Space Propulsion
A Materials-Based Perspective

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Image source: https://www.nasa.gov/mission_pages/tdm/sep/index.html

Overarching Themes

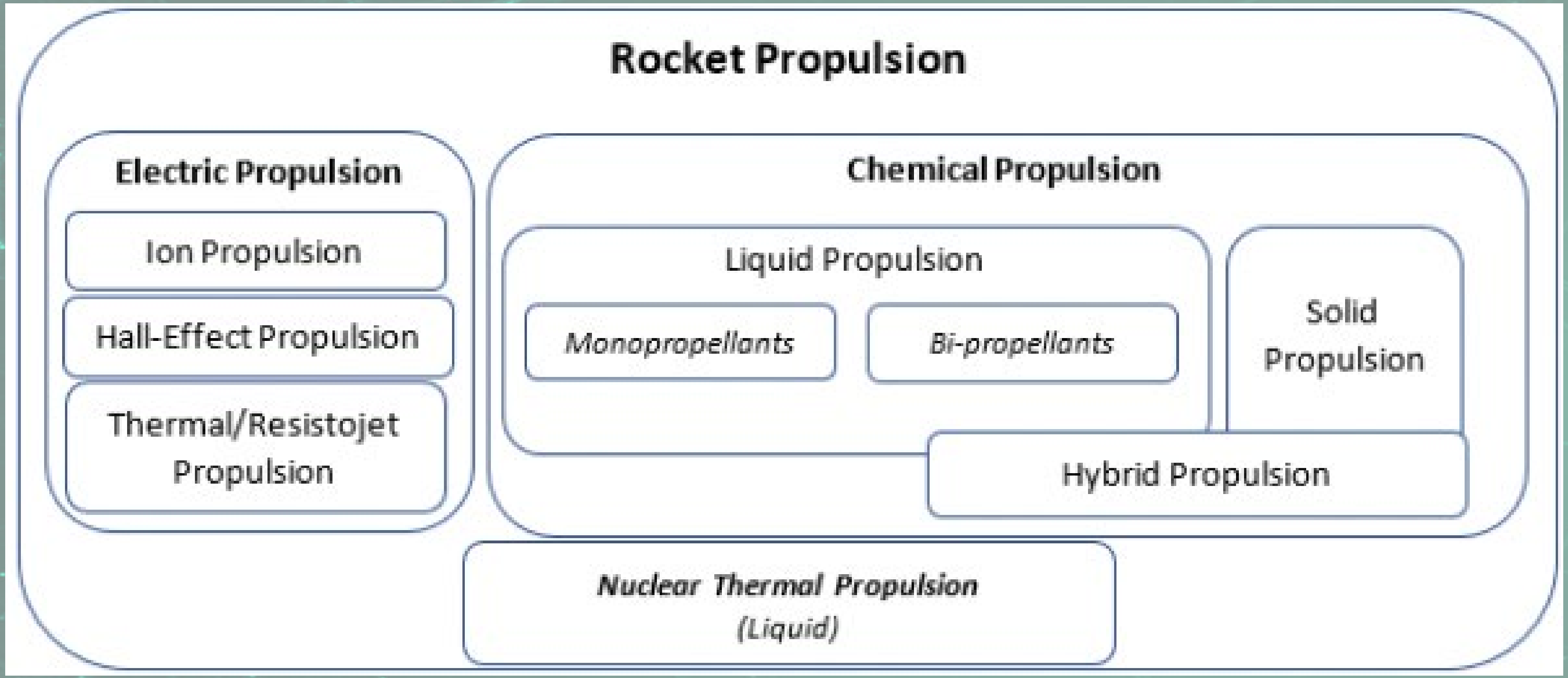
- Organizing space propulsion materials research and how best to accomplish this
- Additive manufacturing (AM) – it has already changed things, and it will keep changing them
- Miniaturization (to address cubesats (microsats/nanosats) of various types)
- If not physically smaller, can I make it lighter?
- Interesting results come from thinking “outside the box”

Breaking Out the Types of Propulsion

- There are LOTS of different types of space propulsion technologies
- Viability determined by technology readiness level (TRL)
- Ranges from Solid Fuel Rocket Motors (TRL 9) to Bussard Ramjets (TRL 2)
- For this work, we placed a cutoff at TRL 6

TRL	Description
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in an operational environment
TRL 7	System prototype demonstration in an operational environment
TRL 8	Actual system complied and "flight qualified" through test and demonstration
TRL 9	Actual system flight proven through successful mission operations

Breaking Out the Types of Propulsion

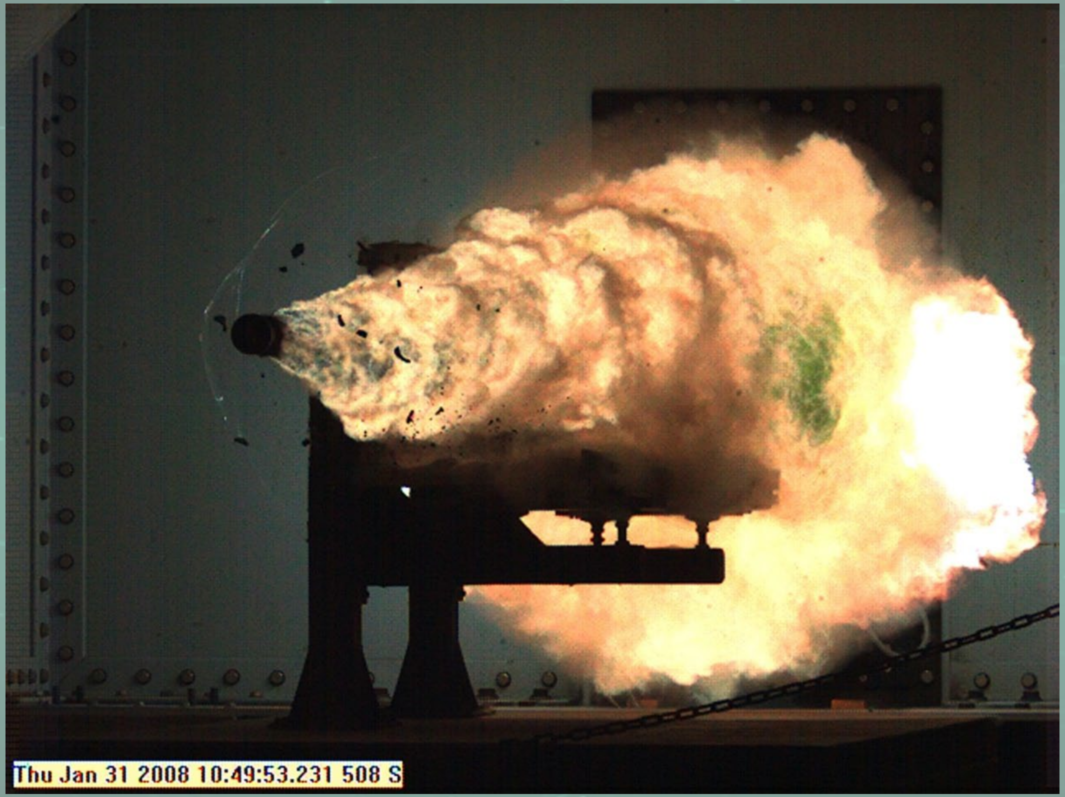


Nontraditional Propulsion

Image source: https://www1.grc.nasa.gov/research-and-engineering/nuclear-thermal-propulsion-systems/

Breaking Out the Types of Propulsion

- Chemical Propulsion
- Electric Propulsion
- Nuclear Thermal Propulsion
- Other Propulsion



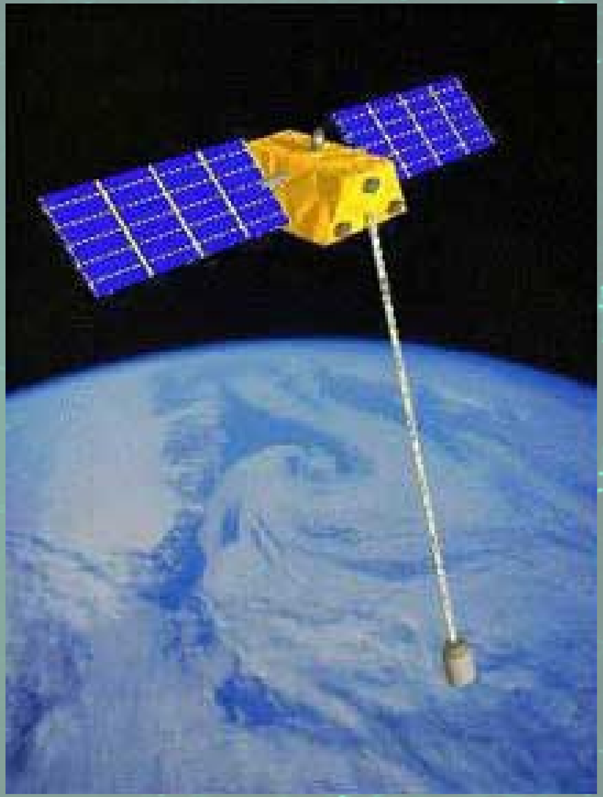


Image source: https://www.navsea.navy.mil/Media/News/Article/2485415/nps-railgun-lab-propels-technology-leaders-alumnus-into-award-winning-research/

Chemical Propulsion

- Solid Propellant Rockets
- Hybrid Propellant Rockets
- Bi-Propellant Rockets
- Tri-Propellant Rockets
- Liquid Propellant Rockets
- Air-Liquid Engines (LACEs)
- Monopropellant Rockets
- Nonreactive Propellant Engines (commonly referred to as cold gas thrusters)

Image source: https://www.flickr.com/photos/spacex/29916104756/in/photolist-MzzRFA-LFbFbJ

Electric Propulsion

- Electrothermal Propulsion
  - Resistojet Engines
  - Arcjet Engines
- Gridded Electrostatic Ion Engines
- Hall Effect Thrusters
- Field-Emission Electric Propulsion (FEEP)
- Magnetoplasmadynamic (MPD) Thrusters
- Pulsed Plasma Thrusters

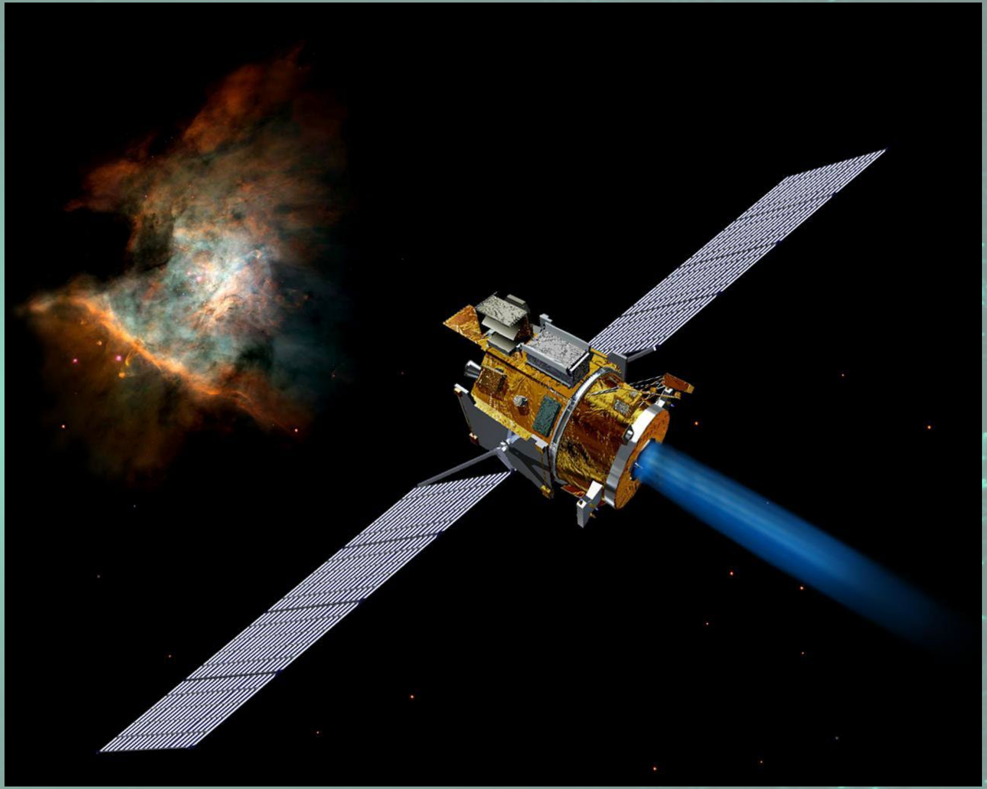


Image source: https://solarsystem.nasa.gov/missions/deep-space-1/in-depth/

Nuclear Thermal Propulsion

Focus is solely on nuclear thermal rocketry.

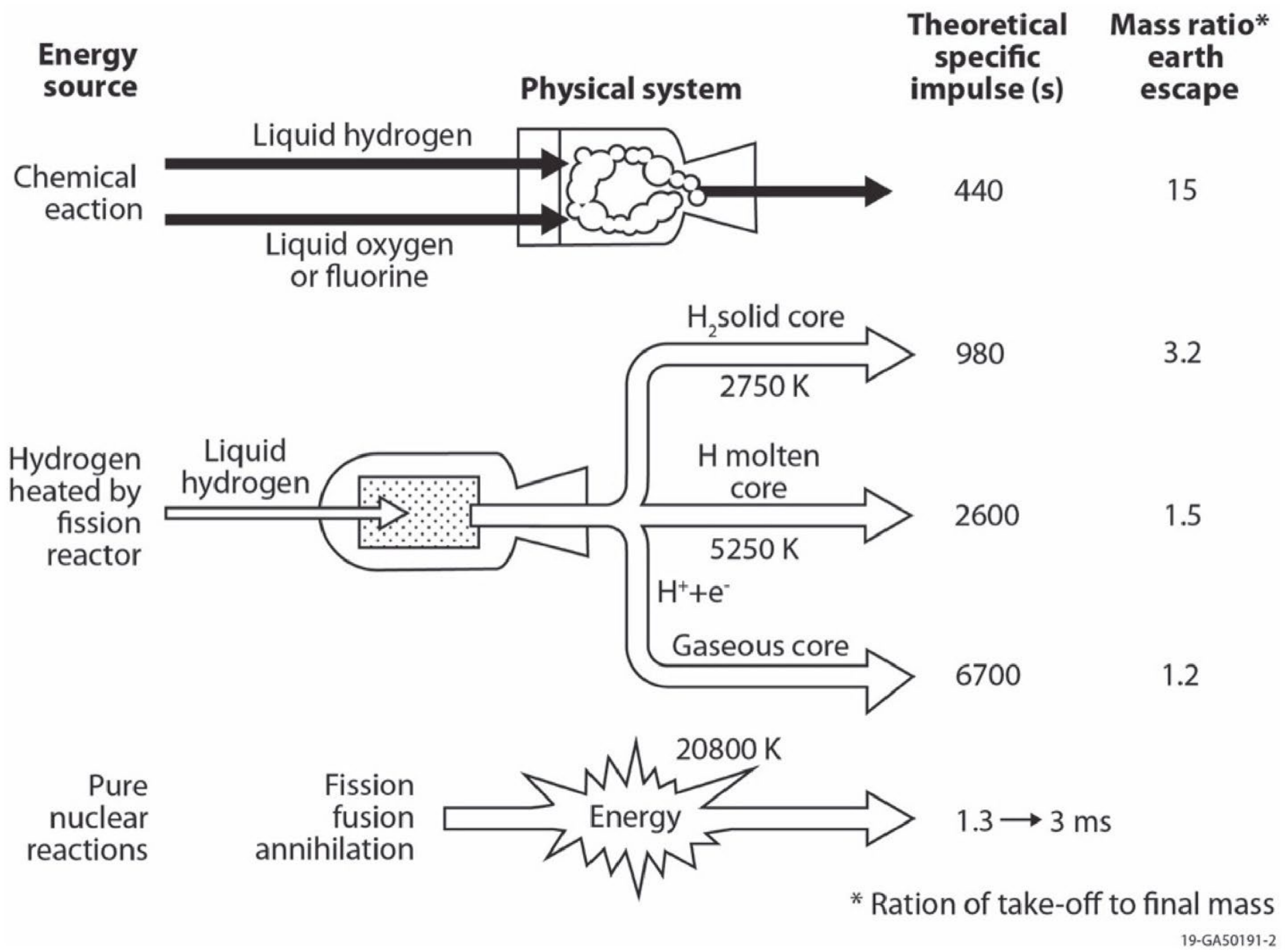


Image source: https://www.intechopen.com/chapters/71396

Propellantless Propulsion Technologies

- Mass Drivers
  - Railguns
  - Coilguns
- Space Tethers
  - Electrodynamic
  - Momentum Exchange
  - Formation
  - Universal Orbital Support System
- Solar Sails

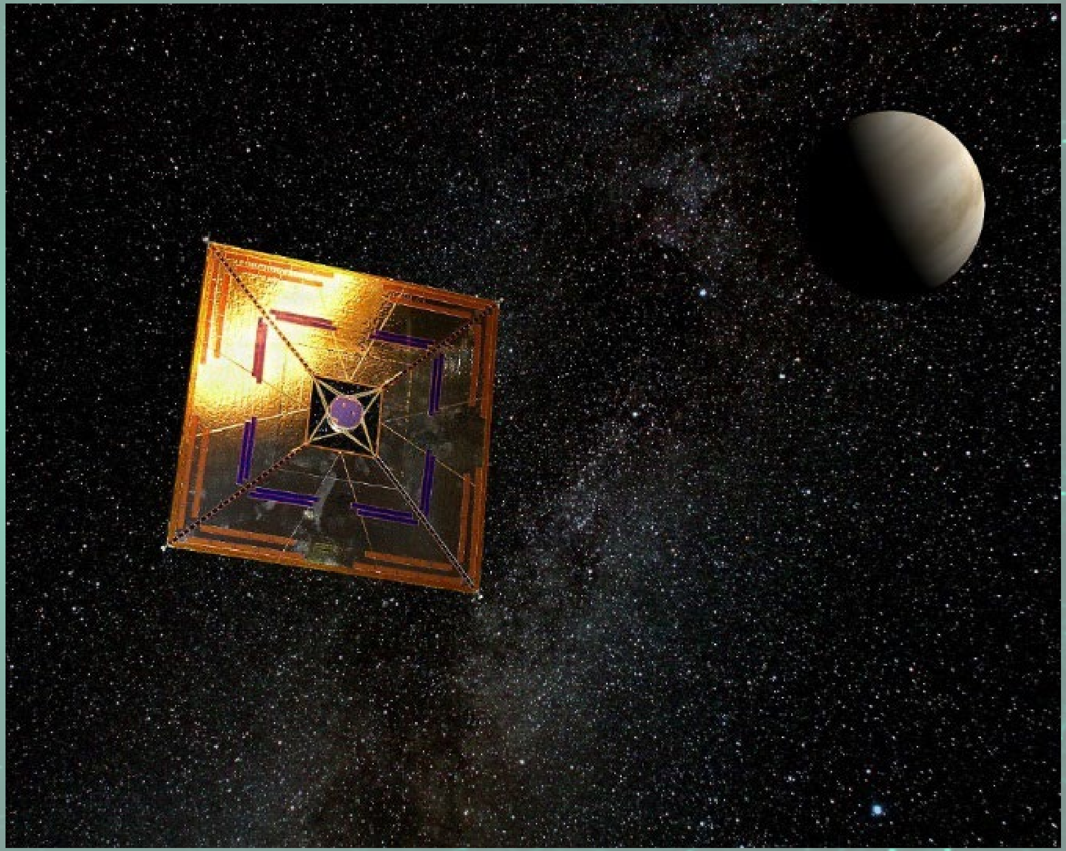


Image source: https://en.wikipedia.org/wiki/IKAROS#/media/File:IKAROS_solar_sail.jpg

Chemical Propulsion

Image source: https://www.nasa.gov/mission_pages/shuttle/flyout/shuttleachievements.html

Chemical Propulsion

- Very mature technology
- Works for launch (within an atmosphere[s]) or in space
- Significant energy stored (good for high acceleration to reach high velocities quickly)
- Fuel gets used up relatively quickly (especially compared to electric propulsion)
- Lots of mass required both in terms of fuel (and/or oxidizer) and support systems (tankage, pumps, etc.)

Chemical Propulsion – Solid Propellant

- Earliest forms date back to 13th century
- Designed for long-term storage and to launch reliably (applicable to the solid portion of hybrid rockets)
- Materials concerns
  - Different materials used
  - Manufacturing of propellant material (casting and AM)
- Geometry of casting (AM is an enabler here)
- Quality control testing
- Thermal protection

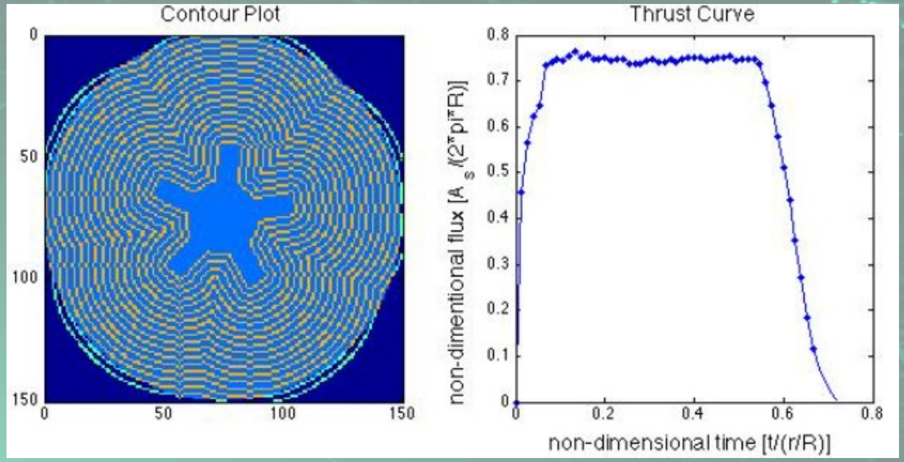


Image source: https://commons.wikimedia.org/wiki/File:Moon_ex.jpg

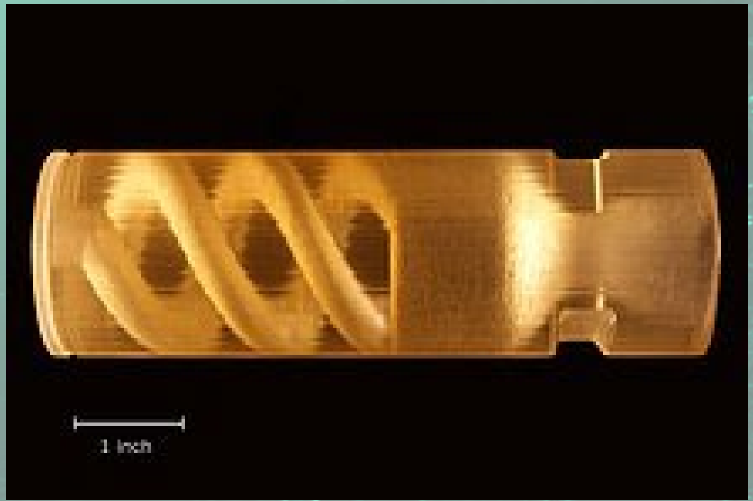


Image source: https://upload.wikimedia.org/wikipedia/commons/e/e2/3D_Printed_Hybrid_Rocket_Fuel_Grain.jpg

Chemical Propulsion – Monopropellants

- Hydrazine (the gold standard)
  - Most mature and used technology
  - Number of issues (toxicity, corrosion, etc.)
- Green monopropellants
  - Energetic ionic liquids
  - Nitrous oxide propellants
  - Hydrogen peroxide
- Catalysts
  - Present day (need heat)
  - Desired (room temperature)

Chemical Propulsion – Cold Gas Thrusters

- **Focus on nonreactive materials**
- Materials areas (propellants and support systems)
- Technology is mature, materials research optimizing existing items
- Any number of new materials are available now
- Supporting systems being largely evolved via AM

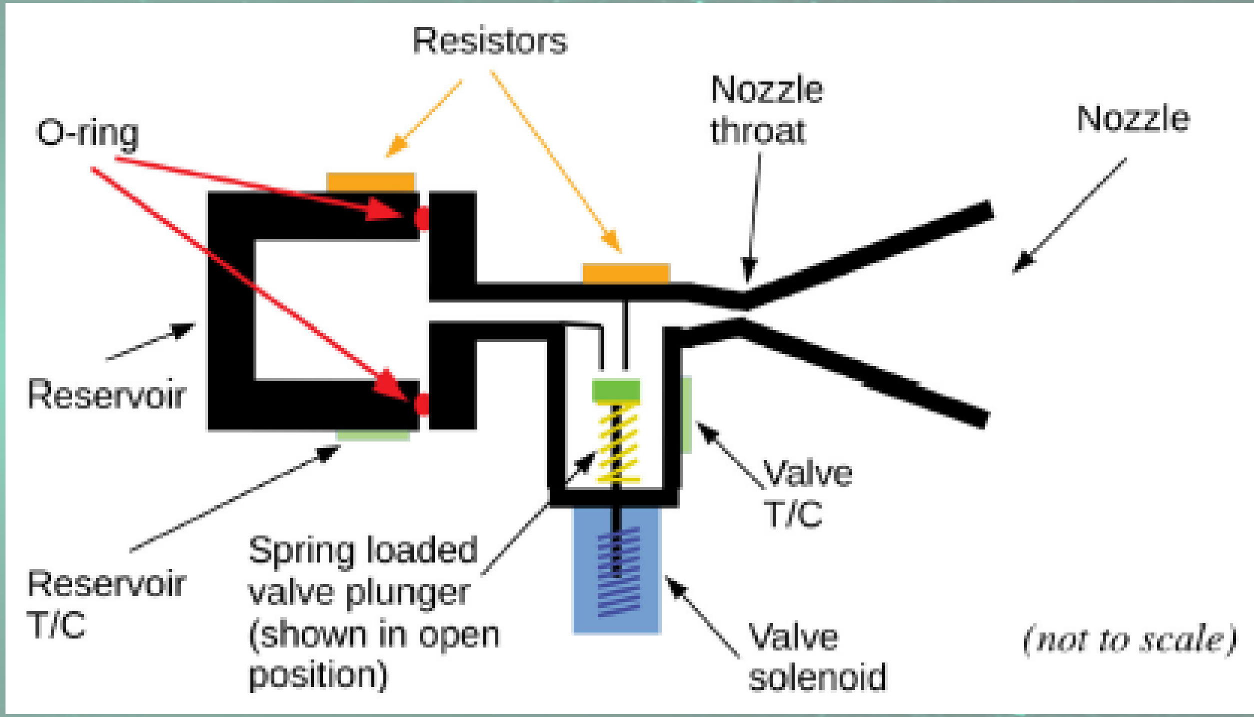


Image source:
https://www.frontiersin.org/articles/10.3389/fphy.2020.00389/full#:~:text=It%20was%20shown%20that%20the,power%20limitations%20of%20a%20cubesat

Chemical Propulsion – Liquid Propellants

- Oxidizers and fuels (addressed bi-propellants and tri-propellants)
- Dealing with liquid hydrogen (cryogenic materials issues)
- Dealing with liquid oxygen (not quite as cryogenic)
- Hypergolic propellants
- Materials issues addressed in next slide….

Chemical Propulsion – Universal Issues

- Motor casings and/or pressure vessels
- Nozzling
  - de Laval nozzles
  - Regeneratively cooled nozzles
- Sealing (high pressure and cryogenic issues)
- Quality control

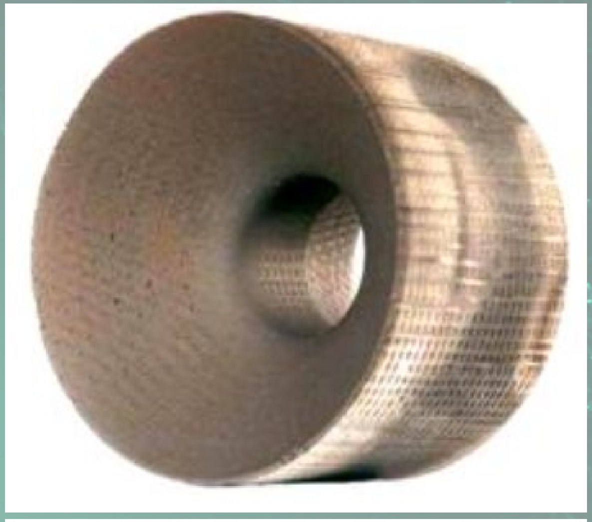


Image source: https://ultramet.com/propulsion-system-components/solid-rocket-engines/

Electric Propulsion

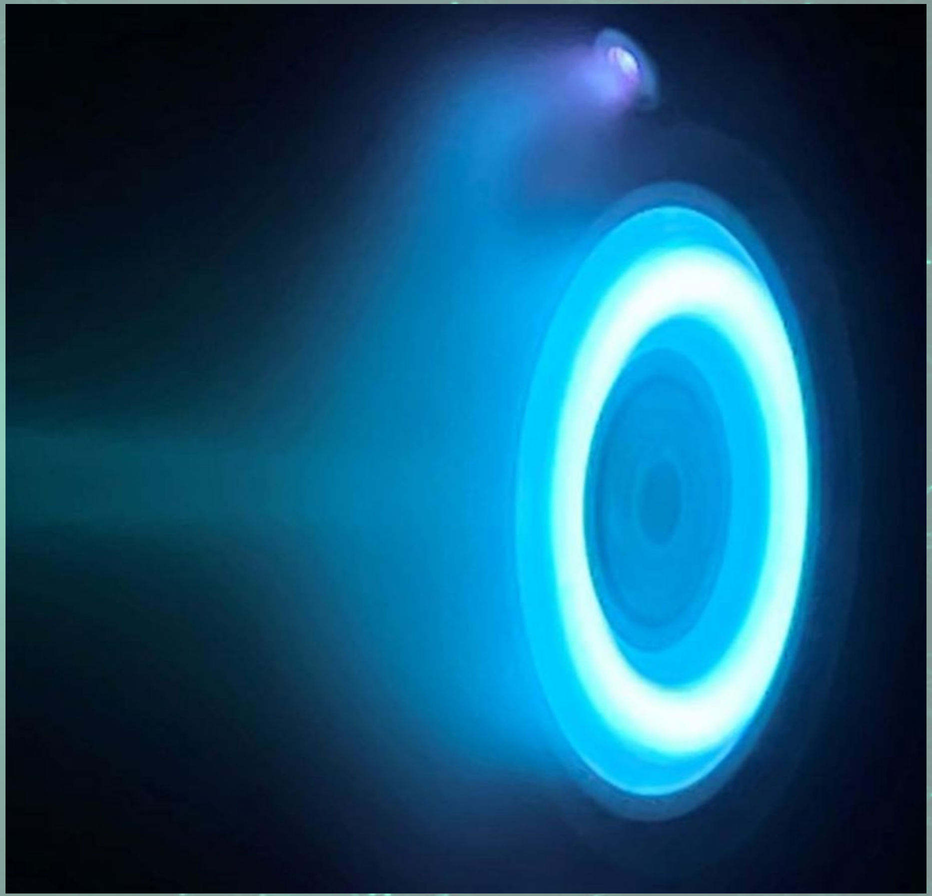


Image source: https://www.jpl.nasa.gov/images/pia24030-psyches-hall-thruster

Electric Propulsion

- Very mature to reasonably mature
- By and large, suitable only for in-space use (no atmosphere - possible exceptions include arcjets and resistojets)
- Very fuel efficient (exceptions include arcjets and resistojets)
- Low acceleration but can be run for very long times - can achieve very precise force levels (μN)
- Notable success was the Dawn mission (able to orbit, break orbit, and go into orbit of another object)

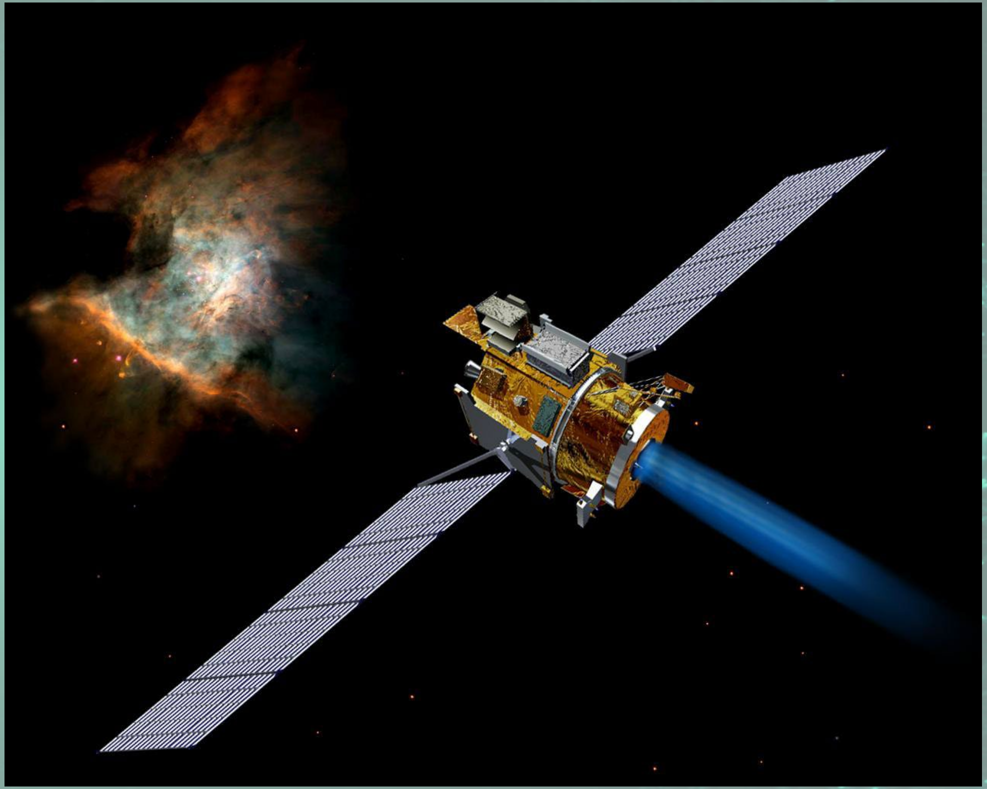
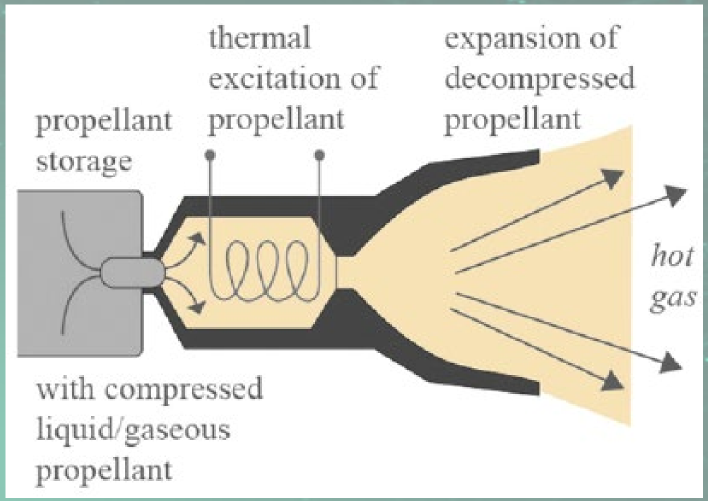


Image source: https://solarsystem.nasa.gov/missions/deep-space-1/in-depth/

Electric Propulsion – Electrothermal

- Combines propellants and electricity
- Includes arcjets and resistojets
- Uses heat (either resistive heating or an arc) to heat propellant gas
- Not necessarily efficient
- Materials concerns
  - Leveraging AM
  - Cathode materials
  - Miniaturization
  - Propellant gas



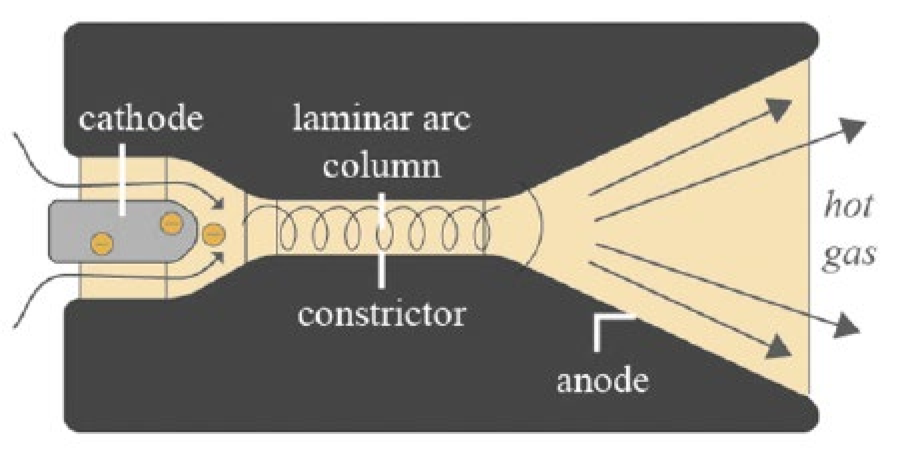


Image source: https://pubs.aip.org/aip/rsi/article/91/6/061101/957865/Ion-thrusters-for-electric-propulsion-Scientific

Electric Propulsion – Gridded Electrostatic Ion Thrusters

- In development since 1960s
- Propellant is ionized in discharge chamber (usually Xe)
- Ionized propellant accelerated by voltage between different grids
- These ions are ejected out of the engine
- To keep spacecraft from achieving a net charge, a cathode (neutralizer) is placed near the engine to emit electronic charge into the beam of ions to render them neutral

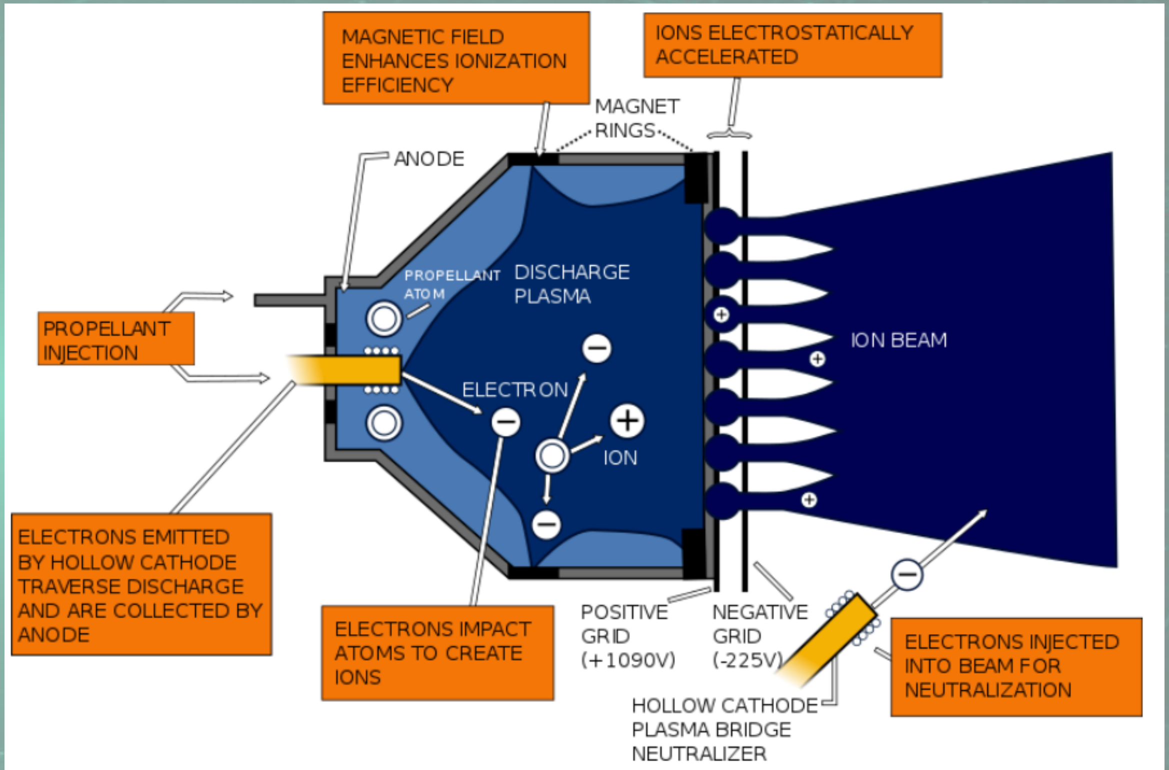


Image source: https://en.wikipedia.org/wiki/Ion_thruster#/media/File:Ion_engine.svg

Electric Propulsion – Hall Effect Thrusters

- Similar to gridded ion engines but architecture is smaller
- Xe most common propellant but can use a wider variety of propellants
- Flying in space since 1971 (Soviet Meteor satellite)
- In use on China's Tiangong space station
- Planned for use on NASA's Lunar Gateway
- Shorter lifetime than gridded ion engines

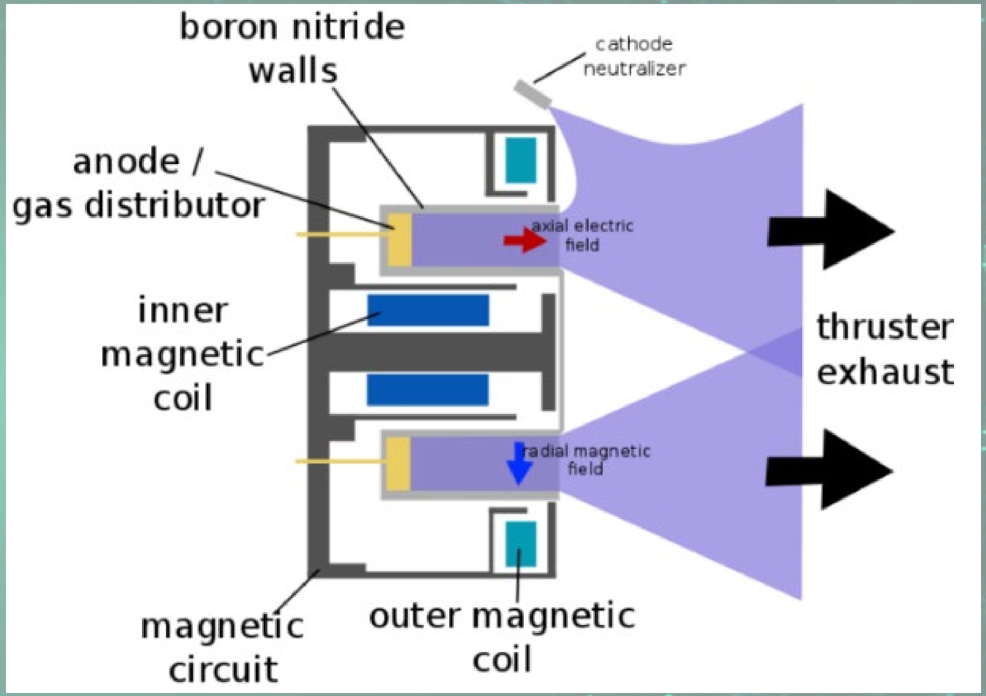
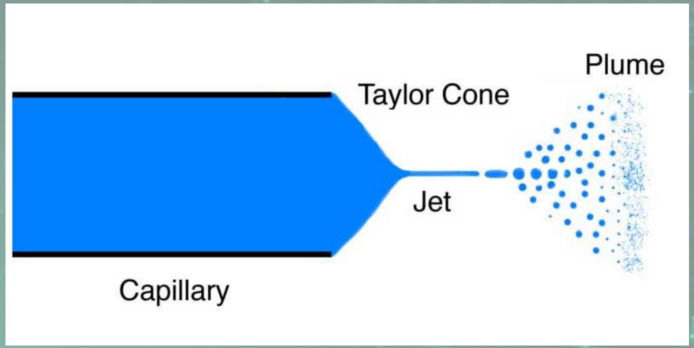


Image source: https://en.wikipedia.org/wiki/Hall-effect_thruster#/media/File:Wfm_hall_thruster.svg

Electric Propulsion – Field Emission

- FEEP uses room temperature liquid metals (e.g., In, Ce and Hg)
- Need fuels with high atomic numbers, low ionization potentials, and low melting points
- Metal flows through narrow tube or parallel plates
- Electric field applied between end of tube/plates and an accelerator to create a Taylor cone
- At a high enough voltage, positive ions emit from the cone tip
- Also needs a neutralizer
- Very low thrust (μN to mN), so used for altitude control



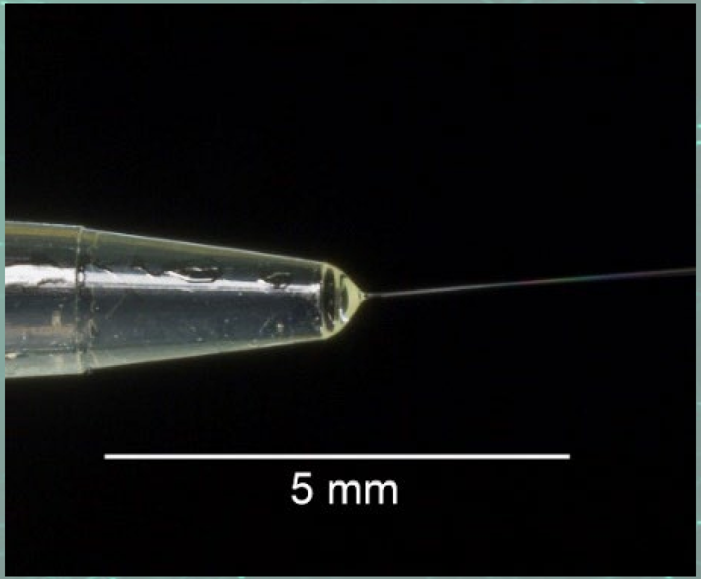


Image source:
https://en.wikipedia.org/wiki/Taylor_cone#/media/File:Taylor_cone.jpg

Electric Propulsion – Magnetoplasmadynamic Thrusters

- Also known as a MPD arcjet or a Lorentz force thruster
- Operates somewhat similarly to an arc welder
- Numerous propellants examined (Li offering the best performance)
- Efficient performance
- As cathode heats, it emits electrons which ionize a propellant
- The magnetic field interacts with the current flowing from anode to cathode and pushes plasma out, creating thrust (velocities in excess of 100 km/s possible)

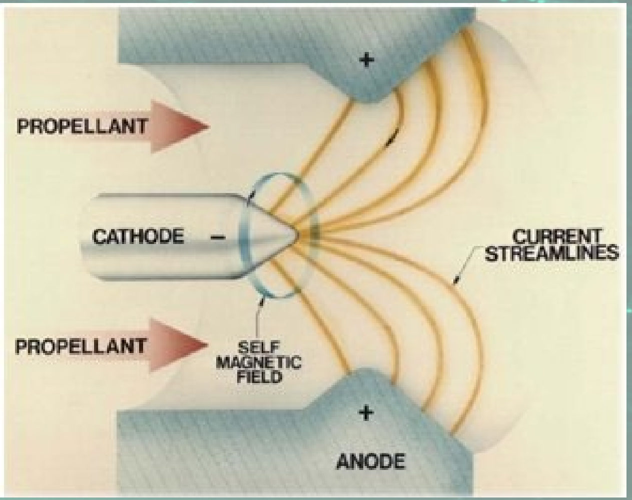


Image source: https://www.nasa.gov/centers/glenn/about/fs22grc.html

Electric Propulsion – Pulsed Plasma Thrusters

- Able to use a solid propellant source and an arc to ablate/sublimate material
- Material forms a plasma, allowing the flow of current (somewhat like a capillary discharge)
- Material/current flowing produces an electric field to expel plasma, creating thrust
- Varying current discharge time allows tailoring of thrust

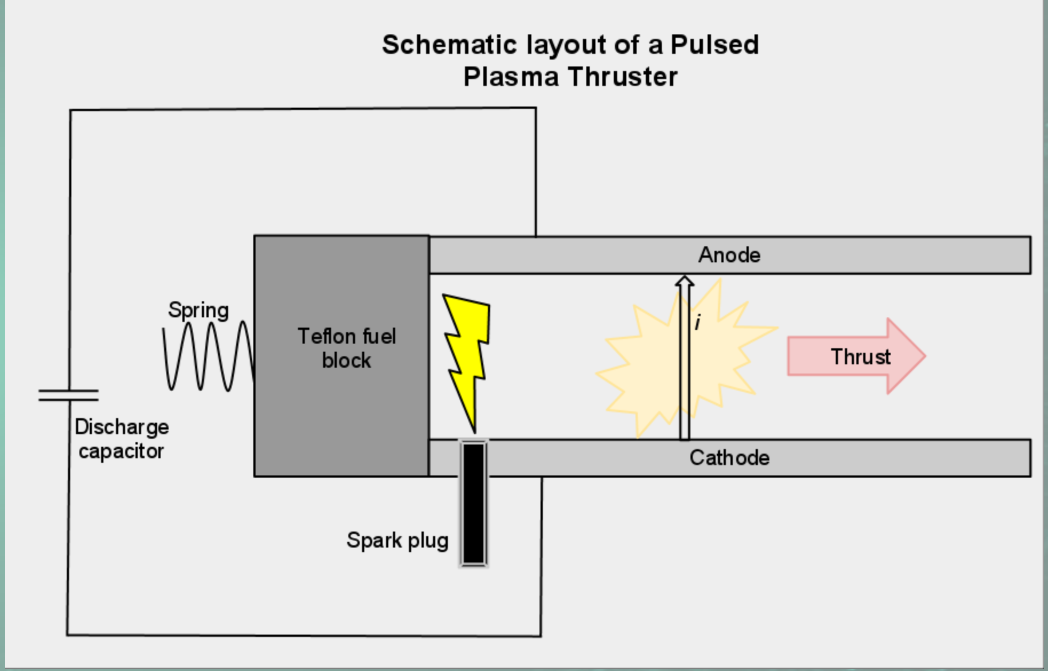


Image source: https://en.wikipedia.org/wiki/Pulsed_plasma_thruster#/media/File:SchematiclayoutofaPulsedPlasmaThruster.png

Electric Propulsion - Universal

- Electronics protection
- Alternative fuels
- Low work function insert materials
- Anode/cathode materials (battling erosion)
- Sputtering
- Electromagnetic compatibility
- **TESTING**
  - Particle density in space - ~1 atom/cm^3 (average)
  - Not many places on Earth can achieve this…

Nuclear Thermal Propulsion

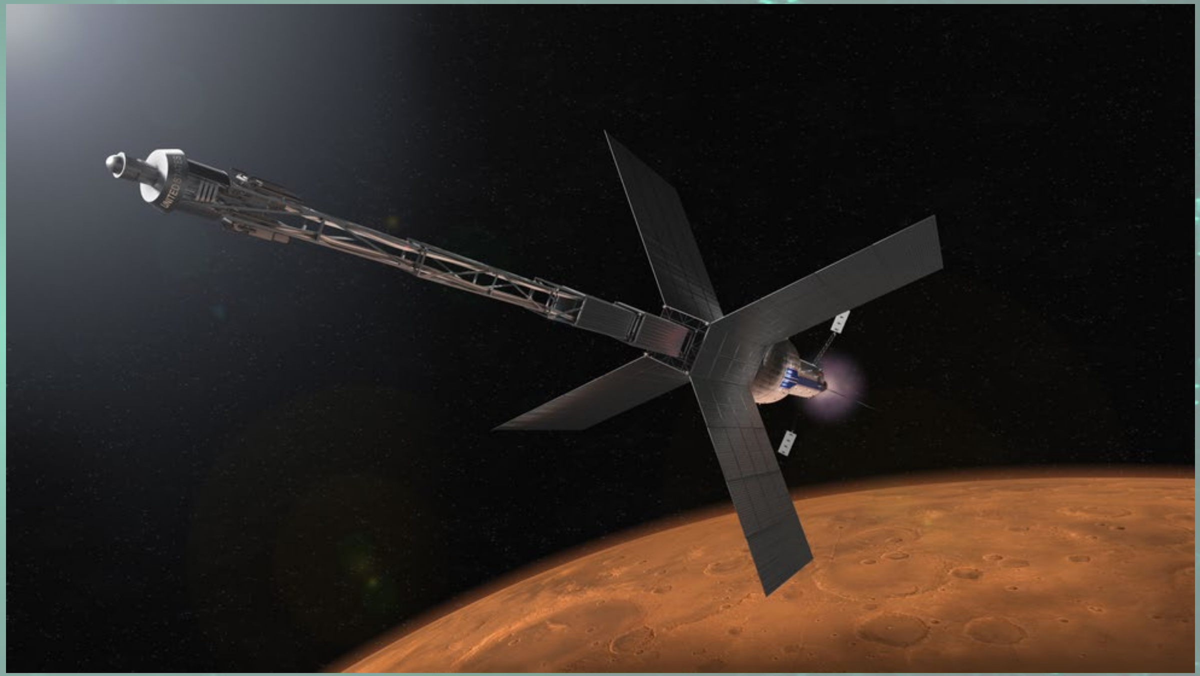


Image source: https://www.nasa.gov/directorates/spacetech/nuclear-propulsion-could-help-get-humans-to-mars-faster

Nuclear Thermal Propulsion

- An already complicated situation becomes more complicated…
- Basic operation is:
  - Launch with a lot of cryogenically stored hydrogen
  - Launch with a lot of radioactive material
  - Operate reactor (heat it up)
  - Flow hydrogen into reactor, heats up, expands through nozzle, producing thrust

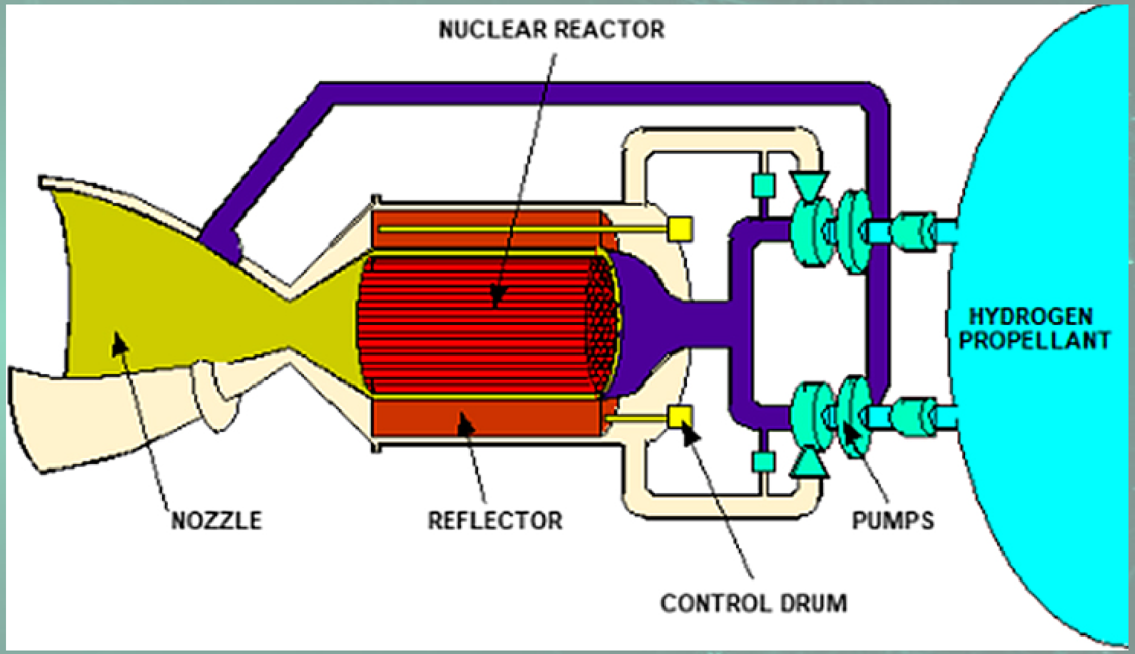


Image source: https://www1.grc.nasa.gov/research-and-engineering/nuclear-thermal-propulsion-systems/typical-components/

Nuclear Thermal Propulsion

- Individual systems include:
  - Hydrogen storage
  - Reactor fuel assembly
  - Control rod/drum assembly
  - Reflector
  - Nozzling
- Materials issues include:
  - Graphite and carbon-based fuels
  - Hydrogen storage
  - Hydrogen corrosion

Propellantless Propulsion

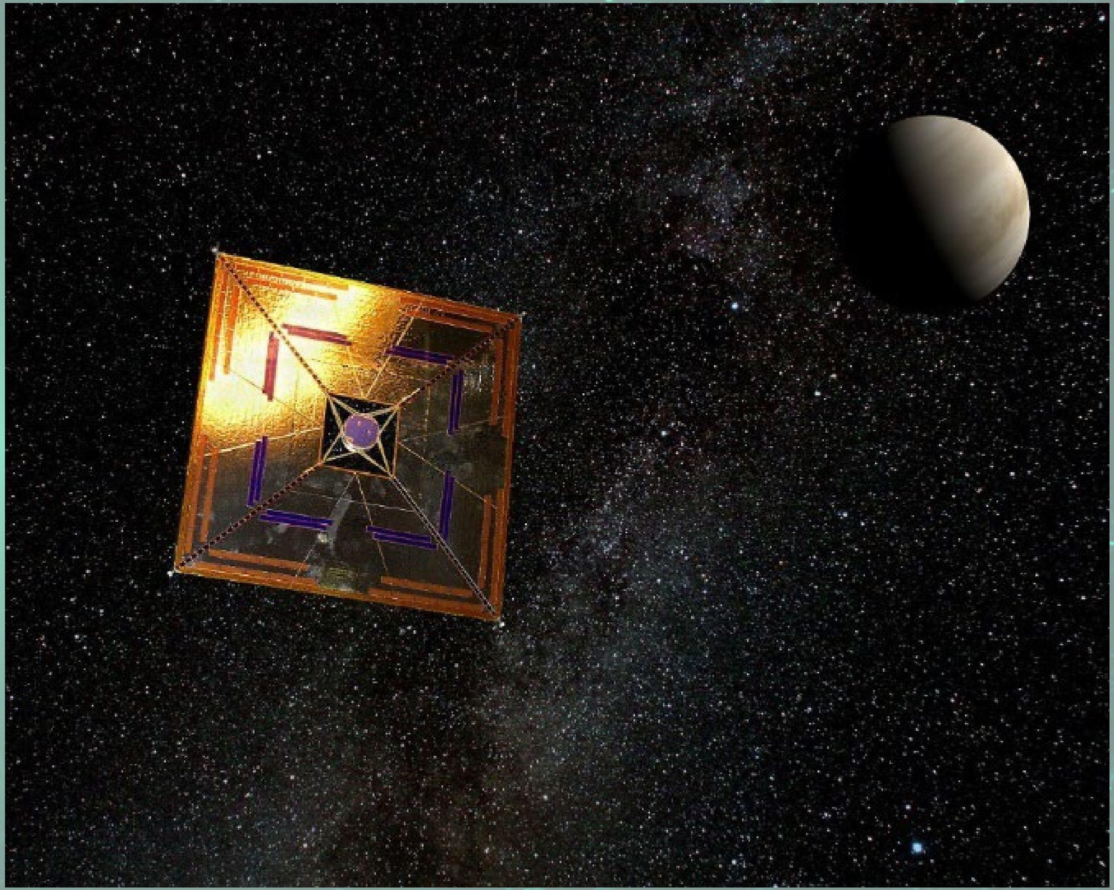


Image source: https://en.wikipedia.org/wiki/IKAROS#/media/File:IKAROS_solar_sail.jpg

Propellantless Propulsion

- Range from matured on Earth to initially being tried out in space
- No stored propellant needed (in the traditional sense)
- This section acts as a “catch-all” for other propulsion methods that reach the TRL cutoff but do not fall neatly into the other sections

Propellantless Propulsion – Mass Drivers

- Mature technology on Earth, not in a vacuum
- Come in two types - railguns and coilguns
- Capable of very large accelerations in a short length
- Require very large electric currents and very fast switching
- Very high current draw large arcs (erosion)
- Railguns involve high-speed sliding contacts (tribological problems)
- Thermal management a problem

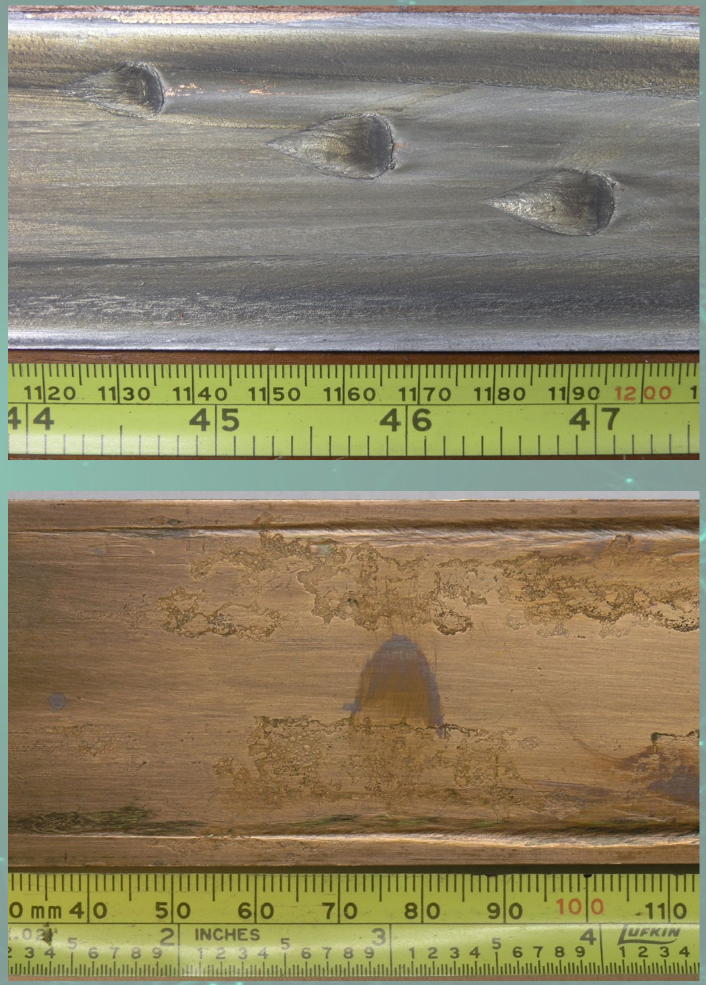


Image source: https://ieeexplore.ieee.org/abstract/document/5639091

Propellantless Propulsion – Solar Sails

- Long proposed, only recently tested
- Most common configuration is aluminized mylar (metallized sails)
- Offer very high potential velocities
- Issues include:
  - Mechanical (substructure and sails)
  - Thermal management
  - Radiation damage
  - Integration of enabling technologies
  - Optimizing to leverage the solar spectrum
  - Need to make them **MUCH bigger**

Image source:
https://science.nasa.gov/heliophysics/programs/solar-cruiser

Propellantless Propulsion – Space Tethers

- Long envisioned, example of demonstration in 2022 via TEPCE (NRL)
- Different tethers, different purposes
- NRL's tether provides power and propulsion
- Composite tether material used to optimize conductivity and material strength
- Need to make stronger and more electrically conductive (metallics with structural tether material)

Image source: https://apps.dtic.mil/sti/pdfs/AD1161973.pdf

Customers and Funding Mechanisms

Image source: https://www.armyupress.army.mil/Journals/NCO-Journal/Archives/2018/February/Funding-Terrorism/

United States Based

- NASA
  - Technologies related to exploration
- NSF
  - Basic technologies
- DoD
  - Applied and basic technologies
  - USN, USAF, USSF, MDA, and DARPA
- U.S. Private Industry
  - SpaceX, Blue Origin, Firefly, etc.

Foreign Agencies

- European Space Agency (ESA)
  - Storable, hybrid, solid, and methane base propulsion
- China National Space Agency (CNSA)
  - Publicly available, material limited
  - Development of "innovative" propulsion technologies, propulsion for space debris cleanup, in-orbit servicing
- Russian Federation Space Agency (Roscosmos)
  - Research focus on Angara and enhancements to Soyuz
  - Suffering from effects of Ukraine war
- Japanese Aerospace Agency (JAXA)
  - Research focus on electric propulsion

Summary/Wrap-Up

- The United States and near-peer nations are continuing to push development in the Earth/Moon system.
- Advances in technology (such as AM) are driving lower mass and miniaturized propulsion systems.
- Alternative fuels will increase the availability of propulsion systems to a wider range of missions (private, exploratory, and military).
- Cubesat (and micro/nanosat) formation flying will be driving the production of production-scale, miniaturized propulsion systems – we will need to be ready for this.