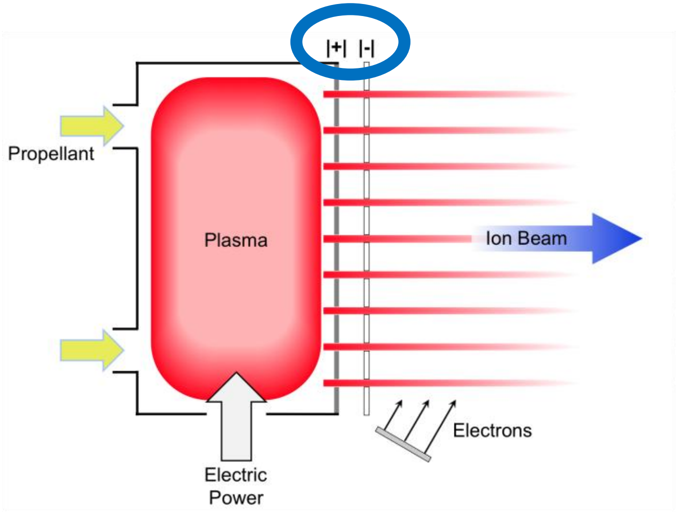
- Major uses for Electric Propulsion
  - Drag compensation of satellites
    - Earth orbiting satellites experience minor air resistance that constantly needs to be overcome
    - A ΔV on the order of 50 m/s per year is needed
  - Orbit raising
    - Slowly transitioning satellites between different orbits
    - Time is not a major issue due to low drag
  - Interplanetary travel and deep space probes
    - High efficiency means deep space travel is possible
    - Potentially unsuitable for human travel (too slow)

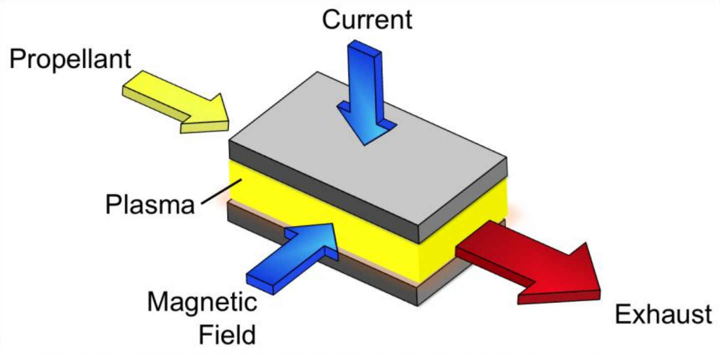


Electric Propulsion

- Three primary forms of electric propulsion
- Electrothermal propulsion
  - Propellant heated electrically and expanded thermodynamically with C-D nozzle
- Electrostatic propulsion
  - Acceleration achieved by interaction of electrostatic fields with charged particles
- Electromagnetic propulsion
  - Acceleration achieved by interaction of electrostatic + magnetic fields with plasmas

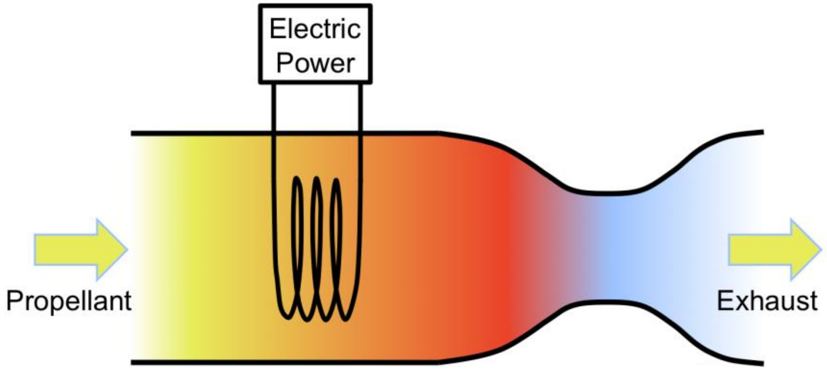


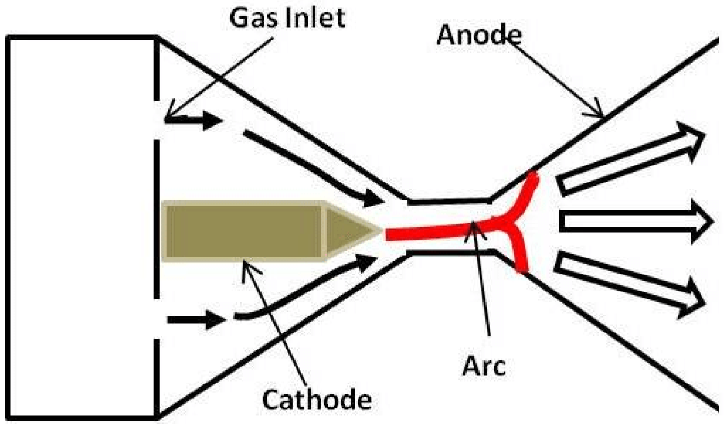




Electric Propulsion

- Electrothermal propulsion
  - Resistojet – Use resistors to convert electricity to heat which is added to propellant
    - Solid material (resistor) is being heated
    - Temperature limitations lead to cap of $I_s = 300\ s$
  - Arcjet – Electric discharge directly heats propellant gases
    - Less solid material being heated
    - Higher temperatures (and I_s) can be achieved
    - Arc is relatively thin and spurious
      - Good mixing is required after arc

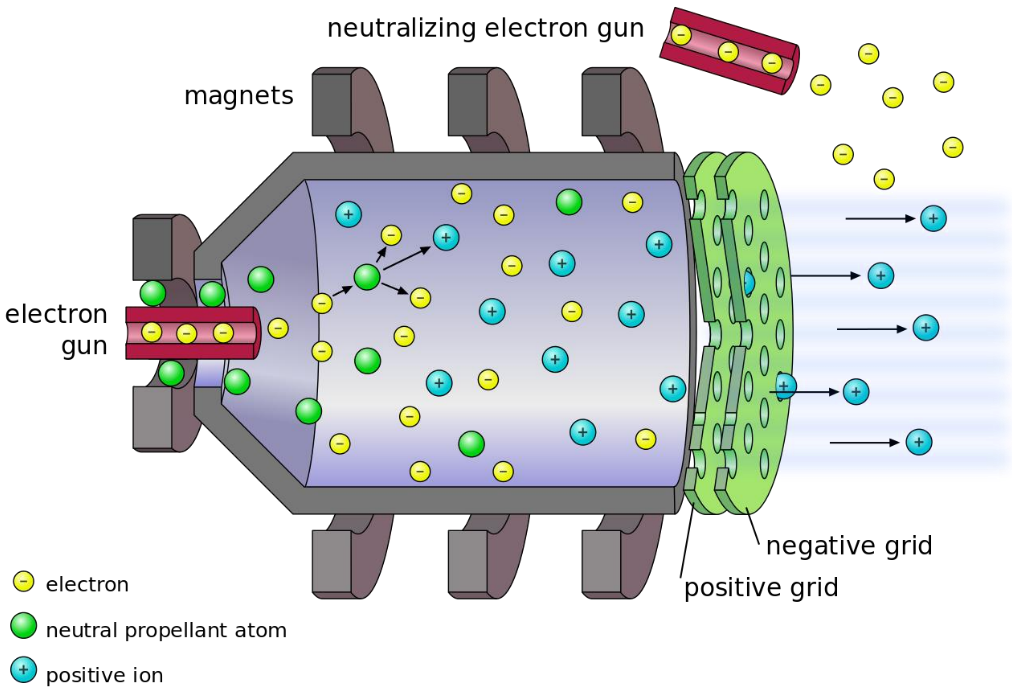




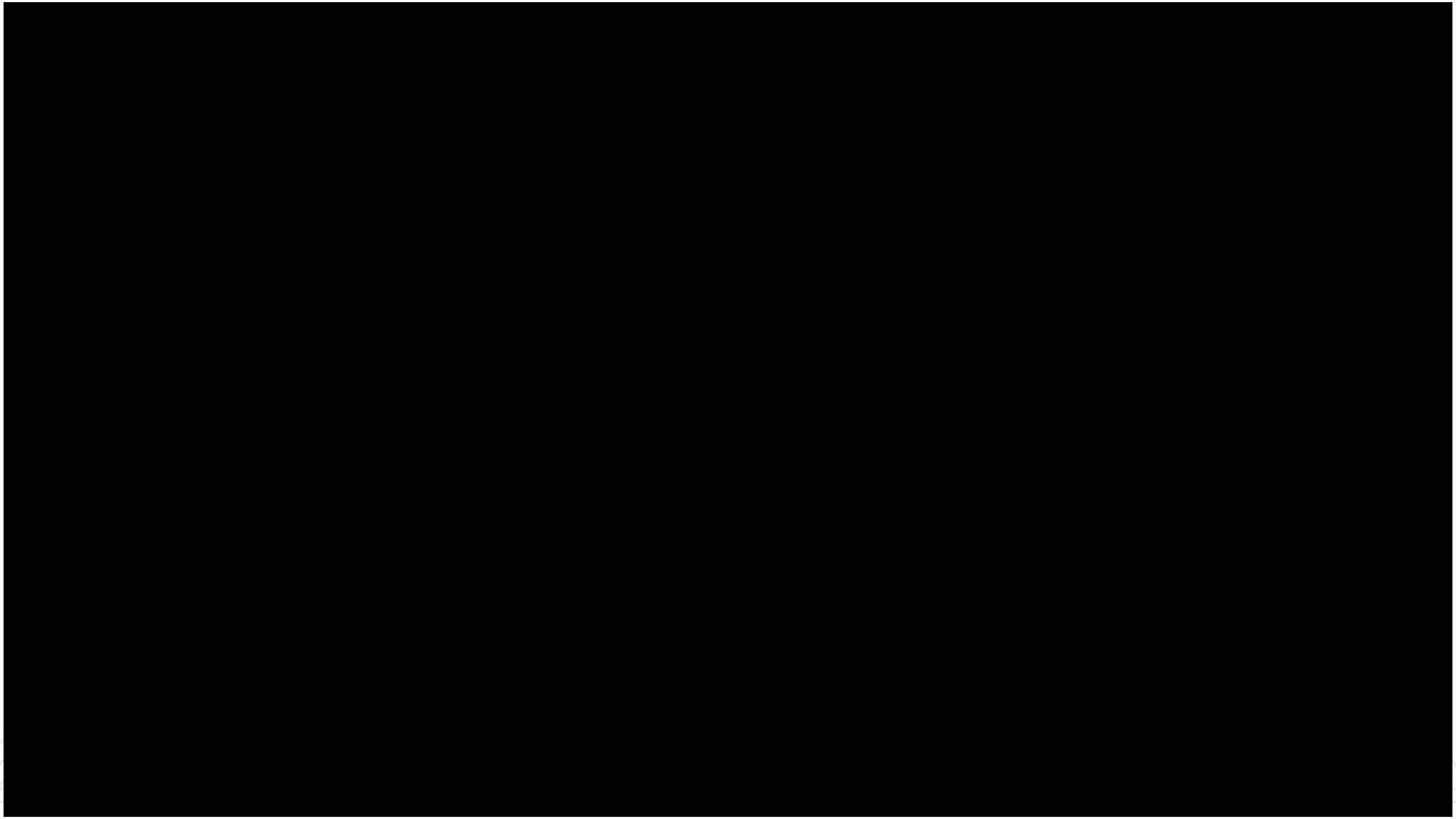
Electric Propulsion

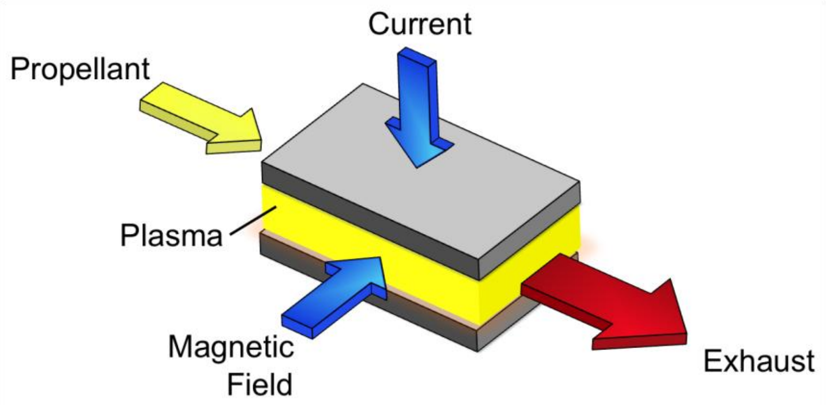
- Electrostatic propulsion
  - $F = \rho_e E$
    - Electric current density ρ_e
    - Electric field E
  - Ion Thruster
    - Create positive charge in neutral propellants
    - Positive molecules accelerate through electric field
    - (Electron acceleration inefficient because they have tiny mass and therefore momentum)
    - Must avoid negatively charging engine by ejecting electrons

Gridded Ion Thruster



Electric Propulsion

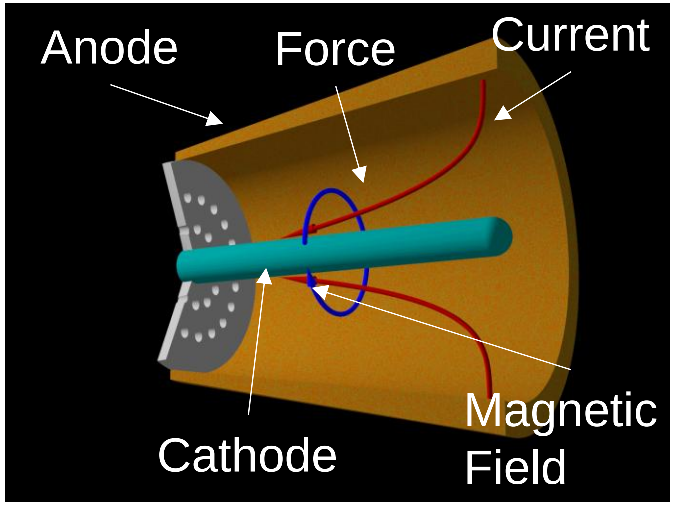




Electric Propulsion

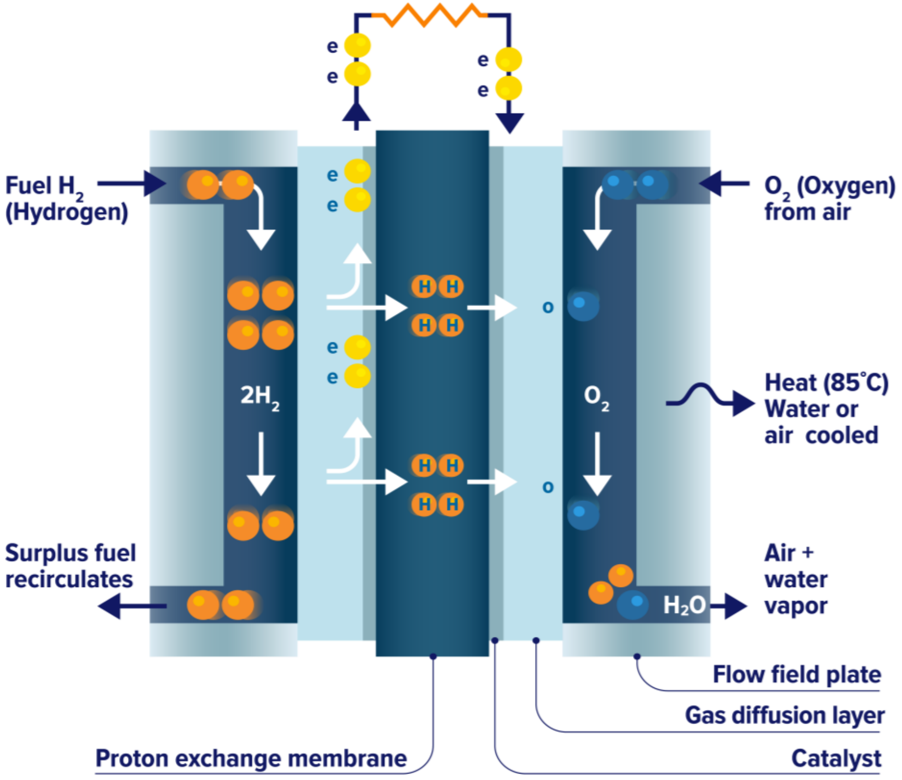
- Electromagnetic propulsion
  - $F = \boldsymbol{j} \times \boldsymbol{B}$
    - Electric current density $\boldsymbol{j}$
    - Magnetic field $\boldsymbol{B}$
    - Force requires perpendicular electric current and magnetic field

  - Note that plasmas are neutrally charged so electric field force is irrelevant



Electric Propulsion

- Power Sources
  - Batteries
    - General low energy density, especially compared to chemical fuel energy density
    - Rarely the main propulsion power source
  - Fuel cells
    - Electrical energy comes from chemical processes controlled by catalysis
    - Generally large and so mostly used on manned missions (with larger rockets)



SOURCE: Wikipedia Membrane electrode assembly

Electric Propulsion

- Power Sources
  - Solar Arrays
    - Photovoltaic solar cells that convert the sun's electromagnetic radiation into electricity
    - Only 20-30% efficient, however, energy is somewhat "free" and "unlimited"
    - Have supplied electric power in most long-duration space missions
    - Additional weight to be considered for batteries and orientation equipment

Electric Propulsion

- Power Sources
  - Nuclear reactors
    - Deliver electricity through the long-decay of radioisotopes
    - Very low power output
    - Functions for extremely long
      - Voyager 2 spacecraft launched in 1977 and is still in operation
    - Nuclear reactors are not efficient (<10%)
    - Must deal with significant amount of heat coming from reactor

Voyager 2